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Small-Scale Biogas Applications

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SMALL-SCALE BIOGAS APPLICATIONS

Tennessee Valley Authority Solar Applications Branch

By Energy Research & Applications, Inc.

SMALL-SCALE BIOGAS APPLICATIONS

Prepared For

TENNESSEE VALLEY AUTHORITY

Solar Applications Branch

By

ENERGY RESEARCH & APPLICATIONS, INC.

August 1981

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CHAPTER 1

INTRODUCTION

Generating and using biogas helps solve two present-day problems -- environmental pollution and dwindling domestic sources of conventional energy. It is a rare technology which assists in both these areas and is economically attractive as well. Municipal wastewater treatment plants have been capturing and using biogas for years, and recently, due to rising energy costs and increased pressure to reduce water pollution from livestock wastes, biogas systems have become feasible at farms.

The purpose of this manual is to guide the interested farm owner through the exercise of determining whether a biogas system is worthwhile. This book is not intended to serve as a design, construction, or operating manual, though it covers these areas to give an idea of what it takes to generate and use biogas. The final chapter offers directions for collecting site data and a method for performing a preliminary economic analysis of a given operation. Appendices 1 and 2 contain lists of firms and individual consultants with experience in the design and construction of biogas systems.

ENERGY PRODUCTION POTENTIAL OF BIOGAS SYSTEMS

Biogas is a versatile fuel. The gas is basically a mixture of methane (CH_4) and carbon dioxide (CO_2). Natural gas is nearly 100% methane, while 60% methane for biogas is common. The lower methane content of biogas reduces its heating value relative to natural gas, but otherwise the gases have equivalent uses.

There are four basic steps involved in producing and using biogas, as shown schematically in Figure 1. First, manure must be collected regularly and centrally stored. Second, the wastes are stabilized by bacteria in an airless tank. This stabilization process is known as anaerobic digestion, and the anaerobic bacteria actually generate the biogas. Collecting the gas and putting it to work constitute the third step. Finally, digested manure must be removed from the digester. This residue has considerable value as fertilizer, animal bedding, or even animal feed.

Depending upon the amount of biogas potentially available from digesting wastes at a particular site, the fuel can provide for different energy needs. At any given location, the best use of biogas might be:

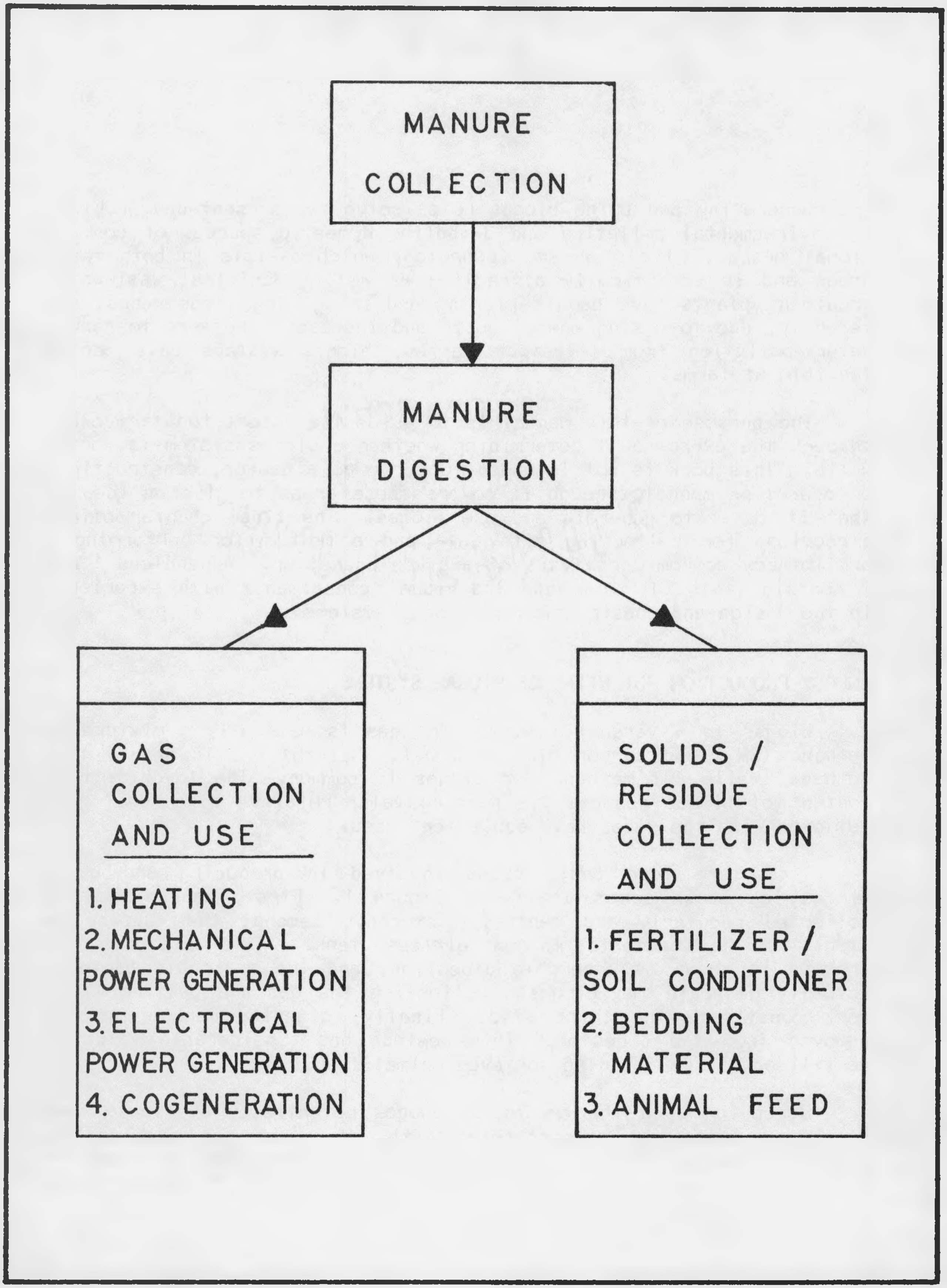

Figure 1. Biogas System Parts.

1) Replacing natural gas in gas-fired appliances.

2) Generating mechanical power by combusting the gas in an engine.

3) Generating electricity by running an engine-generator on biogas.

4) Cogenerating--making mechanical power or electricity and capturing prime mover waste heat to do work.

The short-term economics of each of these options can be worked out to help make a decision, if the best use of biogas at a site is not obvious.

The last listing above--cogeneration--describes an old practice whose time has come again. If electrical or mechanical power as well as heat are needed, cogeneration is the most efficient use of biogas fuel. It takes much less fuel to produce power and heat simultaneously than separately. Because most farms have use for both power and heat, it is the cogeneration application which receives the most attention in this manual.

Cogeneration occurs in "topping" and "bottoming" cycles as shown in Figure 2. The "topping" cogeneration concept is to burn fuel in an engine to produce shaft horsepower for any desired electromechanical workload, then recover engine waste heat to do further work. The most versatile application of the rotating shaft is to drive a generator for electricity production, but direct shaft drive of other machinery might be preferable in certain situations.

"Bottoming" cogeneration involves producing heat directly from fuel, as in an industrial furnace, for example, then capturing very high temperature process exhaust to generate electricity, usually with a waste heat boiler and steam turbine. Biogas cogeneration applications discussed in this manual are all topping cycles.

Table 1 introduces numbers for energy production by small biogas systems. The entries in the table are, of course, estimates; all kinds of local factors can drive the potential up or down, and the upcoming chapters explain some of these. The numbers in Table 1 can be multiplied directly to match the size of a particular farm. If this exercise yields some interesting results, then read on!

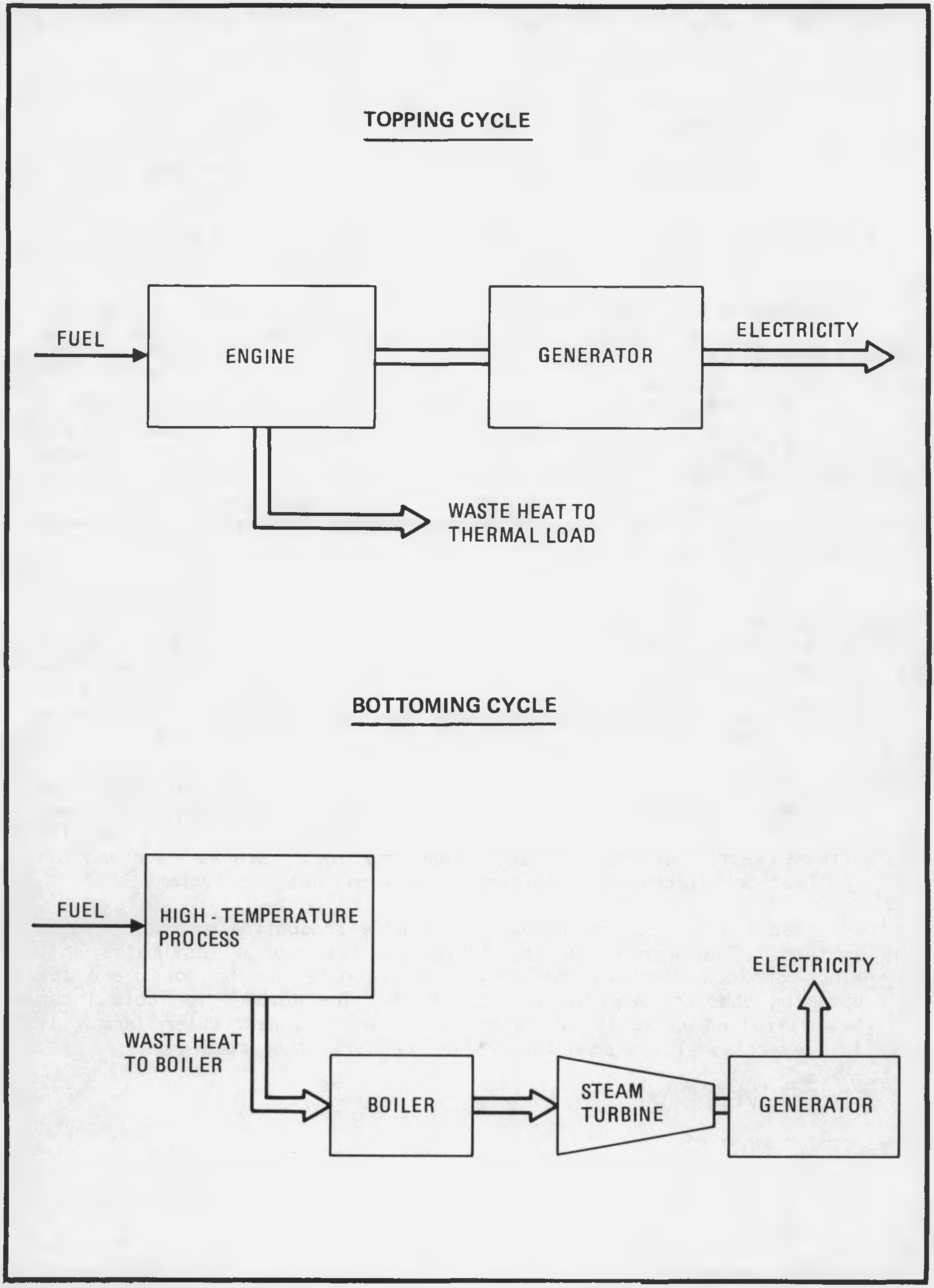

Figure 2. Topping and Bottoming Cogeneration Cycles.

Table 1
Sample Biogas Energy Production Figures
(1 KW Equivalent Size)

No. Animals		10 Dairy Cows	14 Steers	58 Hogs	1200 Layer Hens
Total Wastes/Day (lb)		980 @ 10% Solids	980 @ 10% Solids	580 @ 17% Solids	390 @ 25% Solids
Total Wastes/Day (ft^3)		16	16	9	6
Daily Gas Production (ft^3)	a)	550	550	550	550
Equivalent Hourly Heat Rate (Btu/hr)	b)	13,500	13,500	13,500	13,500
Mechanical Power Equivalent (HP)	c)	1.34	1.34	1.34	1.34
Electrical Power Equivalent (KW)	d)	1	1	1	1
Recoverable Heat from Engine (Btu/hr)	e)	6,800	6,800	6,800	6,800

Assumptions:

a) Calculated using 80% volatile solids and 7 ft^3 of gas generated per pound of volatile solids destroyed: ft^3 gas = (lb wastes/day) x (% solids) x (% volatile solids) x (7 ft^3/lb VS).

b) 600 Btu/ft^3 biogas.

c) 25% engine efficiency (18,300 Btu/hr/HP).

d) 25% engine-generator efficiency (13,650 Btu/hr/KW).

e) 50% of total heat input recoverable.

CHAPTER 2

THE NATURE OF BIOGAS

Biogas is a by-product of anaerobic digestion, the decomposition of organic wastes by bacteria in an oxygen-free environment. The process does not completely stabilize municipal and farm wastes, but it can break down many of the degradable materials which are a nuisance or health hazard. Other stabilization methods do not offer the advantage of producing both fuel and a material which can be used as an animal feed, soil conditioner, or livestock bedding.

ANAEROBIC DIGESTION

The production of biogas through anaerobic digestion of wastes is not a perfect process controlled by a strict recipe because wastes of variable character yield gas of variable character in environments of variable character. The high energy component of biogas is methane (CH_4). Natural gas is almost 100% methane, while biogas might vary between 35 and 70%, depending on the feedstock, digester design, and location. This section provides background about anaerobic digestion which is a prerequisite to learning the art of maximizing methane production.

Digestion is basically a three-phase biochemical sequence. The anaerobic bacteria which produce methane will not begin to multiply until all the oxygen present in the sludge is consumed by aerobic bacteria either before or after loading it into the digester. Anaerobic digestion can be partitioned into: 1) hydrolysis and acid formation and, 2) methane formation, with different bacteria accomplishing the last two steps. In a balanced digester, the anaerobic phases occur simultaneously, at the same rate.

In the first anaerobic (oxygen-free) step, bacteria break down complex sludge particles into simpler organic substances which they can metabolize. Simple organic acids formed during this stage serve as substrate for the second group of bacteria, the methane-producers. These bacteria cannot utilize more complex sources of nutrition, and are thus dependent on the acid formers for their food. In simple terms, successful digestion depends on achieving and maintaining a balance between those bacteria which produce organic acids and those which produce methane from the organic acids.

Three major factors contributing to digester balance for maximum methane production are pH, temperature, and composition of wastes. Each factor is discussed below.

1) Acid or Alkaline Condition (pH).

Acid-forming bacteria can tolerate acidic (low pH) conditions while the methane producers cannot. Keeping both types of microbes present in balanced numbers requires a near neutral (pH 6.8-7.2) or slightly alkaline pH. An observable drop in digester pH (in other words, increase in acidity) indicates a digester is in serious trouble.

2) Temperature.

Within the 40-105°F survival limits for what are called mesophilic methane-forming bacteria, gas production is optimized between 86°F and 98°F. Above this range, a group of thermophilic methane-formers functions well between 120 and 140°F. Either set of microbes can do the digesting job, but digesters should be maintained to favor one or the other. Operators have found thermophilic bacteria more finicky about digester conditions than mesophilic bacteria, but higher temperature digestion offers the prospect of shorter term sludge processing in smaller digesters. Short-term drops in digester temperature from optimum reduce gas production rates but usually do not harm the essential bacteria.

3) Composition of Wastes.

Bacterial populations of digesters need carbon, nitrogen, and other nutrients to grow, multiply and thereby produce gas. A shortage of any basic nutrient can inhibit microbial activity, but most typical farm feedstocks are of suitable composition.

The amount and spatial distribution of volatile solids (materials which can be decomposed by the bacteria) in the sludge also affects gas production. This volatile fraction is generally reduced by: 1) water and, 2) the presence of inert solids such as soil, clay, calcium carbonate and salts. Not all the stubborn solids are inorganic. Lignin, a structural organic material in wood, is particularly difficult to break down. Skimming, thickening, continuous loading, and mixing enhance digestion by increasing the fraction and uniform distribution of volatile solids.

Substances toxic to bacteria are sometimes present in sludge. Materials such as heavy metals, antibiotics, phenols, pesticides, detergents, sulfur compounds, and disinfectants are common inhibitors of anaerobic digestion. The source of the wastes is often a good predictor of the toxic constituents. Some of these substances can be diluted to non-toxic concentrations, some can be precipitated out of the sludge, and still others must be removed from wastes before they enter digesters.

CHARACTERISTICS OF BIOGAS

The major ingredients of biogas are always methane (CH_4) and carbon dioxide (CO_2), but the proportions of these gases and other minor constituents vary with the composition of the wastes and particular digester. The heating value of biogas is directly proportional to its methane content. Methane has a fuel value of about 1000 Btu per ft^3, so biogas containing 35-70% methane measures about 350 to 700 Btu per ft^3.

Table 2 lists the gases which commonly make up biogas and typical proportions of constituents recorded by digester operators. The methane value generally observed in the U.S. is about 60%, and many sources agree that this figure represents a reasonable estimate for planning purposes. While the non-methane components of biogas do little to affect the overall heating value, H_2S should be removed because of its corrosiveness. H_2S, CO, O_2, and CH_4 (methane) also can be hazardous in sufficient concentrations, the former two gases because of toxic physiological effects and the latter two because of explosion risk when they are mixed.

Causes of Reduced Methane Content

In general it is carbon dioxide which reduces the heating value of biogas. The minimum CO_2 fraction of about 30% arises as a respiratory product of microorganisms essential for anaerobic digestion. Among controllable factors contributing to increased CO_2, thus less methane, are:

1) Introduction or diffusion of O_2 into the digester.
The presence of oxygen allows aerobic decomposers, which "exhale" CO_2, to grow in the digester. Removal of O_2 in sludge prior to digester loading and a well-sealed digester minimize this production of CO_2.

2) Digester pH imbalance.
A great deal of CO_2 is generated when digester conditions have shifted significantly to favor either the acid-formers or methane producers at the expense of the other group. High loading rates are a common cause of digester low pH problems. Maintaining the digester in a state where neither group of bacteria dominates, alleviates this problem of unnecessary CO_2 production.

ECONOMIC VALUE OF BIOGAS

In spite of the fact that biogas has only about two-thirds as much heating value as natural gas, and may contain one or more contaminants as well, there are several factors that enhance the economic value of biogas as a fuel. First and foremost is the fact that once the digester is installed and paid for, the gas is nearly free. The gas really would be free if all the costs of installation and operation could be assigned to the pollution control side of the picture. Not only is this fuel source inflation-resistant, but it also avoids payments to foreign suppliers.

