

Table 56.0 Example Commercial Scale Bioethanol Manufacturing Utilizing Corn Feedstock

Product	Value	
<u>Material Input</u>		
Corn	6,869,600	kg
Fresh Water	1,314,154	kg
Heat Energy	4,376	GJ
<u>Material Output</u>		
Ethanol	1,573,825	kg
Carbon Dioxide	1,775,105	kg
Distillers Dried Grain @ 10% moisture	2,919,580	kg

The relationship between scale of operations is nearly linear with deviations from linearity resultant from equipment efficiencies (or inefficiencies) and proprietary processes which may be used for optimization.

7.0 BIOGAS (Anaerobic Digestion)

Anaerobic digestion involves the decomposition of organic matter in the absence of molecular oxygen. Biomethanization of organic wastes for the manufacture of biogas can be subdivided into four stages: pre-treatment, digestion, biogas upgrading and digestate treatment. Pre-treatment is employed to pre-condition the feedstock for optimum bioconversion in the digestion process. Pre-treatment technologies to enhance the biodegradability of the feedstock can include magnetic separation, particle size reduction, pulping with gravity separation, screening and pasteurization. Additional pre-treatments by way of chemical or thermal hydrolysis processing may also be necessary depending on the feedstock type to further improve the biodegradability and for disease control.

Following pre-treatment, the pre-conditioned feedstock is processed by anaerobic digestion whereby fermentation occurs within an oxygen deprived environment at an approximate temperature of between 25 to 55°C. There exist many types of digesters configured to operate at different temperatures using a variety of different mixing systems. Example types of digesters include single stage, multi-stage and batch. In addition, digestion can be conducted by a variety of methods using plug flow or continuously stirred reactors. Example methods of digestion include dry and wet digestion. Dry digestion is considered to be those systems in which the physical consistency of the waste has a total solids content of between 20 to 50 % by wt. Dilution is only utilized for feed stock material with a percent total solids content in excess of 50%. Wet digestion is considered to be those systems in which the physical consistency of the organic wastes has been substantially diluted with water to produce resultant feed total solids concentrations of 15 % by wt or less, necessary to attain maximum efficiency of the process. Furthermore, the above categories can be further individually divided into three categories of digestion operating temperature. They are psychrophilic, mesophilic and thermophilic. Biogas produced during the digestion stage must be upgraded to

remove impurities that can damage boilers or engines. This includes H₂S and water vapor. Carbon dioxide removal can also be conducted if the gas is to be used as a natural gas or fuel for vehicles. Digestate treatment can include post-digestion, mechanical de-watering and nutrient recovery/water treatment.

7.1 Limiting Factors

Anaerobic digestion takes place under a controlled environment designed to maintain conditions conducive to microbial degradation. Two major general limitations are characteristic of optimal conditions: feedstock composition and inoculum characteristics.

With regards to feedstock composition, the chosen organic material limits the amount of biogas produced (for instance, fats and proteins produce more biogas than oxidized sugars characteristic of cellulose based feedstocks). But overall biodegradability of the organic components is the main determinant of methane yields. Particular organic materials resist anaerobic digestion, even under long residence times; one example of such material is lignin in cellulose based material. Lignin goes further than resisting anaerobic digestion, to bond with other molecules creating a larger complex organic material resistant to anaerobic digestion. This difficulty is a major challenge for feedstock viability.

Limitations related to inoculum characteristics refer to the absence of organisms capable of degrading the organic component(s). This may be overcome in many instances through 'seeding' the material with appropriate organisms which can utilize the feedstock.

7.2 Process Conditions

Examples of the environmental conditions conducive to anaerobic degradation by microbes which produce methane within an anaerobic digester is listed as follows:

1. Anaerobic environment – The absence of molecular oxygen is an essential parameter for biological activity and the manufacture of biogas.
2. Water content – Water content within the digester will be a function of the method of digestion employed. In wet digestion the water content is 85 % or greater. The dry digestion the water content can range from the 50 % to 80 %.
3. Temperature – Temperature influences not only metabolic activities but it also has a profound effect on factors such as gas transfer rates and the settling of biological solids. In anaerobic digestion temperature is important in determining the rates of hydrolysis and methane formation. It also establishes the minimum solids retention time required to achieve a given amount of volatile suspended solids destruction. Currently biological activity in a digester takes place at three different temperature conditions:

- a. Psychrophilic: < 30°C
 - b. Mesophilic: 30 to 40°C
 - c. Thermophilic: 40 to 55°C This strain has the highest biological activity.
4. Retention Time – Anaerobic digesters are sized based on providing sufficient residence time in a well mixed reactor to allow significant destruction of the volatile suspended solids. The sizing criteria can be based on (1) solids retention time, the average time the solids are held within the digester or (2) the hydraulic retention time, the average time the liquid is held within the digester. The hydraulic retention time equals the solids retention time for systems without recycle. The required retention time is dependent upon temperature:
- a. Psychrophilic: 40 to 100 days
 - b. Mesophilic: 25 to 40 days
 - c. Thermophilic: 10 to 25 days
5. Alkalinity and pH – The digestion process produces ammonium bicarbonate from the breakdown of protein. This acts to buffer the water to resist changes in pH from the production of carbon dioxide during fermentation and methanogenesis. Carbon dioxide is the greatest consumer of alkalinity in a digester. The concentration of alkalinity in a digester is in part proportional to the solids feed concentration. The optimal pH for both the acidogenesis and methanogenesis stages is between 6.4 to 7.5, a significant process criteria when working with food wastes and various materials on which organic acids reside.
6. Loading – Bacteria require a maximum and minimum loading for optimal production. Organic loading should fall within the parameters of 0.5 kg and 5 kg per m³ of digester tank per day, with loading between 1 kg and 3 kg per m³ being ideal.
7. Auxiliary substances – Nitrogen compounds, minerals and trace elements are required for microbial metabolism. For example, the typical nutrient requirements for nitrogen, phosphorus and sulfur are in the range from 10 to 13, 2 to 2.6, and 1 to 2 mg per 100 mg of biomass, respectively.
8. Toxic substances – Disinfectants, antibiotics and organic acids can impede or even halt biological activity. Pre-treatment steps may be used to remove toxic constituents.
9. Particle size – Reduction of particle size is necessary to increase surface area and allow ease of digestion for microorganisms.
10. Mixing – Mixing within the digester improves contact between the microorganisms and substrate. It also prevents the formation of scum and the development of temperature gradients within the digester. Excessive mixing however, should be avoided so as not to disrupt the microorganisms.

11. Consistent operation – Rapid changes in operation should be avoided. Gradual addition of feedstock and change of feedstock allows the bacteria to adapt to a new environment.
12. Carbon to Nitrogen Ratio (C:N) – Both nitrogen and carbon are necessary elements for bacteria metabolism. The optimal C:N ratios for anaerobic digestion are between 20:1 and 40:1.

7.3 Biogas Cleaning Systems

Biogas upgrading and purification may be required to remove:

- Water to reduce condensation of acid gases during startup and shutdown,
- Particulates
- Sulfur compounds for reduction of corrosion
- Ammonia to avoid problems of toxicity

Further processing may be necessary to improve the consistency of the gas product. The following discussion is obtained from Schomaker et al. 2000.

Condensation

Condensed water can be separated using the idea that water droplets are able to be entrapped. Techniques for water removal include:

- Demisters – separation using a wired mesh of micropores
- Cyclone separators – centrifugal forces force separation through rotational forces
- Moisture traps – biogas expansion forces water condensation
- Water taps – locations for emptying water from gaspipes

Drying

Biogas can also be dried to reduce water content. Techniques for water reduction include:

- Cooling and channeling through a demister
- Silica adsorptive dryer – gas flows through a column containing silica reducing the dew point to as low as -10 to -20°C.
 - Regeneration of the material is accomplished through heating the material to recover the absorbed water for disposal
- Glycol – glycol is used to lower water dewpoint and glycol is regenerated under temperatures of approximately 200°C.

