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Data Summary of Municipal Solid Waste Management Alternatives

Volume X: Appendix H—Anaerobic Digestion of MSW

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SRI International
Menlo Park, California

NREL Technical Monitors: Bimleshwar Gupta
Philip Shepherd

National Renewable Energy Laboratory
(formerly the Solar Energy Research Institute)
1617 Cole Boulevard
Golden, Colorado 80401-3393
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This report, *Data Summary of Municipal Solid Waste Management Alternatives*, comprises 12 separately bound volumes. Volume I contains the report text. Volume II contains supporting exhibits. Volumes III through X are appendices, each addressing a specific MSW management technology. Volumes XI and XII contain project bibliographies. The document control page at the back of this volume contains contacts for obtaining copies of the other volumes.

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H.1 INTRODUCTION/OVERVIEW

While municipal solid waste (MSW) thermoconversion and recycling technologies have been described in Appendices A through E, this appendix addresses the role of bioconversion technologies in handling the organic fraction in MSW and sewage sludge. Much of the organic matter in MSW, consisting mainly of paper, food waste, and yard waste, has potential for conversion, along with sewage sludge, through biochemical processes to methane and carbon dioxide providing a measurable, renewable energy resource potential (814). The gas produced may be treated for removal of carbon dioxide and water, leaving pipeline quality methane gas. The process also has the potential for producing a stabilized solid product that may be suitable as a fuel for combustion or used as a compost fertilizer (850).

Anaerobic digestion can occur naturally in an uncontrolled environment such as a landfill, or it can occur in a controlled environment such as a confined vessel. Landfill gas production is discussed in Appendix F. This appendix provides information on the anaerobic digestion process as it has been applied to produce methane from the organic fraction of MSW in enclosed, controlled reactors.

H.1.1 Background

Conventional anaerobic digestion processes have been used since about 1860 to stabilize settled sewage solids. The technology was first investigated as a means of MSW disposal in the early 1930s, but early experiments were not successful. It met with renewed interest in the late 1960s. Golueke, at the University of California, directed a 5-year program to determine the technical feasibility of digesting municipal waste with large quantities of animal waste (343).

In 1969, the Office of Solid Waste Management of the U.S. Public Health Service (later to be transferred to the U.S. EPA) funded a research project to investigate the processing conditions that would result in the maximum conversion of MSW to gas. Conducted by Pfeffer, at the University of Illinois, the intent of the process was to reduce the weight and volume of the solid waste remaining for disposal; energy recovery was not a major factor at that time (814). The work demonstrated the feasibility of methane production from solid waste, with limited additions of sewage sludge; and included an evaluation of gas production as a function of pH, temperature, solids loading, retention time and slurry concentration, and an evaluation of the costs and net economic benefit of the system (343). Also in 1969, Consolidated Natural Gas Service Company performed laboratory and engineering studies to evaluate biogas production from MSW. These studies reconfirmed the technical feasibility of the anaerobic digestion process to convert organic wastes to pipeline quality fuel gas.

In the early 1970s, the impending energy crisis led to an increased interest in anaerobic digestion as an alternative for realizing energy from MSW, while reducing the volume of waste to be disposed and controlling emissions. In 1973, the National Science Foundation (NSF), under the Research Applied to National Needs Program, awarded a contract to Dynatech R/D Company for an indepth study to determine the potential for developing the anaerobic digestion process for the organic fraction of MSW and the cogeneration of the resulting biogas (343, 814, 850). A comprehensive model of a 1,000 TPD facility was developed to evaluate economic feasibility. Based on this work, NSF recommended funding for a proof-of-concept facility. Waste Management, Inc. was awarded a contract to develop the facility at its Pompano Beach, Florida Solid Waste Reduction Center site. Prior to project initiation, project administration and funding was transferred to the then newly formed U.S. Energy Research and Development Authority; and subsequently came under the sponsorship of the U.S. DOE (343, 814). Known as RefCoM (Refuse Conversion to Methane), the proof-of-concept facility operated from 1978 to 1985 when the demonstration period ended and the project was shut down.

H.1.2 Status

The productive use of biogas has not become a widespread practice in the United States nor throughout the world. RefCoM remains the only large-scale facility to have been developed in the United States; no controlled commercial MSW anaerobic digesters have yet been placed in operation in this country (010).

Because of the increasing interest in the development of low-cost, environmentally-acceptable alternative energy sources, the conversion of MSW to methane through anaerobic digestion has become the subject of extensive research and development efforts throughout the world (450). In 1988, several countries including Austria, Canada, Denmark, Finland, Ireland, New Zealand, Norway, Sweden, the United Kingdom, and the United States have agreed to coordinate their research in biomass conversion through Task IV of the Bioenergy Agreement of the International Energy Agency (09).

In the United States, advanced biological and engineering research projects are being conducted, as part of the Energy from Municipal Waste Program, by the Department of Energy now under the field management of the National Renewable Energy Laboratory (NREL), formerly the Solar Energy Research Institute (SERI). Research is being conducted in a number of areas where technological improvements must be made in order to economically produce methane from MSW. Areas being investigated include: 1) increasing solids loading, 2) decreasing solids residence time, and 3) improving conversion efficiency. In 1987, Goodman noted the following DOE/SERI research objectives with respect to these key operating parameters:

	1987	Goal
Solids Concentration in Digester	10%	20-30%
Solids Residence Time in Digester	25 days	5 days
Conversion Efficiency	55%	80%

The overall goal of this research is to reduce the cost of producing methane from waste or biomass from $5/million Btu to less than $3.50/million Btu by the year 2000 (425).

Advances are being made in the development of high-solids anaerobic digestion processes at NREL and elsewhere. Much of the initial work in this area was conducted by Jewell and Wujcik (853, 855). Jewell's research on treating organic wastes and farm crop residues by means of dry fermentation indicated that significant methane production rates could be obtained at total solids contents of up to 40 percent (290). Research and development is ongoing at the University of Florida (851, 852), Cornell University (851), the University of California (850), and the University of Maine (851).

The Gas Research Institute completed biogasification studies at a pilot-scale experimental test unit located in the Disney World Resort Complex, Florida. From 1984 through 1988, the SOLCON (solids concentrating) reactor was utilized to convert a variety of individual and mixed feedstocks, including refuse-derived fuel (RDF), to methane (802).

In Europe, a pilot-scale facility in Gent, Belgium operated for one-year (1985) using the DRANCO (dry anaerobic composting) process, producing methane from the organic fraction of MSW and a commercial humus-like end product. The Valorga process appears to be the most developed anaerobic digestion technology for MSW in the world (450). This process was demonstrated at pilot/industrial-scale in La Buisse, France; and a commercial-scale facility has been operational since October, 1988 in Amiens, France with the objective of treating 100,000 tonnes of MSW per year (450, 812, 815).

H.2 TECHNOLOGY DESCRIPTION

The digestion process utilizes microorganisms to stabilize organic matter and to produce enzymes to catalyze the process. The details of the process are not completely understood because many of the organisms have not yet been isolated. Nonetheless, the biochemistry of the overall process is thought to proceed in three distinct stages. The first stage is fermentation. Faculative bacteria, which can live either in the presence or absence of oxygen, and their enzymes reduce complex molecules (polymeric solids such as cellulose, fats, and proteins) to simple organics (monomers such as sugar, fatty acids, and amino acids). In the second stage, acidogenic bacteria reduce the monomers to acetic acid and hydrogen. In the third stage, methanogenic bacteria use the acetic acid and hydrogen to produce methane and carbon dioxide. The methanogenic bacteria, essential to the success of the system, are strictly anaerobic, and thus must be contained in an airtight reaction vessel. Other essential factors are a neutral pH, proper nutrients (nitrogen, phosphorus, trace metals), absence of toxins, and proper temperature. The microbial population which affects the digestion may be introduced with the organics or may be seeded into the digester when the substrate does not have a large population of its own, as is the case with MSW (010, 271).

H.2.1 Operating Parameters

An important consideration in the anaerobic digestion process is the rate at which the active organisms double their population. First, the substrate is hydrolyzed. For feedstocks such as sewage solids and manures, the organisms double and hydrolyze the substrate very rapidly. The doubling rate for the more recalcitrant substrates such as paper and wood is more limited. Once the substrate is hydrolyzed, the acetogenic bacteria grow rapidly, while the methanogenic bacteria grow more slowly (10). To enhance microbial activity and thus affect the biological conversion efficiency of the system, the digester operating parameters must be controlled. In general, these parameters include the following:

- Volatile Solids(VS)/Feedstock Composition. VS is the measure of organic material in a substance (10). The best digester feedstock is one which is high in volatile solids and low in nonbiodegradables (271). Although a large fraction of MSW is biodegradable, certain organics such as plastics and fibers resist breakdown (as noted above) and further, can cause problems in subsequent unit processes. Therefore, preparation of MSW is required to remove metals, glass, textiles, and plastics from the feedstock in order to minimize digester volume and wear on the equipment (290), as well as to minimize the residue for disposal (814). The amount of gas produced is dependent upon the volatile solids fed at a specific temperature and retention time (271).

- Temperature and Retention Time. The production of biogas is maximized at a reactor mesophilic temperature of 37°C, and at a thermophilic temperature of 60°C. The hydraulic residence time (HRT), the time required for the average particle of liquid to move through the system, equals the reactor volume divided by the total volume fed per day. Typical design HRTs are on the order of 20 days at mesophilic temperature and 5 days at thermophilic temperatures. The solids retention time (SRT) is a measure of the time the solids remain in the system, exposed to the bacteria (271). Isaacson (814) notes that operating with a temperature in the thermophilic range significantly reduces the retention time necessary for good conversion. Further, retention time and slurry concentration determine the reactor volume required to process a given tonnage of MSW. A reduction in both capital and operating cost can be achieved by operating at a short retention time with a high concentration of solids in the feed slurry.

- Solids Concentration. An increase in the solids content in the reactor results in a comparable decrease in the reactor volume. If the reactor is continuously stirred (as in a conventional anaerobic digestion system), the input feedstock to the reactor is limited to about 10 percent solids (271). Since about 50 percent of the volatile solids are converted to gas, the digester contents will then be about 5 percent solids (271). In the case of MSW, in a conventional digestion system, this means that, 6 to 10 m^3 of water must be added per metric ton of organic material to reduce the total solids content from about 55 percent to about 5 percent (290). Recycle filtrate is used to reduce the solids content (271). High-solids concentrations up to 40 percent are now being achieved in research and laboratory studies (850).

- Particle Size, pH, and Nutrients. These variables appear to have a lesser effect on the process conversion efficiency. Particle size, however, is a factor in the rate of biodegradation of organic material. In addition to size reduction and screening in the MSW separation/preparation system, the particle size of the organics (including paper) is effectively reduced by the digester mixing process (814). Methanogenic bacteria are sensitive to pH and are generally inhibited when the pH drops below 6.6. Lime can be added to the reactor to provide additional alkalinity. However, recycled filtrate significantly reduces or eliminates the lime requirement. Similarly, the use of filtrate recycle and/or the addition of sewage sludge provides sufficient nutrients such that phosphorus and nitrogen are required only on an intermittent basis (814).

H.2.2 Conventional MSW Anaerobic Digestion System

A general flow diagram for a conventional MSW anaerobic digestion system is shown in Figure H-1 (010). The overall process can be divided into four steps: feedstock preparation, feed dilution and digestion, gas recovery, and residue treatment.

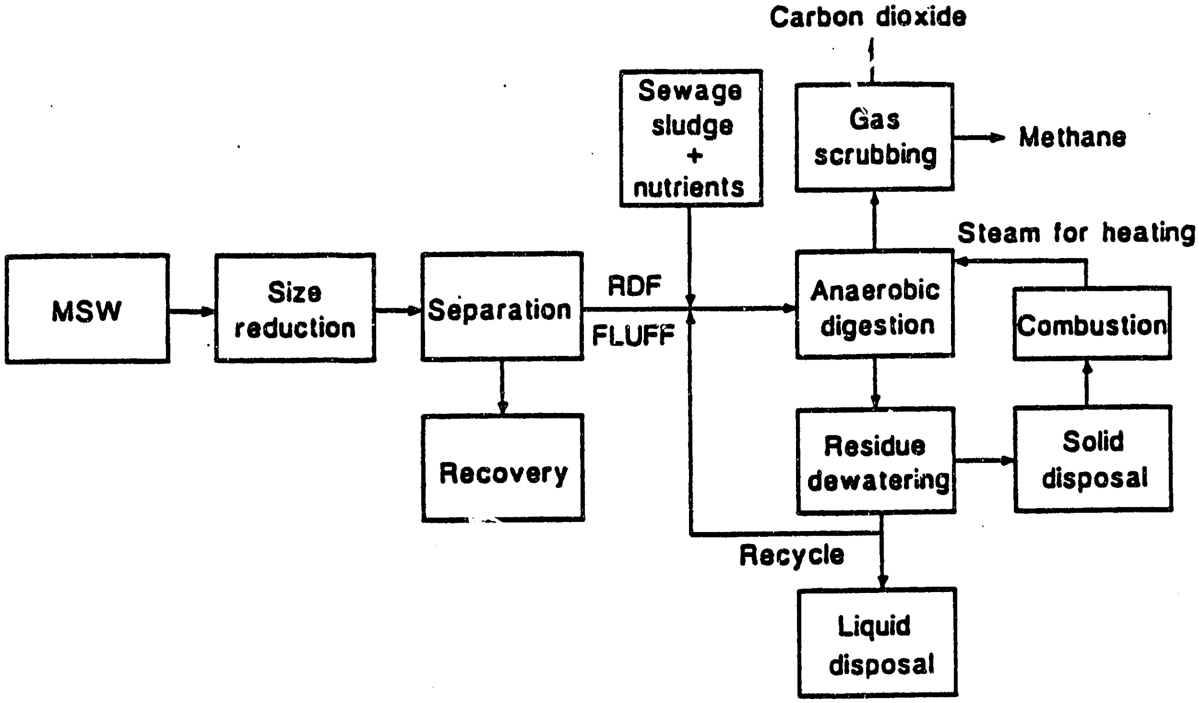


Figure H-1. Anaerobic Digestion of MSW (010)

In order for MSW to be introduced into the digestion system, it must first be processed through size reduction and separation techniques to remove metals, glass, and other inorganics producing a relatively homogeneous feedstock devoid of large and irregular pieces including, in particular, plastic stringers and textiles (271, 450). These latter materials caused considerable problems in the RefCoM facility where they wrapped around the digester mixer shafts and also affected mixing action by forming excessive scum layers (429). The preparation or pre-processing step, including the recovery of recyclable materials such as ferrous and aluminum, is similar to the waste processing operations utilized for the production of RDF, as described in Appendix B.

