# Dairy Waste Anaerobic Digestion Handbook

***Options for Recovering Beneficial Products From Dairy Manure***

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## Introduction

The rapid growth in the size of dairy operations has resulted in new laws and regulations governing the handling and disposal of manure (Mitchell and Beddoes 2000). Requirements for nutrient management plans, manure solids disposal, and odor control (HouseBill 2001) make it necessary that new manure management approaches be considered. One of the more promising methods is anaerobic digestion.

Anaerobic digestion is a natural process that converts biomass to energy. Biomass is any organic material that comes from plants, animals or their wastes. Anaerobic digestion has been used for over 100 years to stabilize municipal sewage and a wide variety of industrial wastes. Most municipal wastewater treatment plants use anaerobic digestion to convert waste solids to gas. The anaerobic process removes a vast majority of the odorous compounds (Lusk 1995),(Wilkie 2000),(Wilkie 2000). It also significantly reduces the pathogens present in the slurry (Lusk 1995). Over the past 25 years, anaerobic digestion processes have been developed and applied to a wide array of industrial and agricultural wastes (Speece 1996), (Ghosh 1997). It is the preferred waste treatment process since it produces, rather than consumes, energy and can be carried out in relatively small, enclosed tanks. The products of anaerobic digestion have value and can be sold to offset treatment costs (Roos 1991).

Anaerobic digestion provides a variety of benefits. The environmental benefits include:

- Odors are significantly reduced or eliminated.
- Flies are substantially reduced.
- A relatively clean liquid for flushing and irrigation can be produced.
- Pathogens are substantially reduced in the liquid and solid products.

- Greenhouse gas emissions are reduced.
- And finally, nonpoint source pollution is substantially reduced.

On the economic side, additional benefits are provided.

- The time devoted to moving, handling, and processing manure is minimized.
- Biogas is produced for heat or electrical power.
- Waste heat can be used to meet the heating and cooling requirements of the dairy.
- Concentrating nutrients to a relatively small volume for export from the site can reduce the land required for liquid waste application.
- The rich fertilizer can be produced for sale to the public, nurseries, or other crop producers.
- Income can be obtained from the processing of imported wastes (tipping fees), the sale of organic nutrients, greenhouse gas credits, and the sale of power.
- Power tax credits may be available for each kWh of power produced.
- Greenhouse tax credits may become available for each ton of carbon recycled.
- Finally the power generated is "distributed power" which minimizes the need to modify the power grid. The impact of new power on the power grid is minimized.

In order to achieve the benefits of anaerobic digestion, the treatment facility must be integrated into the dairy operation. Unfortunately, no single dairy can serve as a model for a manure treatment facility. The operation of the dairy will establish the digester loading and the energy generated from the system. The anaerobic facility must be designed to meet the individual characteristics of each dairy.

This manual provides an introduction to the anaerobic digestion of dairy manure. It is divided into three parts. The first describes the operation and waste management practices of Idaho dairies. The second introduces anaerobic digestion and the anaerobic digestion processes suitable for dairy waste. The third presents typical design applications for different types of dairies and establishes the cost and benefits of the facilities.

# Dairy Operations

Dairy operations significantly affect the quantity and quality of manure that may be delivered to the anaerobic digestion system. In addition to the number of milk and dry cows, the housing, transport, manure separation, and bedding systems used by the dairy establishes the amount of material that must be handled and the amount of energy produced.

## *Housing System*

Confined dairy animals may be housed in a variety of systems. Commonly used housing systems include free stalls, corrals with paved feed lanes, and open lot systems. Milk cows, dry cows and heifers may be housed in free stalls, corrals, and open-lots on the same dairy. The type of housing used determines the quantity of manure that can be economically collected.

### Free Stall Barns

Free stalls are currently the most popular method for housing large dairy herds. Free stall housing provides a means for collecting essentially all of the manure.

Typical Free Stall Barn with Center Feed Lane



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## Corrals

Corral systems with paved feed lanes are also commonly used. The manure deposited in the feed lanes can be scraped or flushed daily. From 40 to 55-percent of the excreted manure may be deposited and collected from the corral feed lane. The balance of the manure may be deposited in the milk barn (10 to 15 percent) or the open lot (30 to 50%). Typically the manure deposited in the open lot is removed two to three times a year. It may have little net energy value after being stored in the open lot over prolonged periods of time. For corral systems one must make a reasonable determination of the recoverable manure deposited in the feed lane, corral, and milk barn.

Corral with Paved Feed Lane for Scrape or Vacuum Collection

Corral systems also use a considerable amount of bedding material during the winter months. The straw bedding is generally removed in the spring and placed on the fields prior to spring planting.

## Milk Barn

Dairy cows are milked two to three times a day. The cows are moved from their stalls to the milk parlor holding area. The milk parlor and holding area are normally flushed with fresh water. From 10 to 15 percent of the manure is deposited in the milk parlor. In addition to the manure that is flushed, the cows may be washed with a sprinkler system. Warm water that is produced by the refrigeration compressors, vacuum pumps, and milk cooling system may be used for drinking water, manure flushing or washing the cows.

It has been estimated that 5 to 150 gallons of fresh water per milk cow is used in the milking center. More common values are 10 to 30 gallons of fresh water per milk cow. The quantity and quality of water discharge from the milk parlor must be accurately measured. In many cases, the waste deposited in the milk barn is processed in a separate waste management system.

### Open Lot

In open lot systems the manure is deposited on the ground and scraped into piles. The manure is removed infrequently (once or twice a year). A significant amount of manure degradation occurs resulting in greenhouse gas emissions. In many cases, the open lot degradation produces manure that has little or no net energy value.

Open Lot System

## *Transport System*

The commonly used manure transport systems are flush, scrape, vacuum, and loader systems. In free stall barns the manure can be flushed, scraped, or vacuum collected.

## Flush Systems

If a flush system is used the manure is substantially diluted. The quantity of water used in a flush system depends on the width, length, and slope of the flush isle. The feed isles are generally 14 feet wide while the back isles are generally 10 feet wide. The slope varies between one and two percent. A flush system will generally reduce the concentration of manure from 12 1/2 percent solids, "as excreted", to less than one percent solids in the flush water. Flush systems are however more economical and less labor-intensive than scrape or vacuum systems.

Free Stall Flush System - Flushing Feed Lane

## Scrape Systems

Scrape systems are simply systems that collect the manure by scraping it to a sump. Under normal weather conditions the scraped manure has approximately the same consistency as the "as excreted" manure. During the warm dry summer manure may be dewatered on the slab.

## Front end Loader

Front-end loaders are used to stack and remove corral bedding and manure.

## Vacuum Systems

Vacuum systems collect "as excreted" manure with a vacuum truck. Generally, the trucks collect approximately 4000 gallons per load. The manure can be hauled to a disposal site rather than to an intermediate sump. Vacuum collection is a slow and tedious process. The advantage is that the collected manure is undiluted and approximately equal to the "as excreted" concentration.

Vacuum Truck Collecting Manure Solids

## *Bedding*

The type of bedding used can significantly alter the characteristics of the manure being treated. Typically straw, wood chips, sand, or compost are used as bedding material. In some cases paper mixed with sawdust is used. Compost usually has some sand mixed with the organic constituents. If composting is carried out on dirt lots, a significant amount of sand and silt may be incorporated into the compost. Since anaerobic digestion will not degrade the wood chips, sand, or silt, it is necessary to remove those constituents prior to, or during anaerobic digestion process. The quantity of non-degradable, organic and inorganic material can significantly impact the performance of the anaerobic digester.

The quantity of bedding added to the manure is a function of the design and operation of the dairy. Generally only the "kick-out" from the stalls is added to



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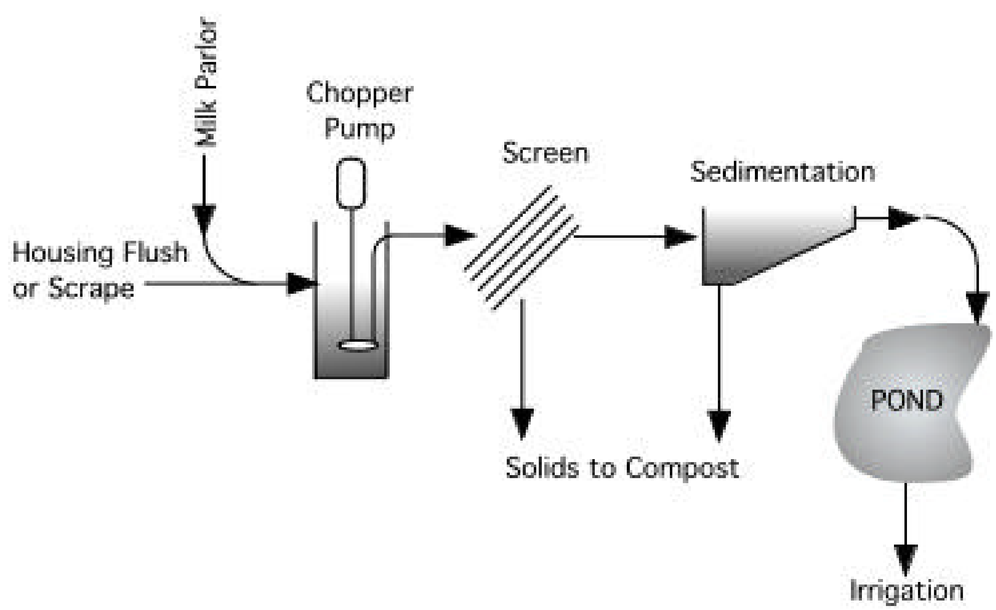
the manure. The quantity that is "kicked-out" is a function of the design of the dairy housing system as well as the type of bedding used.

## *Manure Processing*

Each dairy has its own manure processing system. Scraped or flushed manure may be processed in a system separate from the milk barn waste, or the collected manure waste may be processed with the milk barn waste. In general, current manure processing consists of macerating the waste with a chopper pump, screening the waste to remove the organic fibers, followed by sedimentation to remove the sand, silt, and organic settable particles. Much of the degradable manure is removed during the separation processes. Up to 80% of the COD and 30% of the total Nitrogen and Phosphorous can be lost in the solids removed by the screen and sedimentation process. Detailed sampling and analysis is required to confirm losses.

***Figure 1 - Conventional Manure Handling***




### Holding Tanks and Chopper Pumps

A wide variety of holding tanks and chopper pumps are used throughout the dairy industry.  Typically, the tanks are relatively small but in some cases they are designed to hold several hours of flush water.

Typical Manure Sump with Chopper Pump

## Primary Screens

An equally wide variety of screening systems are used.  In many cases the screens are housed in separate enclosures to prevent freezing during the winter months.  Outdoor screens are generally problematic during cold weather months. Fan separators (screw press) are also used to provide efficient separation of the fibrous solids.

Primary Screens Background with Gravity Separators Foreground

The primary screens will remove a significant amount of degradable organic material that could be converted to gas in an anaerobic digester. The screened materials are generally used to produce bedding after being composted for the required time periods.

## Gravity Separators

Gravity separators varying in size from 10 feet wide by 30' long to 24 feet wide by 80 feet long are usually placed after the primary screens. The purpose of the gravity separator is to remove the sands and silt present in the waste stream. If gravity separators are used without screening a thick mat of straw and fibers may develop on top of the gravity separator.

Floating Solids on Top of Gravity Separator

The gravity separators often incorporate weeping walls for the removal of liquid from the sedimentation chamber. The ability of the weeping wall to remove liquid waste depends on the periodic cleaning of the perforations to maintain flow.

In many cases the gravity separators remove a significant amount of degradable organic material that could be utilized to produce gas. The COD test is a direct measure of the quantity of material that could be converted to methane gas. Recent tests have established that screen and gravity separators can remove 75% to 80 % of the COD present in the waste stream. In one test the dairy parlor COD was reduced from 31,000 mg/l to 8,600 mg/l in the effluent from the gravity separator. In another the flush water influent to a separator system was 10,900 mg/L while the effluent was 1,800 mg/L. While a significant portion of the organic carbon (COD) is retained with the separated solids, an equal percentage of the nitrogen and phosphorus is not. The separation process alters the carbon to nitrogen ratio of both the liquid and solids streams.