A second quality that often makes biogas cogeneration economically attractive is that generally this energy source "fits" on-site energy use in a number of ways:

Table 2

Composition of Biogas

	Gas	Percent
CH_4	Methane	55-70%
CO_2	Carbon Dioxide	30-45%
N_2	Nitrogen	Trace*
H_2	Hydrogen	0.1-2%
CO	Carbon Monoxide	0.1%
O_2	Oxygen	Trace*
H_2S	Hydrogen Sulfide	Trace-0.3%
H_2O	Water Vapor	

*The presence of significant quantities of these gases indicates air leaks into the digester.

NOTE: H_2S becomes toxic at concentrations in air of around 0.04%. CO is a threat at 0.05%.

1) The quantities of power and heat produced will often be of the same order of magnitude as required at the site.

2) The installation can usually be made reasonably compact, with gas production near areas of energy use. This feature will be especially significant at remote sites with high fuel delivery costs.

3) The technology used in biogas systems is largely within the experience of a seasoned farmer.

4) Allowing for short-term lags, the timing of gas production will coincide with fluctuations in energy demand. For instance, if manure supplies drop off (perhaps as a result of selling some livestock), both manure pumping and digester heating requirements will decline immediately, followed a short time later by reduced gas production and hence less energy availability.

A third factor which enhances the economics of biogas cogeneration is the tax picture. In addition to the standard investment tax credit and depreciation and interest writeoffs, biogas cogeneration systems may qualify for either an energy tax credit (if owned by a business) or alternative energy credit (if owned by an individual). Public entities, such as municipal wastewater treatment plants, do not benefit from these tax incentives.

Finally, within the reliability limits of the equipment and the diligence of the maintenance person, biogas production is under the sole control of the owner-operator. Fuel scarcity arising from national or international events is not a problem.

CHAPTER 3

DIGESTERS

This chapter discusses basic features of anaerobic digesters. For additional information, Appendices 2 and 3 contain lists of individuals and firms experienced in digester design and construction. The purpose of this chapter is to introduce readers to a technology that may be unfamiliar and demonstrate that, though digesters are not without complexities, they are not more intimidating to understand, select, operate, and maintain than any other farm equipment. There is much current experimentation and debate over how to optimize digestion. Therefore, the equipment available to accomplish anaerobic digestion ranges widely in size, design and operation. Certain functions are generally needed, in any case, to transform the raw feedstock (manure) into a digested product.

The basic functions are:

1) Feeding manure to the digester.

2) Heating manure and maintaining digester temperature.

3) Holding material during digestion process.

4) Keeping oxygen out of digester.

5) Mixing digester contents.

6) Accumulating and releasing biogas.

7) Discharging digested manure.

8) Sampling material in the digester.

While not directly part of anaerobic digestion, collection and disposal of manure must also be accomplished as part of a successful overall biogas system.

Table 3 lists examples of collection and disposal systems at existing farm biogas installations. The simplicity of most methods of collecting is notable as is the variety of uses for the digested manure. The value of digested sludge products varies with the local (or on-farm) demand and the cost of the product it replaces. If a dairy farmer currently purchases sawdust for bedding material, a free digested manure substitute would be attractive. On the other hand, if the in-laws own a lumber yard and bring a truckload of sawdust every Sunday when they come to dinner, then digested sludge has little value as a bedding material for that site.

Table 3

Manure Collection and
Disposal Systems in Livestock Operations

Type of Installation	Waste Collection Method	Ultimate Fate of Digested Manure
Feedlot (Imperial Valley, CA)	Collected by front loader from dirt floor, dumped into spreader, fed into mix tank then slurried, pumped into digester.	Dewatered in centrifuge then used as high-protein feed.
Feedlot (Bartow, FL)	Manure falls through slatted floors into 3' deep "basement," scraped into troughs and pumped into digester.	Stored in ponds on-site and used for land reclamation.
Feedlot (Guymon, OK)	Manure piled for storage, loaded into shredders, passed through shakers, emptied into mix/settling tanks, "defibered," and pumped into digester.	Dewatered. Liquid sprayed on fields, solids refed to cattle.
Swine Farm (Wyoming, MN)	Central sloping gutter in hog building feeds covered steel holding tank. Overflow into storage lagoon. Pumped to digester from tank.	Applied to land.
Dairy (Gettysburg, PA)	Manure on sloped, concrete floors washed into troughs on low end. Piped to settling tank and pumping basin where pumped to digester.	Pressed dry and used as bedding material.
Dairy (Bedford, VA)	Manure on dirt barn floors pushed into holding pit with small front loader. Slurry stirred; then pumped to digester.	Lagooned; then spread on fields.

SUCCESSFUL DIGESTER DESIGNS

Several types of digesters perform all the above functions satisfactorily, but most are variations of the two principal designs described here. One widely operated anaerobic digester is the complete-mix tank commonly used in municipal wastewater plants.

Complete Mix Digesters

A complete-mix or high-rate digester is, by definition, a design which incorporates stirring or agitation of the contents to achieve good mixing and which also has a means of heating to ensure that digestion takes place at the correct temperature. Mixing increases the rate of digestion by keeping the anaerobic bacteria always in contact with fresh food. These digesters were first developed for the wastewater disposal field, but there are now many alternative types available, and it is generally recognized that, for maximum efficiency coupled with short retention periods, the high-rate concept is probably essential.

The traditional complete-mix digester installed in a wastewater treatment plant is an expensive structure, usually built of concrete and steel and set into the ground. The mixing is provided by either gas circulation or mechanical stirrers, and movable dome roofs allow some storage of biogas. Such a digester is pictured in Figure 3. The elaborate mixing systems are important not only to keep the anaerobic bacteria constantly in contact with their food, but also to prevent the build-up of materials such as grease, hair and dirt in the digester. Because a farmer has much more control over what enters a digester than a municipal treatment plant operator, the traditional complete-mix digester is really overdesigned for farm use. There are simpler digester designs currently available which function in a similar manner.

Figure 4 depicts a clever variation on the traditional complete-mix system. This digester has no provision for active mixing, but heat applied around the bottom half of the unit sets up thermal currents which keep contents from settling. An actual operating unit appears in Figure 5. This digester is basically a steel tank covered with urethane foam insulation on the outside and epoxy on the inside. The heat to keep the digestion process at proper temperature (and the digester contents mixed) is supplied by a cogeneration system. This digester was built by Anaerobic Energy Systems, Inc. and it operates at a ninety cow dairy farm in Bedford, Virginia. This digester does not store much gas; rather, the biogas discharged at the top of the digester is pressurized and stored in 1000 gallon cylinders.

Small- and medium-sized digesters have been promoted heavily in rural India. The Indian designs are generally variations on the complete-mix theme, with floating covers, agitators, and heating (in cold regions) not uncommon. Most designs call for below ground installation. Figure 6 shows a composite Indian design. Ram Bux Singh presents several detailed designs in his book Bio-Gas Plant.

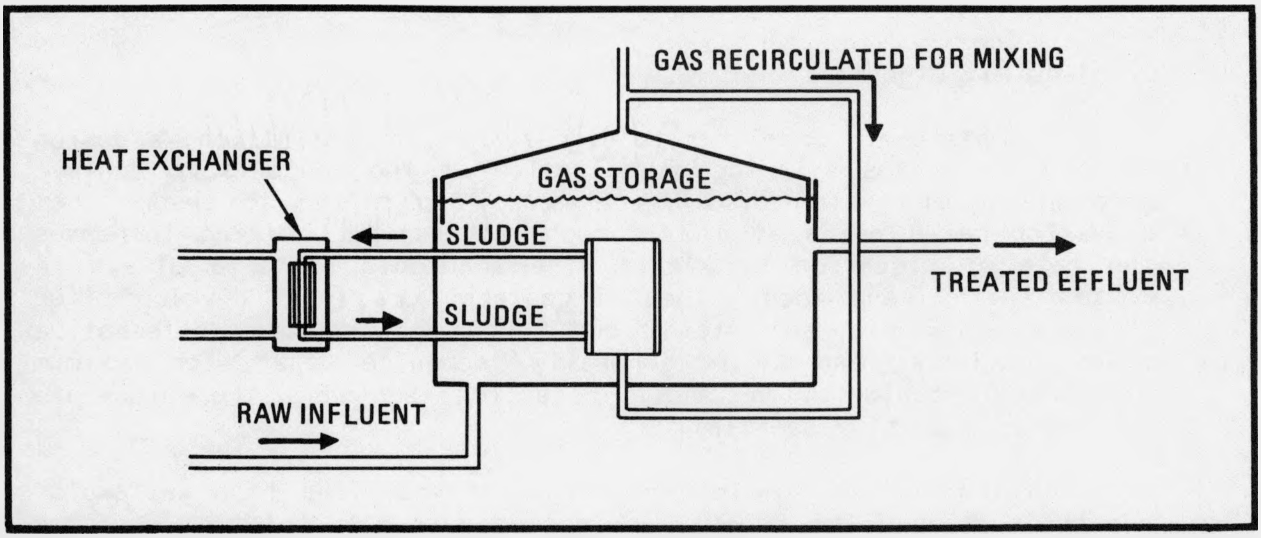

Figure 3. Traditional Complete-Mix Digester.

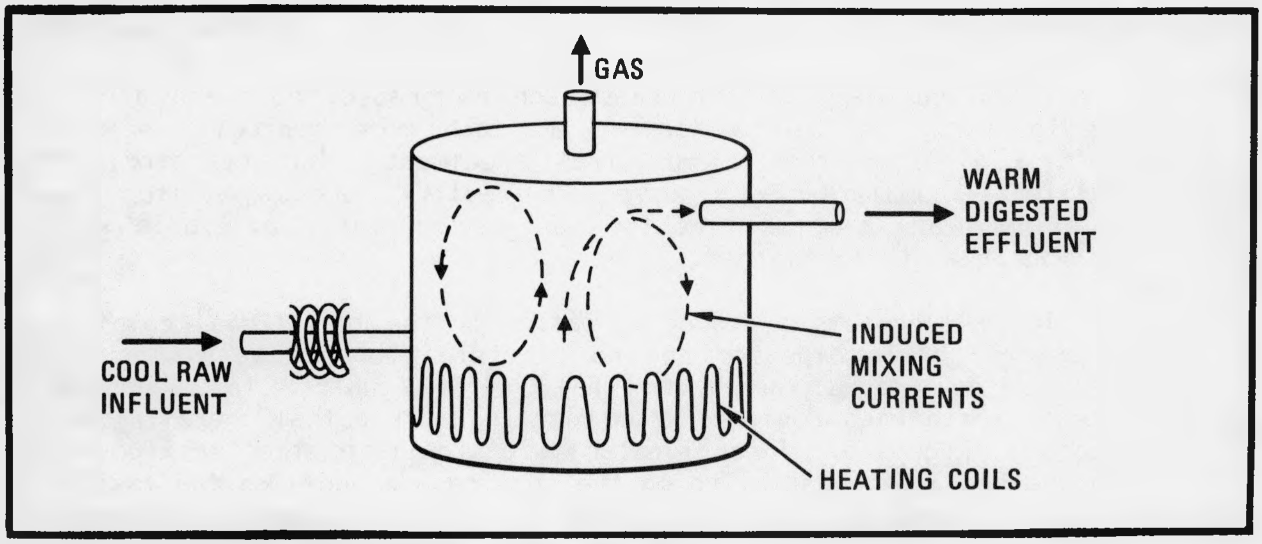

Figure 4. Simple Complete-Mix Digester.

Figure 5. 21,000 Gallon Simple Complete-Mix Digester in Bedford, Virginia. Bumps showing through the bottom half of the tank are pipes carrying warm water to heat the digester. Adjacent building houses cogeneration equipment.

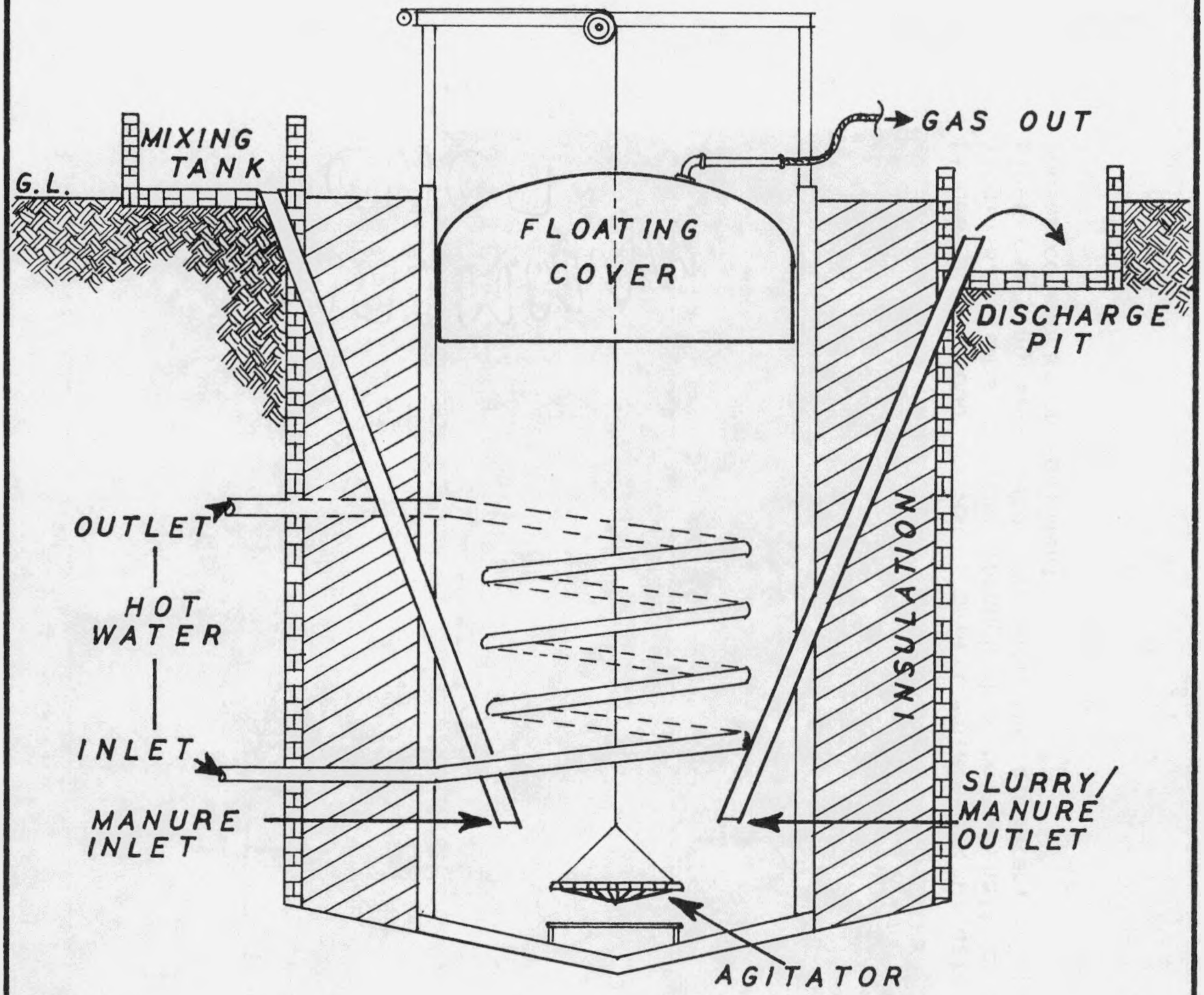

Figure 6. Composite Indian Biogas Plant.

The substitution of biogas for cow dung as cooking fuel in India has noticeably improved villager health.

Al Rutan, in his colorful classic, The Do's and Don't's of Methane, presents a design for a mixed digester which differs quite a lot from the previous two designs. He points out that wastes sitting in a basically vertical digester are bound to separate into temperature layers, thus digesters should be a horizontal shape. He also questions placing digesters in the ground in parts of the country like Minnesota, where the top layers of soil freeze in winter. Rutan opts for an above ground, insulated tank equipped with solar heating. A simplified schematic of the Rutan digester appears in Figure 7; consult his book for more detailed schematics of digester parts.

Plug-Flow Digesters

The second arrangement which has been used successfully to digest uniform sludges in farm settings is the plug-flow or canal digester. Although not a pure plug-flow in the hydraulic sense (totally without longitudinal mixing), manure is fed into a long trough at one end and removed from the other, undergoing very little mixing in between. A schematic of a digester trough appears in Figure 8.

This type of digester might typically be built as a long, concrete-lined excavated trough with an impermeable "balloon" cover. Other construction possibilities include horizontal metal tanks or plastic-lined canals. In the canal-type digester, the sludge must be warmed before entering the chamber in order to prevent thermal stratification with the cold sludge flowing undigested along the bottom of the tank. For a plug-flow digester to digest wastes completely, retention time must be on the order of one to two months.

Other Designs

The previous two general digester types are usually built to allow continuous removal of biogas as it accumulates. These digesters can thus provide a reliable source of fuel for a continuous demand. A batch digester is a simple device which is filled with waste once then sealed. Because of problems associated with one-time loading, unloading, and gas evacuation, these digesters are only practical on a very small scale. A series of small batch digesters might provide more operational flexibility. A lab-scale batch digester is a simple but effective tool for assuring the digestability of certain waste types.

