5.0 SUMMARY OF COMBUSTION, GASIFICATION AND ANAEROBIC DIGESTION SYSTEMS

Over time manure accumulates and decays, releasing gaseous compounds into the atmosphere and soluble compounds into the surface water and groundwater supplies. Several techniques are available to avoid this contamination problem and convert the manure into useful energy either for thermal (heating) facility requirements or as a combustion gas. This section provides an overview of the combustion, gasification and digestion systems that are most suited for incorporation into the best management practices (BMPs) developed by individual WRBEP states for livestock operations. Simplified flow diagrams of each system described below are located in Appendix F.

5.1 Combustion Systems

The combustion process burns manure in a manner that produces more energy than is consumed by igniting the manure and involves five steps. The first two steps (dehydration and evaporation) remove water from the manure. The third step, pyrolysis, heats the manure and causes volatile substances to be released into the air. These substances combust and produce heat when they reach a set temperature. Finally, the remaining solid material oxidizes and generates more heat. The heat from the combustion process is then recovered and used for production processes.[26]

There are two combustion systems that are commercially available to burn manure. These systems are the single chamber and the fluidized bed. Both systems require that the manure be air dried prior to combustion. Table 5.1 lists some of the characteristics of the combustion systems.

Table 5.1. Combustion Process Characteristics

Combustion Process	Capital Costs	Operating Costs	Combustion Temperature	Fuel Moisture Content	Comments
Grate Systems	Low	Low	N/A	55%	A, B
Fluidized Bed	Medium - High	Medium - High	1,400 °F	N/A	C, D

A = Can be a retrofit
B = Fuel materials can include non-manure items
C = Salts in fuel materials must be considered
D = Particle size limitations
N/A = Not Available

Modular Single-Chamber Combustor

Though the modular single-chamber combustors vary slightly and can have multiple-fuel feeding and removal mechanisms, each variation has the same basic process. First, material is fed onto a grate. The grate has pin-holes in it to allow the heat produced from the "under-fire" to percolate up into the manure. When the manure first enters the chamber and falls on the grate, it proceeds through the dehydration and evaporation stages. While remaining on the grate, the manure enters the pyrolysis stage. The volatile substances are driven off the manure and react in the "over-fire" area. Finally, the solid material oxidizes on the grate before being removed from the chamber.

The grate can be fixed or may move to facilitate the removal of solid waste byproducts (i.e., ash). The air pollutants are removed using a fabric filter baghouses or more sophisticated equipment (i.e., scrubbers or electro-static precipitators). The fuel used in modular single-chamber combustors can contain up to 55 percent moisture and include non-manure material (e.g., sawdust, sander dust, paper mill sludge, rice hulls, bark chips, and municipal solid waste). Since fuel feed and removal can be continuous, labor requirements are reduced and full automation of the system is possible.

There are several design advantages of the single-chamber combustor. First, systems can vary to handle different loads, depending on the flow rate of manure. Second, the combustors can be modular in design. This modularity results in the ability to produce large biomass heat recovery systems. Third, the single-chamber modular is adaptable and can be used in a retrofit situation, resulting in an opportunity to convert from fossil fuel to biomass fuel at a reasonable cost.

Fluidized Bed Systems.

Fluidized bed systems provide a definite advantage over the "fixed" bed combustor (single-chamber). In this combustion system, a bed of heated particles such as sand or limestone is "fluidized" by passing combustion air upward through it. The upward moving air creates a buoyancy that lifts the sand particles and manure, allowing free movement of the mass within the mass. When this mass of "bubbling" solids reaches a temperature of 1,400°F - 1,500°F, the fuel material pyrolysizes, combusts, and oxidizes. Some of the released heat is contained in the bed material allowing the system to be self-contained while the remaining heat is recovered for facility use.