Weeping Wall with Clogged Holes

The sedimentation process concentrates the organic solids, which are periodically removed. A recent analysis showed the flush water had a COD concentration of 25,500 mg/l while the concentrated solids from the separator had a COD of 115,800 mg/l. (Burke, 2001)

Organic Solids on Top of Gravity Separator

Anaerobic decomposition of settled solids can be observed in separators that have a surface covered with methane gas bubbles. It is clear that existing solids handling practices contribute to greenhouse gas emissions and prevent efficient energy recovery from manure waste.

Gravity Separator with Anaerobic Decomposition of Organic Solid

**Primary Holding Ponds**

Most dairies will discharge the screened and settled waste to a primary holding pond.

Partially Empty Primary Holding Pond Showing Sediment

The primary holding pond is a secondary sedimentation basin where the fine solids are separated from the liquid waste.

Eventually the fine solids must be removed from the bottom of the primary holding pond. Odors generally accompany the removal of solids.

## Secondary Holding Ponds

It is common to have a number of holding ponds that provide the required detention time (180 days) following the primary holding pond. The irrigation and flush pumps are normally installed in one or more of these ponds.

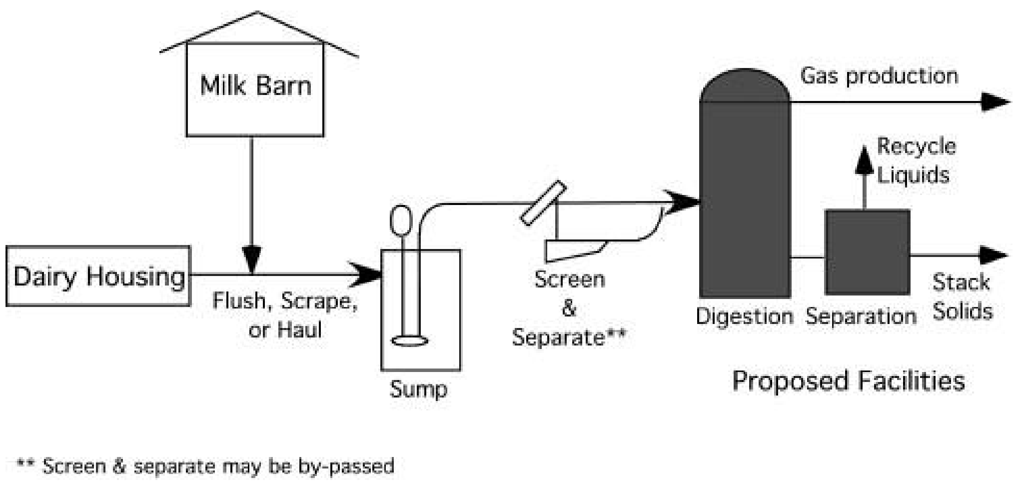
Typical Secondary Holding Pond

## *Summary*

As indicated above, two separate waste streams, the milk parlor and confinement area wastes, makeup the dairy waste that can be treated through anaerobic digestion. The type of bedding used, as well as the manure transport, and subsequent manure processing will change the characteristics of both waste streams. The dilution of waste will require larger anaerobic digestion facilities. The removal of organics through screening and sedimentation will reduce the quantity of organic solids that can be converted to gas in the digester. The presence of sand and silts will clog pipes, damage equipment, and fill anaerobic digestion tanks. Sand can only be removed from dilute waste streams. Thick slurries retain sand that precipitate in the digester when the organics are converted to gas and the solids concentration is reduced. If thick slurries are processed in an anaerobic digester, intense mixing is required to maintain the solids in suspension.

Modification of existing dairy management practices may be required to achieve the full benefits of anaerobic digestion. Figure 2 below, shows how a solid waste management facility can be incorporated in an existing dairy waste-processing stream. If low or moderate concentrations of sand are present the entire waste stream may be discharged to an anaerobic digester, bypassing the existing screen and gravity separators.  If high concentrations of sand are present, the existing gravity separators may remain in place.  Under such conditions, a reduced quantity of organics will be converted to gas.

***Figure 2 – Integration of Anaerobic Digestion in Dairy Waste Stream***



## Anaerobic Digestion

Anaerobic digestion is the breakdown of organic material by a microbial population that lives in an oxygen free environment. Anaerobic means literally "without air". When organic matter is decomposed in an anaerobic environment the bacteria produce a mixture of methane and carbon dioxide gas. Anaerobic digestion treats waste by converting putrid organic materials to carbon dioxide and methane gas. This gas is referred to as biogas. The biogas can be used to produce both electrical power and heat. The conversion of solids to biogas results in a much smaller quantity of solids that must be disposed. During the anaerobic treatment process, organic nitrogen compounds are converted to ammonia, sulfur compounds are converted to hydrogen sulfide, phosphorus to orthophosphates, and calcium, magnesium, and sodium are converted to a variety of salts. Through proper operation, the inorganic constituents can be converted to a variety of beneficial products. The end products of anaerobic digestion are natural gas (methane) for energy production, heat produced from energy production, a nutrient rich organic slurry, and other marketable inorganic products.

The effluent containing particulate and soluble organic and inorganic materials can be separated into its particulate and soluble constituents. The particulate solids can be sold or exported from the dairy while the nutrient rich liquids are applied to the land.

### *Bacterial Consortia*

Anaerobic digestion is carried out by a group, or consortia of bacteria, working together to convert organic matter to gas and inorganic constituents. The first step of anaerobic digestion is the breakdown of particulate matter to soluble organic constituents that can be processed through the bacterial cell wall. Hydrolysis, or the liquification of insoluble materials is the rate-limiting step in anaerobic digestion of waste slurries. This step is carried out by a variety of bacteria through the release of extra-cellular enzymes that reside in close proximity to the bacteria. The soluble organic materials that are produced through hydrolysis consist of sugars, fatty acids, and amino acids. Those soluble constituents are converted to carbon dioxide and a variety of short chain organic acids by acid forming bacteria. Other groups of bacteria reduce the hydrogen toxicity by scavenging hydrogen to produce ammonia, hydrogen sulfide, and methane. A group of methanogens converts acetic acid to methane gas. A wide variety of physical, chemical, and biological reactions take place. The bacterial consortia catalyze these reactions. Consequently, the most important factor in converting waste to gas is the bacterial consortia. The bacterial consortia are essentially the "bio-enzymes" that accomplish the desired treatment. A poorly developed or stressed bacterial consortium will not provide the desired conversion of waste to gas and other beneficial products.

## *Factors Controlling the Conversion of Waste to Gas*

The rate and efficiency of the anaerobic digestion process is controlled by:

- The type of waste being digested,
- Its concentration,
- Its temperature,
- The presence of toxic materials,
- The pH and alkalinity,
- The hydraulic retention time,
- The solids retention time,
- The ratio of food to microorganisms,
- The rate of digester loading,
- And the rate at which toxic end products of digestion are removed.

Each of these factors is discussed below.

### Waste Characteristics

All waste constituents are not equally degraded or converted to gas through anaerobic digestion. Anaerobic bacteria do not degrade lignin and some other hydrocarbons. The digestion of waste containing high nitrogen and sulfur concentrations can produce toxic concentrations of ammonia and hydrogen sulfide. Wastes that are not particularly water-soluble will breakdown slowly. Dairy wastes have been reported to degrade slower than swine or poultry manure. The manure production from a typical 1,400-pound milk cow is presented in the table below.

***Table 1 –Dairy Manure Production***

| **Manure Produced by a 1,400 pound Cow** | |
|---|---|
| Manure (pounds) | 112 |
| Manure (gallons) | 13.5 |
| Total Solids (dry pounds) | 14 |
| Volatile Solids (dry pounds) | 11.9 |
| COD (pounds) | 12.5 |
| TKN (pounds) | 0.63 |
| Total Phosphorus (pounds) | 0.098 |
| Total Potassium (pounds) | 0.36 |

The composition of the manure solids is presented in Table 2.

***Table 2–Dairy Manure Composition (Stafford, Hawkes et al. 1980)***

| Component | % Dry of Matter |
|---|---|
| Volatile solids | 83.0 |
| Ether Extract | 2.6 |
| Cellulose | 31.0 |
| Hemicellulose | 12.0 |
| Lignin | 12.2 |
| Starch | 12.5 |
| Crude Protein | 12.5 |
| Ammonia | 0.5 |
| Acids | 0.1 |

As can be observed from Table 2, the majority of the volatile solids are composed of cellulose and hemicelluloses. Both are readily converted to methane gas by anaerobic bacteria. As pointed out earlier, lignin will not degrade during anaerobic digestion. Since a substantial portion of the volatile solids in dairy waste is lignin, the percentage of cow manure volatile solids that can be converted to gas is lower when compared to other manure and wastes.

The manure characteristics also establish the percentage of carbon dioxide and methane in the biogas produced. Dairy waste biogas will typically be composed of 55 to 65% methane and 35 to 45% carbon dioxide. Trace quantities of hydrogen sulfide and nitrogen will also be present.

### *Dilution of Waste*

The waste characteristics can be altered by simple dilution. Water will reduce the concentration of certain constituents such as nitrogen and sulfur that produce products (ammonia and hydrogen sulfide) that are inhibitory to the anaerobic digestion process. High solids digestion creates high concentrations of end products that inhibit anaerobic decomposition. Therefore, some dilution can have positive effects.

The literature indicates that greater reduction efficiencies occur at concentrations of approximately 6 to 7 percent total solids. Dairy waste "as excreted" is approximately 12 percent total solids and 10.5 percent volatile solids. Most treatment systems operate at a lower solids concentration than the "as excreted" values.

Dilution also causes stratification within the digester. Undigested straw forms a thick mat on top of the digester while sand accumulates at the bottom. The optimum waste concentration is based on temperature and the quantity of straw and other constituents that are likely to separate within the anaerobic digester. It is desirable to keep the separation or stratification in the digester to a minimum. Intense mixing involving the consumption of power may reduce the stratification of dilute waste.

The use of flush systems to remove the manure from the dairy barns has major economic advantages to the dairy. Flush systems normally use 100 to 200 gallons per cow, per day of dilution water. The flush volumes required are based on the lane or gutter length, width and slope (Fulhage and Martin 1994). The flush water usually contains very low concentrations of total and volatile solids. At 100 gallons per cow of flush water, the waste has only 12.5 percent of the "as excreted" concentration. At 200 gallons per cow per day of flush water the waste contains only 6.25 percent of the "as excreted" concentration. Table 3 below presents the waste characteristics using various flush volumes.

***Table 3 – Manure Waste Concentration with Various Flush Volumes***

| | "As Excreted (AE) Manure" | Manure with 100 gal per Cow Flush Water | Manure with 200 gal per Cow Flush Water |
|---|---|---|---|
| Gallons for 1000 milk cows | 14,267 | 114,000 | 214,000 |
| Total Solids Concentration (mg/l) | 120,000 | 15,000 | 8,000 |
| Volatile solids Concentration (mg/l) | 102,000 | 12,750 | 6,800 |
| COD Concentration (mg//) | 129,400 | 16,176 | 8,627 |
| TKN Concentration (mg/l) | 5,294 | 662 | 353 |
| Total P Concentration (mg/l) | 824 | 103 | 55 |

The milk parlor also produces a substantial amount of dilute waste. Approximately 15% of the animal manure is deposited in the milk parlor. The resulting milk parlor waste has a composition similar to the flush waste presented in Table 3.