Another design variation involves multiple, continuously loaded digesters. Most common are two-stage digesters, which basically consist of some sort of high-rate digester coupled with a second unheated, unstirred chamber which allows still further digestion. In

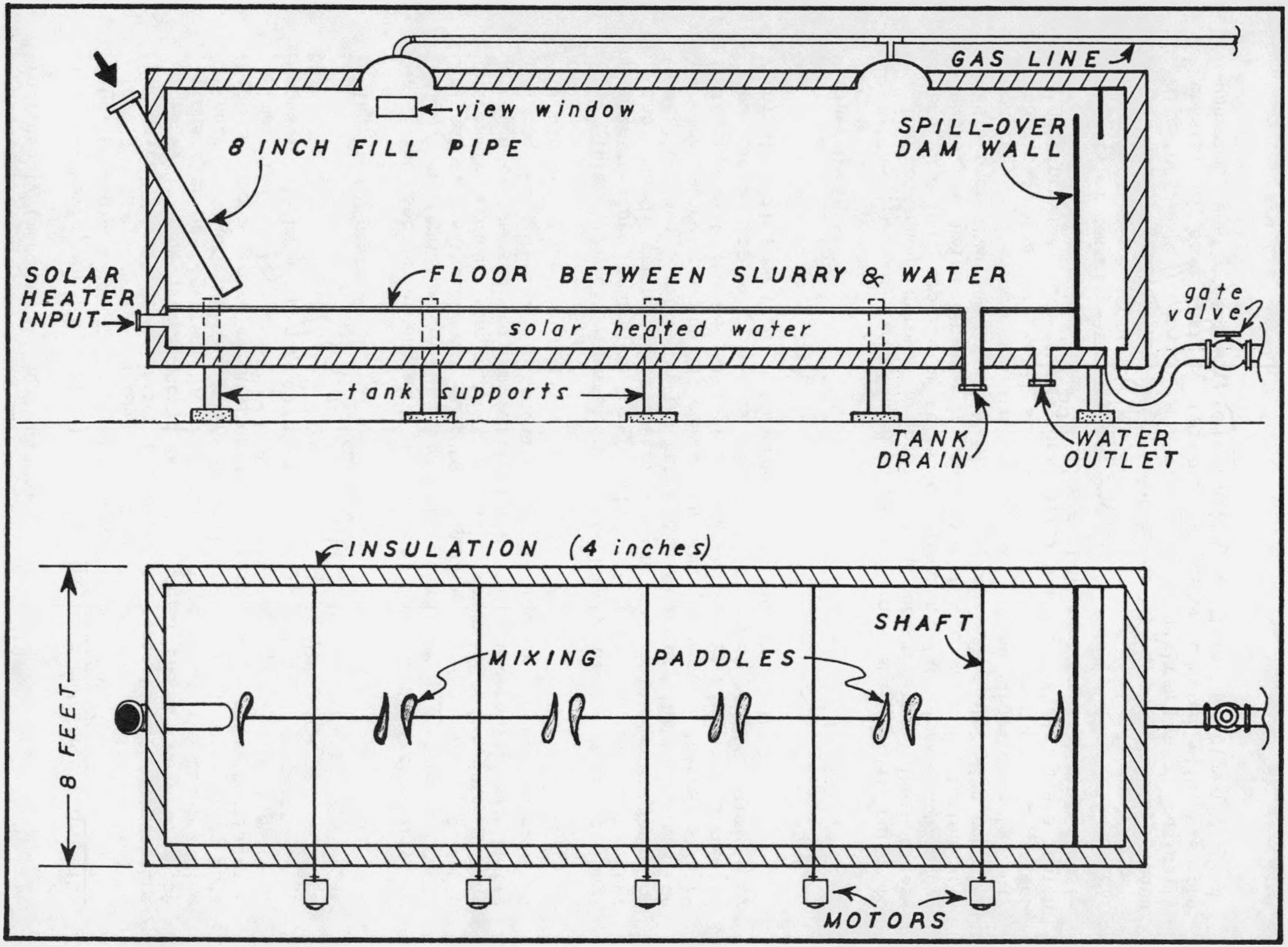

Figure 7. Rutan Digester.

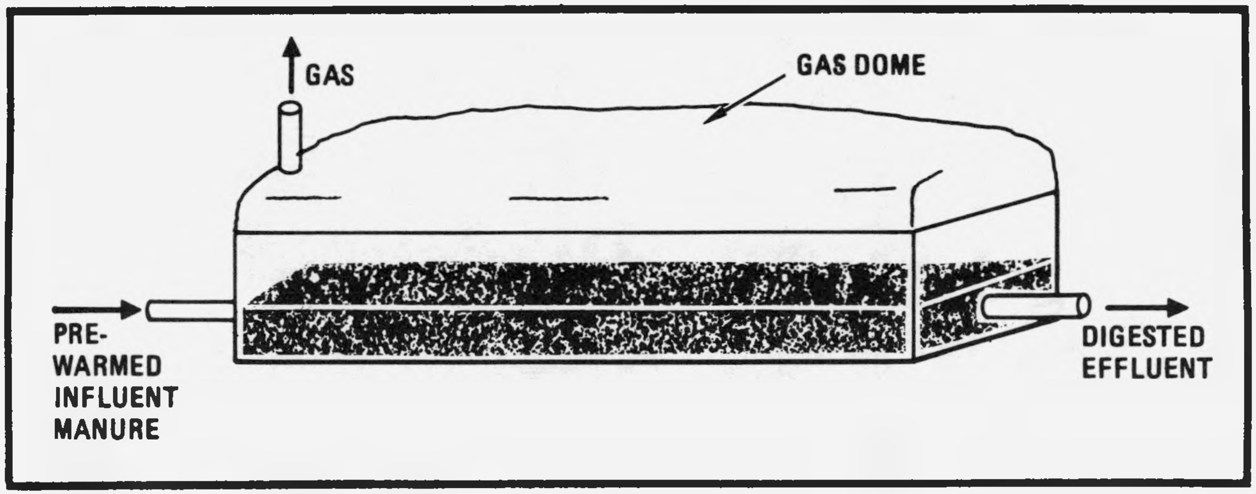

Figure 8. Plug-Flow Digester.

the second digester, solids and liquid are sometimes permitted to separate. The liquid might be siphoned off to slurry incoming wastes (chicken and pig manures need diluting) and the solids carted off to the fields for fertilizer.

CHOOSING A DIGESTER

The preceding description of digester types is not exhaustive, yet it probably offers enough variety to foster some confusion. The choice of digester design must be a matter of desired function, site resources, and economics.

A decision between complete-mix and plug-flow digesters should be based on several factors, which are summarized in Table 4. There is divided opinion as to which of these two digester types is better able to withstand operating upsets from overloading, excess acidity, and toxic exposure. It is highly desirable to operate any digester carefully to avoid such stresses.

While batch digesters are probably not a serious consideration, a two-stage digester might be. Factors to consider before deciding upon this design include: 1) the value of the biogas produced during the second stage, 2) the cost of the second chamber, and 3) the comparative cost of building a single, larger digester which accommodates longer retention and can produce equivalent gas. Issues such as in-ground versus above-ground and horizontal versus vertical have to be resolved by considering individual site conditions.

DIGESTER HEATING

As mentioned in Chapter 2, temperature is a key controller of methane production in anaerobic digestion. Digester heating needs will be an important design parameter of a biogas system. Digester heat requirements can be broken into two components:

1) Heat required to raise the temperature of the incoming raw sludge flow to digester operating temperature.

2) Heat required to maintain the digester operating temperature (make up for heat losses).

The incoming sludge is rarely at the operating temperature of the digester and, therefore, heat must be added before digestion can proceed. Calculations of initial heat demand can be found in Chapter 6. Necessary heat is a function of incoming sludge temperature, sludge volume, and digestion temperature.

Since digester temperature must be maintained around 95°F for mesophilic bacteria and little can be done to control the incoming sludge temperature, the volume of influent becomes the crucial factor in reducing the sludge heat requirements. Reduction in sludge volume by increasing solids concentration directly reduces the amount of

Table 4

Comparison of Complete-Mix and Plug-Flow Digesters

	Advantages	Disadvantages
Complete-Mix Digester	Little land required.	High capital cost.
	Maximum gas production.	Energy required for mixing.
	Short retention time (15-20 days).	Difficult to clean.
	Slow solids buildup.	
Canal Plug-Flow Digester	Lower capital cost.	Large land requirements.
	No mixing required.	Less gas production.
	Cleanable with bulldozer or other means.	Long retention time.
		Rapid solids buildup.

heat required to raise the incoming sludge to the digester operating temperature. The simplest method of increasing the solids is to let the wastes settle prior to digester loading. Sludge is removed from the bottom of a settling tank for loading into the digester and excess water is drained from the top.

Indirectly, a reduction in sludge volume reduces heat loss which occurs through the digester vessel, since the digester's surface area can be reduced. There is an upper limit to solids concentration of about 8-10%, however, in order to maintain a pumpable sludge. Six percent solids concentration should be the minimum concentration sent to the digester if recovered engine heat is to satisfy the total demand.

Heat losses occur through the digester's walls, floor and cover, and are a function of digestion temperature, ambient temperature, surface area and insulating value of the container's sides. Again, since the temperature is less susceptible to change or control, the minimization of heat needs can only be accomplished by reducing surface area and providing some insulation for the vessel. Heat loss calculations appear in Chapter 6.

The foregoing discussion applies to either mesophilic (86-98°F) or thermophilic (120-140°F) digester operation, but clearly the higher thermophilic temperatures will demand more heat input both to attain digestion conditions and to overcome heat losses. In addition to heating requirements which favor the use of mesophilic digestion, other factors argue against the thermophilic condition. Although the higher temperatures yield slightly more gas in a shorter time, which reduces necessary digester size, the number of successful thermophilic digesters in operation is small compared to mesophilic. Thermophilic bacteria are more sensitive to change in digester conditions, thus thermophilic digesters demand more frequent attention and precise control. For these reasons, mesophilic digestion is recommended for cogeneration with biogas and its selection will be assumed through the remainder of this book.

Techniques for applying heat to the digesting sludge mass include the following:

1) Circulating sludge through an outside heat exchanger is a widely used technique for warming anaerobically digested manure. This method is only suitable for very low solids content wastes, but its big disadvantage is that the heat exchangers quickly become fouled and regular maintenance is essential. The external heat exchanger has to be relatively small, and in order to transfer the quantity of heat needed, the surface temperatures are relatively high. This results in a fast build-up of crusted sludge and other material which effectively reduces the rate of heat transfer. If this method is to be used, careful attention must be paid to the design of the heat exchangers that are to be used, and provision for regular maintenance must be made.

2) Heating coils inside the digester circulate warm water in tubes usually situated on the walls of the digester (or around the draft tube if one is used in the mixing method chosen). With wall-mounted heating coils, the surface area is large, and the surface temperature can be much lower, thus reducing the fouling of the heat transfer surface. The disadvantage of this system is that when defouling of the heating coils is eventually required, the digester has to be emptied. Heating coils mounted on the outside of a metal tank digester can be effective if covered with sufficient insulation. (See Figures 4 and 5.)

DIGESTER OPERATION

While this book is not intended to be an operation manual, it is only fair to introduce some digester operating intricacies to anyone considering biogas applications. An effective anaerobic digester is not a device which will run automatically without attention, but neither does it require full-time attendance. In general, wastes should be loaded frequently--not less than daily for most installations--in order to avoid losing solids volatility to oxidation and aerobic bacteria. Wastes fed to the digester should be measured, or at least approximated, by a count of contributing animals, pump timing, or direct weighing. Similarly, gas production should be continuously metered and recorded daily, as any fall off of gas production will usually be the first signal of digester upset. (See Table 5.)

The material to be fed to the digester should be inspected before entering the process. Slugs of unusual constituents, such as grain or fertilizer, for example, are to be avoided (whether or not they are suitable food for the anaerobes). A good rule of thumb is not to feed more than 10% by weight of any out-of-the-ordinary material to the tank. Obviously, toxic substances such as chlorinated hydrocarbons, pesticides, strong acids and bases, and heavy metals should never enter the digester--after all, it is a living process. In addition, straw and other floatable material should be avoided because they tend to form an undesirable scum layer on the surface of digesting fluid. Excess water will also slow digestion by diluting the active sludge mass, and will waste energy by increasing heating requirements.

The digester itself should be checked several times a week for acidity. Simple color-indicator test papers are available for this purpose. Also, the color and odor of the digesting or digested sludge should be monitored every day. Sludge color should be black--a grey color indicates acid build-up and insufficient digestion. The odor of a healthy digester is described as pungent; that of a "sour" digester as nauseating, acidic and fatty. An experienced nose will detect the change immediately. Table 5 presents a few common digester ailments and corrective measures. The vast majority of digester failures are due to excess acidity, caused by overloading. A small, bench-scale digester is very helpful in testing sludge, evaluating methane production, and identifying toxic materials. Such a device

Table 5

Common Digester Ailments

Problem	Symptom	Recommended Response
Shock overload (too many volatile solids)	1) Increased gas (CO_2) production (abrupt and significant) followed by a decrease. 2) pH reduction. 3) Excessive foam generation.	1) Reduce feeding. 2) Add soda ash (quantity based on bench test of fresh samples).
Toxic failure - mild	1) Decline in total gas production and methane fraction. 2) pH reduction. 3) Excessive foam generation.	1) Stop feeding. 2) Neutralize acidity with soda ash. 3) Reinnoculate with digested sludge.
Toxic failure - severe (critical poison and high dosage)	1) Cessation of gas production.	1) Empty digester and start over with new innoculum.
Loading rate too high	1) Excessive scum. 2) Diminished gas production. 3) pH reduction.	1) Reduce loading rate.

NOTE: Many digester aids on the market are merely freeze-dried healthy sludge and can be obtained fresh for free at most municipal wastewater plants.

needn't be costly or elaborate to provide valuable operating information.

Aside from on-going operation and maintenance, a few comments should be made about start-up and shut-down of the digester. In order to begin digestion in a period of weeks rather than over the course of many months, a starter "seed" of previously digested sludge should be fed into the digester and then raw sludge added to it gradually. "Seed" is usually available at the local sewage plant or from a neighboring digester owner. The more "seed" used for start-up, the better. Initial loading rates should be kept down to 0.01-0.03 lb volatile solids/day per ft^3 of digester volume until gas production is well under way. After gas production begins, feeding rate can be increased gradually until the design loading rate is achieved.

As to digester shut-down, it will be necessary to empty any digester for accumulated solids removal occasionally, depending on system design and degree to which indigestible solids have been introduced into the digester feed. At such a time, it is highly desirable to have more than one digester, so that gas production (albeit reduced) can continue and a fresh starter will be readily available for restarting the cleaned-out digester. Whereas complete mix digestion tanks will require considerable labor to clean with shovels, buckets and high-pressure hoses, a well-designed canal-type digester can be rid of its solid build-up with a front end loader or similar farm equipment.

A trait which all types of gas-recovering anaerobic digesters share is explosiveness, which is especially acute during periodic cleaning of the tank. Methane gas may remain in the digester even after extended airing of the tank, posing a real risk of spontaneous or spark-induced explosions. Every precaution should be taken to ensure that the tank is totally evacuated of gas before cleaning. The tank should always be treated as a fire hazard, and workers should avoid smoking and open flames when they are close to the tank.

Every digester is unique by virtue of its location, design, and feedstock. The key to successful operation is not following an instruction manual, because it is likely one doesn't exist. Rather, passing along some conventional sewage plant wisdom, the operator must work with the principles underlying his or her system design to develop operating procedures which yield desired results. The patient digester operator with the ability and courage to experiment will achieve the long-term rewards of stable operation and reliable biogas production.

CHAPTER 4

PUTTING BIOGAS TO WORK

This chapter discusses the use of biogas, starting with gas collection at the digester and ending with waste heat recovery in biogas cogeneration systems. The chapter emphasizes cogeneration and electricity production because: 1) cogeneration is the most efficient use of the fuel and 2) generating electricity with biogas provides a versatile form of energy which is universally in demand. Direct heating with biogas is covered briefly in this manual, but references listed in Appendix 4 offer more on the subject. The following sections discuss the parts of a working biogas system.

COLLECTING BIOGAS

The biogas formed during anaerobic digestion will naturally collect in the top of the tank. As shown in Figure 9, most commonly used digesters allow some space for gas storage within the digester. Since both gas production and gas consumption rates fluctuate, it is necessary for a good design to provide some flexibility in the gas space volume by using either a floating digester cover or an inflatable bladder-type cover. Since the gas stored will be at a very low pressure, only a small amount of gas (possibly a few hours' equivalent in engine operation) can be contained.

If additional gas storage is required, a separate high-pressure vessel will be needed, along with a gas compressor. Pressurized tanks are available as horizontal cylinders for small installations. Even these high-pressure vessels will typically store only a few days' gas supply eliminating the potential for storing gas excess to summer needs for the following winter's use. Assuming that some source of backup energy is available to the site, it may be difficult to justify the expense and safety requirements of high pressure biogas storage.

The piping through which biogas exits the digester may be of any standard piping material (even PVC pipe), but brass or copper fittings must be avoided because of their tendency to react with the hydrogen sulfide in the gas. Low-carbon steel is suitable for the piping. The gas exit must be situated at the highest point in the digester and equipped with a pressure-relief valve (in case the exit valve is blocked for some reason) and a flame arrester (to prevent a fire in the pipe from entering the digester), as illustrated in Figure 9. Also, a simple drain-down dewatering chamber may be desired, fed by gently sloping pipes. Because of the water content of the biogas, pipes must be protected from freezing where subfreezing temperatures occur, and condensation drain points should be provided.

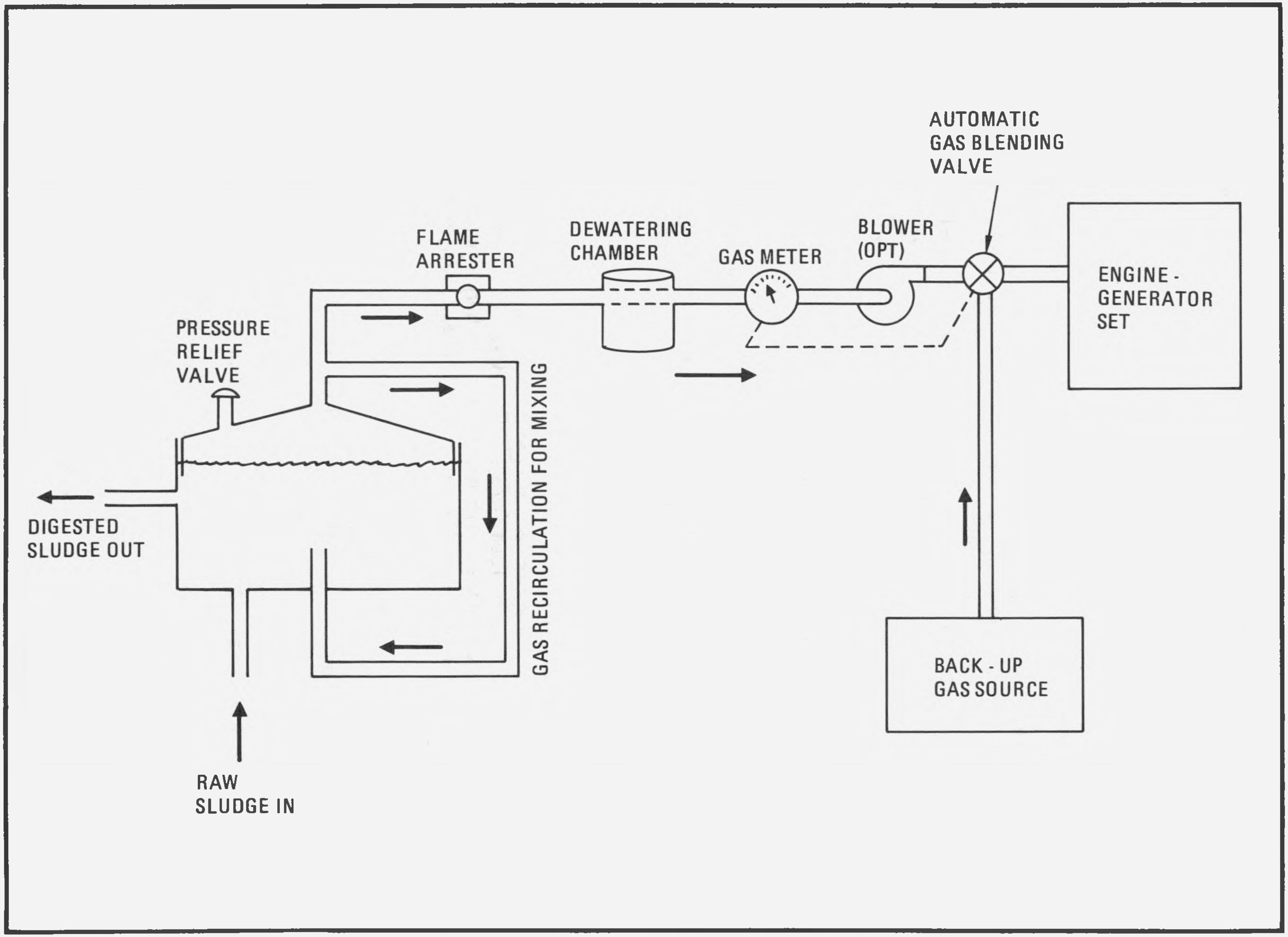

Figure 9. Biogas Plumbing.

