AN ASSESSMENT OF ANAEROBIC DIGESTION IN U.S. AGRICULTURE

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Anaerobic digestion is a biological process in which bacteria break down organic matter to produce methane, partially stabilized effluent, and other products. Although the process has been advocated as a source of fuel, feed, and fertilizer, its widespread adoption in American agriculture is doubtful. The cost and complexity of most digestive systems make them difficult to incorporate in agricultural operations. Although site specific applications may be feasible, these will not have a major impact on the agricultural sector. As a source of energy, there is little possibility of anaerobic digestion providing even a small percentage of national energy requirements.

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SUMMARY AND CONCLUSIONS

Anaerobic digestion is a biological process in which bacteria break down organic matter in the absence of oxygen to produce a methane-rich gas and a partially stabilized sludge. The gas can be used as a substitute for natural gas while the sludge can be used either as a fertilizer or as a feed ingredient for livestock. The process has been viewed as a means of using renewable resources to produce energy, fertilizer, and feed. Since some environmental nuisances, such as manures or processing wastes, can serve as inputs, anaerobic digestion is also advocated as a means of converting undesirable materials to valuable products.

Both technical and economic considerations militate against widespread adoption of anaerobic digestion in American agriculture. Technical factors include the difficulty of gathering and storing input materials, reliability of the process, and finding suitable uses for the outputs. Economic factors include the large capital investment required, the high cost of outputs, and economies of scale favoring large over small installations.

Although the technology will not be generally adopted, site specific applications may be feasible. Large-scale cattle feeding and dairy operations, and certain meat and crop processing operations, may provide concentrated sources of inputs for use in digesters. But widespread application of anaerobic digestion technology in American agriculture does not now, nor in the foreseeable future, appear economically feasible.

AN ASSESSMENT OF ANAEROBIC DIGESTION IN U.S. AGRICULTURE

by Ted Thornton [1]

INTRODUCTION

Anaerobic digestion is a biological process in which bacteria break down organic matter in the absence of oxygen to produce a methane-rich gas, a partially stabilized sludge, and other potentially valuable products.

The process of anaerobic digestion is common in nature. Natural gas is created by bacteria acting on decaying plant and animal material over thousands of years. Swamp or marsh gas is the result of bacterial decay of organic matter in a lake bed.

Progress in scientific investigation over the past two centuries has made possible human control of anaerobic digestion. Rural Korea, Taiwan, and India utilize small digesters to produce methane gas. Larger digesters are used in Europe. Anaerobic digestion is used at many municipal treatment plants in the United States for waste stabilization and disposal. In American agriculture anaerobic lagoons are a component of some livestock waste management systems.

Anaerobic digestion is receiving increased attention as a process with agricultural applications. It is viewed as one method of using renewable resources and unwanted agricultural wastes to augment scarce national energy supplies. It is also regarded as an environmentally acceptable method of waste treatment, as a way of conserving fertilizer materials to replace increasingly expensive chemical fertilizers, and as a source of protein for animal feed.

Technology to apply anaerobic digestion exists. New, lower cost digestion systems are being extensively investigated by a number of universities. Equipment and components for anaerobic digestion systems are available on the market and some private firms are prepared to custom design and install digestion facilities. Greatly expanded application of the technology to agricultural situations could occur in a short time should conditions warrant such application.

To date, however, anaerobic digestion has had only very limited application in American agriculture. There are significant economic and structural barriers to adoption. These barriers, and the possibility of their alleviation, are a major focus of this report. Specifically, this study aims to describe the technology of anaerobic digestion and various anaerobic digestion systems in use, and identify the economic considerations affecting feasibility of anaerobic digestion systems. The nature of adoption of anaerobic digesters in American agriculture is also

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discussed, and the feasibility and potential impacts of expanded use of anaerobic digestion technology in American agriculture is assessed.

This report is based on an extensive review of literature and interviews with the Nation's anaerobic digestion experts. Although a considerable body of literature on anaerobic digestion has developed, much of the work has been of a technical nature with only cursory interest in economic or practical feasibility. Extensive interviews were conducted with university and private researchers to supplement findings from the technical literature. Trips were made to several sites to observe the agricultural applications of the technology. The findings of this report on system applications and economic feasibility are the results of these observations, interviews, and literature reviews.

This study could aptly be described as a "state of knowledge" assessment rather than a technology assessment. The intent was to ascertain the current status of the arts and agricultural applications of anaerobic digestion prior to the launching of studies of costs, returns, and impacts associated with specific agricultural uses of the technology. Future studies, if made, will focus upon the specific situations as well as upon alternatives to the anaerobic digester in converting agricultural products into energy.

THE ANAEROBIC DIGESTION PROCESS

Biological Agents

On the surface, anaerobic digestion appears to be an automatic process with common organisms routinely consuming organic matter. This apparent simplicity, however, masks a complex biological system. This system, and the factors which influence it, must be understood to realize the full potential of digestion.

Anaerobic digestion depends upon two groups of bacteria living harmoniously in the same environment (3-581). [2] The first of these groups of bacteria is called the "acid formers." The acid formers convert biodegradable organic compounds, such as fats, carbohydrates, and proteins, into simple organic compounds, such as acetic acid, propionic acid, carbon dioxide, and hydrogen (20-182, 3-581). The second of these groups, the methanogenic bacteria, converts simple organic compounds made by the acid formers into methane and carbon dioxide.

The acid forming group comprises both faculative and obligate anaerobic bacteria (20-182, 183). They are generally capable of rapid reproduction and are relatively insensitive to changes in environment. Their role in the digestion process is to convert the incoming materials into a form which can be used by the methanogenic bacteria.

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[2] The first number in parenthesis gives the appropriate citation in the bibliography. The second number gives the page in the reference.

The methanogenic bacteria have more demanding environmental requirements. They are among the most anaerobic organisms in nature, unable to tolerate even the slightest trace of oxygen. Most of these bacteria grow quite slowly. They exhibit an extreme degree of substrate specificity, each type being able to use only one particular substance as an input. A mixed population of bacteria is needed to digest complex mixtures of organic compounds.

Methanogenic bacteria are generally unable to react to changes in their environment. Instead of existing species adapting to the environmental change, new cultures tolerant to the new conditions often have to form. The slowness of this process limits the flexibility of the digester.

Functional Requirements

The environment in the digestion chamber must be able to support the simultaneous growth of both the acid forming and methanogenic bacteria. Among the more important environmental factors are the nutrient composition of the incoming material, temperature, pH, and solids retention time.

Material. Almost all organic materials can serve as inputs to the anaerobic digestion process. The input material must satisfy the nutritional demands of the populations of bacteria and provide the nitrogen, phosphorus, trace minerals, and biodegradable carbon required. For best results, the input material should be free of foreign matter such as sand and stone, vegetable matter high in fiber content, and toxic substances. The particular kinds of inputs used in the digester are not as critical as consistency of the input mix. As the input mix changes, new cultures of bacteria usually must be formed to utilize the new substrate, thereby interrupting the digestion process.

Input materials differ substantially in their ability to meet the nutrient requirements of the digestion bacteria. They differ in the volume and quality of gas they can produce. Most digesters proposed for American agriculture, and most research work being done, are based on animal manures. This reflects both the suitability of animal manures for digestion and the concentration of manures within feedlots and other livestock and poultry production facilities.

Temperature. Anaerobic digestion occurs most rapidly at two temperature ranges, namely,

Mesophilic range: $90^{\circ}F - 100^{\circ}F$ ($32^{\circ}C - 38^{\circ}C$)

Thermophilic range: $125^{\circ}F - 135^{\circ}F$ ($52^{\circ}C - 57^{\circ}C$)

Precise limits to these ranges have not been established. Although digestion proceeds more rapidly in the thermophilic range, the mesophilic range is generally preferred. Mesophilic bacteria are capable of digesting most materials satisfactorily. Some investigators have noted difficulties in the thermophilic range with foul odors and in dewatering the sludge.

Thermophilic bacteria appear to be quite sensitive to small variations in temperature (20-177). Also, thermophilic operations may require more energy than is justified by the increase in biological action.

Anaerobic digestion can occur at temperatures below the mesophilic range. The lower temperatures would require lower energy requirements for heating, but would entail slower process rates, longer retention times, and larger storage facilities.

pH. The pH range for anaerobic digestion is about 6.6 to 7.6. Outside these limits, the efficiency of the anaerobic process decreases rapidly. The importance of pH arises from the sensitivity of the methanogenic bacteria to extreme pH ranges. Equilibrium in the digester requires that the methanogenic bacteria absorb the acids as rapidly as they are produced by the acid formers.

Time. The average length of time that the cultures of bacteria remain in the digester usually ranges from 3 to about 30 days. Lower retention times may not allow sufficient time for the bacteria to reproduce with the result that the cultures of bacteria would be flushed out of the system.

Factors influencing retention time include the temperature of the process, the volatility of the total solids entering the digester, the concentration of total solids in the raw sludge, the degree of stabilization required, and the rate of gas production required (39-321). Operation in higher temperature ranges reduces retention times. The amount of volatile solids influences the length of time needed for digestion. Lowering retention times increases gas production per unit of volume of the digester, while increasing retention times increases the total product of gas per unit of weight of the input material.

Balance. When the digestion process is in balance, the methanogenic bacteria consume the products of the acid forming bacteria as rapidly as produced. The populations of both groups of bacteria adjust with changes in the digestion environment. Since the acid forming bacteria adjust more rapidly than do the methanogenic bacteria, the populations may become unbalanced.

Sudden changes in temperature, in organic loading, or in the nature of the input material may cause a temporary imbalance. Prolonged imbalance may result from the presence of toxic materials, an extreme drop in pH, or slow bacterial growth during start up. In an extreme case, an over production of acids may inhibit the methanogenic bacteria, which can then allow a further increase in acid concentration. The end result of this process could be destruction of the methanogenic bacteria, creating a "stuck" digester. There is no single way to restore a stuck digester. Often the only way is to clean it out and start again with fresh input material.

The literature gives several indicators of satisfactory digestion (3-583). These include:

1. The methane content of the gas lies between 55 and 75 percent, and the sum of methane and carbon dioxide constitute approximately 95 percent of the gas produced.

2. Solids concentrations are below about 15 percent with the optimum 8-10 percent; volatile matter comprises about 50 percent of the solids.

3. pH of the digested sludge is between 7.0 and 8.0.