The digester feed is then blended with nutrients and slurried with recycled filtrate, and makeup water if necessary, to achieve the desired solids content before being fed into the anaerobic digester where it remains for the specified retention time. Sewage sludge can be mixed with the prepared waste such that both types of wastes can be codisposed. The digester tank is stirred continuously by one or more mixing devices (gas recirculation, liquid recirculation, or mechanical agitation) and is equipped with a floating cover to maintain the system at constant pressure. Steam is generally used to control the temperature (271).

The continuous stirred reactor (CSTR), shown in Figure H-2, is typical of conventional anaerobic digestion systems. The stirring action of the mixer enhances the contact of organisms with the feed, provides uniformity in tank contents, and breaks up scum and other inhibiting conditions (271). The drawback to conventional CSTRs for the digestion of MSW is the large digester volume required because of the relatively low suspended solids concentrations and high retention times.

The anaerobic bacteria and faculative bacteria break down and decompose the organic matter in the digester, producing methane and carbon dioxide. The gas is saturated with moisture and is typically 50 to 75 percent methane and 25 to 50 percent carbon dioxide. The gas can be scrubbed to remove carbon dioxide producing a relatively pure methane product which researchers have suggested can be converted to pipeline quality gas. The successful application of a membrane process to the gas cleanup will produce a low-grade waste gas that can be co-combusted with the dry residue from the process (450).

In the residue treatment phase of the system, the effluent from the digester is dewatered to the maximum extent possible, and the liquid recycled for use as makeup to the feed slurry, thus conserving heat, water, nutrients, alkalinity, and inoculum. Researchers have suggested that the filter cake, which is 25 to 30 percent of the original feedstock volume, may be combusted (if sufficiently de-watered) to produce power and/or steam (450). Despite its low nutrient value, the fibrous cake may also find application as a soil conditioner (271).

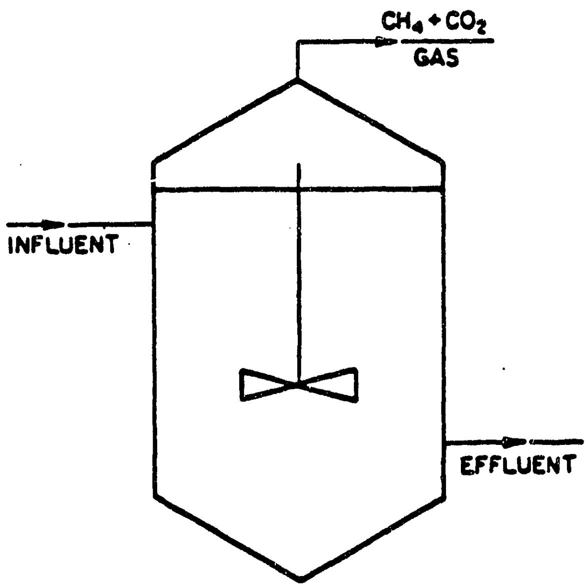
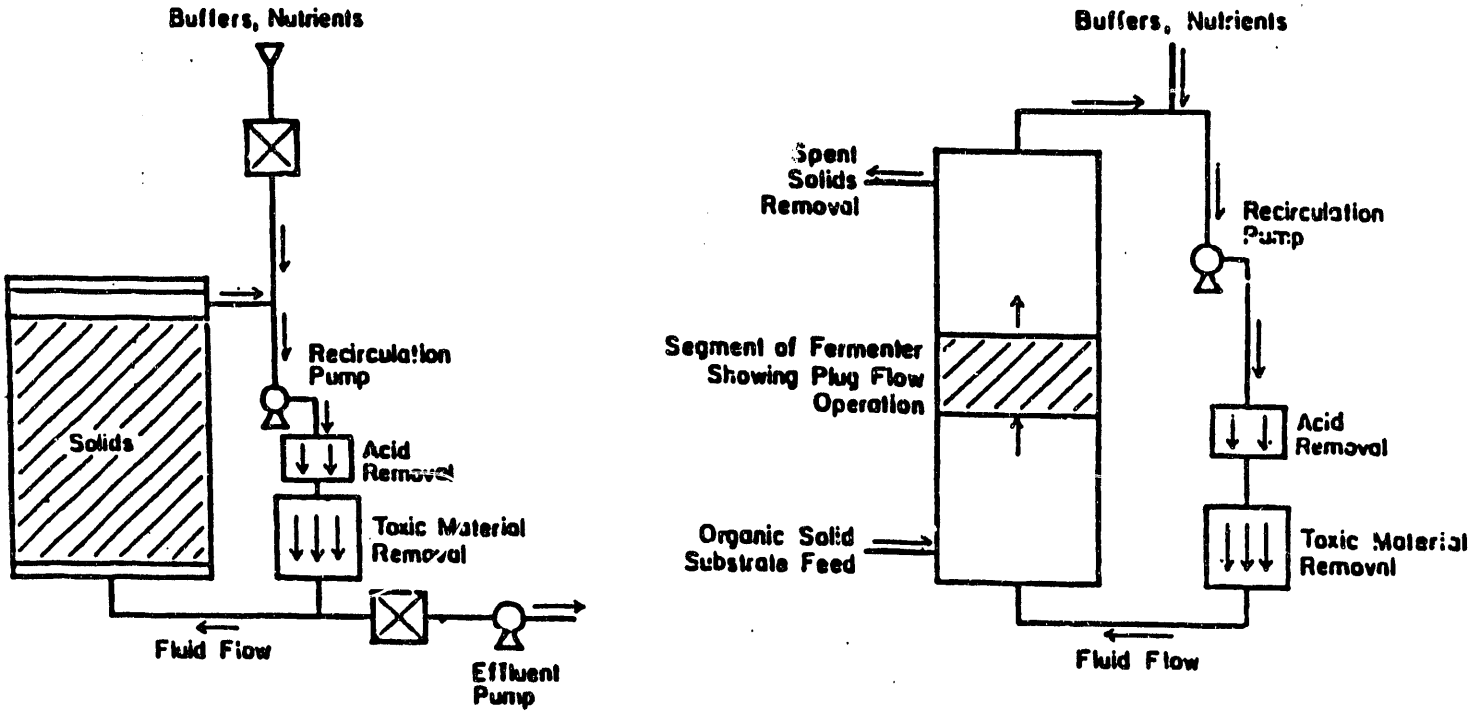


Figure H-2. Continuous Stirred Tank Reactor (803)

H.2.3 High-Solids Concentration Systems

A number of research efforts have been undertaken to modify CSTR design to allow high solids concentration and significantly reduce digester volume in order to improve the economics of anaerobic digestion (426, 802). Packed bed and fluidized bed digesters (Figure H-3) have been investigated to produce higher yields of gaseous and liquid fuels from an MSW (RDF) substrate, employing high solids concentrations in the process (343, 476). As shown on the figure, the packed bed digester is comprised of a containment vessel, inert bed material which supports biological growth, circulating fluid, substrate (organic fraction of MSW), pumping system, and in some cases, an extraction/purification system. The fluidized bed is similar in design, except that the inert bed material is fluidized by the substrate. As noted by Scaramelli (343), in addition to higher energy yield, these digesters have the potential for reducing the overall cost of anaerobic digestion systems through reductions in digester capital cost, water requirements, energy requirements for mixing and heating, and residue disposal costs.



SCHEMATIC DIAGRAM OF FIXED PACKED BED FERMENTER

CONTINUOUS FLOW PACKED BED FERMENTER

Figure H-3. Packed Bed Anaerobic Digester (343)

Multi-phase digestion systems have also been investigated for MSW feedstock. Two-stage digestion involves a combination of high-rate digestion and conventional unmixed digestion where the first digester maximizes biological decomposition and therefore gas production, while the second digester provides for solids separation and concentration. Two-phase digestion involves two (or three) biologically active digesters in series whereby each functions to optimize the specific conditions (hydrolysis, acidification, and methanization) for active metabolism of the microorganisms. This system focuses on bacterial growth rates; for example, acidogenic bacteria double their population in less than a day while methanogenic bacteria require 3 to 5 days retention time. Advantages of two-phase digestion over conventional high-rate digestion as stated by Scaramelli (343) include: increased control of the growth of bacteria populations, substantial reduction in total reactor volume and therefore, reduction in capital and operating costs; decreased heat requirements and increased thermal efficiency; high rates of solids stabilization; and increased methane yield and production rate. In a plug flow digestion system, digester substrate moves continuously; feedstock is loaded from one end and effluent is discharged from the other. There is virtually no blending or mixing of solids. Liquids trickle downward by gravitational forces, but essentially remain with the solids with which they were introduced (343).

H.2.4 Case Studies

The literature review has identified four facilities which were placed in operation to convert the biodegradable, organic fraction of MSW to methane: 1) the RefCoM proof-of-concept facility in Pompano Beach, Florida; 2) an experimental test unit in Walt Disney World, Florida, that used the SOLCON reactor; 3) a pilot plant demonstrating the DRANCO process, located at a solid waste treatment plant in Gent, Belgium; and 4) a plant in La Buisse, France that uses the Valorga process. There are a number of promising research and development activities and pilot-scale systems in the United States that are investigating the conversion of MSW to methane and a compost product. Some of these projects are discussed in Section H.2.4.5.

H.2.4.1 RefCoM Process - Pompano Beach, Florida

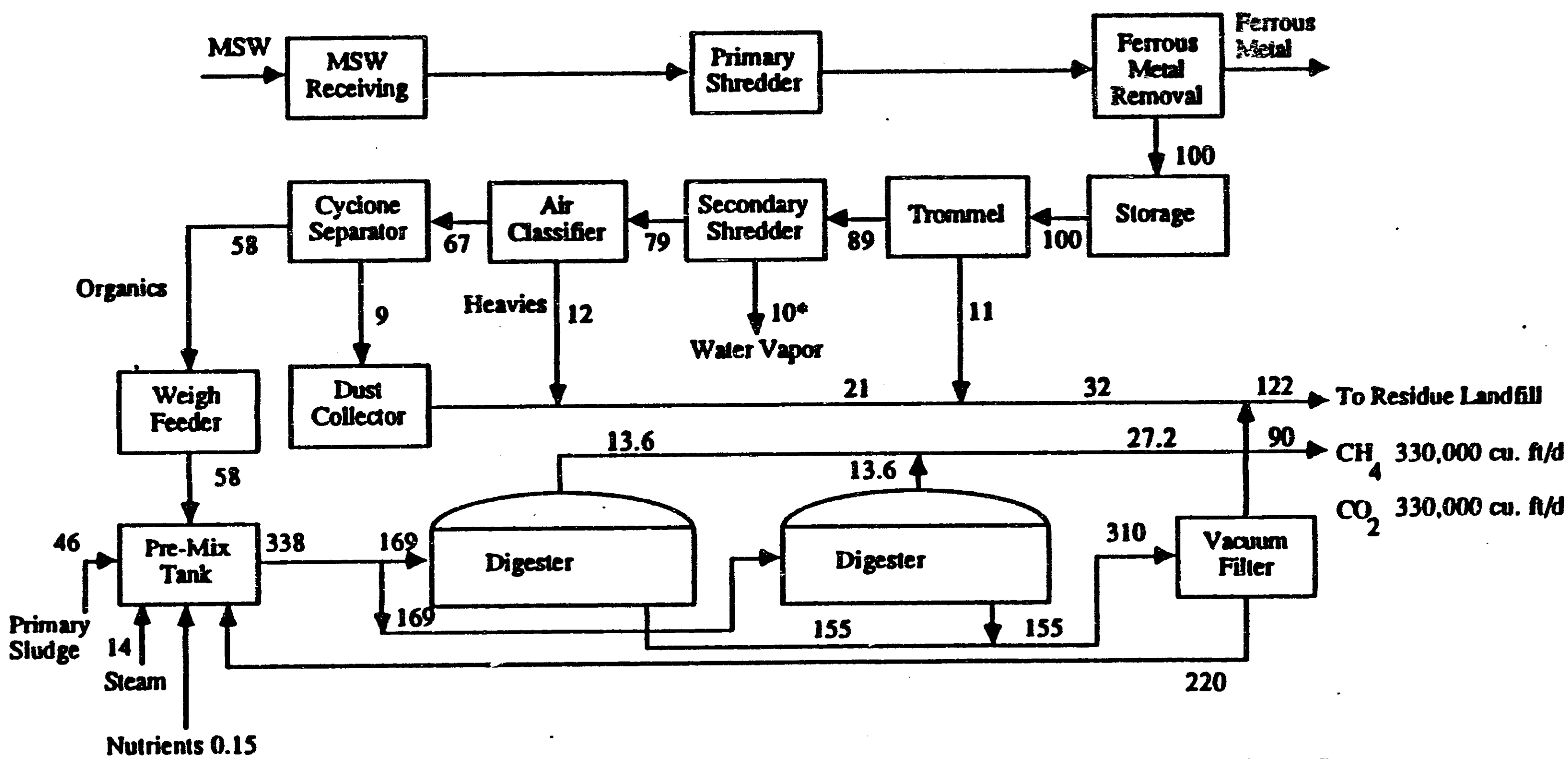
The RefCoM (Refuse Conversion to Methane) project was the culmination of a number of studies and laboratory research sponsored by the EPA and the National Science Foundation and conducted by the University of Illinois and others in the early 1970s. The facility was designed to demonstrate the technical feasibility of anaerobically digesting MSW and sewage sludge to produce methane, obtain operating data that could be used to improve the design, and provide cost data for use in evaluating the economic feasibility of the process (814).

Construction of the facility was completed and operation began in 1978 under the sponsorship of the U.S. Energy Research and Development Administration. A variety of unexpected operational problems were experienced with the preparation system. Sufficient modifications to the system were made by late 1981 to achieve a feedstream to the digestion process.

Unfortunately, funding lapsed and then became again available in late 1982 at which time the system was restarted. In 1983, sponsorship shifted to the U.S. Department of Energy, the Gas Research Institute, and the contractor, Waste Management, Inc. Still plagued by operational problems, the preparation system was extensively modified in early 1984 and subsequently operated satisfactorily to produce feed for the testing in the digesters (814).