Due to the presence of H₂S, removal is necessary for use in cogeneration units and for release of combusted gas to the environment. The amount of H₂S can vary significantly. Removal of H₂S includes:

- Air/oxygen dosing - Biological means of reduction using approximately 5% more oxygen, whereby biological aerobic oxidation is used to change gaseous sulfur to elemental sulfur: $2 \text{H}_2\text{S} + \text{O}_2 \rightarrow 2 \text{S} + 2 \text{H}_2\text{O}$. Removal efficiency is between 80 and 99%.
- Iron Chloride – This compound is added to the digester and forms insoluble iron sulphide salts as precipitate: $2 \text{Fe}^{3+} + 3 \text{S}^{2-} \rightarrow 2 \text{FeS} + \text{S}$.
 - This prevents H_2S formation through removal of S in the digesting material. Reductions of 100 ppm are attainable using this method.
- Iron oxide – Gas is diverted through a container holding iron oxide pellets which reacts with the H_2S as follows: $\text{Fe}_2\text{O}_3 + 3 \text{H}_2\text{S} \rightarrow \text{Fe}_2\text{S}_3 + 3 \text{H}_2\text{O}$
 - Regeneration of the iron oxide pellets is accomplished using oxygen as follows: $2 \text{Fe}_2\text{O}_3 + 3 \text{O}_2 \rightarrow 2 \text{Fe}_2\text{O}_3 + 6 \text{S}$
- Liquid Absorption:
 - Sodium hydroxide (NaOH) – reaction with H_2S forms Na_2S or NaHS .
 - Iron salts – formation of an insoluble precipitate occurs and is removed
 - Closed system – Gluud-process whereby H_2S removal occurs through formation of Fe_2S_3 . Regeneration occurs using oxygen-air. Iron(III) chloride solution could also be used to produce elemental sulphur.
- Other:
 - Membrane separation – membrane filtration allowing CH_4 and CO_2 to pass through and disallowing H_2S .
 - Biological treatment – H_2S is first absorbed to a liquid phase and then oxidized by bacteria
 - Activated carbon process – catalytic conversion of H_2S to either elemental sulphur or sulphuric acid, or a combination.³
 - Molecular sieves – Synthetically produced zeolites which are a crystalline form of alkali metal (calcium, sodium, potassium) aluminosilicates similar to natural clays. These materials are highly porous with a very narrow range of pore sizes and high surface area per package volume. These materials can simultaneously dehydrate and desulphurize sour gas, (Emerson).

In the following table, a general comparison of the above technologies is presented showing appropriate H_2S removal technologies under a variety of process conditions. See Table 57.0.

³ Activated carbons have a limited capacity for H_2S and are only able to hold approximately 6 – 8 lbs of H_2S per 100 lbs of carbon. Carbon impregnated with caustic can significantly increase the holding capacity improving cost effectiveness.

Table 57.0 H₂S Removal Techniques for Biogas

Removal Technique	1	2	3	4	5	6	7
Air Dosing	+	+	+	+	+	+	++
FeCl ₃ dosing	+	+	+	+	+	+	+
Fe ₂ O ₃	+	+	+	±	+	±	±
Chemical absorption using caustic	±	+	±	±	+	±	±
Chemical absorption using iron solution	±	+	±	±	+	±	±
Chemical absorption based on closed loop system	±	+	±	±	+	±	±
Membrane separation	-	-	-	-	+	+	-
Biological treatment	-	±	±	±	+	+	±
Activated carbon	-	±	±	±	+	±	±
Molecular sieve	-	±	±	±	+	±	±

Notes:

- | | |
|---|---|
| 1. Application on a small scale (+ = yes) | 5. H ₂ S treated gas < 250 ppm (+ = yes) |
| 2. Application on a large scale (+ = yes) | 6. Environmental impact (+ = low) |
| 3. Simplicity (+ = simple) | 7. Costs (+ = low) |
| 4. Operation and maintenance (+ = little) | |

Schomaker, Boerboom, Visser, and Pfeifer, 2000

Dust Removal

Dust removal may or may not be necessary, depending on feedstock used. Dust filters would be placed behind condensation traps.

7.4 Co-Generation

Co-generation involves the production of both power and heat. Conventional power generation is approximately 35% efficient whereby 65% of the energy generation is lost as waste heat. Recovery and utilization of this waste heat can improve energy efficiency to nearly 55%, not including energy losses due to transmission and distribution

Advantages of cogeneration include:

- Improved energy efficiency through utilization of waste heat
- Lower GHG emissions due to more efficient usage of energy produced
- Provision of local energy supply whereby transmission losses are avoided due to the close proximity of energy generation
- Promotes further competition of supply within the electricity market place.

A cogeneration plant consists of four elements:

- Engine
- Electricity generator
- Heat recovery system
- Control system

Reliability

Cogeneration is a well established technology having come into commercialization since the beginning of the 20th century with thousands of sites in Europe. Approximately 10% of the EU energy needs are met through cogeneration.

Table 58.0 Typical Cogeneration Systems

Prime Mover	Fuel Used	Size Range (MWe)	Heat: Power Ratio	Electrical Generating Efficiency	Typical Overall Efficiency	Heat Quality
Pass out steam turbine	Any fuel	1 to 100+	3:1 to 8:1+	10 – 20%	Up to 80%	Steam at 2 press or more
Back pressure steam turbine	Any fuel	0.5 to 500	3:1 to 10:1+	7 – 20%	Up to 80%	Steam at 2 press or more
Combined cycle gas turbine	Gas Biogas Gasoil LFO LPG Naphtha	3 to 300+	1:1 to 3:1	35% - 55%	73 – 90%	Medium grade steam high temperature hot water
Open cycle gas turbine	Gas Biogas Gasoil HFO LFO LPG Naphtha	0.25 to 50+	1.5:1 to 5:1	25 – 42%	65 – 87%	High grade steam high temperature hot water
Compress. Ignition Engine	Gas Biogas Gasoil HFO LHO Naphtha	0.2 to 20	0.5:1 to 3:1	35 – 45%	65 – 90%	Low pressure steam low and medium temperature hot water
Spark ignition engine	Gas Biogas LHO Naphtha	0.003 to 6	1:1 to 3:1	25 – 43%	70 – 92%	Low and medium temperature hot water

