Fuel Gas Developments

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Chapter 4

BIOCONVERSION OF CLASSIFIED MUNICIPAL SOLID WASTES: STATE-OF-THE-ART REVIEW AND RECENT ADVANCES

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I. INTRODUCTION

Rising energy costs have created a fresh interest in novel, renewable, but heretofore uneconomical, energy sources. A number of alternate technologies for using these resources have been described, including solar heating, wind and wave energy generation, and biomass conversion.

The importance of biomass is recognized by the many energy conversion processes under current scrutiny such as direct combustion, novel pyrolysis techniques, and fermentation to produce solvents and gases. Anaerobic digestion to produce methane from wastewater-derived sludges is a particularly well-known biomass energy recovery technique in use for over 50 years. The process was traditionally aimed at the stabilization and decomposition of organic waste materials from domestic sewage by conversion to carbon dioxide and methane. In the complete anaerobic dissimilation of organic matter, only CO_2 and CH_4 are formed; about 90% of the original energy in the substrate is retained in the resultant methane gas.[1] This fact, coupled with current interest in renewable energy resources, has refocused attention on anaerobic digestion because of primary interest in energy production and secondary interest in waste treatment or biomass decomposition.

The use of anerobic digestion for fermenting organic matters other than wastewater-derived sludges is not commercially widespread. A number of farm wastes such as cattle and swine manures have been treated in anaerobic lagoons for many years, but this application was strictly for the purpose of waste disposal and not CH_4 production. Only relatively recently has the use of anaerobic digestion for energy production from organic substrates been seriously considered.

Of the many types of organic products generated nationally as waste material (including municipal sewage sludge, industrial wastes, agricultural manures, crops and forestry residues), municipal solid waste (MSW) has gained recognition as a potentially valuable resource, contrary to its customary problematic reputation associated with land fills and incineration. The energy and resource potential of MSW is demonstrated by its heat value (about 4700 Btu/lb as discarded wastes);[2] by the presence of recyclable metals, glass, and fibers; and by its cyclic generation. With the cost of energy continuing to rise and the obvious need for resource conservation, such potentials give MSW increased value.

Municipal solid waste production is a major concern in urban areas. Increased waste production is accompanied by decreased land-fill sites for waste disposal. The ongoing legal, financial, environmental, and societal problems of developing new land-fill sites delay and restrict future uses of land for this purpose. Thus, anaerobic digestion and recycling of MSW as an alternate means of disposal is finding greater interest because of this need.

Anaerobic digestion of classified MSW (garbage and refuse which has been shredded and sorted) has the advantages of reducing the fermentable MSW fraction from 40 to 55% and producing a clean-burning, medium Btu gas (550 to 650 Btu/ft^3), thus avoiding any air quality problems associated with direct MSW incineration. In many urban areas, this can be a major advantage.

The anaerobic digestion of MSW for the purpose of methane formation (methanogenesis) is a technology really in its adolescence. Much of the basic knowledge of anaerobic digestion was developed by wastewater treatment engineers; fermentation of MSW has consequently relied on the traditional anaerobic digestion technology commonly employed in the treatment of sewage and related waste sludges. In this sense, the methanogenic digestion of MSW had some predictable basis as a viable process. This chapter will describe and evaluate the state-of-the-art of methanogenic MSW digestion and present recent advances in laboratory- and pilot-scale studies of this developing technology. One prime target is to establish the conditions for maximum conversion of MSW to methane.

II. STATE-OF-THE-ART REVIEW

Anaerobic digestion has been used for wastewater sludge volume reduction and stabilization for many years. The production of low-to-medium Btu gas from this process provides a portion of the heat and power requirements for the treatment plant. Successful application of anaerobic digestion of wastewater sludges led Babitt et al.[3] to ferment domestic solid wastes by the anaerobic digestion process. However, these early results were generally unsuccessful and consequently application of this process to wastes other than those from wastewater was not pursued for many years.

Interest in the digestion of MSW was revived in the late 1960s, principally because of its potential for energy recovery. As part of a 5-year comprehensive study on solid waste management, Golueke[4] examined the feasibility of digesting "synthetic" MSW with sewage sludge and animal manure. Results showed a high percentage of the organic refuse was anaerobically digested to methane and carbon dioxide. Klein[5] and McFarland et al.[6] investigated MSW "as received" (minimally pretreated by shredding only) by fermenting it in a 400-gal, pilot-scale digester. The effect of the solid wastes on the digestion process and its potential for reducing the bulk of the input material were evaluated. They confirmed Golueke's initial laboratory findings and further demonstrated that a high proportion of the "as received" MSW could be digested with sewage sludge over an extended period of time. The digestion of processed MSW with limited addition of sewage sludge was evaluated economically to determine the cost of methane production using a multistep process of pretreatment, digestion, gas separation, sludge dewatering, and residue disposal.[7] The reactor was a 100-gal thermophilic digester fed processed MSW from 3 geographical locations. Data on the effects on digestion of effluent sludge recycling, nutrient addition, caustic pretreatment of substrate, and the settling and dewatering characteristics of the resultant sludge were used in computer simulation study. The simulation showed that the overall process was cost-effective; credit allowed for refuse disposal was the most sensitive economic factor.

Some private industries and governmental agencies currently working on research in this field include Biogas of Colorado, Cal Recovery Systems, Institute of Gas Technology, Dynatech, Systems Technology Corporation, Southern California Edison, California Energy Commission, and the U.S. Department of Energy (DOE).

Presently, the only large-scale MSW digester in operation is the DOE-sponsored Refuse Conversion to Methane (RefCom) project in Pompano Beach, Fla. This process involves primary shredding, ferrous metals recovery, secondary shredding, trommeling, and air classification. The resulting classified MSW is premixed with raw sludge, nutrients, and water and pneumatically transferred into two mechanically agitated anaerobic digesters. The RefCom facility is designed to process up to 100 ton of MSW per day, and its primary objective is the demonstration of reliable and cost-effective conversion of MSW to methane gas. No data have yet been reported.

A. Anaerobic Digestion Process

Anaerobic digestion is widely employed at most major municipal wastewater treatment plants but is used less frequently in the treatment of industrial and agricultural wastes. Consequently, there exists an abundance of literature pertaining to empirical applications in the sewage sludge treatment field. But, the fundamental microbiological determinants for operational process control were overly simplified mainly because of a poor basic understanding of the microbiology of the fermentation. An understanding of the basic biology of the methanogenic bacteria and their complex microbial interactions will almost certainly yield more reliable engineering designs and operational criteria for methane production.

The basis of the methanogenic digestion process is an interdependent metabolism of

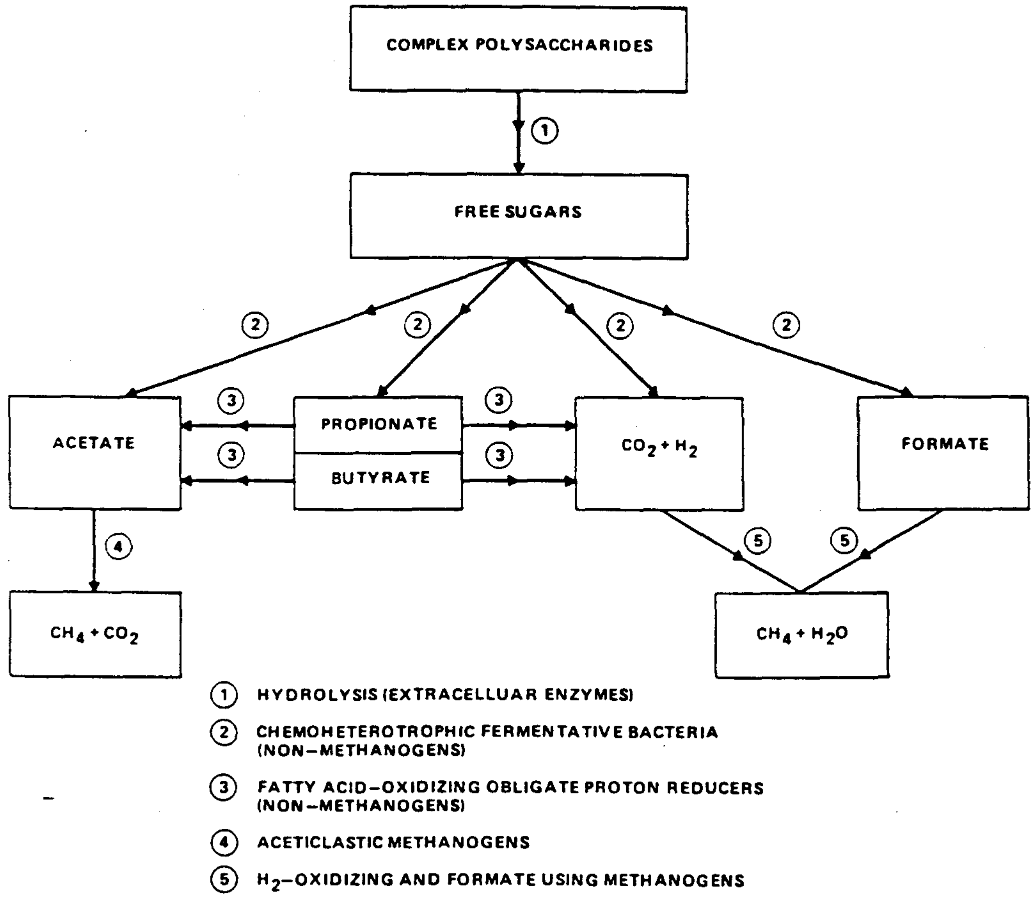


FIGURE 1. Methanogenic degradation of organic matter.

complex substrates mediated by a mixture of facultative and strictly anaerobic bacteria which mineralize organic matter in anoxic environments. The end-products of complete dissimilation of carbohydates, lipids, or nitrogenous organic compounds are methane and carbon dioxide, with only a small yield of microbial cells.

The basic elements involve conversion of complex substrates through intermediate compounds to the terminal products, methane, and carbon dioxide. Figure 1 summarizes the current conception of this fermentation as a series of 3 simultaneous events comprised of 3 interdependent reactions. First, complex organic compounds are hydrolyzed by extracellular enzymes and fermented to hydrogen, carbon dioxide, and smaller organic products, primarily fatty acids. Secondly, these organic intermediates are metabolized by acetic acid producing (acetogenic) bacteria including obligate hydrogen-producing bacteria.[8,9] Finally, the methanogenic bacteria rapidly metabolize hydrogen and carbon dioxide to methane and by doing so maintain a low enough hydrogen concentration to make thermodynamically feasible[8,9] continued oxidation of low molecular weight compounds to acetate, H_2, and CO_2.[10] The acetate generated in these reactions is metabolized by a specialized group of aceticlastic methanogens to CH_4 and CO_2. Acetate is quantitatively the most significant methanogenic substrate in these sludge fermentations. About 70% of the total methane is produced directly from cleavage of the methyl group of acetate to form methane. In a properly operating digester, these bacteria interact in a conjoint metabolic conversion of the starting substrates to CH_4 and CO_2. Careful control of the digestive process is required to maintain proper physiologic balance between the acid-forming, acetogenic, and the methane-producing bac-

Table 1
TYPICAL OPERATIONAL CRITERIA FOR ANAEROBIC DIGESTION, AT MESOPHILIC TEMPERATURE

Criteria	Standard rate digestion	High rate digestion
Solids, detention time, days	30—60	10—20
Solids loading rate		
lb VS ft^3/day	0.04—0.1	0.15—0.40
kg VS/m^3/day	0.65—1.62	2.43—6.48
Volatile solids reduction percent	40—60	40—60
Gas production		
ft^3/lb VS destroyed	12—17	12—17
m^3/kg VS destroyed	0.74—1.05	0.74—1.05
ft^3/lb VS added	8—12	8—12
m^3/kg VS added	0.49—0.74	0.49—0.74

(Adapted from U.S. EPA, Process Design Manual for Sludge Treatment and Disposal, Municipal Environmental Research Laboratory, Center for Environmental Research Information Transfer, EPA 6251, 179-011, 1979. With permission.)

teria. Stable digestion is aimed at maintaining favorable environmental conditions for balanced microbial populations. Control parameters include organic loading rate, feed quality and concentration, temperature, pH and solids, and hydraulic retention time.

