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ADVANCED SYSTEM EXPERIMENTAL FACILITY - SOLID WASTE TO METHANE GAS: BACKGROUND AND PROCESS DESCRIPTION

by

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ABSTRACT

The Refuse Conversion to Methane Facility in Pompano Beach, Florida, a 100-ton/day experimental plant to convert municipal solid waste (MSW) to methane for fuel, has been built and is being tested. The facility has been designed to assess the technical merit of anaerobic digestion of the MSW process. Approximately 40 ton/day of volatile solids are fed to the digesters; of this, about 25 ton/day will be converted to gases. For each pound of volatile solids destroyed, 6.6 std. ft^3 of methane gas and 6.6 std. ft^3 of CO_2 will be produced. Thus, the plant will yield approximately 330,000 std. ft^3/day each of methane and CO_2.

This project provides a critical test of the most important process variables, thus allowing judgments to be made on scale-up considerations. The successful operation of this facility will yield information with a significant impact on potential commercial-scale plant developments.

The background and theory involved in applying this technology to MSW, as well as details of the specific process line, are presented.

1 INTRODUCTION

Anaerobic digestion technology has long been used for the stabilization and disposal of wastes. In the past, it was employed mainly for the treatment of sewage solids; however, due to the national energy situation, there has been recent interest in using anaerobic digestion not only as a disposal method, but also as a means to produce methane, a fuel gas.

The Refuse Conversion to Methane (RefCoM) Facility in Pompano Beach, Florida, has been designed and constructed, and is being tested, to demonstrate the anaerobic digestion of municipal solid waste (MSW) to methane. The scale of this facility is such that the technical issues facing a full-scale plant can be considered.

The advancement of a technology to convert refuse material to methane is justifiable since such a technology will reduce the amount of waste solids for disposal and produce a desirous gaseous fuel. Economically, it is expected to produce this gaseous fuel at a cost competitive with that of mined natural gas.

2 BACKGROUND

The Methane Fermentation Process

The methane fermentation process is an established technology that has been employed for decades to stabilize the organic sludges produced in wastewater treatment. These sludges are processed in a heated and mixed anaerobic reactor where organic carbon and the associated hydrogen and oxygen are converted to methane and carbon dioxide. Methane fermentation consists of three basic steps. First, organic solids, primarily polymers of carbohydrates with some lipids and proteins, are hydrolyzed by microorganisms that produce the appropriate exoenzymes. The products of this hydrolysis are soluble monomers that are fermented to various intermediate products. Second, these intermediates are processed further by a group of microorganisms that are referred to as the "acetogenic" bacteria, which produce acetic acid, hydrogen, and carbon dioxide. Finally, the "methanogenic" bacteria complete the process by cleaving acetic acid to methane and carbon dioxide and by using the hydrogen produced by the acetogenic bacteria to reduce carbon dioxide to methane.

The methane formed in this last stage, being relatively insoluble in water, escapes to the gas phase. It can be collected and used for its fuel value. Essentially all water pollution control plants use this gas for heating the fermentation tanks or digesters. Many water pollution control plants have sufficient gas to power internal combustion engines that drive pumps and compressors; however, this practice is not widespread and much available energy is lost through flaring.

The carbon dioxide evolved partially escapes to the gas phase. However, carbon dioxide is relatively soluble in water and is chemically reactive with any basic (OH^-) substance. Therefore, a portion of the carbon dioxide remains in the water either as the soluble gas or as bicarbonate (HCO_3^-). The carbon dioxide content, and, hence, the fuel value of the gas, will be a function of many factors, including fermentation pH, bicarbonate concentration, fermentation temperature, and substrate composition.

Methane Use

Gas produced from methane fermentation systems has been used for decades in the United States, European countries, India, China, and other nations. Gas produced from sewage sludge digestion has been a source of heat for digester heating as well as for power for on-site use. Historically, this gas has been used extensively in Europe. Tietjen[1] presents a review of the many uses of this gas; e.g., power production, street lighting, motor vehicle fuel, etc. The gas produced from sewage sludge digestion was used for street lighting in England in the late 1800s. Tietjen refers to a report showing that in 1951, 16 million m^3 of sewage gas was produced from 48 sewage treatment plants in West Germany. The gas was used in the following manner: 3.4% for power production, 16.7% for digester heating, 28.5% for the municipal gas supply system, and 51.4% for motor fuel use. Much of the gas presently being produced is flared.