Fluidized beds can be complex, incorporating multiple hearths for drying fuel, cyclones to prevent bed material from entering the boilers, and extensive air pollution controls to control particulates. The fuel must be fairly uniform and cannot be below 1/4 inch. In addition, because of the salt content of biomass materials, care should be used with the fluidized bed combustors to prevent salt buildup that could cause combustor failure.

5.2 Gasification Systems

Gasification of manure results in a net heat gain since the energy used to heat the manure is less than the energy derived from the burning and oxidation of the fuel material. The thermal/chemical process previously discussed in the combustion process is repeated in the gasification systems with some important variations.

The gasification process occurs in four steps. A major difference between the combustion and gasification process is that gasification requires little or no oxygen. For the first step, the fuel material is dried to remove the water. This step occurs in a total absence of oxygen. The second step, pyrolysis, occurs when temperatures reach 1,400°F - 1,600°F and no air is present. At this temperature, gases and volatiles are released from the material, separated and combusted, leaving a solid material, char, which is mostly carbon.[27] At this point, the char undergoes two different processes. First, a heat-absorbing reaction occurs and the char reacts with carbon dioxide to produce a variety of gases which can be combusted. Second, a small portion of the char is burned with a set quantity of oxygen. This oxidation process occurs in the 1,950°F to 2,650°F temperature range. The heat generated in this process provides a significant amount of energy for the gasification process.[28]

Gasification can occur in one of two ways. The first method simply adds the fuel to a fixed bed, a process used in both updraft and downdraft gasification. The second gasification method utilizes the fluidized bed approach. Both systems require that the manure be air dried prior to gasification. Table 5.2 lists some of the characteristics of the gasification systems.

Table 5.2. Gasification Process Characteristics

Gasification Process	Capital Costs	Operating Costs	Chamber Temperature	Fuel Moisture Content	Comments
Fixed Bed					
Updraft	Low - Medium	N/A	1,950 - 2,650	< 40	A
Downdraft	Medium - High	Medium - High	N/A	< 30	A,B,C
Fluidized Bed	Medium - High	Medium - High	1,400 °F	N/A	D,E,F

A = Fuel materials can include non-manure items
B = Clean gas product
C = Manure in pellet form
D = Particle size limitations
F = High Fuel output
E = Salts in fuel materials must be considered
N/A = Not Available

Updraft Gasifier

The updraft gasifier pulls the hot air from the bottom of the container up through the fuel material drying it. As the material sinks, pyrolysis occurs, then reduction, and finally high temperature oxidation. The produced gas is a low Btu (150 Btu/cubic foot) gas that contains tars and moisture.

The gas produced cannot be transported through a pipeline for any distance because the tars and non-reacted solids will condense. Several proprietary modifications and additions have been made in order to clean the gases produced so they can be used as engine fuel or pipelined. This "cleanup" results in tar residues that pose a disposal problem unless there is a provision to reintroduce them into the gasification process.

There are a few advantages with this gasifier design. First, the gasifier can be made in a variety of sizes. These sizes can range from small "household" units to large 8,000-pounds-per-hour units. The large units are constrained by the possibility of unmixed spots occurring in the reacting mass. A second advantage is that the ash produced is a low carbon residue that are not an environmental disposable problem.

Downdraft Gasifier

Although the downdraft gasifier differs only slightly from the updraft gasifier, the differences are important. As in updraft gasification, fuel materials are added to the top of the container, the material is heated to evaporate water and the pyrolysis process occurs in downdraft gasification. However, the downdraft gasifier locates the high temperature oxidation process after the pyrolysis rather than after the reduction stage. This allows the tars and oils from the gasification process to be filtered by the char in the reduction stage. As a result, the low Btu gas that is produced is a very clean gas mixture that can be used for boilers, furnace fuel, or for internal combustion engines.

The advantages of sizing and low ash content mentioned for the updraft gasifier are also available with the downdraft gasifier. However, the downdraft gasifier has the additional advantage of producing clean gas that can be pipelined. However, a potential drawback of downdraft gasification is the requirement for pelleting of the manure. This requirement may add a cost of $25 to $35 per ton for fuel preparation. In addition, not all manures are suitable for the pelleting process. Any biomass containing abrasive substances would damage the dies of the presses leading to unacceptable maintenance costs.