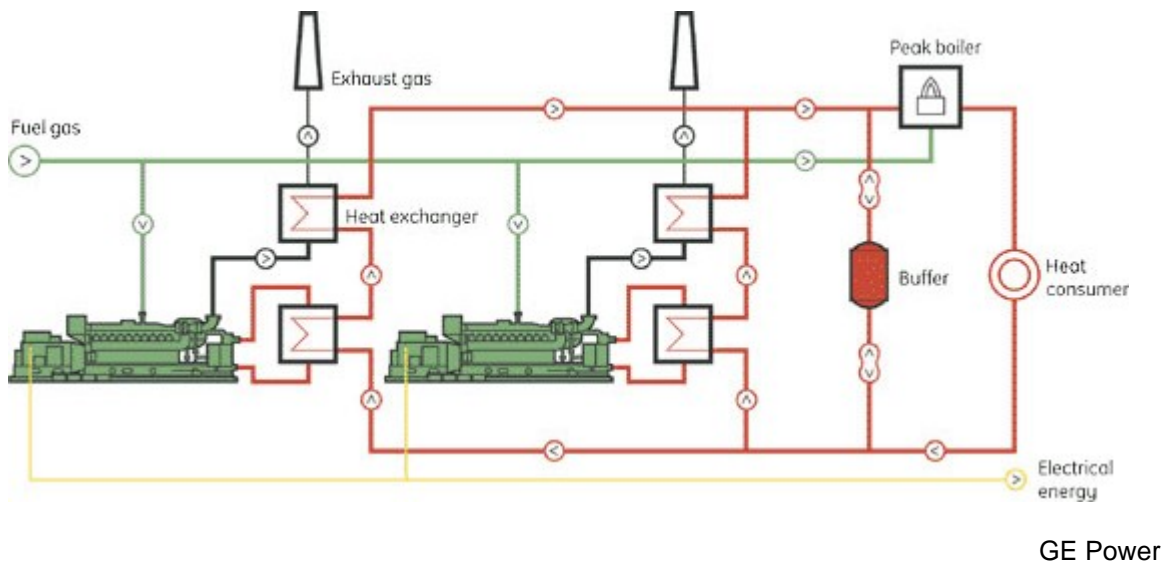
European Association, 2001

In the generation system planned, a gas turbine will produce both electricity and hot water. According to European literature, this type of system is easier to install than other technologies, such as a high-pressure boiler plant and steam turbine (EDUCOGEN, 2001). The associated capital cost is lower and has improved reliability, in comparison with boiler systems.

In a gas turbine, fuel gas is pressurized and ignited within a combustion chamber. High temperature gases (900°C to 1200°C) turn a series of fan blades to produce mechanical energy. As the turbine is in direct contact with the hot flue gases from combustion of biogas, the biogas must be free of corrosive gases such as H₂S for shutdown and startup considerations.

Subsequent to the generation of power is the generation of hot exhaust gases. These combustion gases are directed through a heat exchanger whereby water is heated and further energy recovered. Hot water created through this method provides approximate 36.2 m³/hr per cogeneration unit at 90°C. The process flow of hot water provision is outlined in Figure 4.0 below.

Figure 4.0 Combined Heat Power (CHP) Plant



7.5 Digester Heating

Anaerobic digesters are typically operated in the temperature range of 35°C to 55°C. The heat requirements of a digester consist of the thermal energy required to raise the incoming sludge to the digestion tank temperature and to compensate for heat losses through the walls, floor and roof of the digester. The sludge in the digester is either pre-heated via a double pipe heat exchanger upon input using hot water (90°C) derived from the co-generation units or is heated by pumping the sludge and supernatant through external heat exchangers and back into the tank.

7.5.1 Thermal Pre-Treatment of the Feedstock

Primary sludge	This feedstock does not require thermal hydrolysis pre-treatment and is transferred from a mixing tank, directly into the anaerobic digester. Heat is recovered from the exhaust of the cogeneration units by heating circulating water. This warm water is transferred to a heat exchanger whereby heat is transferred to the primary sludge to produce a slurry of approximate temperature 55°C.
Animal byproducts (prior to thermal hydrolysis)	Animal by-products stored in a mixing tank after tanker unloading is transferred to the thermal hydrolysis units following pre-heating. Hot water preheats the feedstock using heat exchanged from exhaust from the hot oil heater.

7.6 Biogas Feedstocks

Anaerobic digestion relies on biological degradation of organic material by a grouping of microbes. As such, efficient biogas production, i.e. high volume and high methane content biogas, results from feedstock that is most appropriate for consumption. Feedstocks most appropriate for degradation have a high volatile solids (VS) content and are presented in a favorable manner. The following discussion details feedstocks and most appropriate for digestion in Alberta.

Feedstocks high in Volatile Solids (VS) will in general, have an associated high biodegradability and produce a greater amount of methane. Feedstocks with C:N ratio outside of optimum conditions (i.e. not within 15 – 25) will require additional feedstock from another category for balance. Feedstocks having a risk of containing toxic substances which halt or slow the digestion process, or contaminate effluent will be eliminated from the selection. In addition to process information, associated feedstock risks/challenges are presented with emphasis on health and safety, and environmental impact.

The following matrix will serve as a summary of individual feedstock suitability. See Table 59.0.

Table 59.0 Feedstock Suitability

Characterization
TS (%)
VS (% of TS)
C:N Ratio
Biodegradability (general)

7.6.1 Animal By-products

Animal by-products are waste materials generated through slaughter or packing processes. These processes generate both edible and inedible meat, whereby the inedible fraction is generally referred to as animal by-products.

By-product recovery volume varies between animals. The amount of by-product generated from pigs and poultry is generally estimated to be 30% of live weight, whereas with beef and dairy cattle, the utilization rate is lower and by-product production is estimated to be approximately 46% of live weight.

Table 60.0 Products and By-products from the Slaughter of a 1150 lb Steer

	Weight (lb)	Percentage of LCW
Live Carcass Weight (LCW)	1150.0	100%
Boned meat	460.0	40%
Inedible material for rendering (bones, fat, head, condemned offal, etc.)	448.5	39%
Hide	80.5	7%
Edible offal (tongue, liver, heart, kidneys, plucks, etc.)	57.5	5%
Blood	34.5	3%
Miscellaneous (paunch manure, shrinkage, blood loss, etc.)	69.0	6%

Adapted from, United Nations Environment Program, 2001.

Table 61.0 Products and by-products from the slaughter of a 268 lb pig

	Weight (lb)	Percentage of LCW
Live Carcass Weight (LCW)	268.0	100%
Boned meat	171.5	64%
Inedible material for rendering (bones, fat, head, hair, condemned offal, etc.)	53.6	20%
Edible material (tongue, liver, heart, kidneys, trotters)	26.8	10%
Blood	8.0	3%
Miscellaneous (stomach contents, shrinkage, blood loss etc.)	8.0	3%

Adapted from, United Nations Environment Program, 2001.
 Agriculture and Agri-Food Canada, 2005

Animal slaughtering produces varying amount of by-products depending on animal. Poultry slaughtering produces approximately 19.3% by broiler live weight of by-products: waste blood, heads, feet and intestines/organs. A moisture level of 63% was used to determine the total dry matter (Dupps,2004)

Table 62.0 By-product production from poultry slaughter

	Weight (kg)	By-product Production (%LCW)
Live Carcass Weight		100%
	1.4 kg	30%
Chicken, broilers	1.4 – 2.7 kg	32%
	2.7 + kg	23%

Adapted from Annual Poultry Market Review – 2000.
Agriculture and Agri-Food Canada.

Table 63.0 Poultry by-products as percentage of live weight

	Weight (lb)	Percentage of LCW
Live Carcass Weight (broiler)	4.6 (avg)	100.0%
Total Offal	0.73	15.8%
Blood	0.16	3.5%
Feathers	0.28	6.0%
Moisture	0.41	9.0%
Total	1.58	34.3%

(Boushy and Powel, 1994)

Composition

By-product as featured in beef, swine and poultry by-products, have large VS concentrations. Efficient methane production results from anaerobic digestion of these feedstocks.

Table 64.0 Volatile Solids as a percentage of live weight

	By-product % live weight	TS %by-product	VS %TS
Beef	46%	64%	85%
Swine	30%	64%	85%
Poultry* (meat)	28.3%	63%	85%
Poultry* (Feathers ⁴)	6%	93%	96.7%

* Poultry by-products were separated into meat and feathers due to the large differences in VS production. Differences between by-product classifications of Beef and Swine are not as significant.

Bertsch, and Coello, 2005

⁴ Feathers are almost a pure keratin protein and feature high solids percentage.

