ANAEROBIC DIGESTION OF BIODEGRADABLE ORGANICS IN MUNICIPAL SOLID WASTES

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Submitted in partial fulfillment of the requirements for Master of Science Degree in Earth Resources Engineering

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May 2002

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Executive Summary

This study examined in depth the current status of the anaerobic digestion technologies for the treatment of the organic fraction of municipal solid wastes (MSW). Anaerobic digestion (AD) consists of the degradation of organic material in the absence of oxygen. It produces mainly 55 % methane and 45 % carbon dioxide gas and a compost product suitable as a soil conditioner.

A review of systems in operation worldwide was made, including types of process design and their engineering and environmental performance. The study also provided information on the trend in installed capacity and size of plants, which indicated that in the late 90's there was a notable rise in size of new plants. The report compares various AD systems such as mesophilic vs thermophilic operation, low-solids vs high-solids feed, multi-stage vs single stage reactors, and AD systems treating mixed wastes vs biowaste. The report also describes in detail the most important AD processes based on the total solids (TS) content of the slurry in the digester reactor. Some of these processes are further explained with case studies.

The AD systems for MSW digestion are widely used throughout the world. Commercially available digesters range from $70m^3$ to $5000m^3$ reactor capacity. The smaller digesters make use of the generated biogas (i.e. mixture of CH_4 and CO_2) for heating the digester while larger units generate up to 2 MW of electricity. Much of the technology is based in Europe, with Germany and Denmark leading the field in technology.

Evaluation of various AD processes showed that single stage processes are leading. Multi-stage reactors are too expensive and more complex to operate; however, these systems provide separate reactors for hydrolysis and methanogenesis and provide more favorable conditions for the reaction of low-cellulose materials such as manure, poultry waste. The comparison between single stage, low-solids (LS) and single stage, high-solids (HS) operation indicates higher gas yields from

high solids facilities. For example, the Waasa LS process reports 100-150 m^3/ton of waste input and the Valorga HS process 220-250 m^3/ton of feed to digester. In addition, the organic loading rate for single stage high-solids (e.g., DRANCO, 15 kg of Volatile Solids per m^3 per day) is twice that of the single stage low-solids (Waasa, 6 kg VS/(m^3.d)).

A well-designed AD fosters sustainable development since it recovers energy thus reducing fossil fuel use and reducing greenhouse gas sources. It also allows nutrients in the form of compost product to be returned to the land maintaining nutrient closed loop system.

The advances of AD technology have been supported by legislation. Most European countries are aiming to limit MSW disposal to landfills to no more than 5% of the collected material and have increased taxes on landfilling. This will ensure that waste is properly treated for combustibles and organics rather than being buried in the ground. The 15% renewable energy by 2010 target as well as schemes such as "green pricing" in The Netherlands and some other European countries allow AD facilities to sell biogas for electricity generation at a premium. Similarly, in the United Kingdom, under the Non-Fossil Fuel Obligation (NFFO) act, electricity is sold at a premium from AD system.

Another factor that has triggered opting for energy recovery from waste is international agreements with respect to greenhouse gas emissions. Landfills are the source of large emissions of methane to the atmosphere and methane gas has a global warming potential (GWP) that is over twenty times that of carbon dioxide. Also, many utilities are very interested in earning credit for reducing GHG emissions. These utilities foresee the risk of mandatory GHG control imposed by future regulatory or legislative actions. Therefore, AD plants will be very attractive for utilities to earn GHG reduction credits.

In future, the best practicable environmental option will be deriving energy from waste. Energy recovery technologies include combustion of waste and anaerobic digestion (AD). However, combustion of the wet stream of MSW does not provide efficient energy recovery. So the advantages offered by AD are worth exploring for the wet stream of Municipal Solid Waste (MSW) of New York City and elsewhere.

Acknowledgements

The author is deeply grateful to the faculty of the Department of Earth and Environmental Engineering who have contributed their time, knowledge and expertise in helping me to make this study. They have shaped the contents and presentation of this work on the basis of their experience and interest. In particular, the author thanks:

Prof**.** N.J. Themelis for helping me select the topic for my thesis, supervising and guiding me at each step. I value the indefatigable and skillful way in which my manuscript was shaped by him. He provided both technical insight and a broad overview essential to this thesis.

Prof**.** Young Hwan Kim for enlightening discussions on solid waste management.
Prof**.** Nada Asaf Anid for her constant help, timely counseling and motivation.
Prof**.** Peter Strom for sharing his laboratory research work at Rutgers University.

Special thanks are due to Ms. Stefka A Tzanova of the SEAS Engineering Library for making available papers and books for thesis.

Deep appreciation is extended to my fellow students and friends Joe Di Dio, Claire Todd, Alex Klein, Ko Matsunaga, and Panos Deriziotis for their constructive criticism, support, and sitting patiently through my weekly presentations

1. Introduction

Municipal solid waste (MSW) is the waste generated in a community with the exception of industrial and agricultural wastes (Tchobanoglous, 1993). Hence MSW includes residential waste (e.g., households), commercial (e.g., from stores, markets, shops, hotels etc), and institutional waste (e.g., schools, hospitals etc). Paper, paperboard, garden and food waste can be classified in a broad category known as organic or biodegradable waste.

The organic compound fraction of MSW in the US represents 70% of the waste composition and consists of paper, garden waste, food waste and other organic waste including plastics. The biodegradable fraction (paper, garden and food waste) accounts for 53% of waste composition (Kayhanian, 1995). Therefore, treatment of these wastes is an important component of an integrated solid waste management strategy and reduces both the toxicity and volume of the MSW requiring final disposal in a landfill. This study explores the anaerobic digestion technology (AD), i.e. in the absence of oxygen, as one of the main options for processing the biodegradable organic materials in MSW.

The biodegradable fraction of MSW contains anywhere from 15%-70% water. Themelis and Kim (2002) showed that a representative average molecular formula for organic wastes, excluding nitrogen and other minor components, is $C_6H_{10}O_4$. The anaerobic decomposition of organic materials yields principally methane (CH_4), carbon dioxide (CO_2) and a solid compost material that can be used as soil conditioner.

This thesis examines in depth anaerobic digestion (AD) technologies in order to determine their economic and environmental competitiveness, as one of the options for processing the biodegradable organic materials in MSW.

2. The Anaerobic Digestion Process

Anaerobic biodegradation of organic material proceeds in the absence of oxygen and the presence of anaerobic microorganisms. AD is the consequence of a series of metabolic interactions among various groups of microorganisms. It occurs in three stages, hydrolysis/liquefaction, acidogenesis and methanogenesis. The first group of microorganism secretes enzymes, which hydrolyses polymeric materials to monomers such as glucose and amino acids. These are subsequently converted by second group i.e. acetogenic bacteria to higher volatile fatty acids, H_2 and acetic acid. Finally, the third group of bacteria, methanogenic, convert H_2, CO_2, and acetate, to CH_4. These stages are described in detail below. The AD is carried out in large digesters (Figure 1) that are maintained at temperatures ranging from 30°C - 65°C.

Figure 1. The digesters at Tilburg Plant in The Netherlands

Ref: http://www.steinmuller-valorga.fr/en

2.1 Hydrolysis/liquefaction

In the first stage of hydrolysis, or liquefaction, fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble molecules such as sugars, amino acids and fatty acids. The complex polymeric matter is hydrolyzed to monomer, e.g., cellulose to sugars or alcohols and proteins to peptides or amino acids, by hydrolytic enzymes, (lipases, proteases, cellulases, amylases, etc.) secreted by microbes. The hydrolytic activity is of significant importance in high organic waste and may become rate limiting. Some industrial operations overcome this limitation by the use of chemical reagents to enhance hydrolysis. The application of chemicals to enhance the first step has been found to result in a shorter digestion time and provide a higher methane yield (RISE-AT, 1998).

Hydrolysis/Liquefaction reactions

Lipids $\rightarrow$ Fatty Acids

Polysaccharides $\rightarrow$ Monosaccharides

Protein $\rightarrow$ Amino Acids

Nucleic Acids $\rightarrow$ Purines & Pyrimidines

2.2 Acetogenesis

In the second stage, acetogenic bacteria, also known as acid formers, convert the products of the first phase to simple organic acids, carbon dioxide and hydrogen. The principal acids produced are acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), and ethanol (C_2H_5OH). The products formed during acetogenesis are due to a number of different microbes, e.g., s*yntrophobacter wolinii*, a propionate decomposer and s*ytrophomonos wolfei*, a butyrate decomposer. Other acid formers are *clostridium spp., peptococcus anerobus,lactobacillus*, and *actinomyces* (www.biogasworks.com- Microbes in AD). An acetogenesis reaction is shown below*:*

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

2.3 Methanogenesis

Finally, in the third stage methane is produced by bacteria called methane formers (also known as methanogens) in two ways: either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methane production is higher from reduction of carbon dioxide but limited hydrogen concentration in digesters results in that the acetate reaction is the primary producer of methane (Omstead et al, 1980). The methanogenic bacteria include *methanobacterium, methanobacillus, methanococcus and methanosarcina*. Methanogens can also be divided into two groups: acetate and H_2/CO_2 consumers. Methanosarcina spp. and methanothrix spp. (also, methanosaeta) are considered to be important in AD both as acetate and H_2/CO_2 consumers. The methanogenesis reactions can be expressed as follows:

$$\underset{\text{(acetic acid)}}{CH_3COOH} \rightarrow \underset{\text{(methane)}}{CH_4} + \underset{\text{(carbon dioxide)}}{CO_2}$$

$$\underset{\text{(ethanol)}}{2C_2H_5OH} + CO_2 \rightarrow CH_4 + 2CH_3COOH$$

$$CO_2 + \underset{\text{(hydrogen)}}{4H_2} \rightarrow CH_4 + \underset{\text{(water)}}{2H_2O}$$

2.4 General Process Description

Generally the overall AD process can be divided into four stages: Pretreatment, waste digestion, gas recovery and residue treatment. Most digestion systems require pre-treatment of waste to obtain homogeneous feedstock. The preprocessing involves separation of non-digestible materials and shredding. The waste received by AD digester is usually source separated or mechanically sorted. The separation ensures removal of undesirable or recyclable materials such as glass, metals, stones etc. In source separation, recyclables are removed from the organic wastes at the source. Mechanical separation can be employed if source separation is not available. However, the resultant fraction is then more contaminated leading to lower compost quality (RISE-AT, 1998). The waste is shredded before it is fed into the digester.

Inside the digester, the feed is diluted to achieve desired solids content and remains in the digester for a designated retention time. For dilution, a varying range of water sources can be used such as clean water, sewage sludge, or re-circulated liquid from the digester effluent. A heat exchanger is usually required to maintain temperature in the digesting vessel (Figure 2). The biogas obtained in AD is scrubbed to obtain pipeline quality gas. In case of residue treatment, the effluent from the digester is de-watered, and the liquid recycled for use in the dilution of incoming feed. The biosolids are aerobically cured to obtain a compost product.

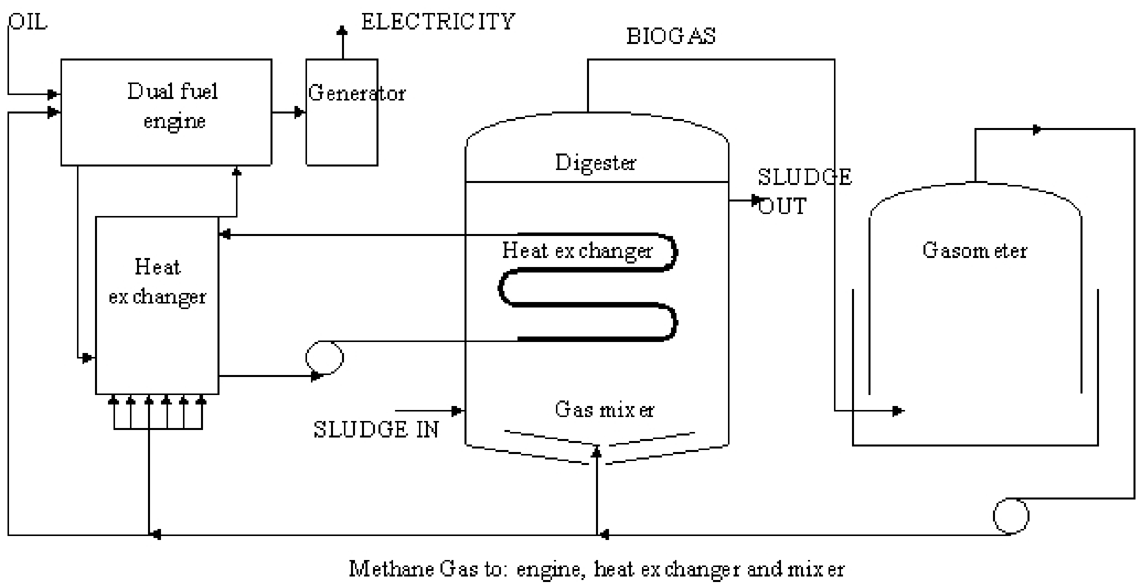


Figure 2. The flow diagram of low solids AD

Ref: http://www.soton.ac.uk/~sunrise/anaerobicdig.htm#ADsolidwaste

2.5 Various AD systems

AD processes can be classified according to the total solids (TS) content of the slurry in the digester reactor. Low solids systems (LS) contain less than 10 % TS, medium solids (MS) contain about 15%-20%, and high solids (HS) processes range from 22% to 40% (Tchobanoglous, 1993). AD processes can be categorized further on the basis of number of reactors used, into single-stage and multi-stage. In single stage processes, the three stages of anaerobic process occur in one reactor and are separated in time (i.e., one stage after the other) while multi-stage processes make use of two or more reactors that separate the acetogenesis and methanogenesis stages in space. Batch reactors are used where the reactor is loaded with feedstock at the beginning of the reaction and products are discharged at the end of a cycle. The other type of reactor used, mostly for low solids slurries, is continuous flow where the feedstock is continuously charged and discharged.