Control and optimization of the methane fermentation in digester systems will depend on further elucidation of the metabolic interactions and interdependencies among the microbial constituents. In the future, it may be possible to achieve physical separation between some of these microbial couplets in the form of two-stage or three-stage fermentation systems.

A closed reactor tank made of concrete or steel is commonly used for anaerobic digestion. Either one of two methods of operation may be employed: standard- or high-rate digestion. In the standard-rate process, the digester is usually unheated and unmixed and retention times may vary from 30 to 60 days. In the high-rate process, the digester is heated and completely mixed; the retention time is usually 10 to 30 days. A combination of these two processes is known as a two-stage digestion process. In such a two-stage system, the second stage, which is essentially a standard-rate digester, functions to separate the digested solids from the supernatant liquor. U.S. Environmental Protection Agency (EPA)[11] design criteria for sewage sludge digesters are shown in Table 1.

B. Technical Evaluation

The process parameters used in digestion of MSW are identical to those used in sewage sludge fermentation. Four major technical elements are important: preprocessing, digestion, gas recovery, and residue disposal. In the following sections, considerations essential for establishing the digestion process design criteria will be discussed. These include the sources and characteristics of MSW, MSW preprocessing and pretreatment, and digester control parameters such as nutrient requirements, organic loading rate, retention time, feed slurry concentration, temperature, mixing, gas quality, and quantity. Residue dewatering characteristics, ultimate disposal, and reactor design will also be considered.

1. Sources, Quantity, and Composition of MSW

The sources, quantity, and composition of MSW may vary significantly with season and

Table 2
PROJECTION OF MSW GENERATION RATES

Year	Million tons/year: Total gross discard[a]	Million tons/year: Net waste[b]	Capital/day (lb)
1975	136	128	3.40
1980	175	156	4.28
1985	201	166	4.67
1990	225	167	5.00

[a] Residential and commercial sector generation only.
[b] Net waste is referred to total gross discards minus recovered.

(Adapted from U.S. EPA, A Technical, Environmental, and Economic Evaluation of the Wet Processing System for the Recovery and Disposal of Municipal Solid Waste, SW-109C, 1975. With permission.)

geographical location. These characteristics determine the use of any one of several mechanical preprocessing configurations to produce the feed quality required by the digestion process. Hence, their consideration is of primary importance.

A definition of solid waste is essential for the estimation of quantities and composition of solid waste. "Post-consumer solid waste" includes the solid refuse and garbage generated from private houses and apartments, small commercial businesses, and office buildings. This definition excludes mining wastes, agricultural wastes, industrial processing wastes, demolition and construction debris, and wastewater-derived sludges. Post-consumer waste is commonly referred to as Municipal Solid Waste (MSW). In general, this is the waste "that garbage trucks take away."

In 1975 the Environmental Protection Agency (EPA)[12] using government and trade association statistics, estimated that an annual solid waste production of 136 million tons are generated by residential and commercial sections in the U.S. This is equivalent to 3.4 lb of solid waste per capita per day. The projected solid waste generation for the years 1980, 1985, and 1990 using agency-generated data are summarized in Table 2. By 1985, the predicted MSW generation rate will increase 37% to 4.67 lb per capita per day.

The variation in MSW composition due to geographical location, seasons, and type of dwelling is illustrated in Tables 3 and 4.[13] Table 3 gives data from various U.S. locations. The composition data were generated by methodological sampling, segregation, and weighing of MSW.

Table 4 shows the seasonal variation of municipal solid waste composition for the southern U.S. The discarded solid waste mixed with other refuse materials may either lose or gain moisture. For example, food wastes transfer a significant amount of moisture to paper and textiles. The choice of wastes "as discarded" is useful for true relative magnitude of waste generation of various categories for estimating garbage potential and forecasting refuse generation rates. Consequently, the data (Table 4) were adjusted for moisture content corresponding to the original value as the material entered the refuse storage bins on an "as discarded" basis and prior to moisture equilibration.

The composition and projected quantities of MSW in Southern California[14] are shown in Tables 5 and 6. The composition data for Los Angeles County were based on a weight averaging survey in the City of Los Angeles and an estimation of the commercial waste generated in the county. The national average composition of MSW[14] obtained from 1968-1972 is also included in Table 6.

Table 3
REFUSE-COMPOSITION DATA

Location	Notes	Food wastes	Yard wastes	Misc.	Glass ceramics	Metal	Paper products	Leather	Plastics	Rubber	Textiles	Wood	Oil, paint, chemicals	Total
De Kalb County, Ga.,	Residential from 12/11/68—12/13/68, as received-average	16.10	3.76	5.50	5.17	8.71	52.78	2.39			2.38	3.21	—	100
Delaware County, Broomal, Penn.,	Municipal, commercial, industrial from 1/26/70—1/30/70, as received-average	17.12	0.32	3.19	11.68	8.15	52.40	3.66			2.10	1.38	—	100
New Orleans, East	Residential, commercial, from 2/10/69—2/14/69, as received-average	11.46	9.81	7.09	9.50	8.21	44.18	3.48			3.32	2.95	—	100
City of Memphis, Tenn.	Residential from 7/29/68—8/1/69 average	19.70	12.13	12.53	9.78	6.63	29.67	3.05			4.79	1.72	—	100
Fulty County, Ga. Atlanta area	Commercial, industrial, municipal—as received average	13.08	1.40	3.18	9.82	8.72	58.34	3.25			1.78	0.43	—	100
Southeastern community #1	Residential—as fired basis	20.3	11.1	11.1	10.5	6.8	30.2	3.1			5.2	1.7	—	100
Southeastern community #2	Residential — as fired basis	11.0	9.8	6.9	9.5	8.1	44.9	3.5			3.2	3.1	—	100
Southeastern community #3	Residential — as fired basis	17.5	2.8	3.4	6.5	8.8	53.2	2.6			2.0	3.2	—	100
Southeastern community #4	Residential, commercial, industrial — as fired basis	12.2	1.6	3.4	10.3	8.6	58.7	3.0			1.8	0.4	—	100
Long Island, N.Y. Town of Babylon	Predominantly household minor quantities commercial and industrial	10.0	5.0	6.0	12.0	10.0	47.0	4.0	3.0	1.0	3.0	3.0	—	100

Table 3 (continued)
REFUSE-COMPOSITION DATA

Location	Notes	Food wastes	Yard wastes	Misc.	Glass ceramics	Metal	Paper products	Leather	Plastics	Rubber	Textiles	Wood	Oil, paint, chemicals	Total
City of Berkeley, Calif.,	Residential, Commercial 1967 — as received basis	20.06	5.02	7.10	11.33	8.71	44.61	2.11	1.85	0.26	1.06	—	—	100
Long Island, N.Y.	Household — June 1966	9.89	26.17	9.62		8.05	36.26	2.95			3.16	3.90	—	100
	Household — February 1967	16.70	0.26	11.37		10.60	53.33	3.54			2.24	1.46	—	100
City of New Orleans, La.	Household average — (1969) May 15, 1978	18.90	9.20	—	16.2	12.2	39.4	1.5			2.6	—	—	100
4-City, N.J. region	Average for Paterson, Clifton, Passaic, Wayne	8.3	13.3	8.96	6.44	9.44	43.87	2.66			4.52	2.96	—	100.49
Composite	As collected, includes 9.05 adjusted moisture	8.40	6.88	10.01		6.85	52.70		1.52	0.76	0.76	2.29	—	99.98
Hempstead, Long Island, N.Y.	Predominantly residential —	10.9	17.6ᵃ	—	9.6	8.5	42.6	4.6			3.1	3.2	—	
	as received	12.0	20		8		46.0	4.0			3.0		—	
	Residential and commercial excluding bulky and industrial											7.0	—	100
Johnson City, Tenn.,	Residential, 10/67	26.1	1.6	1.0	11.0	10.9	45.0		1.7	1.0	1.4	0.4	—	100.01
	Municipal, 7/68	34.6	2.3	0.2	9.0	10.4	34.9		3.4	2.4	2.0	0.8	—	100.0
Weber County, Utah	Residential and commercial, 4/68	8.5	4.2	5.9	4.6	8.4	61.8	2.5			2.0	2.2	—	100.1
Cincinnati, Ohio	Residential, 10/66	28.0	6.4	—	7.5	8.7	42.0		1.6	1.0	1.4	2.7	—	99.3
Alexandria, Va.,	Residential and commercial, 5/68	7.5	9.5	3.4	7.5	8.2	55.3	3.1			3.7	1.7	—	99.9
San Diego, Calif.	Residential and commercial, 1967	0.8	21.1	—	8.3	7.7	46.1		0.3	4.7	3.5	7.5	—	100
Genesee County, N.Y.	As collected, includes commercial, industrial, domestic, and demolition wastes	7.11	1.99	23.62	3.34	4.64	20.39	1.49			3.01	22.41	12	100
Flint, Mich.	Annual average	32.0	13.5	0.3	17.9	14.5	17.5	2.3			0.5	0.9	—	100

Genesee County, Mich.	Domestic	26.0	10.8	0.2	14.3	11.8	34.0	1.8			0.4	0.7	—	100
Santa Clara, Calif.	As collected, domestic, average	2.3	23.8	—	12.7	7.6	47.5		1.0	1 (ave.)	1.2	1 (ave.)	—	100
Philadelphia, Penn.	Includes significant quantities of industrial wastes, as collected	5.0	—	16.4	9.1	8.4	54.4		0.2	1.5	2.6	2.4	—	100
Jefferson County, Ky.	As collected, residential; average 66/67	19.8	—	1.3	10.5	9.3	59.1			—	—	—	—	100
New Jersey	As collected	10.0	—	—	4.0	8.0	51.0	4.0	4.0	4.0	4.0	4.0	—	81
Ohio	As collected	28.0	—	—	8.0	9.0	42.0	3.0	3.0	3.0	3.0	3.0	—	93.50
Arizona	As collected	22.0	—	—	8.0	10.0	43.0	1.0	1.0	1.0	1.0	2.0	—	86
California	As collected	15.0	—	—	2.0	7.0	54.0	2.0	2.0	2.0	2.0	2.0	—	82
Tennessee	As collected	26.0	—	—	11.0	11.0	46.0	5.0	5.0	5.0	5.0	0.3	—	• 99.3
General analysis	From study made by Purdue University	12.0	12.0	14.5	6.0	8.0	42.0		0.7	1.0	0.6	2.4	0.8	100
Hamilton, Canada	June 28—July 26	31.0	13.0	—	7.0	5.0	33.0		1.3	1.0	2.0	6.0	—	99

• Average of 4 tests, percent of yard wastes: 6/1/66, 33.3; 6/23/66, 19.0; 2/21/67, 0.3; 4/3/67, 17.9

From Wilson, D. G., *Handbook of Solid Waste Management*, Van Nostrand Reinhold, New York, 1977, chap. 2. With permission.

