GREENING WASTE: ANAEROBIC DIGESTION FOR TREATING THE ORGANIC FRACTION OF MUNICIPAL SOLID WASTES

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EXECUTIVE SUMMARY

Anaerobic digestion (AD) has the opportunity to be an integral part of the solution to two of the most pressing environmental concerns of urban centers: waste management and renewable energy. Through AD, organics are decomposed by specialized bacteria in an oxygen-depleted environment to produce biogas and a stable solid. Each of these products can be used for beneficial purposes to close the loop in organic waste management. The biogas, which consists of up to 65% methane, can be combusted in a cogeneration unit and produce green energy. The solid digestate can be used as an organic soil amendment. As a waste management strategy employed in over 20 countries, AD has been successful in reducing the volume of waste going to landfill, decreasing emissions of greenhouse gases and creating organic fertilizer, all at a profit. Despite global success, the United States has not employed AD on a large scale, and nowhere is it used to treat MSW. This paper outlines the processes of AD, reviews the current technology available and proposes the adoption of the technology in the United States, beginning with commercial waste in New York City. The greatest concerns for New York are space and transportation, indicating that the most appropriate system is one using high solids located near the site of waste generation. Therefore, the Hunt's Point Market in the Bronx is an ideal location for a demonstration facility for AD. This plant will improve local environmental conditions, create jobs, and generate electricity. For the plant to be economically viable, public policy must proactively support AD.

Acknowledgements

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Note: The color figures in this publication are available on request to the author (kmo2004@columbia.edu).

Introduction

The process of anaerobic digestion (AD) employs specialized bacteria to break down organic waste, converting it to a stable solid and biogas, a mixture of carbon dioxide and methane. The oldest type of digestion to occur on Earth, AD takes place naturally in oxygen-depleted organic environments, such as bogs, rice paddies, landfills and improperly aerated compost piles. Humans have been able to harness this process for benefit in several contexts. Rural areas, especially in China and India, take advantage of AD extensively to process farm waste, such as manure. In North American farming communities, AD is used in large farms to treat manure and control odor. The only other application of AD in North America is at wastewater treatment plants where, in modern facilities, sewage sludge is anaerobically treated to reduce biological and chemical oxygen demands. European nations take advantage of the next logical application and employ AD to process more complicated waste streams, including industrial and agricultural wastewaters and the organic fraction of municipal solid waste (OFMSW).

Because of the proven feasibility of the process and the multitude of environmental benefits, the use of this technology has been firmly established in Europe, where over 160 facilities with an annual installed capacity more than 5 million tons generate electricity in excess of 600 MW (IEA, 2002). By doing so, these countries reduce the volume of waste being sent to landfill, and therefore decrease methane emissions produced from its decay. The biogas generated at these sites is used to produce electricity and heat that is then sold to utilities, making the facilities profitable. Additional environmental gains include improvements in water and air quality over current practices of waste management.

The opportunity to use AD for the OFMSW exists for the United States, where our annual waste generation is 780 kg per capita (EPA, 2003). The targeted waste streams are food scraps, 11.4% of the total, and yard trimmings, an additional 12.2% (EPA, 2003). Though the feedstock is clearly available, implementing AD presents several obstacles that must be overcome. The first is simply perception. AD treats putrescible waste, which produces highly unpleasant odors. The NIMBY principle is strong for AD treatment plants, despite the fact that odors can be controlled with negative pressure and biofilters. Another obstacle is a lack of knowledge and information dissemination. There are very few North American companies manufacturing facilities, little research being done outside of the farming community, and no professional trade organizations promoting the technology specifically for MSW. The *BioCycle Journal of Compost and Organics Recycling* is one of the few sources of facts on AD and organizes nationwide conferences. Currently, however, this information focuses on farming applications. Municipalities are very hesitant to be the first to try a new technology for MSW. Finally, environmental policy in the United States offers no incentive to avoid landfilling, a cheap and simple waste management strategy with existing infrastructure. This will not change until environmental damage is taken into account when pricing and choosing waste management strategies.

The organic fraction of MSW makes up nearly 25% of urban waste streams, or about 4 million tons in New York City (NYDS, 2004). At least one million tons of this is paper, which can be recycled, but the remaining waste is food and other highly degradable materials that pose health and sanitation concerns. Most of this waste is trucked to landfill, imposing economic and environmental burdens on the city. Even the most optimistic plans for the future of waste management do not predict a reduction in the volume of organic waste, a stream that contributes disproportionately to landfill gas emissions and odor. These concerns make a city a good location for implementing AD. Processing waste locally not only takes responsibility for one's own waste, but also reduces truck traffic and air emissions associated with it. An AD facility, however, requires land allocation, a valuable commodity in urban areas. One method to hasten the adoption of AD is to make the process more efficient, thereby reducing retention time and the space requirements. Another way to encourage AD is to solidify markets for its products, especially the compost product. Research into these two areas, along with changing public policies, can significantly change the feasibility of realizing AD in New York.

The best waste management strategy should protect public health and the environment, lessen the burdens on present and future generations, conserve resources, and minimize cost. Carefully planned and implemented anaerobic digestion facilities can accomplish all of these goals in the United States as they have in Europe.

1 History of AD

Anaerobic digestion dates back as far as the 10th century, when the Assyrians used it to heat bath water. It was historically insignificant before reappearing in 17th century Europe, when it was determined that decaying organic matter produced flammable gases, again used to heat water. The first full scale application was in the 1890s when the city of Exeter, UK used it to treat wastewater. From there, it continued to be widely used as a way to stabilize sewage sludge, as it is today (Mahony, O'Flaherty et al. 2002). The first systems were large, unheated and unmixed tanks with significant operational problems due to solid settling and scum formation. These frequent system disturbances limited the adoption of the technology until the twentieth century.

Rural areas, especially in developing countries, have employed AD for centuries. It is used as a sanitary and economic way to treat waste and generate fuel for use in heat and cooking. Many of these facilities continue to operate in countries such as China and India, where organics dominate the waste stream. In China, for example, organics make up 60% of the municipal solid waste in the country as a whole, and an even greater percentage in rural areas (Henderson and Chang 1997). Most digesters are small and characterized by minimum technical automation and high levels of manual labor, such as the fixed dome reactor seen in Figure 1. They treat a combination of organic waste including food trimmings, human sewage and animal manure, and are usually for multiple households in a village. One family's waste can produce up to 60% of their energy needs, reducing the workload on women and decreasing the amount of coal burned (Guidotti 2002). Although AD was useful in providing fuel for cooking and lighting in developing economies, most were much too small to be useful to farmers in the developed world. The typical small-scale digester, for example, produces about the same amount of energy daily as is contained in one gallon of propane (Lusk 1999).

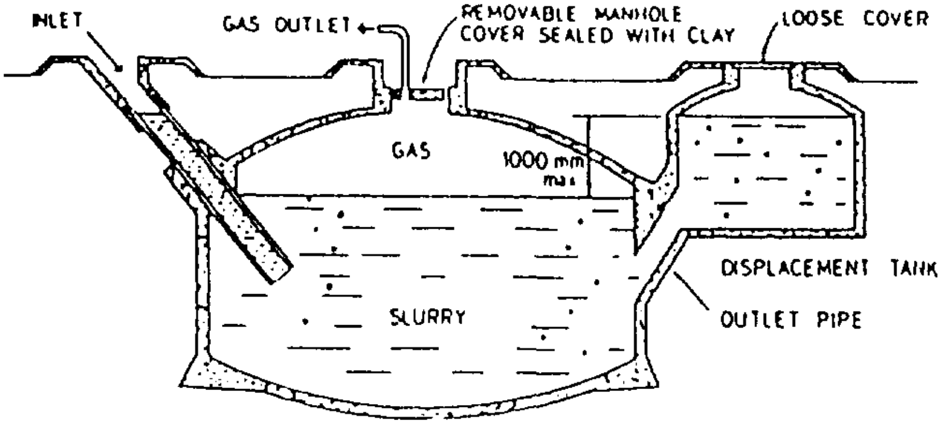

Figure 1 Chinese Fixed Dome Anaerobic Digester (Guidotti, 2002)

The development of the field of microbiology in the 1930s allowed scientists to identify that the mechanism of gas production depended on anaerobic bacteria (Lusk 1998). Subsequent experiments were carried out to determine the optimal environmental conditions for gas production. As a result, heated and mixed digesters of increasing complexity came to the market in the middle of the twentieth century in Europe. The first commercial applications were on farms where manure was digested to produce heat and later electricity. As the knowledge base expanded, AD was employed to treat other farm wastes, wastewater, industrial organics and finally Municipal Solid Waste (MSW), though the predominant use continues to be on farms.

The energy crises in the 1970s prompted American research into alternative energy strategies, and AD was one such option. This push resulted in the first farm digester built in America in 1970 where the biogas could be used for heat and power (Lusk 1999). Farm digesters often occupy large areas, such as the lagoon digester shown in Figure 2. At present, development continues on farms as well as wastewater treatment plants, where anaerobic processes and subsequent gas recovery are an industry standard. Expansion into other areas of waste treatment has been neglected partly because landfilling remains inexpensive and fossil fuels are, falsely the economic energy choice. In fact, as energy prices have fallen, odor control became the primary incentive to use AD. Today, it is shocking to know that often the benefits of methane production are not used on methane -producing plants (e,g, wastewater treatment plants and landfills) because the gas is flared. Another barrier to the expansion of AD has been the high failure rate of AD systems, as high as 80% in the United States (Themelis and Verma 2004).

Figure 2 Lagoon Digester in Oregon Farm (Mattocks, 2004)

Through government funded research and pilot demonstrations over the past 30 years, AD facilities have been dramatically improved in Europe. The academic work led to the launch of the commercialization phase where research continues today. Development has been encouraged by higher tipping fees at landfills, stricter environmental legislation, including renewable energy laws and landfill restrictions, and other tax incentives (Nichols 2004).

The more recent development in AD technology worldwide is in the treatment of industrial wastes and wastewater. In Europe, Australia and Asia, AD has become a typical option for treating the organic fraction of industrial waste with applications ranging from breweries to paper mills to food processors, as seen in figures 3 and 4. The designs of these facilities reflect the need for shorter retention times, smaller reactor volume and higher loading rates, indicative of their urban locations. The companies benefit by using the biogas produced, reducing odor and the volume of sludge produced, as well as sanitizing the waste. Germany and Denmark, where environmental legislation concerning waste disposal is stringent, lead the way. Although some private industrial facilities in the United States do choose to treat industrial effluent using AD, e.g., the Anheuser Busch plant in St. Louis (Figure 5), its application is not as widespread as in most other developed world countries.

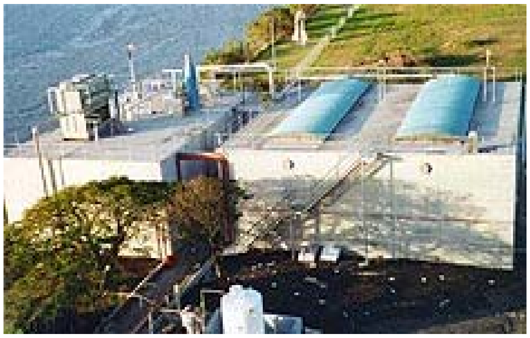

Figure 3, Visy Paper AD Plant, Brisbane, Australia (Field and Sierra, 2003)

Figure 4, Kohn Kaen Brewery AD Plant, Thailand (Harris, 2004)

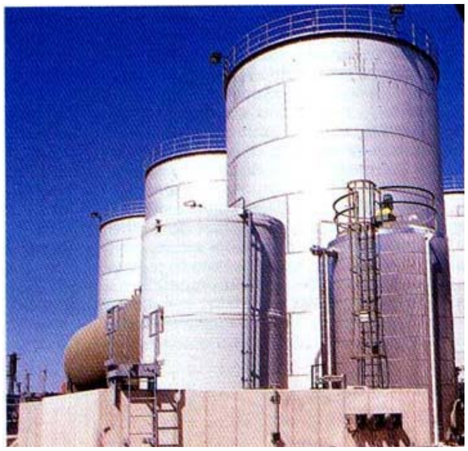

Figure 5 Anheuser Busch Plant, St. Louis (Foo and Senta, 1998)

The treatment of solid wastes using AD adds several new challenges because of the variety in the feedstock and the space limitations where such facilities would be located. The organic fraction of MSW (OFMSW) may contain food, yard waste or paper in varying concentrations, sizes, and composition. Furthermore, MSW is contaminated with non-organics, such as glass and metal, and therefore requires pre-treatment to separate the feedstock. Though the ideal waste stream for an AD plant would be source-separated organics, the reality is that there is always a small degree of contamination that must be handled on site.

Despite these challenges, European nations have led the way to expanding AD to be a significant part of MSW management. Over 70 plants process MSW either alone or with sewage (De Baere 2001) in Germany, Denmark, France, Spain, Austria, Holland, England, Belgium, and other European nations. Additionally, Israel, Australia and Canada have at least one AD plant treating MSW. The typical plant processes between 50,000 and 80,000 tons of organic waste per year, with the largest treating 100,000 tons annually. Some plants accept mixed MSW, for example the Vagron plant that treats 232,000 tons of mixed waste per year, 92,000 tons of which are organics (Grontmij, 2003). The expansion to the American market has been stalled by failed attempts, such as that in Los Angeles, as well as by lack of government incentives.

The future of AD as a MSW management strategy depends on several factors ranging from environmental concerns to economic considerations. Some of these include increased process efficiency, reduced construction and operation costs, expanding markets for products and decrease in the availability of landfills. It seems that AD will continue to play a role in MSW, but to what extent is unknown.

2 Biochemical Reactions

AD is a series of chemical reactions during which organic material is decomposed through the metabolic pathways of naturally occurring microorganisms in an oxygen-depleted environment. AD can be used to process any carbon-containing material, including food, paper, sewage, yard trimmings and solid waste, with varying degrees of degradation. The Organic Fraction of Municipal Solid Waste (OFMSW), for example, is a complex substrate that requires an intricate series of metabolic reactions to be degraded. This section describes these reactions detailing the intermediary products produced and the bacteria involved.

The full process can be considered to occur in four stages as illustrated in Figure 5: hydrolysis, in which complex molecules are broken down to constituent monomers; acidogenesis, in which acids are formed; acetogenesis, or the production of acetate; and methanogenesis, the stage in which methane is produced from either acetate or hydrogen. Digestion is not complete until the substrate has undergone all of these stages, each of which has a physiologically unique bacteria population responsible that requires disparate environmental conditions.

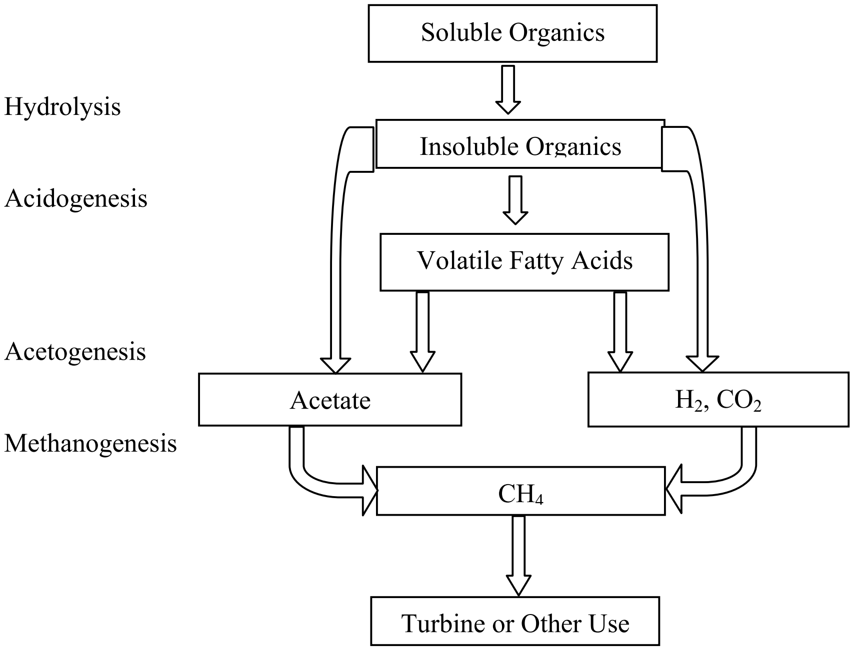

Figure 6 The Four Processes of Anaerobic Digestion (Garcia-Heras, 2003) (White, 2004)

2.1 Hydrolysis

In the first stage, complex organic materials are broken down into their constituent parts in a process known as hydrolysis. The result is soluble monomers: Proteins are converted to amino acids; fats to fatty acids, glycerol and triglycerides; complex carbohydrates such as polysaccharides, cellulose, lignin, starch and fiber converted to simple sugars, such as glucose. Hydrolic or fermentive bacteria are responsible for the creation of monomers, which are then available to the next group of bacteria. Hydrolysis is catalyzed by enzymes excreted from the bacteria, such as cellulase, protease, and lipase. If the feedstock is complex, the hydrolytic phase is relatively slow. This is especially true for raw cellulolytic waste, which contains lignin (United Tech 2003). For this reason, woody waste is not an ideal feedstock tfor the AD process.. Carbohydrates, on the other hand, are known to be more rapidly converted via hydrolysis to simple sugars and subsequently fermented to volatile fatty acids (Mata-Alvarez, 2003).