As noted earlier, the AD systems treat various types of waste-streams and in some plants MSW is mixed with sewage sludge or other type of waste. These types of processes will be discussed in more detail later.

3. Important Operating Parameters in AD Process

The rate at which the microorganisms grow is of paramount importance in the AD process. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the anaerobic degradation efficiency of the system. Some of these parameters are discussed in the following section.

3.1 Waste composition/Volatile Solids (VS)

The wastes treated by AD may comprise a biodegradable organic fraction, a combustible and an inert fraction. The biodegradable organic fraction includes kitchen scraps, food residue, and grass and tree cuttings. The combustible fraction includes slowly degrading lignocellulosic organic matter containing coarser wood, paper, and cardboard. As these lignocellulosic organic materials do not readily degrade under anaerobic conditions, they are better suited for waste-to-energy plants. Finally, the inert fraction contains stones, glass, sand, metal, etc. This fraction ideally should be removed, recycled or used as land fill. The removal of inert fraction prior to digestion is important as otherwise it increases digester volume and wear of equipment. In waste streams high in sewage and manure, the microbes thrive and hydrolyses the substrate rapidly whereas for the more resistant waste materials, such as wood, digestion is limited.

The volatile solids (VS) in organic wastes are measured as total solids minus the ash content, as obtained by complete combustion of the feed wastes. The volatile solids comprise the biodegradable volatile solids (BVS) fraction and the refractory volatile solids (RVS). Kayhanian (1995) showed that knowledge of the BVS fraction of

MSW helps in better estimation of the biodegradability of waste, of biogas generation, organic loading rate and C/N ratio. Lignin is a complex organic material that is not easily degraded by anaerobic bacteria and constitutes the refractory volatile solids (RVS) in organic MSW. Waste characterized by high VS and low non-biodegradable matter, or RVS, is best suited to AD treatment. The composition of wastes affects both the yield and biogas quality as well as the compost quality.

3.2 pH Level

Anaerobic bacteria, specially the methanogens, are sensitive to the acid concentration within the digester and their growth can be inhibited by acidic conditions. The acid concentration in aqueous systems is expressed by the pH value, i.e. the concentration of hydrogen ions. At neutral conditions, water contains a concentration of 10^{-7} hydrogen ions and has a pH of 7. Acid solutions have a pH less than 7 while alkaline solutions are at a pH higher than 7. It has been determined (RISE-AT, 1998) that an optimum pH value for AD lies between 5.5 and 8.5. During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control. The retention time of digestate affects the pH value and in a batch reactor acetogenesis occurs at a rapid pace. Acetogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5. Excessive generation of acid can inhibit methanogens, due to their sensitivity to acid conditions. Reduction in pH can be controlled by the addition of lime or recycled filtrate obtained during residue treatment. In fact, the use of recycled filtrate can even eliminate the lime requirement.

As digestion reaches the methanogenesis stage, the concentration of ammonia increases and the pH value can increase to above 8. Once methane production is stabilized, the pH level stays between 7.2 and 8.2.

3.3 Temperature

There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – the mesophilic and thermophilic ranges. The mesophilic range is between 20°C-40°C and the optimum temperature is considered to be 30°C-35°C. The thermophilic temperature range is between 50°C-65°C (RISE-AT, 1998). It has been observed that higher temperatures in the thermophilic range reduce the required retention time (National Renewable Energy Laboratory, 1992).

3.4 Carbon to Nitrogen Ratio (C/N)

The relationship between the amount of carbon and nitrogen present in organic materials is represented by the C/N ratio. Optimum C/N ratios in anaerobic digesters are between 20 – 30. A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in lower gas production. On the other hand, a lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. Optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with sewage or animal manure.

3.5 Total solids content (TS)/OrganicLoading Rate (OLR)

As discussed earlier, Low solids (LS) AD systems contain less than 10 % TS, medium solids (MS) about 15-20% and high solids (HS) processes range from 22% to 40% (Tchobanoglous, 1993). An increase in TS in the reactor results in a corresponding decrease in reactor volume.

Organic loading rate (OLR) is a measure of the biological conversion capacity of the AD system. Feeding the system above its sustainable OLR results in low biogas yield due to accumulation of inhibiting substances such as fatty acids in the digester slurry (Vandevivere, 1999). In such a case, the feeding rate to the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failures due to overloading (RISE-AT, 1998). Vandevivere (1999) reports OLR is twice in HS in comparison to LS.

3.6 Retention (or residence) Time

The required retention time for completion of the AD reactions varies with differing technologies, process temperature, and waste composition. The retention time for wastes treated in mesophilic digester range from 10 to 40 days. Lower retention times are required in digesters operated in the thermophilc range. A high solids reactor operating in the thermophilic range has a retention time of 14 days (Personal Communication with M. Lakos, May 2001).

3.7 Mixing

The purpose of mixing in a digester is to blend the fresh material with digestate containing microbes. Furthermore, mixing prevents scum formation and avoids temperature gradients within the digester. However excessive mixing can disrupt the microbes so slow mixing is preferred. The kind of mixing equipment and amount of mixing varies with the type of reactor and the solids content in the digester.

3.8 Compost

When the digestion is complete, the residue slurry, also known as digestate, is removed, the water content is filtered out and re-circulated to the digester, and the filter cake is cured aerobically, usually in compost piles, to form compost. The compost product is screened for any undesirable materials, (such as glass shards, plastic pieces etc) and sold as soil amendment.

The quality of compost is dependent on the waste composition. Some countries have prescribed standards for compost quality. The U.S. Department of Agriculture has set standards for heavy metals in the compost (Table 1). These standards are for compost treated by the aerobic process but may also be applied to AD compost product.

Table 1. US Department of Agriculture Compost Heavy Metals Standards (ppm)	
Heavy Metal	**Standard***
Cadmium (Cd)	10
Nickel (Ni)	200
Lead (Pb)	250
Copper (Cu)	1000
Chromium (Cr)	1000
Zinc (Zn)	2500
Source : USEPA 1995 * standard for compost produced by aerobic process	
Ref: Hickman, L.H., (1999) Principles of Integrated Solid Waste Management, American Academy of Environmental Engineers Publication	

Some of the European Union (EU) countries have set standards for the quality of compost produced by anaerobic digestion of solid wastes.

Table 2. Limits concentrations (mg/kg total solids) of heavy metals and arsenic in compost according to regulations in different countries

Country	**Cd**	**Pb**	**Hg**	**Ni**	**Zn**	**Cu**	**Cr**	**As**
Austria	1	150	1	60	400	100	70	-
Denmark	0.8	120	0.8	30	4000	1000	100	-
Finland	3	150	2	100	1500	600	-	50
France[a]	8	800	8	200	-	-	-	-
Germany, class 1[b]	1.5	150	1	50	400	100	100	-
Ireland	-	-	-	-	-	-	-	-
Italy[c]	10	500	10	200	2500	600	10[d]	500[d]
Netherlands, "superclean compost"[e]	0.7	65	0.2	10	75	25	50	5
Netherlands, ”clean compost”[e]	1	100	0.3	20	200	60	50	15
Norway, class I[f]	0.8	60	0.6	30	400	150	60	-
Norway, class II[f]	2	80	3	50	800	650	100	-
Spain	40	1200	25	400	4000	1750	750	-
Sweden (guidelines)	1	100	1	50	300	100	100	-
Switzerland	1	120	1	30	400	100	100	-
UK	-	-	-	-	-	-	-	-

a) No official legislation.
b) Class I-compost is used for food production.
c) Regulations for source sorted compost varies between regions.
d) Chrome (III) 500 mg/kg ts. Chrome (VI) 10 mg/kg ts.
e) The division into two classes was made in order to stimulate an improved compost quality. The quality is generally so good that a change to only one class is discussed.
f) The maximum application of class I is 40 tonnes/ha during 10 years and for class II maximum 20 tonnes/ha during 10 years.

Reference: AD-NETT Technical summary, Legislation in different European countries regarding implementation of anaerobic digestion Åke Nordberg Swedish Institute of Agricultural Engineering, ake.nordberg@jti.slu.se, www.ad-nett.com

3.9 Biogas Composition

The gas obtained during AD comprises of methane, carbon dioxide, some inert gases and sulfur compounds (Table 3). Usually 100-200 m^3 of total gas are produced per ton of organic MSW digested (RISE-AT, 1998).

Table 3. Typical Biogas Composition	
Methane	55-70% by vol.
Carbon dioxide	30-45% by vol
Hydrogen sulphide	200-4000 ppm by vol
Energy content of AD gas product	20-25MJ/standard m^3
Energy content of CH_4 per ton MSW	167-373MJ/Ton MSW
Reference: Regional Information Service Centre for South East Asia on Appropriate Technology (RISE-AT) (Nov 1998), Review of current status of Anaerobic Digestion Technology for treatment of MSW	

4. Development and present status of AD Technology

4.1 Historical Background

Historical evidence indicates that the AD process is one of the oldest technologies. Biogas was used for heating bath water in Assyria during the 10th century BC and in Persia during the 16th century (www.biogasworks.com). AD advanced with scientific research and, in the 17th century, Jan Baptista Van Helmont established that flammable gases evolved from decaying organic matter. Also, Count Alessandro Volta in 1776 showed that there was a relationship between the amount of decaying organic matter and the amount of flammable gas produced. In 1808, Sir Humphry Davy demonstrated the production of methane production by the anaerobic digestion of cattle manure (Lusk, 1997).

The industrialization of AD began in 1859 with the first digestion plant in Bombay, India. By 1895, AD had made inroads into England where biogas was recovered from a well-designed sewage treatment facility and fueled street lamps in Exeter. Further AD advances were due to the development of microbiology. Research led by Buswell and others (Lusk, 1997) in the 1930s identified anaerobic bacteria and the conditions that promote methane production.

Prior to 1920, most of the AD took place in anaerobic ponds. As the understanding of AD process control and its benefits improved, more sophisticated equipment and operational techniques emerged. The result was the use of closed tanks and heating and mixing equipment to optimize AD. The primary aim of waste stabilization in due course led to the basic municipal sludge digester. This design then spread throughout the world. However, methane production suffered a setback as low-cost coal and petroleum became abundant. AD systems made a comeback during WWII with fuel shortages hitting Europe but after the war AD was once again forgotten. Another factor that led to declining interest in AD was increased interest in aerobic digestion systems.

While the developed world shunned AD except as a wastewater sludge digestion technique, developing countries such as India and China embraced this technology. These countries saw gradual increase in small-scale AD systems used mostly for energy generation and sanitation purpose. In the developed countries, industrial expansion and urbanization coupled with low-cost electricity resulted in aerobic composting and landfilling to become the choice technologies for waste treatment, until recent times. The energy crisis in 1973 and again in 1979 triggered renewed interest in development of simple AD systems for methane production as an energy source. India, China and Southeast Asia responded to the crisis with marked expansion of AD. Most of the AD systems were small digesters using combined human, animal and kitchen wastes. Many community digesters were installed to produce large volumes of biogas for village electrification. Also, Europe, North America and the Soviet Union became involved with research in AD for methane production from animal manure. The U.S. established renewable energy programs, emphasizing the AD of biomass for energy production.

The rush for deployment of AD systems to meet energy needs also led to many foreign-aid projects. Unfortunately, the knowledge on AD was still in a fledgling state and there were numerous failures. China, India and Thailand reported 50% failure rates. Failures of farm digesters in the U.S. approached 80%. Europe and

Russia also experienced high farm digester failure rates (Lusk, 1997). Nevertheless, those designs that succeeded furthered the interest in research and development of AD. Apart from biogas production, AD found wider acceptance as an inexpensive technology for waste stabilization, nutrient recovery, reduction in biological oxygen demand (BOD), and sludge treatment. The dominant application of AD technology has been in farm-based facilities. About six to eight million family-sized, low-technology digesters are used to provide biogas for cooking and lighting fuels with varying degrees of success.

China and India have now adopted a trend towards larger, more sophisticated farm-based systems with better process control to generate electricity. With time, AD systems are becoming more complex and not limited to agriculture or animal waste treatment. The technology is now being applied for municipal waste treatment as well as industrial waste. Taiwan flares most biogas from waste treatment and has cut down river pollution, caused by direct discharge from the animal production industry, by simply using standard AD systems that serve 5,000 farms (Lusk, 1996).