Because of budget limitations, the RefCoM installation included only part of the planned system; the MSW separation subsystem, the methane digestion subsystem, and the dewatering system. The facility was originally designed to process 50 to 100 TPD of MSW, depending upon digester operating temperature, and 5 to 10 TPD of sewage solids (118). The as-built configuration is shown in Figure H-4.

The original preparation system, as indicated on Figure H-4, consisted of a 60 TPD vertical shredder and ferrous removal system (later operated separately by the contractor), a trommel with 3/4-inch openings, a secondary shredder, and an air classifier. Significant changes were made to correct problems experienced with this system. The trommel was first converted to a two-stage unit and later was replaced with a two-stage disc screen. The secondary shredder and air classifier were eliminated, and extensive modifications were made to the shredder. The changes to the preparation system resulted in a drastic simplification of the process evidenced by a drop in horsepower requirements from 425 to 81 (429).



* Denotes tons per day of mass flow.

Figure H-4. As-Built RefCoM Facility Process (526)

The digestion system consisted of a premix tank and two 45,000 cf, 50-ft diameter digesters with mechanical mixers (450). The effluent from the digesters was dewatered via a vacuum filter, and the filtrate was recycled back to the premix tank. The mixers experienced a number of operational problems. Although rated at 125 hp, the mixer motors were never able to draw more than 35 hp (429). Initially, when feed rates and solid contents were low in the digesters, the mixers worked well; however, as the feed rate increased, mixer shaft failures occurred due to a build up of long stringy materials (i.e., plastics, textiles) around the shaft in both the digesters and the premix tank. This problem was eliminated by the revisions to the preparation system which removed the problem materials before digestion, and by modifications to the paddle configuration.

Performance data was collected over 10 intermittent digester test runs between December 1981 through July 1985. Thermophilic temperatures (57-60°C) were maintained throughout. Retention times ranged from a low of 6.4 days to a high of 26.6 days (814). As an example, during February and March 1983, the retention time was 8 days. The average feed rate was 6.07 TPD, and 5.95 scf gas/lb feed material (volatile solids) was produced. The feed rate during this period was limited by the vacuum filter's ability to dewater the effluent (118). A belt filter press was used and evaluated in the later stages of the project, however not under optimum conditions. Isaacson (814) noted that it was probable that the belt filter press would produce a cake with a higher total solids content if operating conditions were optimized.

Although the system design capacity could not be fully realized during testing due to the types of problems indicated, the capability to feed a concentrated slurry was demonstrated. Solids concentration as high as 10.3 percent were fed into the digesters resulting in a slurry solids concentration of 6.33 percent. Tests also demonstrated that, at the longer retention times, substantially higher volatile solids destruction took place and consequently, more gas production per unit of feed to the reactor. Longer retention times also resulted in a more stable operating system. Gas composition was relatively consistent, with the methane content ranging between 50 and 54 percent.

It should be noted that beginning with the initial operation in 1978, the digesters continuously produced gas and displayed no unusual microbial problems (118). The RefCoM experimental program verified that, at that scale, the process produced methane of the same quality and quantity as established in the laboratory research (814).

H.2.4.2 <u>SOLCON Process - Walt Disney World, Florida</u> (802)

Noting that the RDF fraction of MSW represents a significant waste resource, equivalent of up to 2 EJ of energy per year in the United States, the Institute of Gas Technology developed a program to study the implementation of low-cost, non-energy intensive waste treatment technologies and the net production of energy (methane) from waste sources. As a part of this program, a SOLCON (solids-concentrating) bioreactor was placed in operation between 1984 and 1988 at an experimental test facility in the Walt Disney World Complex, Florida.

The facility included front-end feed processing and slurry preparation equipment, a cold-flow test column, a 1200-gallon (4.5-m^3) SOLCON digester, digester effluent processing equipment, and gas handling equipment. Four different feedstocks were tested: water hyacinth, primary sludge, sorghum, and the refuse-derived fuel (RDF) component of MSW. The RDF was obtained from a Baltimore, Maryland resource recovery plant sized at 10 mm, thus eliminating the need for preparation equipment (shredding, sizing, separation) at the facility. Table H-1 summarizes the physical, chemical, and biological characteristics of the feedstocks. The RDF was dry (less than 7 percent moisture) and contained low levels of nutrients (nitrogen, phosphorous, sulfur), requiring nutrients to be added to sustain an uninhibited level of anaerobic digestion when digester effluent was not recycled.

A schematic diagram of the pilot-scale test facility is shown in Figure H-5. The feed was first fine-ground to a 3-mm size and diluted with influent sewage to 5 to 10 weight percent solids and stored in an enclosed tank. A mixer and pump recirculation were provided to guarantee uniform product delivery to the feed blending tank where the feed was mixed with the primary sludge. Influent sewage was received from the resort's wastewater treatment plant and stored in a tank. A feed heat exchange automatically preheated the blend feed to minimize temperature fluctuations in the digester. The nominal feed rate to the digester was 790 wet kg/d of diluted feed containing 5 percent solids.

The SOLCON digester is a novel design that is non-mixed, relying on passive settling and flotation to concentrate solids. It can be operated in either an upflow mode whereby the feedstock is injected at the bottom and effluent removed from near the top of the digester, or in a downflow mode whereby the feed is injected at the top of the digester and the effluent removed from the bottom. Whereas RDF has a low specific gravity and a tendency to float, the digester was operated in an upflow mode as shown in Figure H-6. For comparison, a 13-gallon (50-L) continuously stirred tank reactor (CSTR) was operated simultaneously at the same operating conditions, with the same feed material (802).

TABLE H-1. PHYSICAL, CHEMICAL AND BIOLOGICAL CHARACTERISTICS OF SOLCON FEEDSTOCKS (802)

	Primary Sludge	Hyacinth	Sorghum	MSW[a]
Feed Type (As-Received)				
Total Solids (TS), % wet wt	4.8	4.9	27.5	93.3
Volatile Solids (VS), % TS	83.6	82.9	93.8	91.1
Elements, % TS				
Carbon (C)	47.1	40.7	44.4	41.9
Hydrogen (H)	7.04	5.72	6.16	5.67
Nitrogen (N)	3.75	3.02	1.15	0.59
Phosphorus (P)	0.56	0.73	0.24	0.05
Sulfur (S)	0.49	0.76	0.10	0.12
Nutrient Ratios[b]				
C/N	13	13	39	71
C/P	84	56	190	840
C/S	96	54	440	350
Energy (Heating) Value, kJ/kg VS	25,600	19,500	19,000	17,000
(Btu/lb VS)	(11,000)	(8,370)	(8,160)	(7,320)
Biologically Recoverable Energy in Product Gas,[c] kJ/kg VS	23.300	11,600	14,000	9,300
(Btu/lb VS)	(10,000)	(5,000)	(6,000)	(4,000)
Recovery Efficiency, %	91	60	74	55

[a]RDF fraction.

[b]Preferred C/N, C/P, and C/S ratios are 15, 100, and 150, respectively.

[c]As determined by anaerobic biogasification potential (ABP) assays (3). These data are accurate to within ±10%.

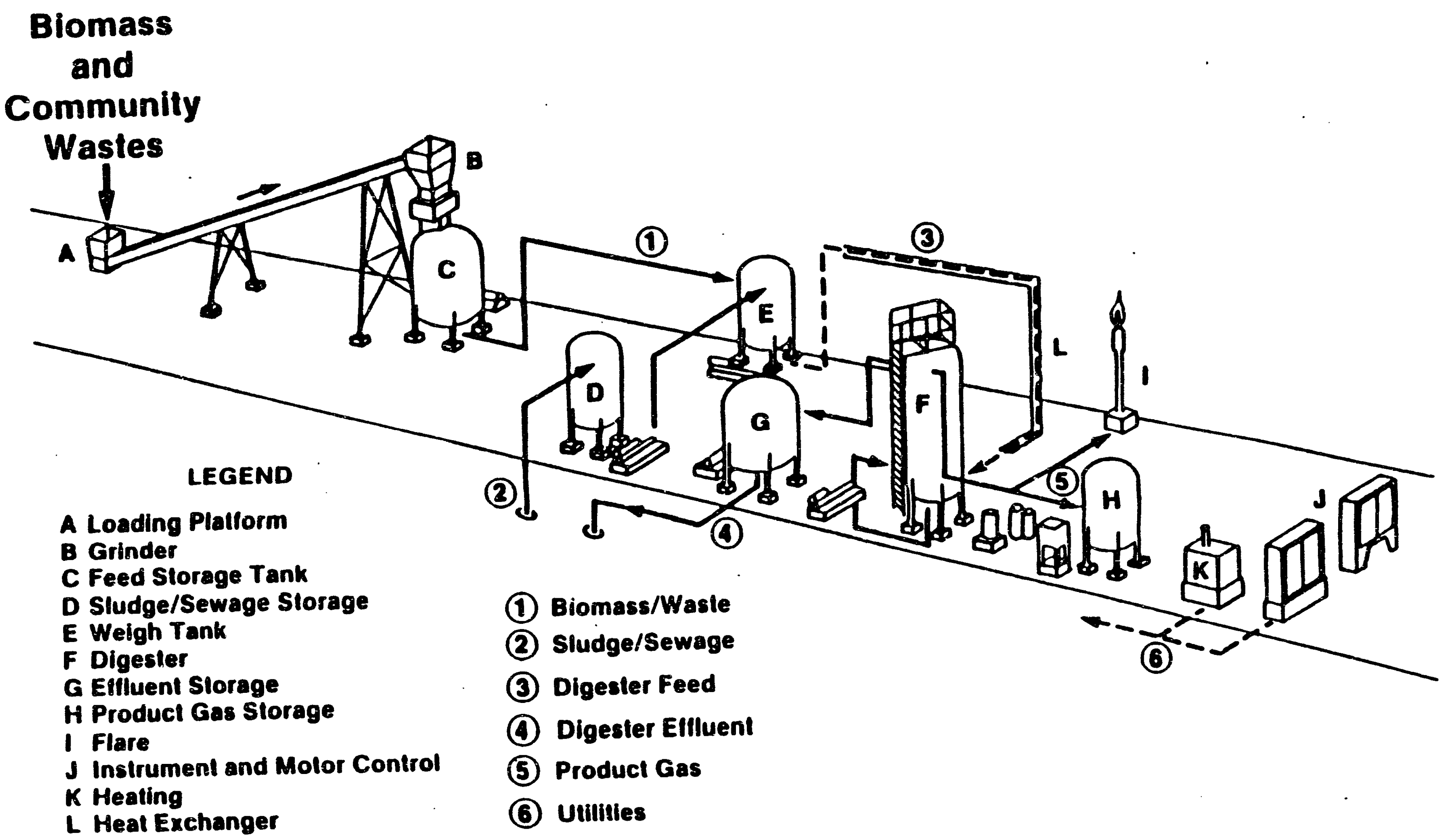


Figure H-5. SOLCON Experimental Test Facility (802)

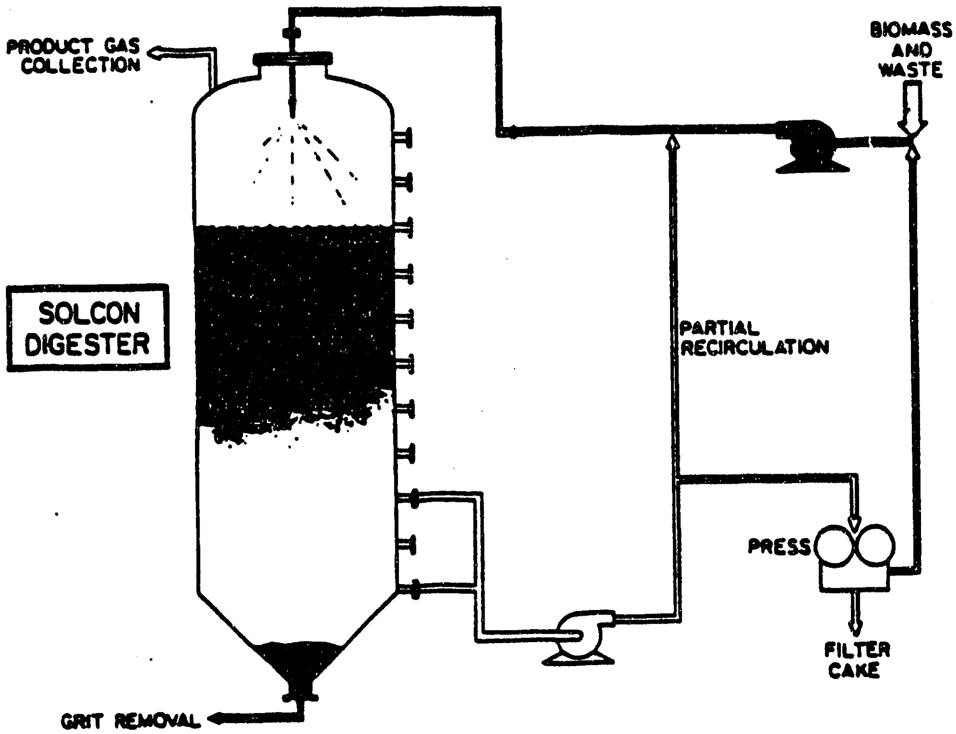


Figure H-6. SOLCON Digester (802)

Two test runs were performed on the RDF. The first used a 15:1 RDF/primary sludge blend fed with external nutrients to obtain the desired ratios for C/N, C/P, and C/S (15, 100 and 150, respectively). The blend was fed at a loading rate of 3.2 kg VS/m^3-d to the SOLCON digester operated at mesophilic conditions and a hydraulic retention time of 16 days. The second test was conducted with the same 15:1 RDF/sludge feed but with effluent supernate recycle. The data showed that liquid recycle can eliminate the need for daily addition of nutrients when nutrient-deficient feed is used.

The performance data for the digester is presented in Table H-2. The digester produced methane yields of up to 0.27 m^3/kg VS added exceeding the yields from the CSTR operated at both mesophilic and thermophilic temperatures. Further, during the second test run, part of the effluent was recycled resulting in a drop of over 60 percent in nutrient requirement.