4. The concentration of volatile acids is below about 2,000 mg/liter.

5. The alkalinity of the material is above about 2,500 mg/liter.

Products

The two major products of anaerobic digestion are the biogas and the effluent. Both can be used without further processing or they can be processed for specific uses.

Biogas. The biogas is about 50 percent to 70 percent methane and 30 percent to 50 percent carbon dioxide, and contains trace amounts of other gases, most notably hydrogen sulfide. The volume of gas produced varies according to the type of raw material used and the environmental conditions within the digester. The maximum yield of gas cannot exceed 8 to 9 cubic feet per pound of volatile solids placed in the tank, or slightly more than double the volume per pound of volatile solids digested (3-590). Vegetable wastes generally produce more gas than animal wastes. However, the biogas resulting from plants has a higher proportion of carbon dioxide, thereby reducing its heating value as a fuel (10-160, 161).

The energy value of the biogas depends on the proportion of methane it contains. Methane has a heating value of about 1,000 Btu per cubic foot. Assuming biogas which is 60 percent methane, 1,000 cubic feet of biogas is equivalent to about 600 cubic feet of natural gas, 6.4 gallons of butane, 5.3 gallons of gasoline, or 4.6 gallons of diesel oil (3-605, 606).

Effluent. The effluent from a mixed digester is a liquid slurry which is partly stabilized and has an inoffensive odor. It may be separated into a liquid and a thick sludge.

Anaerobic digestion preserves the nutrients in the input material and puts them in a more available form in the effluent. The effluent also contains part of the culture of bacteria which makes it a source of single cell protein. The nitrogen content of the effluent will be essentially the same as the input material, while its phosphoric acid content will vary between 0.3 percent and 1.5 percent (3-584). The effluent will require storage and handling facilities. It remains high in biological oxygen demand and is still a pollutant.

FEATURES AND APPLICATIONS OF ANAEROBIC SYSTEMS

An anaerobic digester can be regarded as a source of energy, fertilizer, or feed, and as a method of waste treatment in agriculture. Each of these purposes may involve substantially different types of supporting equipment. Likewise, different inputs will require different facilities. Manures will be treated differently than vegetable materials. The exact type and purpose of a digester, and, therefore, the type of associated installation, vary by location.

The need for supporting equipment is often underestimated in the literature. Substantial costs and changes in usual farming methods and practices may be necessary to accommodate a digester. Several decisions must be made regarding the use and purpose of output. The appropriate equipment and procedures will depend upon purposes and inputs of a particular site.

Digester Designs

A digester is basically a container designed to hold the input material and the cultures of microorganisms. It must be airtight, must permit the loading and unloading of materials, and, if the biogas is wanted, it must have a means of collecting the gas produced. Structures meeting these requirements can range from a used oil drum buried in the ground to a sophisticated structure with pumps, heating coils, insulation, and automatic input and output handling equipment.

Designs. The simplest design structure is the batch digester (fig. 1). Organic material is placed in the container and the container is sealed. As the digestion process proceeds, the inputs separate into biogas, scum, supernatant, digested solids, and undigestible solids. When the digestion process is complete, the residual contents are removed and the container is filled with fresh organic material.

The scum consists of undigestible materials that float to the top. The supernatant is a liquid material situated next to the scum. The sludge is composed of the digested remains of the incoming materials. Undigestible solids include residue such as sand and dirt which entered the digester and settled to the bottom. Most digesters have some means of mixing the materials to eliminate the various layers.

A simple batch digester is unsatisfactory for most agricultural applications in the United States. Because of its ability to handle only one load of inputs at a time, it is inflexible in input handling and produces gas only sporadically. There is no gas production during loading, unloading, and start up. Other designs give greater flexibility.

One simple modification of the batch digester is the batch load process. This process consists of operating two batch digesters simultaneously (fig. 2). As one unit operates and produces gas, the other is unloaded and fed. Thus, one unit is in operation at all times. This arrangement permits a more continuous use of inputs and supply of outputs.

Figure 1
Simple batch digester

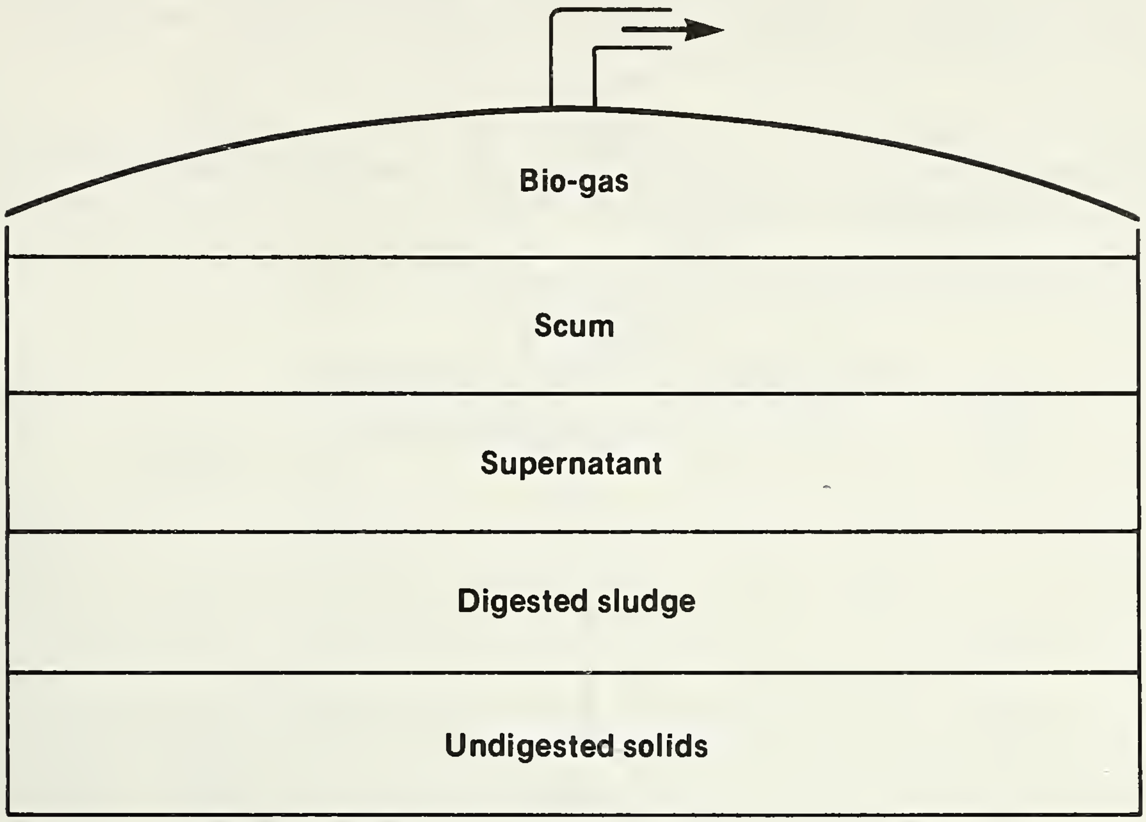
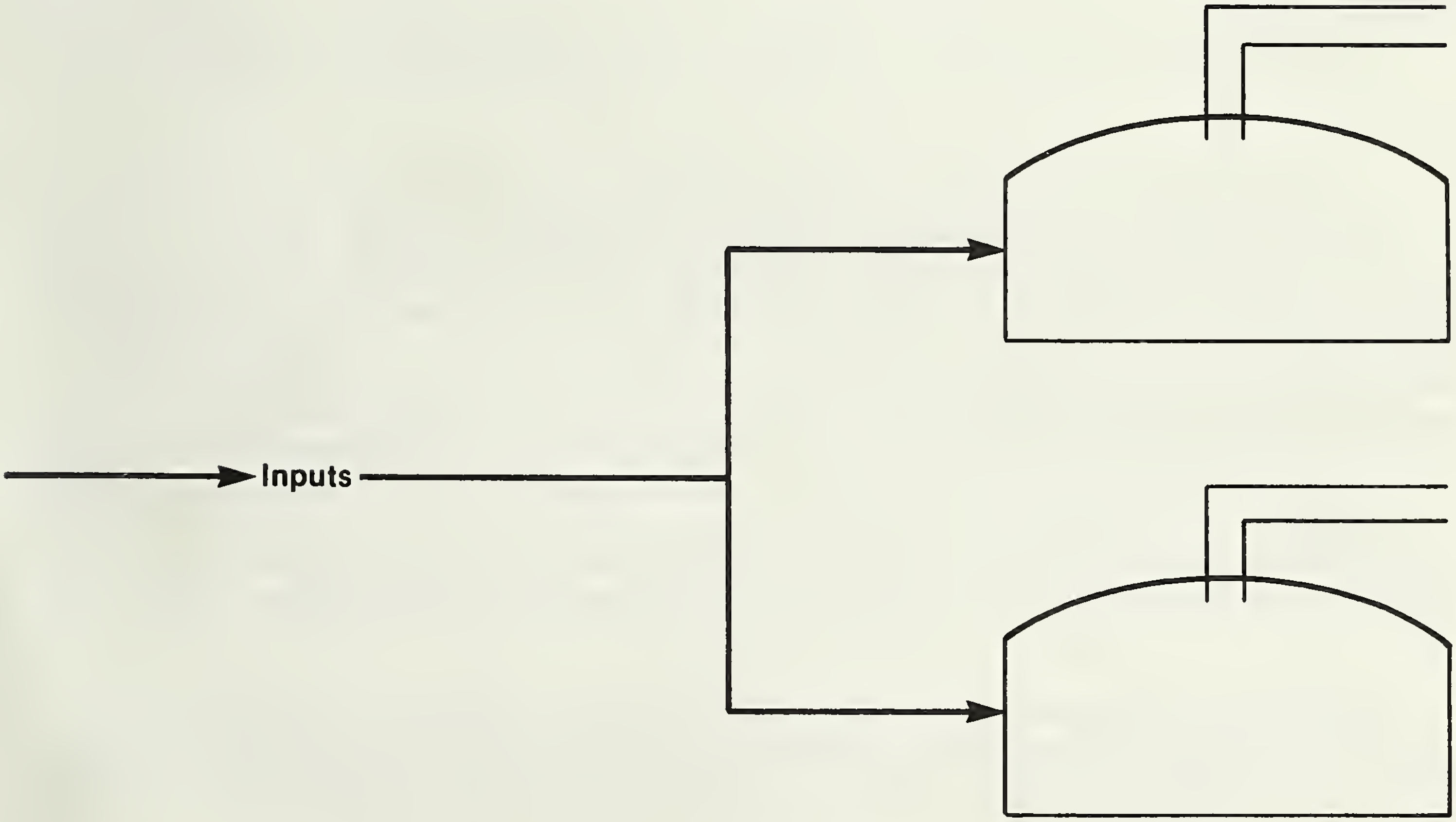