In recent times, Europe came under pressure to explore AD market because of two significant reasons: High energy prices and stringent environmental regulations, especially controls on organic matter going to landfills as well as further expansion of landfills (Table 4).

Table 4. Current and Planned Waste Legislation in Europe*

Country	
Austria	Aims to ban landfilling of more than 5% organics by 2004
Belgium	Soon to ban direct landfilling of combustible MSW
Denmark	Banning and landfilling of combustible MSW
Finland	Policies to encourage co-combustion of MSW with other fuels
France	Banning landfilling of combustibles by 2002.Landfill levy of 20FF/tonne
Germany	Restricting landfilling of waste with more than 5% organic carbon content by 2005.
Netherlands	Landfilling of combustibles banned.Direct landfilling of other MSW banned by 2000.
Sweden	Decrease in reliance on landfill by increasing recycling rates and WTE rates.
UK	Recycling target of 25% by 2000. Lanfill tax of 7 pounds/tonne since 1996.
Ireland	Considering imposition of landfill tax.

*Data source: The Bioreactor Landfill, A white paper from Waste Management, Inc. 2000

Because of environmental pressures, many nations have implemented or are considering methods to reduce the environmental impacts of waste disposal. Both Germany and Denmark have pledged to double their biogas production by the year 2000 and triple it by the year 2005 (Lusk, 1996). The incentive comes from the "Green-Pricing" initiative of government that allows biogas-generated electricity to be sold at a premium. Also, the co-generated “waste” steam and hot water is used in district heating systems, thereby earning additional revenue for project developers.

In Europe, AD facilities generally have had a good record in treating a wide spectrum of waste streams like farm, industrial, and municipal wastes. Some AD facilities in Europe have been in operation for over 20 years. More than 600 farm-based digesters operate in Europe, where the key factor is their design simplicity. Around 250 of these systems have been installed in Germany alone in the past five years. In addition to farm digesters, Europe leads in large centralized AD systems. Between 1987-95, there were more than 150 new AD plants constructed in Europe (www.biogasworks.com). In Europe, there are 30 large centralized digesters of which 15 are in Denmark alone and 30 more are under construction. The Danish facilities co-digest manure, clean organic industrial wastes, and source-separated municipal solid waste.

The AD technology is also used for treating industrial wastewater. The treatment of high-organic industrial wastewater is less costly by AD then by aerobic composting. There are now more than 1000 vendor-supplied systems in operation or under construction throughout the world. According to Lusk (1996), European plants comprise 44% of the installed systems, with only 14% of the systems located in North America. A large number of plants are located in Brazil treating vinasse from sugar cane-based for ethanol production. Over 35 industries have been identified using AD. They include chemicals processing, fiber, food, waste meat and milk, and pharmaceuticals. In many cases, AD is used as a pretreatment step to lower sludge disposal costs and odors, thus reducing the costs of final treatment onsite or at a municipal wastewater treatment.

Both AD and aerobic composting offer a biological route for the recovery of nutrients from the organic fraction of MSW. However, aerobic composting is energy consuming, requiring 50-75 kWh of electricity per ton of MSW input. In contrast, AD is an energy producer, with around 75-150 kWh of electricity generated per ton of MSW input (www.biogasworks.com). Using the data of Table 3 and applying the usual 31% efficiency of U.S. power plants using fossil fuels, the electricity generated from methane per ton of MSW processed by AD is calculated to be in the range of 48-104 kWh.

5. Types of AD Systems

As discussed previously in the methods used to treat MSW anaerobically can be classified into following categories:

- Single Stage
- Multi Stage
- Batch

These categories can be classified further, based on the total solids (TS) content of the slurry in the digester reactor. As noted earlier, low solids (LS) contain less than 10 % TS, Medium solids (MS) contain about 15-20% High solids (HS) processes range from about 22% to 40%. The single stage and the multi stage systems can be further categorized as single stage low solids (SSLS), single stage high solids (SSHS), multi stage low solids (MSLS) and multi stage high solids (MSHS). The drawback of LS is the large amount of water used, resulting in high reactor volume and expensive post-treatment technology. The expensive post treatment is due to de-watering required at the end of the digestion process. HS systems require a smaller reactor volume per unit of production but this is counterbalanced by the more expensive equipment (pumps, etc.) required. Technically, HS reactors are more robust and have high organic loading rates. Most AD plants built in the 80's were predominantly low solids but during the last decade the number of high solids processes has increased appreciably. There is substantial indication from the obtained data that high solids plants are emerging as winners.

5.1 Single Stage Process

Single stage reactors make use of one reactor for both acidogenic phase as well as methanogenic phase. These could be LS or HS depending on the total solids content in a reactor.

5.1.1 Single Stage Low Solids (SSLS) Process

Single stage low solids processes are attractive because of their simplicity. Also they have been in operation for several decades, for the treatment of sludge from the treatment of wastewater. The predominant reactor used is the continuously stirred tank reactor (CSTR). The CSTR reactor (Figure 2) ensures that the digestate is continuously stirred and completely mixed. Feed is introduced in the reactor at a rate proportional to the rate of effluent removed. Generally the retention time is 14-28 days depending on the kind of feed and operating temperature.

Some of the SSLS commercial AD plants are the Wassa process in Finland, the EcoTec in Germany, and the SOLCON process at the Disney Resort Complex, Florida (www.soton.ac.uk). The plant examined in more detail is the Wassa process plant (10%-15 % TS) that was started in 1989 in Waasa, Finland (Figure 2). Currently there are three Wassa plants ranging from 3000-85000 tons per annum, some operating at mesophilic and others at thermophilic temperatures. The retention time in the mesophilic process is 20 days as compared to 10 days in the thermophilic. The feed used in this process is mechanically pre-sorted MSW mixed with sewage sludge. The organic loading rate (OLR) differs with the type of waste. The OLR was 9.7 kg/(m^3 day) with mechanically sorted organic MSW and 6 kg/(m^3 day) with source separated waste. The gas production was in the range of 170 Nm^3 CH_4/ton of VS fed and 320 Nm^3 CH_4/ton of VS fed and 40-75% reduction of the feed VS was achieved (Vandevivere, 1999).

The advantages offered by SSLS are operational simplicity and technology that has been developed for a much longer time than high solids systems. Also, SSLS makes use of less expensive equipment for handling slurries. The pre-treatment involves removing of coarse particles and heavy contaminants. These pre-treatment steps cause a loss of 15 - 25 % VS, with corresponding decrease in biogas yield. The other technical problem is formation of a layer of heavier fractions at the bottom of the reactor and floating scum at the top, which indicate non-homogeneity in the reacting mass. The bottom layer can damage the propellers while the top layer hinders effective mixing. This requires periodic removal of the floating scum and of the heavy fractions, thus incurring lower biogas yield. Another flaw is the short-circuiting, i.e. a fraction of the feed passes through the reactor at a shorter retention time than the average retention time of the total feed. This lowers the biogas yield and impairs hygienization of the wastes.

For the solids content to be maintained below 15%, large volumes of water are added, resulting in large reactor volumes higher investment costs, and amount of energy needed to heat the reactor. Also, more energy and equipment are required for de-watering the effluent stream. The high investment costs associated with dilution and reactor volume plus the complex pre-treatment step offset the gains from the low cost equipment to handle slurry.

5.1.2 Single- Stage High Solids (SSHS) Process

The advances of the HS technology were the result of research undertaken in the 80's that established higher biogas yield in undiluted waste. Some of the examples of SSHS are the DRANCO, Kompogas, and Valorga processes. The DRANCO and Valorga processes are described in more detail later in this thesis. All three processes consist of a single stage thermophilic reactor (mesophilic in some Valorga plants) with retention time of 14-20 days.

In the DRANCO reactor (Figure 3a), the feed is introduced from the top and digested matter is extracted from the bottom. There is no mixing apart from that occurring due to downward plug-flow of the waste. Part of the extracted matter is reintroduced with the new feed while the rest is de-watered to produce the compost product.

The Kompogas process (Figure 3b) works similarly, except the movement takes place in plug flow in a horizontally disposed cylindrical reactor. Mixing is accomplished by the use of an agitator. The process maintains the solids concentration at about 23 % TS. At solids content lower than 23%, the heavy fraction such as sand and glass can sink and accumulate at the bottom; higher TS concentrations impede the flow of materials (Vandevivere, 1999).

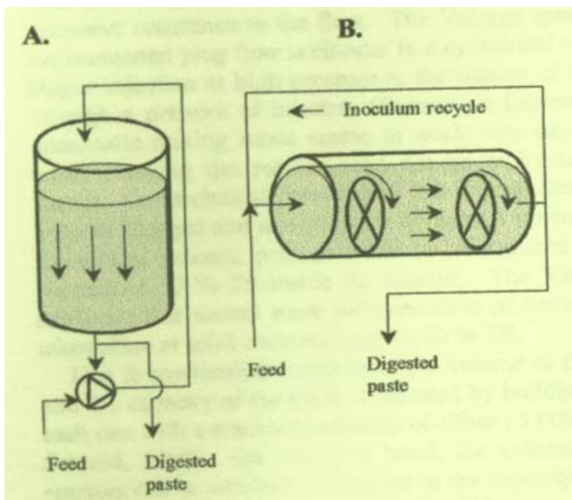


Figure 3. The DRANCO reactor (A) and Kompogas Reactor (B)

Ref: Vandevivere, P., De Baere, L., Verstraete, W. (1999) unpublished manuscript

The design of the Valorga process is unique. The reactor is a vertical cylindrical reactor divided by a partial vertical wall in the center (Figure 4). The feed enters through an inlet near the bottom of the reactor and slowly moves around the vertical plate until it is discharged through an outlet that is located diametrically opposite to the inlet. Re-circulated biogas is injected through a network of injectors at the bottom of the reactor and the rising bubble result in pneumatic mixing of the slurry. The injectors require regular maintenance, as they are prone to clogging.

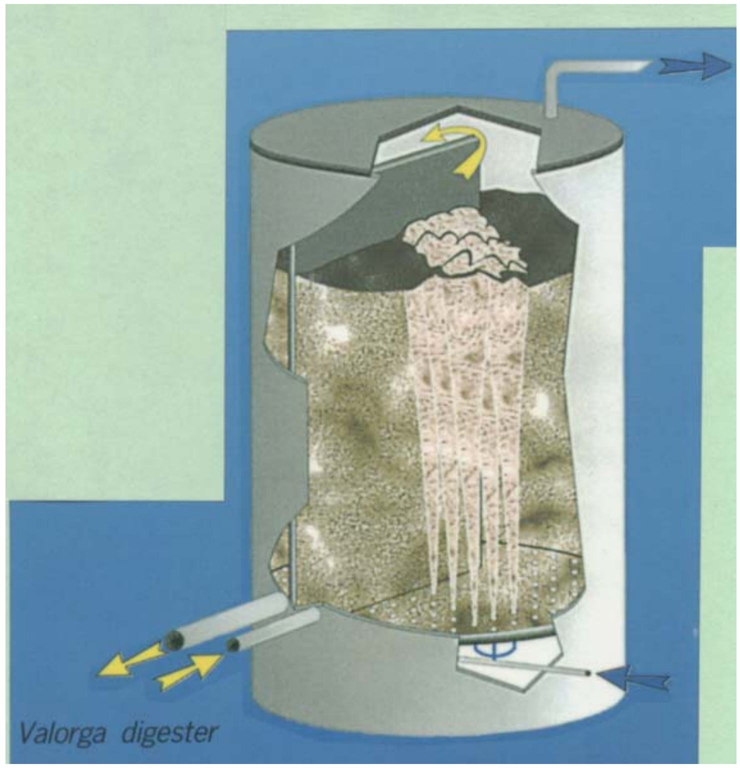


Figure 4. The Valorga Digester

Ref: The Anaerobic Digestion and the Valorga Process, Jan 1999, Literature and brochures provided by the company

The high solids content in HS systems requires different handling, mixing and pre-treatment than those used in the LS processes. The equipment needed to handle and transport high solids slurries is more robust and expensive than that of the LS, comprising of conveyor belts, screws, and powerful pumps. On the other hand, the pre-treatment is less cumbersome than for LS systems. The HS systems can handle impurities such as stones, glass or wood that need not be removed as in SSLS. Contrary to the complete mixing prevailing in SSLS, the SSHS are plug-flow reactors hence require no mechanical device within the reactor (De Baere, 1999). The economic differences between the SSLS and SSHS are small.

SSHS processes exhibit higher OLRs, as compared to SSLS; for example, OLR values of 15 kg VS/m^3 per day are reported for the DRANCO plant in Brecht, Belgium, where, whereas in the Waasa Process the OLR is 6 kg VS/m^3 per day. The biogas yield is usually high in SSHS as heavy fractions or the scum layer is not removed during the digestion.

There are pronounced differences between SSHS and SSLS reactors, in terms of environmental impacts. The LS process consumes one m^3 of fresh water per ton MSW treated whereas the water use in HS is one tenth of that (Nolan- ITU, May 1999). Consequently, the volume of wastewater to be discharged is several-fold less for HS reactors.