Table 4
ESTIMATED AVERAGE MUNICIPAL SOLID WASTE COMPOSITION, SOUTHERN STATES, 1970 WEIGHT % AS DISCARDED

Category	Summer	Fall	Winter*	Spring	Average: As discarded	Average: As mixed
Paper	31	38.9	42.2	76.5	37.4	44
Yard waste	27.1	6.2	0.4	14.4	13.9	9.4
Food waste	17.7	22.7	24.1	20.8	20	17.1
Glass	7.5	9.6	10.2	8.8	9.8	8.8
Metal	7	9.1	9.7	8.2	8.4	8.6
Wood	2.6	3.4	3.6	3.1	3.1	3
Textiles	1.8	2.5	2.7	2.2	2.2	2.6
Leather and rubber	1.1	1.4	1.5	1.2	1.2	1.5
Plastics	1.1	1.2	1.4	1.1	1.4	1.4
Miscellaneous	3.1	4	4.2	3.7	3.4	3.6
Total	100	100	100	100	100	100

* The refuse composition in winter in southern states in similar to that shown in fall.

(From Wilson, D. G., *Handbook of Solid Waste Management*, Van Nostrand Reinhold, New York, 1977, 17. With permission.)

Table 5
QUANTITIES AND PERCENTAGES OF MUNICIPAL REFUSE IN SOUTHERN CALIFORNIA

County	1980 Quantity (ton/day)	1980 Percent of total	1990 Quantity (ton/day)	1990 Percent of total	2000 Quantity (ton/day)	2000 Percent of total
Los Angeles	17,100	61	18,200	54	19,000	50
Orange	5,700	20	7,300	22	8,600	23
Riverside*	1,800	6	2,600	8	3,200	8
San Bernardino*	2,400	8	3,300	9	3,900	10
Ventura	1,500	5	2,400	7	3,400	9
Total	28,500	100	33,800	100	38,100	100

(Taken from Brown and Caldwell Consulting Engineers, Energy Recovery from Waste and Biomass. Site Specific Studies, prepared for Southern California Edison, Rosemead, Calif., 1979, 2.)

The following trends in MSW composition (Table 6) were noted in Los Angeles during a 6-year period.

1. There was a substantial decline in the proportion of mixed paper. This was attributed to a small reduction in the newspaper component and an increase in yard trimmings. The net effect was an approximate 20% decline in total digestible organic material.
2. Plastic increased by about 50%, textiles by more than 80%, and lumber by more than 200%. Overall total undigestible organics increased by more than 120%.
3. Ceramics and stone increased threefold and dirt and miscellaneous doubled. Total inorganics increased about 10%.

Comparing the county data with the national data revealed the following:

Table 6
LOS ANGELES MUNICIPAL REFUSE COMPOSITION, PERCENT BY WEIGHT

Item	City of Los Angeles 1971—72[a]	1973—74[b]	1976—77[c]	Commercial[d]	Los Angeles County average	National average 1968—72[f]
Digestible Organics						
Paper						
Cardboard	3.7	10.1	3.6	5.4	7.6	11.6
Newspaper	11.3	8.9	7.8	4.2	9.1	8.6
Mixed paper	25.2	4.6	3.9	2.0	4.4	22.3
Food wastes	5.4	4.3	4.3	3.7	6.4	14.6
Yard Trimmings	26.9	31.7	34.8	1.1	23.0	12.5
Subtotal	72.5	59.6	54.4	16.4	50.5	69.6
Undigestible Organics						
Plastics	2.3	3.4	3.4	3.1	5.3	1.7
Textiles	2.3	3.3	4.3	2.2	4.9	2.4
Leather and rubber	0.5	1.4	1.7	0.5	1.5	1.8
Lumber	2.1	6.3	6.7	8.4	12.6	2.5
Subtotal	7.2	14.4	16.1	14.2	24.3	8.4
Inorganics						
Metals						
Ferrous	5.2	3.5	4.8	2.6	5.5	6.7
Aluminum	0.7	1.6	0.9	0.4	1.0	0.9
Other	0.2	0.6	0.4	0.2	0.4	0.4
Glass	7.3	4.3	7.1	3.4	7.9	10.3
– Ceramics and stone	0.7	1.9	2.5	0.1	1.7	NA
Dirt and miscellaneous	6.2	14.4	13.8	0.0	8.6	4.5
Subtotal	20.3	26.3	29.5	6.7	25.1	22.8
TOTAL	100.0	100.3	100.0	37.3	99.9	100.8

[a] Source: Envirogenics Systems Co., Systems Engineering analysis of Solid Waste Management in the SCAG Region, June 1973

[b] Source: Alpern, R. M., as reported in Zinder et al., Quantity and Composition of Organic Solid Wastes in Southern California and Their Potential as Substrates for Microbial Methane Production, 1978.

[c] Source: Alpern, R. M., interdepartmental correspondence to William Guber, Assistant Director, Bureau of Sanitation, City of Los Angeles, July 1977.

[d] Source: Huitric, R. personal communication, Los Angeles County Sanitation Districts, February 1979.

[e] Weighted average of "1976-77 City of Los Angeles" and "Commercial."

[f] National Center for Resource Recovery, Inc. Municipal Solid Waste, Its Volume, Composition and Value, NCRR Bulletin, Volume III, No. 2, Spring 1973.

(Taken from Brown and Caldwell Consulting Engineers, Energy Recovery from Waste and Biomass, Site Specific Economic Studies, 1979, 2.)

1. The proportion of total digestible organic matter for the county, 50.5% was significantly less than the national 69.6% average.
2. The proportion of total indigestible organic matter for the county, 24.3%, was greater than the national 8.4% average.
3. The proportion of total inorganic matter for the county, 25.1%, was slightly higher than the national 22.8% average.

These generation rate and MSW composition data for Los Angeles County and the nation are indicative of the variation of MSW with time and location. Thus, extrapolation of results from one location to another may not be valid and should be done with caution. Because of these variabilities, the design of solid waste management systems must have a high margin of operations flexibility and must be designed for extraordinary contingencies. These requirements often result in overdesign in order to accommodate the variation in MSW composition.

2. Physical Properties of MSW

For the design of resource recovery equipment, knowledge of the physical, chemical, and biological properties of mixed refuse is essential. The most important factors are moisture content, particle size, particle density, chemical composition, and mechanical properties.

a. Moisture Content

Moisture content of various components of refuse changes with time because time-dependent movement of moisture occurs during transfer and storage. The moisture content is very important in the design of storage and conveying equipment because material characteristics such as size, density, and abrasiveness are altered with changes in water content.[15] Furthermore, moisture content of MSW influences shredding energy requirements; energy requirements are least at a moisture content of 35 to 40%.[16] An increased moisture content also exerts a deleterious effect on the purity of and recovery of ferrous metals by magnetic systems. However, ferrous metals recovery increases with increased moisture content when electronic separators are used.[17] A lower MSW moisture content also reduces the overall energy requirements for pyrolysis since less heat is required to reach operating temperatures.

b. Particle Size

Particle size is an important factor in resource recovery because most separation processes require specific and relatively uniform particles for efficient operation. Particle size measurement of MSW is difficult because of the presence of odd shapes and the common use of sieving as a method of measurement. Eddy current processes used in resource recovery are also affected by particle size.[18] Particle size also has a significant effect on land-fill gas production. A 10-fold decrease in refuse particle size increases land-fill gas production by 4.4 times.[19] Digester efficiency and mixing requirements may also be a function of particle size. Conversely, the energy consumption of MSW preprocessing systems is inversely related to particle size; smaller particles require more energy.

c. Particle Density

Material density is an important factor in any resource recovery operation. The low initial density and poor compaction property (at moderate pressures) of municipal solid waste decrease carrying capacity and contribute to high cost collection and hauling. Density of shredded refuse is also important for the design of storage tanks and retrieval systems because of the effect of gravity during long-term storage. Also, in land fill operations, the greater the refuse density the less methane produced.[19] This effect may be due to reduction of exposed surface area available for microbial degradation.[20]

d. Chemical Composition

The economic recovery of materials and energy ultimately depends on the chemical composition of the refuse which determines its potential heating value. Toxic and caustic substances in municipal refuse may cause corrosion of refuse-processing equipment, may be a potential source of air and water pollution, and may inhibit eventual digester performance. Hydrochloric acid formed from plastics such as polyvinyl or vinylidene chloride is commonly found when refuse is combusted. The proportion and type of organic matter in the refuse may also be correlated to its energy value. Fats and lipids yield more methane than proteinaceous substrates.[21,22] Garbage has a typical heating value of 8484 Btu/lb, but paper is lower (7572 Btu/lb) and fats are much higher (16,700 Btu/lb.)[23] Soluble and simpler organic compounds are assimilated and metabolized more readily by microbes; consequently, the presence of lower molecular weight substrates may give rise to methane very rapidly. Such compounds may be metabolized at higher substrate loading rates and lower retention times. Recalcitrant organic matter, such as lignins or celluloses, may be pretreated by hydrolysis with enzymes, acids, alkali, or heat. The carbon to nitrogen (C:N) ratio is often reported in evaluating digester substrate composition. A certain C:N ratio in the feed is necessary for optimal microbial metabolism, but an exact ratio for methane production has not been established. In the co-digestion of urban refuse and sewage sludge, a C:N ratio of 50:1 to 70:1 was recommended by Klass et al.[24] A reported C:N ratio up to 90:1 did not significantly affect methane production. Digestion failure was predicted if the D:N ratio exceeded 45:1 during fermentation of paper pulp and sewage sludge.[25] At C:N ratios below 25:1, normal digestion occurred, and, at C:N ratios greater than 25:1, acid-forming bacteria predominated.[26]

e. Mechanical Properties

Information on mechanical properties of materials is important for identifying the requirements for comminution of heterogeneous materials in MSW. Stress strain data are especially important for the design of shredding equipment.

3. Preprocessing Unit Operations for Resource Recovery

Various commercial systems have been developed for processing MSW to recover valuable materials (aluminum, glass, etc.) and to produce a fraction commonly referred to as refuse-derived fuel (RDF). These systems were developed for specific requirements of market conditions and other factors unique to the particular project. However, despite the commercial availability of unit processing modules, a standard preprocessing system does not exist.[27] Lack of sufficient operating information and experience, the variable nature of MSW, and diverse site-specific objectives actually preclude any standardization.