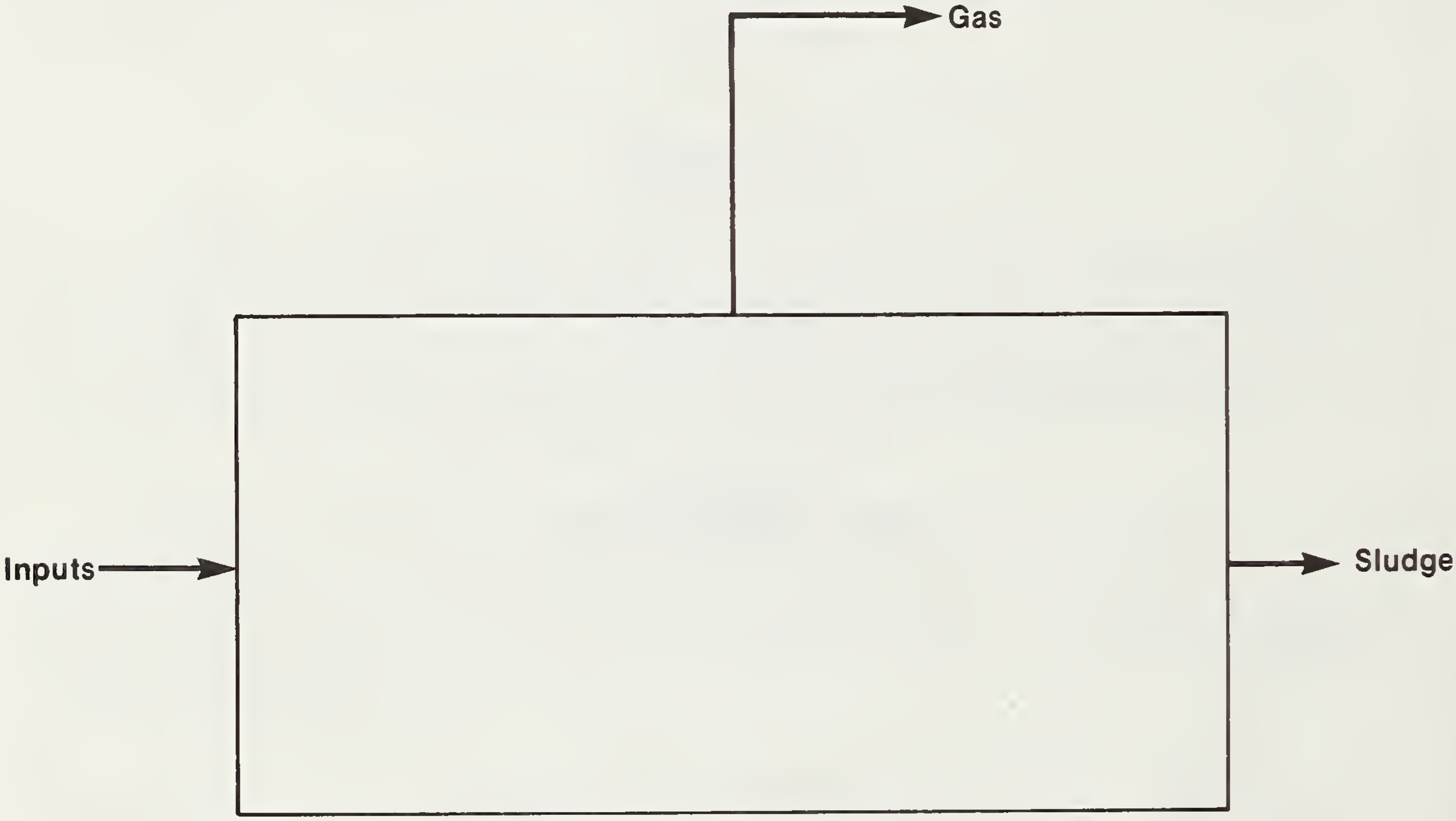
Figure 2
Batch load process



Continuous flow digesters constitute a fundamental change in design of digesters. For the continuous flow process, material is placed in the digester periodically or continuously without interrupting the digestion process. This procedure eliminates the irregularity in gas production associated with the batch digester.

One form of the continuous flow digester is the plug flow or displacement design (fig. 3). In this process, input materials are placed in one end of a longitudinal digester and spent materials are forced out of the other end. If there is no mixing in the digester, the input material digests as it moves from one end of the tank to the other.

Figure 3
Plug flow or displacement digester

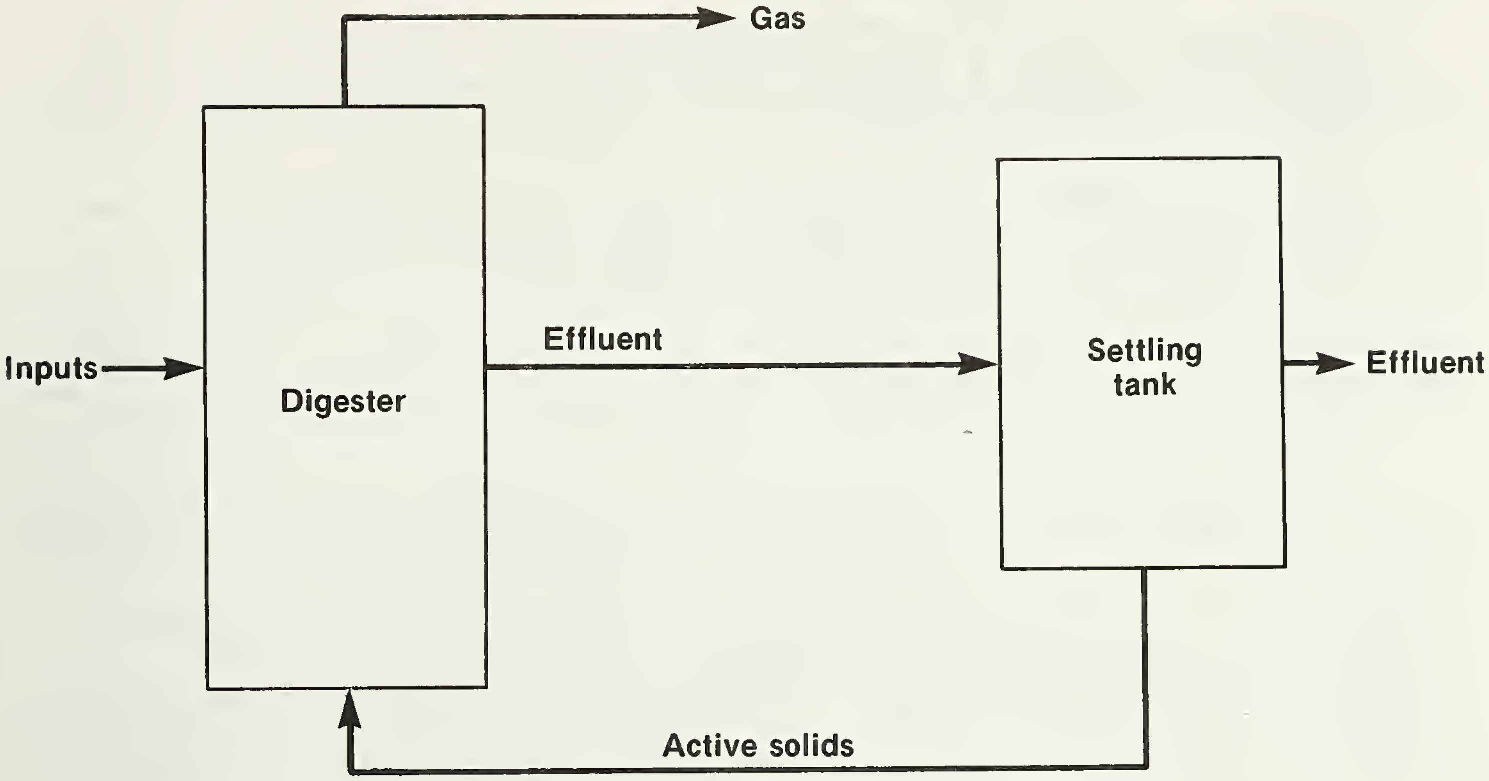


The anaerobic contact process is another continuous flow modification. This process is designed to retain the biologically active population in the digester while removing the spent effluent (fig. 4). The effluent from the digester is fed into a settling tank where the biologically active solids are separated and fed back into the digester. The biological population is thereby retained and the retention time is decreased.

These four concepts represent the most common forms of anaerobic digestion design. More experimentation may result in new and improved designs. A great deal of variation is possible within each design. The type and size of digester actually installed is very site specific.

<u>Agitation</u>. The digestion process can be improved by periodic mixing or stirring of the tank contents. Without stirring, the digester contents tend to stratify. A thick scum on the top can hinder the digestion process and prevent gas from rising. Some vegetable matter can settle to the

Figure 4
Anaerobic contact process



bottom and slow the digestion process. Agitation improves the homogeneity of the digestible material and insures that the bacteria come into more even contact with their feed supply.

No standard method for stirring has emerged. The mechanisms can be simple or sophisticated. Mixing can be accomplished by a hand-operated chain or plunger inserted through the top of the digester; by power driven, automatic rotors; pumps; or by recirculation of the biogas through the material being digested.

Heating and insulation. Although heating and insulation are not strictly necessary, operation in the mesophilic and thermophilic range will require both. Methods of heating vary widely. The source of energy to heat the digester may be the biogas itself with part of the biogas being channeled into burners or heat exchangers. If the biogas is used to power an internal combustion engine, waste heat from the engine may be used as a heat source. For some installations, an external source of energy may be desirable.

The requirement for heat can entail a substantial energy input into the digestion process. Calculations of the energy value of the biogas produced, therefore, must consider the needs of the digester itself.

Input Materials

Input materials must be collected, stored, and placed in the digester. It may be necessary to preprocess some input materials before digestion.

Collection. The collection of materials for input into the anaerobic digestion process presents technical and economic barriers to the adoption of anaerobic digestion technology.