### *Foreign Materials*

Addition of foreign materials such as animal bedding, sand and silt can have a significant impact on the anaerobic digestion process. For example, the poor performance of the Monroe, WA dairy digester was attributed to the use of cedar wood chip bedding (Ecotope 1979). The quantity and quality of the bedding material added to the manure will have a significant impact on the anaerobic digestion of dairy waste. Sand and silt must be removed before anaerobic digestion. If it is not removed before digestion it must be suspended during the digestion process.

***Toxic Materials***

Toxic materials such as fungicides and antibacterial agents can have an adverse effect on anaerobic digestion. The anaerobic process can handle small quantities of toxic materials without difficulty. Storage containers for fungicides and antibacterial agents should be placed at locations that will not discharge to the anaerobic digester.

***Nutrients***

Bacteria require a sufficient concentration of nutrients to achieve optimum growth. The carbon to nitrogen ratio in the waste should be less than 43. The carbon to phosphorus ratio should be less than 187. Hills and Roberts showed that a non-lignin C/N ratio of 20 to 25 is optimum for digester performance. Typically, “as excreted manure has a C/N ratio of 10.

## Temperature

The anaerobic bacterial consortia function under three temperature ranges. Psychrophilic temperatures of less than 68 degrees Fahrenheit produce the least amount of bacterial action. Mesophilic digestion occurs between 68 degrees and 105 degrees Fahrenheit. Thermophilic digestion occurs between 110 degrees Fahrenheit and 160 degrees Fahrenheit. The optimum mesophilic temperature is between 95 and 98 degrees Fahrenheit. The optimum thermophilic temperature is between 140 and 145 degrees Fahrenheit. The rate of bacterial growth and waste degradation is faster under thermophilic conditions. On the other hand, thermophilic digestion produces an odorous effluent when compared to mesophilic digestion. Thermophilic digestion substantially increases the heat energy required for the process. In most cases, sufficient heat is not available to operate in the thermophilic range. This is especially true if flush systems are used or the milk parlor waste is mixed with the scraped manure. Large quantities of dilution flush water must be heated to the digester's operating temperature. During cold weather, control of the flush volume is critical in maintaining adequate digester temperatures.

Seasonal and diurnal temperature fluctuations significantly affect anaerobic digestion and the quantities of gas produced. Bacterial storage and operational controls must be incorporated in the process design to maintain process stability under a variety of temperature conditions.

Temperature is a universal process variable. It influences the rate of bacterial action as well as the quantity of moisture in the biogas. The biogas moisture content increases exponentially with temperature. Temperature also influences the quantity of gas and volatile organic substances dissolved in solution as well as the concentration of ammonia and hydrogen sulfide gas.

**pH**

Methane producing bacteria require a neutral to slightly alkaline environment (pH 6.8 to 8.5) in order to produce methane. Acid forming bacteria grow much faster than methane forming bacteria. If acid-producing bacteria grow too fast, they may produce more acid than the methane forming bacteria can consume. Excess acid builds up in the system. The pH drops, and the system may become unbalanced, inhibiting the activity of methane forming bacteria. Methane production may stop entirely. Maintenance of a large active quantity of methane producing bacteria prevents pH instability. Retained biomass systems are inherently more stable than bacterial growth based systems such as completely mixed and plug flow digesters.

### Hydraulic Retention Time (HRT)

Most anaerobic systems are designed to retain the waste for a fixed number of days. The number of days the materials stays in the tank is called the Hydraulic Retention Time or HRT. The Hydraulic Retention Time equals the volume of the tank divided by the daily flow (HRT=V/Q). The hydraulic retention time is important since it establishes the quantity of time available for bacterial growth and subsequent conversion of the organic material to gas. A direct relationship exists between the hydraulic retention time and the volatile solids converted to gas. Such a relationship for dairy waste is shown in Figure 3.

### Solids Retention Time (SRT)

The Solids Retention Time (SRT) is the most important factor controlling the conversion of solids to gas. It is also the most important factor in maintaining digester stability. Although the calculation of the solids retention time is often improperly stated, it is the quantity of solids maintained in the digester divided by the quantity of solids wasted each day.

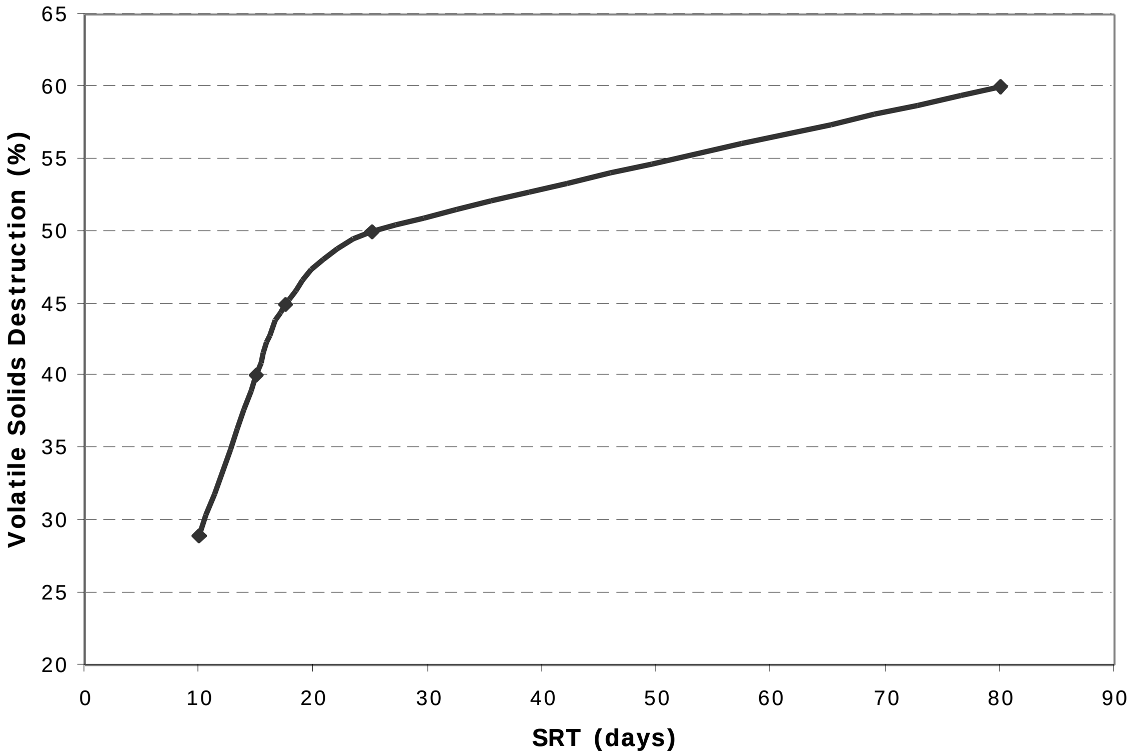
$$SRT = \frac{(V)(C_d)}{(Q_w)(C_w)}$$

Where V is the digester volume; $C_d$ is the solids concentration in the digester; $Q_w$ is the volume wasted each day and $C_w$ is the solids concentration of the waste.

In a conventional completely mixed, or plug flow digester, the HRT equals the

SRT. However, in a variety of retained biomass reactors the SRT exceeds the HRT. As a result, the retained biomass digesters can be much smaller while achieving the same solids conversion to gas.

***Figure 3 Dairy Waste Volatile Solids Destruction***




The volatile solids conversion to gas is a function of SRT (Solids Retention Time) rather than HRT. At a low SRT sufficient time is not available for the bacteria to grow and replace the bacteria lost in the effluent. If the rate of bacterial loss exceeds the rate of bacteria growth, "wash-out" occurs. The SRT at which “wash-out” begins to occur is the "critical SRT".

Jewel established that a maximum of 65 percent of dairy manure's volatile solids could be converted to gas with long solids retention times. Burke established that 65 to 67 percent of dairy manure COD could be converted to gas. Long retention times are required for the conversion of cellulose to gas.

The goal of process engineers over the past twenty years has been to develop anaerobic processes that retain biomass in a variety of forms such that the SRT can be increased while the HRT is decreased. The goal has been to retain, rather than waste the biocatalyst (bacterial consortia) responsible for the anaerobic process. As a result of this effort, gas yields have increased and digester volumes decreased. A measure of the success of biomass retention is the SRT/HRT ratio. In conventional digesters, the ratio is 1.0. Effective retention systems will have SRT/HRT ratios exceeding 3.0. At an SRT/HRT ratio of 3.0 the digester will be 1/3rd the size of a conventional digester.

## Digester Loading (kg / m$^3$ / d)

Neither the hydraulic retention time (HRT), nor the solids retention time (SRT) tells the full story of the impact that the influent waste concentration has on the anaerobic digester. One waste may be dilute and the other concentrated. The concentrated waste will produce more gas per gallon and affect the digester to a much greater extent than the diluted waste. A more appropriate measure of the waste on the digester's size and performance is the loading. The loading can be reported in pounds of waste (influent concentration x influent flow) per cubic foot of digester volume. The more common units are kilograms of influent waste per cubic meter of digester volume per day (kg / m$^3$ / d). One (kg / m$^3$ / d) is equal to 0.0624 (lb / ft$^3$ / d).

The digester loading can be calculated if the HRT and influent waste concentration are known. The loading in (kg / m$^3$ / d) is simply:

$$L = \left(\frac{1}{HRT}\right)(C_I)$$

Where $C_I$ is the influent waste concentration in grams. Increasing the loading will reduce the digester size but will also reduce the percentage of volatile solids converted to gas.

## Food to Microorganism Ratio

The food to microorganism ratio is ***the key factor*** controlling anaerobic digestion. At a given temperature, the bacterial consortia can only consume a limited amount of food each day. In order to consume the required number of pounds of waste one must supply the proper number of pounds of bacteria. The ratio of the pounds of waste supplied to the pounds of bacteria available to consume the waste is the food to microorganism ratio (F/M). This ratio is the controlling factor in all biological treatment processes. A lower the F/M ratio will result in a greater percentage of the waste being converted to gas.

Unfortunately, the bacterial mass is difficult to measure since it is difficult to differentiate the bacterial mass from the influent waste. The task would be easier if ***all*** of the influent waste were converted to biomass or gas. In that case, the F/M ratio would simply be the digester loading divided by the concentration of volatile solids (biomass) in the digester (L / $C_d$). For any given loading, the efficiency can be improved by lowering the F/M ratio by ***increasing the concentration of biomass in the digester***. Also for any given biomass concentration within the digester, the efficiency can be improved by decreasing the loading. Unfortunately, a portion of the influent waste is not processed or converted to biomass or gas by the bacteria. In that case the F/M ratio is equal to the VS loading divided by the digester VS measured ($VS_D$) minus the unprocessed Volatile Solids ($VS_{UP}$). The unprocessed volatile solids may include refractory or non-degradable biological products produced by the bacteria.

$$\frac{F}{M} = \frac{L_{VS}}{VS_D - VS_{UP}}$$

## End Product Removal

The end products of anaerobic digestion can adversely affect the digestion process. Such products of anaerobic digestion include organic acids, ammonia nitrogen, and hydrogen sulfide. For any given volatile solids conversion to gas, the higher the influent waste concentration, the greater the end product concentration. End product inhibition can be reduced by lowering the influent waste concentration or by separately removing the soluble end products from the digester through elutriation. Elutriation is the process of washing the solids (bacteria) with clean water to remove the products of digestion. The contact process provides an efficient means of removing the end products of digestion. End product removal can be enhanced by elutriation, which is easily incorporated into the contact process (Burke 1997).