Biological Risks

In handling animal by-products, many avenues exist for entry of bacteria and pathogens. Salmonella organisms can infect both animals and humans, and because there are many different types, one basic practice to mitigate this risk will not capture all possible areas of associated risk, “Of the more than 2,300 recognized stereotypes (salmonella), only 100 are routinely isolated from food, animals, and humans, and only 23 to 25 are deleterious to man and animals.”(pp. 22) In a study conducted by the Fats and Proteins Research Foundation, pathogens were found in a number of raw tissue samples of material to be rendered. See Table 65.0.

Table 65.0 Percentage of Samples Containing Pathogens

Bacteria	Raw Tissue
Clostridium perfringens	71.4%
Listeria species	76.2%
L. Monocytogenes	8.3%
Campylobacter species	29.8%
C. Jejuni	20.0%
Salmonella species	84.5%

Adapted from Trout, Schaeffer and Pearl, 2001

7.6.2 Municipal Sludge

Municipal sludge is a natural waste product of microbial degradation in wastewater treatment. Microbes consume a large portion of VS matter leaving mainly stable cellular material, which is generally considered safe for land application. Due to the already degraded nature of the material, this material provides a limited amount of VS matter for further biological degradation in anaerobic digestion systems. However, municipal sludge has other potential benefits due to provision of balancing nutrients for utilization along with other feedstock, to provide an optimum configuration for biogas production.

Composition

The composition of municipal sludge is defined as a percentage of primary sludge (PS) and of waste activated sludge (WAS). The biological WAS, which is aerated and subjected to bacterial action, is separated and thickened from PS. See Table 66.0 for general composition.

Table 66.0 Composition of untreated wastewater sludge

Parameter	Primary Sludge	Waste Activated Sludge	Mixed Sludge
Total Solids (TS) %	2-8	0.6-1.2	
Volatile Solids (% of TS)	60-80	60-88	
Protein (% of TS)	20-30	32-41	
Fats and Grease (% of TS)	6-30		
Nitrogen (% of TS)	1.5-4.0	2.5-5.0	
Phosphorous (% of TS)	0.8-2.8	1.5-11.0	
Potash (% of TS)	0-1.0	0.5-0.7	
Alkalinity (mg/L as CaCO ₃)	500-1500	580-1100	
Organic Acids (mg/L as acetic acid)	2,000-10,000		
Fecal Coliforms (no./g TS)			10 ⁶ -10 ⁷
<i>Salmonella</i> sp (no./g TS)			5 x 10 ²
Heavy Metals (median, mg/kg TS)			
Cd			24.86
Pb			170
Hg			2.33
Ni			70.6
Mo			24.93

Note: 1) TS refers to Total Solids
2) VS refers to Volatile Solids
3) CN ratio refers to carbon to nitrogen ratio

Metcalf and Eddy, 1991 and Bastian, 1997

In most cases, the methanogenesis stage is the rate-limiting step, but when feedstock that is rich in organic solids (such as municipal sludge) is used, hydrolysis becomes the rate-limiting step. Pre-treatment of these feedstocks at 70°C results in higher organic matter removal efficiency and enhances their digestibility through increased solubility. Destruction of pathogens is another key advantage to this hyper-thermophilic step (I.V. et al. 2005).

Other studies have focused on the optimization of pretreatment conditions. Pretreatment of sludge at 170°C with a pH of 10 results in 71% COD (chemical oxygen demand) degradation, 59% TS degradation and a 54% improvement in biogas production. However, addition of potassium hydroxide (KOH) has no appreciable affect on VS solubilization (Valo et al., 2004). Valo et al. determined that thermal hydrolysis alone is more advantageous as a pre-treatment than pre-treatment at lower temperatures with high pH. They argue that the added chemicals to increase the pH are an additional cost and as they are not biodegradable, they limit the positive effect of pre-treatment on sludge reduction. Damage to sludge composition and bacteria may also result from chemical additions (Onyeche, 2004).

The most efficient disintegration process may be through mechanical means, when exhaust gas treatment and energy requirements of thermal hydrolysis are taken into account. Testing of a high-pressure homogenizer revealed improved anaerobic digestion demonstrated by increased biogas production, and reduced sludge production. The reduced volume of sludge requires a smaller digester capacity, which lowers the investment and operational costs. Onyeche calculated a payback period for the homogenizer of less than two years based on these factors (Valo et al., 2004).

7.6.3 Food Residuals

Food residuals are organic matter remaining from food consumption and preparation. Food residuals are generated at every step in the processing and distribution chain from growing area to final product. Some examples of food residuals generation include:

- Low grade produce
- Food processing waste
- Supermarket discards

Quantities of this feedstock can vary considerably between season and consumption patterns.

Composition

Food residuals are the organic wastes that result from preparing and selling food. About 74% of the waste produced by food service establishments is organic and between 75 and 90% of the waste produced by food retailers is organic (JTR Recycling Market Development Roundtable, 2001). The waste from both sources is heterogeneous, and is *usually* not segregated from non-organic waste.

However, one type of organic waste that is segregated by food service establishments is grease. High in energy and source separated, waste grease is a potential feedstock for a bioenergy facility. The two types of waste grease, yellow and brown are managed in very different ways. Additional waste streams of food residuals include food processing wastewater effluents. Wastewater derived from a variety of food processing can be a viable feedstock for anaerobic digestion. Some examples include meat-packing plants, vegetable canneries, breweries, soft drinks, and potato processing.

Yellow grease is derived from deep fat fryers used in food service establishments. There are different grades of yellow grease – the Number 2 grade must have less than 10% free fatty acid (FFA) content. Number 3 can have up to 20% FFA content (Boyd, et al, 2004).

Brown grease is available from restaurant grease traps and often makes its way to waste water treatment plants. Ware washing at restaurants releases the grease into the ware sink and is either washed down the drain or is captured by a grease trap. Grease traps prevent the brown grease from entering the sewer system where it can create blockages.

The FFA content for brown grease is higher than that of yellow grease at greater than 20% and may be as high as 50-100% (Tyson, 2002). Because of this, brown grease is highly odorous. Due to its source, it is also moisture contaminated.

Food processing wastewater is often a good candidate for anaerobic treatment because of the high BOD₅ or COD (chemical oxygen demand) concentrations, which signify high organic content, and low concentrations of inhibitory compounds. Inhibitory compounds that can be found in food processing wastewater include reduced sulphur compounds, cleaning agents, biocides, volatile organic acids, heavy metals, organic chelating agents and oxidants. Removal, dilution or conversion of these compounds must take place prior to digestion, but in low concentrations, microbial acclimation is an option. There is a significant amount of variation in the composition of food processing wastewater in terms of alkalinity and trace nutrients such as iron, nickel, cobalt, molybdenum and selenium.

Pre-processing is required to convert oil and grease with a FFA content of greater than 1.5% to other energy products such as biodiesel. Without a hydrolysis stage, which breaks triglyceride chains, separation of the FFA from glycerine may be blocked, and instead will form soaps (Boyd, et al, 2004).

The amount of volatile solids (VS) as a percentage of total solids (TS) provides an index of methane production in anaerobic digestion. The estimated VS content of yellow grease is 90% of TS and the VS content of brown grease is 90% TS (Frear, et al, 2005). Vegetable oils can have a low TS content of 10% but a very great amount of VS at 98% (Chen, et al, 2003). Food waste varies in composition but as a general guideline, has 80 - 90% TS, 90 – 94% VS (Chen, et al, 2003).

7.6.4 Manure

The composition of manure varies with the type of livestock and to some extent, the practices used on a specific farm, such as water usage, which alters the dry matter fraction. The type of feed used affects the biogas yield.

Composition

Reduction of total solids (TS) to 6-7% from the excreted 12% TS is an important factor in the anaerobic digestion of waste. The ratio of total solids needed is based on the type of digester employed, as described in the criteria.