The application of this process to solid waste in the United States was first investigated by Babbitt et al. in 1936.[2] The introduction of the home garbage grinders posed the question of the compatibility of these solids with the anaerobic digestion process. To answer this question, a series of experiments was undertaken using a mixture of garbage (food wastes) and sewage sludge as the substrate for laboratory fermentation systems. The results clearly showed that the garbage was amenable to methane fermentation.

Ross[3] reported on the dual disposal of garbage (food waste) and sewage sludge in Richmond, Indiana. In this process, the garbage was shredded and, after washing for grit removal, pumped to an enlarged sludge digestion system. This digestion system was operated in the mesophilic temperature range. The process worked satisfactorily and the gas was used to provide the power for operation of the water pollution control plant. The author reported a net profit from the operation of this system.

Although this system was successful, it was not adopted at other locations for garbage disposal. After a number of years of successful operation of the Richmond plant, the process was discontinued. There were several reasons for this. Extensive natural gas supplies were being developed at very low prices. Therefore, the economic incentive for using the digester gas, a somewhat lower quality gas, was lacking. Furthermore, the characteristics of the garbage were changing. Because of developments in the food processing industry, the quantity of food waste was decreasing and more food was receiving preparation before distribution. In addition, the quantity of packaging material (paper and plastics) was increasing, and paper, plastic, cans, and bottles were assuming a much larger percentage of the refuse. The inability to separate the garbage and other biodegradable organics from these constituents and the inconvenience of having the producer involved in source separation essentially eliminated this process for solid waste disposal.

With natural gas priced so low, it was far less expensive to haul the solid waste to a "dump," rather than to process it for energy or material recovery. The passage of legislation in 1965 to provide money for research into processes for disposal of solid waste initiated a new round of research efforts. This research activity was on two fronts. First, several research groups started to study processes that would separate various components of solid waste. This research generally investigated existing technology to determine what modifications were needed to process urban solid wastes. Since an existing technology was being modified, progress was rapid. Within a few years, large-scale material recovery systems were being constructed. The U.S. Environmental Protection Agency (EPA) demonstration project with the city of St. Louis and Union Electric Company resulted in a prototype system for producing a light fraction that was primarily organic material. This light fraction was used as fuel for a coal-fired boiler system. Product specifications were poorly defined, but it was thought that this light fraction would be suitable feed for the anaerobic fermentation system.

Systems developed by the U.S. Bureau of Mines and the National Center for Resource Recovery, Inc. (NCCR) concentrated more on material recovery than on the production of fuel. During this same period, extensive research at Warren Spring Laboratory, United Kingdom, and ENADIMSA, Madrid, Spain, resulted in processes that were very effective in separating various refuse components. The processes developed in Europe required much less power than the U.S. systems. They effectively utilized screens to separate refuse that had been subjected to a minimum amount of size reduction.

A second line of research was initiated with the U.S. Bureau of Mines and NCCR funding. This line concentrated on processes for reducing the amount of organic waste remaining for disposal. Pyrolysis, enzymatic hydrolysis of the cellulose, direct combustion, and refuse-derived fuel were some of the systems investigated. Work was also initiated on the use of methane fermentation as a means of converting the organic carbon, hydrogen, and oxygen into gaseous methane and carbon dioxide. Work was initiated at the University of California in Berkeley on the characteristics of solid waste and on the effect of solid waste on the methane fermentation process. Golueke and McGauhey[4] estimated that digestion of paper accounted for about 67% of the total methane produced from the digestion of refuse. Garbage accounted for only 12% of the biodegradable refuse. The total nitrogen content of urban refuse is extremely low unless some industrial solid waste is contributing nitrogen. Consequently, it was found that supplemental nitrogen from either sewage sludge, animal manure, or other sources was necessary for balanced fermentation. These studies investigated other sources of organic material as a substrate for methane fermentation either alone or in combination with solid waste.