An approximate chemical formula for the mixture of organic waste is $C_6H_{10}O_4$ (Themelis and Verma 2004). A hydrolysis reaction where organic waste is broken down into a simple sugar, in this case glucose, can be represented by the following:

$$C_6H_{10}O_4 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2 \qquad (1)$$

2.2 *Acidogenesis*

Hydrolysis is immediately followed by the acid-forming phase of acidogenesis. In this process, acidogenic bacteria turn the products of hydrolysis into simple organic compounds, mostly short chain (volatile) acids (e.g., propionic, formic, lactic, butyric, or succinic acids), ketones (e.g., ethanol, methanol, glycerol, acetone) and alcohols. The specific concentrations of products formed in this stage vary with the type of bacteria as well as with culture conditions, such as temperature and pH (United Tech 2003).

Typical reactions in the acid-forming stages are shown below. In equation 2, glucose is converted to ethanol and equation 3 shows glucose is transformed to propionate.

$$C_6H_{12}O_6 \leftrightarrow 2\ CH_3CH_2OH + 2CO_2 \qquad (2)$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2\ H_2O \qquad (3)$$

2.3 *Acetagenesis*

The next stage of acetagenesis is often considered with acidoenesis to be part of a single acid forming stage. Biological oxygen demand (BOD) and chemical oxygen demand (COD) are reduced through these pathways. Acetagenesis occurs through carbohydrate fermentation, through which acetate is the main product, and other metabolic processes. The result is a combination of acetate, CO_2, and H_2. The role of hydrogen as an intermediary is of critical importance to AD reactions. Long chain fatty acids, formed from the hydrolysis of lipids, are oxidized to acetate or propionate and hydrogen gas is formed. Under standard conditions, the presence of hydrogen in the solution inhibits the oxidation. The reaction only proceeds if the hydrogen partial pressure is low enough to thermodynamically allow the conversion. The presence of hydrogen scavenging bacteria (HMBs) that consume hydrogen, thus lowering the partial pressure, is necessary to ensure thermodynamic feasibility and thus the conversion of all the acids. As a result, the concentration of hydrogen, measured by partial pressure, is an indicator of the health of a digester (Mata-Alvarez, 2003).

As an example, the free energy value of the reaction that converts propionate to acetate, shown in equation 4 below, is +76.1 kJ, so that this reaction is thermodynamically impractical . When acetate and hydrogen are consumed by bacteria, however, the free energy becomes negative. In general, for reactions producing H_2, it is necessary for hydrogen to have a low partial pressure for the reaction to proceed.

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2 \qquad (4)$$

Other important reactions in the acetogenic stage involve the conversion of glucose (5), ethanol (6) and bicarbonate (7) to acetate.

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2\,CO_2 + 4H_2 \qquad (5)$$

$$CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^+ \qquad (6)$$

$$2HCO_3^- + 4H_2 + H^+ \leftrightarrow CH_3COO^- + 4H_2O \qquad (7)$$

The transition of the substrate from organic material to organic acids in the acid forming stages causes the pH of the system to drop. This is beneficial for the acidogenic and acetagenic bacteria that prefer a slightly acidic environment, with a pH of 4.5 to 5.5, and are less sensitive to changes in the incoming feed stream, but is problematic for the bacteria involved in the next stage of methanogenesis (Gas Technology 2003).

2.4 Methanogenesis

The methanogenic anaerobic bacteria involved in the third stage, known as methanogenesis or methane fermentation, are the same fastidious bacteria that occur naturally in deep sediments or in the rumen of herbivores. This population converts the soluble matter into methane, about two thirds of which is derived from acetate conversion (equation 8 followed by 9), or the fermentation of an alcohol, such as methyl alcohol (10), and one third is the result of carbon dioxide reduction by hydrogen (11) (United Tech 2003).

$$2\,CH_3CH_3OH + CO_2 \leftrightarrow 2\,CH_3\,COOH + CH_4 \qquad (8)$$

$$CH_3COOH \leftrightarrow CH_4 + CO_2 \qquad (9)$$

$CH_3OH + H_2 \leftrightarrow CH_4 + H_2O$ (10)

$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$ (11)

Methanogens are very sensitive to changes and prefer a neutral to slightly alkaline environment (Gas Technology 2003). If the pH is allowed to fall below 6, methanogenic bacteria cannot survive. Methanogenesis is the rate-controlling portion of the process because methanogens have a much slower growth rate than acidogens. Therefore, the kinetics of the entire process can be described by the kinetics of methanogenesis (Davis and Cornwell 1998).

$CH_3COO^- + SO_4^{2-} + H^+ \rightarrow 2HCO_3 + H_2S$ (12)

$CH_3COO^- + NO^- + H_2O + H^+ \rightarrow 2HCO_3^- + NH_4^+$ (13)

Although AD can be considered to take place in these four stages, all processes occur simultaneously and synergistically, in as much as the first group has to perform its metabolic action before the next can take over, and so forth.

3 Material and Energy Balances

The material balance in Figure 7 shows a typical flow of materials for an anaerobic digestion system. The moisture content of raw waste is normally between 50 to 65%, and so water must be added to raise it above 75%. This is provided by dewatering the final solid digestate and recirculating the water back to the mixing tank. High moisture is critical for feedstock in an AD plant so that it can be pumped. The materialbalance shows that this amount of additional water can be supplied entirely by recycled process water, saving money and resources for the plant. The disadvantage of using strictly process water, however, is that salts can concentrate in the water and remain in the fertilizer. Most plants use a combination of fresh and process water (Cluff, 2003). The exception is in locations where water is a valuable commodity, such as Israel (Finstein, 2003).

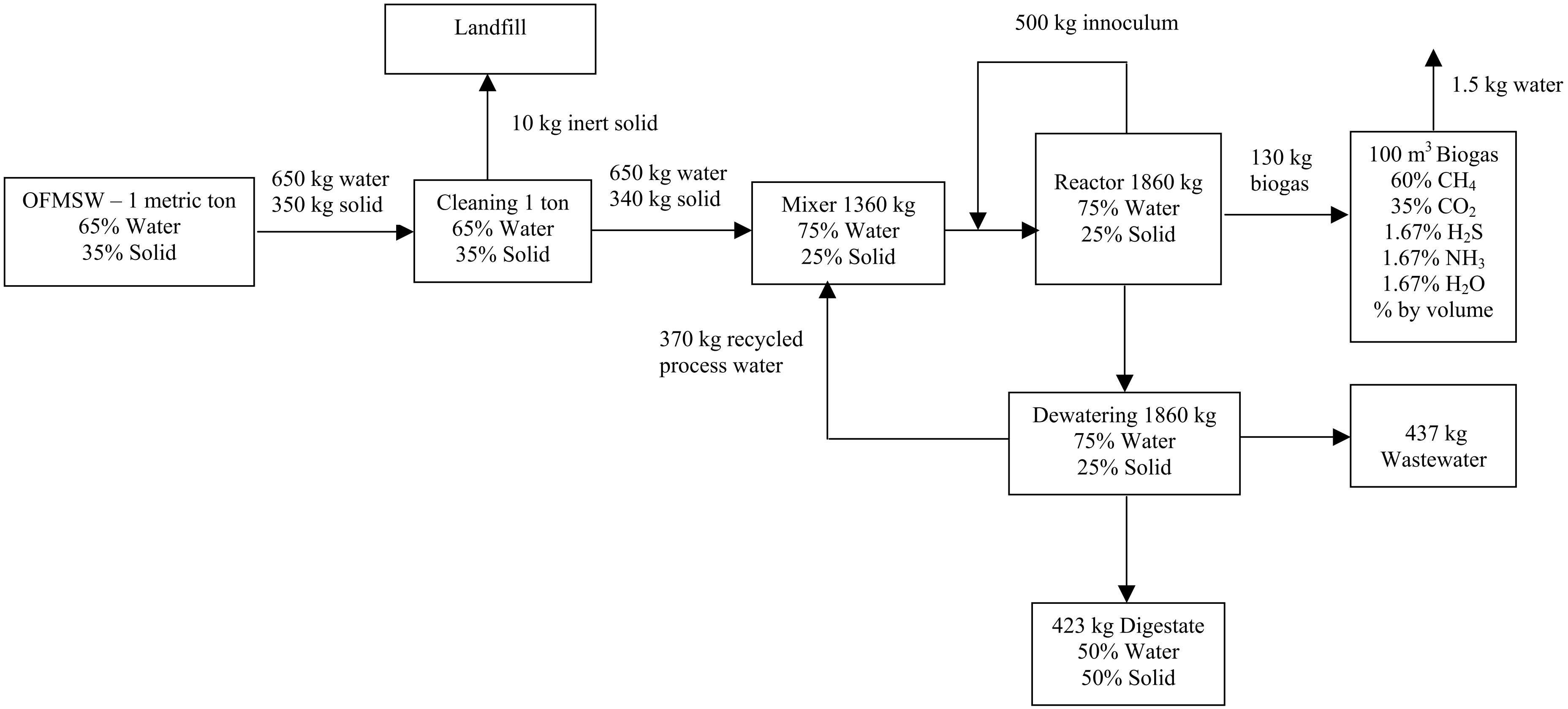

Figure 7, Material Balance

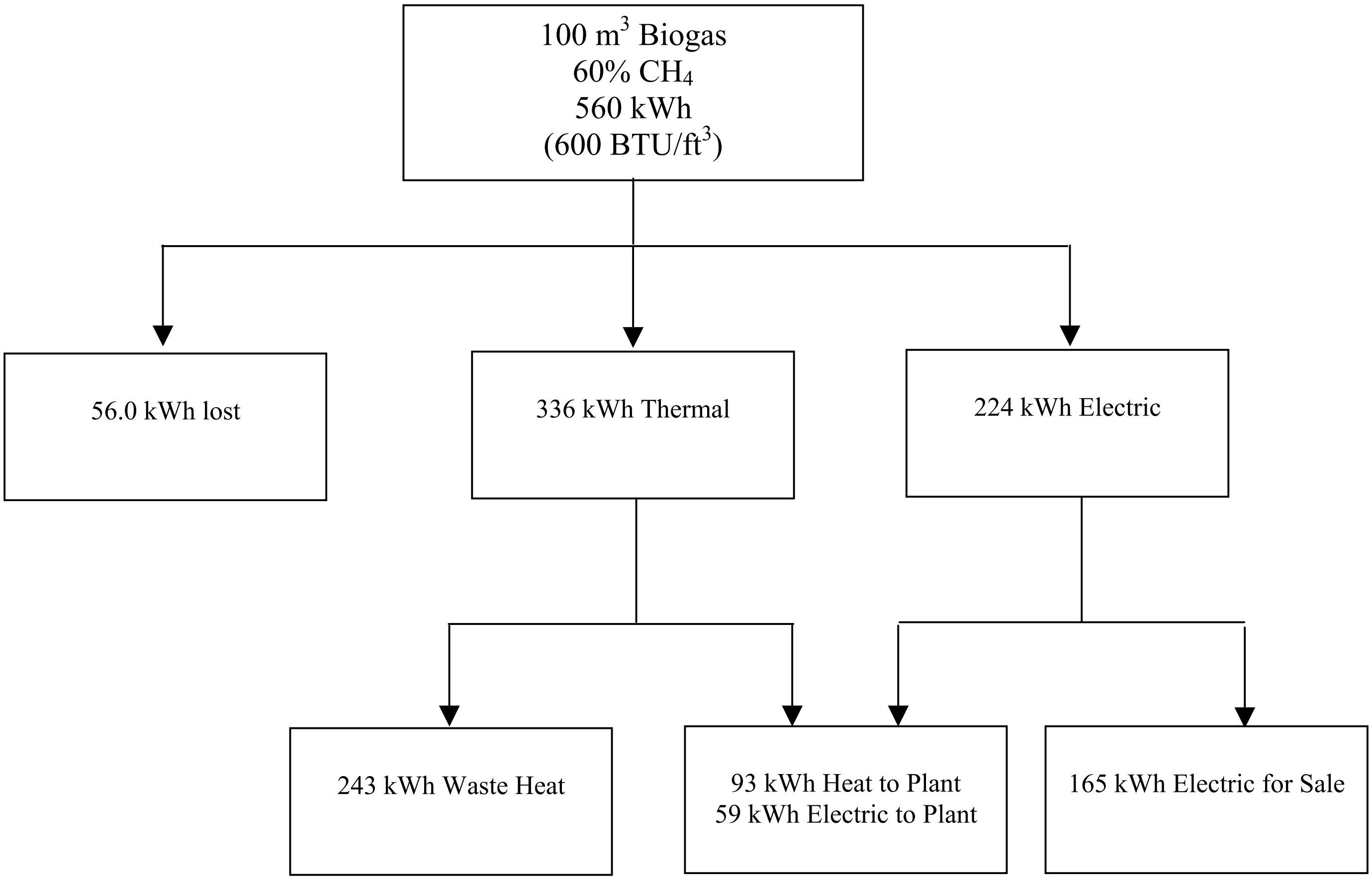

Figure 8, Energy Balance

Typical values for biogas production range from 80-130 m^3 per ton of waste feedstock, as shown in Table 1. The methane content of biogas ranges from 50% to as high as 75%, though most plants report values close to 60%. The remainder of the gas is predominately carbon dioxide, with trace elements of other gases, such as hydrogen sulfide, ammonia and water vapor. Though these are insignificant from the material balance perspective, they play a critical role in how the gas is used.

The biogas is the energy carrier in the process, and its use is detailed in the energy balance shown in Figure 8. Plants large enough to produce electricity in a cogeneration unit can be entirely self-sufficient on the power produced from their biogas. The low temperatures required for AD (less than 110°F), allow the heat to be supplied entirely from the biogas as well. Because heat is a necessary byproduct of electricity generation, it makes little sense for a large AD plant to combust biogas in a boiler.

4 Products

The end products of AD are biogas and digestate, a moist solid which is normally dewatered to produce a liquid stream and a drier solid. The components of the biogas depend on the process of digestion, but are predominately methane and carbon dioxide. The solid is a humus-like, stable, organic material, the quality and subsequent use of which is determined by the characteristics of the feedstock to the AD process. The liquid contains soluble materials, including dissolved organic compounds. In a typical AD facility processing OFMSW, the gas mass comprises about 15% of the output stream and the liquid and solid compose approximately equal parts, or 42.5% each.

4.1 Biogas

The production of biogas, which contains between 50 and 70% methane, is the most valuable aspect of the AD process. As seen in the material balance, biogas is made up mostly of methane and carbon dioxide, with trace amount of other gases. Before being used for electricity generation, water vapor and hydrogen sulfide should be removed to protect machinery against corrosion. Ammonia is often removed as well. The resulting gas, a mixture of methane and carbon dioxide, can be used directly as a fuel in electricity generating equipment that is designed to operate with low heating value gas. The heating value of biogas is directly proportional to the percent methane content, as expressed by the relationship:

$1{,}000\ \mathrm{BTU/ft^3} * (\%\ \text{methane content}) = \text{Heating Value of biogas}\ \mathrm{BTU/ft^3}$

One ton of waste produces between 80 and 150 m^3 of biogas, depending on the process. Table 1 shows the reported biogas outputs of several large AD designs treating MSW. A very conservative value of 100 m^3 of biogas per ton of feedstock is assumed in subsequent sections.

Table 1 Biogas Yield of Several AD Designs Treating MSW

AD Design Firm	Biogas Yield (m^3/metric ton feedstock)
BTA	80-120
Valorga	80-160
WAASA	100-150
DRANCO	100-200
Linde	100
Kompogas	130

The fuel equivalents of 100 m^3 of biogas, resulting from the anaerobic digestion of about a ton of waste, are shown in Table 2.

Table 2 Fuel Equivalents of Biogas generated per ton of organics

Gasoline	61 liters
Charcoal	90 kg
Electricity	170 kWh
Heat	250 kWh
CHP – Electricity and Heat	170 kWh + 250 kWh

The smallest AD facilities, usually found on farms, often flare the biogas, reasoning that the cost of equipment to use it is greater than the benefits they would realize. Some small AD facilities use biogas strictly for heat, used to bring the temperature of the waste to desired digestion ranges. The larger facilities generate electricity, usually in cogeneration equipment, which also supplies them with the requisite heat. Besides lowering the electricity bill, there are several advantages to generating electricity. First, because biogas is generated from biomass, producing electricity qualifies for renewable energy tax credits, where available. Another advantage for the plant is independence from the grid and therefore continued electricity during black-outs. This reliability is important for institutions such as computer data storage facilities and hospitals. For this reason, even in New York City, cogeneration has been in place for over a decade, at locations including Staten Island University Hospital, Methodist Hospital, Montefiore Hospital, St. Mary's Hospital, Verizon and the Red Hook Wastewater Treatment plant, where biogas from the anaerobic treatment of sewage sludge is used.