Fluidized Bed Systems.

Fluidized bed gasification is similar to fluidized bed combustion. This difference is the greater amount of gas produced in the fixed bed gasifier and the fact that the produced gas is a medium Btu gas (500 Btu plus per standard cubic foot). This gas is clean and can be used as engine or boiler fuel. In addition, because of the high hydrogen, high carbon monoxide content, the gas can be used to synthesize methanol.

5.3 Process Equipment

The following briefly discusses some of the supportive equipment required for some of the gasifiers or combustors described above.

Dryers

If the destruction of manure through combustion or gasification is to be effective in removing a threat to the environment, rapid drying is necessary. Suitable dryers are available that will economically remove excess moisture using flue gases. Drying equipment is designed to meet very specific demands at each facility.

Densification

Where a densified, uniform fuel is needed, rotary or flat die densifying presses are required. Several makes, primarily designed to manufacture animal feeds are on the market. These can be used to densify manures as long as there are no abrasive materials present.

Grinders/Shredders

The reduction of lumpy materials to facilitate automatic handling in conveyors, augers, and stokers is readily done with grinders, hammermills or shredders. This equipment is readily available from the agricultural or waste handling industries.

5.4 Anaerobic Digester Technology

The following discussion is presented in three parts: a description of the overall anaerobic digestion process, a description of the digestion process at the bacteria level, and a description of the digestion process at the digester unit process level.

Digestion Process Overview

A digester is essentially a vessel containing bacteria that decompose organic matter in the absence of oxygen and produce biogas. In order to produce biogas the feedstock manure must be fed at a rate equal to or below the maximum bacterial growth rate for the temperature in the vessel. At a proper feed rate, in the absence of oxygen, with a neutral pH and temperature above freezing, the process proceeds.

Biogas contains methane, carbon dioxide, and small amounts of ammonia and hydrogen sulfide. With the digestion process in proper balance the biogas is at least 60% methane and 39% carbon dioxide.

Anaerobic digestion is an incomplete decomposition process. Material fed to digester contains at most 14% total solids (86% water). At most 60% of the solid portion of the manure will be converted to biogas leaving at least 40% of the solids and close to 100% of the original liquid as effluent.

Agricultural digester effluent is most often used directly as a fertilizer. Solids can be separated from dairy and beef manure effluent that are valuable as animal bedding or as a salable peat moss replacement.

Anaerobic Digestion at the Bacteria Level

The anaerobic digestion process occurs in three stages: hydrolytic, acid forming, and methanogentic. These three stages decompose the proteins, fats, and carbohydrates found in animal manures.

Stage 1 - Hydrolytic Process

During the first stage bacteria break complex organic materials into simple sugars (e.g., glucose) using the hydrolytic action of enzymes. The amount and rate of the breakdown process is highly dependent on the waste characteristics and environmental factors such as temperature.

Stage 2 - Acid Production

Anaerobic and facultative heterotrophic bacteria break down the simple sugars into simple organic acids.[29] Bacterial utilization of simple sugars and water produce acetic acid, carbon dioxide, and hydrogen (see Figure 5.1). Though other acids (proprionic and butyric) are formed in the process, acetic acid is the major product.

Figure 5.1. Acid Formation Stage

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3OOH + 2CO_2 + 4H_2$$

(glucose) + (water) → (acetic acid) + (carbon dioxide) + (hydrogen)

Stage 3 - Methane Production

Methane producing bacteria, methanogens, utilize simple organic acids in two decomposition pathways to produce methane. The first reaction splits acetic acid into methane and carbon dioxide while the second reaction combines hydrogen and carbon dioxide into methane and water (see figure 5.2). Methanogens can not survive in oxygen and are very sensitive to temperature and pH.