## *Digester Types*

A vast array of anaerobic digesters have been developed and placed in operation over the past fifty years. A variety of schemes could be used to classify the digestion processes. For dairy waste, the most important classification is whether or not it can be used to convert dairy waste solids to gas while meeting the goals of anaerobic digestion. The goals of dairy waste anaerobic digestion are as follows:

1. Reduce the mass of solids
2. Reduce the odors associated with the waste products
3. Produce clean effluent for recycle and irrigation
4. Concentrate the nutrients in a solid product for storage or export
5. Generate energy
6. Reduce pathogens associated with the waste



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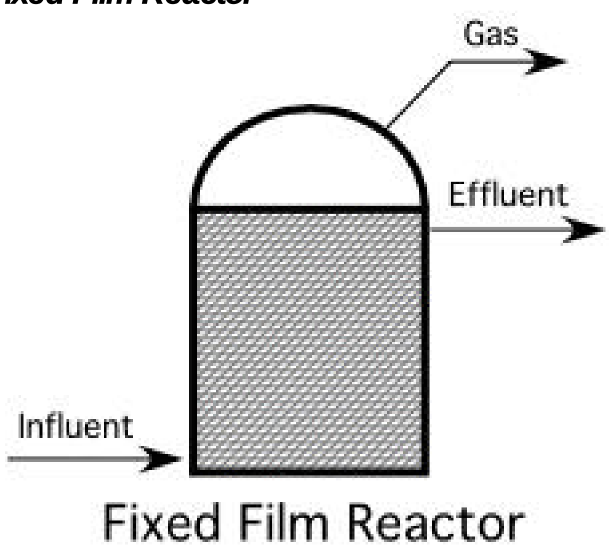
In addition, the digester must be able to handle or process the dairy waste stream. Dairy waste is a semi-solid slurry. Much of the energy value is in the solids. Consequently, the process must be able to convert solids to gas without clogging the anaerobic reactor. The process must also be able to handle bedding material, sand and other foreign materials associated with typical dairy waste. In addition, if the dairy manure is a dilute waste, the process must be capable of mitigating stratification and solids separation within the reactor.

## Processes that are not Appropriate for Digesting Dairy Manure

A variety of high rate anaerobic processes, which retain bacteria have been developed to treat soluble organic industrial wastes. These “high rate” digesters have reduced hydraulic detention times from 20 days to a few hours. They include anaerobic filters, both upflow and downflow, and a variety of biofilm processes such as fixed film packed bed reactors. Bacteria are retained in these reactors as films on carriers such as plastic beads, or sand, or on support media of all configurations. The waste washes past the retained bacteria. The bacteria convert the soluble constituents to gas but have little opportunity to hydrolyze and degrade the particulate solids, unless the solids become attached to the biomass.

These reactors are ***not*** suitable for digesting dairy waste since they are not effective in converting particulate solids to gas and tend to clog while digesting dairy manure slurries. These high rate reactors can treat the soluble component of dairy waste. But only a fraction of the available energy will be recovered.

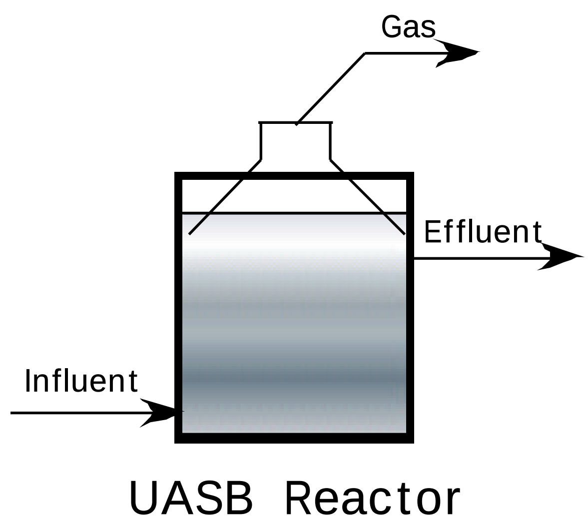
***Figure 4- Packed Fixed Film Reactor***




A widely used industrial waste anaerobic digester is the UASB or “Upflow

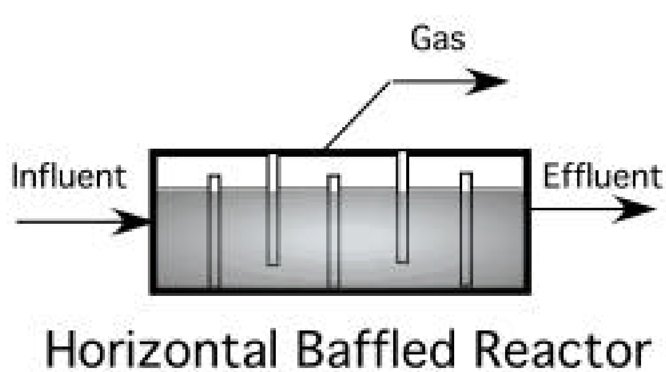
Anaerobic Sludge Blanket", reactor. The process stores the anaerobic consortia as pellets, approximately the size of a pea. The upflow anaerobic sludge blanket reactor (UASB) is widely used in industrial treatment processes throughout the world. It is an extremely effective process for converting soluble organic materials, such as sugar to methane gas. It has not been used for processing dairy waste since it is ineffective in converting solids to gas. It is primarily used to convert non-particulate or soluble waste to gas.

***Figure 5 - Upflow Anaerobic Sludge Blanket Reactor***




The anaerobic baffled reactor is a horizontal version of the upflow anaerobic sludge blanket reactor. Both store large quantities of anaerobic bacteria as pellets approximately the size of a pea. Unfortunately, these very successful anaerobic reactors are not effective in digesting particulate waste.

***Figure 6 - Baffled Reactor***



Particulate solids tend to settle in the horizontal baffled reactor (HBR) while organic fibers will form a mat on the surface. There are no known instances of the HBR being used for the treatment of dairy waste. Unless the dairy waste was thoroughly screened and all particulate matter removed the HBR would tend to become clogged. The removal of solids by screening and gravity sedimentation will eliminate up to 80% of the energy generating potential from dairy waste.

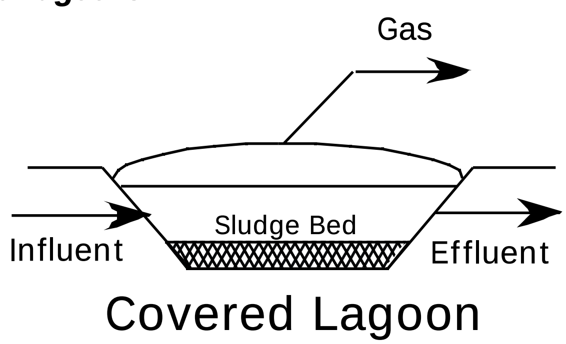
## Processes that can be used for Digesting Dairy Manure

The processes that have been used for digesting dairy waste can be subdivided into high rate and low rate processes. Low rate processes consist of covered anaerobic lagoons, plug flow digesters, and mesophilic completely mixed digesters. High rate reactors include the thermophilic completely mixed digesters, anaerobic contact digesters, and hybrid contact/fixed film reactors.

### *Anaerobic Lagoons (Very Low Rate)*

Anaerobic lagoons are covered ponds. Manure enters at one end and the effluent is removed at the other. The lagoons operate at psychrophilic, or ground temperatures. Consequently, the reaction rate is affected by seasonal variations in temperature.

***Figure 7 – Anaerobic Lagoons***




Since the reaction temperature is quite low, the rate of conversion of solids to gas is also low. In addition, solids tend to settle to the bottom where decomposition occurs in a sludge bed. Little contact of bacteria with the bulk liquid occurs. The biomass concentration is low, resulting in very low solids conversion to gas (High F/M ratio with poor growth rates at low temperatures). Little or no mixing occurs. Consequently, lagoon utilization is poor. Anaerobic lagoons have been used to treat parlor and free stall flush water. Gas production rates have been low and seasonal. Solids may be screened and removed prior to entering the lagoon. A considerable amount of energy potential is lost with the removal of particulate solids. The advantage of anaerobic lagoons is the low-cost. The low cost is offset by the lower energy production and poor effluent quality. Periodically the covered lagoons must be cleaned at considerable cost.

Nuisance odors may be generated while cleaning the lagoons.

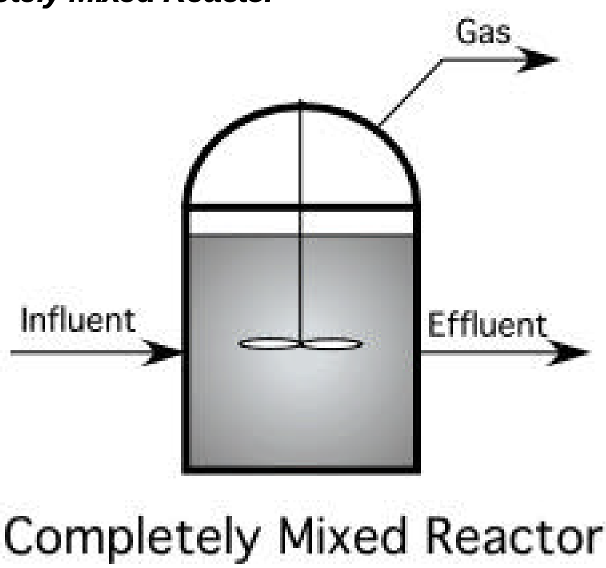
***Completely Mixed Digesters (Low Rate)***

The most common form of an anaerobic digester is the completely mixed reactor. Most sewage treatment plants and many industrial treatment plants use a completely mixed reactor to convert waste to gas. The completely mixed reactor is a tank that is heated and mixed.

Most completely mixed reactors operate in the mesophilic range. All of the initial anaerobic digesters used to treat dairy manure were completely mixed mesophilic digesters. The cost of mixing is high, especially if sand, silt, and floating materials, present in the waste stream, must be suspended throughout the digestion period.

Some completely mixed reactors operate in a thermophilic range where sufficient energy is available to heat to reactor. Highly concentrated readily degradable waste is required in order to generate sufficient heat for the thermophilic range of operation. Completely mixed thermophilic digesters are used in the EEC to treat animal manure(Ahring, Ibrahim et al. 2001). Recently, completely mixed thermophilic digesters were proposed in Oregon to treat dairy manure(Tillamook 1999).

***Figure 8 – Completely Mixed Reactor***




Most completely mixed reactors are heated with spiral flow heat exchangers. These heat exchangers apply hot water to one side of the spiral and the anaerobic slurry to the other. The spiral heat exchangers have proven to be a successful method of efficiently transferring heat.

Completely mixed reactors can be constructed of a variety of materials. In the U.S. most completely mixed reactors have a low profile with a diameter greater than the height. Some municipal digesters in the U.S., and most in Europe have an egg shape with a height much greater than the diameter. The egg shape enhances mixing while eliminating much of the stratification.

Completely mixed reactors can have fixed covers, floating covers, or gas holding covers. Most municipal digesters have floating covers. Floating covers are more expensive than fixed covers.

Mixing can be accomplished with a variety of gas mixers, mechanical mixers, and draft tubes with mechanical mixers or simply recirculation pumps. The most efficient mixing device in terms of power consumed per gallon mixed is the mechanical mixer. Most municipal digesters are intensely mixed to reduce the natural stratification that occurs in a low profile tank. A large amount of evidence has been accumulated over the past 10 years indicating that intense mixing may inhibit the bacterial consortia. But, intense mixing is required to keep sands and silts in suspension.

The advantage of the completely mixed reactor is that it is a proven technology that achieves reasonable conversion of solids to gas. It can be applied to the treatment of slurry waste such as dairy manure (Ecotope 1979). The disadvantage of the completely mixed reactor is the high cost of installation, and the energy cost associated with mixing the digester. The completely mixed conventional anaerobic digester is a biomass growth based system. The process requires a constant conversion of a portion of the feed solids to anaerobic bacteria rather than gas. Since anaerobic bacteria are constantly wasted from the process, new bacteria must be produced to replace the lost bacteria. If the bacteria are retained, the portion of the waste that would have been converted to new bacterial cells will be converted to gas. For this reason, bacterial growth based systems are not as efficient as retained biomass systems.