Normal operating pressure within the digester is usually 6 to 8 inches water column, just enough pressure to move the gas slowly a few hundred yards, although it may reach 15 inches water column safely. The addition of a low-pressure blower, or gas pump, may be needed to satisfy engine manufacturers' intake manifold pressure requirements, when biogas is used to generate power.

Gas pumps can be sophisticated and relatively expensive items. Although many working digesters have been constructed by "do-it-yourself" enthusiasts, this is one area, at least, where they should proceed with great caution. The pump itself must be absolutely leak-proof, for apart from the obvious explosive gas hazard, a gradual depletion of gas from the digester will disturb the normal operating pressure, and could well introduce air into the anaerobic environment and so cause digester failure. On large digesters, a small amount of gas leakage would obviously be insignificant, but on smaller units gas systems must be virtually leak-proof. Unless inspection is vigilant and regular, leakage can go undetected until digester performance deteriorates noticeably.

Figure 9 shows a backup gas source as part of a biogas system. The need for this reliability can naturally be assessed by the biogas user. Existing energy sources (natural gas, propane, electricity) can provide backup, and it is recommended that equipment be left in place beside a new biogas system. If biogas and another fuel will be used to run gas appliances or drive an engine, the backup fuel must be metered differently to compensate for its different (probably higher) energy value.

CLEANING BIOGAS

As discussed in Chapter 3, biogas is basically a mixture of methane and carbon dioxide (see Table 2). However, other gases are present in small quantities. Among these "other" gases are two trouble makers: water vapor and hydrogen sulfide. Both gases create corrosion problems.

Much of the suspended water vapor in wet digester gas can be precipitated out with a simple water trap; along with the water vapor goes a significant portion of the H_2S. The remaining H_2S may range widely in concentration. Some biogas plant owners have successfully designed and operated their systems to allow for residual H_2S by replacing critical equipment parts with substitutes made from corrosion resistant metals. Others have installed devices to remove the rest of the H_2S from the digester gas. Passing the gas through heated iron oxide (iron sponge) is one of the simplest techniques to remove H_2S when concentrations are low. When H_2S levels in the digester gas are <u>very</u> low, successful equipment operation may occur with only the water trap.

Removal of carbon dioxide from biogas is optional. Removing CO_2 yields mainly methane, and this remaining fraction can be burned in any device which accepts natural gas as fuel. The other approach is to use burners which have been specifically designed for the lower Btu biogas or, for engine applications, adjust carburetion systems accordingly. The theory behind carbon dioxide removal from biogas is simple, but the practice involves significant cost and bother as the quantity of gas needing treatment increases. Carbon dioxide (and, incidentally, hydrogen sulfide) will react with limewater to form salts. This "scrubbing" leaves a fuel which is nearly 100% methane, but it also consumes lime and yields salts which require disposal.

According to calculations in Al Rutan's book The Do's and Don't's of Methane, 1 lb of lime will scrub 20 ft^3 of digester gas containing 35% CO_2. A gas production rate of 20 ft^3/day arises from, for example, about a 45 hen operation. Any sizable farm will generate far more gas and consequently consume far more lime. Most large-scale users of digester gas do not scrub; rather they make adjustments for the composition of the gas in handling and combusting equipment.

Small-scale combustion of biogas will not require cleanup at the other end of the process. Emission standards for stationary source combustion go into effect for minimum 250 million Btu/hr. Equivalent biogas power theoretically is generated by: 1) 220,000 dairy cows, 2) 330,000 feedlot steers, 3) 2,000,000 hogs, or 4) 28,000,000 layer hens.

There are clear environmental benefits to the site producing the feedstock and to society from generating power with biogas. It is ironic that flaring biogas or venting it to the atmosphere to "dispose" of it (as has been practiced for years at some wastewater treatment plants) is not subject to emission control regulations, while putting the gas to work potentially is.

BURNING BIOGAS IN GAS APPLIANCES

When CO_2 is removed from biogas, burners of existing appliances require no modification to handle the gas. For "unscrubbed" biogas, burners must accommodate lower Btu fuel. Burner design is based on the mixture of air and gas needed to achieve complete combustion. If too much air is introduced, heat is wasted bringing the extra mass to combustion temperature. Too little air allows incomplete fuel combustion which wastes gas and creates pollutants such as carbon monoxide and hydrocarbons. Because such products of incomplete combustion are hazardous, burners are generally maintained for combustion with some excess air.

The following excerpt from Ram Bux Singh's Bio-Gas Plant explains burner design for biogas (see Figure 10):

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*Limewater is formed by a reaction between lime (CaO) + Water (H_2O) = Limewater ($Ca(OH)_2$).

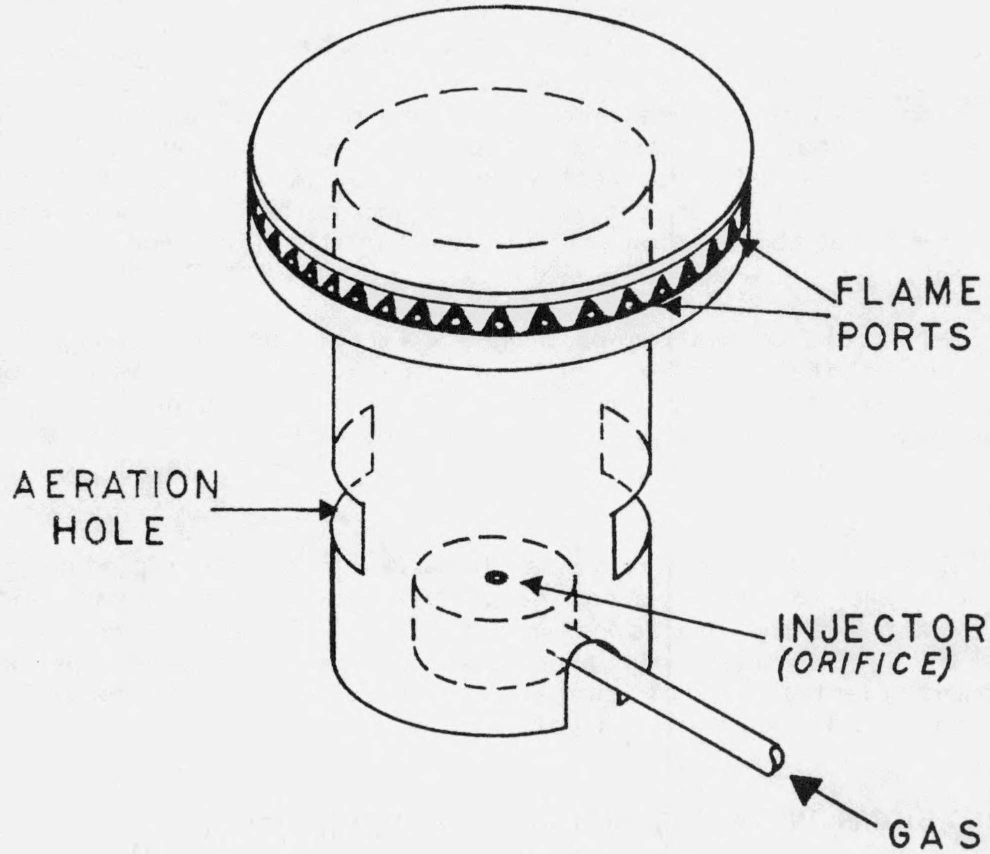

Figure 10. Burner Design Features.

Bio-gas cannot be burned on just any burner with maximum efficiency. Its flame speed factor, which is a measure of the speed at which a flame will travel along a column of the gas, is low compared to that of natural gas. This means that when bio-gas is fed to a burner built for natural gas the flame will tend to lift off from the burner. Bio-gas fed at a lower pressure would stay on the burner, but may not burn efficiently and less heat would be recovered from each cubic foot of gas. The Watson House Laboratory recommended a burner with a flame port area (the sum of the areas of the individual flame ports) to injector area ratio of about 300 to 1. Using a burner with 36 ports of 0.114 inches diameter each, injectors with orifice diameters of 0.038 and 0.041 inches respectively and supplying the gas at pressures ranging from 1-8 inches on a water gauge (.43-.44 lbs./sq. in.), they obtained efficient, stable flames. The heat input under these conditions ranged from 3,360-11,000 Btu/hr./sq. in. of flame port area. The laboratory recommended that heat inputs be kept in this range.

Any direct use of the gas should consider heating efficiency. Many conventional gas-fired appliances such as water heaters and stoves do a poor job of transferring heat during combustion to the medium requiring heating. Thus, getting the best return on a biogas investment means not only proper combustion but also efficient heat transfer.

BURNING BIOGAS IN ENGINES

Almost any type of engine can run on biogas. For the scale of operation covered by this manual, however, spark ignition engines are the most available equipment. Larger biogas producers might consider compression ignition engines, which use 5-15% diesel fuel for starting and lubrication. Gas turbines run on biogas so far have a mediocre record, but with some improvements they offer many advantages.

Spark ignition engines have been used successfully with medium Btu gas, such as biogas, in many different situations. These installations range from small self-contained generator units running on biogas, for home or farm use, to junked automobile engines being used in wastewater treatment plants to run pumps and blowers. While biogas has potential use as a vehicle fuel, the engine application stressed in this manual is stationary power generation.

Where feasible, in addition to burning biogas in an engine to make power, the recovery and use of engine waste heat is recommended.

This sequential production of power and heat is known as cogeneration. "Electric" cogeneration implies that engine power turns a generator.

When examining available spark ignition engines two distinct groups emerge: a larger more traditional spark ignition engine in the 15-45 HP range and a smaller 2-15 HP engine. Table 6 presents manufacturer's data on specific brands of both groups of engines. The conversion rate from horsepower to kilowatts is somewhat less than the standard .75 KW = 1 HP, due to the inefficiency of the smaller generators. Many of the engines are marketed with electricity production in mind, and distributors will package them with generators. The small sets are actually self-contained engine generators, usually sold for running appliances in remote areas.

In order to function with unscrubbed biogas (gas which has not had CO_2 removed) as the prime fuel source both groups of engines need to be modified. Biogas has a lower heating value than the gasoline which the engine was originally designed to burn. To correct for this difference when burning biogas, the carburetor must be modified to admit less air to the combustion chamber. Resulting biogas combustion is more efficient due to the absence of unnecessary air.

The larger (15-30 HP) engines can be modified with a kit made by IMPCO industries in Cerritos, California. The smaller (2-15 HP) engines can be modified with a kit made by Beam Products in Los Angeles. Both companies' products are sold nationally (even internationally). Currently Beam has off-the-shelf equipment for Honda and Onan units, and is in the process of developing the same for Yamaha and Kawasaki. Beam stressed that they custom build their own kits and that the only difference between kits is the fitting for the carburetor. Beam could most likely fit any brand of small engine, but assume longer delivery time for custom kits.

Small vs. Large Engines

The choice of engine will depend on the amount of biogas produced, but above a minimum production level there is the option of using multiple small units rather than a single large unit. Different sizes and makes of engines have advantages and disadvantages that the buyer should be aware of before making a choice.

In addition to carburetor modification, smaller engines run on unscrubbed biogas will usually require a pressure regulator in order to feed the gas into the combustion chamber quickly enough to keep the engine running. There are two ways to avoid using a regulator: 1) store the gas in a pressurized vessel, or 2) use a dual fuel system. A dual fuel system starts the engine with higher Btu propane or gasoline, then switches to biogas. The smaller engines are limited to producing electricity because the generator is built into the unit. Also, unless the electricity can be used at the location where it is generated, the engine will need some rewiring since it is designed to have electrical appliances plugged directly into it.

Table 6

Engines For Use In Biogas Systems
(Self-Contained Generator Units)

Engine Manufacturer	Honda	Yamaha	Kawasaki	Onan
Model	E 2500 ES 3500 ES 4500	EF 1800 EF 2600	KG 1500B KG 2600B	6.5 PM-3P 15.0 JC-3CR
Rated KW a)	2.5 3.5 4.5	1.5 2.2	1 2	6.5 15
Rated HP a)	7 10 10	6 7	5 6.5	14 30
Engine Engine/Generator	Engine Generator Set	Engine Generator Set	Engine Generator Set	Engine Generator Set
Cooling	Air	Air	Air	Air Air or Water
Cost	828.00 1077.00 1349.00	615.00 795.00	618.00 818.00	1200.00 600.00
Delivery Time	10 days	10 days	10 days	10 days
Major maintenance required every:	3000 hrs.	1000 hrs.	2500 hrs.	2500 hrs.
Modification Cost	85.00 119.00 119.00	———	———	90.00 115.00
Recommended Regular Maintenance Interval Continuous Operation		1 week	1 week	1 week 1 week

a) The use of biogas will derate output about 50%, if fuel is fed at the rated flow.

Table 6 (Continued)

Engines For Use In Biogas Systems
(Separate Engine & Generator Units)

Engine Manufacturer	Jeep	Volkswagen	Fiat	Kohler	Caterpillar
Model	I-6 258	126A	Totem	K141 K301 K582	3306
Rated KW a)	28	30	12 b)	4.6 8.9 17	70
Rated HP a)	40	44		6.25 12 23	95
Engine/ Engine Generator	Engine	Engine	Engine Generator Set + Heat Recovery	Engine	Packaged Engine and Generator
Cooling	Water	Air	Water	Air	Water
Cost	1,100.00	3,350.00	10,000.00	382.53 681.58 1277.20	$20,000
Delivery Time	6 weeks	2 weeks	6 weeks	2 weeks	12-16 weeks
Major maintenance required every:	2500 hrs. (12hr.days) 2/3 year	5000 hrs. (12hr days) 1-1/3 years	18,000 hrs. (12hr days) 4 years	4000 hrs. (12hr days) 1 year	10,000-12,000 hrs. (12 hr days) 3 years
Modification Cost	300.00	500.00 700.00	500.00 700.00	300.00	None needed
Recommended Regular Maintenance Interval Continuous Operation.	1-2 months	1-2 months	1-2 months	1-2 months	1 month

a) The use of biogas in an engine will derate output about 50%, if fuel is fed at the rated flow.

b) This is the manufacturer rated output running the engine on biogas, horsepower is not included because engine and generator are one complete unit.

Overhaul time is another parameter which should be examined when considering engine size (see Table 6 for quoted times from manufacturers). Overhaul time for the larger engines is not as long as one would imagine. The time ranges from 2500 to 18,000 hours, or between 208 and 1500 12-hour days of operation. It is important to remember here, however, that when manufacturers make these recommendations they couch them in terms of driving time because most of these units were designed as automobile engines. In this application the engine is being run at constant speed, as opposed to stop and start of driving, which greatly reduces engine wear and tear. It is hard to say by what factor this continuous duty operation will extend the time between overhauls, especially with the varying characteristics of biogas. It is fair to anticipate that the time between needed overhauls will be greater than stated, by a maximum factor of two. Overhaul time on the smaller engines runs about 1/2 to 3/4 the time of the larger engines, or 1500 hours to 3000 hours, depending on the brand of engine and amount of preventive maintenance.

Maintenance

Regularly scheduled preventive maintenance on both the larger and smaller engines should include the following tasks:

a) Checking and changing the oil.

b) Checking and cleaning the air filter.

c) Checking the coolant (this applies mainly to large engines).

d) Checking and replacing hoses, belts, etc.

e) Checking and tightening nuts and bolts which come loose during operation.

Manufacturers advise changing the oil once a week with the small engines, and keeping constantly on top of maintenance requirements for a long engine life. The larger engines can run about 2 months before needing an oil change, though in the first few months of operation, it certainly couldn't hurt to do it once a month. Other considerations include the need to prevent corrosion of the engine parts due to the hydrogen sulfide in the biogas. Methods for removing H_2S were described earlier in the chapter, but often small quantities of the gas persist. Engines can be protected through high temperature vapor-phase cooling, or by replacement of critical engine parts with ones which are corrosion resistant.

Several operational procedures are widely credited with preventing corrosion and contributing to engine reliability and life when using digester gas as the primary fuel:

1) A water trap is used to remove condensation and with it much of the hydrogen sulfide and/or the biogas is scrubbed

of H_2S.

2) Operation is continuous to avoid condensation during engine shut-down cooling (alternatively, the engine is flushed with air after shut down).

3) Regularly scheduled preventive maintenance described above is performed.

However, most installations have not experienced the "automatic, low-maintenance" engine operation touted by manufacturers when burning biogas. It is a good plan to have someone generally familiar with engines available to adjust, monitor and care for the engine. This service will minimize major maintenance needs and down-time.

Uses of Engine Shaft Power

When burning biogas in an engine, producing electricity is only one option. Shaft horsepower can be used directly in cases where mechanical power needs greatly outweigh electrical power needs. On a farm there are many possibilities for on-site power applications, such as running a conveyor, pumping water for irrigation, or mixing grain. It is important to remember that for mechanical applications the engine must be located where the power is needed. Also, remember the engine ideally sits near the digester. Thus, for using biogas as a fuel for mechanical drives, careful advance planning of the layout of the whole system is imperative.

If generating electricity is the selected option, there are other considerations. First, prime movers not packaged as engine-generator sets will need to be coupled with generators. Selecting a generator is a matter of matching the output of the generator (power output and shaft speed) with that of the engine. In the case of a spark ignition engine, the gearbox joining the engine to the generator will increase the speed of the engine to match that of the generator. In most cases, as mentioned before, the manufacturers listed in this manual will match the engine to an appropriate generator set, or can recommend a distributor who does.

In addition to a generator, the system will include electrical equipment, either for interface with the utility grid or delivery of power on site. If selling excess power to the local utility is planned, there will be equipment requirements (in compliance with TVA regulations) which must be adhered to.

The relationship between the utility and the small power producer has two parts: technical and contractual. These requirements are inter-related because certain technical conditions must be satisfied before contracts can be signed. As part of these conditions, the local utility requires that the power producer provide, install, and maintain switchgear, wiring and controls if parallel operation of the unit with power purchased from the grid is planned. Controls which protect the unit from under/over voltage conditions, and automatic circuit breakers with manual reset to separate the system from the distributor line in the event of a power outage, are also required.

In the TVA region, the TVA sets physical hookup requirements since it owns and operates the grid. Local electric distributors, however, are the ones with whom contracts for purchase will be made. Rates for buying cogenerated power are set by TVA, from whom the local distributors purchase the power they retail to the consumer.