The advantages of a SOLCON digester as concluded by the researchers whose work is described above are as follows:

- Does not require continuous mixing; reducing energy consumption
- Promotes retention of solids; smaller digester, higher conversion rates and efficiencies
- Has no internals; ability to process fibrous and particulate slurries
- Has no attached mechanical equipment; no forced downtime, low operating and maintenance cost
- Provides hydraulic recirculation of surface layer; prevents formation of scum layers, continuously provides nutrients and inoculum for improved solids reduction

H.2.4.3 DRANCO Process - Gent, Belgium

De Baere and others (290) developed the DRANCO (dry anaerobic composting) process which was installed at a solid waste treatment plant in Gent, Belgium in late 1984. The pilot plant, with a reactor volume of 56.5 m^3 processing 3 tonnes of material per day, operated for approximately 1 year to determine the technical feasibility and reliability of the process. Chynoweth and Legrand (450) noted that a larger-scale demonstration project employing this technology was in the planning stage in 1988.

TABLE H-2. SOLCON DIGESTER TESTS WITH 15:1 RDF/SLUDGE (802)

Test No.	1	2
Duration, months	5	5
Steady-State Period, weeks	5	5
Nutrient Recycle	No	Yes
Operating Mode, flow	Down	Down
Average Feed Solids Content, wt %	7.1	7.8
SOLCON Temperature, °C	35	35
Loading Rate,		
kg VS/m^3-d	3.2	3.2
kg org. matter/m^3-d[a]	3.5	3.4
HRT, days	17	18
SOLCON Methane Yield, m^3/kg VS added	0.27	0.25
SOLCON Methane Production Rate, vol/vol-d	0.87	0.81
SOLCON Methane Yield m^3/kg org. matter[a]	0.24	0.22
SOLCON Effluent Solids Content, wt %	6.1	6.1
SOLCON Effluent, pH	7.2	7.1
SOLCON Organic Matter Balance, %	104	106
CSTR-1[b] Methane Yield, m^3/kg org. matter[a]	0.19	0.18
CSTR-2[c] Methane Yield, m^3/kg org. matter[a]	0.21	0.19

[a]Organic matter is defined as the volatile solids, determined by standard methods plus volatile acids that were lost during solids analyses. This loss was experimentally determined.

[b]Mesophilic temperature, 35°C, as in the case of the SOLCON digester.

[c]Thermophilic temperature, 55°C.

A flow diagram of the overall DRANCO process is shown in Figure H-7. The preparation steps include shredding, screening, and air classification for the removal of metals, glass, plastic, recoverable paper, and other non-biodegradables from the organic fraction. The resulting organic stream is mixed with recycled water and supernatant and pumped into the top of an intensive fermentor at 35 to 40 percent total solids for a period of 12 to 18 days. Movement is downward in a plugflow manner without mechanical mixing with a volatile solids reduction of about 55 percent. This step is followed by a post-fermentor with a retention time of 2 to 3 days. Both steps occur at a thermophilic temperature of 55^{o} C and a solids concentration of 30 to 35 percent. Depending on the composition of the substrate, 125 to 185 m^3 of biogas per metric ton of digester feed material are produced. The methane content of the biogas is approximately 55 percent.

The DRANCO process flow diagram shows that water removed by mechanical filtration of the digester residue is recycled to adjust the solids content of the raw incoming substrate. It is claimed that no wastewater is produced. The filter cake is dried, shredded, and screened to produce a stabilized humus-like product. The biogas recovered at the top of the digesters, is used to produce electricity sufficient to meet the needs of the overall solid waste treatment facility and for sale to the electric utility. Waste heat is used to heat the digesters and dry the filter cake.

The Gent pilot plant was initially operated under mesophilic (35^{o} C) conditions. The methane content in the biogas reached 55 to 60 percent while the pH of the digested residue rose from 6.5 to 8.5 within a period of 8 weeks. During this time, gas production rates reached 2 to 3 m^3 of biogas/m^3 reactor - day. After 16 weeks, the process was adjusted to operate at thermophilic temperature. Steady state gas production at a rate of 6 to 8 m^3/m^3 reactor - day was achieved. The digested residue had a total solids concentration of 32 to 35 percent and a pH of 8.2 to 8.5 percent under these conditions (290).

As noted above, the DRANCO process produces a stabilized end product, Humotex, which was evaluated in comparison to conventional compost produced with an aerobic process. Humotex had a carbon to nitrogen ratio of 12 to 15, and virtually no fecal bacteria (290).

Reported advantages of the DRANCO process compared to aerobic composting (290) are:

- Needs a minimum of surface area (about 20% that of aerobic systems)
- Minimizes odor problems since entire fermentation takes place in sealed-off reactors
- Does not attract rodents, birds or insects and does not produce any (runoff) wastewater

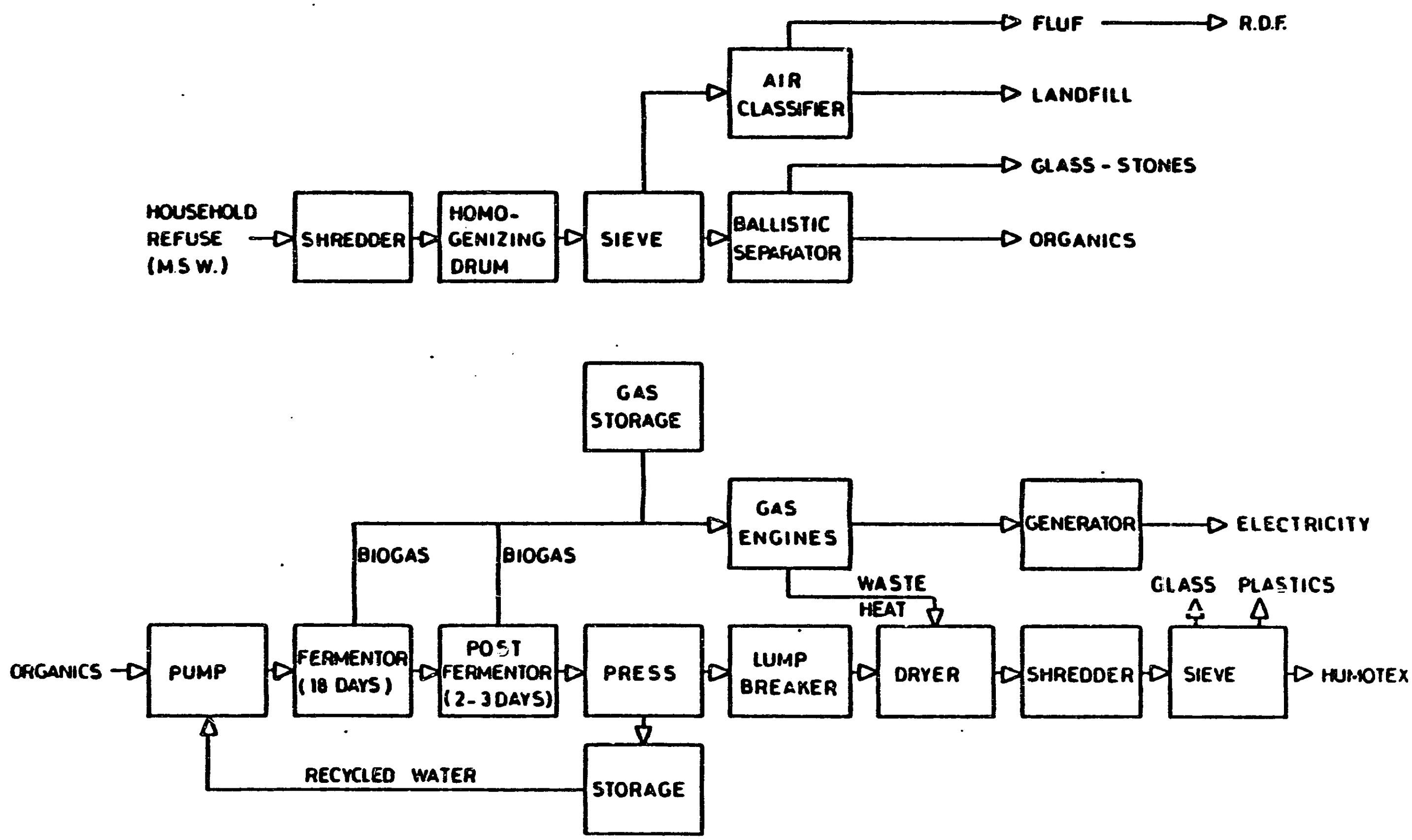


Figure H-7. DRANCO Process (290)

H.2.4.4 Valorga Process - La Buisse, France (156, 815)

In 1980, the CARENE engineering and design office undertook a project to determine the possibility of using the pressure from a portion of the biogas produced by fermentation to mix the substrate in the digestion system. This concept had been proposed by Professor Ducellier, one of the pioneers in methanization in France. In collaboration with Professor Pavia, Director of the Laboratoire de Chimie Appliquee de L'Universite des Science et Technoques du Languedoc in Montpellier, CARENE demonstrated, at pilot-scale, that a substrate with solids concentration as high as 35 percent could be methanized.

Since the structure of the CARENE organization was not well suited to continue the work on an industrial scale, the Valorga company was created in 1981. A 2-year research and development program resulted in the industrial-scale implementation of the Valorga methanization process at La Buisse. Originally a composting plant, methanization and refining units were placed in operation in 1984. A combustion unit was added in 1987. La Buisse operates 6 hours a day, 260 days per year, processing 66 TPD (60 tpd) of MSW, or 17,600 TPY (16,000 tpy).

An overview of the Valorga process is shown in Figure H-8. The overall system consists of five units: preparation, methanization, refining, combustion, and gas treatment. Waste delivered to the plant is dumped into a receiving/storage pit, from which it is fed into the preparation system via a grapple. After shredding, ferrous metals are removed magnetically for recycling. The waste then passes through three trommels, each with a different mesh size. Approximate mesh sizes are 0.6, 2, and 8 inches (6 mm, 50 mm, and 200 mm). The plus 0.6 in./minus 8 in. material forms the highly organic feed stream to the digester; the plus 2 in./minus 8 in. material (the combustibles) forms the refuse-derived fuel fraction for incineration. Wastes greater than 8 in. are landfilled.

The digester feed stream from the second trommel is approximately 55 percent total solids. Recycled water is added to dilute this stream to between 35 and 45 percent prior to injection into the digester. Material is pushed through the digester by the incoming material and by pressurized gas circulated through the digester. The digestion process is schematically depicted in Figure H-9.

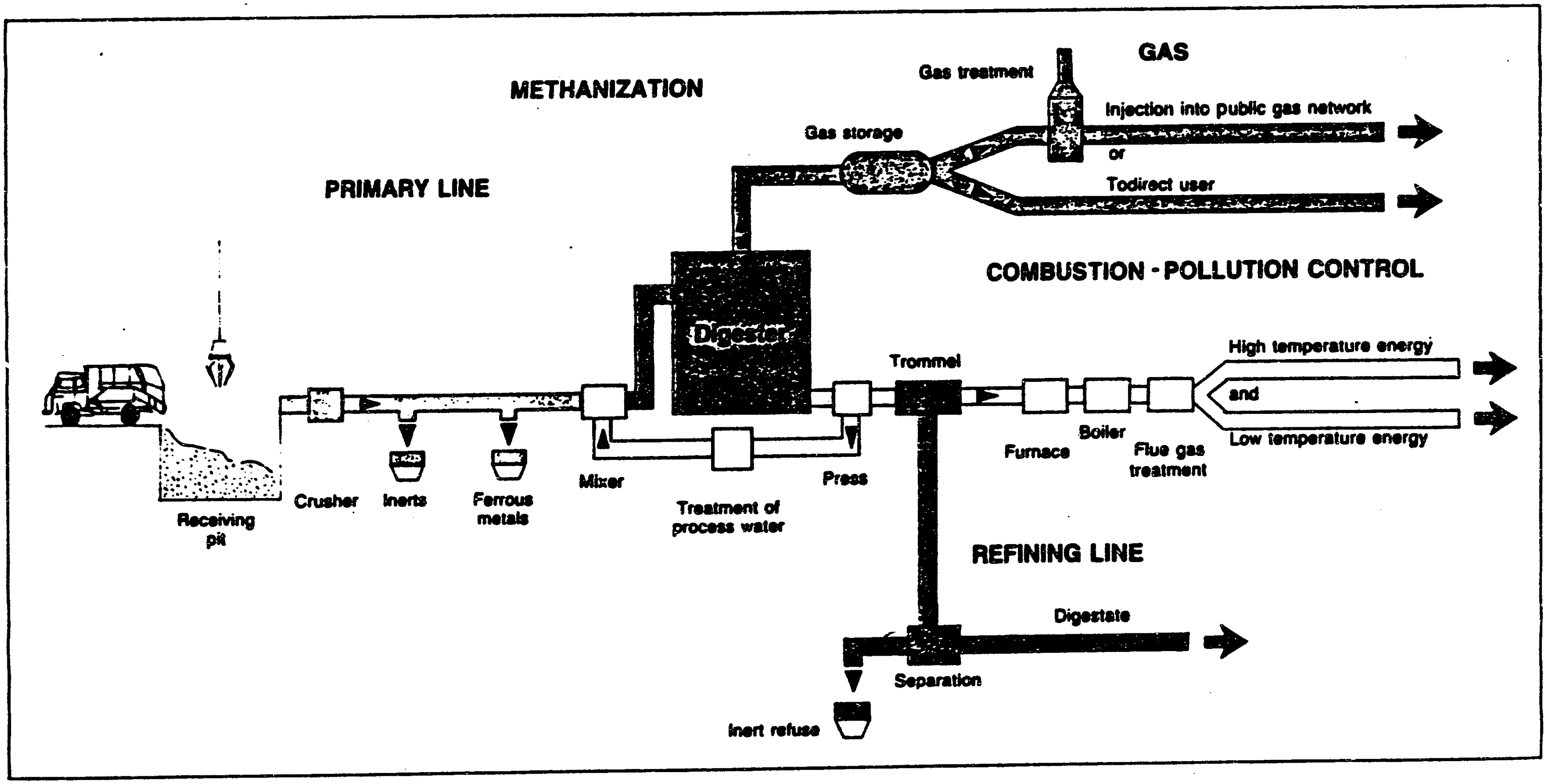


Figure H-8. Valorga Process (812)