The advantage of the completely mixed thermophilic reactor is the rapid conversion of solids to gas and biomass (Ratkowsky, Olley et al. 1981). Some claim that the rate of conversion is three times greater with thermophilic reactors. Consequently, the HRT can be lower and the gas production greater. The disadvantage of the thermophilic reactor is the energy required to heat cold dairy manure to thermophilic temperatures. Additional costs are incurred in tank insulation and heat exchangers. Sufficient heat may not be available from the gas produced unless the solids are highly concentrated. Thermophilic digestion of dairy manure cannot be used with manure diluted with parlor or flush water since sufficient energy will not be available to meet the heat requirements. In addition, the higher temperature thermophilic reactors increase end product inhibition, especially ammonia and organic acids (Ahring, Ibrahim et al. 2001).

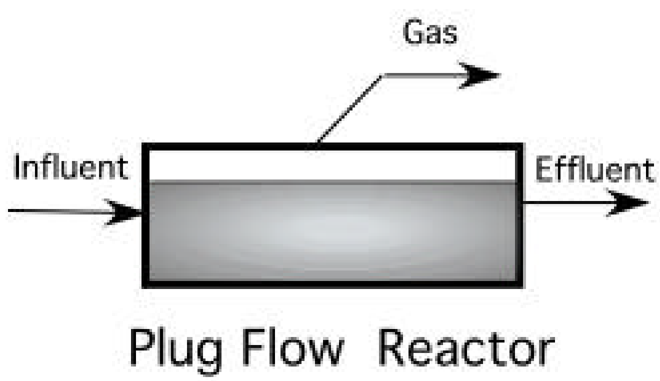
***Plug Flow Digesters (Low Rate)***

The plug flow anaerobic digester is the simplest form of anaerobic digestion(Jewell, Kabrick et al. 1981). Consequently, it is the least expensive (Jewell, Dell-Orto et al. 1981). The plug flow digester can be a horizontal or vertical reactor. The horizontal reactor shown in Figure 9 is the most commonly used configuration. The waste enters on one side of the reactor and exits on the other. Since bacteria are not conserved, a portion of the waste must be converted to new bacteria, which are subsequently wasted with the effluent. Since the plug flow digester is a growth based system, it is less efficient than a retained biomass system. It converts less waste to gas.

Plug flow systems are subject to stratification wherein the sands and silts settle to the bottom and the organic fibers migrate to surface. The stratification can be partially inhibited by maintaining a relatively high solids concentration in the digester.

Periodically, solids must be removed from the plug flow reactor. Since there is no easy way of removing the solids, the reactor must be shut down during the cleaning period. The cost of cleaning can be considerable. Since the solids concentration must be maintained at high levels, dilute milk barn waste is normally excluded from the digester. Plug flow reactors are normally heated by a hot water piping system within the reactor. The hot water piping system can complicate the periodic cleaning of the reactor.

***Figure 9 – Plug Flow Reactor***




The plug flow reactor is a simple, economical system. Applications are limited to concentrated dairy manure containing a minor amount of sand and silt. If stratification occurs because of a dilute waste or excess sand, significant operating costs will be incurred.

### *Contact Digesters (High Rate)*

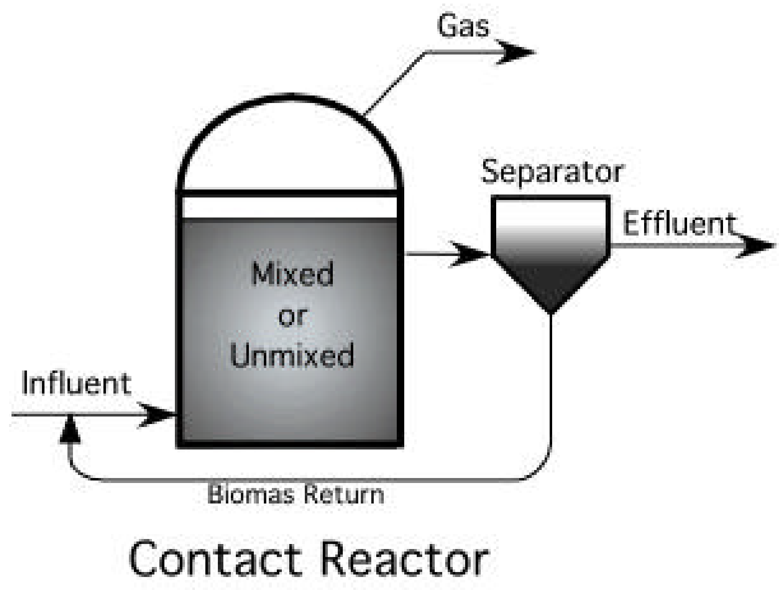
The contact reactor is a high rate process that retains bacterial biomass by separating and concentrating the solids in a separate reactor and returning the solids to the influent (Ettinger, Witherow et al. 1957; Eckenfelder 1966; Loehr 1974). More of the degradable waste can be converted to gas since a substantial portion of the bacterial mass is conserved. The contact digester can be either completely mixed or plug flow. It can be operated in the thermophilic or mesophilic range. The contact reactor can treat both dilute and concentrated waste provided the separator can concentrate the digester effluent solids sufficiently to enhance the process.

A wide variety of separators have been tested over the past 30 years. Initially gravity separators (settling tanks), or solids thickeners were used. It was soon discovered that the solids could not be sufficiently concentrated in a gravity separator without degassing to remove the gas bubbles attached to the solids. Actively fermenting digester effluent containing gas bubbles floated rather than settled in the separator. Lamella or plate separators have also been used to concentrate the biomass after degassing**.** Both of these gravity-settling techniques are not effective for concentrated digester solids. Gravity separation techniques are effective with dilute waste following a completely mixed reactor. Separation requires several days of detention(Duke Engineering & Services 2001). The completely mixed digester will prevent stratification. The effluent is then allowed to separate by gravity in the separation reactor. The digester solids concentration should be less than 2.5% for gravity separation to be used. Long separator detention times are required.

Mechanical separation devices have been tested to reduce the detention time required by gravity separation. Centrifuges, gravity belts, membranes, and other mechanical separators have been used with limited success. These disruptive devices have been shown to inhibit the bacterial consortia and thus limit the effectiveness of the contact process.

Burke used gas flotation to separate and concentrate the digester effluent for the efficient and tranquil recovery of the anaerobic consortia. The process has been used for the digestion of dairy manure(Burke 1998), sewage sludge (Burke and Yokers 1999), and potato waste(Burke 1997). It has been shown to be effective for concentrating the biomass from actively fermenting digester liquors without the need for degassing. The process has been referred to as the AGF or "anoxic gas flotation" process. Gas flotation can achieve significantly greater biomass concentrations than gravity separation without the adverse consequences associated with disruptive separation techniques.

***Figure 10 – Contact Reactor***




Gas flotation can also remove enzymes(Burke, Butler et al. 1997), organic acids (Burke 1997), and other products of digestion that cannot be removed through settling or other mechanical means. Finally, gas flotation can be performed in a non-mechanical manner, which is simple to operate and maintain.

During the contact process, refractory organic and inorganic solids accumulate within the system. The accumulated sands, silts, and non-degradable organic fibers dictate the rate of solids wasting. Wasting the nonbiodegradable solids causes the loss of bacterial mass and reduced process efficiency. The anaerobic contact process can utilize mechanical separating devices to remove refractory solids from the digestion system (Burke 2000).

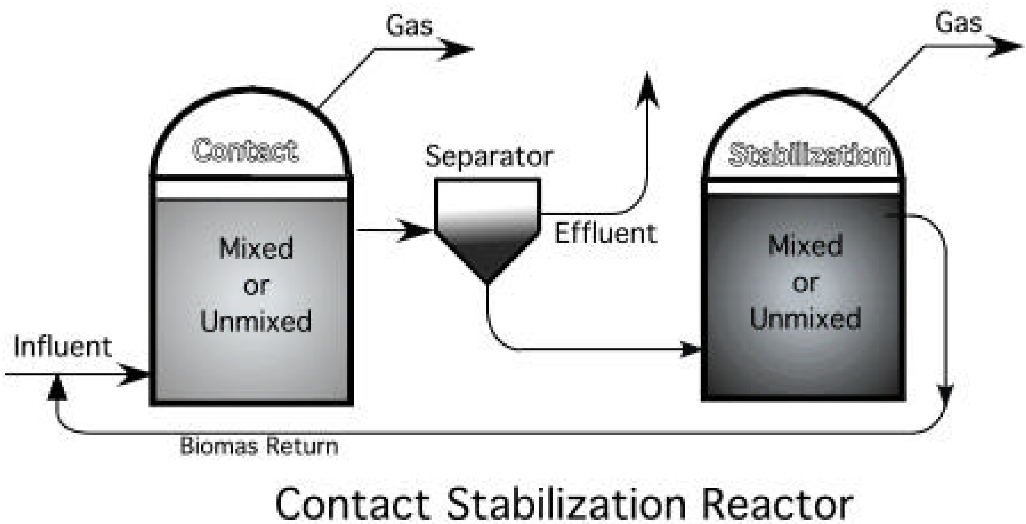
### *Sequencing Batch Reactors (High Rate)*

A sequencing batch reactor is a contact digester, which utilizes the same tank for digestion as well as separation. In a sequencing batch reactor the same tank is used to digest the waste and separate the biomass from the effluent liquor (Dugba, Zhang et al. 1997). Generally, two or more tanks are used. The tanks are operated in a fill and draw mode. The separation is accomplished by gravity. Consequently, a more dilute, screened waste is treated. Laboratory scale sequencing batch reactors have been used to digest dairy manure.

### *Contact Stabilization Reactors (High Rate)*

The anaerobic contact stabilization process is a more efficient contact process. Burke used the anaerobic contact stabilization process for the digestion of both dairy manure and potato waste. The process has the advantage of efficiently converting slowly degradable materials such as cellulose in a highly concentrated reactor (Burke 1997). Organic materials, which can be degraded rapidly, are digested in the contact reactor. The bacteria and slowly degradable organics are removed and degraded in a highly concentrated reactor.

***Figure 11– Contact Stabilization Reactor***



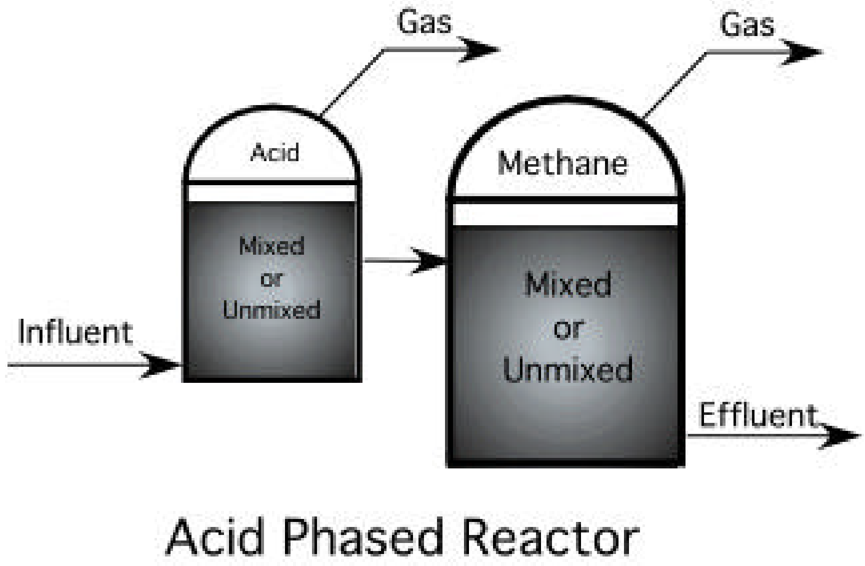

***Phased Digesters***

Both acid phased and temperature phased digestion have been used to convert municipal sludge to gas. Acid phased digestion (Ghosh 1987) takes advantage of the fact that the acid forming bacteria have a much higher growth rate than the methanogens.

Consequently, the initial reactor can be much smaller than the subsequent methane producing digester. Acid phased digestion offers greater efficiency in the size of the anaerobic digesters. Acid phased digestion has not been applied to dairy waste.