In general, agricultural crops may be collected in three ways for use in energy production. First, they may be harvested in conventional ways and then converted into energy instead of being used for food, feed, or fiber. Second, they may be harvested in conventional ways, and the residue remaining following extraction of food, feed, or fiber products can be used for energy. Third, "energy farms" may use techniques and equipment specifically designed for whole crop collection and conversion to energy.

The equipment, farming practices, and institutional structures to grow, harvest, process, and market agricultural crops relate primarily to the use of the crops as food, feed, or fiber. These uses are not always directly compatible with their use as an energy source. For example, corn hybrids have emphasized grain yield at the expense of plant mass. For many bioconversion techniques, greater plant mass would be desirable. Corn harvesting equipment is designed to collect the grain and leave the rest of the plant in the field. For bioconversion, collection of the entire plant would be desirable.

The use of crop residues as an input material for bioconversion is often advocated. They are regarded in some sense as having no alternative use, as being abundant, and as offering a possible new source of income to the agricultural sector. But there are substantial barriers to collecting and removing some residues from the land. Some of the residue can be collected jointly with harvest for food, feed, or fiber. Many crop residues, however, would necessitate gathering materials widely scattered in space. This would likely involve additional or modified equipment and additional field operations. Increased demands would be placed on the farmer's time, often when he is busy harvesting the crop. Residues are often seasonal, while inputs for digestion are needed throughout the year. Thus, some sort of storage would be needed. If storage is prolonged, the crop materials could deteriorate, reducing their value for digestion.

Crop residues have uses other than that as an energy source. Not the least of these uses is as a source of soil nutrients or as a means of erosion control if left in the field. For many soil conditions, some crop residue is required to control erosion. Other uses of crop residues, such as feeding to livestock, have long been the subject of research. The alternative use values of residues have not been fully evaluated.

An "energy farm" is currently a concept rather than a reality. Under this concept, crops are grown strictly as a source of energy and harvested for processing at a central facility and converted to gas. This idea has some advantages, foremost of which are that operations could be designed for one purpose only (energy production), plant species could be selected and developed on the basis of their desirability for bioconversion, and profitable use possibly could be made of lands now marginal or submarginal for use in food or feed production.

One advantage of manures for inputs is that they are somtimes collected in connection with other agricultural operations. Feedlots and confined dairy operations provide concentrated sources, and are generally regarded as likely sites for the installation of an anaerobic digester. But even when manures are already collected they may not be immediately available for use. For example, if the feedlot has earth floors, the manure may be mixed with undesirable quantities of dirt, sand, and other inorganic materials. Weather could act adversely on the manure. If the pens are scraped and cleaned infrequently, the manure may decompose and dry before it reaches the digester for processing, thereby lowering its value for digestion. At the present time the best circumstance for the anaerobic digestion of animal manures appears to be a closed confinement facility with slotted floors and facilities to move manure to the digester site, or other similar installation to facilitate collection and transportation of manure.

The cost to the feedlot operator of changing his manure collection and handling practices to accommodate a digester must also be considered. A feedlot owner will not install an anaerobic digester unless it can be clearly shown that the installation is profitable or is needed to solve an odor or other waste management problem.

Storage and handling. Most inputs will arrive at the digester on a periodic basis, ranging from several times a day to once a year. To permit timely loading of the digester, some form of storage may be necessary. The type and size of storage unit will depend on the type and amount of material processed and on the frequency of input collection.

Many materials will have to be processed prior to entering the digester. Water should be added to manure to optimize the solids content. Coarse organic materials may be chopped to permit greater decomposition and flow through the system. Materials may be mixed and/or heated before being placed in the digester.

Input materials must be transferred from the storage area to the digester. Although it is possible to do this by employing labor, most systems for use in American agriculture will employ some sort of powered mechanism. Pumps and augers are the most common devices for digester charging. If the digester is not fed continuously, some form of timing mechanism may be installed to periodically turn the equipment on and off.

Energy Production

The biogas is the energy output of the anaerobic digester. The biogas may be stored and cleaned before use, used locally or in a centralized transmission system, or converted to other energy forms such as electricity.

Cleaning the biogas. The biogas consisting of 50 percent to 70 percent methane can be used for many purposes including burning and as a fuel for internal combustion engines. It may also be cleaned by several common processes to produce almost pure methane.

A primary advantage of removing the carbon dioxide from the biogas is the improvement in the fuel value per cubic foot, which results in a reduction in the amount of storage needed per Btu. If facilities such as burners and internal combustion engines are available which can operate on natural gas, removal of the carbon dioxide will reduce the need to have these facilities altered.

The biogas will often contain trace amounts of hydrogen sulfide. Because of its strong offensive odor, hydrogen sulfide can be valuable in detecting the presence of gas leaks. But hydrogen sulfide is very corrosive and may over time corrode storage facilities, piping, and burners. If the biogas is used to power an internal combustion engine, the hydrogen sulfide could do significant damage. Removing the hydrogen sulfide is a relatively simple process but will entail some additional costs.

It is not always necessary for the biogas to be purified. For biogas use near the digester, such as on-farm heating of water or buildings, the raw biogas may be preferred to incurring the cost and effort needed to install and maintain gas cleaning facilities. Also, internal combustion engines can be modified to run on mixtures with substantial carbon dioxide content.

Storage. Because the amount of biogas used may vary with the time of day or time of year, some form of storage for the gas may be required. The biogas cannot be liquified at ambient temperatures at any pressure. Therefore, unless very expensive cooling equipment is installed, the storage necessarily will be in the form of gas.

Gas storage can be accomplished by equipping the digester with a floating cover. As gas production continues, the gas is trapped under the floating dome and the dome rises, thereby providing gas pressure. Large inflatable bags in lagoons have also been used as gas storage facilities. Expansible steel gas tanks and compression facilities are more elaborate and expensive.

Uses of the gas. Biogas has the potential for being used in most applications where natural gas is used. One immediate application is as a source of energy to heat the digester. Unless the digester is well designed and insulated, a substantial amount of the produced energy could be lost because of the requirement for heat.

Biogas is best adapted to fixed uses of power. It is difficult to compress the gas to the extent necessary to allow it to power a machine such as a tractor for reasonable lengths of time with portable gas containers. Water and building heating are often mentioned as likely uses for the gas. An internal combustion engine used to power an electrical generator or a pump for irrigation purposes are also possibilities.

Anaerobic digestion can be used to provide energy for distribution in a centralized transmission system. Pipeline-quality methane from manure is technically feasible. But rather rigid specifications must be met in use of natural gas pipelines. Typically, gas eligible for pipelines must be at least 98 percent methane and not more than 2 percent carbon dioxide. If the gas contains other elements, they either must be present in minute amounts or else removed. The gas must also be pressurized before it can be injected into the pipeline, often at a pressure of several hundred pounds per square inch. The initial capital cost of such an operation would be high. It would also require a considerable amount of labor to operate and supervise a pressure system.

Fertilizer Conservation

Fertilizer from anaerobic digestion is usually in the form of digested animal manures. The advantages of this fertilizer are usually mentioned with regard to the original animal manure. Thus the effluent is more uniform in quality than the incoming manures. The effluent has an inoffensive odor, and there is a minimal attraction of pests such as flies.

The digested slurry will require facilities and operations similar to those found in conventional manure handling operations. The liquid slurry can be used as part of a liquid manure handling system, or it can be dewatered and handled much like regular manure. In either case, digestion does not necessarily eliminate the need for storage and treatment facilities such as lagoons and spreaders.

Feed Production

The slurry from the digester can be dewatered and used as a protein feed supplement for livestock. For use as feed it must be dewatered, stored, and mixed with other feed ingredients. The dewatering may be done by lagooning or by powered centrifuge. The effluent may also be used to grow aquatic plants, to feed single cell protein in lagoons, or to provide feed in enterprises such as catfish farming.

Waste Management

Anaerobic digesters can facilitate better management of animal waste. The digester converts raw manure into a nearly stabilized product with a less offensive odor. The fact that a digester produces other potentially valuable products makes it a candidate for a least cost waste management system.

As is the case with fertilizer conservation, anaerobic digesters do not eliminate the need for manure handling and storage facilities. The manure still has to be collected and brought to the digester. Once digested, the manure will have to be processed in conventional ways. Anaerobic digestion, therefore, does not eliminate the need for a complete waste management system, such as lagoons and ponds, if the need for this existed before. Further, water must usually be added to manures to achieve the required solids concentration for digestion, thereby increasing the volume of material to be disposed of. The effluent also pollutes lakes and streams and cannot be disposed in waterways in large quantities without environmental damage.

ECONOMICS OF ANAEROBIC DIGESTION

The extent to which anaerobic digestion systems will be adopted in American agriculture will depend on their technical and economic feasibility. From a technical standpoint digestive systems of various degrees of complexity are feasible although there may be need for developing new systems to meet specific technical or economic requirements. Whether new technical developments in the application of anaerobic digestion occur, however, will depend primarily on economic considerations.

Initial investments in anaerobic digestion systems can range from a few thousand to several million dollars. Some investigators have tended to underestimate the costs involved by assuming that equipment is readily available secondhand or can be home built. Also, the biogas and sludge are often valued at the digester without asking if there might be feasible uses for them at the site, or what processing, storage, and transportation requirements would be necessary. In addition, requirements for such items as pumps and meters, and factors such as labor and depreciation, are often ignored.

This section will review three sets of cost data that have appeared in the literature to indicate the economic feasibility of anaerobic digestion systems. The first set, developed by Burford and Varani (8), is for a system which produces pipeline-quality methane from the manure of large feedlots. The second set of cost data, developed by Jewell and his colleagues (28), is based on digestive systems for 40- and 100-cow dairies and for a 1,000-head beef feedlot. The third set, developed by Bailie (5), considers digesters of several sizes which could be applied to different sizes of operations. These three sets give representative cost data for large-, medium-, and small-scale operations using manure as an input.

Burford-Varani System

The system proposed by Burford and Varani is designed for use in the Four Corners area of Colorado, Utah, Arizona, and New Mexico and reflects local conditions. It is based on the assumption that a private firm or cooperative will collect manure from nearby feedlots and sell the purified gas to pipelines and the digested sludge to farmers as fertilizer. Concentrations of cattle feedlots located near existing natural gas pipelines and a local market for the sludge, conditions that exist in parts of the Four Corners area, are necessary prerequisites for the cost estimates.