Table 67.0 Total Solids in Cow, Pig and Chicken Manure (Planning and Installing Biomass Energy)

Feedstock	Total Solids (%)
Cattle Manure	7-15
Pig Manure	3-13

Dilution will also maintain levels of hydrogen sulphide below inhibitory levels. However, dilution causes stratification to occur, with solids such as straw forming a mat on the surface unless intense mixing is incorporated into the process.

The C:N ratio for cattle, pig and poultry manure are presented below. See Table 68.0. The ideal C:N ratio for anaerobic digestion is between 15:1 and 25:1. Co-substrates with a higher carbon content (such as straw) are required in order to increase the C:N ratio to within the appropriate range.

Table 68.0 C:N Ratio for Select Manure Types

Animal	C/N Ratio
Cattle	19
Pig	5-10
Poultry	7

Behmel, (n.d.)

VS levels in manure vary depending on the livestock species, as shown in Table 69.0.

Table 69.0 Manure Volatile Solids Content

Feedstock	Volatile Solids (% of TS)	Average VS Value (% of TS)
Cattle Manure	65-85	Dairy – 83
		Beef – 85
Pig Manure	65-85	78
Poultry Manure	70-80	76

Planning and Installing Biomass Energy and Frear, et al, 2005

The majority of the volatile solids in dairy cattle waste are composed of cellulose and hemicelluloses. Both of these carbohydrates are readily converted to methane gas by anaerobic bacteria. Lignin is not readily degradable in anaerobic digestion. Because 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 (Burke, 2001).

Table 70.0 Dairy Manure Composition

Component	% of Dry 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

Stafford and Hawkes, et al., 1980

Biological Risks

The thermophilic temperature range is the most optimal for pathogen removal. *Salmonella* and *Mycobacterium paratuberculosis* are inactivated within 24 hours at thermophilic temperatures (El-Mashad et al. (2004). Table 71.0 shows a comparison of the decimation times, or 90% removal of various pathogens (T. Al Saedi et al., 2001).

Table 71.0 Pathogen Removal

Bacteria	Digested Slurry 53°C (hours)	Digested Slurry 35°C (days)	Untreated Slurry 18-21°C (weeks)	Untreated Slurry 6-15°C (weeks)
Salmonella typhimurium	0.7	2.4	2.0	5.9
Salmonella dublin	0.6	2.1	-	-
Escherichia coli	0.4	1.8	2.0	8.8
Staphylococcus aureus	0.5	0.9	0.9	7.1
Mycobacterium paratuberculosis	0.7	6.0	-	-
Coliform bacteria	-	3.1	2.1	9.3
Group of D-Streptococci	-	7.1	5.7	21.4
Streptococcus faecalis	1.0	2.0	-	-

Pretreatment by pasteurization is an added measure that will ensure reduction of pathogens to a satisfactory level. This sanitation process, which involves heating the slurry to 70°C for one hour usually takes place in a small separate tank. Both pre-sanitation and post-sanitation are effective (Planning and Installing Biomass Energy).

By varying the retention time of the hydraulic retention time (HRT) and the solids retention time (SRT), greater nutrient retention is achieved. Using an anaerobic sequencing batch reactor (ASBR), both N and P levels remain approximately the same in the effluent as in the influent. Increased removal of Volatile Fatty Acids (VFA) is also achieved, increasing the stability of the effluent. Effluent value is also increased by the elimination of large clogging particles and the reduction of odor potential (Ndegwa et al. 2005).

Fertilizer produced by the mixing and digestion of cattle and hog manure contains both phosphorous, which is deficient in cattle manure, and potassium, which is deficient in hog manure. Therefore, the mixed slurry is of greater value because it contains a more complete set of nutrients for plant growth and a higher proportion of the nutrients can be absorbed. See Table 72.0.

Table 72.0 Cattle and Pig Slurry and 50/50 Cattle/Pig Digested Slurry

	Dry Matter %	Total N kg/tonne	NH ₄ -N kg/tonne	P Kg/tonne	K kg/tonne	pH factor
Cattle Slurry	6.0	5.0	2.8	0.8	3.5	6.5
Pig Slurry	4.0	5.0	3.8	1.0	2.0	7.0
Digested Slurry	2.8	5.0	4.0	0.9	2.8	7.5

Birkmose, 2000

Digested manure is much safer to use for field application because it is free of pathogens and weed seeds. New technology had been developed in Denmark to enhance spreading of the effluent. Savings for farmers therefore result from the higher quality fertilizer and lower cost, in addition to the reduced storage requirements, as storage is maintained at the biogas facility (Danish Institute of Agricultural and Fisheries Economics, 1999).

7.6.5 Commercial Crops and Residues

Straw Residue

Straw has a characterization which is not readily conducive to anaerobic digestion mainly because of the high lignin content. Estimations on straw characterization based on organic composition analysis done by Van Soest using the detergent fiber method, show significant quantities of lignin. See Table 73.0

Table 73.0 Composition Analysis of Straw

Sample	Volatiles Solids % TS	Neutral Detergent Solubles % VS	Crude Protein % VS	Total Cell Wall % VS	Cellulose % Cell Wall	Hemicellulose % Cell Wall	Lignin % Cell Wall
Wheat Straw	92.0	21.3	8.3	78.7	41.8	22.2	14.7

Adapted from Van Soest, 1963

The volume of straw available for baling varies with crop type and variety, but can be estimated as 1.66 lbs of residue per lb of grain harvested. This amount varies greatly depending on growing conditions, fertility, variety and grain class. The amount of straw that can be removed by baling is between 0.6 to 0.8 lb for every lb of grain.

Commercial Crops

Alberta lies in a very productive agricultural region and produces large amounts of cereal grains for export world wide. As such, residue from commercial crop production and low value crops are ample volume organic sources for feedstock consideration.

The suitability of cereal grains for anaerobic digestion usage is the subject of many studies. Suitability depends partly on the stage of plant growth at which harvesting occurs and suitable pretreatment for anaerobic digestion. The possibility may exist for co-fermentation along with a primary feedstock. Physical characteristics of cereal grains, as determined by plant growth, are related to potential biogas production.

Biological characteristics, total solids content (TS) and volatile solids content (VS) determine biogas yield and is approximated in Table 74.0. In addition, Chynoweth and Isacson detail VS reduction for wheat straw (similar composition to barley straw) at 55% (Chynoweth and Isaacson, 1987). The CN ratios for wheat and barley are 156 and 88 respectively (Sinigani and Safari, et al, 2005).

Table 74.0 TS, VS Content of Barley, Rye and Triticale Feedstocks⁵

Co-ferment			TS [% FM]	VS [%TS]	pH	VFA [g kg ⁻¹ FM]
Barley	Anthesis	FM	18.8	90.2	6.6	0.2
		S	38.2	90.2	4.7	5.4
	Milk	FM	27.4	93.2	6.6	0.2
		S	25.3	93.4	4.33	4.7
	Dough	FM	46.5	94.7	7.2	0.3
		S	-	-	-	-
Rye	Anthesis	FM	25.0	92.2	370	370
		S	45.9	91.4	476	476
	Milk	FM	29.3	-	410	410
		S	32.9	64	492	492
	Dough	FM	61.0	61	283	283
		S	-	-	-	-
Triticale	Anthesis	FM	804	69	534	534
		S	866	65	555	555
	Milk	FM	751	63	461	461
		S	794	66	509	509
	Dough	FM	599	59	337	337
		S	-	-	-	-

Note: 1) TS refers to Total Solids
 2) VS refers to Volatile Solids

Adapted from Heiermann et al. 2002.