An alternative to producing electricity from biogas is cleaning the gas of carbon dioxide and marketing it as natural gas. The market for this option is established because of the natural gas infrastructure. The expansion into the higher value market of vehicular fuel would improve the economies of AD.

The production of biogas represents the most significant advantage of AD over composting. Between 70 and 80% of the energy content of the initial organic compounds is preserved in the methane, so growth in bacterial biomass is lower for anaerobic digesting than aerobic, resulting in greater volume and mass reduction (Mahony, O'Flaherty et al. 2002).

4.2 Digestate

The digestate leaving the chamber is a thick sludge with a moisture content of about 80%, close to the consistency of a milk shake. To transport this would be uneconomic, and so digestate is normally dewatered. The solid is reduced to a liquid content of about 50% - 70% and the remaining water can be collected. The smell of fresh digestate is unpleasant, and coupled with the malodorous characteristics of putrescible waste, it is necessary for these processes to occur inside a building with continuous air flow that is then passed through a biofilter.

The quality and composition of the dewatered solid depend on the feedstock and the digestion process. Only soluble organics are degraded in the digester, so other materials, such as glass or plastics, or trace elements, such as heavy metals or salts, will be present in the solid if they entered in the feedstock. For these reasons, companies intending to market their digestate must be vigilant in the screening of incoming waste. Additionally, even if digestion were allowed to proceed for long time periods, a maximum of only about 70% of the total organics are available for degradation, as seen in Figure 9 (Mata-Alvarez, 2003).

The safety of the digestate, measured by the concentration of pathogens present, is of great concern of end users. Pathogen destruction can be guaranteed at thermophilic temperatures with a high SRT (solid retention time). A sufficient degree of pathogen destruction can also occur at mesophilic temperatures and at lower SRT. In general, the lower the SRT, the more biologically active the solid will be. If solid digestion has occurred for at least 15 days, most of the organics have been degraded and the resulting solid is stable. If AD is being used strictly to reduce the volume of the waste before going to landfill, then biological activity, measured by BOD, of the digestate should be reduced as much as possible. If, on the other hand, the digestate will be used as a soil amendment, a biologically active solid is beneficial.

Many AD facilities post-treat the digestate aerobically, in a process known as curing, in order to produce high quality compost. AD does not reduce NPK content, making the digestate more valuable as a fertilizer (Mahony, O'Flaherty et al. 2002). Compost from digestate is produced at many AD sites in Europe, but without research addressing its safety and benefits in comparison to other compost, the degree of market penetration will be minimal. When this is established, AD can also be seen as an integral part of the disease management system in agriculture as well as urban settings (Wheeler, 2001).

The liquid remaining from the dewatering process can be used in three ways. Least advantageously, it can be discharged as sewage to a wastewater treatment plant, as it is too active to be discharged directly to fresh water. It can also be recycled in the process for waste pretreatment or to adjust the moisture content in the digester. Finally, it can be sold as a liquid fertilizer. Because nutrients are present in the liquid, this option is attractive. The logistics of transporting high quantities of water, however, usually make this option prohibitively expensive except where AD is used on farms.

The use of AD to treat solid waste is likely to be expanded, but the rate and degree of this expansion will depend on how well the products are marketed. Because there are multiple products, this process is more complex and additional resources are required to penetrate the varied markets.

5 System Classifications

The digestion efficiency and stability can vary significantly depending upon the type of digester used and the parameters of its operation. Digesters range in complexity from simple cylindrical cans with no moving parts to fully automated industrial facilities. The simplest, used in rural China and India, are easy to design and maintain, but require consistent monitoring and are less efficient. The most complex, on the other hand, are designed to automatically detect subtle changes in environmental conditions and warn operators, such as would occur with a change in the feedstock. The latter are used in developed nations to treat unpredictable waste flows, such as those from an OFMSW.

Design considerations for such facilities are capacity, vertical or horizontal orientation, batch or continuous flow total solids content, number of stages, mixing and pretreatment. The multitude of digester varieties are designed to optimize the process for specific geographic locations, types of waste, and other considerations. Each of these can be modified to provide the desired degree of autonomy and complexity.

5.1 Capacity

The capacity of a digester depends on the availability of feedstock. With MSW as the feedstock, urban or populated suburban areas are the most likely choice. The capacity of a system may include simply organics or mixed waste, in which case a separate materials recovery facility would be placed on the front end of the system, such as at ArrowBio in Israel (Finstein, 2003) or Canada Composting in Toronto (Cluff, 2003). As the systems have been proven to be reliable and economic, larger sizes have become more popular. The Friesland plant in the Netherlands, for example, has a capacity of 230,000 metric tons per year. (Grontmij, 2004) For MSW management systems in the developed world, the smallest digester that is economic is about 50,000 tons per year (Cluff, 2003). Many plants under construction are close to 100,000 tons per year. The size of individual chambers ranges from 70 m^3 to 5000 m^3 (Themelis and Verma 2004). Larger capacities are normally accommodated by the use of multiple chambers because incomplete mixing occurs when an individual chamber gets too large.

5.2 Orientation

The selection of a horizontally or vertically oriented tank depends on how material is intended to flow through the system. Vertical tanks are predominately gravity driven forcing the material to flow generally downward, though the exact path can very depending on interior boundaries in the chamber. In some cases, material is pumped into the bottom of the tank and removed from the top, causing general upward flow that is further mixed by a lesser, downward, gravity driven flow. While vertical tanks have a smaller footprint, this implies that stratification occurs over a smaller cross-sectional area, which in turn is harder to prevent. Horizontal tanks minimize the area over which the substrate can settle, but require greater space. It may take less input to mix a horizontal tank because the direction of settling is perpendicular to the direction of propagation.

5.3 Feedstock Pretreatment

There are a variety of pretreatment processes that are chosen based on the characteristics of the incoming waste and the effects they have on digestion. Separation technologies for metals, glass and plastic are usually necessary and similar to those used in material recovery facilities. This section will focus on pretreatment processes unique to the AD process.

Mechanical pretreatment reduces the size and solid content of entering waste, increasing the amount of soluble organics. Shredding, pulping, crushing, or otherwise reducing the size of the waste gives bacteria access to a greater surface area, reducing retention time. Diluting the waste with water also allows the bacteria to move more freely inside the digester. Sometimes the recovery of recyclable materials is done simultaneously with preparing the organic suspension.

In the BTA process, for example, a hydropulper sorts incoming MSW into heavy and light fractions of non-organic material as well as creating a mixed organic slurry (Cluff 2003). In another process, a method of jetting the waste into a collision plate has been tried to rupture bacterial cell membranes, form soluble waste and accelerate the availability of useable substrate. This was found to speed up the process of hydrolysis and reduce solids retention time without major effects on process efficiency and effluent quality. It also enhanced volatile mass reduction, which was attributed to the destruction of solids during pretreatment, and increased gas production (Nah, Kang et al. 2000).

Chemical pretreatment changes the composition of waste by reducing particulate organic matter to soluble form, i.e. proteins, fats, carbohydrates or lower molecular weight compounds (Karlsson and Goranssonh 1993). Chemical pretreatment has been tried in a variety of temperature regions, from 35 to 225°C and over a variety of times, from 15 to 120 minutes. Alkalis are added to boost the pH to 8-11 during this process. This strategy particularly helps with the degradation of fats, which is troublesome because of their insolubility in water and their semi-solidification in room temperature. In order for fats to be able to be digested by bacteria, they must be emulsified to enhance their bioavailability in water. Pretreating with sodium hydroxide, lithium hydroxide or potassium hydroxide increases the hydrolysis rate. (Mouneimne, Carrer et al. 2003) Thermochemical pretreatment has been shown to reduce retention time by 5 days, resulting in 5-10 day retention times (Li and Noike 1992; Lin, Chang et al. 1997).

Thermal and chemical pretreatments do improve hydrolysis and promote solubilization (Li and Noike 1989). Ultrasonic pretreatment also has been researched to reduce retention time (Shimizu, Kudo et al. 1992; Wang, Kuninobu et al. 1999). In one case, freezing the waste at -10°C was attempted (Wang, Kuninobu et al. 1999).

In a review of pretreatment procedures for AD, thermochemical pretreatment offered the best results (Kim, Park et al. 2003). In practice, however, designers recognize that a significant advantage of AD is its simplicity in operation, owing in part to low temperatures and pressures. The most common pretreatment, therefore, is simple and proven: separation followed by shredding.

5.4 Batch and Continuous Digesters

In AD process technology, two general models are used: the batch process and the continuous process. In the batch process, the substrate is put in the reactor at the beginning of the degradation period and sealed for the complete retention time, after which it is opened and the effluent removed. In the continuous process, fresh material continuously enters the tank and an equal amount of digested material is removed. There are distinct stages of digestion throughout the batch process whereas equilibrium is achieved in the continuous process.

On the simple end of the spectrum, AD occurs in sealed volumes in which the substrate resides for a predetermined amount of time and effluent is removed as a batch at the end of that time. Usually batch reactors are cylindrical, but on farms, where land is readily available, digestion can also occur in large covered lagoons. The process inside these types of facilities is identical to what occurs in bogs, rice fields and other naturally anaerobic conditions. The reaction stages occur more or less consecutively, and the production of biogas follows a bell curve with time. When waste is first loaded, hydrolysis takes place and gas production is low, forming only carbon dioxide. Methane production increases during the acid forming stages and is maximum halfway through the degradation period when methanogenesis dominates the processes. Toward the end of the degradation period, only the least easily digestible material remains, and gas production drops.

The sludge in a batch reactor is normally not mixed, allowing the content of the digester to stratify into layers of gas, scum, supernatant, an active layer, and stabilized solids at the bottom. Influent and effluent valves reside in the supernatent layer and solids must be removed near the bottom. Retention times range from 30-60 days with an organic loading rate between 0.48 and 1.6 kg TVS/m^3 reactor volume/day (Davis and Cornwell 1998). The disadvantage of this type of system is the large tank volume required due to the long retention time, the low organic loading rate and the formation of a scum layer. Only about 1/3 of the tank volume is used for active digestion, making this a poor option in crowded urban settings (Davis and Cornwell 1998).

In a continuous process, fresh substrate is added and an equal amount of effluent is removed in an ongoing process. With consistent feedstock input, all reactions occur at a fairly steady rate resulting in approximately constant biogas production. The structure for a continuous process can be identical to a batch process, a cylindrical tank with influent and effluent valves. Because there is constant movement, however, material inside the tank is mixed and does not become stratified. This allows for more optimal use of the tank volume. The disadvantage of the continuous process is the removed effluent is a combination of completely digested and partially digested material. To minimize the removal of partially digested material, some designs dictate the path of the digestate inside the chamber, for example through the use of interior walls. The reported residence time for a continuous process is an average across the substrate.

Mixed forms of these two models have been developed including the plug-flow reactor and the sequencing batch-reactor, which try to combine the advantages of the two extremes (United Tech 2003).

5.5 Staged Digesters

The first digestion facilities were simple, single chamber designs where every stage, i.e. hydrolysis through methanogenesis, occurred in the same volume. This approach is still the most often used in modern designs (Themelis and Verma 2004). Some recent designs, however, take advantage of the fact that the biochemical pathways of digestion occur in phases, each one optimized under distinct environmental conditions. The design physically separates the bacteria populations according to these stages; usually they consist of two stages, though some have as many as eight.

In a single stage digester, all of the bacteria exist in the same volume and the environmental conditions are kept at equilibrium. These parameters are not necessarily optimal for any bacteria, but are acceptable to all. The most crucial parameter is the pH, which must always be kept close to neutral in order to ensure the survival of the methanogens. A pH lower than 5.5, in which acidogens thrive, is fatal to methanogens. Once in operation, these digesters are simpler to operate than multi-stage digesters because the equilibrium is fairly stable.

In a multiple stage digester, the substrate is transported to sequential chambers where progressive stages of AD occur according to prescribed timing. Each chamber maintains environmental conditions most favorable to the bacteria present. If two tanks are used, the first tank allows hydrolysis, acidogenesis and acetagenesis to occur while the second optimizes methanogenesis. The first tank is mixed and heated to a uniform temperature and fed continuously. The pH is allowed to fall. The residence time in this chamber is anywhere from 10-15 days. The second tank must maintain a higher pH and provide capacity for gas collection or storage. In more complex multiple stage digesters, up to eight tanks are used, with each tank having a unique purpose and living environment. There have not been studies on the optimal number of tanks.

Two-stage digesters can be more efficient because the microorganisms have separate nutrient needs, growth capacities, and abilities to cope with environmental stress. The need to construct multiple tanks, however, may offset the cost savings incurred by reduced retention time. Additionally, the BOD is higher at the conclusion of a multiple stage digester, and total solids can be as high as 12,000 mg/L (Davis and Cornwell 1998).

There are other multiple stage systems with different criteria for separation. In the BTA process, described in detail later in this thesis, solids and liquids are separated. Incoming waste is pulped and dewatered, and the liquid, which contains soluble organics, is sent immediately to a methane-producing tank. The remaining solid is hydrolyzed in a different tank, dewatered, and the liquid from that tank is also sent to the methane-producing tank. The advantage to this system is that it can take advantage of the significantly lower retention time of liquids compared to solids (Cluff, 2003).

5.6 Solids Content

Digestion is practiced in two broad categories of solid content: “dry digestion,” with a typical dry solids content of 25-30% and “wet digestion,” with a dry solids content of less than 15%. When the feedstock is MSW, both systems require adding water to the feedstock in order to lower the total solids (TS) content.

A higher TS contents leads to smaller, and thus less costly, reactors. This price savings may be offset, however, by the more expensive pumps needed to move denser material. Higher TS values cause excessive resistance to flow in pipes as well (Nichols 2004). Furthermore, the higher solid content puts more wear and tear on the machinery, requiring more maintenance. Systems with lower TS tend to have much better mixing, thus increasing the degree of digestion. It also is more ammenable to codigestion with more dilute feedstocks, such as sewage sludge or manure (Gas Technology 1998). On the other hand, they require a larger reactor and higher energy input because there is more substrate to be heated. For many waste streams, large amounts of water must be added to reduce the solids content, thereby adding to cost of either purchasing water or dewatering the sludge to reuse process water. Additionally, lower TS values tend to have heavy particles, such as sand and glass, settle to the bottom.

In a gravity driven system, the material is fed into a vertically oriented chamber from the top and effluent removed at the bottom, with gravity being the only driving force to bring the waste through the bacteria population living in the chamber. For this system, the ideal solids content is 2-10% (Energy 2003). In a plug-flow digester, undigested slurry enters at one end of a long, horizontal tank and pushes material through the chamber where it is removed at the other end (Energy 2003). This is suitable for a higher solids content, ranging from 11-13%, because it forms a more viscous material and the digested material moves along as a plug through the tank. The method of propagation differs between these two, but otherwise the mechanisms are the same, as are the degrees of digestion and retention times.

5.7 Mixing

The way in which materials flow through the digester impacts the degree of contact substrate has with resident bacteria and therefore how quickly it is digested. In the earliest systems, such as covered lagoons, the feedstock simply sits in a large bath and decomposes without mixing. Improvements on this system focused on changing the way materials flow, such as in complete mix digesters and plug-flow digesters, or in the way materials are mixed, such as through agitation, gas injection, or recirculation.

Mixing can take place as a result of the pathway the waste must travel before it is removed. Some systems have interior walls in a cylindrical chamber that require a greater distance traveled for the waste, thereby increasing mixing.

The material inside any digester may be further mixed through mechanical or gas mixers that keep the solids in suspension. Often biogas is bubbled through the chamber as an inexpensive way to promote movement. Recirculating digested waste continuously through heat exchangers both improves mixing and ensures proper temperature control. Mechanical mixers inside tanks are less common because maintenance is extremely difficult. Sealed tanks must be shut down in order to access interior machinery.

Mixing can also be achieved through the recirculation of waste. After digestate is removed from the chamber at the end of its retention time, a percentage of it is fed into the stream of incoming fresh waste. This serves to inoculate the fresh waste with bacteria and increase movement in the chamber, which prevents the buildup of a scum layer. Excessive mixing, however, may disrupt microbes.

6 Parameters in Anaerobic Digestion

The complete process of anaerobic digestion requires a complex interaction of several varieties of bacteria that must be in equilibrium in order for the digester to remain stable. Changes in environmental conditions can disturb the equilibrium and result in the build-up of intermediaries that may inhibit the overall process or shut it down altogether. It is crucial for the manager to use design control technologies to continually monitor and adjust the environment to prevent this.

Several factors within the digester effect the physical environment and therefore the rate of digestion and biogas production. Facility managers must monitor and maintain the following parameters within acceptable ranges: pH, temperature, C/N ratio, retention time, organic loading rate (OLR), bacterial competition, nutrient content, the presence of toxicants and solids content. The optimal ranges and importance of these parameters are discussed below. Falling outside these ranges can cause digester failure, an expensive misstep as start-up is a slow process.