A typical material processing system employs shredders, trommels, air classifiers, magnetic separators, and glass extractors; these components are combined in a variety of sequences. The RDF production plants presently in operation are representative of first-generation facilities under continuous modification. Among existing RDF-producing facilities some are operational and some are in various states of change.[23]

In the present summary, the following sections provide a brief description of unit operations utilized in material processing systems. A more complete analysis on function and design of unit modules is given by Vesilind and Reimer.[18]

a. Shredders

Size reduction of MSW is important in energy conversion of solid waste. Shredded refuse is relatively uniform in size, more homogeneous, and more compacted than unshredded refuse.[28] Shredding reduces land-fill volume requirements and may be justified solely on this basis. Shredding technology, borrowed largely from mining industries, is difficult to apply in resource recovery because of the nonhomogeneity of MSW. Most of the machines used for shredding MSW are of the hammermill type. These include vertical axis hammermills (Tolle-Mache Ltd., London, England and Heil, Inc., Milwaukee, Wis.,), horizontal axis hammermills (Broyeurs Gonard, Paris, France and Jeffrey Manufacturing Co., Pennsylvania), vertical axis grinders (Eidal-International Corp.), and horizontal axis impactors (Hazemag Co., New York, N.Y.).

The hammermill consists of a central rotor with radial hammers which are free to move on pins and are enclosed in heavy-duty casing. In a horizontal hammermill, the rotor is supported on both ends, and feed is introduced on a conveyor by gravity. A grate below the rotor permits only particles smaller than the grate opening to escape from the casing. The vertical hammermill consists of a vertical shaft with a heavy-duty casing. Vertical clearance of the mill and casing is reduced gradually and thus particle size is reduced as it moves through the machine.

The size reduction of refuse is affected by refuse flow rate, moisture content, residence time, and physical size of the shredder. The product particle size distribution is a function of feed particle size and mean residence time, while energy requirement is a function of holdup and moisture content of the refuse.[29] Higher flow rates produce finer particle sizes but require more energy. However, even at higher speeds, energy consumption decreases with increasing moisture content; the minimum amount of energy is required at a moisture content of 35 to 40%.[16]

b. Screens

The objective of screening is size separation. Screens are used at the beginning of a resource recovery system for rough sorting; toward the end of the process, they are used for reclaiming organic materials and glass. There are two types of screens commonly used for resource recovery: (1) vibrating screens, or (2) revolving screens (also referred to as trommels).

Trommel screens are superior to vibrating screens because of lower capital cost and lower power consumption.[30] A high flow rate reduces the efficiency of any screens, but the rate of reduction is higher for vibrating screens than for trommels. A trommel screen requires about 12% of the energy needed by a comparable vibrating screen. Furthermore, trommel screens have an overall efficiency of about 90% vs. 72% for vibrating screens.

c. Air Classification

The air classification process employs a stream of air to separate light organic matter from heavier inorganic matter. Shredded MSW is introduced near the mid-point of a vertical shaft, and air is introduced at the bottom of the shaft at a high rate. The dense particles move downward and the light particles rise. The lighter particles are usually separated from the air stream by creating a cyclone effect. Air classification geometry can have a significant effect on process performance.

Worrel and Vesilind[31] introduced a "total efficiency" term (the product of light and heavy fraction recovered under a specific set of conditions) for evaluating air classifier performance. Material recovery is a function of air speed, and is apparently maximum at 1500 ft/min air speed. Moisture content has little effect on light products recovery; the efficiency decreases only by about 5% if moisture content is doubled.[32] At higher feed rates, a lower quantity of light products is recovered.

d. Magnetic Separation

Magnetic separators are used primarily for separating ferrous matter from MSW. The recovery of salable ferrous materials and the increase in heat content and biodegradability of the RDF are two important reasons for using this process component. Magnetic separators also improve the life span of downstream processing equipment by reducing the amount of abrasive wear. The magnetic separator is usually located after the primary shredder and air classification units.

Two types of magnetic separators frequently used for resource recovery are holding-type and suspended-type separators. The shredded MSW is fed directly onto the collecting surface of the holding type separator but is loaded onto a conveyor belt below the magnetic collecting surface in the suspended type separator.

4. Preprocessing Systems for Energy Recovery

The physiochemical processes for energy conversion of MSW involve various combustion

Table 7
COMPARATIVE RDF CHARACTERISTICS

	Course	Fine	Densified	Powdered	Wet-Pulped
Higher heating value as received (Btu/lb)	5,319	5,610	6,000	7,740	3,600
Ash (%)	15—17	17	25	15—25[a]	25
Moisture (%)	NA	23	10—16	2.0	55
Nominal particle size (in.)	4—6	1.5	0.5 × 1.25	0.015	NA (<1)
Bulk Density (lb/ft³)	4—6 (Est.)	8	28	30—34	NA
Handling/storage characteristics	Poor	Poor	Good	Good	NA

Note: NA: Not available.

(Taken from Mitre Corp., Resource Recovery Research and Demonstration Plan, U.S. Department of Energy Contract No. EM. 78-C-01-42141, Bedford, Mass., 1979.)

and incineration methods while biological processes include anaerobic methane or alcohol fermentations. The practical application of either process requires preliminary separation of MSW components into combustible and noncombustible fractions and degradable and non-degradable components.

Preprocessing systems may be categorized according to five resultant products: coarse RDF, fine RDF, densified RDF, powdered RDF, and wet pulped RDF.[22] Coarse RDF is produced by a single passage of MSW through a shredder to yield smaller particles of combustible materials. Fine RDF is produced by a second shredding to reduce the particle size even further. Densified RDF is formed by processing fine RDF through a pellet mill. Powdered RDF is produced by mechanical, chemical, and thermal action on MSW; it is dry and free-flowing. Wet pulped RDF is formed by grinding MSW in a wet pulper using a water medium; particles larger than 1 in. are rejected from this system. Comparative RDF characteristics are shown in Table 7.

Patented preprocessing systems are available from Combustion Equipment Associates (Bridgeport, Conn.) which markets powdered RDF known as ECO-Fuel®-II and from Parsons and Whittermore, Inc. (Hempstead, N.Y.) which produces a pulped fiber RDF using the Black Clawson process. These systems produce an RDF for energy recovery by physico-chemical means. Preprocessing systems used in physiochemical conversion do not necessarily yield a readily digestible product for biological energy conversion. Several systems are designed to produce RDF specifically for digestion. These are schematically illustrated in Figure 2.

Of the schemes in Figure 2, the Cal Recovery System is the most promising. In this process, an organic digestible portion is separated from the "heavies" and the fibrous "light" fractions of RDF. Recent studies on the anaerobic digestion of this product are reported in a later section of this paper. The results suggest that certain key innovative features may make methane gas production from MSW economically feasible. A detailed review of the Cal Recovery System is reported by Savage, Diaz, and Trezek.[35]

5. MSW Pretreatment

The digestible fraction of MSW contains lignocelluloses which are not easily fermented; probably less than 50% is degradable. Lignin itself may not be readily broken down under anaerobic conditions, and it seems likely that 50% or more of the MSW fraction remains undigested over extended time.[26] The undegraded lignin/cellulose tends to accumulate in the digester and create mixing and scum problems (see later). Thus, in addition to the prepro-

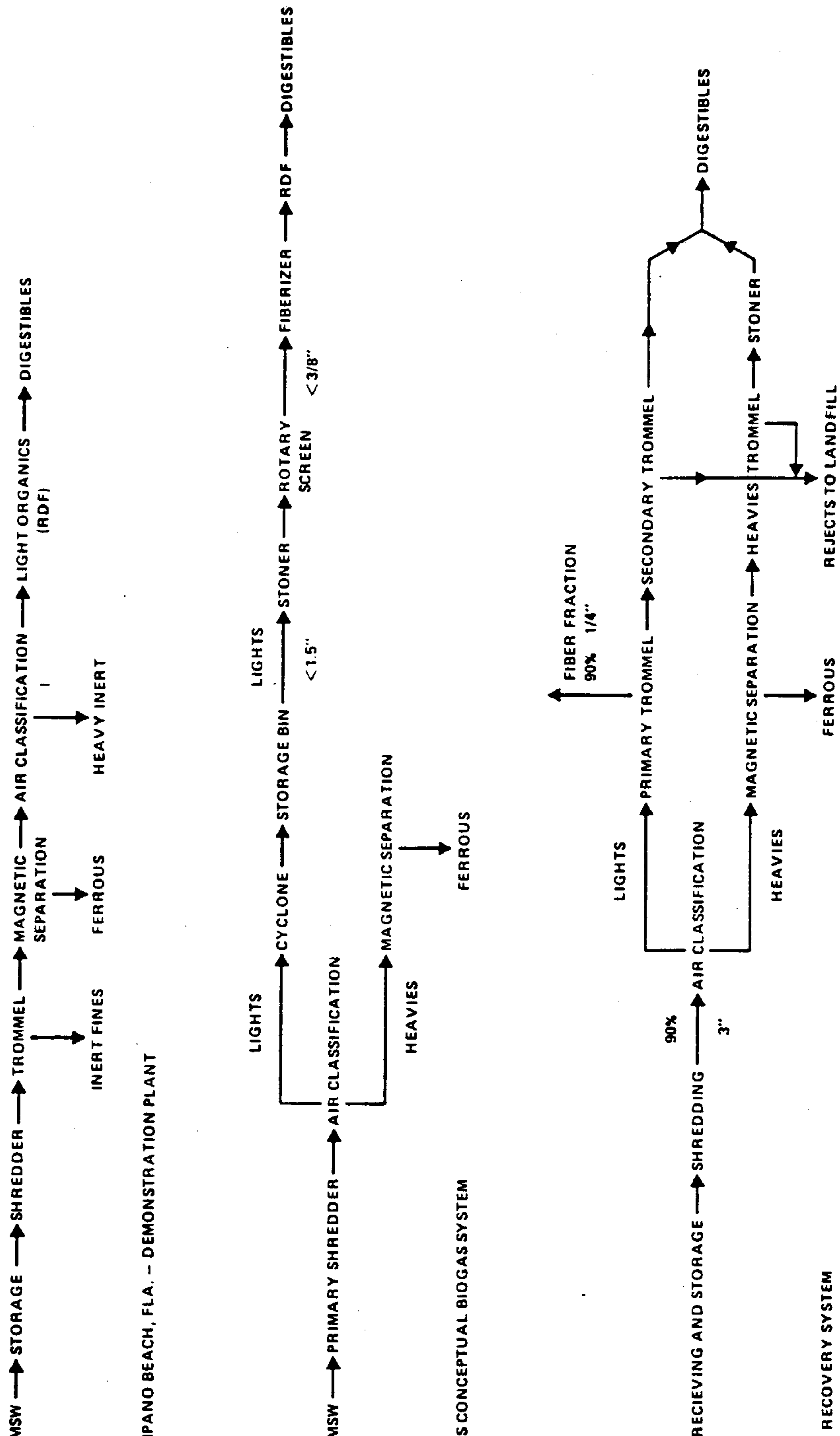


FIGURE 2. Anaerobic digestion preprocessing systems.[27,33,34]

Table 8
METHODS FOR TREATMENT OF CELLULOSE TO INCREASE DIGESTIBILITY

Physical	Chemical
Ball milling	Sodium hydroxide
Hammer milling	Ammonia (liquid)
Weathering	Ammonia (gas)
Boiling	Hydrochloric acid
High pressure steel	Acetic acid
Electron irradiation	Sulfuric acid
Photo-oxidation	Sodium sulfide
Wetting	Sulfur dioxide (gas)
Gamma radiation	Nitrogen dioxide (gas)
	Potassium hydroxide
	Phosphoric acid

Combinations

Hot ball mixing
NaOH and ball mixing
NO_3 and irradiation

(Taken from Brown and Caldwell Consulting Engineers, Microbial Production of Methane from Refuse, Report prepared for So. California Edison Co., Research and Development, 1978.)

cessing stages in MSW bioconversion, pretreatment of the fractionated MSW is also important, primarily since MSW contains mostly cellulosic paper products (75% carbohydrate) and lignocelluloses. The Cal Recovery process tends to by-pass this problem by removing some of the undigestible cellulosic material as RDF.