The importance of cellulose and the rate of cellulose hydrolysis in methane fermentation were first postulated by Maki[5] in his study of pure and mixed cultures of cellulolytic bacteria isolated from a municipal sewage sludge digester. A study by Chan and Pearson[6] on cellulose hydrolysis indicated that the hydrolysis of insoluble cellulose to soluble cellobiose appeared to be the rate-limiting step in the anaerobic decomposition of cellulose. They found that the rate could be characterized accurately by the Michaelis-Menten kinetic model and gave the different kinetic constants and coefficients that apply to the fermentation of cellulose.

In 1969, the Bureau of Solid Waste Management of the U.S. Public Health Service (later transferred to the EPA) funded a research project at the University of Illinois in Champaign-Urbana. The objective of this research was to investigate processing conditions that would result in the maximum conversion of refuse to gas. Energy recovery was not a major criterion. The process was simply a means of reducing the cost and the weight and/or volume of solid waste remaining for disposal. Since natural gas was being marketed at less than $0.50 per million Btu, energy recovery was not economically attractive.

The shredded residential refuse that was used in this investigation was obtained from a shredding facility in Cincinnati, Ohio. The study investigated the kinetics of methane fermentation as applied to shredded urban refuse; the results are presented in detail in Refs. 7 and 8. The most significant finding of this study was the effect of temperature on the rate of methane production and the apparent increase in biodegradability at elevated fermentation temperatures. Very high rates of methane production were obtained at thermophilic fermentation temperatures. Retention times of four to five days resulted in high conversion efficiencies. These high rates, coupled with the ability to feed high solids concentrations to the fermentation tanks, resulted in smaller tankage requirements. A favorable heat balance is also possible because of the limited quantity of water processed and the ability to recycle significant portions of the water removed from the fermented slurry.

All of the research that resulted from the 1965 legislation was funded by grants and contracts from the U.S. Public Health Service, Office of Solid

Waste Management. This office was transferred to the EPA after its formation, and their shift in funding philosophy eliminated any new funds for research in this area. During 1972 and 1973, the impending energy problem became well known. The ability of this process to produce a high-quality fuel attracted the interest of the National Science Foundation (NSF)/Research Applied to National Needs (RANN) Program, and the NSF initiated a funding program.

The University of Illinois studies were continued in 1973 with NSF funding. The major emphasis was on process requirements. It was clear that the refuse needed some preparation before fermentation. Size reduction and inorganic removal greatly improved operation of the fermenter. The proposed refuse preparation step included size reduction, magnetic separation, screening, and air classification. The resulting light fraction was slurried with water and pumped to the fermentation tanks.

A major finding of this study was the excellent dewatering characteristics of the fermenter residue.[9] Because of the fibrous nature of the solids, very high filtration rates were possible with a vacuum filter. The slurry also dewatered exceptionally well in a solid bowl conveyor centrifuge. Cake solids between 35 and 40% were obtained from the centrifuge without any chemical addition for sludge conditioning. This greatly reduced the cost of the dewatering step.

The cake from the centrifuge was ideal for incineration. A heat balance for an incineration system showed that auxiliary fuel was not needed if the cake solids were higher than 32%. In fact, a significant quantity of energy in the form of steam is available from this cake. A waste-heat boiler on this incinerator would more than satisfy the heat requirements for the entire plant. Incineration of the cake not only increases the energy conversion efficiency, but also greatly reduces residue disposal cost. Instead of a large amount of wet cake to haul to a landfill, a much smaller amount of dry ash is produced for ultimate disposal.

The centrate or filtrate produced in the dewatering step is recirculated and used as water to slurry the incoming refuse feed. This recirculation greatly reduces the heat requirements for thermophilic fermentation, conserves supplemental nutrients such as nitrogen and phosphorus, and serves as a pH buffer. A portion of the bacterial population is also recirculated.