A block diagram of the Burford-Varani system is presented in figure 5. The system has components for feed preparation, digestion, heating, sludge dewatering, water purification, residue disposal, and gas purification, compression, and disposal. The specifications for each component and the equipment involved can be found in reference (8).

Capital costs for installations to treat the manure from 50,000, 100,000, and 150,000 head of beef cattle are given in table 1. Substantial equipment costs, ranging from $1.7 to $4.9 million, are required. Most of the engineering cost estimates are linear with respect to size. The largest costs are for the digesters, lagoons, piping, concrete work, and land excavation required.

Tables 2, 3, and 4 give estimated costs of gas production of $2.40, $2.09, and $1.99 per thousand cubic feet (MCF) for installations designed for 50,000, 100,000, and 150,000 head of cattle, respectively. It is assumed that each pound of volatile solids placed in the digester will yield 4.75 cubic feet of methane after purification. Assumed gas sales are 1,235 MCF/day for the 50,000-head unit, 2,469 MCF/day for the 100,000-head unit, and 3,703 MCF/day for the 150,000-head unit.

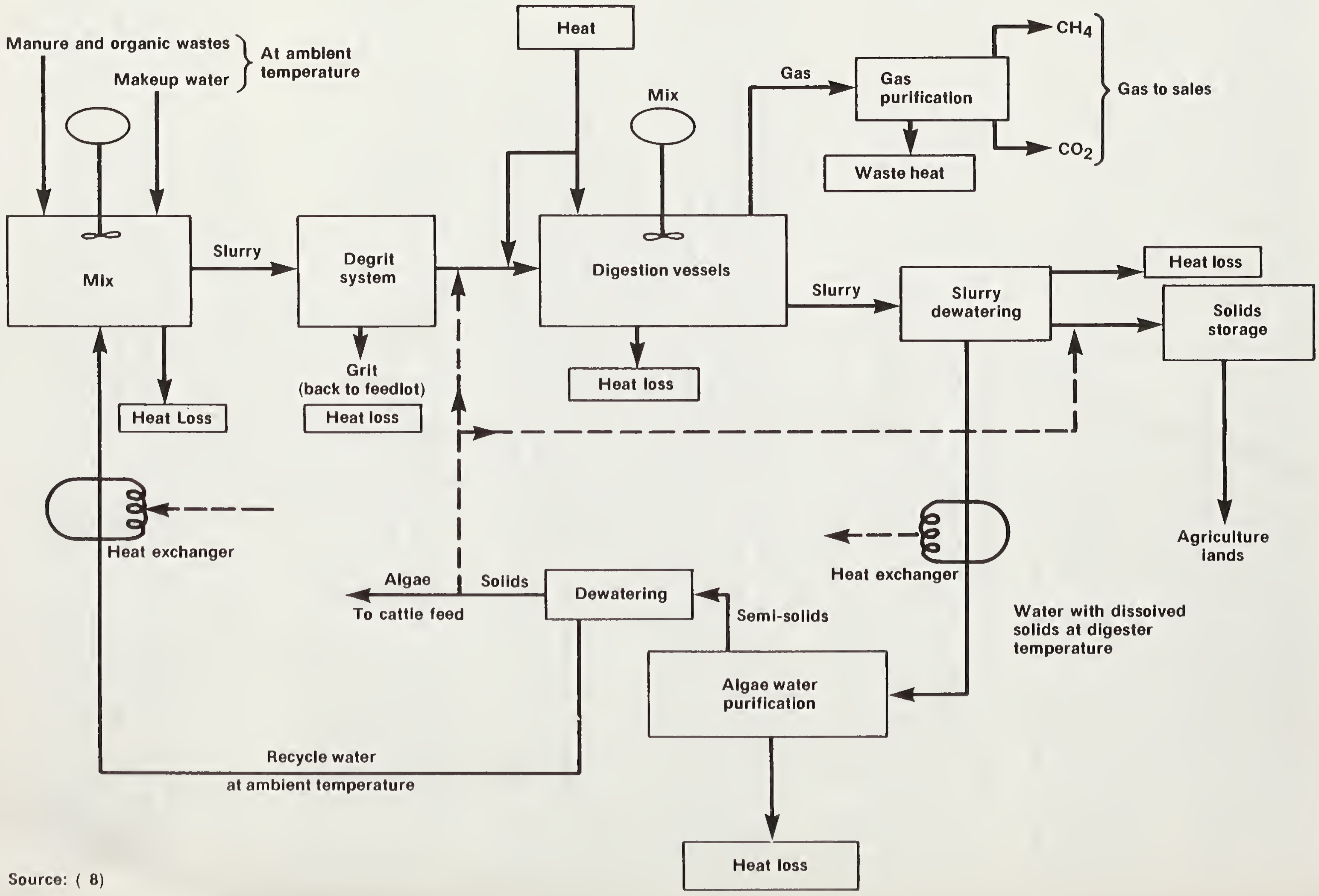
For each size operation, the cost of the manure represents the major direct production cost. Manure is given a value because of the unique manure handling practices in the Four Corners area. Most feedlots are able to dispose of their manure by selling it to local farmers for application to soil. Arrangements vary, but the result is that the manure has a value. The figure of $2.00 per ton represents the net cost of the manure purchased from the feedlot following allowances for transportation to the site, and revenue from the sale of digested sludge to local farmers. If it were possible to install this system in areas where manure had no alternative use value, gas cost per MCF would fall to $1.85, $1.54, and $1.53 for the 50,000-, 100,000-, and 150,000-head lots, respectively. These costs are competitive with proposed interstate natural gas prices of about $1.75 per MCF.

The remaining figures reflect the large-scale commercial nature of the operation. It is estimated that up to 11 persons, with appropriate salary and fringe benefits, are needed to run an operation. Other costs reflect the fact that the system is commercially run as an enterprise independent of the feedlot. No estimate was made for costs to a feedlot operator of owning and operating such a system as an integral part of the cattle feeding operation.

Jewell System

Jewell and others investigated the installation of anaerobic digestion systems for 40- and 100-head dairies and for a 1,000-head cattle feedlot (28). The system was designed for conditions comparable to those of New York State. The digester is assumed to be owned and operated by the dairyman or by the operator of the feedlot. The produced gas is presumed to be used locally with no provision for cleaning or pressurization.

Figure 5
Diagram of Burford-Varani system



Source: (8)

Table 1--Summary of capital costs for Burford-Varani system

Component	Capacity (head of cattle)		
	50,000	100,000	150,000
	Item cost		
	Dollars		
Brine pond	10,000	10,000	15,000
Four fermenters with liners and pond covers	333,000	667,000	1,000,000
Piping	187,000	373,000	560,000
Excavation, compacting, transportation, backfill	130,000	260,000	390,000
Auger and pit	13,000	27,000	40,000
Concrete work	140,000	280,000	420,000
Slurry mix tank	18,000	37,000	55,000
Sand washer	13,000	26,000	39,000
Sand classifier	13,000	26,000	39,000
Two covered gravity settling tanks	43,000	87,000	130,000
Digestor sparging mixer (inc. compressor)	40,000	80,000	120,000
Heat exchangers	43,000	87,000	130,000
Pumps	N/A	N/A	117,000
Dewatering & drying bldg.	30,000	45,000	45,000
Mobile home (office, lab. and so on)	50,000	50,000	50,000
Drying beds and harvest equipment	33,000	67,000	100,000
Gas compression equipment	108,000	217,000	325,000
Gas cleaning equipment	65,000	130,000	195,000
Recycle lagoon + algae pond	200,000	400,000	600,000
Sulfide scrubber + glycol drier	17,000	33,000	50,000
Gas metering equipment	20,000	20,000	20,000
Slurry make-up heater	5,000	5,000	5,000
Coal boiler	33,000	67,000	100,000
Instrumentation and controls	67,000	133,000	200,000
Scrubber and fan	6,700	13,300	20,000
Manure hauling equipment (two D6's)	30,000	60,000	60,000
Fence and hedge (1,000 ft. of work)	3,375	3,375	3,375
Land	27,000	53,000	80,000
Installation not included above	6,700	13,300	20,000
Installed equipment cost	1,684,775	3,269,975	4,928,375
Engineering (5.7% equipment cost)	96,032	186,388	280,917
Inspection ($4,000/mo. for 18 mo.)	72,000	72,000	72,000
Contingency (20% equipment cost)	336,955	653,995	985,675
Escalation (12% equipment cost)	202,173	392,397	591,405
Start up costs-evaluate (60 days direct product cost)	200,000	200,000	200,000
Capitalized investment costs	2,591,935	4,774,755	7,058,372
Working capital requirements (inventories)	50,000	50,000	50,000
Total required investment	2,641,935	4,824,755	7,108,372

Source: (8).

Table 2--Summary of costs for the Burford-Varani 50,000-head cattle site 1/

Parameter	Direct production cost	
	Dollars	
Materials and utilities:		
Manure (343 tons/day at $2.00/ton)	250,000	
Utility cost	143,908	
Labor:		
1 Engineer manager, lab technician, secretary	50,000	
7 Equipment operators	80,000	
Others:		
Fringe benefits (15% labor)	19,500	
Operating supplies (10% labor)	13,000	
General production expenses (20% of labor, operating supplies, repair)	35,339	
Other business expenses	50,000	
Total direct production costs		641,747
Fixed costs:		
Interest expense (total investment financed at 8 3/4% for 20 years)	226,794	
Depreciation (20 yr. straight line)	129,597	
Local taxes (2% equipment cost)	33,696	
Insurance (1% equipment cost)	16,848	
Maintenance and repairs (2% equipment cost)	33,695	
Total fixed costs		440,630
Total costs		1,082,377
Gas production		450,775 (MCF/yr.)
Gas cost per MCF		2.40

Source: Adapted from (8).

1/ The original cost estimates have been rearranged into categories more consistent with the concepts of direct and fixed costs used by economists, and the profit margin usually incorporated in engineering cost estimates was eliminated.