7.6.6 Dairy Processing Waste

Cheese whey is a liquid by-product of cheese manufacturing. Whey is the liquid portion of milk which can be obtained from acid or heat processes instituting coagulation. It is generally greenish-yellow in color and has a total solids content ranging between 6.0 - 6.5%, and a biological oxygen demand of at least 30,000. Approximately 9 lbs of whey is removed in the production of 1 lb of cheese. This high strength waste water contains mainly cheese whey, sugars, proteins, fats and other by-products. Many large operations have wastewater recovery whereby wastewater is recovered however, for smaller operations this is not economically viable. As such, high strength waste water is produced containing primarily cheese whey.

Due to more stringent regulations, disposal has become more problematic. One alternative seen by many cheese manufacturers is anaerobic digestion.

Cheese wastewater varies amongst manufacturers due to differing operations and final product. Because of such variance in COD (chemical oxygen demand) and solids concentrations, the waste can be challenging to treat.

⁵ Anthesis, Milk and Dough refer to stages of growth in grains.

Table 75.0 Characteristics of raw cheese wastewater

Constituent	Concentration (mg/l)	Average (mg/l)
TCOD	18,000 – 76,000	39,000
SCOD	10,000 – 34,000	22,000
FOG	580 – 13,000	3,000
TSS	5,100 – 25,000	11,000
VSS	5,000 – 24,000	10,000
VSS/TSS	80 – 100%	95%
Total P	220 – 490	430
Ortho P	62 – 400	230
Org. N	820 – 1,200	1,000
NH ₃ – N	180 – 790	380
pH	3.6 – 6.6 s.u.	

Note: Unless otherwise indicated, all values are expressed in mg/l.

Adapted from Wust, 2003.

7.6.7 Feedstock Summary

In Alberta, the type of feedstocks suitable for anaerobic digestion vary considerably, yet are mainly derived from the agriculture sector. Differences between feedstocks utilized for on-farm anaerobic digestion systems and commercial anaerobic digestion systems are mainly due to the pretreatment equipment available. For instance, although (bovine) animal by-products provide a concentrated feedstream of TS matter and VS matter, the pretreatment requirement of thermal hydrolysis for maximum feedstock utilization, is not realistically available for on-farm operations. Other animal by-products such as poultry and swine can be used without thermal hydrolysis, yet these feedstocks will not degrade to the same extent without high temperature and high pressure pretreatment. As such, these feedstocks would provide a limited feedstream for on-farm operations. Most on-farm anaerobic digestion systems would utilize manure for balancing nutrients and a higher (less degraded) organic feedstock such as food residuals, dairy waste, and waste commercial crops and residues.

For commercial operations, more rigorous types of pretreatment technologies are available. Thermal hydrolysis technology would most likely be utilized and as such, TS and VS concentrated feedstocks such as (bovine) animal by-products would be utilized. Balancing feedstocks are necessary to provide ammonia control within the digesters, and this is provided through the utilization of other organic feedstocks: food residuals, manure, commercial crops and residues, and cheese whey and dairy waste.

Animal By-products

Characterization	
TS (%)	Beef (64%), Swine (64%), Poultry (Tissue – 64%, Feathers – 6%)
VS (% of TS)	Beef (85%), Swine (85%), Poultry (85%),
C:N Ratio	10
Pretreatment	Thermal Hydrolysis is required for SRM, advantageous for all animal by-products utilization
Biodegradability (general)	Excellent

Deadstock

Characterization	
TS (%)	Beef (64%), Swine (64%), Poultry (Tissue – 64%, Feathers – 6%)
VS (% of TS)	Beef (85%), Swine (85%), Poultry (85%),
C:N Ratio	10
Pretreatment	Thermal Hydrolysis necessary
Biodegradability (general)	Excellent

Municipal Sludge

Characterization	
TS (%)	2% – 8%
VS (% of TS)	60% - 80%
C:N Ratio	
Pretreatment	Thermal hydrolysis optional
Biodegradability (general)	Excellent

Food Residuals

Characterization	
TS (%)	Grease (10%), Food waste (80% – 90%)
VS (% of TS)	Grease (90%), Food waste (90% - 94%)
C:N Ratio	
Pretreatment	Thermal hydrolysis may be required
Biodegradability (general)	Excellent

Manure

Characterization	
TS (%)	Cattle (7% – 15%), Pig (3% - 13%), Poultry (-)
VS (% of TS)	Cattle (65% - 85%), Pig (65% - 85%), Poultry (70% - 80%)
C:N Ratio	Cattle (19), Pig (5 – 10), Poultry (7)
Pretreatment	Dilution necessary
Biodegradability (general)	Excellent

Commercial Crops and Residues

Characterization

TS (%)

VS (% of TS)

C:N Ratio

Barley (-), Straw (92%), Residue (92%)

Barley (88), Straw (80), Residue (80)

Pretreatment

Thermal hydrolysis

Biodegradability (general)

Difficult without pretreatment

Cheese Whey and Dairy Waste

Characterization

TS (%)

VS (% of TS)

C:N Ratio

80% - 90%

Pretreatment

None

Biodegradability (general)

Excellent

7.7 Mass Balance

Anaerobic digestion is a complex biological process whereby microbes degrade organic material. The types of microbes that complete degradation and produce biogas for utilization require a balance of nutrients for optimal biogas production. As such, many plant configurations utilize co-digestion of multiple feedstocks. Manure is an already degraded material and therefore has little VS matter and a lower VS conversion rate than other organic materials which might be considered for feedstocks. See Table 76.0 for example mass balance for anaerobic digestion of 1,000 kg manure (mesophilic process).

Detailed in Appendix C is an example block process flow diagram utilizing a single feedstock of cheese whey at 20% TS and 85% VS. This example is assumed to operate in the mesophilic temperature range of 35°C.

Table 76.0 Example Mass Balance for Anaerobic Digestion of 1,000 kg Manure

Feedstock Input: Manure			Product and Co-product Output		
			Biogas		
Mass	1,000	kg	Methane	28.30	m ³
TS %	11.0%		Carbon Dioxide	15.24	m ³
TS Mass	110	kg	Water Vapour	1.71	m ³
VS %	80.0%		Total	45.25	m³
VS Mass	88	kg	Stabilized Sludge		
Inert Solids	22	kg	TS %	8.4%	
VS Conversion Rate	85.0%		Mass	791.31	kg
C:N Ratio	20		Converted Energy		
C:N Mass Required	0	kg	Electricity (daily continuous)	5.43	kW
			Natural Gas	1,562.6	MJ
			Hot Water (District heating)	3.87	m ³

Note: 1) TS refers to Total Solids
 2) VS refers to Volatile Solids
 3) CN ratio refers to carbon to nitrogen ratio

However, other organic feedstocks have a higher VS conversion rate and more efficiently produce biogas. These feedstocks may use a higher temperature process to obtain the greatest energy production from utilized feedstocks. See Table 77.0 for example mass balance for anaerobic digestion of 1,000 kg animal by-products (thermophilic process).

Table 77.0 Example Mass Balance for Anaerobic Digestion of 1,000 kg Animal By-products

Feedstock Input: Animal By-products			Product and Co-product Output		
Mass	1,000	kg	Biogas		
			Methane	156.8	m ³
TS %	30.0%		Carbon Dioxide	84.4	m ³
TS Mass	300	kg	Water Vapor	9.5	m ³
VS %	85.0%		Total	353.78	m³
VS Mass	255	kg	Stabilized Sludge		
Inert Solids		kg	TS % (before process water recovery)	4.3%	
VS Conversion Rate	85.0%		Mass	788.8	kg
C:N Ratio	10		Converted Energy		
C:N Mass Required	77	kg	Electricity	721.3	kWh
			Natural Gas	11,503.0	MJ
			Hot Water (District heating)	21.4	m ³

Note: 1) TS refers to Total Solids
 2) VS refers to Volatile Solids
 3) CN ratio refers to carbon to nitrogen ratio

7.8 Emissions from Biogas Manufacturing

Most problematic odors from agricultural operations come from emissions of H₂S, VOC and ammonia (HN₃-N). Anaerobic digestion is a good method for dealing with these odors especially if used in conjunction with a H₂S scrubbing system. Many states in the US, for example California and Iowa, consider anaerobic digestion systems as a method for controlling problematic agricultural odors.