In addition to the federally funded research previously discussed, Dynatech R/D Company, Cambridge, Massachusetts, started to investigate this process in 1971 under a contract with Consolidated Natural Gas Service Company, Inc., Cleveland, Ohio. Since this was privately funded research, the results were not widely circulated. In 1973, NSF/RANN awarded a contract to Dynatech for an in-depth feasibility study of this process. Dynatech's report showed that the process had potential for development.[10] Based on studies conducted to date, the technical staff at NSF recommended that funds be budgeted for a proof-of-concept experiment. Funds were budgeted and a request for proposal (RFP) was issued in May 1975.

The background work for the RFP initially was funded by the EPA and later by the NSF; the RFP was issued from the NSF. A panel of experts assembled by the NSF evaluated more than 20 responses (Table 1) to the RFP and selected two finalists for a site visit. The decision was made to award

Table 1 List of Respondents to the RFP

Organization	Site Location
Systems Technology Corp.	Dayton, OH
L. Robert Kimball	Monroeville, PA
Ultrasystems, Inc.	Phoenix, AZ
Rechtech, Inc.	Williamsport, PA
Reynolds, Smith, & Hills	Orlando, FL
John R. Snell Engineers, Inc.	Wabash, IN
University of California	Berkeley, CA
Public Service Electric & Gas Company	West Deptford, NJ
Zinder Engineering, Inc.	Michigan State University Campus, E. Lansing, MI
PEDCo - Environmental	Cincinnati, OH
City of Nanticoke	Nanticoke, PA
Institute of Gas Technology	Rolling Meadows, IL
Henningson, Durham & Richardson	Omaha, NE
Battelle Pacific Northwest Laboratories	Richland, WA
Black Clawson Fibreclaim, Inc.	Franklin, OH
Chemico Process Plants Company	Champaign, IL
Citizens Gas & Coke Utility	Indianapolis, IN
Waste Management, Inc.	Pompano Beach, FL

the contract to Waste Management, Inc., Pompano Beach, Florida. During this period, project administration and funding were being transferred from the NSF Fuels from Biomass Program to the newly created U.S. Energy Research and Development Administration (ERDA), Building and Conservation Division. Since ERDA staff had not been involved in the initial evaluation of this system, they requested that the contractor provide additional justification for the study. After considerable effort, the contractor satisfied ERDA, a contract was signed, and the Title I Preliminary Engineering Report was issued in January 1976.

3 REFCOM PROCESS DESCRIPTION

The site selected for construction of the Refuse Conversion to Methane Process (RefCoM) was an operating sanitary landfill. An existing Heil vertical mill with a nominal capacity of 15 ton/h was being used to prepare refuse for landfill without the normally required daily soil cover. The capacity of this shredding station was increased to accommodate a larger volume of refuse. However, the station was not expanded because of construction of the RefCoM facility. With the addition of a Heil vertical mill with a nominal capacity of 62.5 ton/h, the capacity of this site is in excess of 1000 ton/day, operating on the average of five days per week.

Continuous operation of the fermentation system is desirable. However, operating costs will require less than continuous operation for this size processing line. It is planned to operate seven days per week, for one or two shifts, depending on the desired throughput rate. The processing line has been sized to process 100 ton/day of refuse when operated for two shifts per day. Since the refuse from the primary mill is delivered at a rate in excess of 60 ton/h for only five days per week, adequate storage for a seven-day week must be provided.

The process flow sheet and material balance are shown in Fig. 1. This is the maximum rate of throughput for a two-shift/day operation. The line can process 100 ton/day of refuse on an "as-received" basis. A front-end loader retrieves the refuse from storage and dumps it on the pan conveyor, from which it can be fed to the classification building at different rates. Storage on a slab and operator-controlled retrieval were selected to allow better control of the feed rate and better quality of feed.

The primary shredded refuse passes through several processing steps before being fed to the digesters. A trommel screen is used to remove most of the fine inorganic material such as shattered glass, sand, ashes, etc. A second-stage shredder reduces the size of the particles so that they can pass through 3-in. grate openings. A horizontal shaft shredder with a screen is used to ensure a relatively uniform particle size 3 in. or less. From the shredder, the refuse is conveyed to an air classifier. This system produces a "light" fraction consisting of low-density organic material. The high-density inorganic material is landfilled.