5.2 Multi-Stage Process

The introduction of multi-stage AD processes was intended to improve digestion by having separate reactors for the different stages of AD, thus providing flexibility to optimize each of these reactions. Typically, two reactors are used, the first for hydrolysis/liquefaction-acetogenesis and the second for methanogenesis. In the first reactor, the reaction rate is limited by the rate of hydrolysis of cellulose; in the second by the rate of microbial growth. The two-reactor process allows to increase the rate of hydrolysis by using microaerophilic conditions (i.e., where a small amount of oxygen is supplied in an anaerobic zone) or other means. For methanogenesis, the optimum growth rate of microbes is achieved by designing the reactor to provide a longer biomass retention time with high cell densities or attached growth (also known as “fixed film reaction”, where the microbes responsible for conversion of the organic matter are attached to an inert medium such as rock, or plastic materials in the reactor). An important requirement to be met in such reactors is removal of the suspended particles after the hydrolysis stage. Multi-stage processes are also classified as multi-stage low-solids (MMLS) and multi-stage high-solids (MMHS).

There is a lot of similarity, in terms of solids content, pre-treatment steps, handling of waste, requirement of water etc., between SSLS and MMLS as well as SSHS and MMHS processes.

5.2.1 Multi-Stage Low Solids Process

Some of the MSLS facilities are the Pacques process (Netherlands), the BTA process (Germany, Canada) and the Biocomp (Germany) process (www.soton.ac.uk) The Pacques process uses two reactors at mesophilic temperature. Initially, The feed consisted of fruit and vegetable waste but recently source-separated MSW is also being processed. The first reactor where hydrolysis occurs has solids content 10 %. Mixing is achieved by means of gas injection. The digestate from the first reactor is de-watered, and the liquid is fed to an Upflow Anaerobic Sludge Blanket reactor where methanogenesis occurs. The fraction of the digestate from the hydrolysis reactor is re-circulated with the incoming feed to the first reactor for inoculation. The remaining fraction is sent for compost production.

In the BTA process (Figure 5) the solid content is maintained at 10% and the reactors are operated at mesophilic temperatures. This process is described in detail in the case study section. It is very similar to the Pacques process except that the methanogenic reactor is designed with attached growth ("fixed film reaction") to ensure biomass retention. The effluent from the hydrolysis reactor is de-watered and the liquor is fed to the methanogenic reactor. This reactor receives only the liquid fraction from hydrolysis reactor to avoid clogging of the attached growth. At times, in order to maintain the pH within the hydrolysis reactor in the range of 6-7, the process water from the methanogenic reactor is pumped to the hydrolysis reactor.

The multi-stage low solids processes are plagued with similar problems to those of the SSLS reactors, such as short-circuiting, foaming, formation of layers of different densities, expensive pre-treatment. In addition, the MSLS processes are technically more complex and thus require a higher capital investment.

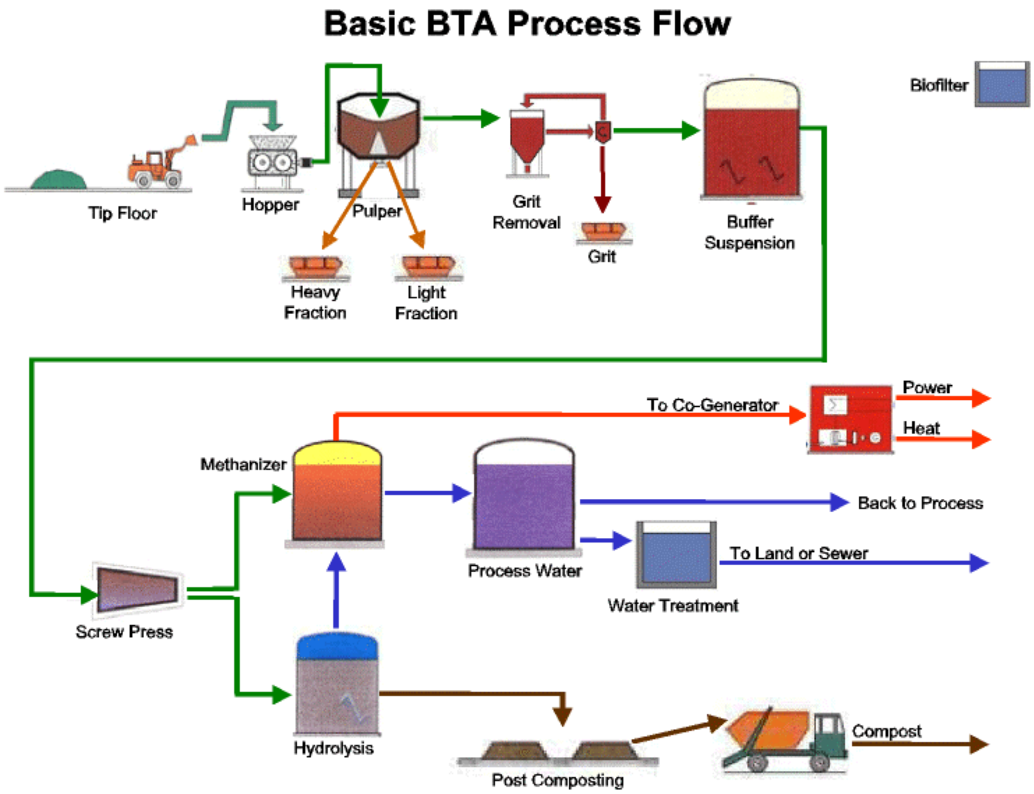


Figure 5. The flow diagram of BTA Process

Ref: www.canadacomposting.com

5.2.2 Multi -Stage High-Solids Process

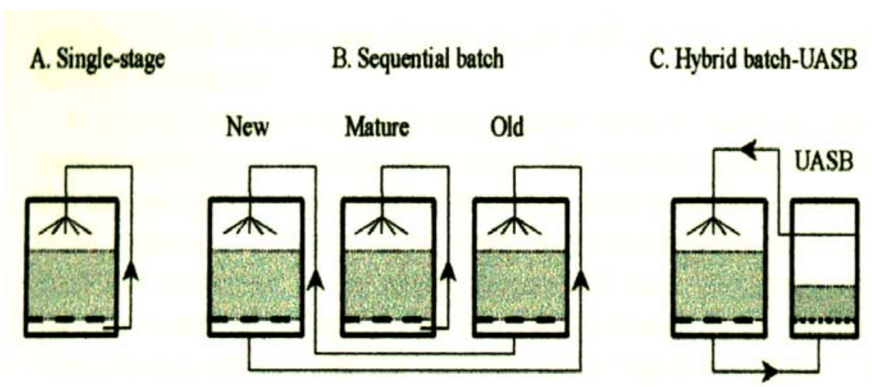
The Biopercolat process is a multi-stage high-solids process but is somewhat similar to the Pacques process (MSLS) in that it consists of a liquefaction/hydrolysis reactor followed by a methanogenic Upflow Anaerobic Blanket Sludge reactor (UASB) with attached growth. However hydrolysis is carried out under high solids and microaerophilic conditions (where limited amount of oxygen is supplied in anaerobic zone). The aeration in the first stage and the attached growth reaction in the second provide for complete digestion at retention time of only seven days.

The advocates of multi-stage processes cite the advantages of high OLR for all types of multi-stage systems, such as 10kg VS/(m^3.d) and 15kg VS/(m^3.d) for the BTA (MSLS) and Biopercolat processes (MSHS), respectively. This is due to higher biomass retention with attached biofilm, which increases the resistance of methanogens to high ammonium concentrations (Vandevivere, 1999). The biological stability thus achieved offers potential for increased OLR. However, high OLR does not result in high biogas yield. The lower biogas yield observed in practice is due to removal of solids that contain some biodegradable matter, after the short hydrolysis period before feeding the methanogenic reactor. In recent years, the single-stage systems have also achieved high OLRS thus canceling this advantage of multi-stage systems.

According to De Baere 1999, commercial applications of multi-stage systems amount to only 10 % of the current treatment capacity, as will be discussed later, under current trends of AD systems.

5.3 Batch Reactors

Batch reactors are loaded with feedstock, subjected to reaction, and then are discharged and loaded with a new batch. The batch systems may appear as in-vessel landfills but in fact achieve much higher reaction rates and 50- to 100% higher biogas yields than landfills for two reasons. First, the continuous re-circulation of the leachate and second, they are operated at higher temperatures than landfills (Vandevivere, 1999). There are three types of batch systems - single stage batch



system, sequential batch system and an Upflow Anaerobic Sludge Blanket reactor (Figure 6)

Figure 6. Types of Batch Reactors

Ref: Vandevivere, P., De Baere, L., Verstraete, W. (1999) unpublished manuscript

The single-stage batch system involves re-circulating the leachate to the top of the same reactor. An example of such a system is the Biocel process in Lelystad, The Netherlands that was started in 1997 and treats 35,000 tons/y of source-sorted biowaste. The system operates at mesophilic temperatures and consists of fourteen concrete reactors each of 480m^3 capacity. The waste fed to these unstirred reactors is pre-mixed with inoculum. The leachates are collected in chambers under the reactors and recycled to the top of each reactor. The waste is kept within the reactor for over 40 days, until biogas production stops. The Biocel plant produces on the average 70 kg biogas/ton of source-sorted biowaste which is 40 % less than from a single stage low-solids digester treating similar wastes (Vandevivere, 1999).

The sequential batch process comprises two or more reactors. The leachate from the first reactor, containing a high level of organic acids, is re-circulated to the second reactor where methanogenesis occurs. The leachate of the methanogenic reactor, containing little or no acid, is combined with pH buffering agents and re-circulated to the first reactor. This guarantees inoculation between the two reactors.

The third type of batch process is the hybrid batch-UASB process, which is very similar to the multi-stage process with two reactors. The first reactor is simple batch reactor but the second methanogenic reactor is an upflow anaerobic sludge blanket (UASB) reactor.

Batch processes offer the advantages of being technically simple, inexpensive and and robust. However, they require a large land footprint as compared to single-stage HS reactors since they are much shorter and their OLR two-fold less (Vandevivere, 1999). Other disadvantages are settling of material to the bottom thus inhibiting digestion and the risk of explosion while unloading the reactor.

6. Trends in AD technology

According to the Bioenergy Report of the International Energy Agency (IEA), in 1996 there were about 90 AD plant around the world and 30 under construction (Table 5). This data includes all plants with treatment capacity of over 2500 tons per year. Around 40 companies are involved in marketing AD technology (Table 6). A 1999 report by the German Technical Cooperation Agency (GTZ) reports around 400 AD plants worldwide treating both municipal and industrial waste.

Table 5. Anaerobic Plants in various nations

Country	No. of plants in operation	No. of plants under construction
Austria	10	0
Belgium	1	2
China	0	1
Denmark	21	1
Finland	1	0
France	1	0
Germany	30	9
India	0	4
Italy	4	2
Japan	0	1
Netherlan	4	0
Poland	0	1
Spain	0	1
Sweden	7	2
Switzerla	9	1
Thailand	0	1
UK	0	1
Ukraine	1	0
USA	1	2
Data Source: IEA Bioenergy AD Activity 1997 Report, Systems & Markets		

Table 6. Companies supplying AD plants of capacity >2,500 tons/year

Company	**No. of plants in operation**	**No. of plants under construction**
Arge Biogas, (Austrian)	2	0
Entech,(Austrian)	7	4
Kompagas,(Swiss)	10	0
OWS-Dranco,(Belgian)	4	1
BTA,(German)	11	0
Steinmuller Valorga, Sarl (French)	2	4
Ecotec,(Finish)	1	7
C.G. Jensen,(Danish)	1	0
BWSC,(Danish)	3	0
NNR,(Danish)	6	0
Kruger,(Danish)	12	2
Bioscan, ,(Danish)	1	1
Prikom/HKV,(Danish)	2	0
Jysk, ,(Danish)	1	0
Citec, ,(Finish)	1	1
Linde-KCA,(German)	1	0
Schwarting UDHE, (German)	1	0
ANM, (German)	1	0
Haase Energietechnik, (German)	1	1
DSD Gas und Tankanlagenbau, (German)	2	0
IMK BEG Bioenergie, (German)	0	1
Bioplan, (Danish)	1	0
TBW, (German)	1	0
BRV Technologie Systeme, (German)	2	0
D.U.T. (German)	1	0
Paques Solid Waste Systems, (Dutch)	3	1
Unisyn Biowaste Technology,(USA)	1	0
Duke Engineering, (USA)	0	2
WMC Resource Recovery, (UK)	0	1
R.O.M. (Swiss)	1	1
Purac, (Swedish)	1	0
SWECO/VBB, (Swedish)	0	1
NSR, (Swedish)	1	0
BKS Nordic, (Swedish)	1	0
Projectror, (Swedish)	2	0
Biocel/Heidermij Realisatie,(Dutch)	1	0
Ionics Italba,(Italian)	1	0
Kiklos, (Italian)	2	0
SPI, (Italian)	1	0
RPA, (Italian)	1	0
Data Source: IEA Bioenergy AD Activity 1997 Report, Systems & Markets Overview of AD		

The Biogasworks (1998) shows a list of 130 plants and 45 and process suppliers of capacity varying from 500 to 300,000 tons/year and treating different waste streams. The distribution is presented in the form of a pie chart in Figure 7. It can be seen that most of the plants are operating in Europe (91%), with some in Asia (7%) percent and a few in the US (2%). Germany is the leader with 35% of all AD plants, followed by Denmark (16%) and Sweden and Switzerland and Austria (8%).