Figure 5.2. Methane Formation Stage

$2CH_3OOH$	$\rightarrow 2CH_4$	+	$2CO_2$		
(acetic acid)	(methane)	+	(carbon dioxide)		

and

$2CO_2$	+	$4H_2$	$\rightarrow 2CH_4$	+	$2H_2O$
(carbon dioxide)	+	(hydrogen)	(methane)	+	(water)

Anaerobic Digestion Unit Processes

Six anaerobic digestion unit processes will be discussed. All of these units require similar equipment to manage manure before and after the digester. The subsequent section describes digester system components. Each unit process is based on the bacterial processes discussed above. The six processes use different equipment configurations to create environments for growth of methanogenic anaerobic bacteria. The environmental conditions controlled include waste characteristics such as solids concentration, loading rates, mixing of bacteria with waste and bacterial growth parameters such as temperature and pH.

The simplest unit process is the ambient anaerobic lagoon. Manure in a lagoon will progress through all three stage of methaogenisis if the lagoon is adequately sized to allow methanogens to grow. Nature governs the environmental conditions (pH, temperature, moisture, etc.) that determine the rate and volume of methane production.

Other unit processes control environmental conditions in the digester to optimize methane production. The five controlled unit processes to be discussed are:

Plug flow;
Complete mix;
Packed reactor;
Upflow sludge blanket; and,
Sequencing batch reactor.

Manure Collection

Manure is delivered to a collection tank or pad for the digester as a solid, slurry or liquid. Digesters require feed on almost a daily basis, therefore manure is usually collected daily. Some storage may be required to maintain a regular digester feeding schedule.

Storage of Digester Feedstock

Storage is a costly feature and is usually minimized when manure collection is daily at a farm. Dry solids, a good digester feedstock, can be stored in piles but liquid and slurry will require extra tankage for storage. Storage is probably not economical for more than 3 days of digester feed.

Mixing Tank

The daily feed for a digester is generally prepared in a mix tank which most often is also the collection and storage tank. A mix tank is a point of control for a digester system. Thick manure can be diluted, thin manure rejected and pH adjusted for sour manure.

Digester Unit Processes

The six digestion techniques have different operating procedures. Table 5.3 illustrates the levels of process and operational complexity. Process complexity refers to the number of mechanical components. For example, the lagoon has a low process complexity since animal wastes only need to be dumped into the pond whereas the sequencing batch reactor requires many mechanical pumps, mixers and controls. Operational complexity refers to the amount of maintenance and labor required to keep the production process in operation. Table 5.3 also shows relative initial and operating costs for the six techniques. It is not surprising that the costs follow the process and operational complexity patterns. In general, the only rationale for using the more complex techniques at a farm would be to save extremely valuable space.

Table 5.3. Digester Characteristics

Digester Process	Process Complexity	Operational Complexity	Limitations	Heating Required	HRT * (days)	Capital Costs	Operating Costs
Ambient Temperature Covered Lagoon	Low	Low	A,B,C	No	60+	Low	Low
Plug Flow	Low	Low	C	Yes	15+	Low	Low
Complete Mix	Medium	Medium	D	Yes	15+	Medium	Medium
Packed Reactor	Medium	Medium	E	Yes	2+	Medium	Medium
Upflow Sludge Blanket	High	High	E	Yes	2+	High	High
Sequencing Batch Reactor	High	High	N/A	Yes	2+	High	High

A =Varying gas output
B = Restricted to warm climates
C = Can not separate sand and rock from input material
D = Digester material requires mixing
E = Soluble waste components only, no solids
NA - Not available due to the experimental nature of the design
* Hydraulic Retention Time

The six processes have limitations in both operation and in the types of animal wastes that can be used in the digester. The limitations relate to the concentration and size of solids in the input material. Table 5.4 shows the animal wastes and solid characteristics that each digester can accommodate.