Pretreatment of the MSW or some removal of undigestible cellulosic matter prior to digestion (Cal Recovery process) are two possible alternatives to deal with this problem. Pretreatment processes may be grouped into three basic methods: physical, chemical-thermal, or a combination of both. Various pretreatment methods for cellulose[26] are listed in Table 8.

In physical pretreatment processes, size reduction and separation of inorganic compounds are apparently the most significant factors affecting the economics of biological conversion processes. Ghosh and Klaus[36] showed that refuse particle size has a significant effect on digestibilty. Laboratory experiments using refuse with median size particles of 10.1 to 5.1 mm demonstrated that lower gas yields and production rates were obtained with coarser refuse. Unfortunately, the cost-effectiveness of process variations for size reduction and separation is not well established. The effect of particle size and separation efficiency is under study by Waste Management, Inc. at the Pompano Beach, Fla. facility. This effort should yield valuable information on the relationship between particle size and biodegradability and the degree of size reduction and separation necessary for material handling of solid waste slurries.

Several chemical and thermal laboratory scale pretreatment methods have been investigated for bioconversion of MSW. The most promising is heat treatment under alkaline conditions. Alkali pretreatment apparently increases digestibility by swelling the substrate and increasing the pore size of the cellulose matrix. Lignin is solubilized to phenols and carbohydrates and consequently subject to microbial enzyme degradation. The rupture of chemical bonds at higher temperatures and pressures produces products susceptible to hydrolytic activity by microbial digestion. Peak biodegradability of alkaline-heated MSW occurs at pH 13 and 392°.[37] Heat pretreatment of newspapers under alkaline conditions increased methane production by 25 to 47%.[38] A caustic dose of 3g NaOH or lime per 100 g of refuse heated to 266°F increased biogas production in laboratory digesters by over 30%.[7] In addition, an increased rate in substrate utilization implied potentially shorter retention times for digestion.

Alkali pretreatment at elevated temperatures is apparently effective for increasing MSW digestibility; however, scale-up parameters, disposal of nonbiodegradable residues, formation of soluble lignins in the digester effluent, and the cost effectiveness of such treatment have not been evaluated.

6. *MSW Digestion Performance Parameters*

After the MSW has been carefully evaluated and preprocessed to yield an organic fraction for digestion, several design factors for optimal gas production and volatile solids destruction may be established: among these are nutrient requirements, organic loading rate, hydraulic retention time, feed slurry concentration, temperature, and mixing.

a. Nutrient Requirements

Typical MSW is deficient in both nitrogen and phosphorus. The quantity of nitrogen required for supplementing anaerobically digesting refuse is 19.32 lb/ton of volatile solids fed.[33] Less information is availble on the phosphorus requirement although it is much less than nitrogen. Any nutrient requirements may be satisfied by chemical addition of synthetic or refined chemicals or by introduction of organic waste materials rich in the deficient nutrients. Addition of refined chemicals may be excessively costly and nutrient supplementation by addition of organic wastes such as sewage or animal wastes may be a more cost-effective approach.

The digestion of classified MSW supplemented with raw sewage sludge has been investigated by numerous workers.[5,33,34,39,40] Optimum gas production was achieved with a mixture of 80% refuse and 20% sludge.[40] The present work demonstrates increased rates and yields of methane from MSW by supplementation with animal manure and sewage sludge.

b. Organic Loading Rate and Hydraulic Retention Time

The organic loading rate (OLR) is the quantity of organic matter fed per unit volume of digester liquid per unit time (e.g., lb volatile solids [VS] per ft^3/day). OLR influences the stability of the process. A sudden increase in feed rate may elicit an increase in acid-forming bacteria; if overloading occurs, unstable conditions may result because of the inability to keep pace with end-product conversion to methane by the slower growing methanogenic bacteria. OLR and hydraulic retention time (HRT), the theoretical time incoming liquid remains in the digester, are mutually dependent variables. OLR and the substrate concentration define the retention time for a given volume: at any OLR, retention time is changed only by changing the substrate concentration. At long retention times (>30 days), biodegradation of organic solids will be essentially complete; however, practical retention times are usually shorter to achieve a more cost efficient process. A typical OLR and retention time for sewage sludge digesters is 0.2 to 0.4 lb VS per ft^3/day and 10 to 15 days, respectively.

Organic loading rates and retention times for MSW digestion may range from 0.07 to 0.35 lb VS per ft^3/day and from 10 to 30 days, respectively. In most reports of MSW digestion, co-digestion of raw sewage sludge is included.[34,39,40] At a 15-day retention time, an OLR higher than 0.3 lb VS per ft^3/day was not satisfactory.[40]

The optimal loading rates and retention times for methanogenic digestion will depend on the quality of the feedstock and the operational objectives of the overall process. For the most cost effective operations, the highest loading rates and shortest retention times require the least cost.

c. MSW Feed Slurry Concentration

The MSW feed concentration is important in the operational design and performance of anaerobic digesters. In sewage sludge digesters, a more concentrated influent feed yielded better digester stability and performance,[41] presumably because of a higher steady-state concentration of microorganisms. Feed concentration also determines the handling and pumping properties of the influent material and the degree of mixing required for efficient operation. Little information is available on an optimal MSW feed slurry concentration; it usually is established by determining organic loading rate, retention time, and physical processing limitations. An upper limit for total influent solids based on pumping and mixing limitations is apparently around 8%.

d. Temperature

Temperature is an important variable in establishing the rate and determining the stability of the digestion process. Digesters may be operated at two temperature ranges: mesophilic and thermophilic. Thermophilic digesters operate in the range of 120°F to 135°F with an optimum at about 130°F. Mesophilic digesters operate between 85°F and 100°F with an optimum at 98°F. Although higher gas yields and gas rates are obtained in thermophilic digestion, it is not commonly used in municipal sludge fermentations because of increased heating (and thus energy) requirements, greater fermentation instability, and general inexperience with the process. In either temperature range, a 5 to 10°C fluctuation in temperature may result in an imbalance in the microbial fermentation and lead to digester instability. Thermophilic digestion is generally more sensitive to such fluctuations.

In contrast to sewage sludge digestion, little information is available on optimal temperatures for large-scale MSW digestion. Laboratory digester experiments on MSW at various retention times and temperatures gave an optimum mesophilic temperature of 107°F and a minimum thermophilic temperature of 140°C.[42] Also, thermophilic digestion yielded higher gas production rates. Slightly different results were obtained by Ghosh et al.[34] using a 12-day retention time. These studies gave an optimum mesophilic digestion of refuse-sludge mixtures between 95°F to 104°F at low loading rate (0.07 lb VS per ft^3/day). At a higher loading rate (0.14 lb VS per ft^3/day), the optimum mesophilic temperature was 95°F. The optimum thermophilic temperature was 131°F. At a given loading rate and retention time, both a higher gas yield and a better effluent quality were obtained at the mesophilic optimum compared to the thermophilic optimum.

e. Mixing

Complete mixing of digester contents is essential for optimal digester performance, especially in sewage digesters where high-volume mixing was found beneficial.[43,44] Most digesters are mixed by gas recirculation, but other methods include mechanical mixing and liquid recirculation.

One major problem with MSW digestion is the formation of thick scum layers because of inadequate mixing; this reduces the efficiency of the digester and has been reported by several investigators.[6,40,45] With hydropulped MSW as substrate, a fibrous mat[45] formed in the upper region of a 55-gal reactor; cellulose tended to float on the surface, adhered together during mixing, and formed large mats of fibrous scum. Two methods of mixing were tested in a 100,000-gal reactor[46] by using either a mechanical agitator or a gas mixing system. The effect of various feed ratios of MSW to sewage sludge, organic loading rates, and feed solid concentrations were examined. The following conclusions were made from this study.

1. A 4% solids slurry can be digested on a short-term basis.
2. Both the gas mixing system and the mechanical agitator maintain fairly uniform solids distribution in the lower and middle levels of the reactor.

3. In both mixing systems build-up of a 1- to 3-ft fibrous scum layer of 20 to 25% total solids occurred with 1 month of operation.
4. Grit content in the feedstock must be lowered to avoid using abrasion-resistant slurry pumps.
5. MSW differs enough from sewage sludge to make unfeasible direct application of sewage sludge digestion practices.

Mixing of RDF slurries still remains a significant operational problem because of stratification of the liquid and binding of mixing shafts and impellers by fibrous matrices which develop. This is the major operational difficulty which must be solved before further large-scale MSW digestion is feasible. Factors influencing mixing such as feedstock preparation, MSW size, impeller and reactor design, and shaft speed must also be carefully evaluated.

f. Gas Quality and Quantity

Several important technical and economic considerations are related to the gaseous end-products of anaerobic digestion. These include gas quantity, quality, processing, and marketing potential. In general, the volume of gas produced in a digester will depend on the feedstock characteristics and digester operational parameters. For mesophilic domestic sewage sludge digesters, the gas produced averages between 16 and 18 ft^3/lb VS destroyed (about 10 ft^3/lb VS added). Gas yields for MSW digestion are substantially less. MSW gas production rates are not only strongly influenced by temperature, retention time, and loading rate, but MSW sources and preprocessing schemes may also account for large variances in gas yields.[7,34,47]

There is little doubt that nutrients from added sewage sludge enhance decomposition and gas production rates in MSW digestion. In two separate studies,[39,40] gas yields from various mixtures of highly processed MSW and raw sludge averaged about 7.8 and 9.3 ft^3/lb VS added, respectively. The variation may be due to several factors including quality of feedstock, raw sludge ratio, retention time, and organic loading rate. An upper limit of gas production from MSW has not yet been reported.

Digester gas consists primarily of methane and carbon dioxide with trace amounts of hydrogen sulfide and nitrogen. Typical gas composition for sewage sludge digesters range from 60 to 70% and 30 to 40% carbon dioxide with a heating value of approximately 600 Btu/ft.[3,48] In contrast, various studies on MSW digestion yielded values closer to 50 to 60% methane and 40 to 50% carbon dioxide with a heating value of about 550 Btu/ft.[3,5,34,40,47]

Unscrubbed digester gas is wet, mildly corrosive, and contains about half the heating value of natural gas. Any cleanup of the product gas will depend on its intended use. In wastewater treatment plants with proper piping and storage facilities, treatment is minimal or unnecessary if the gas is used as fuel for boiler and internal combustion engines. If the gas is used as a natural gas substitute, it must be upgraded to a high-Btu equivalent of pipeline quality by removing the carbon dioxide and hydrogen sulfide. Particulates in the gas may be removed by large sedimentation traps, and water may be removed by use of pipeline traps. A review by Ashare et al.[49] of gas purification systems indicated that commercially available methods for treatment of digester gas include physical and chemical absorption, adsorption, and membrane separation processes. Experience with large-scale MSW digester gas treatment is limited at this time; however, current gas purification processes may be applied to MSW product gas without anticipated problems.

g. Dewatering Characteristics and Residue Disposal

The dewatering characteristics of MSW digester effluent are an economic consideration in the overall bioconversion process. The solid residue must be separated and dewatered to the maximum extent for economical disposal. A low moisture content in the residue is desirable to accomplish the following objectives:

1. Maintain an odorless, biologically stable sludge
2. Reduce fuel requirements if incineration is final disposal mechanism
3. Reduce hauling costs to landfills or drying fields
4. Reduce leachate production at land-fill site.