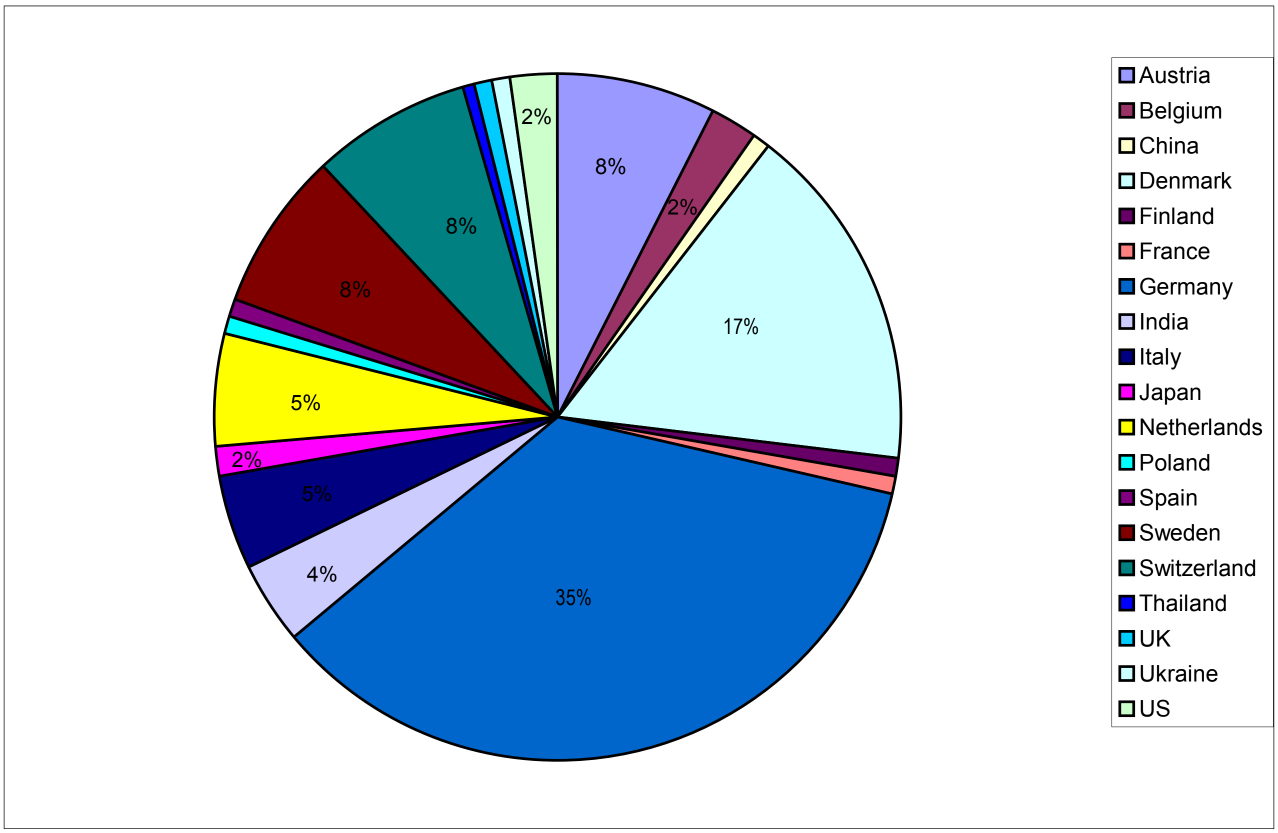


Figure 7. Worldwide Distribution of AD Plants

Ref: Adapted from www.biogasworks.com

The survey of the state of art of AD, with respect to size, capacity and waste-streams and operating parameters, is based on data provided by De Baere (1999). The data included plants operating in Europe with capacity greater than 3000 tons/year. The trend shows that plant capacity and number of plants built annually increased rapidly since 1996.

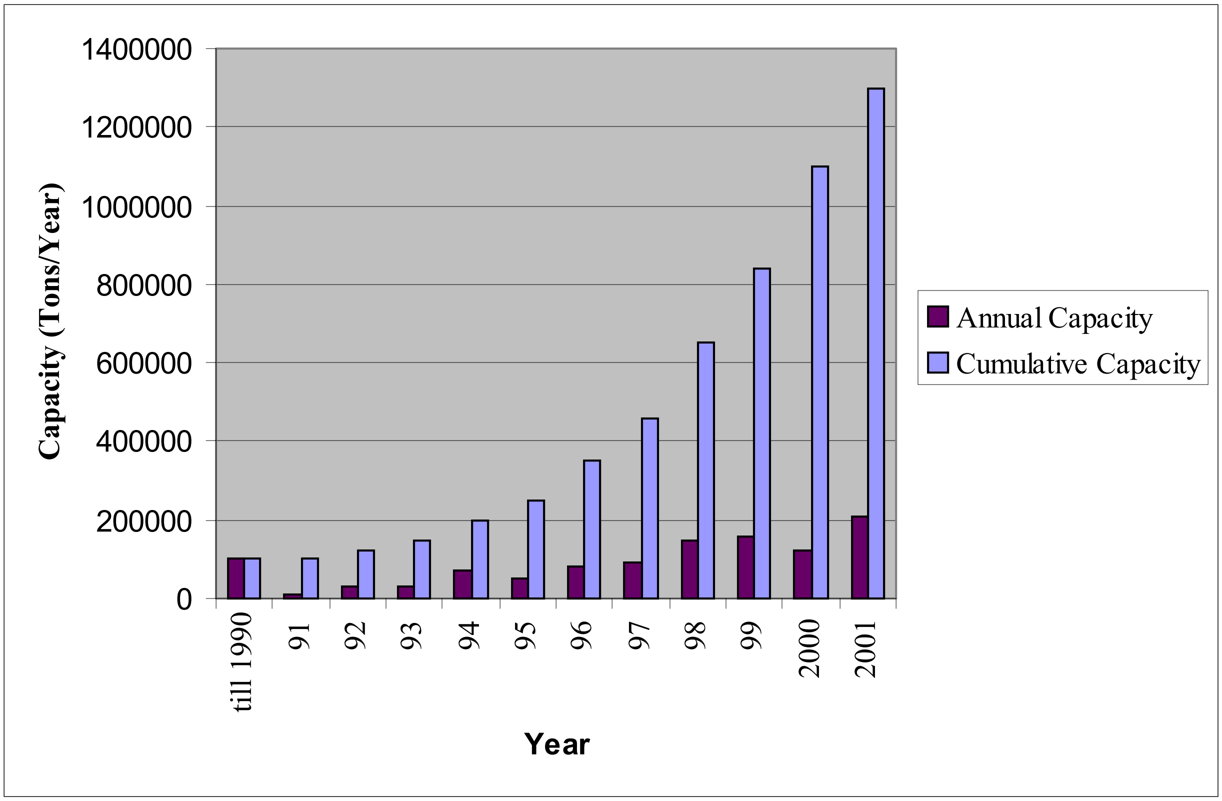


Figure 8. Annual and Cumulative Capacity of AD Plants treating MSW

Ref: De Baere, L., (1999) Anaerobic Digestion of Solid Waste: State of the Art, *Water, Science Technology* Vol. 41, No 3, pp 283-290

Traditionally, AD plants have operated in the mesophilic range as it was difficult to control the temperature of digester at higher temperature; temperatures above 70°C, can kill the microbes digesting the waste. Along with the advent of high-solids AD, there has been progressing in using the thermophilic range. It is now an established technology and many plants are using it. The benefits offered are hygenizaion of waste, lower retention time and higher biogas yield (National Renewable Energy Laboratory, 1992).

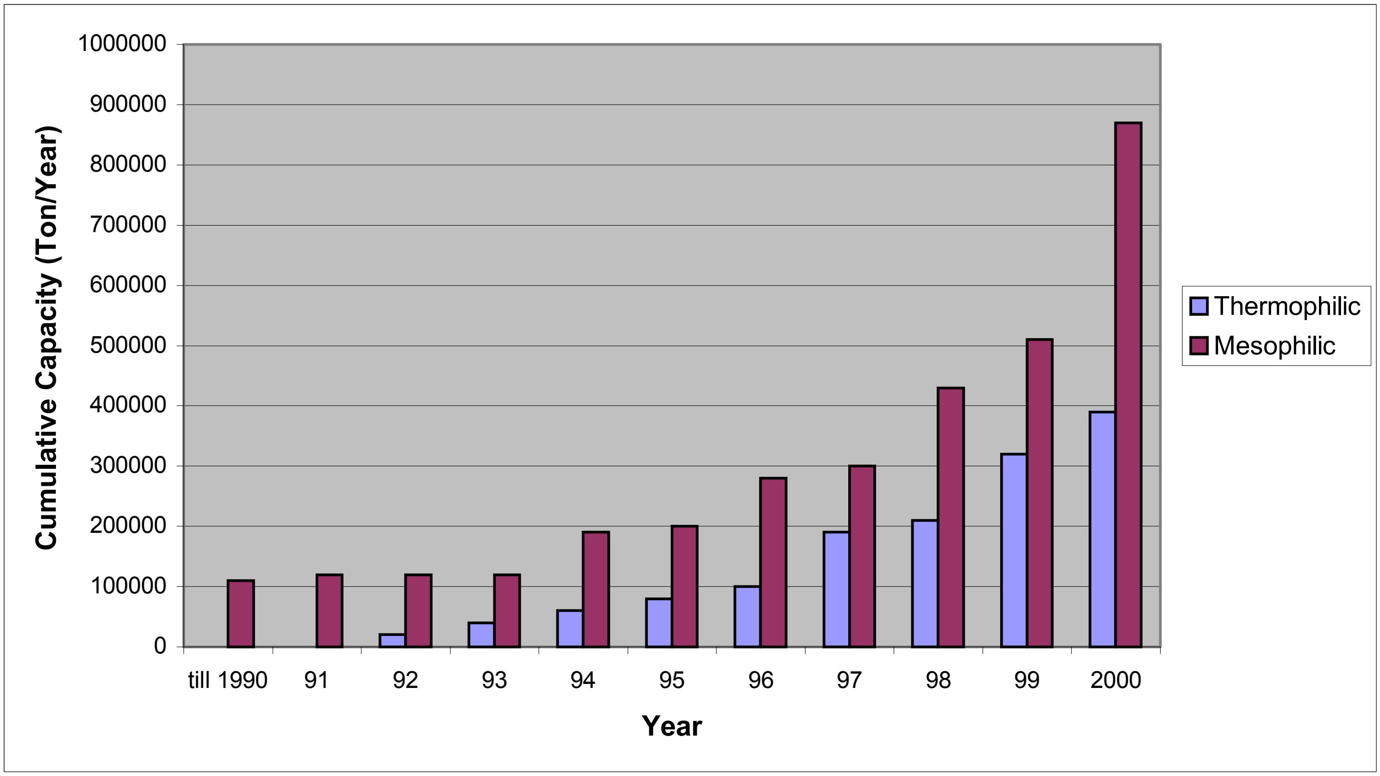


Figure 9. Comparison between Mesophilic and Thermophilic AD Plants

Ref: De Baere, L., (1999) Anaerobic Digestion of Solid Waste: State of the Art, *Water, Science Technology* Vol. 41, No 3, pp 283-290

Industrial applications of single-stage high-solids and low-solids and are about the same (Vandevivere, 1999). Initially, most AD systems were treating dilute wastes. However, more high-solids plants were constructed after 1998. Another advantage of high-solids systems is that they can process "mixed MSW" as well as biowaste. "Mixed MSW" is all material set out as garbage excluding recyclables, compostables or waste diverted from garbage by some other means. "Biowaste" is source separated household waste.