Table 5.4. Characteristics of Digester Solids

Digester Process	Animal Waste Sources					Types of Solids			Solids Concentration
		Cattle							
	Swine	Dairy	Feedlot	Field	Sheep	Soluble	Fine	Coarse	
Ambient Temperature Covered Lagoon	●	●					●		2 - 3 %
Plug Flow		●	●	●				●	11 - 13%
Complete Mix	●	●	●	●	●	●	●	●	3 - 8%
Packed Reactor	●	●				●			0.5 - 2%
Upflow Sludge Blanket	●	●				●			0.5 - 2%
Sequencing Batch Reactor	●	●	●	●	●	●	●	●	0.5 - 8%

The complete mix and sequencing batch reactor can handle the greatest waste diversity including waste source, types of solids, and solid concentration. However, the sequencing batch reactor is in the experimental stage.

Other digester processes are very well suited to a particular type of waste. A plug flow digester digests thick, fibrous solids from dairy and feedlot cattle without mechanical mixing. A lagoon digester will accommodate low solids from almost any animal but large fibrous solids must be separated. Packed reactor, and upflow sludge blanket can only accommodate soluble and suspended solids from swine and dairy cattle. Thus, the type of animal waste determines the digester process if the complete mix option is not used. A brief description of each of the digester unit processes follows.

Ambient Temperature Covered Lagoon

Several unheated, unmixed anaerobic lagoons have been covered with floating covers for recovery of methane from dairy, hog and industrial wastes. These lagoons are located in the southern United States in warm climates. Gas production varies with the season as the temperature of the lagoon controls the rate of gas production.

A lagoon digester is sized to have a loading rate during the coldest part of the year that will foster methanogenic anaerobic decomposition. Generally gas production falls off as the temperature decreases and becomes very low when the lagoon temperature is below 40 °F. A lagoon can be constructed of native soil or lined with clay or a synthetic liner depending on soil conditions. A cover of a synthetic rubber is floated onto the lagoon using a system of float logs to provide buoyancy and gas pathways. The cover is either embedded in the banks of the lagoon or is attached to a short concrete wall along the lagoon perimeter. Several tethered floating covers have been recently constructed. A gas collection pipe is installed under the cover to allow gas collection and removal.

Once installed, a covered lagoon requires little maintenance. However, high levels of coarse, cow manure solids can not be added to a lagoon because the fibers will not decompose, but will float and hinder lagoon performance. Thus, solid separators must be installed to remove fibrous non-degradable solids.

The advantage of a lagoon system is that it is very simple and easily integrated on a farm with liquid manure handling. A covered lagoon requires virtually no maintenance or worry. However, the tradeoff is that gas production will vary.

Plug Flow Digester

Plug flow digesters are long, narrow, rectangular or V-shaped tanks in the ground. They contain no moving parts and require little maintenance. Heat pipes are suspended in the digester to keep the manure warm. Biogas formed in the manure bubbles to the surface, is collected and piped to the gas use. Water is heated using biogas or recovered from waste heat and piped through the digester to keep it at a constant temperature.

Plug flow digesters are used to digest thick wastes (11 - 13% solids) from ruminant animals. Coarse solids in ruminant manure form a viscous material and limit solids separation. If the waste is too dry, water or a liquid organic waste such as cheese whey or waste beer is added. If the waste is less than 10% solids, a plug flow digester is not suitable. Plug flow digesters are heated but not mixed and function by displacement of old material along a rectangular basin by new material. Manure remains in the digester for a period of 15 to 20 days.

Sand and rocks will accumulate in a plug flow digester and cleaning is required on a 4 to 8 year interval. Proper design of a mix tank prior to the digester can limit the introduction of sand and rocks.

Complete Mix Digester

Complete mix digesters are usually above ground, insulated, round tanks. However, inground square tanks are also used. Complete mix digesters are the most flexible of all digesters as far as the variety of wastes that can be accommodated. Wastes with 2 -8% solids are fed to the digester and the digester contents are continuously mixed to prevent separation. Complete mix digesters are usually sized with an HRT of 10 - 20 days.