Various technologies have emerged for processing digester effluent and for ultimate disposal of process waste sludges These are discussed in a comprehensive report prepared by the Los Angeles/Orange County Municipal Association, LA/OMA.[50] For digested sewage sludges, available dewatering processes include vacuum filtration, centrifugation, filter presses, horizontal belt filtration, sand drying beds, and lagoons.

Vacuum filtration and centrifugation for dewatering MSW sludges and the effects of recycling and chemical conditioning prior to dewatering were examined by Pfeffer and Liebman.[47] Buchner funnels and a filter test leaf technique demonstrated that vacuum filtration of digested MSW sludge (5 to 6% TS) may yield a 20 to 25% solid cake with a solids capture of 90 to 95%. Cake solid could be increased to over 30% with a solid capture of 90 to 95% if chemical pretreatment were applied; however, the cost of pretreatment was not offset by the savings in the overall processing costs. Recycling of filtrate resulted in a buildup of fine particles that eventually reduced the filter rate and solid cake content. In centrifugation tests, cake solid concentrations varied between 27 to 40% with solids capture of 61 to 88%, depending on the type of centrifuge used. Thus, centrifugation is a lower total cost system than vacuum filtration provided the solids lost in the centrate are not important and that the resulting cake solid is incinerated.[47] Existing technologies for dewatering domestic sludges can be successfully applied to digested MSW sludge without significant modifications. Filter presses probably may be used to dewater high solids concentration MSW slurries with sizable quantities of fine particles[26] however, supporting experimental evidence is not yet available.

Ultimate disposal of digested sludge after treatment depends on site-specific economics and governmental regulations. Common disposal methods include land-filling, incineration, pyrolysis, solar drying fields, and sludge storage basins. The advantages and disadvantages of various disposal methods for MSW sludges are not well described; however, combustion methods with heat recovery may provide more beneficial effects than land-filling, especially since acceptable land-filling sites are becoming very scarce in major parts of the country.[26]

h. Reactor Design

One major drawback of conventional digester design is the large volume needed. Several design variations have been proposed to reduce capital and operating costs by digester volume reduction. The success of an innovative design could have significant impact on the economics of MSW bioconversion since the digestion process may represent 28% of the energy consumption and 35% of the capital cost in the overall digestion system.[51] Alternate design concepts have been reviewed and discussed in a report by MITRE Corporation.[23] They are summarized here in Table 9.

Several models may be superior to the conventional digester. However, the technology of these novel concepts are at an early stage of development and are still unproven at the practical level. Detailed studies, including economic analysis of these concepts, should be made in order to incorporate any advantages into "established," conventional systems.

C. Economic Studies

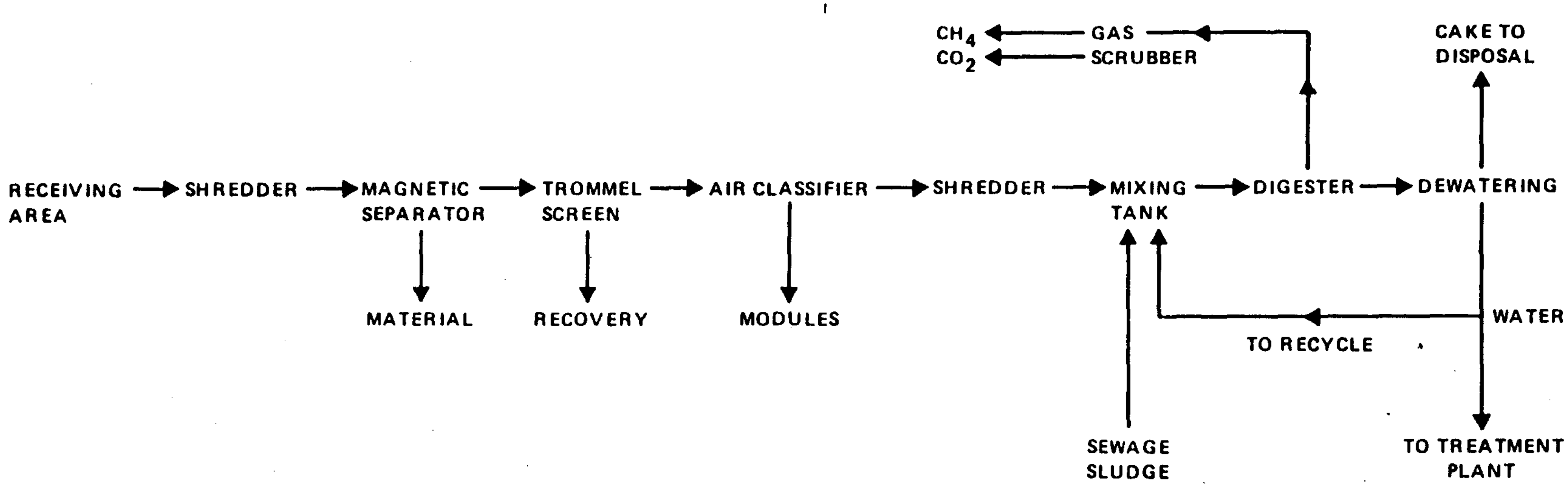
Numerous studies on the economics of MSW bioconversion to methane have been reported.[14,23,26,51,52] A computer model was developed[51] for sizing process equipment at the lowest cost based on the 1000 ton/day Dynatech system shown in Figure 3. Analysis of capital and operating costs, credits for handling MSW (tipping fee) and sewage sludge, and

Table 9
ALTERNATE REACTOR DESIGNS

Process description	Potential advantages	Technical status
Fixed or fluidized bed: packed bed digester composed of containment vessel, inert bed material which support biological growth, circulating fluid, substrate (i.e., MSW)	Specific gas production expressed as Vol. CH_4/Vol Reactor is up to 7 times that of conventional systems. Ability to treat 2 to 3 times the solids concentration of conventional systems. Less energy requirements	Pilot scale application to MSW; plant biomass. No detailed conceptual design or cost analysis of large scale bioconversion facility as yet
2-Stage digestion: incorporates high-rate digestion and standard unmixed digester for solids removal	Lower retention time	Well established for sewage sludge treatment
2-Phase digestion: 2 biologically active digesters in series functioning to optimize conditions for acid-forming and methane-producing bacteria. 2-phase separation can be accomplished by kinetic control of both groups of bacteria through adjustment of organic loading rate and cell retention time	Increased process control, lower overall retention time, improved digester efficiency and hence methane yields, less energy requirements for mixing, and less digester volume required	Laboratory scale kinetic control demonstrated using glucose, sewage sludge and cellulose as substrate; 2-phase sewage sludge digestion plant design developed
Plug flow digestion: conical cylinder lying on its side through which digester substrate continuously moves. Feedstock continuously loaded from one end and discharged from the other end. Virtually no blending or mixing solids	No energy requirements for mixing, lower capital cost, more efficient conversion	Economic feasibility demonstrated with farm and agricultural wastes (pilot scale). MSW/raw sludge acid digestion by plug flow demonstration on bench scale

penalties for the disposal of the effluent were included. To account for uncertain values in the analytical description of the system, a sensitivity study was incorporated to evaluate technological advances or economical changes on the process. The process economics were most sensitive to the digestible fraction of MSW and tipping fees. Other major economic factors included digester operating conditions, dewatering costs, and financing options (i.e., public vs. private). Based on these factors, the cost of methane production was economically acceptable compared with projected costs of natural or synthetic gas. Additional considerations such as cost of disposal facilities for trommel screen "unders" (trommel rejects), air classification of "heavies," dewatered cake, increased electric power requirements, and operating personnel were not considered. Inclusion of these factors into the analysis gave a different picture. It showed that the economic feasibility of the process was not encouraging and that a tipping fee of $15.60/ton (without incineration) to $19 to $22/ton (with incineration) was required as the major source of revenue to offset cost.[23]

The technical and economic feasibility was also examined for various MSW bioconversion processes based on four major process steps: feedstock preparation, feedstock pretreatment, digestion and gas production, and residue disposal.[26] Four process were selected on this basis (Table 10), and cost estimates were prepared for production plant capacities of 1000, 2000, and 3000 ton/day of MSW. A number of process variables affected the cost of gas production for the four alternative processes. The most influential were the manner of financing, feedstock preparation costs, and tipping fees. The following conclusions were reached in the analysis:



DYNATECH'S HYPOTHETICAL SYSTEM

FIGURE 3. Flow process diagram of anaerobic digestion used for Dynatech economic analysis. (Adapted from Kispert, K. G., Sadek, S. E., and Wise, D. L., *Res. Recovery Conserv.*, 1, 95, 1974.)

Table 10
FOUR ALTERNATIVE MUNICIPAL SOLID WASTES DIGESTION PROCESSES

Alternative 1 —	Mesophilic digestion of fluff RDF; residue disposal to landfill
Alternative 2 —	Mesophilic digestion of fluff RDF; thermal processing of residue
Alternative 3 —	Thermophilic digestion of fluff RDF; thermal processing of residue
Alternative 4 —	Mesophilic digestion of Cal Recovery System RDF; thermal processing of residue

(Taken from Brown and Caldwell Consulting Engineers, Microbial Production of Methane from Refuse, Report Prepared for So. California Edison Co., Research and Development, 3—8, 1978.

1. Minimum cost gas would be produced at maximum loading rates of MSW subjected only to shredding and ferrous metals removal.
2. Feed concentration should be the maximum, depending on available mixing.
3. The dewatered residue should be thermally processed, and the heat recovered for plant operation; excess steam should be sold.
4. The Cal Recovery process is apparently the most cost-effective at about 1000 ton/day if excess steam is sold and organic loading rates are restricted to the lower range.
5. The economics of fuel gas production are less affected by process variation than by external factors such as tipping fees, sewage sludge disposal credits, and the method and cost of digested residue disposal.

Site-specific economic studies[14] on the digestion of MSW with thermal processing of the residue disclosed five important factors for establishing the economic feasibility of any MSW conversion process:

1. Capital cost of the facility
2. Operation and maintenance cost
3. Market for recovered steam from thermal processing of the nondigestible fraction or gas from pyrolytic thermal processing of nondigestible fraction
4. Land acquisition and development of cost
5. Tipping fee revenue

The first three factors are a function of process selection and facility design; the remaining two are site specific. Among the major conclusions were

1. A facility designed for anaerobic digestion and thermal processing of MSW in Southern California can produce a medium Btu and/or steam product at a cost as low as $6.00/ 10^6 Btu.
2. The most cost-effective option apparently involves mesophilic digestion of the noncellulose organic fraction, with thermal processing of the nondigestible fraction.
3. Energy recovery from the thermal processing step is necessary for the economic feasibility of the process.