Odors from anaerobic digestion plants can be categorized according to general process description. The receipt and storage of raw materials provides one category while processing and final product utilization provides a second category of emissions production. In the first category, emissions produced are generally the result of aerobic and anaerobic conditions. Storage of raw materials should be such that uncontrolled anaerobic digestion does not occur. For commercial operations utilizing animal by-product feedstock, raw material should be kept at low temperature (~5°C). For other feedstock for both commercial and farm scale operations, low storage volumes are necessary to minimize anaerobic and aerobic gas production. Processing should be mainly due to anaerobic microbial processes. Product utilization of inert solids should be due to aerobic microbial processes.

Biogas produced from anaerobic digestion as a general gas composition with variance depending on feedstock and operating parameters which determine the thoroughness of organic degradation. This level of organic degradation relates directly to the amount (by volume) of methane which is produced.

The gas produced from anaerobic digestion of sludges usually contains 33 – 38 % carbon dioxide, 55 – 65 % methane, small amounts of hydrogen, some nitrogen, and trace amounts of hydrogen sulfide. The composition of biogas changes with substrates utilized however. As shown in Table 78.0, the ratios of methane and carbon dioxide production change according to substrate (Buswell and Boruff, 1932).⁶

Table 78.0 Methane and Carbon Dioxide Ratio Variance due to Substrate Utilization

	Carbon Dioxide	Methane
Carbohydrates	50	50
Low-MW fatty acids	38	62
High-MW fatty acids	28	72
Proteins	24 – 31	69 – 76

Adapted from Sawyer, McCarty and Parkin, 2003

Hydrogen production is an intermediate product and utilized by methanogenic bacteria. For efficient biogas production, the amount of hydrogen produced must be <0.01% v/v. An increase in this amount of hydrogen by up to 100 – 200% v/v could indicate an upset or lack of efficiency in the anaerobic digestion.

There is very little possibility of oxygen being present in the gas produced through anaerobic digestion. The amount of oxygen present is expected to be 0.1 – 0.2 % v/v.

Nitrogen is an inert gas also present in limited volumes in biogas. In determining volumetric production of nitrogen, the amount produced is generally regarded as the remainder after percent measurement of methane, carbon dioxide, oxygen and hydrogen production, then subtraction from 100%.

Volatile Organic Compounds (VOCs) are generally defined as organic compounds that have a boiling point less than or equal to 100 °C and/or a vapour pressure less than 1 mm Hg at 25 °C. (Metcalf & Eddy, 4th ed. 2003. pp. 100) During anaerobic digestion, a number of different VOCs and odorous compounds may be formed including hydrogen sulfide (H₂S), indol, skatol and mercaptans. These compounds are odorous and potentially harmful to a human population. Hydrogen sulfide is produced from anaerobic degradation of organic material containing sulfur through reduction of sulfate by anaerobic microorganisms to produce sulfide. (pp. 70 – 71). The effects these odors may have on a human population include a poor appetite for food, lowered water consumption, impaired respiration, nausea and vomiting, and mental perturbation. Detection thresholds of odorous compounds associated with untreated wastewater are listed in Table 79.0.

⁶ Due to the significantly early date of this publication, the approximate ratios should be treated with caution as equipment utilized during this period is most likely different and less precise than that used currently. The addition of this data however, is to explain the *approximate* varying compositions due to varying substrates.

Table 79.0 Odor thresholds of Odorous Compounds Associated with Untreated Wastewater

Odorous Compound	Chemical formula	Molecular weight	Odor threshold, ppm _v	Characteristic odor
Ammonia	NH ₃	17.0	46.8	Ammoniacal, pungent
Chlorine	Cl ₂	71.0	0.314	Pungent, suffocating
Crotyl mercaptan	CH ₃ -CH=CH-CH ₂ -SH	90.19	0.000029	Skunklike
Dimethyl sulfide	CH ₃ -S-CH ₃	186	0.0001	Decayed vegetables
Diphenyl sulfide	(C ₆ H ₅) ₂ S	186	0.0047	Unpleasant
Ethyl mercaptan	CH ₃ CH ₂ -SH	62	0.00019	Decayed cabbage
Hydrogen sulfide	H ₂ S	34	0.0047 0.13 ^a	Rotten eggs
Indole	C ₈ H ₆ NH	117	0.0001	Fecal, nauseating
Methyl amine	CH ₃ NH ₂	31	21.0	Putrid, fishy
Methyl mercaptan	CH ₃ SH	48	0.0021	Decayed cabbage
Skatole	C ₉ H ₉ N	131	0.019	Fecal, nauseating
Sulfur dioxide	SO ₂	64.07	0.009	Pungent, irritating
Thiocresol	CH ₃ -C ₆ H ₄ -SH	124	0.000062	Skunk, rancid

NOTE:

(a) Supplementary Reference ENFORM, 6th ed.

Metcalf & Eddy, 4th ed. pp. 72. 2003.

Odors from anaerobic digestion facilities mainly result not from additions of chemical substances, but from degradation of organic material. As such, odorous compounds listed in Table 82.0 are potential sources of odors.

Anaerobic digestion can be simplified into two main stages. In the first stage, decomposition is undertaken by fast-growing, acid-forming (acidogenic) bacteria. Organic material in such material as manure is hydrolyzed and metabolized into mainly short-chain fatty acids (acetic, propionic and butyric) along with carbon dioxide (CO₂) and hydrogen (H₂) gases. It is at this stage of organic degradation that noticeable, disagreeable and effusive odors are produced.

In the second stage, most of the organic acids and all of the hydrogen are metabolized by methanogenic bacteria to produce biogas.

Production of VOCs occurs generally at an intermediary stage during degradation of organic material into biogas. The total volume of VOCs produced is related to the total volume of CH₄ produced however, the more effective the methanogenic decomposition, the lower the production of VOC_s as a percentage of the biogas. Remaining VOCs in the biogas should be further reduced through combustion of the biogas. (Krich et al. 2005).

Commercial Operations utilizing Thermal Hydrolysis

Utilization of thermal hydrolysis units for processing animal by-products in high temperature and high pressure cookers, results in emissions similar to that of rendering operations. The approximate description of these emissions is given in Table 80.0.

Table 80.0 Emission Factors for Controlled Blood Dryers

Pollutant	Emissions, lb/ton ^a	Emissions, kg/tonne ^b
Filterable PM-10	0.76	0.380
Condensable PM	0.46	0.230
Hydrogen sulfide	0.08	0.040
Ammonia	0.60	0.300

Note:

^a Emission factors based on weight of dried blood meal product. Emissions are for natural gas, direct fired dryers.

^b Converted emission factors.

Adapted from US EPA, 1995

The approximate size of a thermal hydrolysis unit is 7.6 m³. Considering 80% loading of the unit for safe operation, approximately 1.52 m³ of free space exists. As an example, venting at 85°C produces an exit volume of 2.59 m³ at temperature 85°C. This example also assumes the following:

- Saturated steam exists within 20% of free space of thermal hydrolysis unit;
- Pressure of saturated steam is 157 kPa at approximately 85°C;
- One air change of free space is emitted during cooling and venting before closure of vent for next batch operation;
- Ambient pressure is approximately 92 kPa;
- Approximately 6.0 tonne of animal by-product is thermal hydrolyzed per batch; and
- Density of animal by-products utilized is 985 kg/m³.