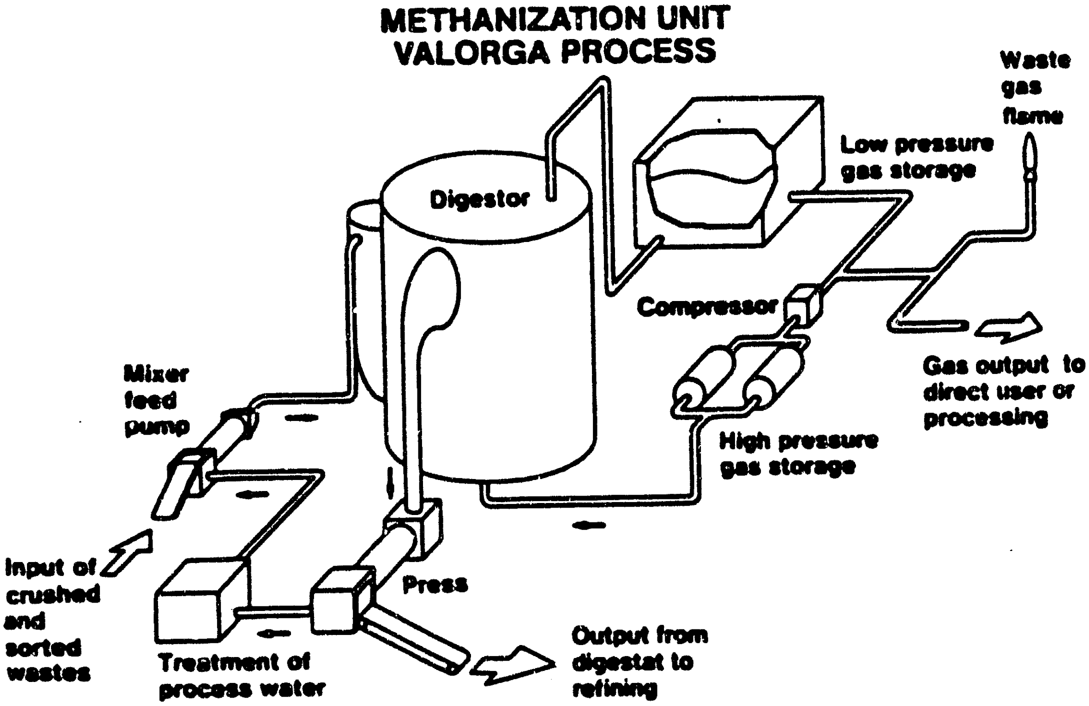


Figure H-9. Valorga Process Methanization Unit (156)

The slurry fed to the digester remains in the tank for 15 days under mesophilic conditions (37°C), or for 8 days under thermophilic conditions (55°C). After digestion, the digestate is dewatered by pressing to increase the dry solids from 30 to 60 percent. The digestate or filter cake is broken up and screened through an 0.4 in. (10 mm) mesh. The resultant final digestate is composed of organic matter with a high nutrient content (nitrogen, phosphorous, potassium) and is sold as a fertilizer, Nutrisol 38.

The biogas produced contains 60 to 65 percent methane and 35 to 40 percent carbon dioxide; it is saturated with water. Its maximum heating value ranges from 625 to 675 Btu/lb. The gas is sold either to a neighboring factory for use in fueling lime kilns or, via a regulation loop controlled by a specialized metering system, can be directed into Gaz de France's main supply network. The average production of biogas, sold untreated by Gaz de France, is reported as approximately 4,500 cf/T (140 m^3/t) of material fed into the digester.

Any combustibles that were screened out after the digestion process are combined with the RDF and fed to a pyrolytic furnace which produces low-temperature heat used to meet the facility's energy needs. Surplus energy is sold to other users of low-temperature heat.

The features of the Valorga process are reported as follows (815):

- Ability to methanize substrates having high solids content (35 percent); yielding a digested effluent of about 28 percent dry matter
- Continuous loading of the digestion system
- A cylindrical tank design featuring an inlet outlet separation wall and transfer by semi-piston
- Pneumatic mixing; no internal mechanical parts
- Adaptability to methanization of polysubstratas (e.g., domestic waste plus sewage sludge plus distillery sludge, domestic waste plus manure)

H.2.4.5 Research Projects

Research on anaerobic digestion as a means of generating methane from MSW, has been conducted over the past three decades (343, 850, 425, 405, 814). This section presents a number of MSW anaerobic digestion projects recently completed or in progress which highlight the state of the art of the technology. Whether sponsored independently or directly by the U.S. DOE's Energy from Municipal Waste Research Program (managed by SERI), these projects target key technological improvements in the areas of: 1) increasing solids loading, 2) decreasing solids residence time, and 3) improving conversion efficiency.

DOE/NREL bioconversion research projects have been conducted at NREL, UCLA, University of Kansas, and the New York State Department of Health. These projects were designed to improve reactor stability and increase process conversion efficiency by identifying, characterizing and optimizing microorganisms responsible for the process (425). Process engineering experiments were funded at the Gas Research Institute's Experimental Test Unit at Walt Disney World, Florida, supported by laboratory experiments at the University of Florida. Biogas production and related studies were co-funded with the

Gas Research Institute and Southern California Edison and Reynolds, Smith, and Hill. Improved reactor concepts, with emphasis on processing higher concentrations of solids were funded at the University of Arkansas, Purdue University, and NREL.

The information presented below covers research into improved reactor concepts and process engineering experiments, which have been reported in the open literature. These studies represent public as well as private/commercial research particularly in the area of increasing solids content in the digester thereby affording a reduction in reactor size while ensuring reasonable methane yields.

H.2.4.5.1 <u>High Solids Process for the Fermentation of MSW for the Production of Methane</u>. In the mid-to-late 1980s, SERI's Biotechnology Research Branch (forerunner to NREL) developed a novel reactor that was able to process high solids concentrations for the anaerobic fermentation of lignocellulosic materials, including MSW (426). Research into the kinetics of high solids anaerobic fermentation led to the belief that decreasing reactor volume would be possible for higher solids concentrations while maintaining the same solids loading rate and retention time. The key to implementing this approach is to provide for effective mixing of the substrate, microorganisms and metabolic intermediates, in either batch or continuous modes at controlled temperatures and inoculation of the incoming MSW organic fraction with leachate from prior fermentation.

The high solids reactor design utilized a low speed high torque hydraulic motor with an optimum blade configuration for mixing (426). The most effective mixing was accomplished by rods spaced at 90 degree angles around the shaft. Initial fermentation runs with high solids, demonstrated the importance of gradually building up solids in order to acclimate microbes to high solids levels. Once the reactor microorganism population has been balanced, stable high solids fermentation will occur (426).

H.2.4.5.2 Argonne/DOE Research In Bioconversion of MSW. Work proceeding at DOE's Argonne National Laboratory includes evaluating the performance of conventional continuously stirred and packed bed anaerobic digesters in producing organic acids from MSW and eventually converting them to liquid (alkane) hydrocarbon fuels (476). Initial efforts have been focused on improving acid production from MSW feedstock and the extraction of organic acids from digester fluids.

H.2.4.5.3 Two-Stage High-Solids Anaerobic Digestion/Aerobic Composting Process, University of California, Davis. The Department of Civil Engineering at the University of California has developed a bioconversion concept, based on the work of Jewell (855, 856) and others that combines high solids digestion with aerobic composting (850). Currently under contract with the California Prison Industry Authority, UC Davis will demonstrate the technical feasibility of this process as applied to the organic fraction of MSW.

The University's pilot-scale research process consists of two stages as depicted in Figure H-10 (850). In the first stage, high solids anaerobic digestion of the organic fraction of the MSW occurs producing principally methane and carbon dioxide in a completely mixed reactor. The second stage involves the aerobic composting of the anaerobically digested solids to increase the solids content from 25 to 65 percent or more. The product produced may be used as high quality compost or co-fired with other fuel in a combustor.

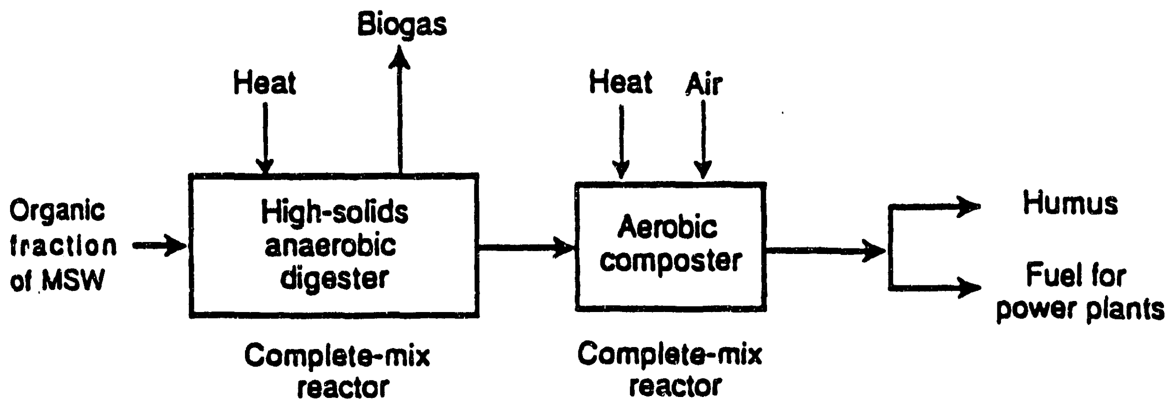


Figure H-10. High-Solids Anaerobic/Aerobic Composting Process (850)

The pilot-scale system, whose physical characteristics are shown in Table H-3, has been operated for a period of 7 months on a controlled mixture of newsprint, mixed office paper, yard waste and food waste to simulate the organic fraction of MSW (850). Table H-4 presents proximate analyses, ultimate analyses and biodegradability parameters as functions of feed substrate suggesting the importance of the C/N ratio for optimum microbial metabolism, the lignin content as an indicator of biodegradability, and the heating value of the material components (850).

Based on an intermittently mixed reactor maintained at thermophilic temperatures and a 30-day residence time for the solids, Table H-5 presents feedstock characteristics before digestion, during digestion, and after aerobic composting (850). In addition to significant biogas production (viz., 6:1 for biogas volume/active reactor volume), a volume reduction of up to 90 percent has been achieved for the uncompacted organic fraction of MSW that is fed to the digester, or 57 percent compared to the same material when placed in a well compacted landfill (850). The humus-like product from the aerobic composter is 65 percent solids, has a density of 35 lb/ft3 and, when dried, a heating value of 6360 Btu/lb. In addition to its proposed use as a soil amendment, it could also be considered as a fuel source.

H.2.4.5.4 Sequenced Batch Anaerobic Composting (SEBAC) Process, University of Florida (852). In an effort to extend the applicability of high solids anaerobic digestion to commercial facilities, the University of Florida has been pilot-testing a sequenced batch anaerobic composting (SEBAC) process, intended to convert the organic portion of MSW to methane and compost (852). Two different types of MSW, characterized in Table H-6, were used in trials with two different leachate recycling efficiencies and two different retention times.

The process accepts the coarsely shredded organic fraction of MSW which is packed into the Stage 1 reactor, shown in Figure H-11, and inoculated with recycling leachate from an active, aged biomass from Stage 3 (852). In addition to biogas, the Stage 1 reactor produces hydrolysis products and volatile acids, which are fed to Stage 3. After the inoculated refuse is operated in the batch mode in the Stage 2 reactor to produce biogas, Stage 3 completes the conversion to biogas and serves as the source for the inoculum for system start-up.

While the feedstock varied considerably (Table H-6), the SEBAC system was able to convert a major fraction of the organic fraction of shredded MSW to methane and carbon dioxide while producing compost quality residue (852). The 42-day residence time runs with Sumter County MSW, shown in Table H-7, produced a mean methane yield of 3.10 scf/lb VS(add) and a mean volatile solids reduction of 49.73 percent. The 21-day trials with Sumter and Levy MSW (not shown) showed mean methane yields of 2.61 and 3.06 scf/lb VS(add), respectively, with volatile solids reduction in the range of 21.1 to 44.6 percent (852).

TABLE H-3. PHYSICAL CHARACTERISTICS OF UC DAVIS PILOT-SCALE HIGH-SOLIDS ANAEROBIC DIGESTION/AEROBIC COMPOSTING PROCESSING UNITS (850)

Item	*Unit*	*Value*
Anaerobic digester		
Reactor type		Complete-mix
Mixing mechanism		Mechanical
Mixing time	min/min	Variable
Total reactor volume	ft^3 (L)	90 (2,250)
Total volume of active biomass	ft^3 (L)	67 (1,900)
Reactor biomass density	lb/ft^3 (kg/m^3)	63 (1,009)
Reactor total solids concentration	% of WW	23 – 30
Aerobic compost unit		
Reactor type		Complete-mix
Mixing mechanism		Mechanical
Mixing time	min/min	Variable
Total rector volume	ft^3 (L)	30 (850)
Total volume of composting mass	ft^3 (L)	27 (765)

TABLE H-4. CHARACTERISTICS OF ORGANIC FEEDSTOCK MATERIALS HIGH-SOLIDS ANAEROBIC DIGESTION/AEROBIC COMPOSTING PROCESS (850)

	Feed substrate (percent dry basis)			
	Newsprint	*Office paper*	*Yard waste*	*Food waste*
Proximate analyses				
Total solids, TS	94.00	96.40	50-90	7-15
Volatile solids, VS[a]	88.00	82.60	72.72	79.71
Ash content	0.88	6.94	11.20	3.16
Fixed carbon	11.15	10.46	16.06	17.13
Ultimate analysis				
Carbon, C	48.90	43.14	44.58	50.31
Nitrogen, N	0.001	0.15	3.34	3.15
Hydrogen, H	6.00	5.80	5.35	5.90
Oxygen, O	43.50	43.82	34.64	36.29
Sulfur, S	0.068	0.079	0.33	0.54
Chlorine, Cl	0.12	0.07	0.56	0.65
Biodegradability				
Lignin content, LC	21.91	0.35	4.07	0.35
Biodegradable fraction[b]	0.22	0.83	0.72	0.83
Energy content				
High heating value, Btu/lb	8,613	7,426	8,570	8,282

[a] *VS = % TS.*
[b] *Computed using Eq. 1.*

TABLE H-5. TYPICAL CHARACTERISTICS OF WASTE FEEDSTOCK HIGH-SOLIDS ANAEROBIC DIGESTION/AEROBIC COMPOSTING PROCESS (850)