Mixing can be accomplished by gas recirculation, mechanical propellers or liquid circulation. Gas bubbling from the digester is usually collected in a dome over the tank and piped to the gas use.

Sand and rocks will accumulate in a complete mix digester and cleaning is required on a 4 to 8 year interval. Proper design of a mix tank prior to the digester can limit the introduction of sand and rocks. In addition, a cone bottom is often installed to allow interim removal of a portion of the sand and rocks.

Packed Reactor

A packed bed reactor concentrates attached microbial masses and rapidly decomposes soluble waste. Unlike in previously discussed digesters, this digester retains anaerobic bacteria on the surface of packing materials or in a sludge blanket. This approach is most successful in digesting dilute, soluble organic wastes. Wastes with particulates plug or overload these digesters. These designs are often used where space is limited. Tank volume is substantially reduced compared to other digester designs, while the amount of equipment to operate the digester is substantially increased.

A packed reactor will contain spheres, plastic baffles, or wood bats. Anaerobic bacteria grow on the media and feed upon soluble organics as waste slowly flows through the media.

Hydraulic detention times in these digesters are between 8 and 48 hours depending upon the waste treated. Biogas formed by the bacteria bubbles to the digester surface and is collected in a dome over the tank and piped to the gas use.

The amount of equipment and operating requirements make this digester technique expensive to build and operate.

Upflow Anaerobic Sludge Blanket

The upflow anaerobic sludge blanket (UASB) also concentrates the bacterial action to accelerate methane production. A UASB digester is slowly fed wastewater from the bottom. The design promotes formation of sludge particles that are heavier than water and stay in suspension in the digester. The result of this separation is a concentrated layer of suspended particles. Bacteria in the sludge blanket feed on soluble organics as waste slowly flows through the sludge blanket. This mass of nutrients intensifies the bacteria action in this area. The methane is produced in the sludge and it bubbles into the tank dome.

The tank volume can be small due the low retention times of 8 to 48 hours. There are some limitations to use of the UASB. The system is most suited to soluble materials since fine particulates may pass through with limited treatment. The amount of equipment and operating requirements make this digester type relatively more expensive.

Anaerobic Sequencing Batch Reactor

This experimental digester technique takes advantage of the different retention times for solid and liquid wastes. This dual retention time, during simultaneous processing, is achieved by separating the solids and the liquids.

The anaerobic sequencing batch reactor (ASBR) uses four steps to produce methane: settle, decant, fill or feed, and react. This process optimizes the micro-environment for both the solid and liquid wastes by tightly controlling the introduction of new wastes, the retention times, and other environmental factors. Waste and settled sludge are pumped into the partially filled digester. The batch is mixed for several hours and mixers are shut off and particulates are allowed to settle. Soluble organics are rapidly decomposed while solids that are not readily treated settle in the digester and are decomposed over a longer period. Treated effluent is decanted off of the top of the digester and excess sludge is wasted from the bottom of the digester. The batch process is then repeated.

ASBR technology takes advantage of high microbial concentration for rapid decomposition of solubles and retention of solids for later decomposition. The process requires significant equipment and process control. At this time, full scale use of this technology has not been demonstrated.

Post-Digestion Product Handling and Use

Gas Handling and Gas Use

Biogas is produced by the digesters at a varying rates throughout the day. Biogas may be pressurized, treated and or stored as required. Storage will either be in an inflatable gas cover on the digester or in a large gas storage tank. Excess biogas can be vented via a gas pressure safety valve to a flare.

Effluent Holding and Use

Some of the effluent from the digester may be returned to the mix tank for diluting and seeding the feedstock. The balance of the effluent will usually be piped to a holding lagoon and held for field application for fertilizer.

Dairy and beef cattle digesters have the option of recovering the remaining solids for bedding or soil amendment.