Venting of the thermal hydrolysis unit after cooling then produces a concentrated emission as described in Table 81.0.

Table 81.0 Calculated Emissions from Thermal Hydrolysis Venting

Pollutant	Emissions, kg/tonne ^b	Emissions, kg/m ³ per batch
Filterable PM-10	0.380	0.877
Condensable PM	0.230	0.531
Hydrogen sulfide	0.040	0.092
Ammonia	0.300	0.692

Note: Batch volume refers to conditions and approximations described in previously referred to text. Volumes and air changes should be regarded as a high level approximation.

The amount of emissions generated as displayed in Table 9.0 should be regarded as a maximum level of emissions. Described in the invention patent is how malodorous gasses due to emission release after treatment are substantially reduced.

In addition to generating denatured products, the invention substantially eliminates unpleasant odors associated with disposal of infectious organic waste material such as sewage sludge and animal waste. Without wishing to be bound by any theory, elimination of these odors is believed to be due to a reduction of the amount of sources of odor production generated from microbial activities, together with production of compounds like those in sugars or molasses that have a more pleasant odor. These compounds having a more pleasant odor are believed to form due to the hydrolysis of cellulose, production of reducing sugars, and oxidation of organic compounds. Elimination of unpleasant odors also is aided by scrubbing the vapor of residual gasses containing carbon dioxide, methane, and volatile sulfide and amine compounds. The invention therefore substantially eliminates the emission of malodorous gasses to the environment. (Schmidt, US Patent No.: 6,197,081 B1, 2001)

Given the likelihood of a periodic emission source with concentrations described in Table 84.0, the thermal hydrolysis unit will likely require emission scrubbing before venting to the atmosphere. This is in relation to Alberta Ambient Air Quality Objectives where, for instance, ammonia levels are to be kept within an hourly range of 2,000 ppbv. Assuming density of 0.8890 kg/m³ (vapor), ammonia emission calculated in Table 81.0 far exceeds this value.

Considering the toxicity of raw biogas due to the presence of H₂S, and the high concentration therein (>10 ppm), all facilities should have flare systems such that during process upset, raw biogas is directed to flare for combustion. Emissions from thermal hydrolysis units as shown in Table 81.0, far exceed concentrations outlined in Alberta's Ambient Air Quality Objectives. However, the requirement for scrubbing from these units should be dependent on emission modeling and nearby resident proximity.

7.9 Farm Operation and Commercial Plant Input and Output Summaries

Farm scale and commercial operations for biogas manufacturing differ not only in processing capacity, but in ability to utilize different feedstocks. For instance, a farm scale operation is not expected to have the necessary equipment to utilize bovine animal by-products. Thermal hydrolysis equipment necessary for the destruction of SRM material is very expensive and requires special operator training and certification. As well, the use of higher temperature processes in the thermophilic range of operation are less stable than lower temperature mesophilic operations. However, a commercial scale facility is expected to have the necessary capital and expertise to both invest in and operate thermal hydrolysis equipment. As well, the less stable thermophilic operation is expected to pose less of a challenge due to specialized skills available to a commercial operation.

In defining capacities for each level of operation, safe operation and feedstock availability are determinant factors. The farm scale operation, assumed to lack necessary resources for utilization of animal by-products, would utilize manure and a higher (less degraded) organic material for co-digestion. Approximate daily mass loading is expected to be in the range of 50 tonne/day. The amount of electricity produced from such a configuration is 435 kW.

The commercial scale operation however, is assumed to possess the necessary resources for utilization of animal by-products. Manure would most likely be used as a balancing feedstock for co-digestion. Approximate daily mass loading is expected to be in the range of 200 tonne/day. The amount of electricity produced from such a configuration is 3.35 MW.

Presented are the inputs and outputs for farm and commercial scale operations that would ideally occur for feedstocks with variable amounts of TS and VS for the process combinations of different feedstocks.

7.9.1 Co-Digestion Configuration of Example Farm Scale Scenario

Described in Table 82.0 is the simplified mass balance for a likely scenario featuring co-digestion of two feedstocks. The most likely scenario for farm scale operation in Alberta is mesophilic digestion of manure + higher value organic material (in this case, dairy waste). Temperature is assumed to be 35°C, continuous loading of organic material and continuous biogas production.

Table 82.0 Example Material Mass Balance for Small Farm Scale Biogas Operation Rated for Design Production Capacity of 50 tonne/day

Feedstock: Dairy waste and Manure			Product and Co-product Output		
Mass	50,000	kg	Biogas		
Dairy waste	25,000	kg	Methane	2,271.60	m ³
Manure	25,000	kg	Carbon Dioxide	1,223.17	m ³
TS %	15.5%		Water Vapour	137.05	m ³
TS Mass	7,750	kg	Total	3,631.82	m³
VS %	80.0%		Stabilized Sludge		
VS Mass	6,200	kg	TS %	7.5%	
Inert Solids	1,550	kg	Mass	45,824.70	kg
VS Conversion Rate	57.5%		Converted Energy		
C:N Ratio	15		Electricity (daily continuous)	435.44	kW
C:N Mass Required	0	kg	Natural Gas	125,405.6	MJ
			Hot Water (District heating)	310.38	m ³

7.9.2 Co-Digestion Configuration of Example Commercial Scale Scenario

Described in Table 83.0 is the simplified mass balance for a likely scenario featuring co-digestion of two feedstocks. The most likely scenario for commercial scale operation in Alberta is thermophilic digestion of manure + animal by-products. Temperature is assumed to be 55°C.

Table 83.0 Example Material Mass Balance for Large Commercial Scale Biogas Operation Rated for Design Production Capacity of 200 tonne/day

Feedstock: Animal By-products and Manure			Product and Co-product Output		
Mass	200,000	kg	Biogas		
Animal By-products	100,000	kg	Methane	18,536.33	m ³
Manure	100,000	kg	Carbon Dioxide	9,981.10	m ³
TS %	28.0%		Water Vapour	1,118.33	
TS Mass	56,000	kg	Total	29,635.76	m³
VS %	80.0%		Stabilized Sludge		
VS Mass	44,800	kg	TS %	6.5%	
Inert Solids	11,200	kg	Mass	166,067.99	kg
VS Conversion Rate	67.5%		Converted Energy		
C:N Ratio	15		Electricity (daily continuous)	3,345.89	kW
C:N Mass Required	0	kg	Natural Gas	963,608.2	MJ
			Hot Water (District heating)	2,384.93	m ³

8.0 BIODIESEL

8.1 Biodiesel B100

Biodiesel is a conventional diesel fuel replacement manufactured from a variety of different feedstocks which includes vegetable oils, animal fats, and recycled cooking oil or greases. The manufacturing process converts fatty acids derived from the above oils and fats into chemicals referred to as long chain mono-alkyl esters commonly referred to as biodiesel. To qualify as biodiesel B100 the fuel must be manufactured in accordance to ASTM specification D6751. This specification defines biodiesel as consisting of long chain fatty acid esters that contain only one alcohol molecule on one ester linkage. Raw or refined vegetable oils that contain three ester linkages do not qualify as legal biodiesel. Biodiesel can be manufactured from methyl, ethyl, isopropyl and other alcohols. However in virtually all commercial production facilities in North America the manufacturing process uses methyl esters.

Primary advantages of biodiesel are that it is one of the most renewable fuels currently available, it is non-toxic and biodegradable. Biodiesel can be used as a fuel in either its neat form as B100 or as a blend with conventional petroleum diesel. Biodiesel blends consisting of mixture of biodiesel and petroleum diesel are commonly referred to as B20,