		Average values		
Parameter	*Unit*	*Input feedstock*	*After anaerobic digestion*	*Humus after aerobic composting*
Total solids, TS	%	61	25	65
Volatile solids, VS	% of TS	82	63	59
Biodegradable volatile solids, BVS	% of VS	68	1	—
Ash content	% of TS	6	22	26
Energy content	Btu/lb	7,575	6,560	6,360
Relative wet mass[a]		1	0.78	0.30
Relative volume				
Uncompacted[b]		1	0.13	0.087
Compacted		1	0.75	0.43

[a] *The reported waste characteristics after digestion and after composting are based on a nominal mass retention time of 30 d in the anaerobic digester and 3 d in the aerobic composting unit.*
[b] *Based on the volume of waste as fed to the digester.*

TABLE H-6. COMPARISON OF MSW COMPOSITION FROM SUMTER AND LEVY COUNTY SEBAC PROCESS FEEDSTOCK (852)

	Sumter[1]		*Levy*[2]	
	Mean	*Range*	*Mean*	*Range*
Paper (%)	47.3	22.0 - 65.2	91.5	85.0 - 98.5
Cardboard (%)	10.9	0.0 - 24.6	4.1	0.4 - 7.0
Plastic (%)	9.7	4.0 - 21.4	0.3	0.0 - 0.9
Yard Waste (%)	5.9	0.0 - 33.0	1.9	0.0 - 8.4
Miscellaneous	22.6	11.5 - 67.7	0.0	0.0 - 7.4

(1) *MSW from Sumter County comes from a recycling facility, where ferrous metal, aluminum and some cardboard boxes and plastic bottles (PET) are removed from the MSW before it is shredded with a hammermill.*
(2) *MSW from Levy County was sorted by hand. The organically degradable fraction used as feedstock for the digesters contained only paper, yard and food waste.*

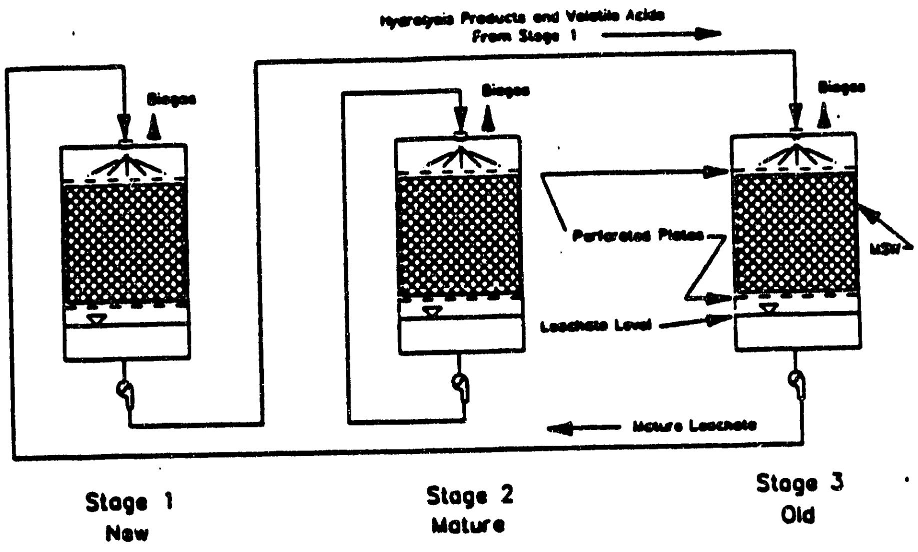


Figure H-11. Sequenced Batch Anaerobic Composting Process (852)

TABLE H-7. PERFORMANCE PARAMETERS, 42-DAY RETENTION TIME, SUMTER MSW SEBAC PROCESS (852)

	Trial 4	*Trial 5*	*Trial 6*	*Trial 7*	*Mean*
Methane Yield (acc.) (SCF/lbs VS)	2.86	2.92	3.52	3.08	3.10
Methane Production Rate (vol/vol-day)	0.64	0.57	0.64	0.60	0.61
Volatile Solids Reduction (%)	51.0	48.9	52.4	46.6	49.7
Volume Reduction (%)	43.2	46.1	42.4	—	43.9

H.3 ECONOMIC DATA

While there is limited commercial scale design and operating experience with MSW anaerobic digestion systems, projected economics and actual data for larger scale operations, as provided in the literature reviewed, are generally comparable with other MSW management approaches. For example, levelized costs for a commercial scale of RefCoM are similar to those of a mass burn facility. A DRANCO facility was reported to be higher than aerobic windrow composting systems but similar to in-vessel composting. The economics for combined anaerobic digestion/aerobic composting systems are highly dependent on the biodegradability of the feedstock, the value of biogas produced and the opportunities for use of the compost residue as a soil amendment.

H.3.1 Conventional Systems

This section introduces two accounts that describe the technoeconomic and market viability of anaerobic digestion in the management of the organic fraction of MSW. Both point to a significant commercial potential for this technology. Since these two reports, which describe technoeconomic model analyses, are rather detailed, only selected highlights are presented here. The reader is referred to the original documents for additional detail.

H.3.1.1 Technoeconomic Computer Model (450)

A computer model has been developed by Chynoweth and Legrand to simulate a prototype MSW anaerobic digestion facility. Based in part on the experience from the RefCom proof-of-concept program, the levelized cost results presented in Table H-8 are constant-dollar costs of service including debt amortization and operating costs assuming full municipal ownership. The tipping fee selected covers the shortfall between revenues and the cost of producing gas, electricity and recyclable materials. Processing of the dewatered residue, landfilling of ash and rejects, and preprocessing of MSW into RDF each account for 25 percent of the cost of service. Anaerobic digestion is shown to be a relatively minor cost item.

TABLE H-8. PROJECTED LEVELIZED COSTS
PROTOTYPE MSW ANAEROBIC DIGESTION FACILITY (450)

	1991 $/tonne	% of Total Cost
1. Costs		
RDF Plant	15.0	27.4
Anaerobic Digestion	8.9	16.2
Gas Cleanup	2.7	5.0
Residue Burning	14.9	27.3
Landfill Costs	13.1	24.0
	------	-----
Total Costs	$54.3	100.0%
2. Revenues		
Gas Sales	14.1	25.8
Electricity/Recyclables (1)	5.1	9.4
Tipping Fee	35.1	64.8
	-----	-------
Total Revenues	$54.3	100.0%

(1) Only aluminum considered

In addition to its use in performing sensitivity analyses of tipping fee as a function of several reactor design parameters, the model has been used to compare the economics of mass burn with anaerobic digestion. Using a life cycle economic analysis, including energy prices, recyclable and economic assumptions, three possible uses for biogas were considered for the comparison. These cases included direct sale of biogas to a nearby industrial/utility custom·· using a dedicated pipeline, combustion in a combined cycle gas turbine on site, and upgrading of the biogas to SNG quality for sale. In addition to the burning of residue with power generation, full air pollution controls were assumed.

The analysis included all operating expenses such as labor, O&M, residue/ash landfilling and debt service as well as revenue from the sale of electricity, recyclables and tipping fee. The computer projected capital cost of an MSW anaerobic digestion facility is approximately equivalent to a conventional mass burning facility. Sensitivity analysis revealed that the break-even tipping fee for anaerobic digestion starts out below mass burning and declines, while mass burn starts out higher and increases.

H.3.1.2 <u>RefCoM Technoeconomic Model</u> (814)

From a detailed technical, economic and market analysis of the experimental RefCoM project conducted by Isaacson et al, the following section highlights key analyses and case studies important for assessing the commercial viability of MSW anaerobic digestion. This is accomplished by determining the optimum tipping fee to satisfy key economic and financial constraints. The 1986 economic model and analysis summarized below are based on vendor design and costing information for a 400 TPD facility. Various scales of operation, by-product credits, and financing options are considered.

All projected costs for this analysis are on a 1990 basis.

H.3.1.2.1 <u>Base Case</u>. For the purposes of this evaluation, the facility is assumed to begin construction in 1988, complete start up in 1990, and operate for 20 years. Funded by a bond with payments starting in 1988, and with a 1.5 year bond reserve, the operating expenses of the plant and bond payments must be offset by its revenues, once the plant is operational. Expenses and revenues for the base case, defined for an equity contribution of 25 percent, are shown in Table H-9. The cost of capital is presented in Table H-10. A corresponding cash flow analysis, showing income from the bond reserve and the expense of the bond payment, is presented in Table H-11.

TABLE H-9. RefCoM BASE CASE - 1990 EXPENSES AND REVENUES ($) (814)

Expenses	
Personnel	1,553,200
Power	1,688,000
Water	2,920
Equipment Replacement	181,700
Maint. Mtls. & Supplies	990,800
Landfill Disposal	235,040
SG&A Expenses	788,375
Mobile Equipment	288,500
Contingency	209,000
Total	5,937,535
Revenues	
Methane	1,578,500
Carbon Dioxide	1,351,000
Metals	275,000
Tipping Fee	5,564,000
Sewage Sludge	952,000
Interest Income	353,000
Total	10,073,500

TABLE H-10. RefCoM BASE CASE - CAPITAL REQUIREMENTS ($) (814)

Total Construction Costs	28,862
Equity	7,034
Bond Capital Requirement	21,828
Bond Issue Costs	1,179
Bond Payment Reserve	4,467
Bond Payment During Construction	4,716
Interest Earned on Reserve	715
Interest on Bond Payment	472
Interest on Construction Funds	1,530
Bond Issue	29,474

TABLE H-11. RefCoM BASE CASE - CASH FLOW ($000) (814)

	----INCOME----		---EXPENSES---	
Year	Other Revenue	Bond Reserve	Operating Expenses	Bond Payment
1990	4157	353	5938	2985
1994	5383	353	7218	2985
1999	7289	353	9211	2985
2004	9962	353	11757	2985
2009	14014	4771	15005	2985

The objective is to ascertain on an annual basis the "break-even" tipping fee required to cover the difference between expenses and other revenue. The "actual" tipping fee required is higher by the amount of the financial return on the capital investment required. A second objective is to ascertain the equity contribution that satisfies multiple profit measures. These are: the pre-tax income ratio (1st yr PTIR = 10 percent); average pre-tax income ratio (PTIR = 25 - 30 percent); and return on invested equity (ROI = 25 - 30 percent).

The trade-off analysis for the base case predicts a 12 to 15 percent equity required to yield the lowest tipping fees (corresponding to $53/T and $57/T, respectively) for both the 25 percent and 30 percent requirements.

H.3.1.2.2 Base Case with Internal Energy Generation. There is a fairly large amount of heat energy which results from incineration of the sludge cake and non-biodegradable combustible streams fed to an onsite incinerator. Considering the energy value of these unused fuel sources and the equipment that would enable such fuel to be utilized, the following summarizes the deviation from the base case.

- Addition of $260,000/yr in electricity sales (considering that the base case already included a $5.2 million incinerator);
- Removal of $1,688,000/yr in power costs (to account for cost associated with power generation); and
- Addition of $8,800,000 in capital for power generation equipment (turbine, generator, condenser, etc.).

The results of this analysis shows that in order to satisfy all of the financial parameters regarding return on investment a tipping fee of $44.50 and $46.50 per ton are required at a 25 percent and 30 percent ROI.

H.3.1.2.3 100 Percent Public Financing. Table H-12 presents capital requirements for the base case, both with and without internal energy generation, when investors choose no equity participation. In moving from 25 percent equity in the base case to a zero equity position, the bond issue only increases 10 percent; 9 percent for the alternate internal energy case. A break-even tipping fee analysis for zero equity, including not only additional bond payment but other operating expenses as well as revenue, is shown in Table H-13.

TABLE H-12. CAPITAL REQUIREMENTS FOR ZERO EQUITY
1990 DOLLARS ($000) (814)

	BASE CASE	INTERNAL POWER GEN.
Total Constr. Costs	28,862	37,662
Equity	0	0
Bond Cap. Requirement	28,862	37,662
Bond Issue Costs	1,154	1,506
Bond Payment Reserve	0	0
Bond Payment During Constr.	4,618	6,026
Interest Earned on Reserve	0	0
Interest on Bond Payment	462	645
Interest on Constr. Funds	1,530	1,996
Bond Issue	32,642	42,553

TABLE H-13. TIPPING FEE CALCULATION FOR ZERO EQUITY
1990 DOLLARS (814)

	OTHER REVENUE ($1000)	OPER. EXPENSES ($1000)	BOND PAYMENT ($1000)	TIPPING FEE ($/ton)
BASE CASE	4,156	5,937	3,306	48.90
BASE CASE with INT. ENERGY GENERATION	4,400	4,249	4,310	40.00

H.3.2 High Solids Systems

While the economics of the Dranco process depend mainly on the revenues obtained from the sale of electricity, the overall investment is comparable to aerobic in-vessel-composting systems complete with controlled fermenters for close control of odors (290). With a net electrical production of approximately 150 kWh per Mg of incoming organic refuse, equal to about $10 (1987 U.S.), the Dranco process can also produce, from the same feed material, nearly $4 of compost. The net operating costs per Mg of organic refuse are similar to those for aerobic windrow composting, ranging from $8 to $10.

The capital cost of the Valorga facility in La Buisse, France in 1985 was 16,000,000 francs (156). Much of the cost of operating the plant was off-set with revenues from the sale of biogas and compost. Biogas was sold untreated to a nearby industrial facility for 35 francs per tonne delivered to the plant. Digestate was sold for 200 and 600 francs per tonne, respectively, for bulk and bagged material (156, 812). Recovered ferrous metal was sold for about 15 francs per ton of metal. For each tonne of material handled at the facility, the sale price for steam was 79 francs (156).

The high solids anaerobic digestion/aerobic composting process developed at UC Davis, is being proposed as an integral part of a proposed 1,000 TPD municipal waste recycling facility at the California Prison Industry Authority (PIA). According to an independent engineering report commissioned by the PIA, the process demonstrated technical feasibility and favorable economics (854).

A summary of all major costs, mass balance and general systems specifications are presented in Table H-14 for the University of Florida's Sequenced Batch Anaerobic Composting Process (852). The minimum economic system capacity, as determined by 1990 tipping fees in the $30/T range, is 30 TPD based on a 7 day per week operation. It is noted that economics are highly dependent on the biodegradability of the feedstock and opportunities for use of the compost residue as a soil amendment.