Table 3--Summary of costs for the Burford-Varani 100,000-head cattle site

Parameter	Direct production cost	
		Dollars
Materials and utilities:		
Manure (685 tons/day at $2.00/ton)	500,000	
Utility cost	287,816	
Labor:		
1 Engineer manager, lab technician, secretary	50,000	
8 Equipment operators	96,000	
Other:		
Fringe benefits (15% labor)	21,900	
Operating supplies (10% labor)	14,600	
General production expense (20% of labor, operating supplies, repair)	45,200	
Other business expenses	50,000	
Total direct production costs		1,065,516
Fixed costs:		
Interest expense (total investment financed at 8 3/4% for 20 years)	417,791	
Depreciation (20 yr. of straight line)	238,738	
Local taxes (2% equipment cost)	65,400	
Insurance (1% equipment cost)	32,700	
Maintenance and repairs (2% equipment cost)	65,400	
Total fixed costs		820,029
Total costs		1,885,545
Gas production		901,185 (MCF/yr.)
Gas cost per MCF		2.09

Source: Adapted from (8).

Table 4--Summary of costs for the Burford-Varani 150,000-head cattle site

Parameter	Direct production cost	
	Dollars	
Materials and utilities:		
Manure (1,027 tons/day at $2.00/ton)	750,000	
Utility cost	431,724	
Labor:		
1 Engineer manager, lab technican, secretary	50,000	
8 Equipment operators	96,000	
Other:		
Fringe benefits (15% labor)	21,900	
Operating supplies (10% labor)	14,600	
General production expenses (20% of labor, operating supplies, repair)	51,834	
Other business expenses	50,000	
Total direct production costs		1,466,058
Fixed costs:		
Interest expense (total investment financed at 8 3/4% for 20 years)	617,608	
Depreciation (20 yr. straight line)	352,919	
Local taxes (2% equipment cost)	98,568	
Insurance (1% equipment cost)	49,284	
Maintenance and repairs (2% equipment cost)	98,568	
Total fixed costs		1,216,947
Total costs		2,683,005
Gas production		1,351,595 (MCF/yr.)
Gas cost per MCF		1.99

Source: Adapted from (8).

Costs were estimated for conventional, batch-load, and plug-flow systems at each of the three installation sites. Detailed descriptions of the systems, equipment, and facilities used are given in reference (28). A summary of capital costs is given in table 5. The capital costs are not as detailed as those developed by Burford and Varani. Some additional items, such as landscaping or lagooning, may have to be considered in an actual installation, thereby increasing the capital costs.

Table 6 lists the assumptions used in computing the operating costs found in table 7. The assumptions reflect the fact that the system is designed for farm use. Labor requirements are 1 to 1 1/2 hours per day for the feedlot. Manure is not listed as a cost because it usually has no alternative use value in the Northeast.

The gas costs shown in table 7, ranging from $4.16 to $13.13 per 10^6 Btu for the two dairy operations, are well above proposed interstate natural gas prices. Conventional and plug-flow digesters on the 1,000-head beef feedlot do appear to be competitive. It should be remembered, however, that these costs are for the raw biogas. If the gas were purified and pressurized, it would be more expensive. Further, to use biogas, most pieces of equipment would have to be modified. The costs of these modifications are not included.

Bailie System

A block diagram of the system proposed by Bailie is given in figure 6. Two general systems, one user operated and the other commercially operated, are discussed. Costs for each system were estimated using a mesophilic digester with long retention times, a mesophilic digester with short retention times, and a thermophilic digester using short retention times. The user operated systems were sized at 2, 5, and 10 tons of manure per day. The commercially operated systems were sized 20, 50, and 200 tons of manure per day. Both systems produce raw biogas from manure. Areas of the country for which the digester were designed were not specified.

Capital costs for the Bailie system are presented in tables 8, 9, and 10. Bailie does not give a detailed description of components or costs involved. Additional processing equipment which may be found in an actual installation are ignored. Even so, the system is instructive since, with only minimum of capital equipment, production costs are prohibitively high.

Bailie's operating costs and gas costs are presented in tables 11, 12, and 13. Variable costs are estimated for labor, utilities, supplies, maintenance, and repairs. No cost was given to the manure input. Fixed costs were given for interest rates of 5 percent and 15 percent. Total fixed costs were calculated by adding capital recovery (payment for the capital investment required plus interest) and the sinking fund (to replace the system after 20 years) minus the straight line depreciation.

In no case could the cost of the gas produced be considered competitive with current natural gas prices. Bailie intentionally kept this system simple to illustrate the high cost of gas production from digestion. If

Table 5--Summary of capital costs for system proposed by Jewell and others

Component	40-head dairy			100-head dairy			1,000-head cattle feedlot		
	Con 1/	B.L. 1/	P.F. 1/	Con	B.L.	P.F.	Con	B.L.	P.F.
	Dollars								
Premix	900	900	2/	2,900	2,900	2/	6,800	6,800	2/
Pump/piping	3,200	4,800	---	3,300	4,800	---	6,000	8,000	---
Digester:									
Structure	4,800	10,000	6,000	6,200	15,500	10,300	14,300	33,700	21,700
Heating	1,200	1,400	1,500	1,200	1,400	1,600	2,500	3,000	3,000
Gas handling	2,400	4,900	2,500	2,400	4,900	2,600	2,400	6,000	2,800
Total	12,500	22,000	10,000	16,000	29,500	14,500	32,000	57,500	27,500
Cost per cow	312.50	550.00	250.00	160.00	295.00	145.00	32.00	57.50	27.50

Source: (28).

1/ Con = conventional, B.L. = batch load, P.F. = plug flow.
2/ Included in digester structure.

Table 6--Assumptions used in system proposed by Jewell and others

---

Life

- 20-year life
  - -Structures
    - -digester tank
    - -predigestion tank
- 10-year life
  - -pump/piping
  - -heat exchange system
  - -gas handling facilities

Amortization

@ 9% for 20, 10-year life

Maintenance

2% investment/year for 10-year life
1% investment/year for 20-year life

Operational

-Taxes & insurance @ 3½% investment/year
-Electric @ $0.30/kwh

	40-head dairy	100-head dairy	1,000-head beef
Con	$25/mo.	$50/mo.	$ 75/mo.
B.L.	50/mo.	75/mo.	100/mo.
P.F.	10/mo.	20/mo.	30/mo.

-Water

40-head dairy - 1560 liters/day - $ 5/mo.
100-head dairy - 1810 liters/day - $ 5/mo.
1,000-head beef - 8860 liters/day - $25/mo.

-Labor @ $2.50/hr.

	40-head dairy	100-head dairy	1,000-head beef
Con	1 hr./day	1 hr./day	2 hr./day
B.L.	1½ hr./day	1½ hr./day	3 hr./day
P.F.	½ hr./day	½ hr./day	1 hr./day

Source: (28).

Table 7--Summary of annual costs incurred in system of Jewell and others 1/

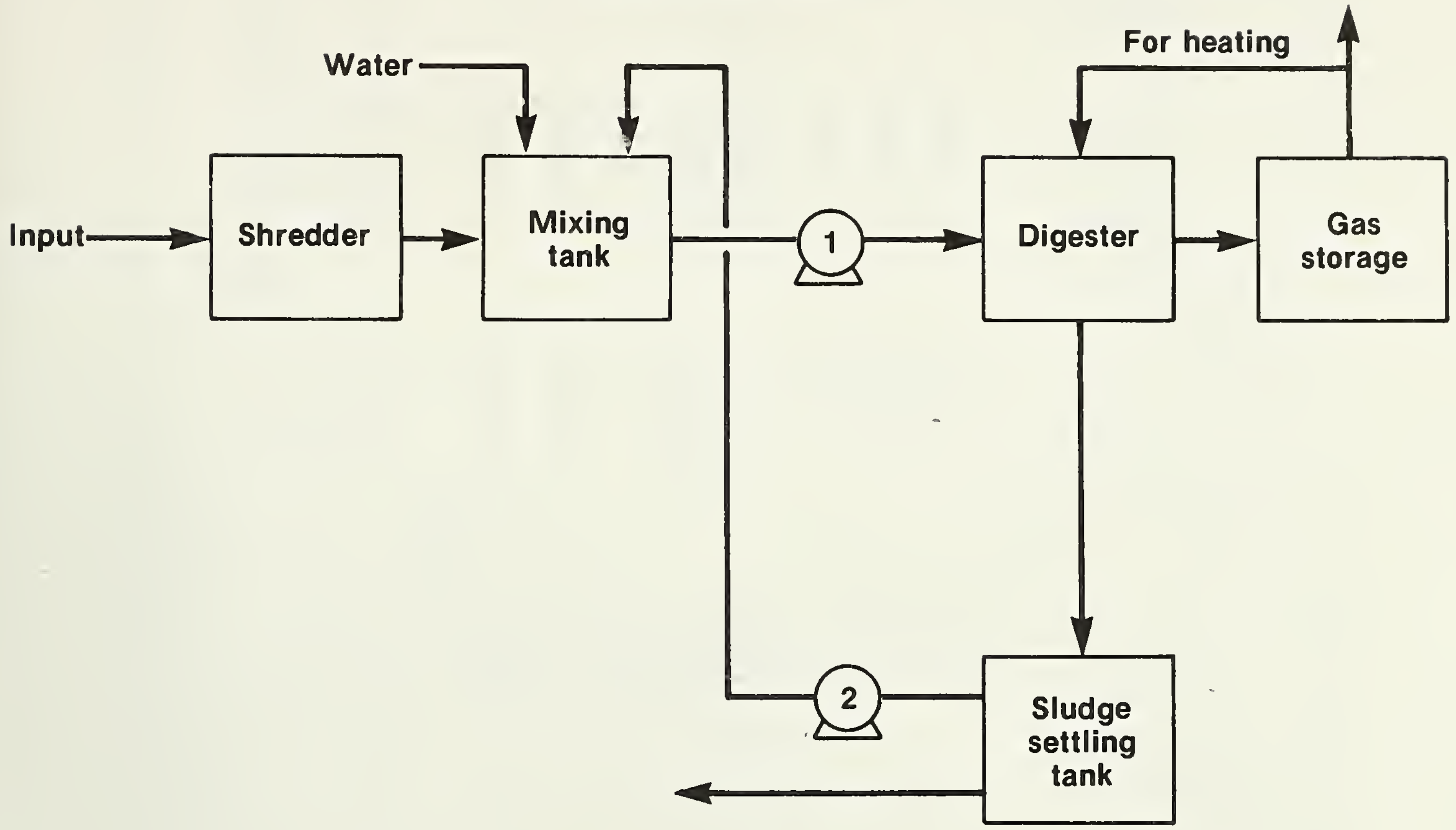
Parameter	40-head dairy			100-head dairy			1,000-head cattle feed lot		
	Con 2/	B.L. 2/	P.F. 2/	Con	B.L.	P.F.	Con	B.L.	P.F.
					Dollars				
Variable costs:									
Labor	915	1,370	460	915	1,370	460	1,830	2,745	915
Power	300	600	120	600	900	240	900	1,200	360
Water	60	60	60	60	60	60	300	300	300
Total variable costs	1,275	2,030	640	1,575	2,330	760	3,030	4,245	1,575
Fixed costs:									
Ammortization	1,740	3,020	1,330	2,135	3,890	1,860	4,170	7,385	3,430
Maintenance	195	330	140	230	400	180	430	755	330
Taxes and insurance	1,715	2,800	990	2,135	3,360	1,260	4,150	6,260	2,540
Total fixed costs	3,650	6,150	2,460	4,500	7,650	3,300	8,750	14,400	6,300
Total costs	4,925	8,180	3,100	6,075	9,980	4,060	11,780	18,645	7,875
					10^6 Btu				
Net energy production	540	623	429	1,175	1,421	976	6,825	7,500	5,535
					Dollars				
Cost per 10^6 Btu	9.12	13.13	7.23	5.17	7.02	4.16	1.73	2.49	1.42

Source: Based on (28).