The light fraction is passed through a cyclone for recovery of the solids from the air stream. This air is then filtered to reduce the particulate load in the exhaust air from the air separation unit. The quality of

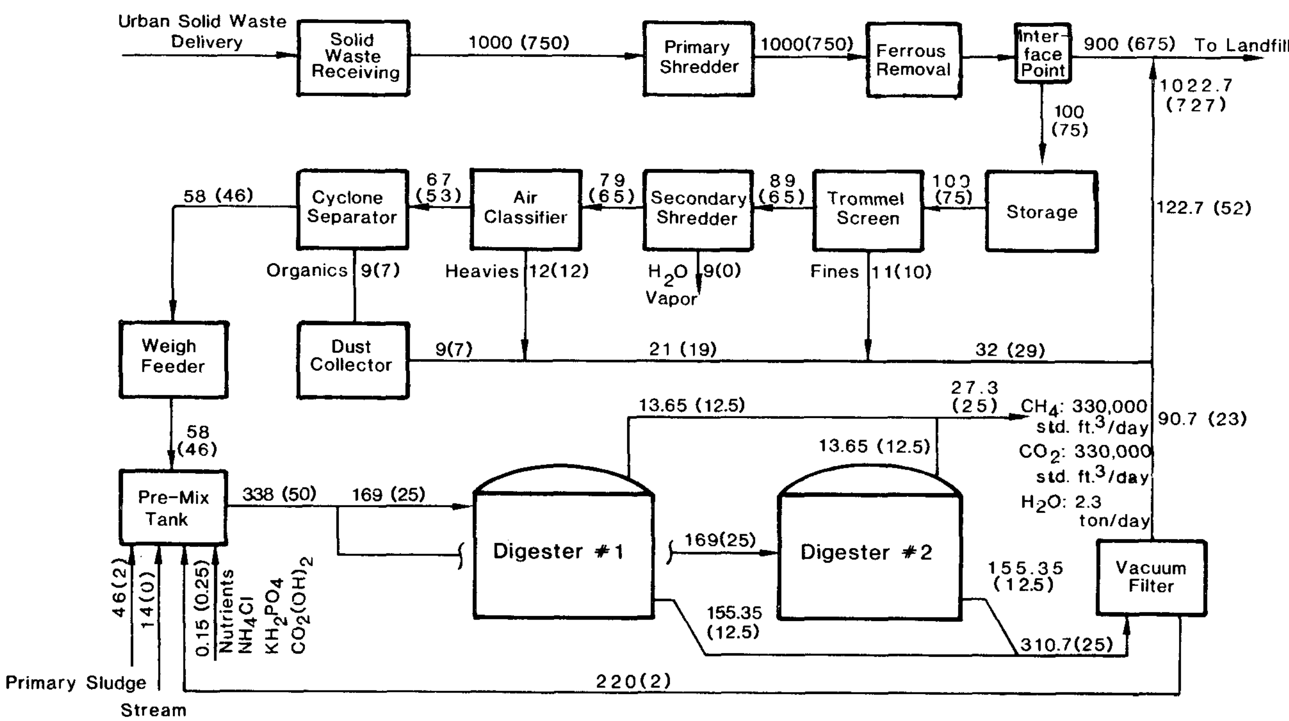

Fig. 1 RefCoM Process Flow Sheet and Material Balance (units are tons/day and dry tons/day unless specified otherwise)

this dust is unknown. If it is primarily organic, a conveyor system will be installed to incorporate this material into the digester feed system.

The separated organic material is conveyed via a weigh-feeder to the premix tank where the digester feed slurry is prepared. Appropriate quantities of makeup water, recycle liquor, sewage sludge, and chemicals are added to prepare the desired feed slurry. Steam is also injected at this point to heat the feed slurry to a temperature greater than the desired fermentation temperature. The excess temperature provides heat to make up for the digester loss. Direct steam injection was selected because of the very poor heat exchange properties exhibited by a slurry that may contain in excess of 10% shredded refuse.