6.1 pH

A primary gauge of digester health is the pH level, which changes in response to biological conversions during the different processes of AD. A stable pH indicates system equilibrium and digester stability. A falling pH can point toward acid accumulation and digester instability. Gas production is the only parameter that shows digester instability faster than pH. The range of acceptable pH for the bacteria participating in digestion is from 5.5 to 8.5, though the closer to neutral, the greater the chance that the methanogenic bacteria will function (Golueke, 2002). Most methanogens function in a pH range between 6.7 and 7.4, and optimally between 7.0 and 7.2.

The greatest potential for digester failure is a result of acid accumulation. This would occur if the amount of volatile solids loaded into the digester as fresh waste increased sharply. The acidogenic bacteria would then thrive, producing high volumes of organic acids and lowering the pH to below 5.0, a level lethal to methanogens. This creates a positive feedback loop as a declining methanogen population will in turn lead to further acid accumulation as the methogens are responsible for consuming acids. An acidic pH indicates that this process has already begun, and immediate action is required, such as by recycling more water. On the other hand, prolific methanogenesis may result in a higher concentration of ammonia, increasing the pH above 8.0, where it will impede acidogenesis (Lusk 1999). This can be opposed by adding a greater amount of fresh feedstock, which will spur acidogenesis and acid formation.

Maintaining pH is especially delicate in the start-up because fresh waste must undergo acid forming stages before any methane forming can begin, which will lower the pH. To raise the pH during the early stages, operators must add a buffer to the system, such as calcium carbonate or lime. The same procedure is followed when the pH drops during operation, for example due to increased loading rate.

It is the responsibility of an operator, therefore, to keep bicarbonate alkalinity as high as possible in order for the pH to remain high enough for methanogens to survive (Vlyssides and Karlis 2003). It may be necessary at times to add alkali, either sodium or potassium hydroxide, to neutralize acids. A bonus of adding alkali is that it induces swelling of particulate organics, making the cellular substances more susceptible to enzymatic attack (Baccay and Hashimoto 1984).

In the past, an AD operator diagnosed problems with the digester when the pH would fall, signifying an increase in VFAs and therefore decreased activity with the methanogens. The cause of the initial difficulties for the methanogens could remain unknown. With new technologies, however, monitoring of conditions earlier in the process, such as gas production, can save the digester from going into such shock.

6.2 Temperature

Due to the strong dependence of temperature on digestion rate, temperature is perhaps the most critical parameter to maintain in a desired range. As Figure 8 shows, anaerobic bacteria can survive in a wide range of temperatures, from freezing to 70°C, but thrive within two ranges: from 25°C (77°F) -40°C(104°F), the mesophilic range, and from 50°C (122°F) to 65°C (149°F), the thermophilic. The optimum temperature for mesophilic digestion is 35°C (95°F) and a digester must be maintained between 30°C and

35°C for most favorable functioning. (United Tech 2003) The rate of AD Process shown in figure 8 is measured by gas production rates, growth rates and substrate degradation performance.

Choosing between operating in either of these temperature ranges involves trade-offs. Thermophilic digestion allows higher loading rates and achieves a higher rate of pathogen destruction as well as a higher degradation of the substrate. It is, however, more sensitive to toxins and smaller changes in the environment and is less attractive from an energetic point of view since more heat is needed for the process (United Tech 2003). Furthermore, thermophilic cultures require a month or more to establish a population (Golueke, 2002). Bacteria operating in the mesophilic range are more robust and can tolerate greater changes in the environmental parameters, including temperature. Temperature fluctuations can be extreme in smaller digesters, poorly insulated digesters or digesters in cold climates, suggesting that these would benefit by being run in the mesophilic range to minimize system crashing. The stability of the mesophilic process makes it more popular in current AD facilities, but at the expense of longer retention times.

Temperature is carefully monitored in all modern digestion facilities through temperature probes at various locations in the chamber. Digester heat is lost through convection or radiation to the surrounding or through the formation of water vapor. Temperature can be maintained through insulation, water baths or through passive solar heating. Heat can be added using heat exchangers in the recycled slurry or heating coils or steam injection directly into the digester.

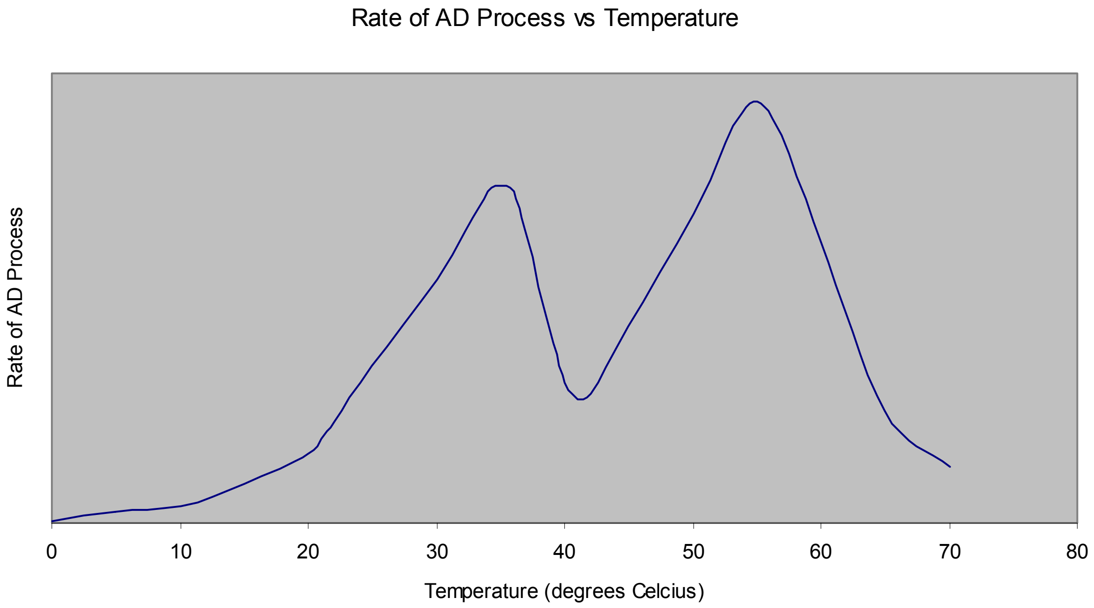

Figure 9, Rate of AD Process vs Temperature (Golueke, 2002)

6.3 C/N Ratio

The Carbon/Nitrogen Ratio is a measure of the relative amounts of organic carbon and nitrogen present in the feedstock. This ratio may either be monitored explicitly or managers may simply keep track of the types of waste entering the facility, knowing the relative make-up of each. For example, proteins such as meats are high in nitrogen while paper products contribute relatively more carbon. If a feedstock is high in carbon, manure can also be added to increase nitrogen. As with composting, the optimum C/N ratio is between 20-30, with most sources citing 25 as the ideal level. A low C/N ratio, or too much nitrogen, can cause ammonia to accumulate which would lead to pH values above 8.5. Additionally, the quality of the compost is lessened with high ammonia production. A high C/N ratio will lead to a rapid consumption of nitrogen by the methanogenic bacteria and lower gas production rates.

6.4 Retention Time

The amount of time that feedstock stays in the digester is known as retention time or residence time. The retention time is determined by the average time it takes for organic material to digest, as measured by the COD and BOD of exiting effluent. The longer a substrate is kept under proper reaction conditions, the more complete its degradation will be. The rate of the reaction, however, will decrease with increasing residence time, indicating that there is an optimal time that will achieve the benefits of digestion in a cost effective way. The appropriate time depends on the feedstock, environmental conditions and intended use of the digestate.

The retention time for most dry processes ranges between 14 and 30 days, and for wet processes can be as low as 3 days. The optimal value varies according to the specific technology in place, the process temperature and the waste composition. A good facility manager will take all of these factors into consideration as she determines the retention time. For a specific digester, therefore, the retention time may change from day to day (with changing feedstock) or from season to season (with changing temperatures.) Recent research has shown that volatile suspended solids in a digester could be reduced by 64-85% after only 10 hours, but retention times of 10 days were typical for complete digestion (Lin, Chang et al. 1997; Vlyssides and Karlis 2003).

Reducing retention time reduces the size of the digester, resulting in cost savings. Therefore, there is incentive to design systems that can achieve complete digestion in shorter times. A shorter retention time will lead to a higher production rate per reactor volume unit, but a lower overall degradation. These two effects have to be balanced in the design of the full-scale reactor (United Tech 2003). Several practices are generally accepted as aiding in reducing retention time. Two of these are continuous mixing and using low solids.

One method generally accepted for minimizing residence time is mixing the digester. Though the most favorable degree of mixing is debatable, most digesters perform some sort of mixing in order to minimize settling within the tank. One method is to recirculate water and biogas in the chamber to keep material moving. This will ensure that bacteria have rapid access to as many digestible surfaces as possible and that environmental characteristics are consistent throughout the digester. A poorly mixed digester will form stratified layers, leading to less working volume and longer retention times. If continuously loaded, large portions of undigested material may exit an unmixed digester.

Decreasing solid content is also known to reduce retention time both because the bacteria can more easily access liquid substrate and because the relevant reactions require water. An additional benefit to lower solids content is that mixing is more complete when the solid content is lower. Many waste streams already have low total solids, such as wastewater, dairy process waste or brewery waste. For other feedstocks with variable solid content, such as MSW, there are methods of lowering it. The German technology ISKA uses a mechanical-biological pretreatment process known as percolation to reduce the solids and increase organic loading. The percolator is a horizontal, continuously operating, cylindrical reactor with a hydraulically driven central shaft and a scraper located over a grate. Soluble substances are washed in the liquid phase over a period of two days by agitating with recirculated high organic load water from the dewatering of solids. The process water leaves through grate while solids are fed to a dewatering screw press. After minerals and fibers are removed, the low solid waste is treated in an anaerobic digester made up of a combination of a solid and fluidized bed reactor (U-Plus 2002). As is demonstrated by this technology, decreasing the solid content comes at the expense of adding significant quantities of water and heavy machinery.

There are also six areas in which new research into reducing retention time has been focused. The first is to separate the stages of the digestion into individual chambers so that the bacteria population in each chamber is optimized for its purpose. Another option is alternating the flow pattern to improve circulation within the chamber. A third alternative is to introduce a surface or combination of surfaces to the chamber on which the bacteria can live permanently, reducing the size of the population that is washed out with the effluent. Strict environmental control of the environment is another way to reduce retention time. The final approach is to use one of various methods of pre-treating waste to increase digestibility. Each of these advances is designed for a particular feedstock, but the principles can be combined for MSW.

6.5 Organic Loading Rate

The final parameter to control is the organic loading rate (OLR), which determines how much volatile solids are input to the digester. A higher OLR will demand more of the bacteria, which may cause the system to crash if it is not prepared. One danger of increasing the OLR would be that the acidogenic bacteria, which act early in the digestion process and reproduce quickly given enough substrate, would multiply and produce acids rapidly. The methanogenic bacteria, which take longer to increase their populations, would not be able to consume the acids at the same pace. The pH of the system would then fall, killing more of the methanogenic bacteria and leading to a positive feedback loop, eventually halting digestion. An early indication of this is lowered biogas production and eventually a lower pH.

Other parameters that can be monitored are the partial pressure of H_2, bacterial competition, nutrient content, the presence of toxicants, solids content and methane formation. Each of these would signify a deviation from equilibrium that would give the operator warning, allowing him to restore equilibrium before too many bacteria die (VanRollegham 2003).

Monitoring all of these parameters inside the digestion chamber would be tasking even for the most experienced facility managers, especially when added to the responsibility of monitoring other facility needs, such as volume of waste, level of contaminants, and biogas and fertilizer management. For most large scale facilities, therefore, these environmental parameters are electronically measured through probes inside the chamber and monitored through custom built software. When any one of them falls outside of the desired range, it is up to the manager to determine why and respond to the issue.

7 MSW and AD

An AD facility designed to treat the OFMSW harnesses the reactions described in Section 4 by creating an environment that provides optimal conditions for the microorganisms, thereby increasing energy production. A typical AD facility has six major components, as illustrated in the diagram below. The first is a tipping floor where trucks deliver organic waste, in either solid or liquid form. In the second stage, the waste is pretreated and contaminants removed. The next stage is the digester where biological degradation occurs. The fourth component treats the solid product and the fifth cleans and consumes the biogas. The final component is a biofilter, which ensures that offensive odors do not leave the facility.

On the tipping floor, waste is received and large, non-digestible objects are removed. The feedstock can include any organics, ranging from food scraps to unmarketable food products to yard waste. On average, this feedstock is extremely wet, with a moisture content between 50 and 70% (Themelis and Verma 2004). Paper and cardboard can also be included in the feedstock, but they are primarily lignocellulosic organics that do not readily degrade anaerobically, and are therefore better suited for recycling (Themelis and Verma 2004).

A facility's tipping floor receives large quantities of organic waste that is subject to rapid decay. This may create odor, attract rodents and cause health and safety hazards if the waste is not removed quickly. The tipping floor, therefore, should be designed to move waste efficiently into the pretreatment facility. Notches in the walls, cracks in the floor, or irregularly shaped objects in the receiving area have the potential to trap raw feedstock and cause the problems listed above, and should be avoided.

The purpose of the pretreatment stage is to remove contaminants and reduce the organics into an easily digestible pulp. The ideal feedstock for an AD facility is source-separated, pure organics, but this will not be feasible in many situations, and so the incoming waste must be sorted and cleaned. Depending on the purity of the feedstock, this may include multiple stages. The removal of glass, metal and plastics occur in much the same way as material recovery facilities. The way in which the organics are made into a pulp varies greatly among manufacturers. Typical methods include shredding, blending and spinning. The result is a homogenous mixture of pure organic material with very little inorganic contamination.

The pulp feed next enters an AD chamber, a sealed, usually cylindrical tank where bacteria decompose the waste to produce biogas and a humus material. The entering waste is often diluted with recirculated liquid from the dewatering of the product. This serves both to inoculate fresh waste with bacteria as well as establish the proper moisture content. The residence time in the digester is between 14 and 30 days for high solid digesters and as low as three days for liquid digesters. The timing depends on the volume of the digester, the loading rate of the feedstock, the removal rate of digestate, the temperature of the digester, the volatile solids content of the feedstock and the desired degree of digestion. In most cases, a heating mechanism is needed to maintain the digester at the desired temperature.

In the next process area, the solid is prepared for the market as a soil amendment. The first step is removing excess water, as the moisture content of the digestate can be as high as 70%. This can be achieved using a screw press, a belt press, a centrifuge or another separating technology. After preliminary dewatering, the digestate is further dried and aerated for between two weeks and a month to produce compost. To adapt to urban space constraints, this process can take place offsite by transporting the wet material to a location outside of the city.

A separate area treats and uses the biogas, and includes a gas storage facility, a scrubber, and cogeneration machinery to produce electricity and heat. The rate of production of biogas is fairly regular, even though the facility's electricity use is not. Some gas may need to be stored, therefore. A spherical tank capable of withstanding high pressure is the most common storage facility. The treatment of the gas after storage involves removing water vapor as well as trace contaminants such as ammonia and hydrogen sulfide. Finally, a facility will include equipment to use the biogas, either a boiler for heat or an electricity generating machine such as a fuel cell (running on hydrogen produced from biogas), a microturbine or a cogeneration engine. The electricity produced can be used to power the facility and the waste heat can be used in the digester.

The final area is the biofilter, as shown in Figure, which filters the air through the plant to eliminate offensive odors to the surrounding area. Odor control can be improved by placing the facility under negative pressure and filtering all of the exiting air through the biofilter. The biofilter can be composed of a field of woody chips that complete the degradation of organics as the gas passes through.

These six components are the basis of a modern AD facility. The specifics of each component differ from process manufacturer to process manufacturer and from location to location, as discussed in the next section.

8 Commercial AD Processes treating MSW

Environmental legislation prohibiting landfilling of organics has driven research of anaerobic digestion technologies for food residuals in the European Union. The increasing number of companies that have proven economic viability of such projects has further encouraged its expansion. Though other nations are slowly investigating the technology, the primary development is in Germany, Switzerland and Denmark, where several AD companies treating MSW are successful.

Most AD facilities incorporate the six stages described in the previous section with some differences in the pretreatment processes and to a lesser extent in the post-treatment of the products. Structurally, the AD chambers are similar, though operating parameters also vary between treatment processes. Table 4 summarizes these differences.

8.1 BTA

The BTA process was initially developed by Biotechnische Abfallverwertung GmbH & Co KG in 1986 to treat OFMSW from households, agriculture and commercial plants. The first industrial scale plant was constructed in Elsinore, Denmark in 1990 with a capacity of 20,000 tons per year (Nichols 2004). There are currently 22 BTA plants in operation and four are under construction (BTA 2004). Three companies hold site liscences for the BTA process, including Canada Composting, Inc. in Toronto, Hitachi Zosen Co. in Tokyo, and BIOTEC Sistemi S.r. in Italy.