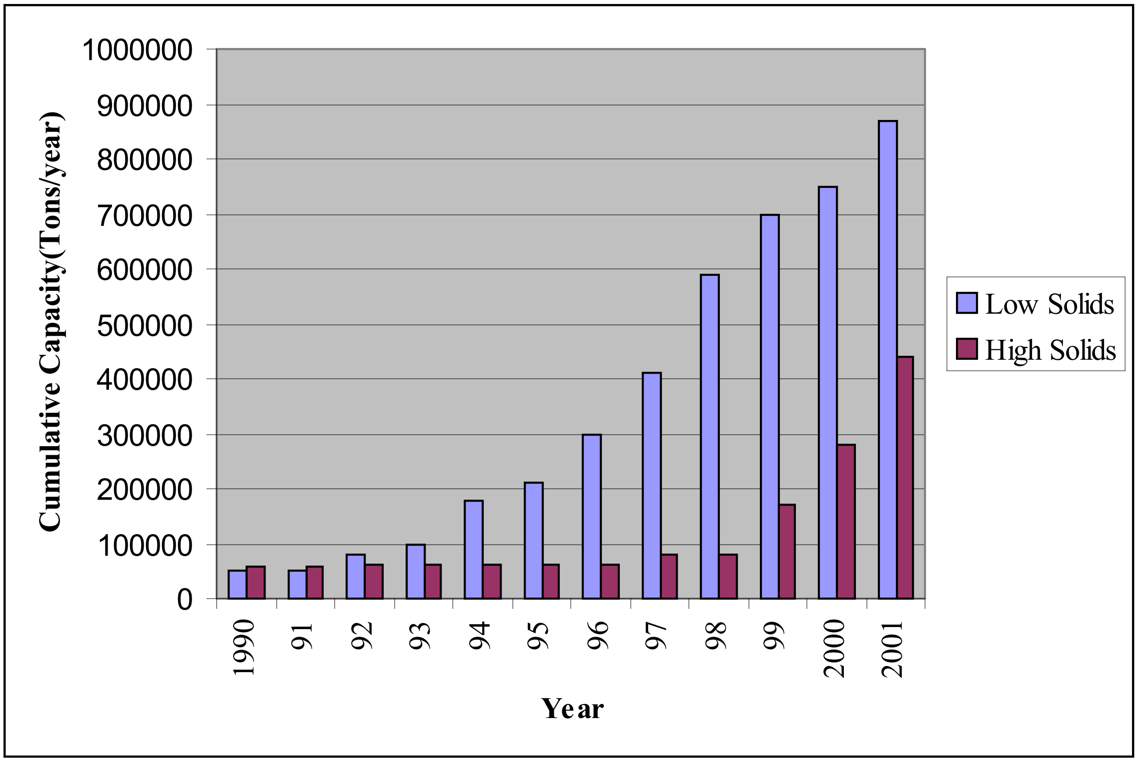


Figure 10. Comparison between Low Solids and High Solids AD Plants

Ref: De Baere, L., (1999) Anaerobic Digestion of Solid Waste: State of the Art, *Water, Science Technology* Vol. 41, No 3, pp 283-290

With regard to single-stage and multi-stage systems, the market has clearly chosen the former. As noted earlier in the thesis the survey of De Baere 1999 indicates that only 10.6% of the current available capacity is provided by multi phase digestion systems.

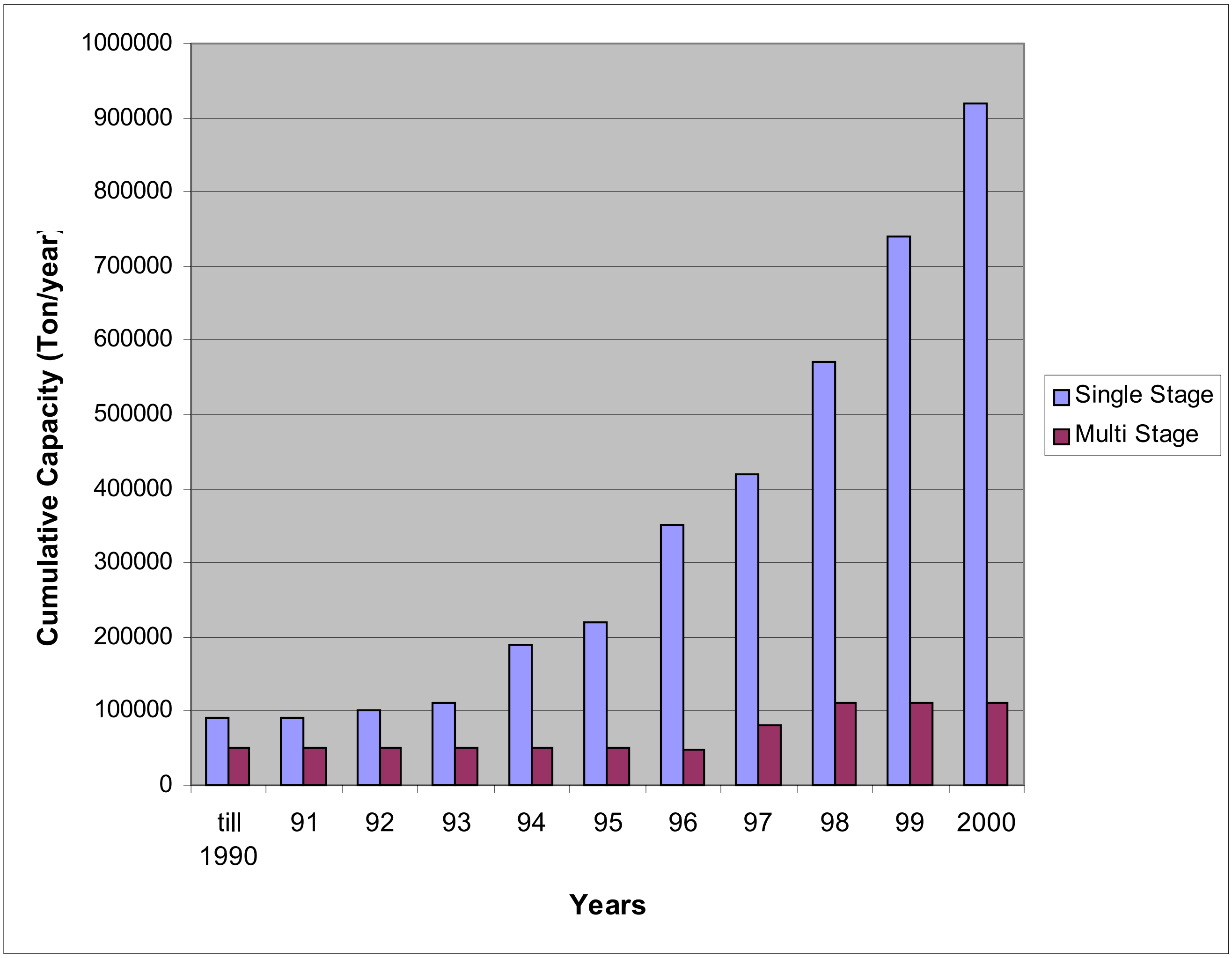


Figure 11. Comparison between Single Stage and Multi Stage AD Plants

Ref: De Baere, L., (1999) Anaerobic Digestion of Solid Waste: State of the Art, *Water, Science Technology* Vol. 41, No 3, pp 283-290

The development of AD systems had been in the treatment of source separated biowaste due to efficient collection system at household level. Recently, the interest has been to treat variety of wastes and led to increase in capacity of plants for mixed waste from 80000 ton/year in 1998 to 380000tons/year in 2001. AD demonstrates high flexibility in treating different waste-streams, from low solids to high solids and clean organic waste to grey waste (De Baere 1999). The three DRANCO plants are examples of this flexibility to treat varied waste. Brecht plant not only treats biowaste collected from rural areas but also non-recyclable papers, diapers, paper napkins etc. High solids content is about 40% whereas Salzburg plant operates at 30% and treats biowaste. The waste composition for Bassum is mainly grey waste as well as food and non-recyclable paper.

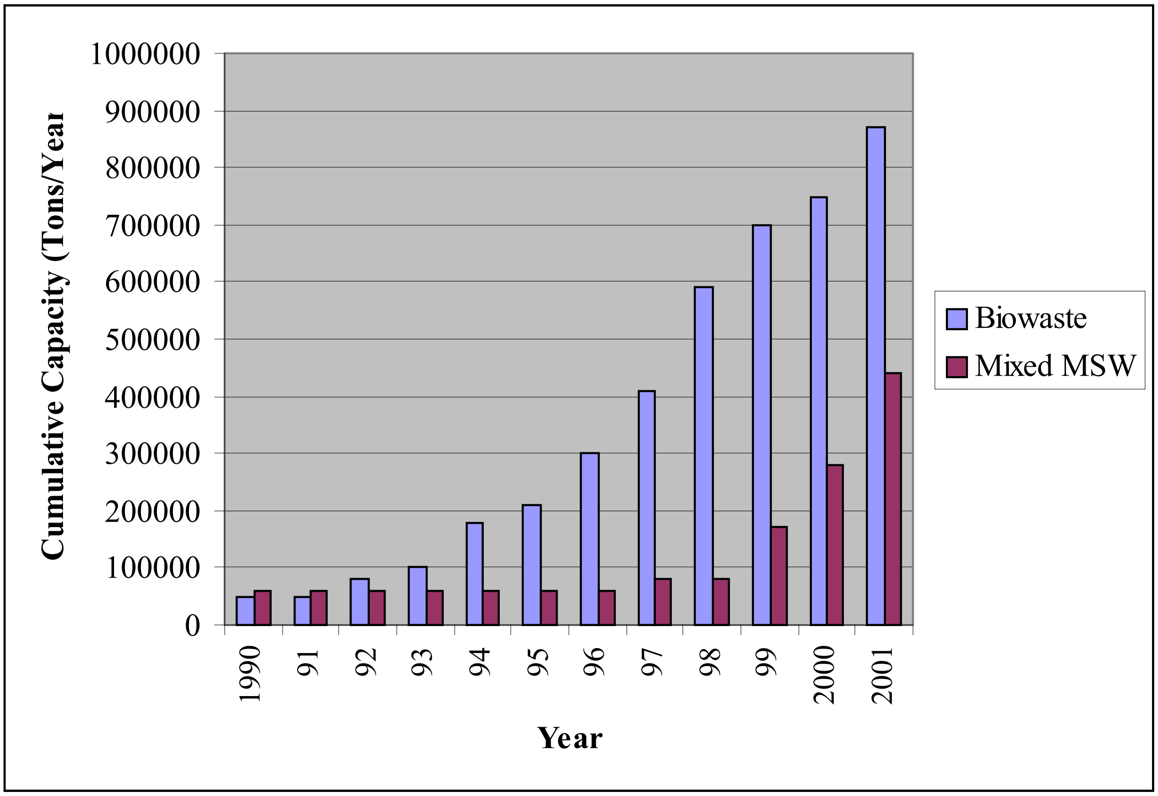


Figure 12. Comparison between AD plants treating Biowaste and Mixed MSW

Ref: De Baere, L., (1999) Anaerobic Digestion of Solid Waste: State of the Art, *Water, Science Technology* Vol. 41, No 3, pp 283-290

7. Case Studies

7.1 Valorga Technology

The Valorga technology was developed initially in France and later by Steinmuller Valorga Sarl, a subsidiary of the German company Steinmuller Rompf Wassertechnik GmbH. The process was initially designed to treat organic MSW and was later adapted to the treatment of mixed MSW, biowaste (source separated household waste), and grey waste (organic residual fraction after biowaste collection) (The Anaerobic Digestion and the Valorga Process, Jan 1999, Literature and brochures provided by the company).

The Valorga process plant (Figure 13) consists of essentially six units: waste reception and preparation unit, AD, compost curing, biogas utilization, air treatment, and an optional water treatment unit (when effluent is not treated in municipal wastewater treatment plant). The reception unit has a scale for weighing the trucks bringing in the organic materials. The waste is unloaded in a closed pit equipped with a foul air collection system. The feed material passes through an electromechanical system, designed according to the waste to be treated, that includes plastic bag opening and size reduction equipment. The waste is then conveyed and fed continuously to the AD unit.

Figure 13. The Flow diagram of Valorga Process

Ref: The Anaerobic Digestion and the Valorga Process, Jan 1999, Literature and brochures provided by the company

In the AD unit, the waste is mixed with re-circulated leachate into a thick sludge of about 20-35% solids content, depending on the type of waste. Therefore, the water requirement is minimal. The digester operates either in the mesophilic range (e.g., Amiens plant) or the thermophilic range (Freiburg plant). The Valorga digesters are concrete vertical cylinders of about 20 meters height and 10 meters internal diameter. They are designed so as to maintain plug flow through the reactor. They are equipped with a vertical partition in the center that extends over 2/3 of the diameter and over the full height of the reactor. This inner partition minimizes short-circuiting of the sludge and ensures plug flow through the entire volume of the reactor. The orifices for introducing feed and removing digestate are located on either side of the inner wall. Mixing of the fermenting material is provided by a pneumatic system i.e. biogas at high pressure is injected through orifices at the bottom of the reactor and the energy of the rising bubbles serves to mix the sludge. There are no mechanical parts and maintenance consists of periodic cleaning of the nozzles at the bottom of the digester

Table 7. Operating Valorga plants

Plant	Plant Start-up Year	Waste Type	Treatment capacity (Ton/year)	Digester Volume (m^3)	Gas Yield Nm^3/ton input digestion	Biogas end-use	Compost Use
Amiens, France	1988 1996	MSW MSW	 85,000	3*2400 1*3500	 140-160	High pressure steam for industrial use (5500 kW)	Agriculture
Engelskirchen(Germany	1998	Biowaste	35 000	2*3000	100-110	Heat & electricity (940 kW)	Agriculture
Tilburg, Netherlands	1994	Biowaste Or Biowaste + Paper	52 000 or 40000 + 6000	2*3300	80-85	Biogas treated and injected into Tilburg City distribution network	Agriculture
Hanover. Germany	Start-up 2002	MSW + sewage sludge	100000 +25000	3*4200	90	Heat & electricity	Landfill according to new legislation
Bottrop, Germany	1995	Biowaste	6500	1*1000	100-120	Heat & electricity	Agriculture
Varennes-Jarcy, France	2001	MSW + biowaste	100000	2*4200 1*4500	110-120	Electricity	Agriculture
Cadiz, Spain	2000	MSW	115000	4*4000	145	Heat & electricity	Agriculture
Geneva, Switzerland	Start up phase	Biowaste	10000	1*1300	110-120	Heat & electricity	Agriculture
Mons, Belgium,	2000	MSW + biowaste	23000 +35700	2*3800	110-120	Heat & electricity	Agriculture
Freiburg*, Germany	1999	Biowaste	36000	1*4000	110-120	Heat & electricity	Agriculture
Bassano, Italy	Start up in 2002	MSW+Bio waste+ Sludge	44200 +8200 +3000	3*2400	129	Heat & electricity	NA

Barcelone - Ecoparque II, Spain	Start up in 2003	MSW	120000	3* 4500	114	Heat & electricity	NA
La Coruña, Spain	2001	Mixed MSW	182500	4*4500	130-150	Heat & electricity (5 *1250 kW)	NA
Adapted from The Anaerobic Digestion and the Valorga Process, Jan 1999, Literature and brochures provided by the company							

* thermophilic operation

The digested material exiting the reactor goes through a filter press that separates the compost material from the leachate solution. The leachate is reused for diluting incoming waste and any excess is transferred to the water treatment unit or the municipal sewage network. The filter cake is transferred to composting piles where it is subjected to curing in a closed building for about two weeks. Stones and other inert materials are removed. The compost product is considered to be of high quality and is sold as soil conditioner.