Two 50-ft-diameter digesters, approximately 45,000 ft^3 in total volume, were constructed. Fixed-cover tanks were selected to permit the use of mechanical mixing. A variable-speed mixer with an impeller diameter of 14 ft was selected to keep the digester contents from stratifying. Little is known about the mixing properties of the concentrated refuse slurry. However, it is expected that a speed of 25 rpm will provide satisfactory mixing.

Some of the gas from the digester will be used to provide the fuel for steam generation. The balance will be burned on site in waste gas burners. After the system has undergone the required testing and modification so that a consistent gas supply is available, gas utilization methods will be studied. At the 100-ton/day processing rate, methane and carbon dioxide production is expected to be approximately 330,000 std. ft^3/day for each gas.

The digesters are operated in parallel, each at the conditions specified by the experimental program. A gravity-fed overflow box receives overflow from the tanks. The slurry flows by gravity to the vacuum filter system and can be pumped to other dewatering systems that can be installed for test purposes. For initial cost consideration, a vacuum filter system was installed for dewatering the digested slurry. Preliminary laboratory tests by Pfeffer and Liebman[9] showed that cake moisture as low as 75% can be obtained without chemical conditioning. Filter loading rates greatly in excess of those commonly found in dewatering chemically conditioned sewage sludge can be expected.

In addition to the lower initial cost, the vacuum filter was selected because the distance to the landfill does not require a dry cake. The 122 ton/day of wet cake are simply added to the additional tonnage of refuse being processed at this site.

Filtrate from the vacuum filter is used as makeup water to slurry the incoming dry refuse. This recycle serves to conserve the chemical nutrients (nitrogen and phosphorus), alkalinity, and heat. It also eliminates the need for disposal of a significant quantity of contaminated water. This water can be treated for discharge, but at a significant cost.

Successful operation of the digester is dependent on maintaining certain conditions within the digester. A brief description of the more important conditions follows.

Anaerobiosis

Oxygen is toxic to the methanogens and must be excluded. Although some of the bacteria can utilize oxygen, by doing so, some of the useful energy will be diverted to a useless form. All the oxygen cannot be excluded since a certain amount will be dissolved in the incoming feed. As a rule, this amount can be tolerated with minimal detrimental effects.

pH and Alkalinity

The different groups of bacteria must be maintained in balance. The methanogens must convert the acids to methane at a rate equal to the production of the acids by the acid formers. If this does not happen, the acids will accumulate, causing the pH to drop. When the pH drops out of the relatively narrow range of 6.5 to 7.5, the methanogens will not function well. The alkalinity is a measure of the chemical ability of the digester contents to buffer or to maintain a certain pH.

Temperature

There are two relevant temperature ranges for anaerobic digestion: mesophilic (30 to 40°C) and thermophilic (50 to 65°C). Within each of these ranges, there is an optimum temperature for gas production. This is usually 37 to 39°C for mesophilic and 60°C for thermophilic. Thermophilic temperature will yield much higher rates of gas production than mesophilic temperature. Above, below, and between these ranges, the productivity of the system decreases significantly. Heating costs will be higher for the thermophilic range; however, these costs will be more than offset by the increased production rate and decreased digester volume.

Nutrients

Since this process depends on the viability of a bacterial system, the nutritional needs of the bacteria must be met. The energy source for the bacteria is the organic matter in the feed. The MSW is usually deficient in nitrogen. Nitrogen can be added as a supplement when needed or supplied, at least in part, by sewage sludge additions. Sewage sludge also will provide some of the required mineral and growth factors.

Retention Time

The retention time (RT) is the volumetric turnover rate of the digester contents. For example, with an RT of 10 days, 10% of the digester volume will be replaced each day. In conventional sewage treatment, long RTs of 30 days are employed. In the RefCoM project, RTs as short as five days will be tested. Bench-scale studies show higher volumetric methane production rates (ft^3/ft^3/day) with the shorter RTs; however, this is accompanied by decreased production per unit weight of MSW.

Feed Concentration

The feed concentration (percent volatile solids) has a significant effect on heating requirements and, thus, on operating costs. The more concentrated the feed, the less water there is to be heated. Higher concentrations also will reduce subsequent dewatering costs. However, these benefits must be balanced with the potential cost increases associated with increased mixing and caustic requirements.