The BTA process begins with mechanical wet pretreatment, where feedstock and recirculated process water are mixed into a pulp in a patented machine known as the hydropulper. For mixed waste, contaminants are separated mechanically using a rake and a heavy fraction trap. The suspension retains the organics, which are pulped into a slurry that has a higher concentration of organic material, smaller surfaces and flows easier than the incoming waste, thereby making organics more accessible to microorganisms. The pulp is subsequently pumped into a grit removal system known as a hydrocyclone that removes the finest materials, such as sand, small stones and glass splinters. The result is a clean, thick suspension that can be pumped into the digester.

Several different designs for the biological conversion are offered by BTA according to the plant capacity and the use of the biogas and compost. One option for small, decentralized units is a one-stage reactor that ferments the pulp in one mixed fermentation reactor. This complete process is shown in Figure . For plants with a capacity of more than 50,000 tons per year, the multi-stage digester was developed, separating the pulp in a solid mass and a liquid phase by using a dewatering aggregate. The dewatered solid is mixed with fresh water to increase the moisture content and fed into a hydrolysis reactor for 4 days. After hydrolysis, the solid is dewatered again, and the liquid is pumped into the methane reactor along with liquid from the original dewatering. The retention time in the methane reactor is 2 days. This process, which ensures optimum environmental conditions for each stage of digestion, is shown in Figure 11. The same process can also be carried out without the solid/liquid separation in a two stage facility for medium capacity plants. The biogas produced at BTA plants is 60-65% methane and the water needs are met entirely by recirculating process water. The solid digestate is aerobically cured for 1-3 weeks (BTA 2004).

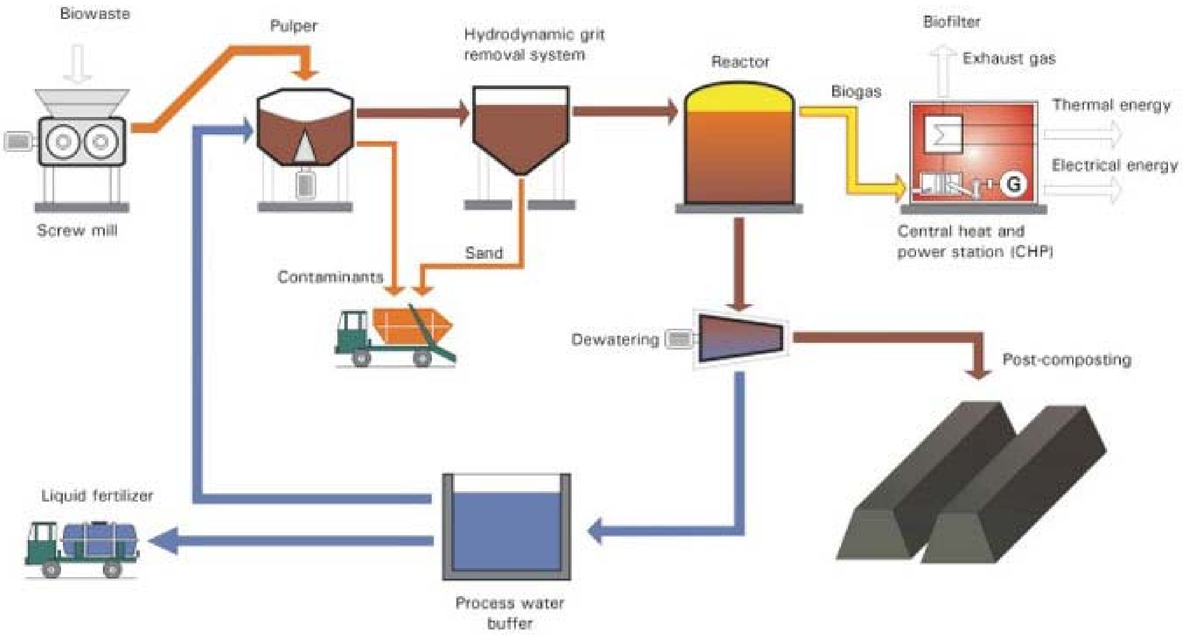

Figure 10 BTA Single Stage Reactor (Canada Composting, 2004)

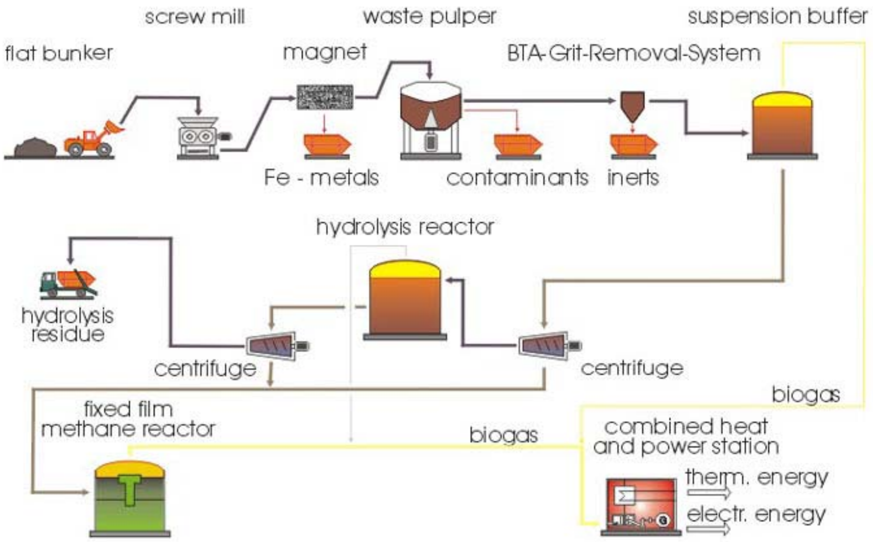

Figure 11 BTA Multi-stage Reactor (Canada Composting, 2004)

8.2 Valorga

The French company Valorga International SAS was formed in 2002 by Steinmuller Valorga Sarl, which was initially founded in 1981 as a MSW treatment company. The first Valorga process pilot plant was built in 1982 in the company's home of Montpelier, France. In 1988, the company started the first factory in the world to treat household waste by continuous anaerobic digestion with a high solids in Amiens, France. Valorga currently runs eleven plants to treat mixed MSW, SSOW and gray waste.

The pretreatment in the Valorga process uses an automatic separator to divide the waste into the organic fraction, including fermentable material, paper and cardboard, and non-organics. The waste is mixed into a thick sludge, with a TS content of 20-35%, and introduced at the bottom of the reactor, which can be thermophilic or mesophilic. The single stage reactor is a vertical, plug-flow cylinder with an inner wall that forces material to go up and around it before being extracted from the bottom. This geometry guarantees that waste has a residence time of 3 weeks in the fermentation chamber, ensuring complete hygenization. Mixing in the digester is done without mechanical mixing equipment through a pneumatic pump that injects biogas into the base of the reactor. The digestate is dewatered through gravity extraction and pressing. Part of the extracted liquid is used to dilute incoming waste and the rest is discharged in sewage. The solid cake, with a TS content of about 40%, is treated aerobically for about two weeks to completely stabilize it. Inert material is separated from the compost through a rotary screen. The biogas is used for heat, electricity, or is purified to natural gas. A biofilter treats the gases produced to eliminate odor (Valorga 2004). It should be noted that the Valorga process is ill suited for low solid concentration "wet digestion," as sedimentation of heavy particles inside the reactor will occur at a TS content less than 20% (Nichols 2004).

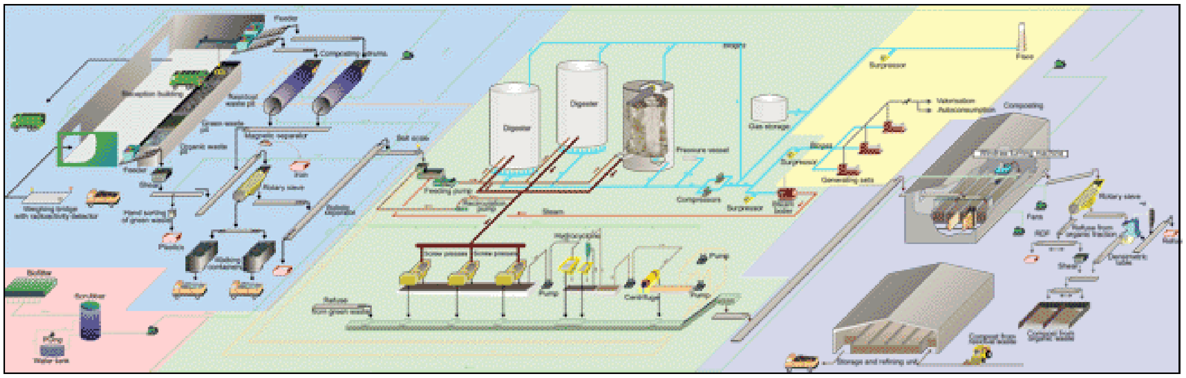

Figure 12 Valorga Processing Unit (Valorga 2004)

8.3 *Linde-KCA/BRV*

Linde-KCA-Dresden GmbH is a subsidiary of Linde AG Wies-baden, a 9 billion Euro engineering group based in Germany. One concentration of the Linde-KCA-Dresden Gmbh is the biological and mechanical treatment of waste. Linde began processing MSW using AD in 1980 and operates over 70 mechanical-biological waste treatment plants worldwide. Linde offers two types of digestion, wet and dry. The Linde wet digestion systems are either one or two stages and can be mesophilic or thermophilic. These plants include pulping waste with water and contaminant removal using a drum screen. The defining characteristic of the Linde system is the gas recirculation in the digester using a centrally located drought tube that also supplies heat. Many wet digestion plants employ codigestion with sewage sludge or manure. Upstream of the digester, the feedstock is treated aerobically allowing hydrolysis and acid formation to occur. The dry digestion process, for 15-45% TS, uses horizontal plug flow reactors of a rectangular cross-section. The dry digestion is particularly suited for mixed MSW and yields biogas at a rate of 100 m3/metric ton of feedstock. The digested solid material is dewatered in a centrifuge and treated aerobically by means of the aerated pile process, tunnel composting or the intensive composting module. Linde has headquarters in Germany, Austria and Switzerland (Linde-KCA 2004).

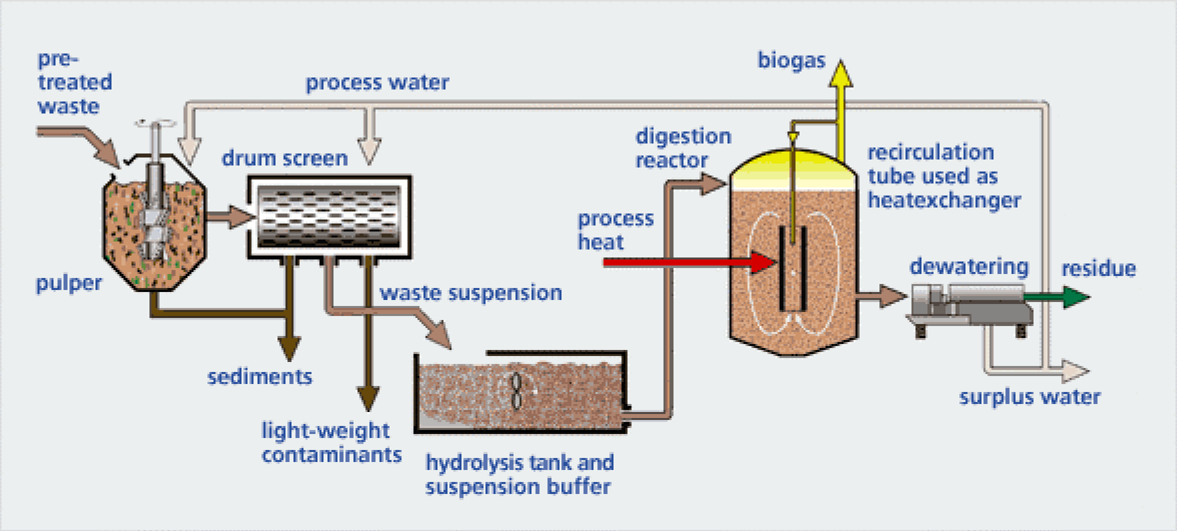

Figure 13 Linde Wet Digestion (Linde 2004)

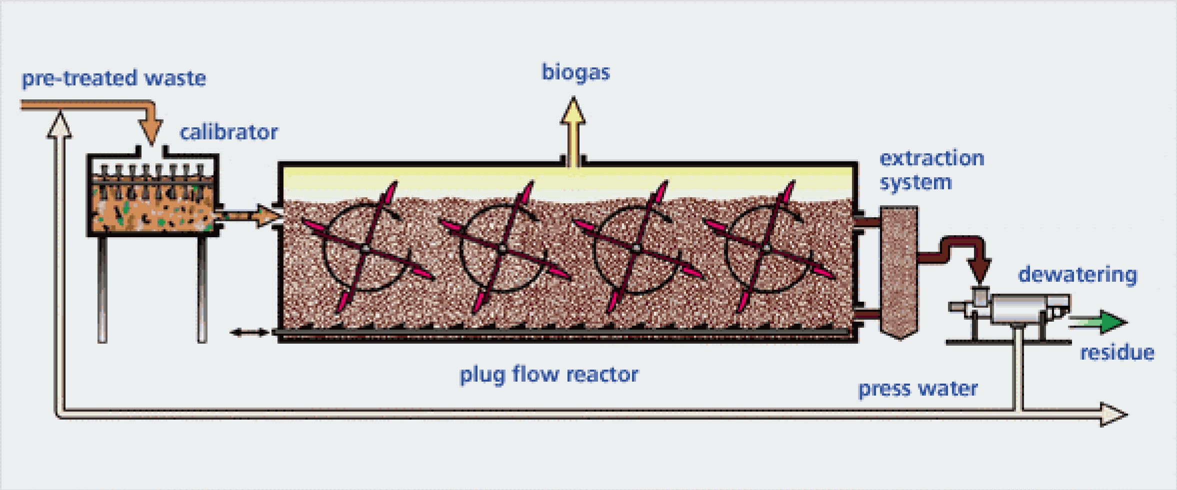

Figure 14 Linde Dry Digestion (Linde 2004)

8.4 DRANCO

Organic Waste Systems of Belgium developed an AD demonstration plant in 1984 in Gent, Belgium. The first full scale commercial plant employing the patented DRANCO process was in Brecht, Belgium with an annual capacity of 20,000 metric tons. Organic Waste Systems currently operates thirteen full scale plants worldwide using the DRANCO process.

Today plants employ the DRANCO process as part of the SORDISEP process (SORting, DIgestion and SEParation) of municipal and industrial waste for a maximum recovery of recyclables and energy. In the dry sorting step, Refuse Derived Fuel (RDF), ferrous and non-ferrous metals are recovered. The remaining feedstock is mixed with digested material, usually at a ratio of 1 part fresh waste to 6 parts digested, to form a mix of 15-40% TS content. DRANCO digestion is a single stage, vertical gravity driven plug flow system, where the waste is introduced at the top of the chamber and removed at the bottom with no other means of mixing. The system is run at low pressures and thermophilic temperatures with a 15-30 day retention time. Biogas production ranges from 100 to 200 m^3/ton of waste. The final step is wet separation, in which sand, fibres and inerts are recovered. The solid digestate is dewatered to about 50% and then processed aerobically for two weeks to stabilize and sanitize the material. The biogas can be stored temporarily and purified before being sold (Organic Waste Systems 2004).

8.5 Kompogas

Kompogas was started in Switzerland at the end of the 1980's by Walter Schmid. With financial support from the Swiss government, the first Kompogas plant was put through in a trial phase in Rümlang, Switzerland in 1991. The company now claims 20 plants and seven others under construction or planning (Kompogas 2004).

Most of the feedstock for Kompogas plants comes from municipalities that support source-separated collection. When it enters the plant, the waste is first mechanically treated to remove ferrous materials and then sent through a size-reduction process. Material is also separated to undergo thermal treatment or biological treatment. The organic portion is placed in intermediate storage to ensure a constant flow into the feeder, which produces a homogenous mixture able to be pumped. After passing through a heat exchanger, it is sent to the digestion chamber, a thermophilic single-stage, horizontal plug-flow reactor, for 15-20 days. Undesirable germs and weed seeds are eliminated in this process. Slowly rotating intermittent propellers help to push the waste through the digester, to homogenize and degas the pulp and to keep heavier particles in suspension. The system must be carefully monitored to maintain the solid content between 23 and 28% so that flow can continue unimpeded and heavy particles remain in suspension (Nichols 2004). Due to the mechanical requirements of the system, the size of the reactors is limited. Added capacity at one site is satisfied by installing additional reactors in parallel. This modular design reduces capital construction costs as well as allowing for a wide range of facility sizes, from 5,000 to 100,000 metric tons per year (Kompogas 2004).