1/ Gas costs were modified to include the variable costs for labor, power, and water.
2/ Con = conventional; B.L. = batch load; P.F. = plug flow.

Figure 6
Anaerobic digestion system proposed by Bailie

User-operated design



Comercially operated design

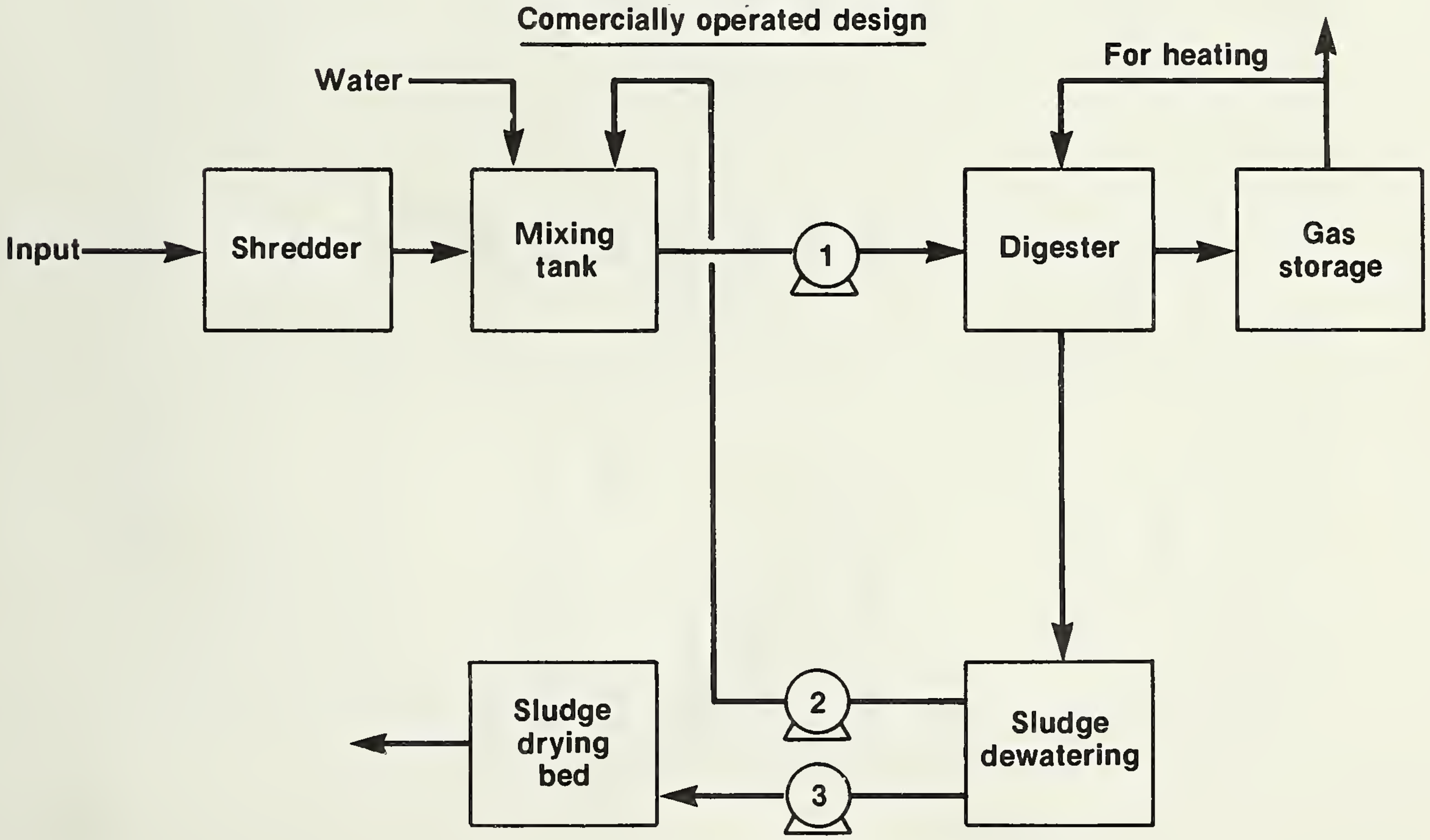


Table 8--Capital costs for system using mesophilic digesters with large retention times as proposed by Bailie

Component	Design capacity (tons of manure/day)					
	User operated			Commercially operated		
	2	5	10	20	50	200
				Dollars		
Shredder	1,000	1,700	2,600	21,000	36,400	83,600
Mixing tank	4,400	4,400	4,400	11,100	15,700	23,100
Pump 1	600	600	600	700	900	1,400
Digester	107,000	217,000	397,000	754,000	1,821,000	7,139,000
Gas storage	225,000	399,000	512,000	1,840,000	2,290,000	3,360,000
Sludge settling tank	700	1,200	2,200	---	---	---
Sludge de-watering	---	---	---	27,200	36,400	82,500
Pump 2	600	600	600	700	900	1,400
Pump 3	---	---	---	700	900	1,400
Sludge drying bed	---	---	---	106,000	353,000	1,630,000
Total	339,300	624,500	919,400	2,761,400	4,555,200	12,322,400

Source (5).

Table 9--Capital costs for system using mesophilic digesters with small retention times as proposed by Bailie

Component	Design capacity (tons of manure/day)					
	User operated			Commercially operated		
	2	5	10	20	50	200
			Dollars			
Shredder	1,000	1,700	2,600	21,000	36,400	83,600
Mixing tank	4,400	4,400	4,400	11,100	15,700	23,100
Pump 1	600	600	600	700	900	1,400
Digester	43,100	64,400	97,900	163,000	352,000	1,291,000
Gas storage	179,000	313,000	403,000	1,410,000	1,740,000	2,610,000
Sludge settling tank	700	1,200	2,200	---	---	---
Sludge de-watering	---	---	---	27,200	36,400	82,500
Pump 2	600	600	600	700	900	1,400
Pump 3	---	---	---	700	900	1,400
Sludge drying bed	---	---	---	106,000	353,000	1,630,000
Total	229,400	385,900	511,300	1,740,400	2,536,200	5,724,400

Source: (5).

Table 10--Capital costs for system using thermophilic digesters with small retention times as proposed by Bailie

Component	Design capacity (tons of manure/day)					
	User operated			Commercially operated		
	2	5	10	20	50	200
			Dollars			
Shredder	1,000	1,700	2,600	21,000	36,400	83,600
Mixing tank	4,400	4,400	4,400	11,100	15,700	23,100
Pump 1	600	600	600	700	900	1,400
Digester	43,100	64,400	97,900	163,000	352,000	1,291,000
Gas storage	245,000	408,000	523,000	1,930,000	2,410,000	3,480,000
Sludge settling tank	700	1,200	2,200	---	---	---
Sludge de-watering	---	---	---	27,200	36,400	82,500
Pump 2	600	600	600	700	900	1,400
Pump 3	---	---	---	700	900	1,400
Sludge drying bed	---	---	---	106,000	353,000	1,630,000
Total	295,400	480,900	631,300	2,260,400	3,206,200	6,594,400

Source: (5).

Table 11--Summary of costs of mesophilic digestion system with large residence times proposed by Bailie

Component	Design capacity (tons of manure/day)					
	User operated			Commercially operated		
	2	5	10	20	50	200
				Dollars		
Variable costs (Labor, utilities, supplies, maintenance, repairs)	18,710	33,200	52,700	265,000	391,000	972,000
Fixed costs @ 5% interest rate						
Depreciation	(33,900)	(62,500)	(91,900)	(276,000)	(456,000)	(1,232,000)
Capital recovery	44,100	81,200	119,500	359,000	592,000	1,602,000
Sinking fund	27,000	49,700	73,100	220,000	362,000	979,000
Total	37,200	68,400	100,700	303,000	498,000	1,349,000
Fixed costs @ 15% interest rate						
Depreciation	(33,900)	(62,500)	(91,900)	(276,000)	(456,000)	(1,232,000)
Capital recovery	67,500	124,400	182,900	550,000	907,000	2,452,000
Sinking fund	16,700	30,800	45,300	136,000	225,000	607,000
Total	50,300	92,700	136,300	410,000	676,000	1,827,000
				10^6 Btu		
Gas production	700	2,250	5,820	8,840	32,200	154,000
				Dollars		
Gas cost per 10^6 Btu						
5% interest rate	79.87	45.16	26.36	64.25	27.61	15.07
15% interest rate	98.59	55.96	32.47	76.36	33.14	18.18

Source: (5).