A general cost evaluation of the co-digestion of MSW and sewage sludge was recently undertaken[52] with the following assumptions: a resource recovery plant sized at 2500 metric tons MSW per day; use of Cal Recovery feedstock; digester operating conditions as specified by Pfeffer and Liebmann,[33] vacuum filtration for dewatering; and land-filling for the residue disposal. The largest projected expense was the vacuum filter dewatering equipment. The difference in cost between the system with and without dewatering was $25.7 million/year without accounting for the tipping fee. Thus, although lower disposal fees were expected for dewatered solids, the savings were not sufficient to augment the capital and operating costs of the filtering equipment.

III. RECENT ADVANCES

Much work (Table 11), mostly at mesophilic temperatures, has been reported on methane production from anaerobic digestion of various organic wastes. The feedstocks included primary and activated sewage sludge, processed municipal solid waste, dairy and beef cattle wastes, water hyacinths, kelp, and peat. The organic loading rate ranged from 0.05 lb VS (volatile solids) per cubic foot reactor to as much as 1.7 lb/ft^3/day. The hydraulic retention time (HRT) also varied widely, from 3 days for cattle feedlot waste at the thermophilic 60°C to 60 days for peat at 35° and 55°C.

The "methane conversion" values (cubic foot CH_4 per pound VS added) indicate the efficiency of the digestion process to convert the organic substrate into methane gas. The maximum biogas yield from protein is 12 ft^3/lb and 20 ft^3/lb for fat.[22] This is equivalent to a range of 5 to 9 ft^3/lb of organic substrate added, assuming the presence of an undigestible component in the substrate. The maximum theoretical yield of 8.4 ft^3 CH_4 per pound VS added for peat[63] should be decreased to 6.7 ft^3 CH_4 per pound VS added if a bacteriological growth yield of 0.2 were used in calculating the methane yield. The maximum theoretical yields of CH_4 calculated for kelp and corrected for cellular maintenance requirements[64] are between 5.84 and 6.77 ft^3 CH_4 per pound VS added. One pound of any digestible substrate (such as MSW) yields a maximum of 6.65 ft^3 CH_4 at standard temperature and pressure.[65]

Methane conversion efficiencies of 4 ft^3 CH_4 per pound VS added are typical for the digestion of various organic wastes (Table 11). However, the digestion of sewage sludge commonly produces 5.5 ft^3 CH_4 per pound VS added, depending on the proportion of methanogenic substrates such as fats and other lipids. The digestion of MSW alone or supplemented with raw sewage sludge yielded methane conversion values in cubic feet CH_4 per pound VS added of 3.80,[34] 5.16,[39,40] 3.85,[5] and 2.73.[47]

When the methane conversion value is divided by the hydraulic retention time, a value called the "specific methane production rate" (cubic feet CH_4 per pound VS added per day) results; this figure is useful for evaluating gas production for organic loading rates and retention times required to achieve that conversion. High relative values for the specific methane rate indicate good methane conversion efficiency without excessive retention time. In the same MSW digestion studies cited above, the respective specific CH_4 production rates were 0.38, 0.17, 0.13, and 0.27 ft^3 CH_4 per pound VS per day. Although an intermediate CH_4 conversion efficiency of 3.80 ft^3/lb VS was reported by Ghosh et al.[34] the specific CH_4 production rate was high at 0.38 ft^3/lb/day because of the low retention time of 10 days. Since the specific CH_4 production rate depends on conversion efficiency and retention time, it is useful for evaluating optimal methanogenic digestion and process design.

Data on the digestion of dairy and beef cattle wastes support the following conclusions:

1. The homogeneous nature of the substrate and its adaptability to thermophilic digestion facilitate the use of high loading rates.
2. Digestion at high loading rates results in relatively high volume CH_4 per volume digester-day production values.
3. Methane conversion efficiency and percent VS reduction values are typically low.

Table 11
METHANE PRODUCTION FROM VARIOUS ORGANIC WASTES

Substrate feed	Temperature	OLR (lb/ft³) per	OLR (g/ℓ) day	DT day	CH_4 conversion (ft³/lb added)	CH_4 conversion ℓ/g	CH_4 production v/v-day	Specific CH_4 production rate SCF/lb VS added	CH_4 (%)	VS reduction (%)	Ref.
1. Primary sludge	35	(0.13)	2.1	15	(7.06)	0.44	0.92	0.47	69	61.3	53
2. Activated sludge	35	(0.12)	1.9	15	(3.05)	0.19	0.36	0.20	75	26.2	53
3. MSW	35	(0.13)	2	12	(5.30)	0.33	0.67	0.44	60	50	54
4. MSW/RSS	35	(0.14)	2.2	10	(3.80)	0.24	—	0.38	61	58.5	34
5. MSW/RSS	35	(0.07)	1.1	30	(5.16)	0.32	—	0.17	—	52	39
6. MSW/RSS	35	(0.07)	1.1	15	(4.80)	0.30	—	0.32	60	60	40
7. MSW/RSS	35	(0.30)	4.8	15	(4)	0.25	—	0.27	65	—	40
8. MSW/RSS	37	(0.08)	1.2	30	(3.85)	0.24	—	0.13	55	67	5
9. MSW/RSS	60	—	—	10	(2.73)	0.17	—	0.27	53	47	47
10. DCW	32	(0.54	8.7	10	(2.28)	0.14	1.23	0.23	64	29	55
11. DCW	32	(0.07)	1.2	30	(3.80)	0.24	0.27	0.13	65	39.8	55
12. DCW	35	(0.44)	7	12	(0.80)	0.05	0.35	0.07	65	21	56
13. DCW	37	(0.28)	4.5	15	(2.66)	0.17	0.75	0.18	65	31	57
14. DCW	37	(0.56)	9	7	(2.29)	0.14	1.27	0.33	64	28	57
15. MSW/DCW	37	—	—		(2.40)	0.15	—	—	54	—	58
16. CFW	55	(0.21)	3.4	20	(3.53)	0.22	0.75	0.18	58	44.2	59
17. CFW	55	(0.32)	5.2	12	(4.97)	0.31	1.59	0.41	55	52.8	59
18. CFW	55	(0.71)	11	6	(3.69)	0.23	2.60	0.61	53	46.1	59
19. CFW	55	(0.94)	15	4	(3.37)	0.21	3.14	0.84	50	39.8	59
20. CFW	60	(0.52)	8.3	12	(3.53)	0.22	1.83	0.29	57	53	60
21. CFW	60	(1.7)	27	3	(2.56)	0.16	4.20	0.85	53	35	60
22. CFW	60	(0.43)	7	10	(2.88)	0.18	1.25	0.29	60	—	60
23. CFW	60	(0.81)	13	9	(1.60)	0.10	1.30	0.18	58	—	60
24. Hyacinths	37	(0.02)	0.26	20	(4.01)	0.25	0.07	0.20	56	66	61
25. Hyacinths	37	(0.03)	0.53	10	(3.21)	0.20	0.11	0.32	56	56	61
26. Kelp	35	(0.10)	1.6	18	(4.49)	0.28	0.45	0.25	58	50.8	62
27. Kelp	35	(0.10)	1.6	40	(4.17)	0.26	0.42	0.10	59	50.8	62
28. Peat	35	(0.05)	0.8	60	(1.14)	0.07	0.06	0.02	59	11.1	63
29. Peat	55	(0.05)	0.8	60	(2.89)	0.18	0.14	0.05	59	16.7	63

Note: MSW — Municipal solid waste classified digestibles
DCW — Dairy cattle waste
CFW — Cattle feedlot waste
RSS — Raw sewage sludge

These highly alkaline wastes probably buffer the acidic products which result from the high loading rates. The dairy wastes are generally less methanogenic than the beef cattle wastes, probably due to the greater plant matter and lignin content of the former. There is also less reduction of volatile solids during digestion of dairy wastes.

Laboratory- and pilot-scale methanogenic fermentations of classified MSW were examined in this study. Experimental findings, conclusions, and recommendations for anaerobic digestion of classified MSW are presented in this section.

Laboratory-scale experiments were conducted using 4 to 1 Pyrex® bottles with a 3 to 1 liquid working volume. Pilot-scale operation involved 50-gal cylindrical stainless steel (alloy 304) vessels with a 45-gal working volume. All fermentations were incubated at 98.6°F (37°C). The Cal Recovery System provided the classified digestible MSW feedstock for digestion. In the bench-scale experiments, the MSW was originally collected from the Berkeley/Richmond, Calif. area. For the pilot-scale studies, MSW feedstock was selected to simulate the composition of the entire city of Santa Monica, Calif. The Santa Monica municipal waste was categorized into the following components and an average proportional value determined for each: mixed paper, newsprint, corrugated paper, plastics, yard waste, food waste, other combustibles, ferrous metals, aluminum, glass, other noncombustibles, and miscellaneous. Cal Recovery System used the component ratios to select similar MSW from the vicinity of the University of California Berkeley Richmond Field Station for preprocessing and classification. The digestible MSW fraction from this operation was used in the pilot studies.

A. Bench-Scale Studies

Digesters were maintained at 98.6°F (37°C) ± 1°F, fed once daily and mechanically mixed thrice hourly. Retention times of 15 and 10 days were used. Digestion of the MSW was initiated by gradually adding MSW to the raw sewage feed of actively fermenting sewage sludge digesters until the desired feed proportion was established for a minimum of three retention times. Nutrient supplementation by addition of raw sewage sludge, cattle feedlot wastes, and dairy wastes was measured by examining MSW digestion and methanogenesis. Organic loading rates from 0.11 lb/ft^3/day (1.7 g/ℓ/day) to 0.35 lb/ft^3/day (5.6 g/ℓ/day) were evaluated.

B. Pilot-Scale Studies

Pilot-scale digesters were also maintained at 98.6°F, fed once daily and mechanically stirred continuously with a 2-impeller vertical shift mounted to a 1/4 hp Bodine motor. MSW digestion was initiated in a manner similar to the bench-scale studies. Retention times were 15, 20 and 30 days and organic loading rates varied from 0.07 lb/ft^3/day (1.1 g/ℓ/day) to 0.25 lb/ft^3/day (4.0 g/ℓ/day). A 20% raw sewage sludge supplementation was tested for enhancement of digestion and methanogenesis.

C. Results

Results, summarized in Tables 12 and 13, show the methane production calculated at standard temperature and pressure (0°C, 1 atm) and corrected for moisture content of the biogas. In the bench-scale studies, the MSW was fermented alone or was supplemented with cattle feedlot waste, raw sewage sludge, or both. When fermented alone, MSW produced 3.75 ft^3 CH_4 per pound VS. When supplemented with sewage sludge and cattle feedlot wastes, 5.70 and 5.94 ft^3 CH_4 per pound VS was formed at retention times of 15 and 10 days, respectively. A high volumetric methane production rate of 2.08 volume CH_4 per volume digester fluid per day was observed. This is particularly impressive for a mesophilic digestion process. A specific CH_4 production rate of 0.59 ft^3 CH_4 per pound VS per day, indicative of the relatively short retention time of 10 days, was also achieved. At a maximum

Table 12
LABORATORY BENCH-SCALE EXPERIMENTS

Digester	#1	#2	#3	#4	#5	#6
Feed	MSW	MSW/CFW	MSW/RSS	MSW/RSS/CFW	MSW/RSS/CFW	MSW/FSS/CFW
Composition (%)	100	75/25	75/25	70/15/15	75/15/15	75/15/15
% VS influent	2.85	2.55	2.85	5.55	8.40	5.60
OLR	0.12	0.11	0.12	0.23	0.35	0.35
HRT	15	15	15	15	15	10
pH	6.7	6.9	7	7.1	7.1	7.1
%CH_4	58	60	63	63	63	60
VVD	0.45	0.53	0.64	1.31	1.94	2.08
ft^3 CH_4/lb VS*	3.75	4.82	5.33	5.70	5.54	5.94
$\frac{ft^3\ CH_4/lb\ VS^*}{HRT}$	0.25	0.32	0.36	0.38	0.37	0.59

Note: MSW — Municipal solid waste classified digestibles.
CFW — Cattle feedlot waste.
RSS — Raw sewage sludge.
VS — Volatile solids.
OLR — Organic loading rate, lb VS/ft^3 reactor/day.
HRT — Hydraulic retention time, days.
VVD — Volume of CH_4 produced/volume of reactor/day.