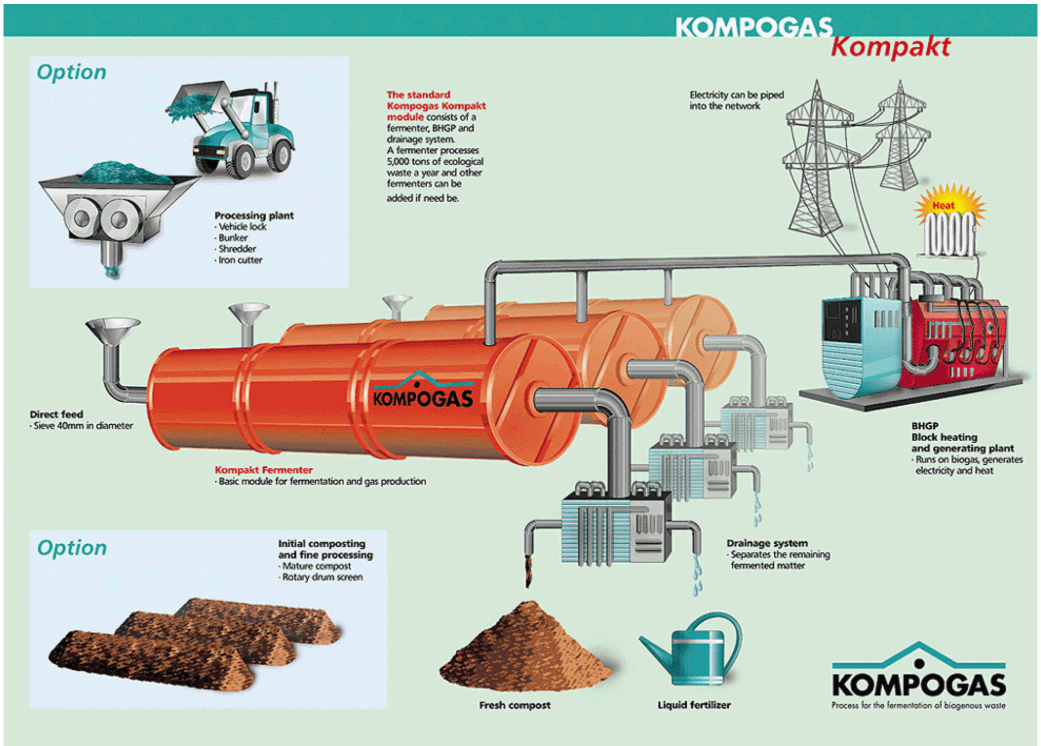

Figure 15, The Kompogas System

The biogas fuels a cogeneration unit that provides 100% of the facility needs as well as additional electricity for sale. In some cases, the biogas is upgraded to natural gas standards for use in vehicles or input to the natural gas network. The extensive natural gas fueling stations in Switzerland allow the gas to be used frequently in the transportation sector, giving rise to a Kompogas-driven vehicle fleet. The digestate is separated into liquid fertilizer and solid compost, both of which are marketed. The solid undergoes additional aerobic curing for three to four weeks in an enclosed facility. For the materials to be sent to landfill, the solid undergoes a total of six weeks of anaerobic stabilization (Kompogas 2004).

8.6 WASSA

The WAASA process, developed by Citec in 1984, has operations in Finland, Sweden, Japan, Spain, France and the Netherlands with annual capacities ranging from 3000-85000 metric tons (Citec, 2004). The process offers waste management options for MSW, slaughterhouse waste, fish waste, industrial liquid waste and codigestion of sewage and household waste.

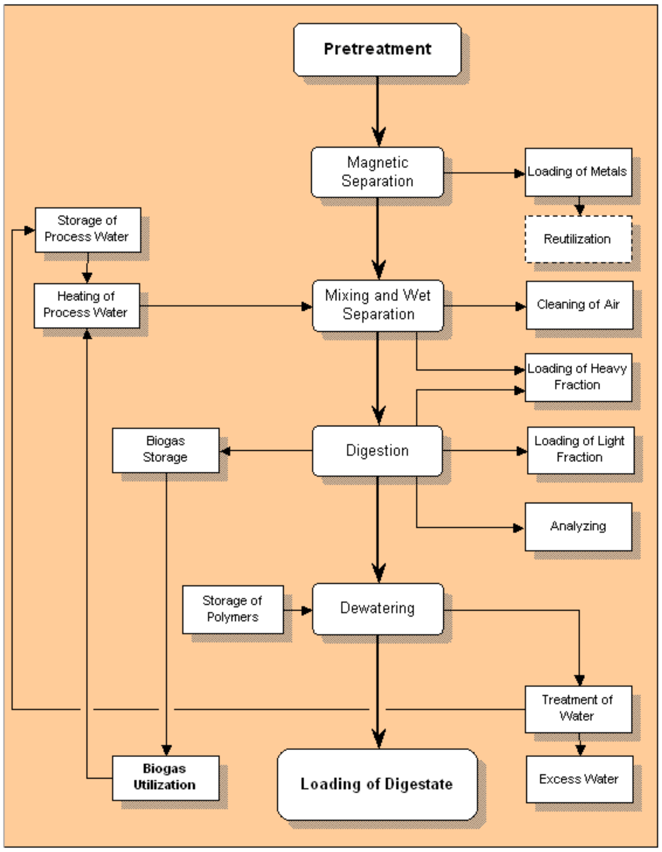

Figure 16, The WASSA Process Diagram

Metals are removed first and the feedstock is then mixed with process water for wet separation. Digestion occurs in a vertical digester and is carried out at either mesophilic or thermophilic temperatures with a TS content of 10-15%. The digester consists of a single vessel that is subdivided internally to create two separate chambers, dividing the single stage reactor into two stages. Mixing is attained through injection of biogas at the base of the reactor and through top mixing when digesting household waste. The digestate is dewatered and can be aerobically composted, depending on the type of waste. The WASSA process achieves 60% volume reduction and 50-60% weight reduction (Citec 2004).

8.7 Maltin

Organic Power Ltd is a British company formed in 1997 to develop and license the patented Maltin® System, which it developed from the concepts of Christopher Maltin and his team at Maltin Pollution Control Systems (1967) Ltd. The Maltin System changed the shape of a digester to ensure more complete mixing. The typical shape of an upright digester is a cylinder, which provides a stable platform, no sharp corners and the greatest volume for minimal surface area. Construction costs are also minimal for cylindrical digesters because they are a standard size. The Maltin System suggests that the digestion process can be improved by changing the shape of the digester to a minimal energy curve produced by folding one end of a rectangular metal sheet onto itself, as seen in Figure. Material enters from one lobe, for example the left, and is removed downstream from the opposite lobe, the right in this case. Additionally, biogas is bubbled through the tank, up from the center cusp, forming a barrier across which the undigested material can not cross. This set-up dictates the flow pattern inside the tank and guarantees that the sludge will undergo a full circuit before being allowed to transfer into the next tank. Additionally, the Maltin system uses eight consecutive tanks, further ensuring that the material will be fully digested as it leaves the final tank. As with other multiple stage digesters, the conditions of each tank are optimized for the processes occurring inside (Maltin 2003).

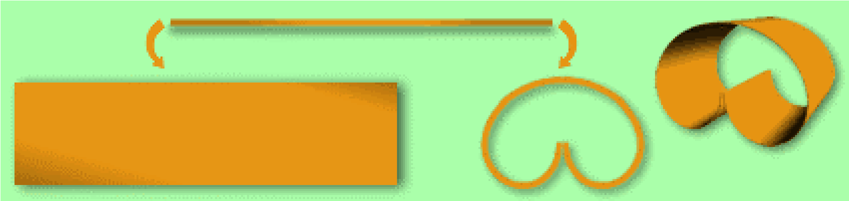

Figure 17 The Maltin Tank (Organic Power 2004)

Christopher Maltin, the designer of this system, has been known to drink process water that is removed from the final tank. This is dangerous in a continuously mixed system because undigested material always leaves the tank, having not been required to follow any flow pattern. For example, a continuous digester with a retention time of 30 days will add and remove 1/30 of the tank volume every day. If the tank is thoroughly mixed, about 1/30 of the volume removed will have only entered the tank on the previous day. This passes inspection because that portion is sufficiently diluted by the fully digested material in the effluent. The Maltin system controls the flow of the material, the length of time it remains inside the digesters and therefore the degree of digestion. Though this system maintains a 15 day retention time, the final organic loads are far lower than traditional tanks, suggesting that the retention time could be cut by using fewer tanks (Maltin 2003).

8.8 HIMET

Gas Technologies, Inc. has developed a multiple stage process to minimize retention time and maximize the production and concentration of methane in biogas. Their systems are called the HIMET Process and the SOLCON design. The HIMET Process is a two stage reactor that physically separates acidogenic and methanogenic bacteria into two smaller tanks, maximizing their growth by maintaining optimum conditions in each tank for that particular group of bacteria. The first group is grown in the acid digester where the pH is naturally low and the residence time is maintained between 1-3 days. The methanogens grow in the methane digester where the pH is higher and residence times range from 7-10 days, depending upon the waste characteristics. When feed is transferred from the first to the second digester, the acidogenic bacteria can not thrive as they have already consumed most of the feed material. Alternately, the methanogenic bacteria will die in the acidic first digester. The two-stage process of GTI was a winner of *R&D* magazine's "R&D

100" award for being "one of the 100 most technologically significant products or processes of 1996." The system provides higher efficiencies, a more stable design, a higher throughput, smaller tank sizes by 40-60%, higher methane content in the biogas (65-75% methane vs. 50-55% for conventional technologies), higher pathogen destruction, and lower volatile solids in the digested solids, thus producing much lower odor and more stable soil conditioners (Gas Technology 2003).

8.9 ArrowBio

The ArrowBio process, developed by Arrow Ecology, is new to the field of AD with only one operational plant. The methods have undergone laboratory and field testing over the past five years at the plant near Hadera, Israel and are being marketed now under the ArrowBio process in Israel, the United States and Europe. The first plant opened in 2002 near Kfar Saba, Isreal, treating 200 tons per day, and has the 20 year contract for the town's MSW.

The ArrowBio process receives unsorted MSW and unloads it into a large water vat where recyclables are separated by density – glass and metal sink to the bottom while plastic floats. The organic fraction remains in solution or fine suspension and is sent to a hydrocrusher and then two sequential upflow anaerobic sludge blanket (UASB) reactors. Waste enters the reactors from the bottom and gas and effluent are removed from the top, resulting in layers of sludge. The chamber is maintained at atmospheric pressure and room temperature, about 35°C.

The digestate is dewatered and the company claims that the solid is immediately available to be sold as fertilizer (Environmental 2004). The liquid portion is either recirculated and used for the water vat or is available as fresh water, a valuable commodity in Israel (Finstein 2003). The plant is module so that it can be scalable from 100-1,000 tons per day.

9 Experimental AD Designs

The technological efficacy of AD has been firmly established in operating plants around the globe. Its success has caused improvements to continue to be sought in all aspects of design. This section describes some of the more promising experimental AD Designs.

In a traditional digester, the only substance inside of the chamber is the slurry that is being digested. When the digester is started, innoculum from a working digester is placed in the chamber in order to establish the bacteria population. From that point forward, feedstock is added appropriately and effluent is removed. In continuous flow digesters, great numbers of bacteria are washed out with the effluent because they are attached to the solids that they are digesting. In digesters on dairy farms, for example, new bacteria populations arrive with incoming manure and leave with exiting effluent. Equilibrium may still be reached, however, because there is very little change in feedstock, ensuring that the same kinds of bacteria are entering and leaving. With variable waste, however, washing out bacteria will alter interior conditions.

The first attempt to try to maintain a higher population of bacteria inside the digester was developed by Stander in 1950. By separating the bacteria from the effluent stream and keeping them in the reactor, he was able to reduce hydraulic retention time to as low as 2 days (Organization 2003). This was done by employing a settling tank located over the digester for the return of bacterial solids. The principle of maintaining the bacteria population was later applied to the development of other anaerobic treatment processes, such as the anaerobic filter designed by Young and McCarty in 1969 and the Expanded Bed reactors that use sand or granular activated carbon as a substrate on which bacteria can live.

These concepts were extended further in the development of the anaerobic attached film expanded bed reactor in 1980 designed by Switzenbaum and Jewell. In this process, waste flows upward through bacteria attached to a bed of suspended media. A similar model is called the upflow anaerobic sludge blanket reactor (UASB). This system uses granular particles containing bacteria that are mixed by the circulating gas. Rotating biological reactors developed by Friedman in 1980 allow wastewater to pass horizontally through baffles that move up and down, impeding movement of bacteria out of the digester. The Internal circulation system (IC), the reactor is compartmentalized and effluent is circulated with a higher upflow velocity.

Researchers at the University of Florida have designed a fixed-film digester. The design is similar to traditional digesters, with the addition of the film. It consists of 100,000 gallon, fixed roof digester tank and pumps for influent, recycling, and effluent. Inside the digester, vertically arranged corrugated polyethylene drainage pipes are installed in four zones as the media on which the bacteria will live. This widely available material is an inexpensive solution to providing sufficient surface area in the digester for microbial attachment on which a consortia of bacteria attach and grow as a biofilm. Immobilizing the bacteria as a biofilm prevents washout of slower growing cells and provides biomass retention independent of residence time, increasing biomass development. The greater number of bacteria per reactor volume means less time is needed, and retention time ranges from 2-6 days (Wilkie 2000). This process is ideal for large volumes of dilute, low-strength wastewater (<1%solids), such as those generated from dairy farms (Florida 2000; Hunter 2003). Also, fixed film digesters have a smaller footprint, which is important where space is an issue. They also are able to accomplish much faster start-up than suspended growth systems because of a higher OLR and colonization of attached growth systems. They are more successful because of the inherent preference for bacterial species to live in an attached growth mode versus a suspended growth system (ONR Environmental Systems 2002).

There is continually research being done on engineering better surfaces on which the bacteria can live. Zeller, International may attempt to use small spheres, about 5 mm in diameter, made of recycled crushed glass to put in chambers to give the bacteria a home. These spheres may also have embedded enzymes to speed up digestion (Zeller 2003). Engineering of sludge granules is a new area of research that serves the purpose of expanding and channeling the catabolic capabilities of the sludge and of shortening the length of adaptation period of the microbes (Verstraete and Vandevivere 1999).

A unique process involving an intermediary stage between the tanks of a two stage process is being tested at the University of Ottawa to process waste with high solid content. In this process, primary digestion of solids occurs for less than twenty days at which point the digestate is subjected to steam pressure disruption and then put into a second chamber for secondary digestion. The intermediary step causes a steam explosion of the internal water in the non-digested fibers, causing fibers to break apart (Vogt, Liu et al. 2002). The disrupted material is then re-inoculated and re-digested in the secondary stage. A benefit to this system is that it can accept mixed or poorly separated waste.

10 NYC and AD

Though AD as a MSWM strategy has had very limited penetration in the North American market, with the only example a demonstration plant in Toronto, there are no insurmountable barriers to its implementation. The means of digestion are proven, the separation technology is firmly established, the waste stream is readily available and the markets for the products, primarily biogas, are readily available. Short sighted public policy and uninformed public perception are the primary obstacles to AD implementation. As a high profile, often visited city, New York City should overcome these and be among the first American cities to take advantage of this responsible technology, giving them environmental, economic and social benefits.

To determine the feasibility of implementing an AD facility in New York City, several factors must be considered. First, the source of the waste must be determined as well as the means to separate and collect it. Next, an appropriate technology must be chosen, such as those detailed above, that best suits the characteristics of the city's waste and space limitations. Finally, the markets for the products, both solid and gas, must be established. If all these criteria are met, the interest and enthusiasm of the governing authorities must be present before a plant can be sited.

The plan outlined below suggests source separated organic wastes from restaurants and food markets in a limited area, such as Hunt's Point, provide the feedstock. Dedicated trucks of the Department of Sanitation of New York City (DSNY) cart the waste to a centralized AD facility that employs dry, thermophilic digestion, such as the firmly established DRANCO or Valorga processes. Finally, the biogas is combusted in cogeneration machinery on site and the solid used as fertilizer for city parks or is sent in bulk to farms upstate.

New York City generates an average of 54,731 tons of waste per day (NYDS, 2002), in a combination of residential and commercial streams. The first priority in waste management is to lower this value, either through waste reduction or reuse. The next best option is recycling, either through AD or other traditional recycling avenues. Waste-to-energy plants represent another option to recover energy and reduce volume. The least desirable option is landfilling the waste. Future research should compare this proposal of implementing AD to other methods for processing waste to determine the optimal solution for each specific region in New York, based on environmental, economic, and social considerations.

10.1 Feedstock

There are two models of AD facilities that should be explored. In the first, a facility collects source-separated organic waste from public sources, such as hospitals and schools, or the commercial sector, such as restaurants, food processors and markets. The second option is a facility that is sited with a MRF and accepts unsorted MSW from curbside collection. Inputs are mechanically separated so that glass, metal and plastic are recycled, and organic material is pulped and sent to AD. The remaining fraction is exported. Due to the added expenses of sorting and transporting non-organic waste, the latter system does not offer as promising a beginning to AD in NYC. Therefore, the targeted feedstock for this proposal is organic waste from the commercial sector. Currently, the annual generation of commercial waste is 3,085,000 tons of putrescibles a value that is increasing at the rate of 0.5% per year (DSNY, 2004).