It is a good idea to get to know the local distributors if you plan to sell electricity to them. Make contacts and explain plans early on to save time and misunderstanding later.

COGENERATION AND HEAT RECOVERY

In larger biogas systems which incorporate engines, cogeneration may be worthwhile. The term "cogeneration" means that the waste heat from the engine is used (sometimes supplemented by additional fuel) to satisfy some further heating requirement instead of being immediately discharged to the environment. Designing for optimum heat recovery starts with the selection of the prime mover, since the different types of engines yield different amounts of recoverable waste heat by virtue of differences in efficiency and ease with which waste heat streams can be captured. A highly inefficient engine may produce substantial recoverable heat at the expense of reduced power output, but this allocation of energy may be desirable for site applications where the thermal load is much higher than the electrical load.

Once the ratio of power to heat is determined by engine selection, the actual use of the heat will guide the design of heat exchange or recovery equipment.

In a large engine, waste heat will be available as a gas (engine exhaust) and a liquid (engine coolant). The Fiat Totem pictured in Figure 11 is an off-the-shelf cogeneration system. The engine drives a 25KW generator, and the heat in the engine cooling water is recovered and put to work. The unit is not designed for exhaust heat recovery, but depending on the potential dollar value of exhaust Btu's, recovering exhaust heat from these units might be worthwhile.

The smaller engines are generally air-cooled (see Table 6) and thus have only one practically recoverable stream of waste heat--exhaust. Again, the decision to recover or not recover this heat depends on how valuable it is. It may be worthwhile to capture it for digester heating. Space and water heating are common secondary uses of available energy.

With all sizes of engines, but the small air-cooled units especially, innovativeness and experimentation with heat recovery are recommended. The "experts" naturally disagree about how much heat is theoretically recoverable from the various systems but there are some

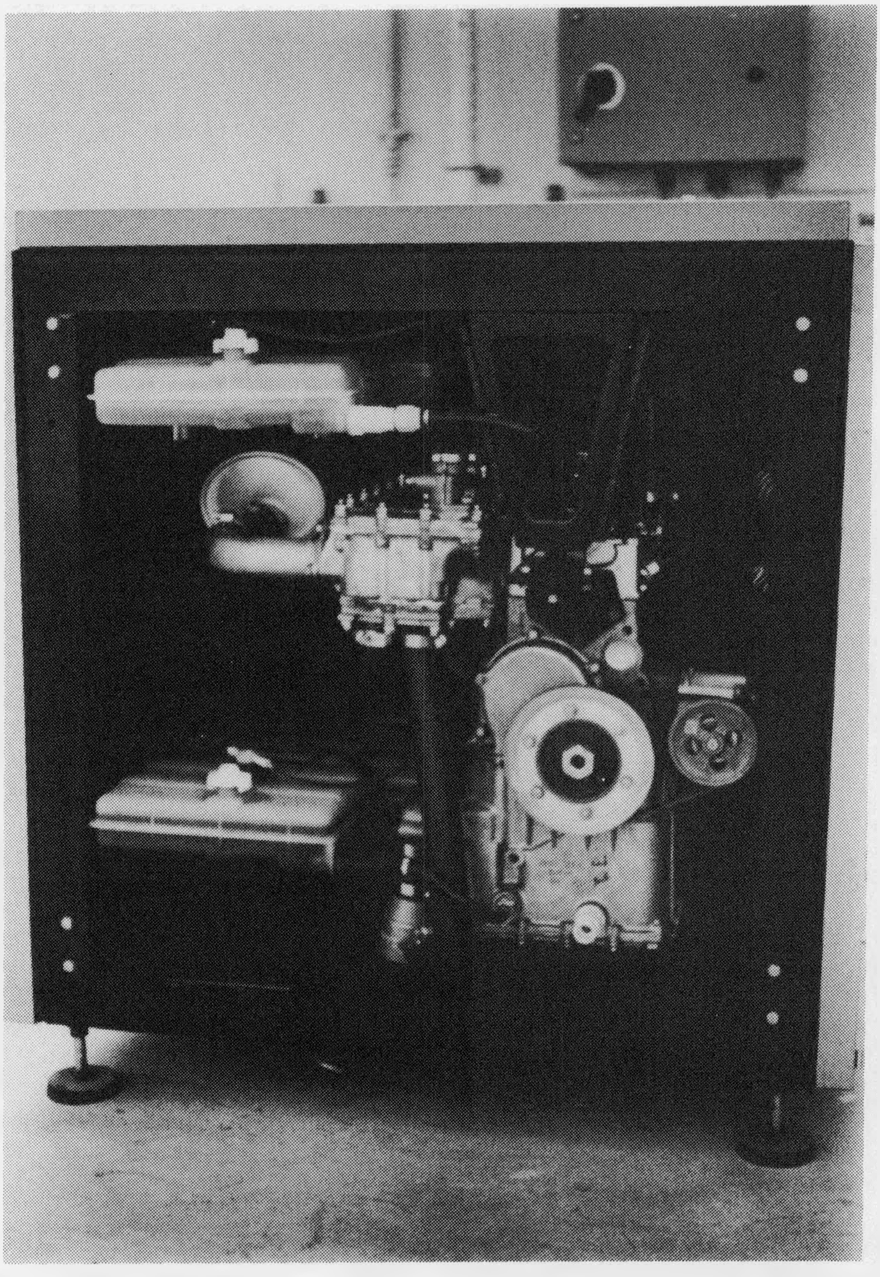

Figure 11. The Fiat Totem comes packaged with 25KW generator and coolant heat recovery equipment. The module enclosed in its case measures about 3½ feet on a side.

rules-of-thumb which might guide a decision about attempting engine heat recovery. Recovery of fifty percent of the total engine input heat value is commonly cited, with 40 to 60 percent also quoted. Given 25% engine efficiency, one source estimates that the remaining 75% of input heat is split almost evenly between exhaust and coolant. In water cooled engines, approximately 75% of the waste heat in both streams can be recovered using the "best" equipment. Heat exchanger manufacturers listed in Appendix 1 may offer some insight into designing a heat recovery system.

Applications of Waste Heat

When digester sludge heating demands most of the engine waste heat, the simplest recovery scheme involves transferring both engine coolant and exhaust heat to water. Figure 12 shows such a system. Sludge is heated by being piped through a hot water bath, with a little heat diverted for building space heating. The closed engine cooling water loop requires highly efficient heat transfer in the water-to-water heat exchanger since the fluid must again act as a coolant when it returns to the engine. In some cases, it will be simpler to pipe hot water through a sludge reservoir for heating rather than the reverse shown in Figure 12. (Also see Figure 4 for a third method.) Standard pumping techniques and materials are suitable for heat recovery systems, except PVC pipe use is limited to cool water returns.

In all designs, extra insulation of pipes, holding tanks, and the digester will reduce heating demands, leaving more heat available for other uses. Short pipe distances will also minimize heat losses. On farms, where the source of the wastes can be a matter of feet or yards from the digester, it is a good idea to remember that the manure begins its life at the ideal temperature for mesophilic digestion, and any design features which slow down cooling of the digester feedstock will pay off.

Figure 13 is a simple schematic showing separate applications of engine exhaust and coolant waste heat. Such a setup would be appropriate for heating hog buildings or chicken coops in winter, provided the animal housing is located close to the prime mover. Transferring heated air over long distances results in substantial losses as well as rising system costs due to extended ducting.

The arithmetic behind heat recovery design is somewhat complex, but some helpful calculations are provided in Chapter 6. Computing sludge heating needs is an obvious first step to system design. Appendix 1 contains a list of firms who sell "off-the-shelf" and custom-designed heat exchange or recovery equipment. Other firms listed in Appendix 1 with complete biogas cogeneration system design capabilities will include the heat recovery component in the package of services and some of the engine manufacturers listed in Table 6 also package heat recovery equipment.

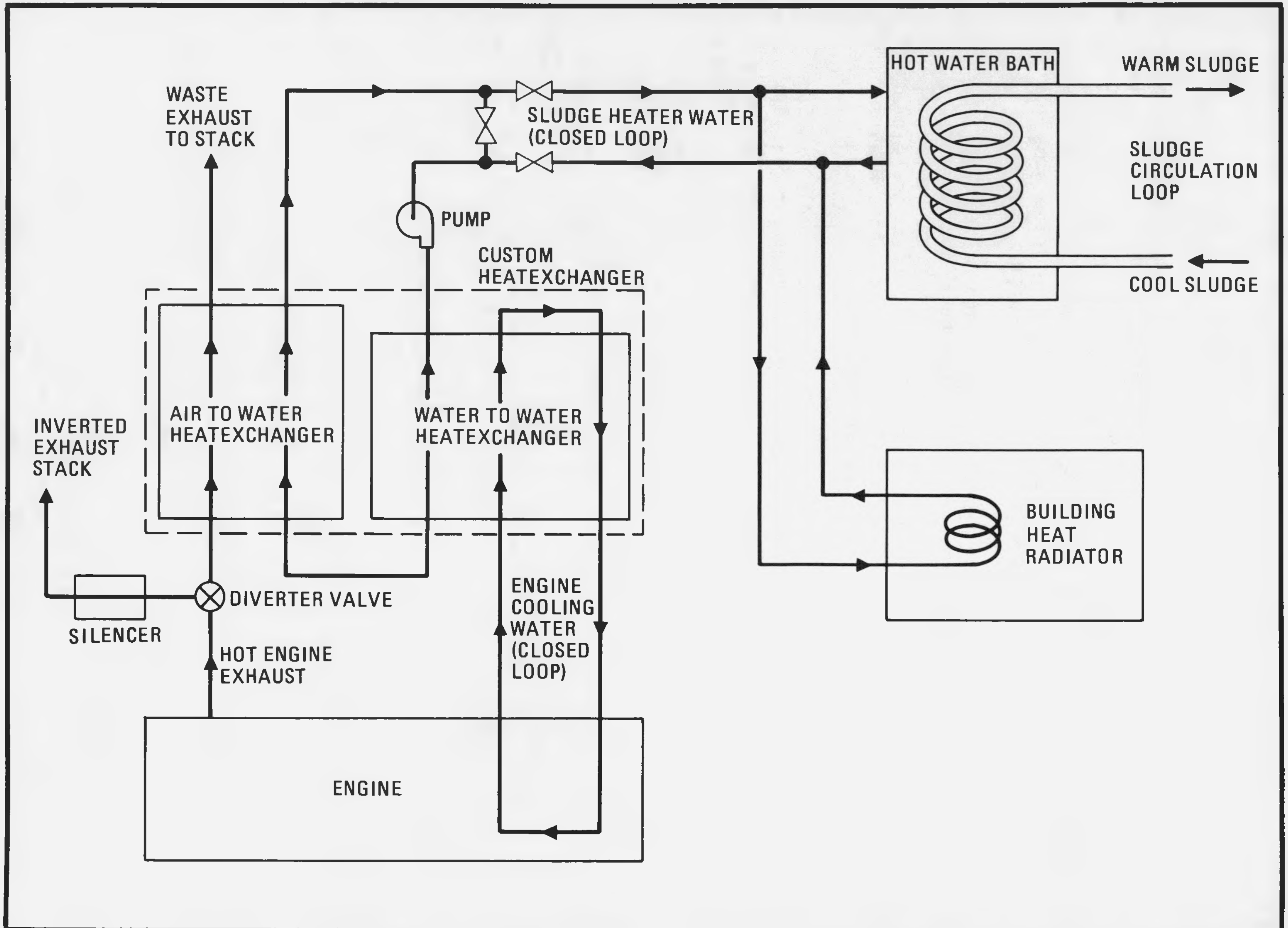

Figure 12. Application of Waste Heat to Sludge Heating.

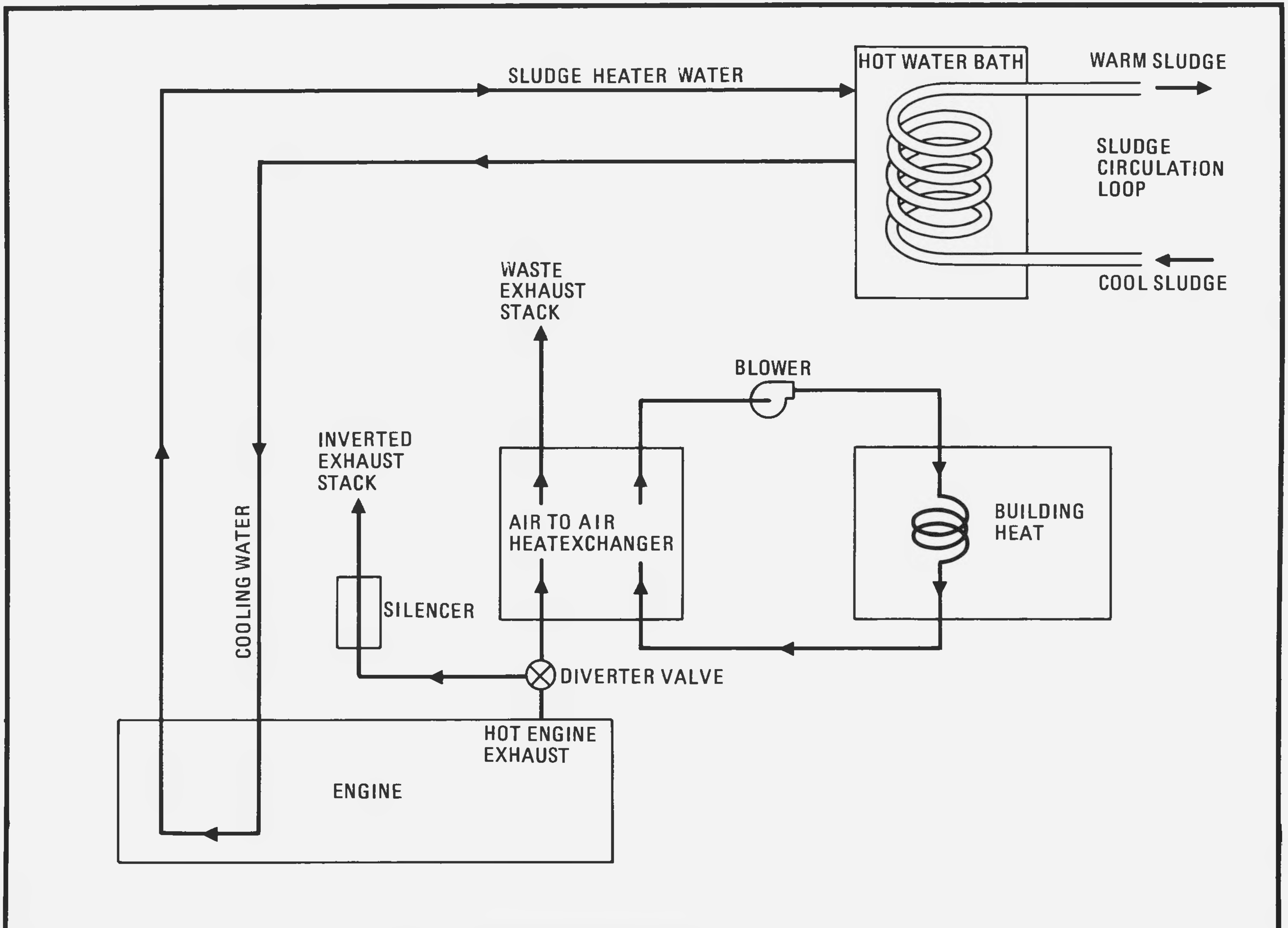

Figure 13. Application of Waste Heat to Sludge and Space Heating.

SUMMARY

It should be evident that many factors enter into choosing the components of a biogas system. For ready reference some essential points are reviewed below:

1. Optimum utilization of the gas is the point of this exercise. Assess on-site power needs to determine if there is a good match between potential biogas production and heating/power needs.

2. Design the most efficient collection system possible. Losing half of the gas before it is utilized is not the object.

3. Does the gas need to be scrubbed prior to combustion? If so, find the simplest, most efficient method of doing so.

4. For engine systems, power potential is based on the amount of biogas available for combustion. This will give a fix on engine size. It may be that there is only one size engine available in the size needed. If, however, there are several engines in the required size, comparison shop and see who offers the best package price.

5. Experience in actual operation of the engine or burner selected on biogas fuel varies widely, so don't rely on just one source of information for how well or how poorly a given type or specific model has performed. There are many factors outside of the engine or burner itself which can determine the success or failure of a biogas use system, including the next factor.

6. With regard to maintenance requirements, there are two main areas of concern: what the schedule of required maintenance consists of and who is going to do it.

7. Comparison shopping in assembling the whole system is important, but especially applicable to engine generator sets. Both the original cost of the engine generator set and the on-going operating and maintenance cost must be carefully evaluated. Be sure that comparisons are made of "apples with apples" when looking at manufacturers' quotes and be sure the overall cost includes total system requirements for heat recovery and application according to the site's energy needs.

8. Availability of the engine or burner from a local regional or national supplier is another important factor. How long will it take to get the selected equipment? Delivery times of up to 10 months from placement of order are common for larger engine generators. Savings from a biogas cogeneration unit are lost during the wait. Also, availability of service and spare parts needs to be determined. At some

point in system operation, despite promises from salespeople, both will be needed.

9. When cogenerating, one of the most important factors is the design of the heat recovery equipment. If the engine manufacturer packages heat recovery equipment for the engine, use it. If not, comparison shop and locate a firm that will design the most efficient equipment for the price. Ask for a list of past customers for reference before committing to a manufacturer.

CHAPTER 5

BIOGAS CASE STUDIES

This chapter reviews biogas systems at three different sites, all with different operational needs. The first example is a California farm which produces veal, dairy cows and hogs. The biogas system at the Morelli farm was originally designed to supply gas heat to barns, but the plumbing required proved too expensive. The owner is looking into an alternative use of the gas. The second site is a dairy in Virginia which fires a cogeneration system with its biogas. The facility produces electricity for sale to the local utility, and recovered engine waste heat keeps the digester warm. The third example is a Tennessee hog farm. Biogas in this case has been successfully applied to heating barns. These sites have different kinds of digesters and different enough operational requirements to introduce a range of biogas system possibilities.

MORELLI FARM

The Morelli operation is a 551 acre ranch in Petaluma, California which has been in the Morelli family for over one hundred years. On the ranch Farmer Bob raises veal, swine, and dairy cows and also operates a firewood business. His biogas system came on line in Fall, 1980.

The Morelli system can be seen in Figure 14. The operation consists of about 100 calves, 100 swine, and 100 dairy cows. All livestock are raised indoors. The calves and dairy cows are confined side by side in a barn with an elevated, slatted wooden floor. The manure falls through the slats in the floor and into a 12 inch wide trough which runs the length of the barn behind the animals. Twice a day the floor of the barn is washed down with a high pressure hose, and the resulting slurry is moved down hill through the trough to the end of the barn where it exits and flows downhill through a pipe about thirty feed to a concrete settling tank. The swine manure is collected in the same manner, though the swine are not confined in individual pens. They reside in one large area with a slanted concrete floor, which is also hosed down daily. This slurry is also carried down hill through a pipe to the concrete settling tank. Once there, the manure remains until the tank is full (about 2 days). At this point a valve is opened and the slurry is sent down a 4 inch diameter pipe about 18 inches underground into the digesting lagoon. The lagoon is 60 by 90 by 8 feet deep and covered with neoprene tarp. The tarp is held down by a two foot trench along the perimeter of the lagoon. Tires are then placed in the trench to hold the tarp down. Of the digesters described in Chapter 3, this lagoon functions most like a plug-flow unit.