Loading Rate

The loading rate is the solids loading per volume of digester per day ($lb/ft^3/day$). It is a function of the RT and feed concentration; i.e., the feed concentration divided by the RT. Inspection shows that different RTs and feed concentrations may yield the same loading rate. While the loading rate is not a process variable, it does provide a ready estimate of the throughput of the system.

4 EXPERIMENTAL PROGRAM

An experimental program has been developed to determine the optimum design and operating parameters associated with the production of methane from MSW; this will result in the maximum net benefits. The primary independent variables and associated ranges to be evaluated are shown in Table 2. These variables will be evaluated in the order in which they are listed. As the optimum condition for each variable is obtained, it will be held constant as the succeeding variable is optimized.

In addition to the above variables, other process options will be evaluated. These will include mixing requirements, effluent dewatering, solids residue utilization, nutrient requirements, and minimization of front-end processing.

Table 2 Primary Independent Variables and their Associated Ranges

Variable	Range
Temperature (°C)	
Mesophilic	35 to 45
Thermophilic	55 to 60
Retention Time (days)	5 to 30
Feed Concentration (percent dry solids)	4 to 10
Particle Size (in.)	1.5 to 3.0
Filtrate Recycle, %	50 to 100

When these studies have been completed, it is presumed that all of the process variables will have been studied adequately so that an optimum process can be defined. It is hoped that the facility can be operated at optimum steady-state conditions for a period long enough to note the inherent variabilities, process sensitivities, or other problems not normally detected during short experimental runs. Sufficient data will be collected throughout the experimental and steady-state operation to allow a critical, technical evaluation of the process.

5 MASS BALANCE

The mass balance for the RefCoM facility is presented in Fig. 1. The landfill facility receives and processes 1000 ton/day of urban solid waste. Table 3 shows the typical composition of this waste.

One hundred tons of shredded MSW (free of magnetic metals) are delivered to the RefCoM facility daily. Of this, 75 ton/day are solids. An additional 29-ton/day total solids are removed by the trommel, air classifier, and cyclone separator. This results in 46-ton/day solids feed delivered to the premix tank. Four ton/day of total solids in the form of primary sludge, filtrate recycle, and nutrients are combined with the 46 ton/day, thus making up the 50-ton/day total solids fed to the digesters. The 50-ton/day are

Table 3 Composition of Urban Waste

Type	As-Received, %	Dry Matter, %
Food	3.2	4.2
Garden	4.3	5.8
Paper	40.9	54.6
PVC, Rubber, Leather	3.3	4.4
Textiles	1.7	2.2
Wood	1.9	2.6
Ferrous Metals	5.4	7.2
Nonferrous Metals	0.9	1.2
Glass, Ceramics	9.0	12.0
Rock, Dirt, Ash	0.1	0.1
Fines	4.3	5.7
Water	25.0	0.0
	100.0	100.0
Total Solids	75.0	100.0
Volatile Solids	50.0	67.0

approximately 80% volatile solids; therefore, 40 ton/day volatile solids are fed to the digesters.

Due to the refractory nature of part of the feed, about 25 of the 40 ton/day of volatile solids will be destroyed or converted to gases. For each pound of volatile solids destroyed, 6.6 std. ft^3 of methane and 6.6 std. ft^3 of carbon dioxide will be produced. Thus, 25 ton/day at 6.6 std. ft^3/lb of volatile solids will yield 330,000 std. ft^3/day each of methane and carbon dioxide.

The undigested residue, about 25 ton/day, will be delivered to the vacuum filter. Most of this will be disposed of as filter cake and about 2 ton/day of the filtrate solids will be recycled to the premix tank.

6 SUMMARY

The RefCoM facility has been constructed to evaluate the anaerobic digestion of MSW to produce methane. The research and events that led to the construction and test program have been discussed. RefCoM is an experimental, not a demonstration, facility; thus, it should be viewed as a research project rather than as a project that will demonstrate how a commercial-scale facility might operate. Many operational and processing problems must be addressed before commercial use of this system. RefCoM is addressing these problems; once they have been solved, the process will be ready for commercial use.

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