The Department of Sanitation defines the putrescible fraction of the commercial waste as any degradable organic waste, including paper, food and yard trimmings. Though paper and yard trimmings would easily degrade in an anaerobic digester, there are better recycling options for these streams. Post-consumer paper has an established market that can be recycled back into paper, a commodity with higher value than AD digestate (see Kaufman, 2004). Yard trimmings can either be left on the lawn as mulch, as in the case of grass cuttings, or can be composted, as Central Park currently practices (Parks Department, 2004). While technically any organic waste can be composted, food is highly degradable and can rot and cause odor and sanitation problems in improperly managed composting sites. For these reasons, only the fraction of the putrescible waste stream that has no post-consumer use should be used for AD. In practice, this includes food waste, wet or soiled paper and the fraction of yard trimmings that are too voluminous for composting. Of the 3,085,000 tons of putrescibles, about 1,158,000 tons is paper (Kaufman, 2004), leaving the remaining 1,1927,000 tons available for other organic recycling. To date, the only method for recycling putrescible waste other than paper is composting, a method which only Central Park and Rikers Island Prison employ.

Table 3 Annual Tons of Commercial Putrescible Waste Generated, Recycled and Disposed in NYC with and without AD Facilities

	2003	2005	2010	2015	2020	2024
Generated (NYDOS, 2004)	3,086,000	3,145,000	3,214,000	3,275,000	3,358,000	3,414,000
Recycled with Current Practices (NYDOS, 2004)	824,000 (26.7%)	840,000 (26.7%)	858,000 (26.7%)	874,000 (26.7%)	895,000 (26.7%)	909,000 (26.7%)
Recycled with AD Facilities	824,000 (26.7%)	915,000 (29.1%)	1,008,000 (31.4%)	1,099,000 (33.6%)	1,195,000 (35.6%)	1,284,000 (37.6%)
Disposed with Current Recycling	2,262,000	2,305,000	2,356,000	2,401,000	2,463,000	2,505,000
Disposed with new AD Facilities	2,62,000	2,230,000	2,206,000	2,176,000	2,163,000	2,130,000

The current amount of commercial putrescible waste generated, recycled and disposed in New York is shown in Table 3. The current recycling rate of 26.7% for commercial putrescibles (NYDOS, 2004) would be increased to 29.1% by 2005 if one 75,000 tpy AD facility is added in 2004. If one such facility is added every five years the recycling rate could increase to 37.6% by 2024. This would be equivalent to recycling 375,000 tpy in AD facilities, only 11% of what is generated. As Table 3 indicates, growth of AD facilities at this rate would outpace the growth in putrescible waste generated, resulting in a decrease in the amount of waste disposed.

10.2 Location

Currently the highly concentrated food waste in New York City is a public nuisance that the city must eventually address. In a new paradigm, however, these source separated organic waste streams can be seen as an opportunity for community benefits through an AD facility. There are several sites in New York City that fit this description. First, concentrated restaurant areas, such as Chinatown and Hell's Kitchen in Manhattan and Flushings in Queens, can be considered. While a great deal of food is discarded in these areas, it can be highly contaminated with take out containers and plastic packaging. Food processing centers offer another prospect where large quantities of whole foods are discarded daily in concentrated areas. This option is promising for New York as there are models in other countries that use food markets as a primary source, such as the Australian BTA plant operated by Earth Power in Sydney (Mendelsohn, 2004).

After the close of the Bronx Terminal Market, the Hunt's Point Cooperative Market in the Bronx will be the only remaining food processing center in the city (Elliot, 2004). The Hunt's Point Market, seen in figure 18, offers the best combination of waste availability and adjacent space for an AD facility. Located on 60 acres in the Bronx, the market is home to 47 independent wholesale food businesses of food production, processing and distribution (Hunt's Point Cooperative Market, 2004). The site has undergone several changes recently, including the addition of the Fulton Street Fish Market and the transformation of the adjacent lot to the south from a site for illegal dumping to a new city park with Bronx River access (New York City Parks, 2004). The area's environment would see upgrading as well because all of the waste from the market would be treated locally and immediately, thereby reducing trucking traffic and odors associated with storing putrescible waste. In addition, the community would benefit from the creation of jobs and locally produced heat and electricity from the plant's biogas.

The specific location for the AD plant is the marine transfer station (MTS) on the 8.6 acre lot bordered by Farragut St (formerly Hunt's Point Ave.) to the north, the East River to the south and east and a piece of land owned by the NYCEDC to the west. This MTS is one of the eight identified by the city to be modified to containerize waste for out of city export (NYDS, 2004). The zoning is M3-1 for heavy industrial use and all adjacent land is owned by the city or its agencies.

The next step in solidifying this location is to measure and analyze the components of the waste for moisture content, salinity, density, volatile solids content and C/N ratio. The market is primarily a meat and fish market, producing waste with high nitrogen content. This will need to be balanced with high carbon loading, such as from vegetables or lawn trimmings. It must also be determined if the waste stream is homogeneous, or subject to wide variations in composition.

Figure 18 Hunt's Point Market (MSN, 2004)

10.3 Transportation

The air pollution associated with diesel truck emissions is of paramount concern in this area of the South Bronx where asthma rates are among the highest in the city (Kappstatter, 2004). The Hunt's Point Market brings in approximately 20,000 trucks each week and the local waste transfer stations add to this (Clean Air Communities, 2004). In 2001, the Hunt's Point Market, Sustainable South Bronx, the New York Power Authority and the EPA cooperated to reduce air emissions from idling trucks (Hunt's Point Market, 2004). Instead of idling for hours or even overnight, trucks that come to the market can hook up to equipment that provides electricity, air conditioning, heating and even phone and internet services (EPA, 2001).

With these concerns in mind, the primary method of collection and delivery for the AD facility would be through a dedicated fleet of natural gas non-compacting trucks, owned either by the DSNY or private haulers. The fueling station would be at the AD facility, with the fuel provided by purified biogas produced at the plant. Another advantage to having a dedicated fleet is that they can operate continuously throughout the day. Because the AD facility is sited on the Hunt's Point peninsula, the trucks will not have to travel throughout the Bronx to drop their load and can therefore pick it up continuously. This avoids time in which decaying waste is left out, thereby reducing odor in the market. Depending on need, supplemental waste would be provided by local restaurants and institutions using the same trucks at different periods during the day. The trucks would be non-compacting because the waste stream is wet and dense, giving very little benefit to compaction. In addition, a compacting truck tends to squeeze out valuable water and discharge it as leachate (UNEP, 2004).

Each company operating at the market would choose to contract with the hauler to sort their waste and provide minimum quantities of organic waste with low contamination.

Other mutual obligations regarding supply and receipt of waste material include the pick-up schedule and location, type of waste bin, and others. In return for sorting waste, the companies will pay a lower tipping fee than they otherwise would. Perfect separation may not be possible, so the facility will have methods to separate out up to 10% contamination.

The removal of the digestate would occur on barges and railways utilizing the planned renovations of the piers and the recently upgraded railways at the market, as seen in Figure 19. The digestate would be transported to a compost farm in upstate NY, Connecticut or another location with more space where the digestate would be aerobically cured and sold to local farms as a soil amendment.

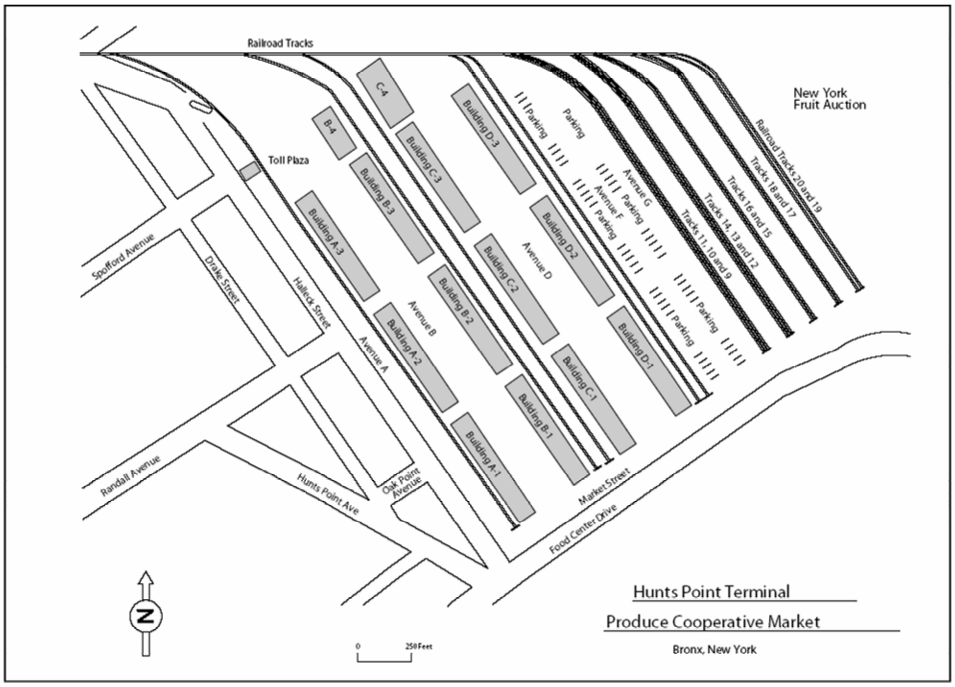

Figure 19 Hunts Point Food Distribution Market (Produce Market Information Directory, 2004)

10.4 Technology

The choice of the technological process for an AD facility involves considering the following factors: space, safety of digestate, biogas production, ease of operation, infrastructure, waste storage method, material handling system, odor control and water and fuel requirements. These considerations point to choosing DRANCO or Valorga for the first digester in New York.

For a pioneer project, a primary concern is system stability. A mesophilic single-stage digester offers the most robust system because it establishes an equilibrium that can cope with greater environmental fluctuations than a thermophilic system. Related to this concern is ease of operation and minimization of maintenance. A system without moving parts inside the digester is preferred so that the digester will not need to be disrupted in order to service mixers, etc. Another factor is experience and success by the designing firm. Though AD is a relatively new field, several companies have established viable plants for over twenty years. The continued operation of older plants and addition of new ones lends credibility to the company's process. There exist a greater number of single-stage, mesophilic digesters than any other.

The scarcity of space in New York City is a crucial consideration. To minimize the footprint of an AD facility, the size of the digester should be minimized, suggesting a high solids content digester. This ensures that the entire volume is used for digestion and water is not taking up additional space. As an added advantage, the water requirements for this type of system are minimized.

The biogas can be used for two major purposes. First, the biogas should be cleaned and used as a vehicle fuel for the trucks serving the system. The second use is in a cogeneration unit, to produce heat for the system and electricity for the plant and surrounding neighborhood. Hunts Point operates 700,000 square feet of refrigerated space, (Hunts Point Cooperative Market, 2004) requiring enormous electrical demand.

10.5 Costs

While there may be widespread agreement that the diversion of organics is an essential part of a MSWM strategy, it is less assured what can make such a project economically viable The order of magnitude capital and operating cost estimate is an essential first step in determining overall economic performance of such a project. Capital and maintenance costs are considered here only as a rough estimate, as there is uncertainty in published data, material availability and operator expertise. Additionally, depending on the competitive nature of the bidding and the detailed plant specifications, the costs could differ from as much as -20% to +50% from the estimates provided here (Whyte 2002). These estimates are valid for plants with annual operating capacities between 50,000 tons and 100,000 tons.

The capital costs of such a project include AD equipment, cogeneration machinery, building construction and site work. Estimates from 2002 indicate that these costs for a source separated waste stream would range from $245 to $635 per ton of yearly design capacity. For a mixed waste facility that requires sorting machinery and greater floor space on which to house it, these costs are 5-10% higher (Whyte, 2002). For this analysis, it is assumed that 80% of the incoming material in a source separated plant would be processed while 20% would be removed at a cost of $40/ton, giving a residue disposal cost of $15/ton of incoming waste. Approximately 40 to 45% of the tonnage delivered would need to be aerobically cured before being sold at a cost of $15/ton, resulting in a final cost of $7/ton of design capacity. Total net annual costs, including capital depreciation, interest, operating expenses, labor and revenue range from $55 to $66 per ton of design capacity for source separated waste streams, while the estimates are up to 35% higher for mixed waste (Whyte, 2002). These values are seen in Table 4 and the details can be found in Whyte, 2002.

The profit from the sale of products is the other piece of the puzzle. Because an AD facility may not be able to produce consistent, high quality compost, the selling price is estimated at $5 per ton for the 40% of the feedstock that is cured. Some of the digestate may also be given to city parks for their compost piles. The loss in revenue is compensated by the savings in transporting and composting the digestate. Biogas is estimated to be produced at 115 m^3/ton of design capacity with a 55% methane content.

The facility consumes about 25% of this for on-site heat and electricity, leaving about 40 m^3 of methane per ton. This can be used to generate electricity, resulting in 150 kWh/ton of waste, sold at $0.04/kWh.

Table 4 Cost of AD Facility for New York

(all values in $/ton of waste)

Annual Cost	50,000 tpy plant (Whyte, 2002)	75,000 tpy plant (extrapolated)	100,000 tpy plant (Whyte, 2002)
Annualized capital,			
including capital depreciation and interest	33	30	26
Plant Operation and Maintenance	9	8	7
Residue Disposal	8	8	8
Aerobic Curing	7	7	7
Subtotal	57	53	48
15% Profit	66	61	55
Revenue			
Sale of Digestate	2	2	2
Electricity Sale	6	6	6
Cost to Process	**58**	**53**	**47**

Table 4 indicates a total cost of between $47 and $58 per ton of incoming waste. In order for a facility to be profitable at the rate of 15%, the tipping fee charged to the organic waste suppliers would need to meet this cost.

A 75,000 tpy plant can serve the needs of NYC well because it takes advantage of the economies of scale while not overburdening one location with the treatment of putrescible waste.

There are several variables that can change these costs significantly, including the price of land, the range and purity of organic materials collected, recovery rates, landfill tipping fees, waste hauling costs, markets for gas and compost, training required for operators, government regulations relating to the use of soil conditioner made from MSW, permitting fees, tax credits, renewable energy portfolio benefits, and advertising or education to encourage the adoption of such a strategy.

In short, the economic viability of such a project depends on three basic conditions. First, landfilling or dumping must be controlled and sufficiently expensive to make the moderate cost of an AD facility competitive. Second, there must be a confirmed market for the products, both compost and biogas. The closer that market is to the city, the better the economics. Finally, the waste streams must be sufficiently clean and have a large organic content so that at least 80% of the input waste will be digested.

10.6 Environmental Considerations

The strongest moral argument for adopting AD is that it gives NYC an opportunity to take responsibility for the waste it generates; that it does so while ensuring environmental and economic benefits is an advantage. Because all of the products of AD have valuable end uses, there is no waste produced and therefore less use of landfills, where methane emissions create environmental damage. Other environmental benefits include improved water quality, renewable energy generation, reduced need for chemical fertilizers, and enhanced air quality due to less truck traffic.

The Rio Framework, Kyoto Protocol and US Climate Change Action Plan have individually concluded that reducing greenhouse gas (GHG) emissions to the atmosphere is desirable. Methane, a GHG 23 times more potent than carbon dioxide, is particularly important in this initiative. In total, human activities result in 380 million tons of methane emission each year, or about 8 billion tons carbon equivalent (TCE) (IPCC, 1990). Methane concentrations have risen from 700 ppb in pre-industrial times to 1,750 ppb today (IPCC, 2001). In the United States, the largest source of anthropogenic methane emissions is putrescible waste decaying in landfills, accounting for 33% of the US total (EPA, 2004). For this reason, the US EPA has enacted the voluntary Landfill Methane Outreach Program that encourages the capture of landfill methane to produce electricity. In New York, the Fresh Kills Landfill, which no longer accepts waste, is currently flaring methane, indicating that the voluntary measures are not incentive enough.

Waste that is processed in an AD facility is reduced to 40% of its original weight and significantly less volume. Therefore, using AD decreases the volume of landfill required as well as associated methane emissions. The rate of greenhouse gas production that can be attributed to wet organic waste is 0.15 metric ton carbon equivalent (MTCE) per ton food waste (EPA, 2002). This would mean that one 75,000 tpy AD facility can decrease GHG emissions by 1,125 MTCE over the course of a year, equivalent to the carbon output of over 400 cars (EPA, 1997).

A longstanding concern in NYC is the burden on the city's wastewater treatment plants, which treat storm water and sewage in combined systems. The capacity of these plants can be surpassed during heavy rain, resulting in the release of untreated wastewater to the city's waterways. The burden on these plants is further amplified when a higher concentration of organics or total suspended solids (TSS) are present in the incoming waste. Organics require time to treat in order to reduce the BOD so as not to lower the dissolved oxygen in the release waterways, which would kill marine life. The TSS increase the load in the plants causing increased maintenance. One option for handling putrescible waste in New York is to allow food grinders, a practice that increases both organic load and TSS in wastewater (NYDEP, 2004). The use of food grinders was banned until 1997, when private residences were permitted to install a grinder. The decision to life the ban was due in part to the assumption that it will not penetrate the market (NYDEP, 2004). As food waste continues to increase, however, there will be increasing pressure on the city to allow food grinders in restaurants in order to decrease odor and filth on the city streets. The city's wastewater plants will need to be significantly upgraded to handle the increased load or the water quality in the rivers will be compromised. If AD facilities are proactively employed for restaurant food waste, however, the burden on the wastewater plants will be minimized.