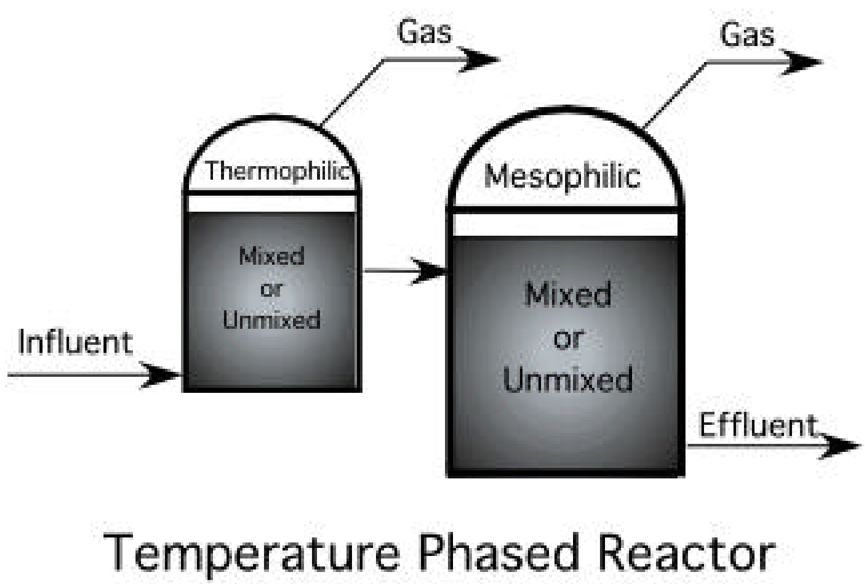
Temperature phased digestion has been applied to the digestion of sewage sludge. The initial digester is operated in the thermophilic mode followed by a second digester, which is operated in the mesophilic mode. In the first thermophilic digester, pathogens are destroyed. In the second mesophilic digester, the mesophilic bacteria consume the organic acids created in the thermophilic reactor. Consequently, the odors associated with a thermophilic effluent are eliminated while achieving the desired pathogen destruction.

***Figure 12– Acid Phased Digester***




Temperature phased digestion has been used to digest dairy manure (Dugba, Zhang et al. 1997). In addition it must be pointed out that completely mixed reactors are not completely effective in removing pathogens.

***Figure 13– Temperature Phased Digester***



***Hybrid Processes***

A number of hybrid processes have been developed and applied to many different kinds of waste materials. The hybrid processes incorporate a combination of the previously described configurations.

## *Qualitative Analysis of Anaerobic Processes*

In order to assess the various digester configurations one must define their limitations for dairy waste digestion. The following pages describe the attributes as well as the limitations of each digester configuration.

### Solids Concentration Limitations

The ability to process a variety of manure concentrations is important. Even though the solids may be collected in a concentrated form, there will be times when the solids become diluted. The inverse is also true. The dilute parlor waste may become concentrated for variety of reasons. The mesophilic and thermophilic completely mixed processes and the contact process can handle a variety of influent manure concentrations. Their operating performance is not limited by the manure concentration. On the other hand the plug flow digester and the anaerobic lagoon are limited by the influent manure concentration. The plug flow digester will stratify at low feed concentrations. The anaerobic lagoon will accumulate non-degraded solids at high influent solids concentrations.

### Digestion of the Entire Waste Stream

The thermophilic and mesophilic completely mixed reactors and the plug flow contact process can digest the entire waste stream since neither are limited by the concentration of the influent waste. Plug flow reactors will be able to process the concentrated or scraped manure. Plug flow reactors will not be able to economically process the parlor waste or a mixture of the parlor and scraped waste. The anaerobic lagoon can process primarily liquid waste after the removal of fibers and particulate solids.

The current practice of screening fibers and settling solids to remove particulate matter is not compatible with achieving high energy yields through anaerobic digestion. It is generally accepted that screening will remove at lease 15% of the influent COD. Recent analysis has shown that screening and sedimentation will remove 60% or more of the COD that could be converted to gas. Solids separation should follow, rather than precede anaerobic digestion.

## Foreign Material Processing

High concentrations of sand and silt are not compatible with the plug flow digester or the anaerobic lagoon. Completely mixed reactors can operate with minor concentrations of foreign material by maintaining the material in suspension through intense mixing. The contact process incorporating grit removal as described by Burke (Burke 2000) is not limited by the concentration of foreign material.

## Odor Control

Most properly operated anaerobic digesters will eliminate the generation of odors from the site(Wilkie 2000). However, both plug flow anaerobic digesters and the anaerobic lagoon must be periodically cleaned. During the cleaning process odors are generated. The thermophilic completely mixed reactors produce an effluent that is far more odorous than mesophically digested waste. Contact and completely mixed digesters significantly reduce odors and may ***not*** require cleaning, especially if refractory inorganic and organic solids removal is practiced (Burke 2000).

## Stability, Flexibility, and Reliability

Each type of anaerobic reactor imposes requirements for its proper operation. The inability to meet those requirements, such as operating temperature, may result in process failure. The mesophilic process is more reliable than the thermophilic process because of the greater risk associated with meeting the thermophilic temperature requirements utilizing a cold waste at cold temperatures.

The anaerobic process has been labeled an unreliable process because of frequent toxic upsets. The contact process is a more reliable process in preventing process failure, foaming, and loss of biomass. Retained biomass systems are the least likely to fail because of a large quantity and diversity of the biocatalyst in the digestion system. The addition of elutriation, or the washing of biological solids to remove inhibitory products, adds further stability to the process.

The contact stabilization process is the least likely to be upset by changes in hydraulic flow, or organic loading.

Since mixing is essential to any completely mixed process, mixing failures, or inadequacies may result in poor performance. The plug flow contact process also poses little risk of failure due to mixing inadequacies or solids accumulation in the digester.

The complexity of the process will also affect its reliability. The thermophilic digestion of dairy manure must incorporate a complex heating and heat recovery system. Its reliability will be less than a system that does not have such complexity. The contact process and the contact stabilization process are also more complex systems. They have more of an opportunity to fail. Redundant equipment and robust controls are essential to improving the reliability of complex systems.

### Nutrient Concentration and Retention

The process of anaerobic digestion will convert nutrients from an organic form to an inorganic form. In plug flow, completely mixed, and thermophilic reactors the quantity of nutrients entering the reactor equals the quantity of nutrients exiting the reactor. However, in retained biomass digesters such as the contact process, sequencing batch reactors, and fixed film reactors, nutrients may be concentrated in a separate waste solids stream. Dugba demonstrated that the effluent from a sequencing batch reactor contained less than 50 percent of the influent phosphorus (Dugba, Zhang et al. 1997). The balance of the phosphorus was concentrated in the biosolids. Burke demonstrated the retention and concentration of 90 percent of the influent phosphorus and 43 percent of the influent total nitrogen in the waste solids that was only 1/5 of the influent volume. The ability to concentrate nutrients is an important characteristic of the selected anaerobic process since it provides the dairy operator with the control necessary to manage nutrient application to the land.

### Additional Substrate Processing

Hobson studied the effect of adding cellulose to dairy manure (Hobson and Taiganides 1983). His research indicated that the volatile solids conversion to gas would be substantially improved through the addition of cellulose. At a 16-day hydraulic retention time the volatile solids conversion to gas increased from 30 percent with no cellulose to 51 percent with a manure containing six percent cellulose. Many commercial digesters supplement the influent with food waste or food processing waste. Collection of tipping fees improves the economic viability of anaerobic facilities. The Tillamook project in Oregon proposed to supplement the influent waste with municipal solid waste to increase revenues. The proposed Myrtle Point project in Oregon (Duke Engineering & Services 2001) may treat milk-processing waste to increase revenues. The ability to treat a wide variety of influent substrates, and thereby enhance the economics, is an important process characteristic. The completely mixed and contact processes can process a variety of added substrates.

## Energy Production

The quantity of energy produced from each gallon of waste processed is strictly a function of the percentage conversion of volatile solids to gas. Each pound of volatile solids destroyed will produce 5.62 cubic feet of methane. Each cubic foot of methane will contain 1000 Btu's of energy. Therefore, each pound of volatile solids converted will produce 5620 Btu's of energy. At 35 percent conversion efficiency, each pound of volatile solids destroyed will produce 0.58 kWh of energy. It is therefore important to look at the conversion efficiencies of the various anaerobic processes.

As pointed out earlier, the conversion of volatile solids to gas is a function of the organic loading to the digester. Higher percentage conversions to gas are achieved at lower organic loadings. Low loadings however, translate into larger digestion facilities. However, it is possible to achieve a higher volatile solids conversion to gas by increasing the digester loading while maintaining a higher biomass concentration in the digester. In other words, the food to microorganism (F/M) ratio remains low resulting in a higher rate of conversion. The rate of volatile solids conversion to gas is related to the type of anaerobic digester used. Conventional completely mixed and plug flow digesters, which do not retain biomass, should have comparable volatile solids destructions. Anaerobic lagoons will have a lower rate of conversion, while high rate retained biomass reactors will have higher rates of solids conversion to gas. Each is discussed separately below.

### *Conventional Digesters*

A review of recent dairy waste anaerobic digestion studies has established that most engineers anticipate a 50 percent conversion of volatile solids to gas. The planned Three-Mile Farm (Oregon) dairy waste ***thermophilic*** anaerobic digestion facility is expected to achieve a 50 percent volatile solids conversion to gas. The C. Bar M. (Idaho) ***plug flow*** anaerobic digester facility anticipated a 50 percent conversion of dairy waste volatile solids to gas. The recently completed Myrtle Point (Oregon) feasibility study utilizing the ***gravity separation contact process*** anticipated a 50 percent conversion of dairy waste volatile solids to gas. Relatively high loading rates were anticipated in each case. The organic loading rates varied between 5.6 and 6.4 kg per cubic meter per day. The available literature does not support such high volatile solids conversions to gas at high organic loading rates. A summary is as follows:

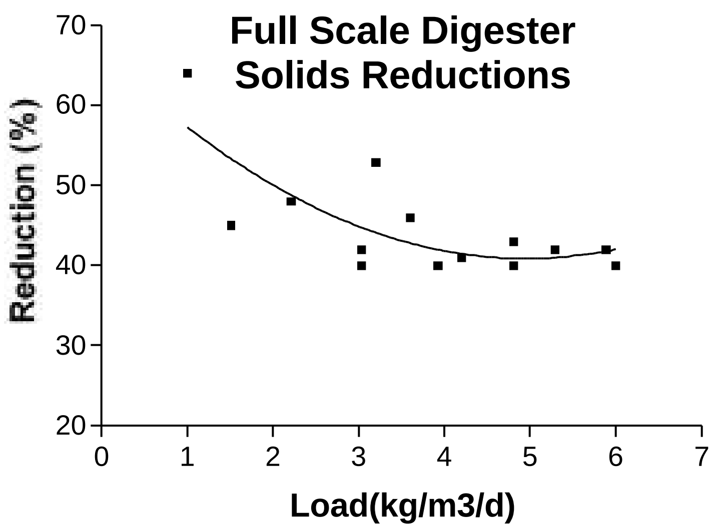
The Monroe Honor Farm (Ecotope 1979) ***completely mixed anaerobic digester*** achieved a maximum of 40 percent volatile solids conversion to gas at a loading rate of 6 kg / $m^3$ / d. Jewel operated a ***plug flow anaerobic digesters*** at an organic loading rate of 2.37 and achieved a 32.4 percent conversion to volatile solids to gas(Jewell, Dell'Otto et al. 1980), (Jewell, Dell-Orto et al. 1981).