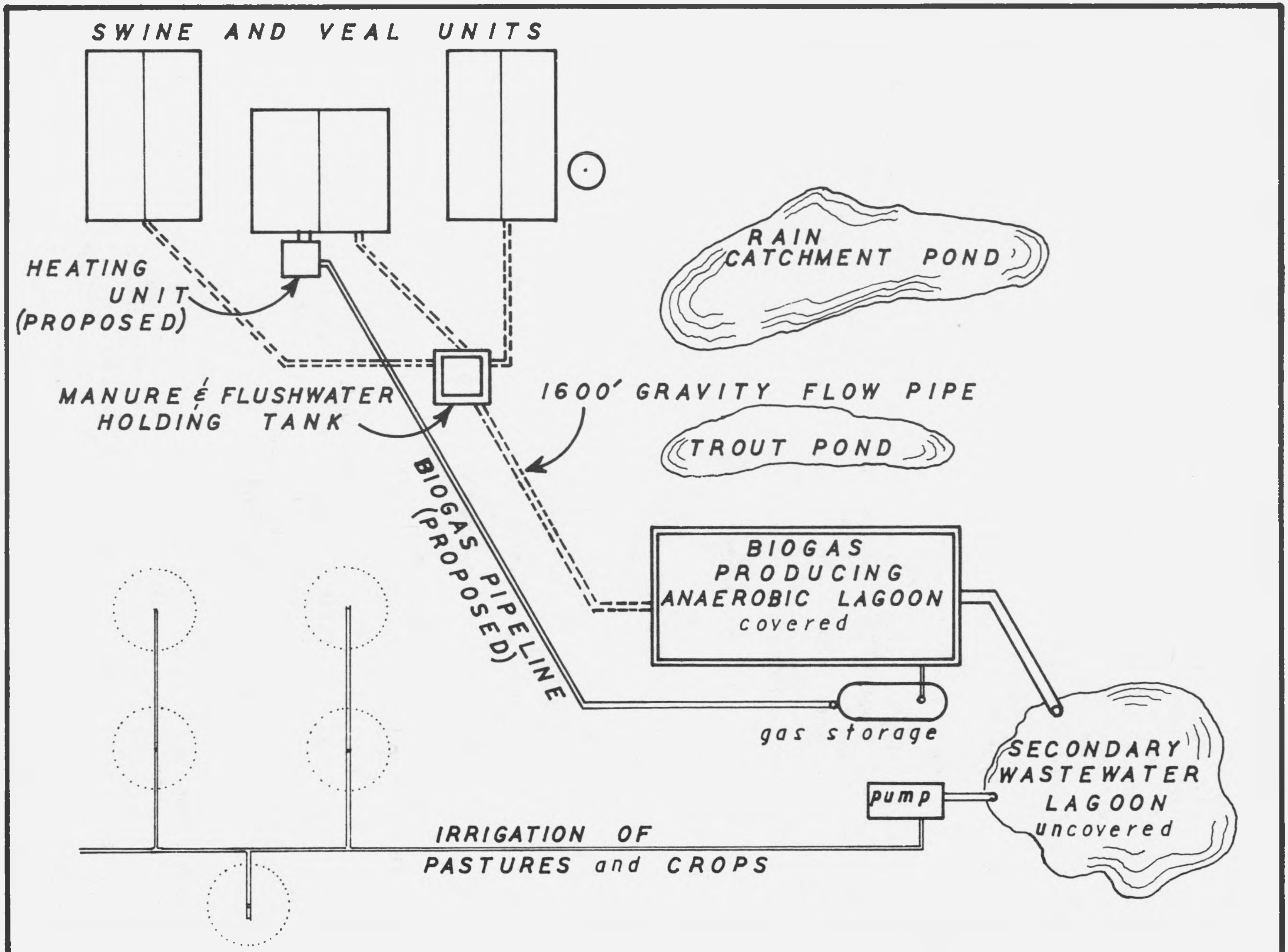

Figure 14. Morelli Farm Biogas Project.

As the sludge digests it begins to form gas. The gas rises to and fills out the top side of the tarp, where it then exits through a large pipe on one of the sides. It appears that the location at which the gas is taken off is worth experimenting with. Farmer Bob claims that by taking the gas off where he currently does, he gets the highest concentration of methane and the lowest concentration of carbon dioxide and hydrogen sulfide. Gas production ranges from 220 to 773 ft^3/day, with an average of about 500. The amount of gas varies with the season (due to the lack of digester heating in the system). The detention time is about 60 days with an average of about 750 Btu's per cubic ft of gas produced.

Below the digesting lagoon is a secondary lagoon. Digested sludge is transferred into the lagoon, then diluted with fresh water (300 gallons of water to 1 gallon of sludge) and is then pumped up hill to irrigate the surrounding fields.

Originally the system design called for piping biogas up the hill through a separate 1600 foot pipe and burning it to heat the confinement barns. The cost of the pipe at this point seems to outweigh the benefits of using the gas to heat the barns. Therefore, Morelli is both seeking out a cheaper means of transporting the gas up the hill and considering alternative uses of the gas.

The Morelli Ranch biogas operation has a couple of notable features:

1) The digester is not heated. While gas production does drop off in winter, the relatively benign climate and lagoon design (which takes advantage of insulative soil properties) promote sufficient gas production in winter without heating.

2) The system is designed so that just about everything runs down hill. The only step at which pumping is needed is the final transfer of diluted sludge to fields for irrigation.

OTTER RUN FARM

Otter Run Farm is a dairy in Bedford, Virginia. The dairy is the site of an experimental biogas cogeneration facility built and operated by Anaerobic Energy Systems, Inc. of Bartow, Florida. Figure 15 is a schematic which illustrates the workings of the system.

At Otter Run Farm, cow manure is scraped from open barns with a small front-end loader, then pushed directly into a covered settling tank. In this tank an agitator-pump works in either mode to stir up manure or send it to the digester. Figure 16 shows the digester and adjacent cogeneration equipment building. Manure is piped through the equipment building where it can be heated before entering the digester. The digester was started up in January, 1981.

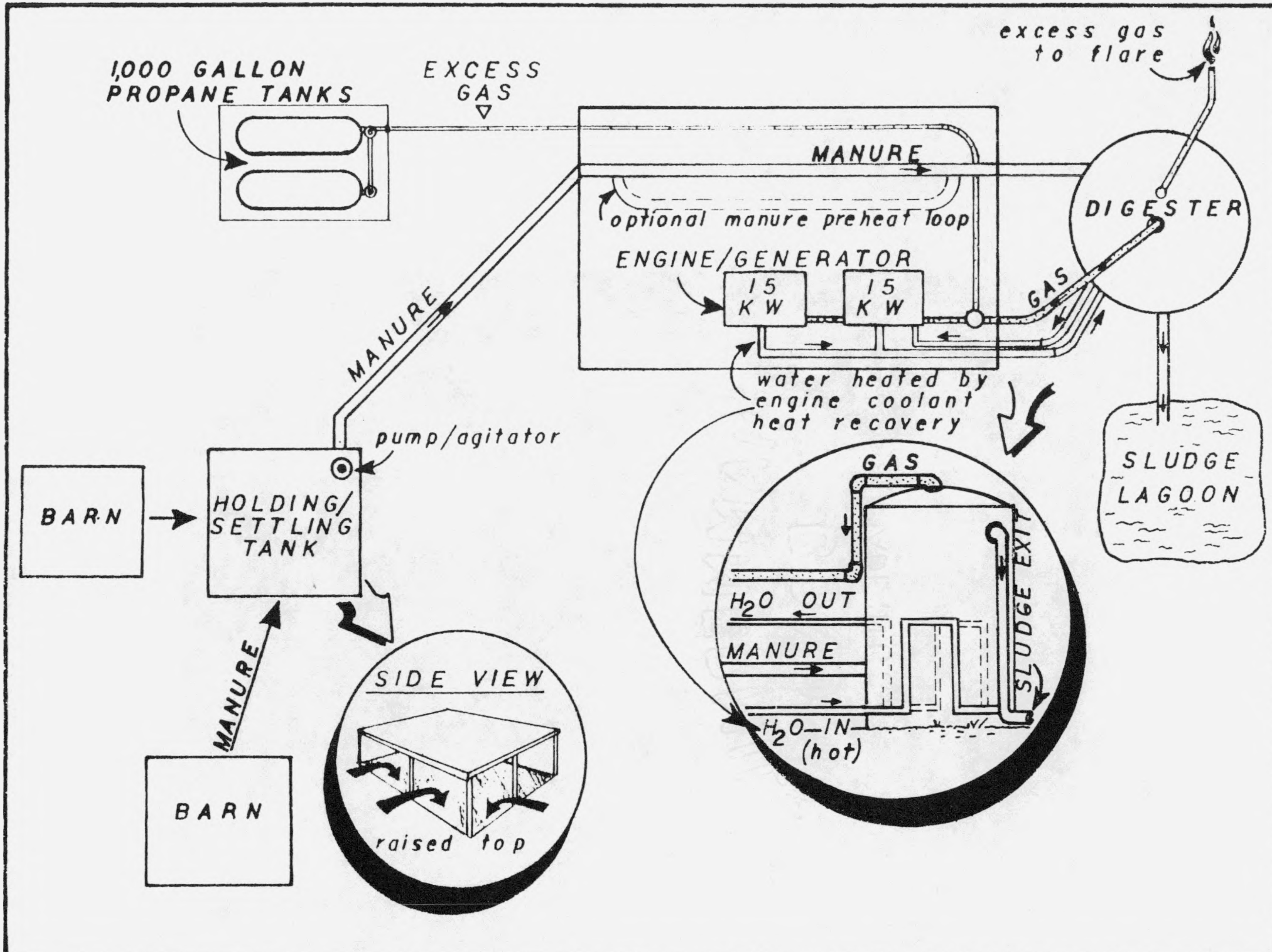

Figure 15. Otter Run Farm Biogas Cogeneration System.

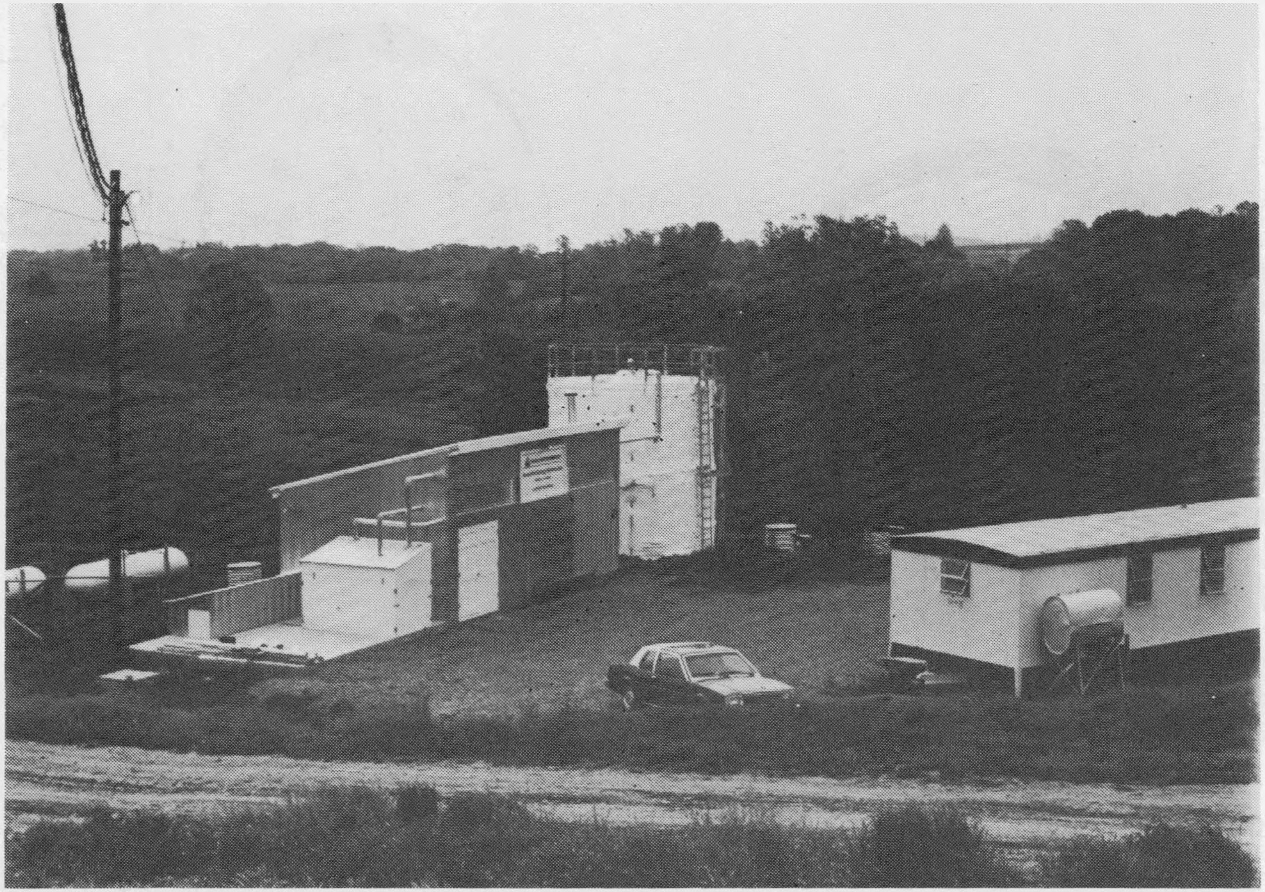

Figure 16. Otter Run Farm.

The digester is the 21,000 gallon unit previously described in Chapter 3 as a thermally mixed digester (See Figure 5). Hot water heated with prime mover waste heat is piped around the bottom half of the digester to keep it at its 95° operating temperature. The heat exchanger pipes along with the entire bottom half of the digester are covered with 6 inches of urethane foam and the upper half (including the top) is covered with 3 inches of the same insulation. Fifteen minutes to one-half hour of pumping per day loads approximately 800 gallons of manure into the digester. Retention time is on the order of 20 days.

The description of gas production and the cogeneration installation comes directly from Anaerobic Energy Systems:

> On the average, there are 90 cows in the milking herd. These cows will produce sufficient manure to create 4,680 ft^3 of biogas/day. This biogas is 60% methane and 40% carbon dioxide and has a Btu content of 600 Btu/ft^3. This amount of biogas is equivalent to 2,808 ft^3 of natural gas/day, or 30 gal. propane/day, or 20 gal. of #2 fuel oil/day. However, in this application the biogas will be burned to generate electricity. The engine-generator used at Otter Run is a Fiat TOTEM. TOTEM is a small on-site generator unit that burns biogas to generate electricity and recaptures the heat to provide hot water or heating.
>
> At a 20% electrical conversion efficiency this engine can produce 164 KWH of electricity/day, and 1.7 million Btu of heat in the form of 195° hot water. At the peak demand of 25 KW, this energy is sufficient to power the milking operation for 6.5 hours.

Arrangements to sell excess electricity to the local power company were concluded and the cogeneration system was scheduled to start up in September, 1981.

STOCKWELL DIGESTER

Jerry Stockwell keeps 20-40 hogs, maintains a broiler finishing operation, and raises grains on 120 acres near Palmer, Tennessee. One of the ways he is working to make his farm less dependent on outside sources of energy is through methane production from his hog wastes. Figure 17 shows a layout of the farm and system. Chicken wastes are not used since the broilers sit on bedding. While the high cellulose and other inert solids content of the bedding complicates use in a simple digester, Jerry has found the bedding makes highly satisfactory fertilizer for his corn crop, replacing commercially purchased fertilizers, and yielding 60 bushels an acre.

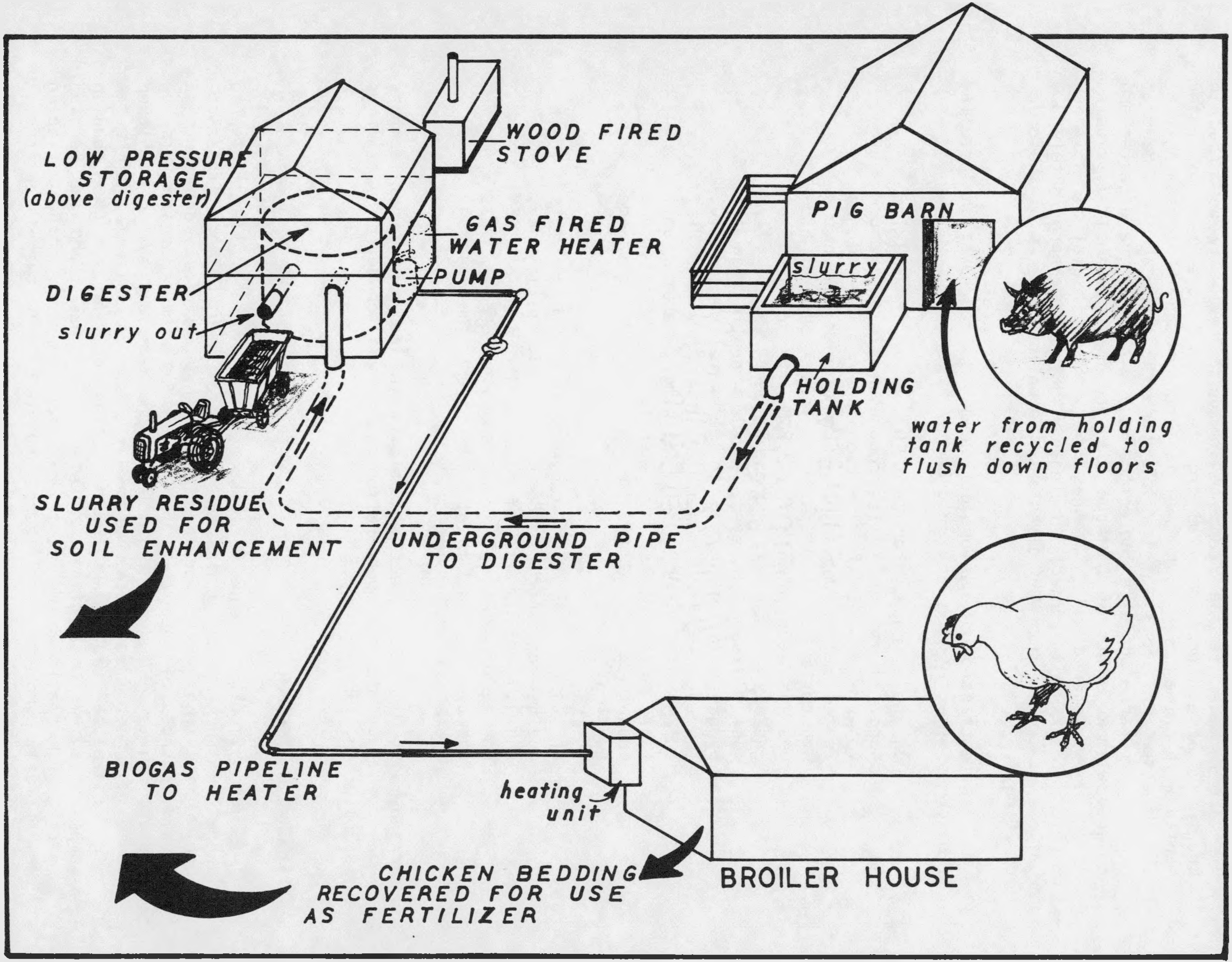

Figure 17. Stockwell Farm Layout.