Water quality is further enhanced when the volume of putrescibles in landfill is shrunk. Landfills are estimated to emit 2350 tons of chlorinated and other volatile organics, approximately 80,000 tons of sulphides/mercaptans and ammonia and an estimated 115 tons of mercury. Leachate containing these chemicals can contaminate nearby water sources even after a landfill is closed. This is due to the time lag associated with the decomposition of waste and the associated reactions of various pollutants in the landfill. This is true even in landfills that are currently collecting and treating leachate (Themelis, 2002).

The electricity generated from biogas is green because it causes no net carbon emissions to the atmosphere. Combustion of methane proceeds according to the equation:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Though carbon dioxide (CO_2) is a product of this reaction, the source of the carbon is from biomass, not fossil fuels. In other words, the CO_2 released will subsequently be used by plants in photosynthesis to produce carbohydrates. These carbohydrates will be processed to form food, the scraps of which will be used as the fuel of the AD facility, thus closing the loop. The benefits of decreasing fossil fuel use are well documented and include reduced dependence on foreign fuel sources, which lessens related military action. The 75,000 tpy facility would generate approximately 7.5 million kWh each year, enough to supply 1250 homes (DOE, 2001) and displace 13 thousand tons carbon dioxide (EPA, 2002).

The use of digestate as a compost material for agriculture is a proven method to maintain or restore the quality of soils. Compost has proven effective globally, for example in southern Europe where it is a valuable method of tacking organic matter depletion, desertification and soil erosion (EUROPA, 2004). In horticulture and home gardening, the use of compost can substitute for peat, thus reducing the exploitation of wetlands. In the United States, only 2.8% of food scraps are currently composted (EPA, 2002). New York City's commitment to composting is minimal, with only 19 tons per day composted in the residential side by the NYDS and very little on the commercial side (IBO, 2004).

Air quality will also improve with the adoption of AD. The first reason for this is the reduced volume of putrescible waste in transfer stations will lead to reduced odor. More significantly, however, is the reduced diesel trucking traffic owing to the treatment of waste locally and the transportation of digestate by alternate means. Diesel garbage trucks are a major source of air pollutants, including smog forming compounds, particulate matter, ozone and toxic chemical constituents. The majority of the nation's garbage trucks are diesel fueled and over 41% are over 10 years old, making them the most polluting vehicles on US roads. In urban areas, over 90% of CO (carbon monoxide) in the air is attributable to motor vehicles, with emissions concentrated in areas where vehicles idle, such as waste transfer stations (Inform, 2003).

10.7 Community Relations

This project is designed to add several benefits to the Hunt's Point neighborhood, a community that carries a disproportionate burden for the city's waste disposal. The Bronx processes 21% of the total MSW, yet produces only 5%; it disposes of 34% of the commercial prutrescible waste from the city, but generates only 13%; it treats 70% of the city's sludge while creating only 29% (South Bronx Clean Air Coalition, 1999; DSNY, 2004). Forty to fifty percent of the city's garbage is dumped in the South Bronx in over 60 waste facilities, 35 waste transfer stations, as well as several sewage treatment plants, medical incinerators and auto salvage operators (Ackman, 2004) (NY League of Conservation Voters, 2004). The environmental justice argument rings strong in this neighborhood as the area is 95 percent black and Hispanic and more than half live below the federal poverty line (Ackman, 2004). The group Sustainable South Bronx has been formed to address concerns of the South Bronx becoming receptacle for the city's industrial and sanitation facilities. Greening for Breathing is another community organization dedicated to responding to deteriorating air quality in the Bronx.

Another "waste" facility in the South Bronx, therefore, is justified only because the benefits outweigh the negative consequences. Some objections to waste transfer stations stem from the fact that waste is uncovered, causing odor and unsightly conditions. The AD facility would be completely enclosed with a negative air pressure system to ensure odor from decaying waste stays within the facility. Additionally, any air released would be filtered in a biofilter to eliminate odor. In sum, this will improve air quality in the area because less waste will be sent to local waste transfer stations. Waste stations are also notoriously unkempt, ugly, smelly dumps. This AD facility would only be successful if it were designed with an eye to aesthetics, including all machinery inside the plant and a well landscaped area surrounding it.

Job creation gives another benefit to the community, as operating the plant would require approximately 10 full time workers, ranging from machine operators to managers. These jobs would be recruited from the community as training for an operator position requires the same skills as a wastewater treatment plant (Mendelsohn, 2004).

Air quality in the South Bronx is a primary concern as a recent study showed that one in four children are afflicted with asthma, one of the highest rates in the country (New York City Council, 2003). These rates have been attributed in part to diesel truck emissions, especially idling trucks (South Bronx Clean Air Coalition, 1999). An AD facility would reduce truck traffic because far less waste would be carried out and it would be done by rail or barge.

The final benefit to the Hunt's Point Community is a local supply of heat and electricity. Several European communities take advantage of integrating resources within industrial parks, a concept known as an ecopark. Excess heat is produced in the electricity generating equipment from the combustion of biogas. This heat can be used in industrial processes or simply to heat surrounding buildings. Alternately, a clean supply of natural gas can be produced at the facility, offering a fueling station for natural gas vehicles. This may be incentive for the MTA to increase the number of clean buses operating in the area.

The partnerships for an AD facility are complex and extensive. Cooperating work must be established between waste suppliers, waste haulers, developers, lending institutions or providers of capital, public relations firms, city and state authorities, regulators, engineers, plant operators, permitting departments, legal assistants, architects, construction firms, energy contractors, compost farms and the general public. The success of the project, however, will only be assured if there is a strong relationship between these parties and the local community.

10.8 Public Policy

Currently the United States has no AD facilities that process MSW, despite the fact that most wastewater treatment plants and many farms in the country employ the technology. Countries with the most stringent environmental legislation, such as Germany and Denmark, also boast the greatest number of AD facilities. These facts indicate that the obstacle to AD in the United States is not a lack of technology, a lack of planning or a lack of expertise, but rather a failure of vision (Lusk, 1999). The United States must use public policy initiatives to expand AD to the MSW market. These policy changes can be in the form of direct support, pricing strategies including taxation and regulations.

One example of direct support for AD is setting premium prices for green electricity, which would increase the revenue from electricity generated at AD facilities. Many European countries promote this in attempts to meet Kyoto Protocol targets, and the same strategy works to increase green technologies in any realm. Some countries give a bonus of \$0.02 to \$0.03 per kWh for electricity generated from biomass in order to meet the goal of 12% renewable electrical energy by 2010, up from 3% in 2000 (DeBaere, 2001). Additionally, if power companies do not have the green certificates to verify their quota, they have to pay an additional \$0.11 kWh fine. In New York, Governor Pataki suggested that energy companies be required to meet a renewable energy portfolio standard. The New York State Energy Research and Development Authority (NYSERDA) is currently investigating how to establish this.

The New York Assembly has begun direct support for AD units on farms in NY. A 2003 bill states that net metering must be offered to any AD facility that generates biogas from the treatment of agricultural waste, with a rated capacity of not more than 400 kW that is fueled by at least 90% livestock manure, farming wastes and food processing wastes and at least 75% livestock manure. Net energy metering means that a facility keeps track of the amount of electricity it generates and how much it uses, regardless of timing. The facility only pays for electricity it uses over what it has generated. In the case that it produces more electricity than it uses, it receives retail price from the utility for every kWh over its use. Identical legislative support can be created for electricity generated from MSW through the same technology.

Support of research and development specific to issues in North American MSW will also lift AD. In January of 2000, the administration's FY2001 budget proposal included a new initiative to develop the research and technology sectors for bioenergy and biobased products. Though this could include AD, there is currently no indication that AD research is being supported in significant ways in areas other than agricultural.

Many of the benefits of AD relate to improved environmental quality, which, with current pricing, unfortunately does not translate into value for the operator. For AD to become economically viable and establish a market in New York, the public benefits have to be returned to the operators. This means that operators should receive credit for improved water and air quality near waste transfer sites as well as for reducing the volume of waste landfilled.

Pricing strategies that reflect environmental damage created by other waste disposal options will assist AD by making the competition more expensive and allowing AD to compete. As the section 12.4 showed, a tipping fee of close to $50 must be charged in order to have an economically viable AD plant. The low hanging fruit in terms of pricing adjustments, therefore, is landfills. Currently the tipping fee to landfill a ton of waste can be as low as $14/ton (Kaufman, 2004), a price that does not reflect environmental damage or limited capacity. Because there is still so much open space in some states, the supply is essentially limitless and the price will not rise to reflect use. In Europe, by contrast, the densely populated areas like Belgium and Holland charge as much as $60 to $80 per ton and add landfill taxes of up to $40 per ton to that (De Baere 2001). Some landfill taxes, such as in the UK, depend on the type of waste disposed, with biologically active taxed at the highest rate (Wealden District Council, 2004).

In New York City, closing of the Fresh Kills Landfill left no options for waste disposal within the city limits. The landfills that are currently accepting New York's waste have a great deal of power as New York has no other options. Additionally, the US has no federal policy on waste transfer or waste handling that would promote AD or other environmentally responsible methods. Therefore local legislation dictates pricing and transport of MSW, which can lead to artificial prices.

An alternative option to pricing is using regulation to prevent the more environmentally damaging options from occurring. The EU generates almost 200 million metric tons of waste every year (Eurostat, 2001) up to 70% of which can be considered biodegradable (EEA, 1999). The governing council recognizes the need to reduce the amount of waste going to landfill, especially biological waste, and so the landfilling of organics is strictly regulated. Though the specific regulations are left to individual countries, in EU Directive 31, the EU Council states that members should take measures to reduce the landfill of biodegradable waste and further encourages the separate collection of biodegradable waste through sorting, recovery and recycling (EU, 2001). Specifically, it requires that member states devise a strategy to ensure that within 15 years after entry, the amount of biological waste going to landfill is only 35% of what was produced in 1995 (Article 5). The federal government in the United States suggests no such limitations on waste, despite the fact that, unlike the EU Council, it actually has enforcement authority. These policy directives make a difference in the European Union, where economic considerations are otherwise comparable. The result is over 70 AD facilities treat MSW and produce over 300MW of electricity in the European Union (Graves 2003).

The United States EPA can look to several European communities as models for forming regulations on waste management. In Denmark, for example, there are similarities in governmental structure as well as priorities. The Danish EPA is responsible for regulations guiding waste disposal, but local government is responsible for the implementing them. Furthermore, the Danish EPA has the same order of priorities as the US EPA, namely reducing and recycling waste (Danish Ministry of Environment and Energy, 2001). Denmark has a strong foothold in AD due to a long history of product development and governmental support to create financially competitive plants. The national program consisted of tests and demonstrations, grant support for new plant construction, the costs and benefits and information dissemination. The US EPA has experience in each of these categories for other technologies; it is time that AD is the recipient.

The regulations described above cut across issues in waste disposal, water quality, air emissions, renewable energy and agriculture. The environmental drivers and institutional responsibilities for each differ, e.g. The Clean Water Act, the USDA, NY DEP. Thus policy from any individual area would not necessarily support AD. The US must consider comprehensive plans that incorporate direct support, pricing and regulations to promote environmentally responsible outcomes, one of which may be AD.

11 Conclusions

AD offers New York City an opportunity to take the lead in sustainable waste management in the U.S. One facility can take the place of a waste transfer station, thereby improving the air and water quality of the surrounding area. Since over 1/3 of the mass of the waste will be converted to gas and consumed on site, fewer trucks will be needed. A community like Hunt's Point in the Bronx that produces large quantities of food waste would gain from these and other benefits if a 75,000 tpy demonstration facility were sited in the area. The location is ideal for such a demonstration facility because the market produces a source of organic waste and the community has suffered from environmental injustice. The city will profit by being able to complete a true cost-benefit analysis on this facility in a NYC context, including environmental benefits such as reduced odor, greenhouse gases, fossil fuel dependence, wastewater requirements, and improved nutrient recycle. Future research should compare this proposal to other methods for processing waste to determine the optimal solution for each specific region in New York, based on environmental, economic, and social considerations.

Because waste is converted into usable products, AD is an important part of an overall reduce-reuse-recycle strategy. The priorities for waste management do not change with the adoption of AD. Prevention and reduction of waste generation remain the primary focus. Reuse of waste, such as cardboard, and recycling waste to the original material are the next steps in the hierarchy. Only after these options have been exhausted should AD be launched in a way in which the digestate is used for agricultural benefit and ecological improvement and the energy is harnessed. Only after these strategies have been employed to the greatest extent possible, should other methods come to the table.

The technological efficacy of AD for MSW treatment has been proven in full-scale operational plants over the past twenty years in European countries and recently in other locations across the globe. Furthermore, the designs of these facilities have been thoroughly researched and optimized for particular uses, feedstocks, locations, and climates. The failure of the United States to adopt AD for MSW, therefore, can only be described as a lack of planning.

The barriers to the implementation of AD include a lack of readily available information as well as policy that does not take into account the cost of environmental damage. The economics of AD in the United States are on the border of profitability, indicating that government support and accurate pricing is required in order for a plant to be developed. The cost to landfill waste, for example, does not include the environmental cost of greenhouse gas emissions or degraded water quality. Only by recognizing public costs and integrating it into facility costs will AD and other environmentally responsible technologies be developed. Surmounting the barriers of AD development will require continued research and development, fair pricing that internalizes environmental considerations, strict environmental regulations and information dissemination.

12 Future Research at Columbia University

AD is successfully operating in many parts of the world; 'modern' plants have been developed, and there now are few technical barriers. The future of research in AD, therefore, should concentrate on improving the functioning and economics of a facility. There are several areas in which research can focus, both for AD for MSW and AD in general.

The first subgroup includes strategies of waste management, such as source separation, waste composition, storage, handling and collection. All of these should take into account issues such as odor, sanitation, pest control and economics. The North American waste stream should also be analyzed for the following characteristics: moisture content, salinity, density, calorific value, chemical composition including the C/N ratio and volatile solid content, all of which determine whether AD is a viable technology. Research should be expanded to optimize the production of biogas with a variable waste stream. Establishing markets for the products of AD derived from MSW is essential. As a summary of all these research endeavors, serious consideration should be given to reduce costs of a project, including plant construction and operation. Finally, the implications of public policy, including direct support, tax incentives, pricing and regulations, must be considered and advanced before AD will take hold as a MSWM option for this country.

An important area of research that will greatly impact urban environments is reducing retention time and therefore the size of the digester. Waste preprocessing, including mechanical, thermal, chemical and thermochemical processes, demand further research. There may be other ways in which to prepare waste such as more efficient mechanical mixing, the use of other alkalis to buffer the sludge, or a combination of these with thermal processes.

Another area for future research is optimizing the environment for the bacteria inside the chamber. Suggestions for this front include: developing fixed substrate on which the bacteria can live while high solid waste flows through the digester; using enzymes that will catalyze biological reactions; developing other biocatalysts; improving inoculation concentrations; exploring new populations of bacteria that are both resistant and efficient; improving automated control technologies so that the digester can diagnose itself and respond to a changing environment; and increasing organic loading to spark the growth of more bacteria.

For practical and policy reasons, the following areas of research can also be investigated: Codigestion of MSW with sewage waste in wastewater treatment plants; separation of the wet and dry steams of MSW to improve resource recovery; feasibility of preprocessing all waste with a hydropulper or similar technology and only using AD for the liquid fractions of waste; developing policies to reduce the amount and types of waste that are allowed to go to landfill, similar to the Europeans; and funding for research and development for AD of MSW.

Current research for AD in the United State is funded primarily by the USDA and other agriculturally minded organizations, resulting in designs tailored for agricultural waste. If more funding and effort were placed on improving AD for MSW, this research may take place and designs would be optimized for the highly variable, high solids MSW. Progress in any one of the topics mentioned above can improve AD and make it a more serious contender in the repertoire of waste management strategies for MSW in the United States.

13 List of Acronyms

AD – Anaerobic Digestion

BOD – Biological Oxygen Demand

COD – Chemical Oxygen Demand

C/N – Carbon (total organic) to Nitrogen ratio

CSWMP – Comprehensive Solid Waste Management Plan

DEP – Department of Environmental Protection

DOE – Department of Energy

DSNY – Department of Sanitation of New York City

EPA – Environmental Protection Agency (US)

EU - European Union

GHG – Greenhouse Gas

HRT – Hydrolic Retention Time

IPCC – International Panel on Climate Change

MSW – Municipal Solid Waste

MTS – Marine Transfer Station

NYSERDA – New York State Energy Research and Development Authority

OFMSW – Organic Fraction of Municipal Solid Waste

RDF – Refuse Derived Fuel

SRT – Solid Retention Time

TS – Total Solids

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