H.4 ENERGY ASSESSMENT

An important part of DOE's plan to accelerate the environmentally acceptable conversion of MSW to energy is the use of biological processes. Biomass conversion of the organic fraction of MSW holds the potential for recovering approximately half of the heating value in the fuel, while achieving a substantial volume reduction, with minimal environmental impact. Anaerobic digestion of MSW is capable of producing 10 to 14 ft^3 per pound of biodegradable organic material fed in (850), with nearly all of the original energy residing with the methane gas produced during the bioconversion process.

TABLE H-14. SEBAC SYSTEM DATA SUMMARY (852)

A. General		
Average MSW Throughput:	49 tpd, 5 days/week (equivalent to 35 tpd, 7 days/week)	
Population Served:	15,000	
Gas Production:	206,000 scf/day @ 550 Btu/scf or 113 MMBtu/day (7 days/week)	
Anaerobic Composting Equipment:	5 tanks, each 25 ft in diameter and 38 ft tall	
B. Mass Balance	*tpd (7 days/week)*	*% of MSW tpd*
Inputs:		
MSW Input	35	100
Wastewater Added	6	18
Outputs:		
Recyclables Recovered	5	15
Converted to Gas	9	26
Compost Produced	20	58
Rejects Landfilled	7	19
C. Economics		
Capital Cost (1990)		$1,600,000
1. Total Annual Cost (debt and operation)		$469,500/yr
2. Income from Gas Sales @ $3.0/MMBtu		$124,000/yr
3. To be financed with tipping fees (1-2)		$345,300/yr
4. Tons of MSW Accepted Per Year		
35.3 tpd x 365 x 0.9 (Service Factor) =		11,596 tons/yr
Tipping fee required (3 ÷ 4)		29.8/ton MSW

H.4.1 Conventional Systems

Chynoweth and Legrand (450) developed a typical mass balance diagram for a conventional MSW anaerobic digestion process operating at 500 TPD, as shown in Figure H-12. The mass balance and associated energy balance provided in Table H-15 were calculated from a model designed with kinetics similar to those achieved with the RefCoM project. To reduce the volume of residue to be disposed and thus improve project economics, combustion with the generation of power in the form of process heat and electricity were assumed. The data indicates that approximately 45 percent of the gross energy contained in MSW can be recovered as a substitute natural gas (SNG). Due to the low moisture content of the MSW feed, process heating needs are minimal.

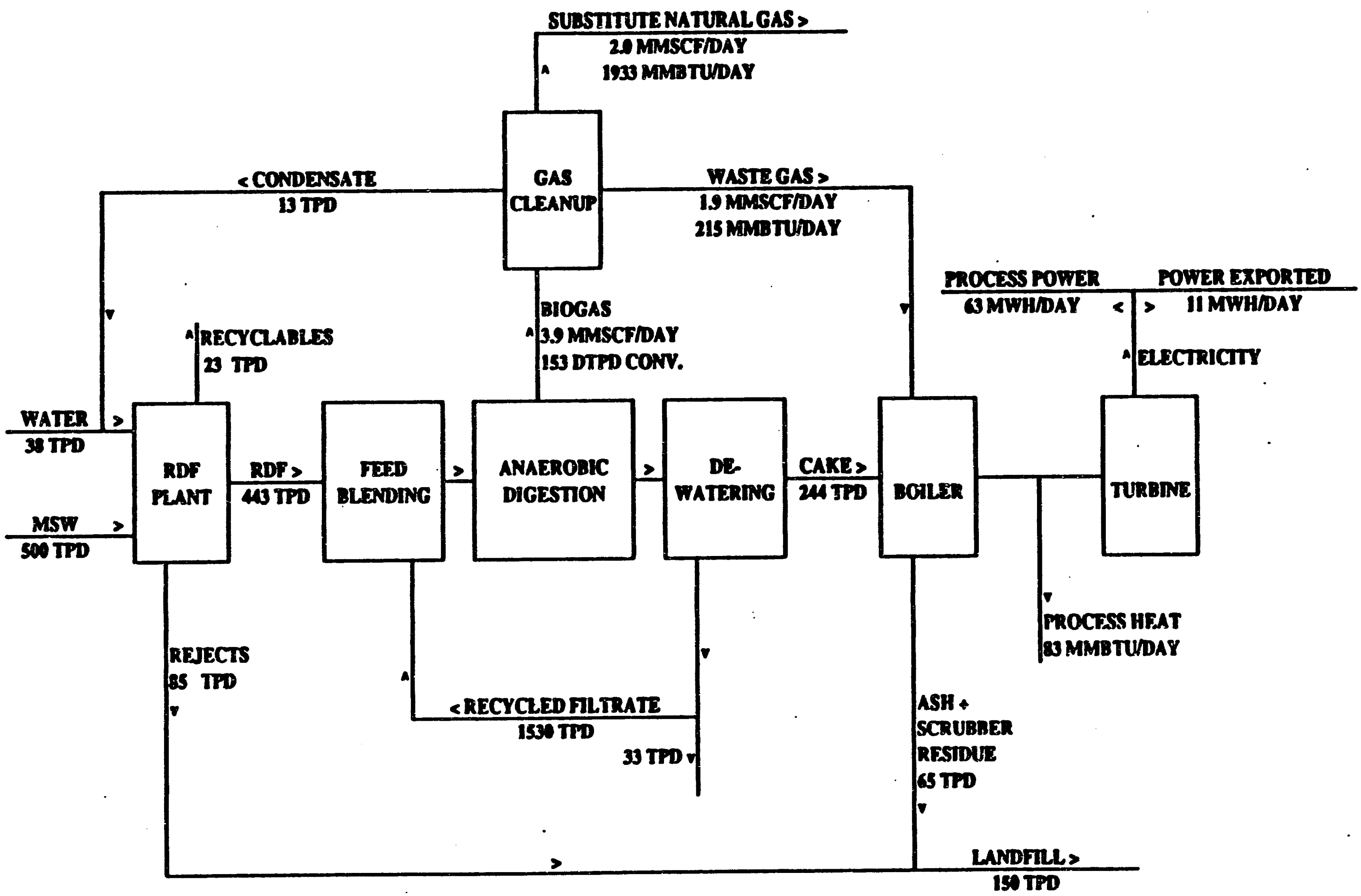


Figure H-12. Typical MSW Anaerobic Digestion System Mass Balance (450)

TABLE H-15. TYPICAL ENERGY BALANCE (450)

	MMkJ/Day	% Gross Biogas Production
MSW Input (approx)	4750	209
Gross Biogas	2266	100
Net SNG	2040	90
Process Heat	88	3.8
Process Electricity	228	10.0
Net Excess Electricity	40	1.8

Electrical power needs are substantial, being equivalent to 10 percent of the energy contained in the total biogas stream. The main electricity consumer is the gas cleanup system where biogas is compressed along with a recycled gas stream which is equivalent to 80 percent of the biogas stream. Savings could be achieved if the operating pressure of the system and the recycle amount could be reduced. Chynoweth and Legrand suggest that a pH/pressure swing system using the digesting slurry to strip off carbon dioxide could have a large impact on savings. The mixing system also consumes a large amount of electrical power. Chynoweth and Legrand note that use of an unmixed reactor would reduce this electricity consumption component by a factor of ten.

Based on the results of the RefCoM field tests and an extensive evaluation of the MSW separation system, Isaacson, Pfeffer et al (814) developed a detailed computer model for a 400 TPD (2000 TPW) facility to calculate mass and energy balances and generate system economic data for the 1990 timeframe. The principal difference between the RefCoM facility and the full-scale plant was the addition of an incinerator to reduce residue volume and to recover additional energy for the heat and electric power needs of the process. Also, the MSW separation system was designed to provide for ferrous and aluminum recovery streams, as well as three other streams: an organics-rich, biodegradable stream for feed to the digester, a combustible oversize for feed to the incinerator, and an inorganic (inert) stream to be landfilled. The model also assumes colocating the facility with a wastewater treatment plant thus minimizing sewage sludge transportation costs as well as allowing for disposal of any excess process water. A mass balance on the overall system is provided in Table H-16. The reduction in weight of disposed material is 83 percent, with a volume reduction calculated at 92 percent.

TABLE H-16. RefCoM SYSTEM MASS BALANCE (814)
(tons/week)

	Input MSW	Sludge	Mater Recov	Gas Streams CH_4/CH_2	Gas Streams Flue Gases	Land-fill	WWTP (water)
Biodegradables	1130.0	70.0	0.0	524.3	619.4	14.0	42.7
Combustibles	204.0	0.0	0.0	0.0	190.5	13.3	0.0
Inerts	287.0	30.1	24.5	0.0	0.0	263.2	29.4
Water	379.0	3236.8	0.0	83.3	704.1	41.3	2786.7
Total	2000.0	3336.9	24.5	607.6	1514.0	331.8	2858.8

The MSW separation equipment includes a shredder, screens, air separators (air knives), air stoners, ferrous and aluminum recovery systems, and associated conveyors. The separation processes were assumed to operate 8 hours per day, 5 days per week. The energy demand for the separation process was estimated at 647,880 kWh per year.

The significant electrical consumers are the gas cleaning and compression system (13,234,000 kWh/year), the reactor mixers (2,505,800 kWh/year), and the incinerator (3,176,300 kWh/year). These units were considered to operate continuously while the balance of the processes, except for the MSW separation system, operate 16 hours per day, 7 days per week. The energy demand for the overall system (including MSW separation processes) was given as 21,178,000 kWh per year (814).

Mass balances were also calculated for the digestion and incineration processes. A retention time of 12 days results in a biodegradable solids reduction of 65 percent. Methane production is 1,011,000 scf/day and carbon dioxide production is 933,000 scf/day. The feed slurry solids concentration is 12 percent and the destruction of solids in the reactor results in a reactor slurry solids of 6.8 percent. The digested slurry is dewatered and the filtercake (along with the combustible oversize from the MSW separation system) is fed to the incinerator.

The combustion process converts 116 TPD of combustible solids to carbon dioxide and water and evaporates 100 TPD of moisture. Allowing for heat to evaporate the moisture and the heat losses in the incinerator, about 1.1 x 10^9 Btu/day are available for recovery. Process heat requirements and reactor heat losses account for 0.15 x 10^9 Btu/day resulting in 0.95 x 10^9 Btu/day available for recovery. The heat available as excess steam is approximately 38,550 pounds/hour. The steam could be sold to other industrial steam users, used to drive in-plant machinery (compressors, mixers, etc) or used to generate electricity for in-plant use and/or sale. The potentially available generated power is estimated as 5650 kw.

H.4.2 High Solids Systems

The dry anaerobic composting process; DRANCO, was installed at a solid waste treatment plant in Gent, Belgium where a 1-year feasibility program was conducted. Energy usage requirements were not provided in the literature reviewed. However, it was noted that the electricity produced was sufficient to meet the needs of the complete waste facility with 50 percent remaining for sale to the electric utility. The waste heat from the engines (running on the biogas produced) was used to heat the digesters and to dry the filter cake solids. The gas yield per ton of organic fraction amounted to 180 m^3 of biogas with a methane content of 55 percent. The net electrical production for export was provided as 150 kWh per metric ton of the incoming organic fraction of MSW (290).

The DRANCO process also produced a humus-like product, Humotex, whose quality and hygienic aspects were superior to conventional compost. The energy implications of compost use are discussed and referenced in Appendix G, section G.3.

Figure H-13 provides a material and energy balance for the Valorga process (812). The process produces an average of 140 m^3 of biogas (methane content of 60 percent) per tonne of material fed into the digester. Energy usage requirements were not provided in the literature reviewed. Approximately half of the organic matter loaded into the digestion system is transformed by methanization, with much of the remainder in the form of a stabilized digested effluent. After refining, this effluent has been sold as a soil conditioner ((812). The potential energy savings using this product as a replacement for conventional inorganic chemical fertilizers is noted in Appendix G, section G.3.

According to one account, the Valorga process produces approximately 710 kWh of non-scrubbed biogas and 375 kWh of high calorific (useful) heat per tonne of household refuse (156). This corresponds to approximately 50 percent recovery of useful energy from feed from this process.

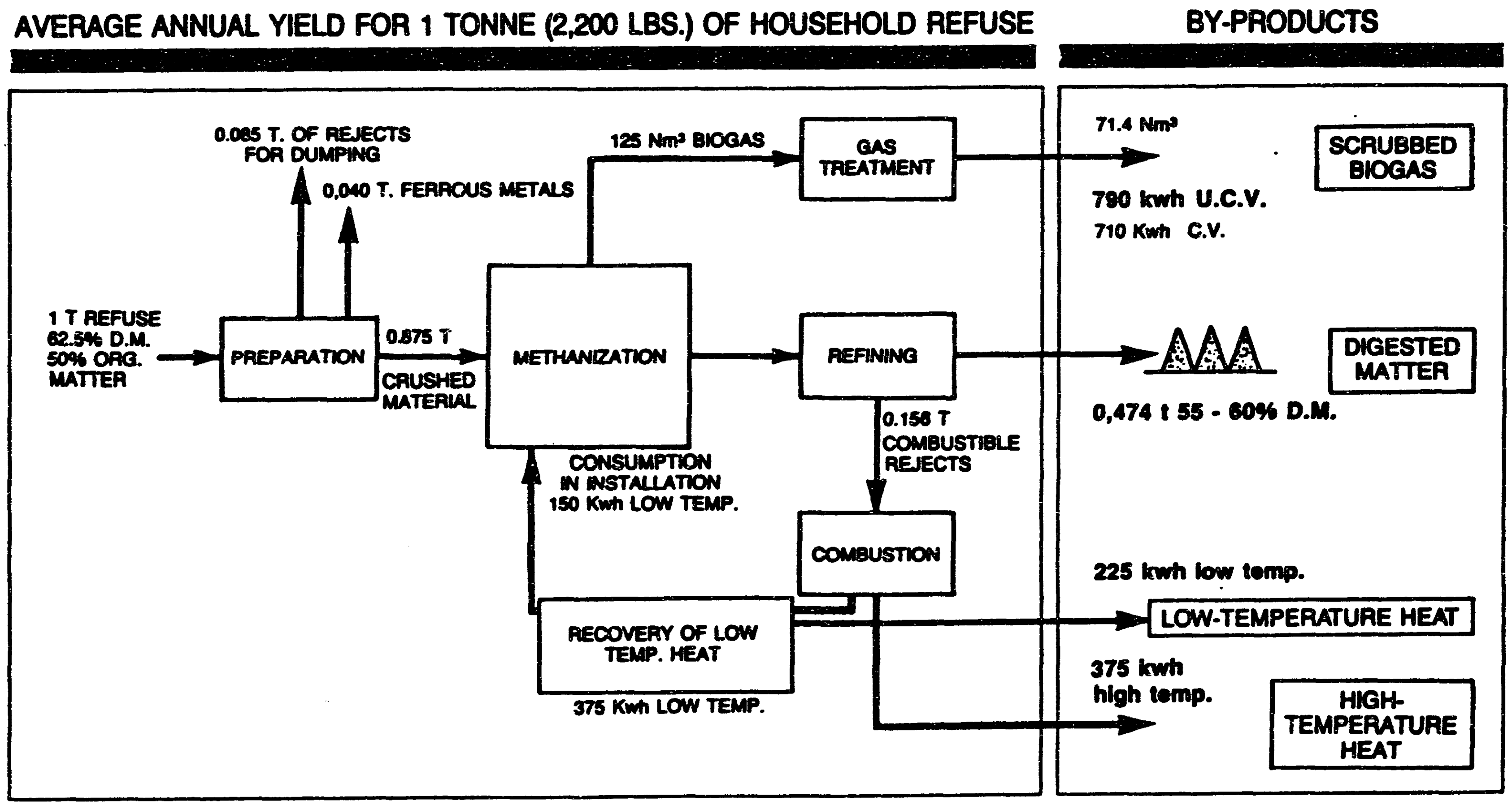


Figure H-13. Valorga Process Matter and Energy Balance (812)

The high solids anaerobic digestion/aerobic composting process developed at the University of California at Davis is reported to have thermal recovery potential from the biogas produced and the solid fuel (compostable fraction) whose heating value is 6360 Btu/lb (850). The developers also suggest the possibility of converting the methane into methanol as a source of fuel.