The Stockwell digester was started up in spring, 1981. Biogas produced by the digester is not used to fuel an engine-generator set, but rather it is directly combusted to warm his broiler sheds. In this application, biogas directly supplants purchased LPG which is costing him about 75¢ a gallon (summer, 1981).

In operation, the sloped concrete floor of the hog barn is washed down periodically into a cinder block holding tank with a 1200 gallon capacity. The tank is pumped from the bottom once a day, during normal operation, which results in a solids concentration of 12-20%. The lighter liquid on the surface of the tank is recycled for flushing down the barn floor, thereby decreasing the amount of water used in the operation. A half horsepower electric motor operates the 3" sludge pump for about 5 minutes to drain the holding tank of the slurry. The slurry travels through buried plastic pipe to the digester house about 150 feet from the collecting tank.

Jerry Stockwell and Dennis Gregg, who directed the construction, were also fortunate to be able to use timber and an old sawmill on the property for making the lumber for the digester house. The building looks nice and fits in well with its surroundings. The use of a shelter to completely enclose the digester offers some attractive advantages:

1) The digester itself does not have to be insulated with relatively expensive polyfoams or other materials. The digester house itself is insulated with R30 ceiling and R19 wall batting. The floor under the digester is also insulated.

2) The digester cover and storage bag are both protected from weather and sun.

3) All pumps, valves, meters and plumbing are contained in a secure, weatherproof structure.

For the digester itself, 4" thick silo block was used to build up a container 18 ft in diameter and 7.5 ft high with two inside baffle walls to separate input from outflow. Total capacity is approximately 1900 ft^3 (15,500 gals.). The introduction of new manure from the hog barn holding tank causes old, digested material to overflow through a liquid trap and plastic pipe to the outside of the digester building. This residue is collected for direct application to the soil for periodic soil enhancement since none of the nitrogen, phosphorus or potassium are lost in digestion.

The digester is not mechanically mixed but is heated internally by circulation of hot water through 1" steel pipes on the floor of the digester. The existing cover is non-reinforced vinyl which was substituted for the hypalon originally specified because of the high cost of hypalon. Unfortunately, the vinyl cover leaks (through pinholes and cracks) and does not seal properly because of too many wrinkles in it. Stockwell plans to install a hypalon cover eventually.

The digester is designed for 15 days retention time with a livestock level of 40 hogs but up to 30 days have been experienced in startup. The digester pH has always balanced around pH = 7 without any acid-base "doctoring" of the slurry. At full capacity gas production should reach up to 2500 ft^3/day (hog population of 250) with a consistent heating value of 650 Btu/ft^3.

A wood-fired stove made out of two oil drums is used to heat water for digester startup or to supplement heat provided by a biogas-burning hot water heater modified by W. L. Jackson Co. Allowance is made for 15-20% of biogas production to be applied for digester warming in the winter with the balance for heating the broiler houses. In the summer, only 60-70% of the gas produced can be effectively used. (Once again, the greater flexibility of using biogas to produce electricity is illustrated--any surplus can be sold to the local utility.)

As shown in Figure 18, gas produced by digestion exits the tank and passes first through a scrubber; then, out to a condensation trap for water removal. The scrubber is a 55 gallon drum filled with a mixture of iron oxide (rusty metal) and sawdust. The hydrogen sulfide (H_2S) in the biogas reacts with the rusty iron to form fereous sulfide and water. A replacement time of six months is assumed on the scrubber material but it could be as long as a year. The combination of scrubber and water trap work very well to provide a dry, odorless gas with consistently high Btu/ft^3 value.

After the condensation trap, gas goes through two one-way valves to interim gas storage. Activation of a sump pump in the lower of two stacked 55 gallon drums drives water up into the upper drum, sending the gas up under slight pressure. Operation of the "drum pump" is elegantly simple. If the gas storage bag is filled (determined by a pressure of .25 - .5 psi), the pump is inhibited from operating. If no gas is being produced by the digester, the pump doesn't operate. If gas is being generated, but the bag is empty, the pump goes on. Gas is then pumped to the broiler house and the hot water heater or, according to demand, to a small high pressure storage bag located conveniently on the second floor of the digester house above the digester (see Figure 18).

Pressure relief valves and a surge tank protect the system from dangerous gas overpressures (Figure 18). One-way valves on each side of the drum pump keep the scrubbed, dewatered gas from mixing with the raw biogas as well as preventing backflow.

Cost of the system shown was between $3600 and $4000 for parts and materials with labor "donated" by Jerry Stockwell and Dennis Gregg. When production reaches 2000 to 2500 ft^3 of biogas a day, with 15-20% applied to digester heating (less biogas could be used for digester heating by fueling the wood stove but then the operation is not automatic), calculated annual energy yield is over 390 million Btu's. This is roughly equivalent to 4280 gallons of propane Jerry Stockwell would otherwise buy to warm his broilers. Annual cost saving is $3210 at the 75¢/gallon price. Electrical consumption of

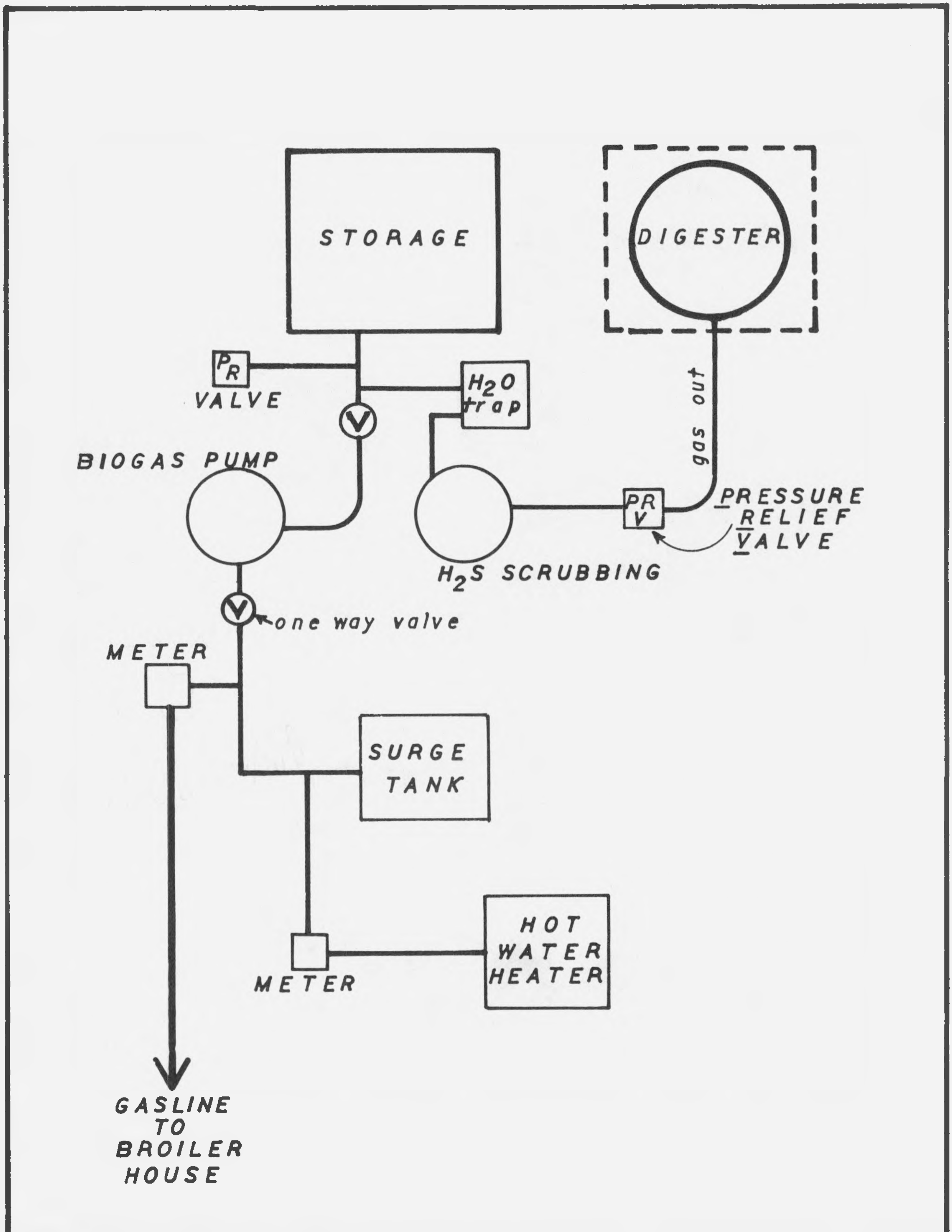

Figure 18. Stockwell Biogas System Schematic.

the pumps is minimal and fuel savings are significant. Building the unit with non-fee labor (just valuable sweat and time) keeps cost down to a point that a payback in less than two years is attainable, even with only partial gas usage in summer months.

CHAPTER 6

SITE EVALUATION GUIDELINES

Because a decision about a biogas system will likely be rooted in dollars, it is the aim of this chapter to guide calculations of:

a) system cost, and
b) annual system benefits,

in order to compute the simple payback period or return-on-investment for a biogas system. The following separate steps are necessary for completing the payback calcuations:

1) Determine the quantity of manure available.

2) Calculate the biogas producible from (1).

3) Determine use of biogas and necessary equipment.

4) Estimate energy production from the system.

5) Select and size the digester to fit (1).

6) Calculate the heat needed for digester (5).

7) Calculate the value of the energy produced by the biogas system.

Some of the steps may need repeating for different times of the year, since digester heat requirements, biogas production, and biogas end-use functions may vary seasonally. A minimum analysis ought to run through both summer and winter conditions. Again, cogeneration applications receive most attention.

STEP 1: DETERMINE QUANTITIES OF MANURE AVAILABLE

There are three values which must be known or estimated about the manure supply: volume (ft^3/day), solids concentration (%), and volatile solids content (lbs/day). Volatile solids are the digestable fraction of the manure. The volume and solids concentration will determine digester size; if the wastes contain more than about 7% solids, they must be diluted to that concentration in order to be pumped. (Manure hosed out of barns will probably not need diluting.) Percent volatile solids plus the other data will predict biogas production.

The most reliable values to use for these variables are, of course, actual measurements of current collections. On a farm, however, this information is not readily available. For an estimate the following suggested values, which are derived from Table 1 (Chapter 1) may be used:

Production Unit	Undiluted Volume (ft^3/day)	Diluted Volume Necessary for Pumping @7% Solids (ft^3/day)	Volatile Solids @80% Volatiles (lb/day)
1 dairy cow	1.6	2.3	8
1 feedlot steer	1.1	1.7	5.5
1 hog	0.16	0.39	1.4
1 chicken	0.0027	0.021	0.04

STEP 2: DETERMINE BIOGAS PRODUCTION

The amount of biogas produced in anaerobic digestion is a function of volatile solids supplied to the process and operating efficiency of the digester. Assuming 40% destruction of volatiles in digestion (a conservative but realistic value), the amount of gas produced is simply:

$$\_\_\_\_\text{lb/day volatiles} \times 7\ ft^3/lb = \_\_\_\_ ft^3/\text{day gas production.}$$

There is likely to be slightly greater gas yield with a complete-mix digester and less gas from a plug-flow unit regardless of the estimating technique used.

STEP 3: DETERMINE USE OF GAS, AND NECESSARY EQUIPMENT

If the best use of biogas at a site is not obvious, working out the economic details of several options might be a helpful exercise. The general categories of use presented in this manual include:

1) Direct combustion for heating.

2) Electricity (or mechanical power) production.

3) Cogeneration of electric or mechanical power and heat.

Equipment needs of these options were discussed in Chapter 4. In Step 4, the theoretical output from the selected system is computed.

STEP 4: ESTIMATE ENERGY PRODUCTION FROM THE SYSTEM

The biogas production rates derived in Step 2 can be easily converted to hourly energy production as follows:

$$\underset{\text{(gas produced from Step 2)}}{\_\_\_\_ ft^3/\text{day}} \times 600\ Btu/ft^3 \times 1/24\ \text{day/hr} = \underset{\text{(value of gas produced)}}{\_\_\_\_ Btu/hr}$$

Where 600 Btu/ft^3 is commonly cited heating value for digester gas. For direct use of the gas the Btu/hr of biogas calculated above allows comparison with heat rates of gas appliances. Actual amount of heat delivered to the medium being heated depends on the efficiency of the appliance:

_____Btu/hr	×	_____%	=	_____Btu/hr
(gas produced)		(appliance efficiency)		(actual heat produced)

If the biogas will be used for mechanical power production, the next step is to calculate roughly how many horsepower can be extracted from this energy flow rate. Assuming an engine which extracts 25% of fuel energy as mechanical power, the calculation proceeds as follows:

_____Btu/hr	×	0.25 ÷ 2544 Btu/HP-hr	=	_____HP
(gas produced)		(conversion factor)		(maximum engine output)

Continuing to calculate electricity production for that application of biogas:

_____HP	×	0.746 KW/HP	×	0.92	=	_____KW
(from previous entry)		(conversion factor)		(assumed generator efficiency)		(maximum generator output)

Finally, for cogeneration applications, the amount of useable waste heat must be computed. Not all prime movers in the biogas application size range addressed by this manual will have recoverable cooling water and exhaust streams. Recovery of cooling water waste heat will be likely for all but air-cooled engines. Two simple rules-of-thumb will aid determination of waste heat available for work:

1) About 50% of the Btu's in the fuel going into the engine end up as recoverable waste heat.

2) Of this recoverable waste heat, about half is available from the cooling water and half from the exhaust.

Thus:

_____Btu/hr	×	0.50	×	0.50	=	_____Btu/hr
(biogas produced)		(recoverable waste heat)		(exhaust fraction)		(waste heat available from engine exhaust)

and

_____Btu/hr	×	0.50	×	0.50	=	_____Btu/hr
(biogas produced)		(recoverable waste heat)		(coolant fraction)		(waste heat available from coolant)

These calculations can serve as a basis for equipment selection. Fuel-burning equipment will not likely be available in the precise size which matches biogas production. For engines, the lower Btu value of biogas necessitates "derating." A reasonable guideline is to select an engine rated at twice the horsepower calculated above.

For many types of equipment, multiple small units might yield a better fit to the biogas produced than a single larger unit. Multiple units also allow more operating flexibility.

STEP 5: SELECT AND SIZE THE DIGESTER

For this simple payback analysis the reader needs to select one type of digester. Then, in order to estimate the approximate cost and heating requirements of the digester, it is necessary to calculate its size. Based on high rate digester loadings of 0.2 lb volatile solids/day/ft^3 of digester fluid volume, and assuming a cylindrical shape, the volume of this type of vessel can be computed as follows:

____ lb VS/day (from Step 1)	÷ 0.2 lb VS/day/ft^3	÷ 0.75 (assumed active fluid volume)	=	____ ft^3 (required total volume of digester)

As a check that this volume will be sufficient to handle the manure volume predicted in Step 1, the following calculation is suggested:

____ ft^3 (total volume from previous entry)	×	0.75 (assumed active fraction)	÷	____ ft^3/day (sludge flow from Step 1)	=	____ days (fluid retention time)

The resulting retention time should be between 10 and 30 days for the complete mix reactor.

The dimensions of the digester tank may vary somewhat and still provide the required fluid volume, but for simplicity, it will be assumed that the tank is cylindrical in shape with height equal to diameter (this configuration will minimize surface area). Thus, dimensions are:

$$\sqrt[3]{\frac{4}{\pi} \times \underline{\qquad} (ft^3) \text{ (digester volume)}} = \underline{\qquad} ft \text{ (digester height)}$$

and radius is one-half the height. (Note: "Height" assumes a vertically placed tank. For a horizontal cylinder such as Rutan's digester, "height" is really the length.)

For the plug-flow type digester, the required volume calculation is the same as before, but a lower volatile solids loading rate must be used:

_____ lb VS/day	÷	0.05 lb VS/day/ft^3	÷	0.75	=	_______ ft^3
(from Step 1)		(loading rate for unmixed reaction)		(assumed active fraction)		(required fluid volume of digester)

As a volume check, the retention time can again be computed by:

_____ ft^3	×	0.75	÷	_____ ft^3/day
(total volume from previous entry)		(assumed active fraction)		(sludge flow from Step 1)

= ______ days (fluid retention time).

In the plug flow case, the resulting retention time should be on the order of 50-75 days for maximum gas production. The trade-off between retention time and digester size (therefore cost) should be considered.

The dimensions selected for a plug-flow digester will depend largely on the owner's individual site characteristics. As a starting point, the trough should be wide enough to admit whatever scooping vehicle is to be used for cleaning out the solids accumulation. Secondly, the fluid depth should be half to three-quarters of the width and the length should not generally exceed 100 feet. Following these guidelines, the digester dimensions can be calculated as follows:

_____ ft^3	÷	_____ ft	÷	$\frac{1}{2}$ W ft	=	_____ ft
(required volume)		(estimated vehicle width, W)		(depth, expressed as a fraction of width)		(length)

Depending on the resulting length, the 100 foot limitation and the land area available for digester installation, the owner may decide to split the total required volume into two or more separate digesters. The length-to-width ratio of the digester should not exceed four or five to one.

When actual digester design begins, one to two feet of freeboard clearance should be allowed above the fluid level in the trough.

STEP 6: CALCULATE DIGESTER HEAT NEEDS

In most areas, digesters will need to be heated, at least in winter. Mesophilic digestion requires manure to be maintained about 95°F. Regardless of how the sludge is to be heated for digestion, the calculations of heat needs are the same. In biogas cogeneration applications it is assumed that the primary function of engine waste heat is warming manure for digestion.