* CH_4 production data presented are standard temperature and pressure (0°C, 1 atm), and corrected for moisture.

Table 13
PILOT-SCALE EXPERIMENTS

Digester	#1	#2	#3	#4	*5	#6
Feed	RSS	MSW/RSS	MSW/RSS	MSW/RSS	MSW/RSS	MSW/RSS
Composition (%)	100	80/20	80/20	80/20	80/20	80/20
% VS Influent	3.3	3.7	3.85	4.8	5.13	7.4
OLR	0.10	0.12	0.16	0.10	0.16	0.23
HFT	20	20	15	30	20	20
pH	7.5	7.2	7.2	7.3	7.2	7.1
%CH_4	60	58	58	58	58	58
VVD	0.81	0.48	0.54	0.50	0.70	0.68
ft^3 CH_4/lb VS*	7.88	4.16	3.38	5.04	4.40	2.95
ft^3 CH_4/lb VS* / HRT	0.39	0.21	0.23	0.17	0.22	0.15

Note: MSW — Municipal solid waste classified digestibles.
RSS — Raw sewage sludge.
VS — Volatile solids.
OLR — Organic loading rate, lb VS/ft^3 reactor/day.
HRT — Hydraulic retention time, days.
VVD — Volume of CH_4 produced/volume of reactor/day.

* CH_4 production data presented are standard temperature and pressure (0°C, 1 atm), and corrected for moisture.

loading rate of 0.35 lb VS per cubic foot reactor per day and an influent concentration of 5.6% volatile solids, the MSW was optimally digested.

The pilot-scale digesters exhibited a conversion rate of 5.04 ft^3 CH_4 per pound VS added at a retention time of 30 days, and the specific production rate was only 0.17 ft^3/lb VS per day. A maximum specific production rate of 0.23 ft^3/lb/day was achieved at a retention time of 15 days and an organic loading rate of 0.16 lb VS per cubic foot reactor per day. Inadequate mixing of the digester material (MSW + sewage sludge) was by far the greatest hindrance and limitation to process performance.

D. Discussion

The disparity in the results between bench- and pilot-scale experiments has not been resolved. Three main factors which influence the scale up studies were the source of the MSW, the preprocessing system for classifying the MSW, and the digestion process design.

1. Source of MSW

MSW composition varies from one part of the country to another. A comparison of the major refuse components in a few urban areas with the national average (Table 14) shows that most components were present in similar proportions although food wastes, yard wastes, and miscellaneous component fluctuations may exist from one geographical location to another. The food and yard wastes contain the most digestible organic materials; they consist of 50 to 70% or more water, are readily solubilized and metabolized by microorganisms. Food and yard wastes have a nutritionally favorable carbon to nitrogen (C:N) ratio (about 16:1) and a carbon to sulfur (C:S) ratio of 120:1 to 150:1. The largest organic component is paper and paper products; its proportion in refuse is highly consistent (Table 14) throughout the country. Paper waste, however, is generally less readily digested, contains only 8% moisture, and a C:N and C:S ratio of 150:1 and 400:1, respectively. The MSW moisture content varies seasonally. Because of such differences, the digestibility and methanogenic potential of refuse-derived organic compounds differ from one source to another.

Bench-scale fermentation of the MSW from Berkeley, Calif. and pilot-scale fermentation

Table 14
URBAN REFUSE COMPOSITION DATA[a]

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Paper products	37.4	44	58.8	31.9	40.2	52.6	44.6	45.7	43.2
Food wastes	20	17.1	9.2	4.3	5.4	2	20.1	10.9[b]	8.1
Yard wastes	13.9	9.4	7.6	30.7	20.7[c]	13.9	5		18
Metals	8.4	8.6	8.6	5.8	6.1	7.7	8.7	13.6	5.4
Glass, ceramics	9.8	8.8	6	7.1	8	6.8	11.3	16.6	10.6
Plastics	1.4	1.4	0.8	2.7	1.3	2.1	2.1[d]	2.1	7
Leather, rubber	1.2	1.5	—	0.9	0.5	0.3		1.1	—
Textiles	2.2	2.6	1.6	2.3	2.5	1.1	1.9	—	
Wood	3.1	3	2.5	4.2	2.1	0.9	—	2.1	—
Miscellaneous	3.4	3.6	4.9	10.1	12.4[e]	10.6	7.1	6	7.5
	100	100	100	100.3	99	99.4	100	100	99.8

Note: (1) — Estimated average municipal refuse, as discarded; 1970[66]
(2) — Estimated average municipal refuse, mixed (moisture equilibrated); 1970[66]
(3) — Typical raw municipal refuse, dry weight; 1973[67]
(4) — Southern California composite; 1976[26]
(5) — City of Los Angeles; 1973[68]
(6) — City of San Diego; 1972[69]
(7) — Berkeley, Calif., 1967[66]
(8) — Indianapolis municipal solid waste; 1977[36]
(9) — Santa Monica MSW survey; 8/80—2/81

[a] Expressed as "weight %, as discarded" unless otherwise noted.
[b] Food wastes and yard wastes.
[c] Tree trimmings.
[d] Plastics, leather and rubber.
[e] Grass and dirt.

of the simulated Santa Monica MSW are compared in Table 14. Significant differences in MSW composition are seen in the organic food wastes which comprised 20% of the Berkeley wastes but only 8.1% of the Santa Monica wastes. The Santa Monica MSW had a higher proportion of yard wastes, whose quantity and quality undergoes seasonal and climatic variation. Such differences no doubt contributed to the disparity in the results of these two studies.

2. *Preprocessing System*

The preprocessing method for classifying the MSW determines in large measure the ultimate methanogenic potential of the refuse-derived fuel (RDF). Although the Cal Recovery System RDF contained only 60% volatile solids compared to about 80% VS in RDF from other processes[69,70] (see Figure 2), the Cal Recovery RDF retained a high (35%) moisture content. In contrast, the moisture content in RDF from other processes ranged from 4 to 10%. The high moisture in the Cal Recovery RDF improved its wetability and susceptibility to microbial and hydrolytic actions. The Cal Recovery RDF originated from both the air-classified light and heavy fractions (refer to Figure 2). The heavy fraction contained moisture-laden food and yard wastes, paper products, and heavier organic substances which are eventually combined with the final light fraction to produce the RDF product. In no other MSW processing system are these moist and heavier organic substances systematically preserved in the RDF. Other processes tend to exclude organic components and favor production of a dry light RDF. Ghosh et al.[34] used a final fiberizer unit to dehydrate the product even further. Others employed a drying unit and a final unit for fine shredding,[69] both of which dehydrate the RDF, although these latter products were used in physioco-

Table 15
STATE-OF-THE-ART DESIGN CRITERIA FOR MSW DIGESTER

Process Parameter	Design Criteria	Ref.
MSW moisture content	35—40% (After ferrous removal)	16
Preprocessing system	Designed specifically to remove fiber portion of MSW yielding a highly organic fraction (as in Cal Recovery System)	26, Present study
Pretreatment	None	26
Particle size	0.5 in. or less	
Nutrient addition	Municipal primary sludge	33, 34, 39, 40
Ratio of MSW to sludge	5:1	40
Organic loading rate	0.10—0.20 lb VS/ day (with raw sludge)	39, 40, Present study
Retention time	10—15 days	40, Present study
Feed slurry concentration	4—6 % total solids	Present study
Temperature of operation	Mesophilic at 95°F	34, 42
Mixing mode	Mechanical agitation	40, 45, 46
Reactor design	"Conventional" municipal sewage sludge digesters	
Dewatering	None or centrifugation	47, 52
Residue disposal	Sludge drying beds or incineration	26
Gas treatment	Degree dependent on subsequent use	

chemical energy conversion processes. An optional secondary shredding and final air classificaton which enhances drying was used by Pfeffer.[70] Each of these methods concentrated the paper products in the RDF. Since paper is a highly processed material and is very dry initially, these products are less soluble and less subject to hydrolysis and microbial attack and exacerbate the scum and floating mat problem in digesters. Thus, the Cal Recovery System produces an RDF much more suitable for anaerobic digestion conversion.

3. Process Design Parameters

One element of the process design which requires more development is the type of mixing system for the large-scale MSW digester. Indeed, the difference between the pilot- and bench-scale studies may be attributed to inadequate mixing at the pilot-scale. In the bench scale studies, the Cal Recovery RDF was easily mixed, however, the pilot-scale studies indicated it was not refined enough for the mixing system used. Novel designs for mixing or methods for changing the physical properties of the final RDF are needed.

Successful methanogenic digestion of the Cal Recovery RDF also depends on influent solids concentration and sludge retention time which determine the organic loading rate (OLR). Because of the low nitrogen content in MSW, nutrient supplementation must also be considered. Optimal MSW digestion occurred at an influent concentration of 5.6% VS at a 10-day retention time (OLR = 0.35 lb VS per cubic foot per day). At the same OLR but an increased retention time of 15 days, the influent concentration was 8.4% VS; under these conditions, the feed slurry was so viscous that mixing performance deteriorated and methanogenic digestion efficiency decreased. A 10-day retention time at the same OLR lowered the influent solids concentration and eliminated the problem by lowering the viscosity. The methanogenic microflora can thus be maintained at a 10-day retention time or lower. Optimal performance may be achieved with proper selection of OLR or influent solids concentration. A concentrated feed may yield better fermentation stability maintained in the digester.[41] Optimal performance was achieved with an influent concentration of 5.6% volatile solids and an OLR of 0.35 lb VS per cubic foot reactor per day.

IV. CONCLUDING REMARKS

Technology for MSW digestion is still at an early stage of development. The technical and economic feasibility of the overall process is dependent on a number of factors, some external to and others within the process itself. The most important factors include the site-specific sources and characteristics of MSW, land availability, local economics, potential market for recovered material, development of "optimal" proprecessing configuration, and methods of pretreatment for increased feedstock digestibility.

Evaluation of work related to MSW digestion performance parameters shows much research still needed, especially in the areas of optimum particle sizes, feed slurry concentration, and acceptable mixing. Anaerobic digestion of MSW is a usable technique for the volume and mass reduction of solid waste and for energy recovery from otherwise useless material. However, continued research is required to make the process an economically attractive one.

The best current and most cost effective process-design criteria for MSW digestion are given in Table 15, which summarizes the present state of the findings from this study and other sources.

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