The nominal economical size of 35 TPD (7 day/week operation) for the University of Florida's sequenced batch anaerobic reactor is projected to yield approximately 206,000 scf/day of methane with a heating value of 550 Btu/scf, or 113,000 MMBtu/day (852).

H.5 ENVIRONMENTAL RELEASES/IMPACTS

Although they have not been studied, the environmental impacts of anaerobic digestion of the organic fraction of MSW are generally considered to be minimal, compared to other MSW management options. Air emissions, especially odors, are minimized as a result of the isolation of the process from the ambient environment. Leachate from the digesters are typically used to inoculate the incoming feed materials to assure optimum anaerobic activity. Pathogenic bacteria in the solids produced from anaerobic digestion are virtually non-existent. An additional environmental benefit (as discussed earlier in Section H.2), is the considerable volume reduction (on the order of 50 percent) of these materials compared to their normal compacted volume in a landfill.

H.5.1 Conventional Systems

Anaerobic digestion systems have the potential to convert up to 50 to 60 percent of the dry solids to gas, thereby significantly reducing the quantity of MSW that must be disposed by other means. Further, the front-end process can remove most of the metals and plastics that can contribute to emissions. The filter cake from an anaerobic digestion process typically has a 15 percent ash content compared to 25% for MSW and requires only 40 to 50 percent excess air compared to 80 to 100 percent for MSW (450). Collectively considered, these factors mean that an anaerobic digestion facility will generally result in two to four times fewer atmospheric emissions than an equivalent mass burn facility. For specific pollutants such as chlorine compounds and hydrocarbons, up to 20 times fewer emissions may be released (450).

H.5.2 High Solid Systems

The environmental releases and/or impacts from the Dranco process are considered to be minimal (290). Odors are minimized because the system is isolated from outside air and wastewater is not produced but rather recycled as an inoculum. The hygienic stability of the compost product (Humotex) is demonstrated in Table H-17 (290). Comparison of the population of potentially pathogenic bacteria in the Humotex after 3 weeks of digestion with aerobic compost after 4 months of curing, demonstrates the absence of fecal contamination in the compost product.

TABLE H-17. HYGIENIC ANALYSIS OF VARIOUS TYPES OF MSW ORGANIC MATERIALS (Colony Forming Units/g Material) (290)

MSW organic fraction	Fresh organic fraction	Humotex		Aerobic compost after 4 months stabilization
	(a)	(a)	(b)	(b)
Yeasts			7x10	4.0×10^5
Fungi			<10	3.0×10^8
Fecal coliform	3×10^3	0	<10	2.0×10^2
Fecal strepto-cocci	2×10^5	0	<100	4.0×10^4
Salmonella (+ or -/25 g DM)			-	-

(a) own results
(b) TNO : independent Dutch research institution

From the French Valorga methanization-from-MSW process, a digestate, Nutrisol 38, is produced for use as a nutrient for plants and gardening. In order to evaluate the possible risk exposure of Nutrisol 38, a study was performed in 1987 by the Physiological and Applied Microbiology Laboratory of the Universite Lyon (156). The findings of researchers placed the bacteriological risk no greater than that associated with aged manure. Also, through the chemical action of chelation by the humic and fulvic acids in the organic matter, the risk of heavy metal transfer to the environment from metals in the digested materials is claimed to be minimized (812).

The rotating drum pyrolytic furnace which serves as the combustion unit in the Valorga process, is claimed to minimize the production of highly-alkaline ash and begin neutralizing the fly ash. A neutralization-scrubber unit follows using a solution of water mixed with 40 percent to 80 percent ash from the furnace combustion to neutralize the flue gas (156).

No detailed environmental data were revealed from the literature for the high solids anaerobic digestion/aerobic composting process developed at UC Davis, although emphasis was placed on the low emissions that are attendant with combustion of methanol, compared to other, alternative fuels (850).

Since mature leachate produced in Stage 3 of the sequenced batch anaerobic reactor (SEBAC) developed at the University of Florida is completely recycled as inoculum for Stage 1 operation, and the biogas, which is generated from the organic fraction of MSW, is relatively "clean", environmental problems are expected to be minimal.

With respect to phytotoxicity issues relating to the compost quality, University of Florida researchers claim that pathogen kill, based on partial results of phytotoxicity tests, is as complete for the SEBAC anaerobic process as it is aerobic systems in general (851).

H.6 SUMMARY

H.6.1 Status

Although anaerobic digestion processes have been in use for well over 100 years, interest in biomass to energy conversion, including MSW, has developed over the past 30 years. Since the first formal experiments of Golueke, several process improvements have been made adding to the collective experience, virtually all of which is at the pilot scale. While technical and economic feasibility studies point to the potential of anaerobic digestion as a viable MSW management technique, sustained experience in day-to-day operations on a large scale, combined with proven markets for the products produced, is essential to its overall competitiveness.

H.6.1.1 Technology Development

Anaerobic digestion offers the potential to convert the organic fraction of MSW into methane using less energy than aerobic systems while also achieving a volume reduction of the solids being processed. One of the important benefits to anaerobic digestion considered singly or in combination with other MSW management options will be its ability to produce methane that is economically competitive with natural gas. Overall, the reactor design needs to be simple and compact to minimize downtime, maintenance and capital costs; require minimum energy to operate; and deliver high gas production rates.

Traditional methods of MSW anaerobic digestion, borrowed from wastewater treatment technology, feature a continuously stirred reactor where the stirring action of the mixer enhances the contact of organisms with feed promoting homogeniety of contents and inhibiting agglomeration. Its drawback is the large digester volume required to accommodate the relatively low suspended solids concentrations and high retention times. This basic technology was employed in the RefCoM proof of concept demonstration plant.

Virtually all of the other pilot and laboratory research projects reviewed employed the high solids anaerobic fermentation approach characterized by plug flow and solids mixing. Available kinetic data predict that gas production rates will increase with solids concentration in the reactor. At higher solids concentrations, the reactor can be smaller, thereby improving the economic attractiveness of anaerobic digestion. The downside is that the higher density solids slurry is very viscous and requires vigorous mixing. Projects that have used this approach include the SOLCON reactor tests at Disney World in Florida, the Dranco process in Gent, Belgium and the Valorga process, in La Buisse, France.

In addition to the research being coordinated internationally through the Task IV of the Bioenergy Agreement of the International Energy Agency, the research funded in the United States in the public sector is under the general sponsorship of the Department of Energy. Working through DOE's Energy from Municipal Waste Research Program, the National Renewable Energy Laboratory continues to manage innovative research in several key areas. These include:

- Increasing solids loading in order to take advantage of reduction in reactor size, without performance degredation

- Decreasing solids residence time in the reactor through improved mixing techniques

- Improving conversion efficiency and reactor stability by identifying, characterizing and optimizing growth conditions for microoganisms best suited for various types of anaerobic digestion and products

H.6.1.2 Economics

Virtually all of the capital and operating cost information in the literature relates to pilot systems which when scaled up may have very different economics at the commercial scale. One study projected that the levelized capital costs of a commercial scale of the RefCoM conventional anaerobic digestion technology are similar to a conventional mass burn facility. Another study provides a detailed analysis of the economic sensitivity of tipping fee and equity financing on conceptual plant costs, based on the RefCom proof of concept experience. "Actual" required tipping fees projected by the RefCom economic model and based on required financial return parameters, are in the $40 and $50 per ton ranges.

An economic study of the Dranco high solids anaerobic digestion system suggests that the capital requirements are essentially equivalent to in-vessel composting with similar levels of environmental control in each design. Projected economics of other high solids anaerobic digestion/aerobic composting systems in the research or near-term pilot stages suggest that breakeven tipping fees in the range of $30 may be possible; actual tipping fees would naturally depend on the level of financial return required. The economics for combined anaerobic digestion/aerobic composting systems are highly dependent on the biodegradability of the feedstock, the value of biogas produced and the opportunities for use of the compost residue as a soil amendment.

H.6.1.3 Energy Implications

As part of DOE's plan to promote the environmentally acceptable conversion of MSW to energy, the use of biological processes holds the potential for recovering nearly half the heat value in MSW while achieving substantial volume reduction. From the RefCoM experience, it was noted that the main electricity consumer is the biogas cleanup system; the mixing system also requires a large amount of electricity. Anaerobic digestion of MSW can produce 10 to 14 ft^3 of biogas per pound of biodegradable organic material from MSW fed in, with nearly all of the original energy residing with the methane produced. Therefore, maximum energy utilization is achieved when the gas requires minimum cleanup and is combusted onsite.

At the experimental test unit, located at Walt Disney World, Florida, a stream of 93 percent pure methane was produced directly from the SOLCON digester without any ancillary cleanup of the gas. If a full scale system could produce that pure a methane product, gas cleanup cost for removal of CO_2 and H_2S could be reduced by more than 80 percent (851). Some developers also suggest the possibility of converting the methane into methanol as a source of fuel.

H.6.1.4 Environmental Issues

The environmental impacts of anaerobic digestion of the organic fraction of MSW, although not reported in the literature reviewed, are generally considered to be minimal. Based on limited tests and model simulations, air emissions from the combustion of anaerobic digester sludge are expected to be less than from a comparable mass burn facility. This is due to: the lower ash content of the RDF from which virtually all inorganic materials have been removed prior to anaerobic digestion; the lower excess air, due to the smaller volume to be combusted after reduction of solids during anaerobic digestion; and the reduced presence of certain emissions associated with the inorganic portion of the MSW, which is removed prior to the digester.

Odors are generally minimized because the anaerobic digester system is isolated from the outside air; wastewater is not produced but rather recycled as an inoculum. Also the hygienic stability of the compost product is minimal -- comparable to that posed by animal manure and much lower than aerobically produced compost.

H.6.2 Integration With Other Technologies

The MSW anaerobic digestion systems discussed in this appendix, whether commercially available or at pilot or laboratory scale, require an organic-rich feedstock, devoid of contaminants. Whereas the larger systems may be slightly more forgiving in accepting non-homogeneous organic materials, anaerobic digestion is much less tolerant of inorganic contamination that cannot be bioconverted. Since plastics, glass, metals and other inorganic materials constitute a sizable portion of typical collected refuse, a highly efficient, multi-staged materials separation or preprocessing system is an essential first step.

The RefCoM anaerobic digestion process, while it clearly demonstrated proof of concept, experienced extended downtime due to problems in preprocessing the MSW feedstock. While the preparation of RDF from MSW had been demonstrated for dedicated RDF and co-fired boilers, separation of contaminant-free organic feed for anaerobic digestion proved more difficult. After several modifications, these problems were overcome.

Other case studies presented and research projects reviewed, also stress the importance of using clean organic feedstock. Experiments with the sequenced batch anaerobic composting process at the University of Florida used hand-sorted MSW from Sumter and Levy Counties, as described in the footnotes in Table H-6. Particular attention was paid to homogeneity of organic content and material size.

For a planned 100 TPD pilot project at the Prison Industry Authority in Folsom, California, the University of California at Davis is conducting a laboratory pilot study using a carefully controlled combination of newsprint, office paper, yard waste and food waste. The actual pilot project, which is to predate a future 1,000 TPD plant near San Diego, can justify testing such a controlled infeed composition because of the plentiful labor force (viz, 80 inmates) available at the prison for materials sorting at a nominal cost. The full-scale facility will draw from a workforce of 800 inmates who, as in the pilot project, will hand sort virtually every constituent of the incoming MSW to ensure a clean organic feed for the anaerobic digester.

In terms of integration with other MSW management approaches, this appendix describes anaerobic digestion in combination with:

- Materials separation to produce a contaminant-free organic MSW feed suitable for anaerobic digestion

- Aerobic composting of the organic fraction of MSW to produce a high quality compost potentially suitable as a soil amendment or in pelletized form that can be co-fired as fuel

- Methane gas combustion onsite or cleanup for sale and combustion locally or sold directly to an SNG pipeline network for general distribution

- Combustion of the filtercake produced, either in a conventional boiler or a pyrolytic furnace.

In addition, feedstock preparation as a materials separation process is certainly compatible with recycling and the production of RDF, if suitable markets exist. This last point underscores the importance of integration in general.

Comparison of its commercial-scale technoeconomic feasibility with other MSW management options is difficult as long as anaerobic digestion of MSW remains unproven in day-to-day operation. Further, the quality of the products (mainly biogas) must be economically produced and require minimum additional cleanup to be competitive with conventionally produced fossil fuels.

APPENDIX H. ANAEROBIC DIGESTION OF MSW
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