Raising Incoming Sludge Temperature

Ideally, the temperature of the incoming sludge should be known to calculate the heat needed to raise it to digestion temperature, but lacking this information some substitutes can be used:

(T_1)incoming sludge temp. ≈Average daily temp.(T_2) -20°F(summer)

≈Average daily temp.(T_2) +5°F(winter)
(but sludge temperature should not be less than 40°F)

The formula for calculating heat needed to raise the manure temperature to an assumed 95°F digestion temperature is:

_____ft^3/day	× 62.4 lb/ft^3	× ($95 - T_1$)°F	÷ 24 hr/day
(manure volume from Step 1)	(conversion factor)	(temperature increase needed)	

= _____Btu/hr (daily influent heat demand)

The Btu/hr rate at which this heat allowance is used will depend on the sludge feeding schedule. It might be that sludge is slowly trickled into the system around the clock, making hourly heat demand 1/24th the daily allowance; or a single hour of pumping might feed all the influent to the digester, making that one hour's heat demand equal to the entire day's allowance. For cogeneration systems run continuously, the engine's waste heat will be produced at a constant rate, and it may be necessary to heat the influent sludge up slowly over most of the day in order to stay within the available waste heat flow rates.

Maintaining Digester Temperature

A second heat requirement for digestion is to maintain the 95° temperature inside the tank in spite of heat losses through the sides, floor and roof. The general formula for these losses is:

_____ft^2	× ($95 - T_2$)°F	× __U__ Btu/hr/ft^2/°F
(wall, floor or or roof surface area)	(differences between inside and outside temperatures)	(a factor describing insulating qualities of building materials)

= _____Btu/hr (heat losses)

Since the digester surfaces are not all the same construction, and hence have different U factors (which, incidentally, are the inverse of the more familiar "R" values), the calculation must be done separately for each surface and then the resulting Btu/hr heat losses can be added together. The surface areas can be obtained from the dimensions established in Step 4 according to these formulas:

	Cylindrical High Rate Digester	Rectangular Plug Flow Digester
Flat Roof or Floor Area*	πR^2	$L \times W$
Domed Roof	$2\pi R^2$	$1.5 \times L \times W$
Wall Area	$2\pi R H$	$2H (L + W)$

(* most gas-filled storage covers will be between these two values)

where R = radius of the cylindrical digester
L = length of the horizontal digester
W = width of the horizontal digester
H = wall height of either digester

The lower U values indicate better insulators.

Some U values likely to be needed for the calculation are:

Material	U
Wood floating cover	.33
¼" steel floating cover	.48
¼" steel floating cover with 2" insulating concrete	.22
¼" steel floating cover with 3" insulating concrete	.17
12" concrete exposed to air	.86
12" concrete exposed to 1" air + 4" brick	.27
12" concrete next to 10 ft of wet earth	.11
12" concrete next to 12 ft of dry earth	.06
1" polystyrene foam (top of plug flow digester under "balloon" cover)	.24

Clearly, the addition of earth embankments around concrete tank sides improves the digester's heat retention significantly.

Heat Needs vs. Fuel Production

Once calculations for 1) heat needed to raise manure temperature to 95°F and 2) heat needed to compensate for losses from the digester are completed, the actual method of heating should be decided. Heat loss values (Btu/hr) should be compared with Btu/hr biogas production and Btu/hr cogenerated engine waste heat (both from Step 4). If heating requirements appear to exceed the Btu/hr value of the gas produced, try recalculating digester heat loss using construction materials with better insulating properties. If heat losses still eat up most of the value of the biogas, solar heating (as suggested by Al Rutan) deserves consideration. Otherwise, unless the value of anaerobic digestion as a means of controlling local water pollution is considerable, it will make little economic sense to produce biogas from manure then use all the biogas (or equivalent purchased energy) to keep the digestion process going.

When calculations indicate biogas production far exceeds digester heating needs, then direct use of some of the gas to keep manure around 95° will make sense. Methods discussed in Chapter 3 use hot water as the heat transfer medium. Perhaps the simplest concept biogas system would apply all the gas to making hot water. Some of the water would be used to heat the manure for digestion, and the rest would displace hot water demand of other farm operations.

If calculations indicate leftover heat is available even after the digester-heating requirements are met, then the following calculations can be made.

For an existing heat application, such as process or space heating, the historical energy used to accomplish the task must be known. For comparison to the biogas combustion or cogeneration waste heat available, the following conversion factors may be used:

1 therm (100 ft^3) natural gas	= 100,000 Btu
1 KWH (1000 watts on for one hour) electric heat	= 3,413 Btu
1 gallon fuel oil	= 140,000 Btu
1 gallon propane	= 91,500 Btu
1 pound coal	= 10,000 Btu
1 pound wood (dry)	= 7,000 Btu

In cogeneration applications, the timing, as well as quantity, of heat demanded must always be considered so that conflicting needs for engine waste heat are avoided. Because the digesters will need less heat in summer than in winter, this would be an ideal time to divert some cogeneration surplus heat to other jobs.

For new heating tasks with no existing fuel records, the heat input must be estimated. Several possible applications follow:

- For heating only fluid, apply the same energy calculations used for sludge heating and temperature maintenance.

- For heating a well-sealed building, use the heat loss calculations explained for a rectangular digester.

- For drying wet, digester manure, use this formula:

$$\_\_\_\_\ ft^3/day \times 62.4\ lb/ft^3 \times \left[1 - \frac{\%\ \text{Solids incoming}}{\%\ \text{Solids desired}}\right] \div 100$$

(digested manure flow rate) (conversion factor)

$$\times\ 1040\ Btu = \_\_\_\_\_\_\ Btu/day.$$

(heat required to vaporize one pound of water)

STEP 7: DETERMINE VALUE OF ENERGY TO BE REPLACED BY BIOGAS

For direct applications of biogas for heating, where all biogas not used to keep the digester warm is used for heating, the value of energy replaced by biogas is easy to compute:

_____Btu/hr	-	_____Btu/hr	=	_____Btu/hr
(Daily biogas production rate from Step 4)		(Daily digester heat input rate from Step 6)		(Net biogas production and use rate)

To get Btu/yr, a number for hours per year of operation is needed. Calculations so far have been based on continuous (8760 hrs/yr) operation, but a lower figure might be used to be conservative:

_____Btu/hr	x	_____hrs/yr	=	_____Btu/yr
(Biogas use rate)		(predicted biogas system operating hours per year)		(annual biogas use rate)

Using the conversions to Btu's from the end of Step 6, the value of the Btu/yr of biogas in equivalent units other sources of heat can be calculated:

_____ $\frac{\text{Btu}}{\text{Yr}}$	÷	_____ $\frac{\text{Btu}}{\text{Unit}}$	=	_______unit/yr
(annual biogas use rate)		(fuel value of replaced heating sources, where units are gallons, lbs, Kwh, etc.)		(amount of fuel or electricity replaced by biogas in gallons, lbs, Kwh, etc.)

Savings in dollars from using biogas become:

_____ $\frac{\text{Unit}}{\text{Yr}}$	x	_____$/Unit	=	_____$/yr
(above replaced fuel or electricity)		(price per gallon, lb, Kwh, etc.; find on bill)		(annual savings)

When electricity is produced, annual output is calculated:

_____ KW	x	_____hrs/yr	=	_____KWH/yr
(from Step 4)		(predicted operating hours per year)		

The value of this electricity depends to some extent on how it is to be used. If all of it will be used on-site, then the value is the price which the site owner pays his utility for electricity, usually shown on the power bill (¢/KWH). Be sure to include taxes and fuel adjustment fees but not fixed charges such as service charges.

If the electricity will be wholly or partially sold to the utility, then the value of the sold energy is the price paid to the owner by the utility for his electricity. It may be necessary to divide the energy output into two blocks with different values in order to compute the total energy value.

_____KWH/yr	x	_____$/KWH	=	_____$/yr
		(price of electricity)		

In a cogeneration system, the value of the engine waste heat put to work is computed using the same method for biogas directly as a heat source (see conversion factors at end of Step 6):

_____Btu/hr (from Step 4)	x	_____hrs/yr (predicted biogas system operating hrs/yr)	=	_____Btu/yr

and

_____Btu/yr	÷	_____Btu/unit (fuel value or replaced heating source, where units are gallons, lbs, Kwh, etc.)	=	_____Units/yr

Dollar savings amount to:

_____Unit/yr (above replaced fuel or electricity)	x	_____$/unit (price per gallon, lb, Kwh, etc.; find on bill)	=	_____$/yr (annual savings)

For mechanical power production only, biogas value would be computed as cost of the amount of another fuel or electricity used to produce equivalent power. The same calculations used at the beginning of Step 7 can be used at this point.

STEP 8: VALUE OF DIGESTER MANURE BY-PRODUCT

If the digester wastes can be dried and used on-site to offset some current expense or sold to a local market, this economic benefit will enter the analysis:

_____ft^3/day (total volume of manure from Step 1)	x	62.4 lb/ft^3 (approximate density of manure)	x	0.20 (factor for weight reduction after drying)	=	_____lbs/day

_____lb/day (digester product in final form)	x	365 days/year	x	_____$/$lb^3$ (local value of digested product)	=	_____$/yr

STEP 9: ESTIMATING BIOGAS SYSTEM COSTS

An entire biogas system will have many parts. The "shopping list" below covers most of the possible parts for the various uses of biogas covered in this manual and includes "extras":

Digester
Manure pump and piping
Gas compressor
Gas storage tank
Valves, meters and piping
New burners for existing gas appliances

New gas appliances
Engine modification kit
Engine-generator set
Heat recovery equipment
Grid protection equipment
Digester/engine building
Engineering services
Licensing and permits

For the purposes of a simple economic analysis of a biogas project, general system costs rather than individual component costs are developed here. These example costs provide ballpark numbers for payback calculations. Items listed under each example are included in the cost.

Example 1: 90 Cow Dairy/Biogas Cogeneration System.
1981 total installed cost (by outside contractor) = $85,000.

- manure collection and pumping system
- 2800 ft^3 thermally mixed digester (epoxy-lined urethane insulated steel tank) (4700 ft^3 gas/day)
- 2 - 12KW (output on biogas) engine generators
- engine heat recovery system applied to digester heating and digester heat exchanger
- 2 - 1000 gallon tanks for pressurized gas storage
- interface for sale of electricity to utility

Example 2: 15,000 Bird Laying Flock/Biogas Heating System.
1981 installed cost (no outside labor) = $35,000.

- plumbing and pumps
- 3400 ft^3 concrete digester with floating steel cover (top covered with fiberglass and insulated with polyurethane foam; sides covered with polystyrene.) (3000 ft^3 gas/day)
- uninsulated digester housing
- boiler/heat exchanger/ducting digester heating

Example 3: 200 Hog Farm/Biogas Cogeneration System.
1981 total installed cost (no outside labor) = $25,000.

- manure flushing system
- steel manure holding tank with wooden roof

- 1600 ft^3 riveted steel plate digester with polystyrene insulation

- wooden digester enclosure

- government surplus 25 KW (biogas rating) engine generator

- carburetor kit

- engine heat recovery/digester heating system

- pumps, plumbing

- 2 surplus 1340 ft^3 rubberized gas storage bags

Example 4: 100 Swine, 100 Dairy Cows, 100 Veal/Biogas Manure Disposal System. 1980 total installed cost (no outside labor) = $16,000.

- 43,200 cubic foot sludge digesting lagoon (excavation)

- digester lagoon trap cover to collect gas

- irrigation and pumping system to mix digester lagoon water and fresh water for irrigation

- pumping for conducting manure from barns to settling tank and down to digesting lagoon

- 320 ft^3 concrete settling tank

Possible additions to the system include an engine generator set and 1600 feet of piping to conduct gas to the planned engine-gen set.

Engine Generator = $ 1,000.

16' Gravity Flow Pipe = $13,000.

Example 5: 40 Hog Farm / Biogas Heating System
1981 total installed cost (no outside labor) = $4,000.

- pipes and plumbing

- cinder block collection tank

- gas pump (dual drum, home-built)

- slurry pump

- hot water circulating pump

- wood-fired hot water heater (home-built)

- biogas-fired hot water heater (converted)

- 1900 ft^3 flow-mixed digester with vinyl cover, built of silo block

- 2500 ft^3 gas storage bag

- gas meters and warning sensor

  rough-sawn lumber (free) digester house with R30 (roof) and R(19 (wall) insulation, on pad

- scrubber and condensation trap

Digester is designed to accommodate wastes for up to 250 hogs. Next phase of development is integration of biogas lines with propane back-up using same burners.

STEP 10: EVALUATING PROJECT ECONOMICS

Throughout this book many technical points have been discussed which boil down to dollars and cents effects on a biogas system. In an evaluation of project economics, these factors are sorted into the categories below:

	Costs (C)	Benefits (B)	Net
One Time Only	Engineering, design, permits. Purchase and installation of equipment. Construction of facilities.	Grants. Avoided cost of another system. Tax credit.	(C) - (B) Net Initial Investment
Annually	Operation and maintenance.	Energy savings. Reduction in waste disposal costs. Value of digester residue.	(B) - (C) Net Annual Benefit

Return-on-investment (ROI) is calculated as:

$$\text{ROI} = \frac{\text{Net Annual Benefits}}{\text{Net Initial Investment}}$$

Payback period is just the inverse of this ratio.

Depending on which economic index is more familiar to the investor, either the ROI or the payback criterion may be used for preliminary economic evaluation. Although these measures are not theoretically rigorous, for a first-cut evaluation they suffice. Two factors which are not included in the analysis may actually cancel each other's effects. There is no provision for the cost of borrowing money in the computations, but neither is there any inflation rate for the value of energy produced in a biogas system. The simple

ROI and payback calculations become more reliable when interest and inflation rates are similar.

Some of the costs and benefits tallied above were not discussed much in the body of this chapter. The tax credit listed as a one-time benefit refers to a credit of 20% of the system capital costs which can be applied against a federal income tax bill. The 20% credit is the sum of 10% investment and 10% energy tax credits. In the work-sheet below the credit is calculated as 15% of the total project cost, which assumes 75% of that total covers capital expenditures. The credit can be carried forward as many as seven years, but is assumed to be used up in year one in this simple analysis.

Operation and maintenance costs will vary depending on the type of system and who does the work. In the worksheet below annual O&M costs are estimated as 5% of the system cost. These costs might actually range anywhere between 1 and 10%. Note there is no provision for inflating these expenses in this simple analysis.

The toughest items to quantify fairly are "avoided" costs. If a biogas system will not be installed, what will be the cost of other energy delivery or waste disposal systems possibly needed? A fair analysis includes such costs and consequently makes biogas investments look more attractive.

Computing ROI or Payback

One Time Costs (C)		Annual Benefits (B)	
1. Installed system cost estimated from Step 9.	$______	1. Net value of biogas end-use energy from Step 7.	$______/yr
		2. Estimated reduction of waste disposal costs.	$______/yr
One Time Benefits (B)		3. Estimated value of digester residue from Step 8.	$______/yr
1. Grants.	$______		
2. Avoided costs of another waste disposal or energy system.	$______	Total Annual Benefits (B)	$______/yr
3. Tax credit estimated @ 15% of installed system cost above.	$______	Annual Costs (C)	
Total One-Time Benefits (B)	$______	1. Estimated system operation and maintenance cost @ 5% of system cost.	$______/yr
Net Initial Investment (C) - (B)	$______	Net Annual Benefits (B) - (C)	$______/yr

$$\text{ROI} = \frac{\text{Net Annual Benefits}}{\text{Net Initial Investment}} \qquad \text{Payback} = \frac{\text{Net Initial Investment}}{\text{Net Annual Benefits}}$$

APPENDIX 1

ARCHITECTURAL AND ENGINEERING FIRMS EXPERIENCED IN BIOGAS SYSTEM DESIGN

Anaerobic Energy Systems — 813/533-4161
PO Box 1477, 170 N. Florida Ave.
Bartow, Florida 33830
Contact: Elizabeth Coppinger

AWARE — 615/794-0110
PO Box 16778
Greenville, South Carolina 29606
Contact: Tony Chatman

Biogas of Colorado — 303/422-4354
5620 Kendall Ct., Unit G
Arvada, Colorado 80002
Contact: Susan Schellenbach

Cal Recovery Systems Inc. — 415/232-3066
160 Broadway, Suite 200
Richmond, California 94804
Contact: George M. Savage

Energy Harvest Inc. — 202/659-3030
Suite 602
1735 I. Street, N.W.
Washington, DC 20006
Contact: Bud Nagelvoort

Engineering-Science Inc. — 404/325-0770
Suite 590
57 Executive Park South
Atlanta, Georgia 30329
Contact: Ernie Schroeder

Engineering-Science Inc. — 205/821-9250
Harmon Engineering and Testing
Auburn Industrial Park
Auburn, Alabama 36830
Contact: Vish Varma

Environmental Dynamics Inc. — 803/292-1921
PO Box 16778
Greenville, South Carolina 29606
Contact Dr. Joseph B. Busey

ER&A, Inc. 213/452-4905
1820 14th Street
Santa Monica, California 90404
Contact: John Huetter

Perennial Energy Inc. 417/261-2204 - 2547
Box 15
Dora, Missouri 65637
Contact: Ted Landers

HEAT EXCHANGER MANUFACTURERS

Bobbitt Company, Inc. 919/273-4743
PO Box 9122, Dept. TR
Greensboro, NC 27408

Gaston County Fabrication 704/263-4765
PO Box 208
Stanley, NC 28164

Industrial Heat Exchanger 901/423-0385
Manufacturing Corp.
PO Drawer 1056
Jackson, Tennessee 38301

Industrial Piping Inc. 704/588-1100
PO Box 518
Route 2, Downs Road
Charlottsville, NC 28134

Metal Equipment Company, Inc. 912/236-3378
PO Box 153
Savannah, Georgia 31402

APPENDIX 2

INDIVIDUAL CONSULTANTS WITH EXPERIENCE IN BIOGAS SYSTEM DESIGN, INSTALLATION AND MAINTENANCE

Bob Morelli (Farmer Bob's) — 707/762-7884
5935 Red Hill Road
Petaluma, California 94952
(Dairy, Beef)

Jim Converse — 608/262-3310
Agricultural Engineering
460 Henry Mall
University of Wisconsin
Madison, Wisconsin 53706
(Poultry)

Dennis Gregg — 615/788-2736
Alternative Energy Farm Project
Rt. 6, Box 526
Crossville, Tennessee 38555
(Hog)

NOTE: The Alternative Energy Farm Project is part of a large non-profit organization designed to aid farmers in becoming energy independent. We recommend that if you are a farmer and can qualify for some type of funding under their program, that you take advantage of its services. If you don't qualify for funding, it would still be worth consulting with Mr. Gregg on the design of your system.

APPENDIX 3

DIGESTER MANUFACTURERS

Anaerobic Energy Systems PO Box 1477, N. Florida Ave. Bartow, Florida 33830	813/522-4161
Biogas of Colorado 5620 Kendall Court Unit G Avada, Colorado 80002	303/422-4354
Energy Harvest, Inc. Suite 602 1735 I Street, NW Washington, DC 20006	202/659-3030
Perennial Energy, Inc. PO Box 15 Dora, Missouri 65637	417/261-2204 - 2547

APPENDIX 4

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