The biogas produced is used to generate electricity and steam or is fed to the city gas network. The biofilters and the water treatment facilities ensure that the Valorga plants control all air and water emissions and meet local regulations.

Valorga operates about 10 plants in Europe (Table 5) treating a variety of wastes but mostly the organic fraction of MSW. The compost is used in agriculture and the biogas is used to provide heat and electricity. The Valorga Tilburg plant is described in the following section.

7.1.2 The Valorga plant at Tilburg, Netherlands

The Tilburg plant began its operation in 1994 and treats primarily vegetable, garden and fruit waste (VGF). The plant capacity is rated at 52000 tons/year of VGF, or 40000 tons VGF plus 6000 tons of non-reusable paper and cardboard. A central refuse treatment company collects and separates municipal waste from the participating 20 municipalities. The feed consists of 75% kitchen and garden waste and 25% paper, cardboard. The annual rate of MSW generation in the Netherlands is nearly 450 kg per capita. Thus, the estimated amount of VGF generated by the Tiburg population of 380,000 is 64,000 tons of VGF per year.

The plant consists of two digesters, each of 3300m^3 capacity, and produces 2.8 million m^3 of methane per year (70m^3/ton). The waste is sheared to less than 10cm particles before being fed to digestion unit. The retention time in this plant is 20 days at a mesophilic temperature of 38° C. The biogas production can be up to 106 m^3 per ton of waste, some of which is pressurized and pumped back into the reactor to improve mixing. The biogas product is piped to an upgrading plant, where it is refined to natural gas quality and then supplied to the municipal network. The biogas contains 56% CH_4 and has a calorific value of about 20 MJ/ m^3 while the refined gas contains 31.7 MJ/ m^3 (Saint-Joly, 1997). Gas refining consists of compressing, cooling, scrubbing, and drying. The methane gas after undergoing refining is fed to the municipal grid. The Tilburg facility highlights the technical and economic feasibility of using energy from waste in the form of biogas to generate electricity. The compost product amounts to 28000 tons/year and is reported to be of high quality for agricultural use.

A technical report produced by the Center for Analysis and Dissemination of Demonstrated Energy Technologies (CADDET) analyzed the economic and environmental performance of the Tilburg facility between 1994 and 1999. CADDET reported that the natural gas yield was about 50 m^3/ton. The net yield of natural gas, i.e. after providing for heating and electrical energy for the plant, was 1,360,000 m^3 of methane per year, i.e. about 44 m^3 of methane per ton of organic material processed. The economic analysis by CADDET reported that the capital investment for the Tilburg plant was equivalent to $17,500,000. This corresponds to $440 per yearly ton processed currently or $146,000 per daily ton of capacity. For comparison, the capital cost of a large size Waste-to-Energy plant (combustion of MSW) amounts to about $120,000 per daily ton of MSW processed (Themelis, 2002).

The main sources of revenue of this plant are the “tipping” fees paid by the municipalities for waste treatment and the sale of natural gas. Between 1994 and

1999, the average fee for waste treatment was \$90/ton resulting in the average annual revenue of \$3,600,000 per year. Assuming an average gas price of \$0.06/m^3 (CADDET, 1998), the gas revenues were \$81,600 per year.

Assuming an administrative and operating personnel of twenty and an average wage and benefits cost of \$40,000 per person, the labor cost is estimated at \$800,000. Assuming an equal amount for all other costs (maintenance, supplies and materials, etc.), adds another \$800,000. For an assumed 20-year life of the plant and at 10% required return on investment, the annual capital charge for repayment of the \$17.5 million principal is calculated to be \$920,000. Subtracting these three cost items from the annual revenues of \$3.68 million, results in a net annual income of \$1.16 million. It can be seen that under the above assumptions the Tilburg operation is profitable.

The environmental performance of the Tilburg indicates that 1.36 million m^3 of methane per year are recovered and used for electricity generation. This corresponds to 728 tons of carbon in the form of CH_4. Considering that one ton of C as methane is equivalent to 21 tons of C as carbon dioxide the Tilburg operation avoids landfill emissions of about 15,000 tons of carbon equivalent.

7.2 The DRANCO Process

The DRANCO process is a proven a high-solids single-stage AD system. It treats various waste streams such as biowaste, mixed waste, industrial organics, paper waste, market waste, rural waste, manure, sewage sludge, and others. The process operates at 50-58°C with retention time 20 days (RISE-AT, 1998). The feed is introduced continuously through the top of the reactor and digested material is removed from the bottom continuously. This stream is de-watered in a screw press and the filter cake is cured for two weeks to produce a compost product. There is no mixing in the reactor apart from the downward plug flow of the waste due to gravity. The filtrate obtained from de-watering is re-circulated and used to adjust the solids concentration of incoming waste. The compost product is marketed as “Humotex” and is used for soil amendment. The biogas yield is between 100-200m^3 /ton of waste and is used to provide electricity and heat. About 50 percent these are used by the plant and the rest sold.

There are seven DRANCO plants (Table 8) operating in Europe with capacity ranging from 10,000 to 35,000 tons/year. The plant discussed in detail in the following section is the Brecht plant in Belgium (capacity12000 tons/year).

Table 8. Operating DRANCO Plants

Country	**City**	**Year**	**Capacity (Ton/Year)**	**Waste Type**
Belgium	Brecht	1992	12000	Biowaste/non recyclable paper
Austria	Salzburg	1993	13500	MSW/Sewage sludge
Switzerlan d	Aarberg	1997	11000	Biowaste
Germany	Bassum	1997	13500	Grey Waste
Germany	Kaiseser--slautern	1998	20000	Biowaste
Switzerlan d	Villeneue	1998	10000	Biowaste
Belgium	Brecth	1998	35000	Biowaste
Reference: www.ows.be				

7.2.1 The Brecht Plant

The Brecht plant in northern Belgium started operation in 1992 and is treating 12,000 tons/year. Food, yard trimmings and non-recyclable paper wastes are collected from 26,000 households. The source-separated MSW collected is weighed and unloaded at the plant. Undesirable materials like stones are removed and then the waste is shredded in a rotating trommel. The waste is fed to the digester of capacity of 808 m^3 (7m diameter, 21m height). The retention time is 12-20 days at 50-58^oC (thermophilic range).

The generated biogas is used in a 290 kilowatt generator to produce electricity of which 40% is used on-site and 60% is sold to the local power grid. At times, the biogas has to be flared as power cannot be sold into the grid after 10 p.m. The digested material is de-watered and cured aerobically for about 10 days in a facility where in-floor ducts provide airflow and the compost is turned periodically by mechanical means. According to an economic analysis by Sinclair and Kelleher in

1995 (www.ows.be), the investment costs for this plant were $6.1 million. This corresponds to $500 per yearly ton processed currently or $170,000 per daily ton of capacity. The revenue from waste treatment amounts to $122 per ton of feed. The compost is sold for $13 per ton. Sinclair and Kelleher also estimated that a similar facility processing 25,000 tons per year would cost approximately $14.3 million. This would correspond to $570 per yearly ton processed currently or $190,000 per daily ton of capacity.

Table 9. Brecht AD facility outputs per ton of feed material	
	Quantity (tons)
Compost product	0.3
Biogas	0.13
Wastewater	0.32
Residue	0.2
Costs and revenues	
Item	Millions of dollars
Investment Cost Administrative & Labor Cost** Operational Cost** Annual Charges**	$6.1 $0.24/year $0.24/year $0.32/year
Revenue Compost Total Revenue**	$122 per ton/feed $13 per ton /compost $1.51 million per year

*Source: Sinclair and Kelleher (1995)
** Author's calculations

Using the data for the plant from Sinclair and Kelleher (Table 9), the total revenue from treating the waste and selling compost amounts to $1,510,800 per annum. Using the similar assumptions as was for the Tilburg plant, with the exception that since the capacity of the Brecht plant is 2/3 that of Tilburg, the annual labor cost is estimated at $240,000 and all other costs, such as maintenance, supplies and materials, at $240,000. For an assumed 20-year life of the plant and at 10% required return on investment, the annual capital charge for repayment of the $6.1 million principal is calculated to be $320,000. The net annual income of $710,800 is obtained after subtracting the labor cost, operational cost and annual capital charges. The positive net income indicates that the plant operation is profitable.

7.3 The low-solids, multi-stage Biotechnische Process

Biotechnische Abfallverwertung GmbH (BTA) of Munich, Germany developed in the 1980s a multi-stage low-solids system for treating mixed waste (all MSW except materials that are currently recycled or composted,) or source separated organic waste (food and garden waste). Germany has BTA plants operating in five municipalities. A research and development facility is located in Baden, Germany. BTA is also operating in other parts of Europe, and in Asia and North America. The BTA process is marketed as both single stage (e.g., Dietrichsdorf plant) as well as multi-stage process. There are eight BTA plants (Table 10) operating with capacity ranging from 1000 to 150,000 tons/year. The plant discussed in detail in the following section is the Newmarket plant in Canada (capacity 150,000 tons/year).

Table 10. Operating BTA Plants

Location	Year	Capacity (Tons/year)	Waste Type
Newmarket (Canada)	Started in July 2000	150,000	Biowaste commercial waste organic sludges
Mertingen (District Donau-Ries)	Operation in spring 2001	1,000	Biowaste
Wadern-Lockweiler (Saarland)	-	20,000	Biowaste commercial waste
Erkheim (District Unterallgäu)	-	11,500	Biowaste commercial waste
Kirchstockach (Munich District)	Start-up in 1997 as MS digestion	20,000	Biowaste
Karlsruhe	Start-up in 1996. On a landfill area; automated feeding system; biogas utilisation.	8,000	Biowaste
Dietrichsdorf (Kelheim District)	Start-up in 1995 as SS digestion	17,000	Biowaste commercial waste
Elsinore* (Denmark)	Start-up in 1991 as MS digestion	20,000	Biowaste
Garching**	Operated 1986 till 1998. Used for tests in the area of R & D	6**	Tested various waste streams
Reference: www.canadacomposting. com * Temporarily not in operation ** Pilot Plant with capacity ton/week - information not available			

BTA combines sophisticated waste pre-treatment and separation techniques within a fully enclosed and highly automated facility. The two unique steps of BTA process are "hydropulping," a process that removes contaminants (plastic, glass, and metals) and homogenises the waste, thus producing an organic suspension that flows through a "hydrodynamic de-gritting system," to remove any remaining shards of glass, small stones or sand (www.canadacomposting.com).

7.3.1 The BTA Newmarket Plant

The plant is located in Newmarket, Ontario, Canada and has a capacity of 150,000 metric tons of organic waste per year. It started operation in July of, 2000 on a 2.2ha (5.4 acres) site.

The facility receives the mixed waste brought in by collection vehicles that unload on the tipping floor. From there, the waste is conveyed to a pre-sort station, where oversized, contaminants as well as recyclables are removed. After the pre-sort station, the material continues through a trommel screen that separates fine materials (mostly organic), medium sized materials (mostly containers) and large objects such as newspaper, cardboard, film, plastic and textiles. The front end of the screen is equipped with a series of knives to rip open plastic bags. A manual sorting station sort plastics (PET, HDPE), glass and textiles. Also magnetic and eddy current separators are used to extract ferrous metals and aluminum cans. The marketable materials are sent for recycling and the non-recyclables are landfilled, while the organic-rich materials are fed to a 32-cubic-metre capacity hydropulper where they are mixed with water over a 16-hour processing period. The hydropulper creates an organic suspension and removes non-organic material that may have escaped pre-sorting and can be either “lights” or “heavies”. The light fraction, is removed by a hydraulic rake attached to the hydropulper while the heavy fraction is captured through a sieve at the base of the hydropulper.