Converse operated both thermophilic and mesophilic completely mixed anaerobic digesters at a loading rate of 4.2 kg / $m^3$ / d (Converse, Zeikus et al. 1975). Both thermophilic and mesophilic digesters achieved a 41 percent conversion of volatile solids to gas. Bryant (1977) on the other hand, operated ***completely mixed thermophilic*** digesters at loadings of 6.5 to 10.78 kg / $m^3$ / d and achieved 50 percent volatile solids conversion to gas. Recently, Ahring reported a 28% volatile solids conversion in a thermophilic digester operated at a loading of 3 kg / $m^3$ / d (Ahring, Ibrahim et al. 2001). Ghaly operated a dairy waste completely mixed mesophilic digester at a loading of 3.6 kg / $m^3$ / d (Ghaly and Pyke 1992). He achieved a 46 percent conversion of volatile solids to gas. Qasim operated a completely mixed mesophilic digester at an organic loading rate of 3.2 kg / $m^3$ / d and achieved a 52.9 percent volatile solids conversion to gas(Quasim, Warren et al. 1984). Echiegu operated a completely mixed dairy waste digester at an organic loading rate of 2 kg / $m^3$ / d but only achieved a 40 percent conversion (Echiegu, Ghaly et al. 1992). Robbins also operated a completely mixed mesophilic digester at an organic loading rate of 2.6 kg per cubic meter per day that achieved a 30 percent conversion of volatile solids to gas (Robbins, Armold et al. 1983). Hills and Kayhanian (1985) operated a completely mixed mesophilic digester at a 1.8 kg / $m^3$ / d loading that achieved a 31 percent volatile solids destruction and a 38 percent conversion at 1.0 kg / $m^3$ / d. On the other hand, Pigg operated a completely mixed mesophilic anaerobic digester at an organic loading rate of 1.0 kg / $m^3$ / d and achieved a peak volatile solids conversion to gas of 64 percent (Pigg 1977).

As can be observed the published literature values are highly variable. The results generally confirm Smith's conclusion that mesophilic digesters can achieve a 40% conversion of volatile solids at a loading of 5.7 kg / $m^3$ / d (Smith, Greiner et al. 1980). Better conversions can be achieved at lower loadings. Thermophilic reactors appear to achieve greater conversions at high loadings while mesophilic reactors appear to achieve greater conversions at lower loadings.

Lusk (1998) provided information on the performance of full-scale plug flow and completely mixed anaerobic digesters treating dairy manure. The loading and percent volatile solids conversion can be calculated from the information he presented. Figure 14 below presents the results of the analysis of the Lusk data.

***Figure 14 Full Scale Mesophilic Digester VS Reductions***




***Lagoons***

California Polytechnic State University in San Luis Obispo constructed an anaerobic lagoon to treat flush waste from a 350 animal dairy (equivalent of 250 animals). The screening system removed 15 percent of the manure volatile solids. The lagoon was projected to achieve a 35 percent volatile solids conversion to gas at a loading of 0.04 kg / $m^3$ / d.

***High Rate Anaerobic Reactors***

Wilkie reported the use of a fixed film reactor treating screened dairy manure having the volatile solids concentration of 3.2 g per liter (Wilkie 2000). The fixed film reactor achieved a 57 % COD conversion to gas. The gas contained 78 % methane. On a COD basis, the loading was approximately 10.7 kg / $m^3$ / d. The hydraulic retention time was three days. Unfortunately, most of the potential gas production was lost in the screened and settled manure that was not processed by the fixed film digester.

Dugba reported on the use of a temperature phased anaerobic sequencing batch reactor system treating dairy manure (Dugba, Zhang et al. 1997). The systems were operated at a three-day hydraulic retention time. The dairy manure was screened utilizing a 2 by 2 mm screen opening. The biogas had a methane concentration of 62 to 66 %. The sequencing batch reactors reportedly had a

SRT/HRT ratio of 3 to 4. (Observation of phosphorus retention indicated that the systems were not very effective in retaining biomass.) The systems were operated at a three-day HRT. The volatile solids feed concentration varied between 0.6 and 1.2 percent volatile solids. The loadings ranged from 2 to 4 kg / $m^3$ / d. The volatile solids conversions to gas ranged from 30 to 41 percent.

Umetsu reported on the performance of a horizontally baffled anaerobic digester treating dairy manure at ambient temperatures (Umetsu and Takahata 1997). The average HRT was ten days. The methane content of the biogas was 58 percent. The digester achieved a 25 percent volatile solids reduction at a volatile solids loading of 7.3 kg / $m^3$ / d.

Wuhou reported on the anaerobic digestion of dairy manure from a 2900 cow dairy (Wuhou, Wenying et al. 1997). The digester was a mesophilic up flow mixing reactor operated at a volatile solids loading of 3.7 kg per cubic meter per day. The digester achieved a 78.2 percent volatile solids conversion to gas.

Burke operated a mesophilic AGF contact reactor at an average loading of 2.13 kg per cubic meter per day. The average COD conversion to gas was 66.3 percent. The maximum COD conversion to gas was 69 % at a loading of 2.4 kg per cubic meter per day. The minimum conversion was 59.2 percent during the startup period. The biogas had a methane concentration between 60 and 65 percent.

A summary of the expected performance for each type of anaerobic reactor is presented in the table below.

***Table 4 Expected Percentage VS Conversion to Gas***

| Process | Load | Conversion to Gas |
|---|---|---|
| ***Entire Waste Stream*** | | |
| Completely mixed mesophilic | High | 35 to 45 % |
| Completely mixed thermophilic | High | 45 to 55 % |
| Contact | High | 50 to 65 % |
| | | |
| ***Partial Waste Stream*** | | |
| Plug mesophilic | High | 35 to 45 % |
| Fixed film | High | 55 to 65 % |
| Lagoon | Low | 35 to 45 % |

Table 5 presents a summary of the attributes of the anaerobic processes that can be used to convert all or a fraction of dairy manure to gas.

***Table 5 Summary of Process Attributes***

| Attribute | Complete mix – mesophilic | Complete mix – thermo | Contact – Mesophilic | Plug Flow Mesophilic | Lagoon | Fixed Film |
|---|---|---|---|---|---|---|
| Not Limited by Solids Concentration | X | X | X | | | |
| Not Limited by Foreign Material | X | X | X | | | |
| Digest Entire Dairy Waste Stream | X | X | X | | | |
| Sand & Floating Solids Processing | X | X | X | | | |
| Best at Odor Control | X | | X | | | |
| Concentrate Nutrients in Solids | | | X | | | X |
| Treat Additional Substrate | X | X | X | | | |
| Stability | | | X | X | X | X |
| Simplicity | | | | X | X | |
| Flexibility | | | X | | | |
| Net Energy Production | | X | X | | | X |

## Cost of Anaerobic Processes for Dairy Waste

The cost of a dairy waste management system can be subdivided into the following elements:

- Housing – Determines the percentage of manure actually collected
- Collection – A means of collecting the waste by manual, or automatic scraper, vacuum truck, or flush.
- Pre-processing – Screening and or sedimentation prior to digestion
- ***Anaerobic Digestion – The solids conversion process***
- ***Post-processing – The concentration of solids after digestion***
- ***Energy Production – Engine Generator or Turbine with heat recovery***
- Liquid Handling & Irrigation – The storage and disposal of liquid waste
- Solids Disposal

As pointed out earlier, use of any particular system will have an effect on the other. For example, if a flush system is used the anaerobic digester must be larger. If pre screening and sedimentation are used, the amount of energy produced will be lower. Post processing will establish the cost of ultimate solids disposal. In many cases, solids must be exported from the site. The use of an anaerobic digestion system may eliminate the need for pre-processing or screening and sedimentation.

The cost of a complete dairy waste management system may exceed $1,200 per cow. Anaerobic digestion system costs however, are confined to the cost of the anaerobic process, post solids handling, and energy production.

A review of the anaerobic digestion system costs at U.S. dairies compiled by Lusk has established that the typical anaerobic system constructed in the U.S. had an average cost of $470 per cow. The proposed thermophilic digestion project at Three Mile Farm (21,000 cows) in Oregon projected a cost of $710 per cow. The proposed contact process at Myrtle Point (4,500 cows) Oregon has a proposed cost of $678 per cow for digestion, solids handling, and power generation. The recently constructed Cal Polly flush system anaerobic lagoon had a cost of $800 per cow.

Anaerobic systems for digestion, solids processing, and generation are expected to cost $500 to $800 per cow.

The per-cow capital cost estimates can be deceptive since some processes treat the entire waste stream while others treat only a portion of the waste stream. For example, the plug flow systems documented by Lusk treat only the concentrated portion of the manure while excluding the milk parlor waste (15% of dairy manure). The table below presents the corrected capital costs for the entire waste stream (100% of cow manure).

Table 6 Adjusted Capital Costs

| System | % Treated | Reported Cost $ / Cow | Adjusted Cost $ / Cow |
|---|---|---|---|
| Lusk U.S. Average | 85 | $470 | $552 |
| Three Mile Farm Thermo | 80 | $710 | $887 |
| Myrtle Point Oregon | 80 | $678 | $847 |
| Cal Poly (lagoon) | 100 | $800 | $800 |

Even the adjusted capital cost per cow does not tell the full economic story. Some systems are far more efficient than others in producing power and sequestering nutrients. The best approach is to report the capital costs in terms of dollars per MBtu generated during the first year of operation or dollars per net kW of power sale capacity. There is little data available in those units for US systems. The costs of a wide variety of European systems have been reported in those units. The capital costs of European systems vary from country to country. Germany produces anaerobic digesters for the least cost per gallon while the

Danish systems produce greater amounts of biogas per pound of solids introduced to the digester. German digester systems are constructed for an average cost of $1.52 per gallon. Danish digesters have a capital cost of $50 per GJ or $5.26 per annual biogas therm (100,000 Btu or 1.06 GJ). Power is produced for a capital cost of $10,000 per kW of export capacity. The table below presents the capital and operating cost of European systems for a large facility and a small on farm system.

Table 7 Capital and Operating Costs of European Digestion Systems

| | **Large 1 MW 5000 Cow Facility** | **Small 25 kW 125 Cow Farm** |
|---|---|---|
| Capital Cost | $9,113,000 | $500,000 |
| Annual Operating Cost | $643,000 | $8,800 |
| Power Sale Rate $/kW | $0.06 | $0.06 |
| Heat Sale $/kW | $0.01 | $0.01 |
| Solids Sales | $700,000 | $20,000 |

It must be noted that the capital and operation and maintenance costs are considerably greater in Europe than those reported the US. On the other hand, income derived from the sale of the solids is considerably greater in Europe.

The capital cost of dairy waste systems in Idaho are expected to be from $2,700 / kW to $6,000 / kW exclusive of sales tax, power connection to the site and financing costs (27 to 60% of the European cost).

## Alternative Waste Management Systems

A Dairyman has many choices in designing and operating in modern dairy. Figure 15 presents the basic options for housing cows, the collection of manure, the pretreatment and treatment of manure, the post treatment and final disposal. Each of the options must be judged by the goals of the Dairymen to maintain animal health, recover nutrients, minimize odors, produce energy, and reduce operation and maintenance costs. The following paragraphs summarize the advantages and disadvantages of each alternative. The better alternatives are shaded in the accompanying figure.

### *Existing Manure Handling*

Existing manure handling consists of screening, and gravity separating the solids for subsequent composting. The existing system is shown in Figure 1 and in Figure 15 (red boxes). The compost produced by existing systems can either be exported or used for bedding material. Up to 70 percent of the phosphorus nutrients can be diverted from the farm through the use of the existing solids removal processes. However, the conventional solids handling process does not reduce the quantity of material to be handled. It simply separates the material into a solid fraction that can be stacked and hauled and a liquid fraction that can be placed in a holding pond for the required 180-day detention time with a minimum of sedimentation. The system does not control odors since the liquid fraction containing large quantities of organic acids is discharged to an open lagoon for further decomposition. The system does not produce any energy. Large quantities of energy are consumed in separating the solids and subsequent composting. The operation and maintenance costs are high but the capital costs are low. Overall the commonly used manure handling system does not pay for self nor meet the environmental goals of the Dairymen.