Table 12--Summary of costs of mesophilic digestion system with small residence times proposed by Bailie

Component	Design capacity (tons of manure/day)					
	User operated			Commercially operated		
	2	5	10	20	50	200
	Dollars					
Variable costs (Labor, utilities, supplies, maintenance, repairs)	13,960	22,250	31,900	221,200	286,000	596,000
Fixed costs @ 5% interest rate						
Depreciation	(22,900)	(38,600)	(51,100)	(174,000)	(254,000)	(572,000)
Capital recovery	29,800	50,200	66,400	226,000	330,000	744,000
Sinking fund	18,200	30,700	40,600	138,000	202,000	455,000
Total	25,100	42,300	55,900	190,000	278,000	627,000
Fixed costs @ 15% interest rate						
Depreciation	(22,900)	(38,600)	(51,100)	(174,000)	(254,000)	(572,000)
Capital recovery	45,600	76,800	101,700	346,000	505,000	1,139,000
Sinking fund	11,300	19,000	25,200	85,000	125,000	282,000
Total	34,000	57,200	75,800	257,000	376,000	849,000
	10^6 Btu					
Gas production	2,090	5,850	13,900	21,500	72,500	337,000
	Dollars					
Gas cost per 10^6 Btu						
5% interest rate	18.69	11.03	6.32	19.13	7.78	3.63
15% interest rate	22.95	13.58	7.75	22.24	9.13	4.29

Source: (5).

Table 13--Summary of costs of thermophilic digestion system with small residence time proposed by Bailie

Component	Design capacity (tons of manure/day)					
	User operated			Commercially operated		
	2	5	10	20	50	200
			Dollars			
Variable costs:						
(Labor, utilities, supplies, maintenance, repairs)	16,810	26,580	38,000	237,000	321,000	646,000
Fixed costs @ 5% interest rate						
Depreciation	(29,500)	(48,100)	(63,100)	(226,000)	(321,000)	(659,000)
Capital recovery	38,300	62,500	82,000	294,000	417,000	857,000
Sinking fund	23,500	38,200	50,200	180,000	255,000	524,000
Total	32,300	52,600	69,100	248,000	351,000	722,000
Fixed costs @ 15% interest rate						
Depreciation	(29,500)	(48,100)	(63,100)	(226,000)	(321,000)	(659,000)
Capital recovery	58,700	95,700	125,600	450,000	638,000	1,312,000
Sinking fund	14,500	23,700	31,100	111,000	158,000	325,000
Total	43,700	71,300	93,600	335,000	475,000	978,000
			10^6 Btu			
Gas production	2,520	7,150	17,000	26,200	89,000	416,000
			Dollars			
Gas cost per 10^6 Btu						
5% interest rate	19.49	11.07	6.30	18.51	7.55	3.29
15% interest rate	24.01	13.69	7.74	21.83	8.94	3.90

Source: (5).

additional capital items had been considered, the production costs would have been still higher. As was the case with the Jewell system, costs for gas purification and compression, and altering equipment to use raw biogas, could further increase gas costs.

Economic Feasibility in Summary

To date, economic analysis has suggested that anaerobic digestion is most feasible with large-scale commercial operations associated with large cattle feedlots. The data indicate that the systems proposed by Burford and Varani and by Jewell, for the digestion of feedlot manure, appear the most feasible while the smaller dairy operations of Jewell, along with the operations of Bailie, cannot be now considered as viable options.

Economies of scale appeared in each of the three systems discussed. The larger the operation of each system, the smaller the cost of the resultant gas. These economies were due primarily to the large initial investment required for each of the three systems.

The data presented suggest that the economic feasibility of small digesters could be the subject of future research. Experience with actual field installations could supply cost data to supplement the engineering estimates presented here. Until this is done, reliance must be placed on engineering estimates that indicate anaerobic digestion is not economically feasible on most U.S. farms.

The potential of a direct positive return from a process or activity, however, is not the best measure of economic feasibility. An individual can typically choose from a wide variety of activities with returns that more than cover costs. Ordinarily he will choose the one which he feels will most improve his overall financial position. In deciding about installing an anaerobic digester, the individual would thus consider whether a digester was a more financially rewarding addition to his business, directly or indirectly, than say, purchasing more land, buying a new tractor, or constructing grain storage facilities. Looked on in this way, an anaerobic digester, even though it is shown not to produce direct profitable outputs, may be economically feasible. Presently, environmental or legal requirements may necessitate the adoption of a waste management system. The outputs of a digester, although not strictly profitable, could be used to defray the cost of the installation, thus resulting in a least cost solution to a waste management problem. If a complete waste management system had to be installed, a digester would represent a relatively small additional cost.

It should be noted that costs and returns for producing methane are usually based on current energy prices. For natural gas in particular, it can be expected that prices will rise dramatically in the future as supplies dwindle. But even dramatic price increases may not make the price of natural gas comparable to the gas costs presented in this report. Nonetheless, when no other supply exists, anaerobic digestion may be called upon to supply gas in specific stiuations. Site specific installations, such as small digesters supplying power for irrigation pumps, may become more common. These situations will probably reflect the unavailability of natural gas at regulated prices rather than equivalence of natural gas and biogas prices.

POTENTIALS FOR ADOPTION AND ENERGY CONTRIBUTION

In looking ahead, there is insufficient information available for judging specific ways and areas anaerobic digesters will be brought into play in agriculture. Enough is known, however, to offer some rather general but conclusive observations about conditions having a bearing on the adoption and contribution of this technology and what the foreseeable outcome will be.

Types of Enterprises

Although anaerobic digestion can accept most organic materials as inputs, adoption will follow concentrations of materials found in association with livestock, meat processing, and fruit and vegetable processing operations. This reflects the suitability of these materials for digestion, their adverse environmental characteristics, and their availability in concentrated form. The dispersed nature of other possible inputs will hinder their widespread use in digestion.

The economic incentives outlined in the last section favor adoption in association with large feedlots. These installations would be large scale, with substantial capital investment, sophisticated equipment, and full-time operators to run the system. It may be economically feasible for these systems to produce methane for pipeline transmission or for local use. In addition, the dewatered sludge may be used as an ingredient for animal feed. Neel and Ziegler (42) have estimated that this latter activity is economically feasible for feedlots of 4,000 head of cattle and greater.

For smaller units the prospects for adoption are not promising. Smaller livestock operations cannot produce biogas in quantities sufficiently large to justify the capital investment required. It is technically difficult for digesters to supply even a fraction of the energy needs of farms with livestock operations. At best, biogas may supplement usual power sources where these sources become prohibitively expensive or nonexistent. Some small farming operations, with small livestock herds and relatively large amounts of time, may use simple, small digesters on a limited scale to produce additional revenue from a local market. For example, some revenue could be realized by packaging digester sludge for use in local gardens. Such applications are site specific, depend on local circumstances, and would be used to supplement already small incomes. They will not have a major impact on the agricultural sector.

Present and future applications of anaerobic digestion will follow concentrations of input materials, primarily manures and animal wastes. Unless new methods of input collection are discovered, the majority of agricultural operations, including cash grain farms, farms with small livestock operations, and small dairies, will be unable to make use of the technology.

Scale of Digester Installations

Some literature on anaerobic digestion has focused on the use of small batch digesters on farms. These digesters are labor intensive and involve a small capital outlay. Proponents of these digesters point to their success in Taiwan, Korea, and India and experimentation done in Europe and South Africa. Input materials are placed in the digester, often by hand, and a simple piping system is used to channel the gas to the place where it is to be used. The simple system is low in cost and permits farmers to be more self-sufficient by supplying more of their fuel and fertilizer.

The small digesters used in other countries were generally designed for underdeveloped areas. They often represent a change in situation from one of no fuel to some fuel and represent the only source of gas for heating and cooking. Labor is employed to move manure from a few head of livestock to the digester and the gas is piped to houses for use. These digesters are unable to handle the amount and variety of energy forms required by American agricultural enterprises.

These small digesters do not provide output in a quantity to justify the time and effort needed to load and monitor them. The value of time for many American agricultural operators is high. Rather than spend the time necessary to load, unload, and monitor the digester, an agricultural operator would probably better devote his time to his usual activities. Utilities will continue to give a more convenient and acceptable form of energy than will these small digesters. The future of small digesters in the United States is not promising.

Reliability of the Process

The dependability of anaerobic digestion as a source of energy has not been demonstrated in field installations. If the digestion process has been started, and if there are no extreme changes in the digestion environment, digesters can furnish a dependable supply of gas. But start up can be difficult. Environmental disturbances can happen. Periods without power could then result.

One important area of concern is the presence of toxic substances in the input materials. Digestion is a biological process. Several circumstances could kill the bacterial population. Thus, concentration of some heavy metals must be avoided. Medications given to livestock pose especially difficult problems. Some medications remain in the manure which could kill the digestive bacteria. The interactions of medication, livestock, manure, and digestion bacteria are extremely complex. Research is needed to determine what constraints a digester would place on the type of medications given to livestock.

State of Practical Knowledge

To a great extent anaerobic digestion represents a new activity to be incorporated into existing activities. There will be initial resistance to the adoption of anaerobic digestion because the process has not been sufficiently demonstrated or because it is unfamiliar. There is also a tendency for individuals to wait for others to adopt the technology and to monitor their experience before adopting it themselves.

Anaerobic digestion is a technolgoy not directly related to the functions of many agricultural enterprises. The function of a feedlot is to produce beef. The function of a farm is to produce food, feed, or fiber. The production of energy represents a different kind of activity. The time and effort needed to establish and run this activity can be considerable. It represents time and effort which would not be available for more conventional agricultural operations. Anaerobic digestion also has to compete with other operations for the individual's investment dollar. Agricultural operators may choose to remain in their usual activities and leave anaerobic digestion as a new enterprise for the "agribusiness" sector to develop, operate, and maintain.

Finance and Credit

Financial institutions are often reluctant to lend money for unproven technologies. Until there has been more experience with anaerobic digestion and knowledge of the process has become more general, financing of the installation capital may be difficult to obtain. The lack of credit can hamper the initial adoption of anaerobic digestion technology.

National Energy Needs

As supplies of natural gas continue to decline and as the prices of conventional fuels continue to rise, interest in nonconventional sources of energy will increase. The use of organic material as a source of fuel is being intensively investigated by many researchers. Anaerobic digestion is one of these means of bioconversion.

It is difficult at this time to see how anaerobic digestion can supply more than a small percentage of national energy needs. As noted earlier, the best prospects for general energy production center on converting manure from large feedlots to methane and feeding the methane into existing pipelines. Even if this practice continues to develop, the amount of energy obtained is small compared to the Nation's total energy requirement.

Further, methane produced for on-farm consumption cannot contribute substantially to overall energy requirements. The percentage of national energy used in the production of agricultural commodities is about 3 percent. A system of digesters on agricultural units producing energy for local consumption could supply only a fraction of this small percentage. Although anaerobic digestion could represent an alternate energy source of agricultural operators in some selected instances, it holds little promise for making a significant contribution to the Nation's overall energy needs.

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