The hydrocyclone, or hydrodynamic de-gritting system, removes the sand and grit left in the organic pulp after hydropulping. The removed sand and grit are sent to landfill. The remaining pulp goes to the anaerobic digester where it is subjected to add for 15 days. The digestate is de-watered in a screw press and the filtrate is re-circulated to the hydropulping process. The filter cake is subjected to curing for 20 days. The 60,000 tons of compost produced annually are bagged and distributed to retail horticultural outlets.

When the compost material does not meet the prescribed standards, it is l used for quarry restoration and other land rehabilitation projects.

The produced biogas is used to provide electrical and thermal energy for the facility. The biogas fuels an 820 KW co-generation generator installed at Newmarket. About 5,000 MWh of electricity is produced annually of which the plant uses 2MWh and the rest sold to the local grid and supplies 3,000 homes is sold to grid (www.canadacomposting.com).

8. Potential for use of AD technology to treat NYC Organic MSW

New York City (NYC) in 2001 generated 4.5 million tons per year of MSW. Most of this waste finds its way into landfills (Columbia University, EEC-SIPA report "After Fresh Kills, December 2001; *www.columbia.edu.cu.earth*). For half a century, the Fresh Kills landfill in Staten Island provided a dumping ground for New York City's MSW. With the closing of this site in 2001, NYC is facing a critical problem of waste disposal. This part of the study explores the possibility if AD can ease some of the burden of NYC waste especially organic MSW.

After the closure of the Fresh Kills, NYC in its long term and short-term waste management plan depends heavily on exporting waste to out of state landfills. This puts NYC at the mercy of legislation that presently is allowing the interstate transport of MSW. NYC will have to rethink its waste disposal policy if legislation passed forbidding exportation of waste. Furthermore, NYC continues to depend on landfill while most of the European countries are moving away from it (Table 4). The legislation in these European countries targets no or minimal organic MSW to landfills. The organic content constitutes about 55 % of NYC MSW which includes paper, wood, textiles, food waste, yard waste and miscellaneous organics (Table 11).

Table 11. Composition of NYC Waste

Waste Component	% Weight
Paper	31.3
Corrugated Cardboard	4.7
Newspapers	9.2
All other papers	17.4
Plastics	8.9
HDPE (clear or color)	1.1
Films and Bags	4.8
PET	0.5
Polypropylene, polystyrene	0.9
PVC	0.1
All other plastics	1.4
Wood	2.2
Textiles	4.7
Rubber & Leather	0.2
Fines	2.3
Other Combustibles	2.3
Food Waste	12.7
Yard Waste	4.1
Disposable Diapers	3.4
Miscellaneous	7.8
Glass	5.0
Clear Glass Containers	2.9
All other glass	2.1
Aluminum	0.9
Ferrous Metal	3.9
Hazardous Waste	0.4
Bulk Items (appliances, furniture etc)	9.9
Ref: Themelis, Kim & Brady, 2001, Energy Recovery from NYC solid waste.	

The waste management options include recycling and waste disposal means could be combustion and composting. The more biodegradable organic fraction or the wet stream such as food and yard waste constitutes19.4 % i.e. 873,000 tons per year (Table 11). The rest of the stream, also known as the dry stream, comprising paper, plastics, metals and glass can be recycled or combusted but. The waste disposal option open for wet stream is combustion and aerobic or anaerobic composting. However, combustion of wet stream does not provide much energy from the wet stream due to its high moisture content (Fig 14). According to Themelis and Kim (2001), the calorific value of food and yards waste is only 5350 kJ/kg (2300 BTU/lb) and of this about 2600 kJ of heat is wasted per kg of water in the feed (Themelis, 2001).

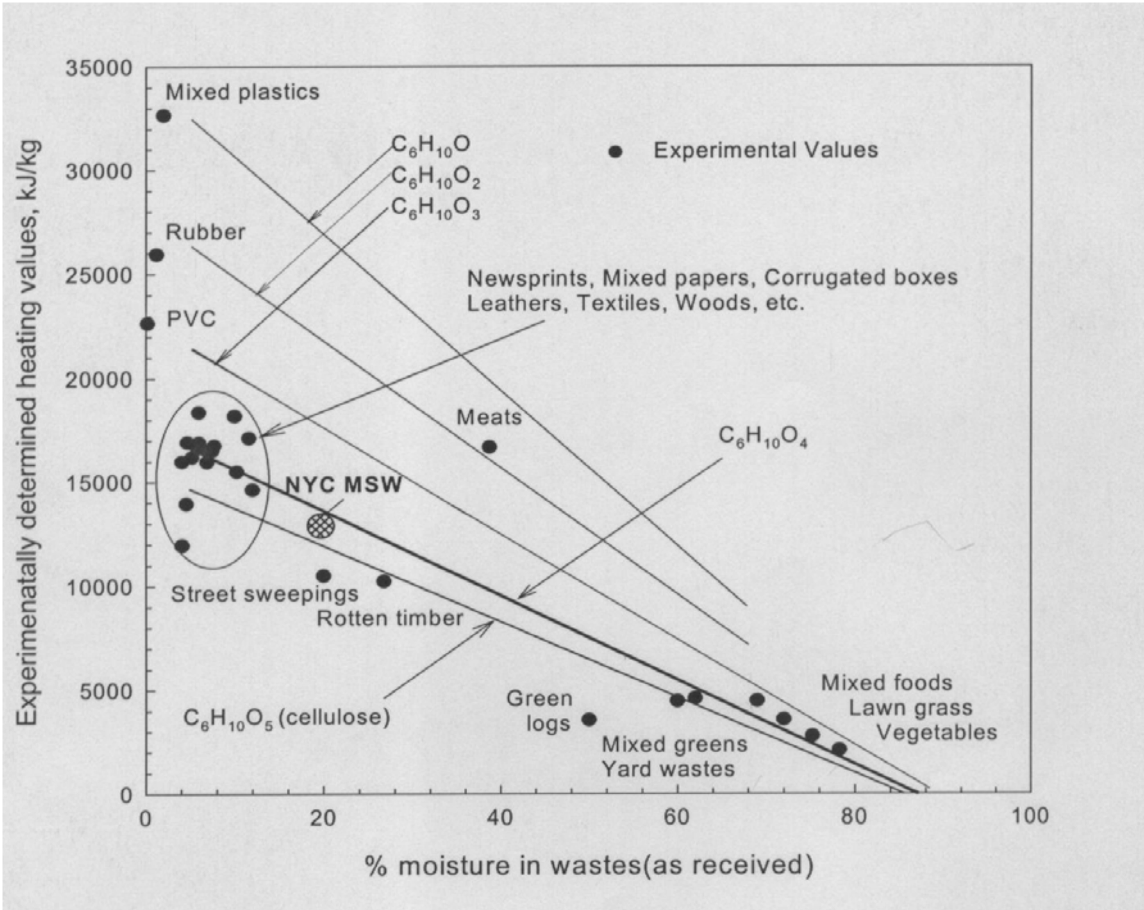


Figure 14. Comparison of heating values of various wastes
Ref: Themelis, Kim & Brady, 2001, Energy Recovery from NYC solid waste

Apart from combustion, the only way to deal with the organic fraction of MSW is aerobic composting (bioconversion in the presence of oxygen) or anaerobic digestion (AD). Aerobic composting is a net energy user rather than energy generator. A study by a Dutch team (CADDET, 1998) that compared an aerobic composting plant with the Tilburg AD facility showed that the AD plant produced 366 MJ of net energy per ton of waste whereas the composting plant consumed 261 MJ per ton. The advantage of energy generation combined with the global movement towards reduction in fossil fuel usage will make AD increasingly attractive.

As described earlier in the thesis, the capacity of an AD plant can be increased by the addition of a reactor to the existing facility. To treat 873,000 tons of waste per year, NYC can implement a facility based on the Valorga process, that consists of four reactors with digester volume 4* 4500 m^2 of the type used at La Coruña (Spain) treating 182,500 tons of mixed MSW per year (Table 5). On the basis of data from the La Coruña plant assume generation of methane from the hypothetical NYC plant would amount to 78570000 m^3 per year (90m^3 per ton of feed). On the basis of the cost data presented earlier for valorga plant, the capital cost of a NYC plant of 900,000 tons capacity is scaled up in terms of 2002 dollars (assumed annual inflation between 1994 and 2002 at an average of 3%) is estimated at about $500062500. This corresponds to $572 per yearly ton processed currently or $209075 per daily ton of capacity. Assuming revenue sources are "tipping" fees paid by the municipalities for waste treatment and the sale of natural gas. Between 1994 and 1999, the average fee for waste treatment was $90/ton resulting in the average annual revenue of $3,600,000 per year. Assuming an average gas price of $0.06/$m^3$ (CADDET, 1998), the gas revenues were $4714200 per year.

Using similar assumptions as for Tilburg plant the administrative, labor and operating expense is estimated at $1600000. However, considering the NYC plant will be treating 873000 tons per year (22.5 times waste treatment) the expense amounts to $36000000. Further assuming 20-year life of the plant and at 10% required return on investment, the annual capital charge for repayment of the $500062500 principal is calculated to be $2600000. Subtracting the expenses from the annual revenues of $83284200, results in a net annual income of $44684200 a profitable operation.

The environmental performance on the basis of 78570000m^3 of methane per year recovered and used for electricity generation. This corresponds to 40000 tons of carbon in the form of CH_4. Considering that one ton of C as methane is equivalent to 21 tons of C as carbon dioxide the NYC operation avoids landfill emissions of about 840000 tons of carbon equivalent.

9. Conclusions

In the last decade of the 20th century, the use of AD technology for the processing of organic wastes has expanded appreciably. Between 1996 and 2000 the number of new AD plants increased from 2 to 7 plants per year. Europe is far ahead in AD technology and Germany and Denmark are leading in the use of AD technology.

AD technology has seen remarkable progress in reactor and process design. Earlier, long periods of time were required for complete degradation. Mesophilic temperatures (about 35°C) would require up to 30 days for digestion. The development of thermophilic (60-65°C) AD has reduced the retention time for solids in the digester to less than 15 days. An example of this change is one of the Valorga plants where the retention time of 28 days was reduced to 14 days by means of thermophilic operation.

AD plants have also made much progress in their capacity to treat a wide range of waste streams. In late 70's, most of the AD plants were designed to treat sewage and were predominantly low-solids operations. However, during the last decade the number of high solids processes has increased appreciably to include organic MSW treatment. If one of the goals of new plants is energy generation, then high solids are more promising. The DRANCO and Valorga case studies are representative of good strategies for obtaining revenues by supplying energy to nearby operations and by creating a market for compost. For example, the Tilburg plant (40,000tons/year MSW capacity) has an estimated annual income of $1.16 million. The advantages offered by HS includes higher methane production (Valorga, 220-250 m^3/ton of feed) as compared with LS operations (Waasa, 100-150 m^3/ton of feed). In addition, the reported organic loading rate for HS (DRANCO, 15 kg VS per m^3 per day) is about twice that of LS (Waasa, 6 kg VS/(m^3.d)).

This study showed that multi-stage processes provide biological stability by keeping the acidogenesis and methanogenesis separately and allowing higher organic loading rate without shock to methanogenic bacteria. However, multi-stage systems are complex and the benefits do not justify high investment costs. Single stage AD processes are starting to dominate the market because of their simple reactor design and low investment and operational costs. The batch system would be right for developing countries for these are cheap and easy to operate. Even though large land acerage is required which is not a problem in rural areas say for India. Also the AD system fits well for them as it generates biogas and their dependence on fuel wood gets reduced.

The advances of AD technology have been supported by legislation. Most European countries are aiming to limit MSW disposal to landfills to no more than 5% of the collected material and have increased taxes on landfilling. This will ensure that waste is properly treated for combustibles and organics rather than being buried in the ground. The 15% renewable energy by 2010 target as well as schemes such as "green pricing" in The Netherlands and some other European countries allow AD facilities to sell biogas for electricity generation at a premium. Similarly, in the United Kingdom, under the Non-Fossil Fuel Obligation (NFFO) act, electricity is sold at a premium from AD system.

Another factor that has triggered opting for energy recovery from waste is international agreements with respect to greenhouse gas emissions. Landfills are the source of large emissions of methane to the atmosphere and methane gas has a global warming potential (GWP) that is over twenty times that of carbon dioxide. Also, many utilities are very interested in earning credit for reducing GHG emissions. These utilities foresee the risk of mandatory GHG control imposed by future regulatory or legislative actions. Therefore, AD plants will be very attractive for utilities to earn GHG reduction credits.

In future, the best practicable environmental option will be deriving energy from waste. Energy recovery technologies include combustion of waste and anaerobic digestion (AD). However, combustion of the wet stream of MSW does not provide efficient energy recovery. So the advantages offered by AD are worth exploring for the wet stream of Municipal Solid Waste (MSW) of New York City and elsewhere.

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