## *Housing*

This type of housing establishes the quantity of manure that can be collected economically. Free stall barns permit the collection of 85 percent of the manure. The remaining 15 percent is normally deposited in the milk parlor where it is collected through a flush system. In corral systems only 40 to 50 percent of the manure can be collected from the feed lanes, which are either scraped or flushed. Manure deposited in the open lot portion of the corral is normally collected once or twice a year. While in the open lot, the manure is degraded both aerobically and anaerobically depending on the moisture content. The degradation process produces odors and greenhouse gases that are discharged to the atmosphere. There is little net energy available from the manure after it has remained in the open lot for 8 to 12 months.

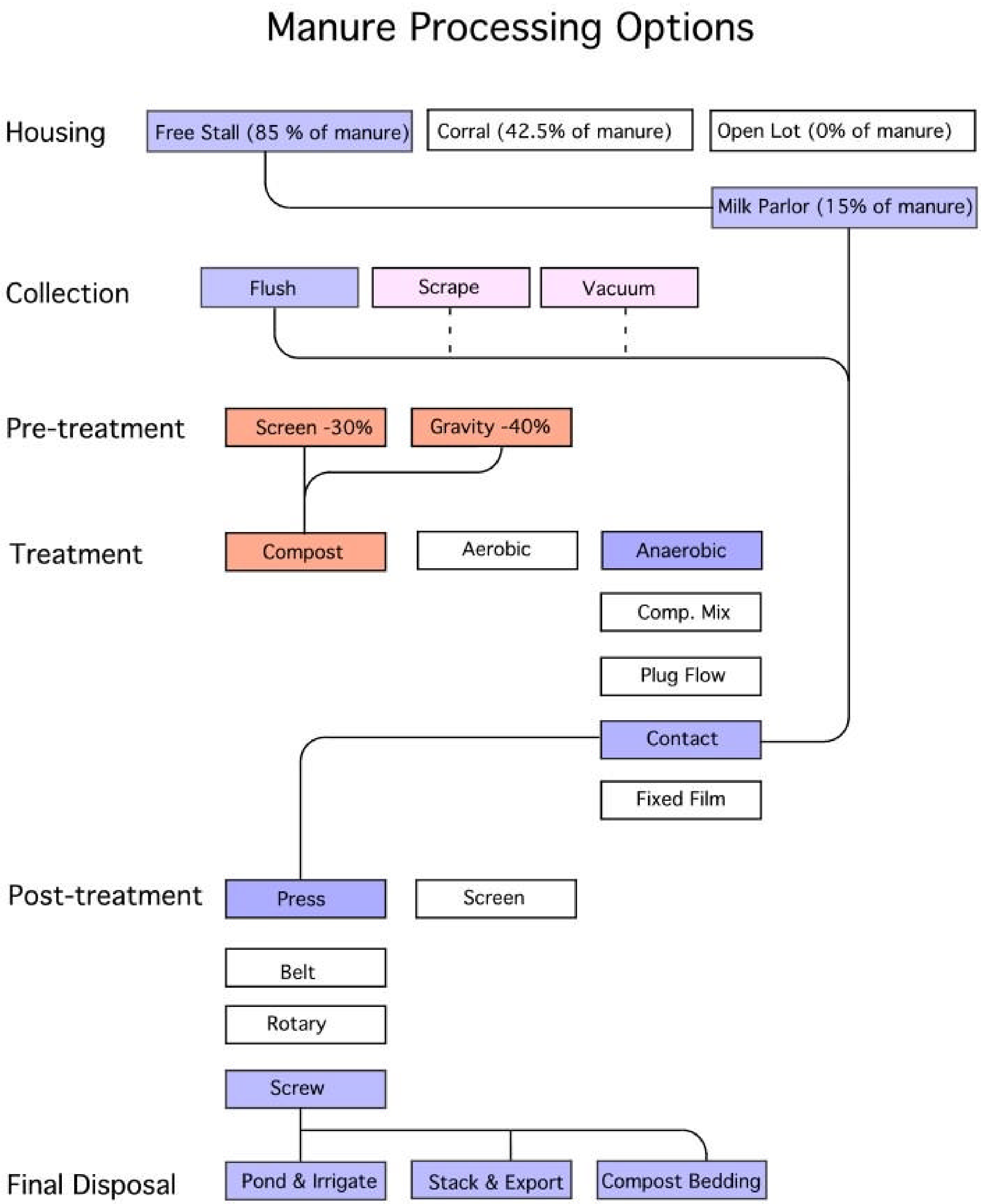
The free stall system is better for animal health since it provides the greatest separation between manure and cow. Since the free stall system provides an opportunity to collect the maximum amount of manure it also provides the opportunity to recover most of the phosphorus nutrients and generate the most energy.

***Free stall barns are more expensive to construct than corral or open lot systems. The operation and maintenance cost of the free stall barn is less than corral or open lot systems. Overall the free stall system provides the best manure processing option.***

## *Collection*

Manure can be collected by flush, scrape, or vacuum collection. Scrape and vacuum collection systems have a higher capital and operation and maintenance costs. Flush systems have the lowest capital and operation and maintenance costs. Flush systems also remove substantially all of the manure. The vacuum and scrape systems do not clean the barns as efficiently as a flush system.

***Figure 15 Manure Processing Alternatives***



Flush systems significantly increase the quantity of waste that must be processed through an energy recovery system. The increased quantity of cold, dilute manure can result in much larger treatment facilities and lower temperatures within the anaerobic digesters. Flush systems have also been associated with severe odor problems. Wet flush aisles promote bacterial activity leading to organic degradation and the generation of odors. The large quantity of untreated wastewater that is discharged to open ponds is an additional source of odorous degradation products. The problems associated with flush systems can be mitigated to a great extent by flushing once a day. By flushing the aisles once a day the volume of flush water will be significantly reduced such that it can be heated and effectively treated with the anaerobic contact process. Flushing once a day will also provide the opportunity for the aisles to dry, eliminating the generation of odors from open-air microbial degradation.

Scrape and vacuum systems provide a concentrated waste flow, which minimizes the size of down-stream treatment facilities. The choice of which collection system to use will be based on economics since all collection systems, if properly operated, provide an opportunity to recover nutrients, enhance animal health, and minimize odors. Scrape and vacuum systems have a higher capital, and operation and maintenance costs. The downstream treatment costs however are lower. Flush systems have a lower capital and operating cost but the downstream treatment costs are higher.

### *Treatment*

A wide variety of pretreatment and treatment options exist. Typically pretreatment consists of screening and gravity separation of the solids. The recovered solids are allowed to drain and may be subsequently composted for animal bedding. Stacked solids are applied to land once or twice a year depending on the phosphorus land application limitations. The stacked solids may also be exported from the site. Many nutrient management plans require 100 percent export of the stacked solids. Unfortunately, pretreatment is not beneficial for energy recovery since a significant portion of the solids that can be converted to gas are removed through the pretreatment activity. Since existing pretreatment processes produce odor, are expensive to operate and maintain, and severely impact potential energy generation it is recommended that pretreatment not be used before anaerobic digestion. Excess sands, silts, and fibers should be removed as part of the anaerobic digestion process.

Aerobic treatment is an effective alternative for reducing odor. Aerobic treatment consumes large quantities of energy and has higher operating and maintenance costs. Aerobic treatment however, has lower capital costs than anaerobic digestion, and it is less effective in recovering nutrients than anaerobic digestion.

Anaerobic digestion is the most beneficial treatment option. The contact process is the most effective anaerobic treatment process. Both the fix film and plug flow processes are concentration limited. The contact process can handle a wide variety of solids concentrations. All of the manure from the milk barn to the free stall can be processed through the contact process. In addition to processing a larger percentage of manure, a greater percentage of the solids will be converted to energy. It provides greater load flexibility, allowing dairymen to process other waste materials for additional gas production.

The contact process requires little operation and maintenance. It can be an automated process. Both the contact process and completely mixed processes can handle sand and floating fibers. The contact process and completely mixed digester use more energy than the plug flow process. However, a greater percentage of the solids will be converted to energy. The plug flow process is less expensive than either the contact process or the completely mixed reactor. The contact process however, uses less energy than the completely mixed reactor and has a much lower capital costs.

All mesophilic anaerobic treatment processes are effective in reducing or eliminating odors. All anaerobic processes can sequester most of the nutrients. Since the contact process produces a relatively clear effluent, additional nutrients can be removed. All anaerobic processes produce energy. The contact process will provide the greatest solids retention time leading to a higher energy yield. The plug flow process has the lowest capital costs followed by the contact process. The plug flow reactor also has the lowest operation and maintenance costs. The contact process will have the highest operation and maintenance costs because of the reagents that are used in the biomass separation process. Overall, the contact process offers a greatest benefit.

### *Post-Treatment*

The final product from the treatment process consisting of undigested solids, biomass, and inorganic precipitates must be separated such that the solids containing a majority of the nutrients can be stored, stacked, and exported if required. The post-treatment process fulfills the same need as conventional pretreatment process. However, after passing through an anaerobic digestion process the solids are substantially reduced and the nutrients are concentrated.

A number of options exist for post-treatment. They include screens and a variety of presses. The screw press requires the least amount of operation and maintenance. Consequently, the recommended post-treatment is to pass the digested solids through a screw press, separate the solids from the liquid, and either export the solids or compost them for bedding. The contact process provides more effective liquid solids separation. If the contact process were used, the liquid from the screw press would be recycled to the contact separator. The clean particle free effluent would be discharged from the contact process separator to the storage pond for irrigation.

## *Final Disposal*

The final products consisting of a liquid stream and a solid stream must be disposed in accordance with the nutrient management plan. The liquid stream will contain inorganic nitrogen as ammonia and a small amount of phosphorus. The solid stream will contain organic nitrogen and a vast majority of the phosphorus. Both the solid and liquid streams will be fully stabilized and odorless. The solids can be stacked for export or composted for bedding.

## *Evaluation*

Table 8 summarizes the attributes of the alternative waste management systems in terms of the dairyman's goals. The most advantageous housing system is the free stall since it is the best system for animal health, nutrient recovery, odor minimization, energy production, and operation and maintenance cost.

The flush system may be the most effective collection system, provided the number of flush cycles can be minimized. The most effective option is to flush once per day. Scrape systems are the most beneficial in terms of net energy production and overall performance. Vacuum systems are also advantageous but consume a considerable amount of energy while collecting the manure.

Treatment can consist of solids composting, aerobic treatment, and anaerobic treatment. Anaerobic treatment is the most effective for nutrient recovery, minimizing odors, and energy production. Aerobic treatment is effective in reducing odors. Composting has the lowest capital cost followed by aerobic treatment. Anaerobic treatment has the lowest operation and maintenance cost.

Table 5 presented an evaluation of the various anaerobic processes. The contact process was the most advantageous for a variety of reasons.

As indicated in Table 8, screw presses provide the most effective post treatment since they are the least costly while producing a highly concentrated stackable residual.

***Table 8 - Evaluation of Alternative Waste Management Systems***

| | Animal Health | Nutrient Recovery | Odor | Energy | Capital Cost | O & M Cost |
|---|---|---|---|---|---|---|
| Housing | | | | | | |
| Free Stall | X | X | X | X | | X |
| Corral | | | | | | |
| Open Lot | | | | | X | |
| Collection | | | | | | |
| Flush | X | X | | | X | X |
| Scrape | X | X | X | X | | |
| Vacuum | X | X | X | | | |
| Treatment | | | | | | |
| Compost | X | | | | X | |
| Aerobic | X | | X | | | |
| Anaerobic | X | X | X | X | | X |
| Comp Mix | | | | | | |
| Plug flow | | | | | X | X |
| Contact | | X | X | X | | |
| Fixed Film | | | | | | |
| Lagoon | | | | | | |
| Post Treatment | | | | | | |
| Screen | | | | X | X | X |
| Press | | X | X | | | |
| Screw | | | | X | X | X |
| Belt | | | | | | |
| Rotary | | | | | | |

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