ANAEROBIC DIGESTION OF CLASSIFIED MUNICIPAL SOLID WASTES

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ABSTRACT

Municipal Solid Waste is presently a serious problem in urban areas such as Los Angeles. There is an increasing demand for more landfill area, but political pressure and the mushrooming cost of real estate makes acquisition of new landfill sites nearly impossible.

In response to the need for municipal solid waste disposal, a number of alternative disposal systems have been proposed. Many are based on classification of waste followed by some type of thermal processing. An alternate method is to use anaerobic digestion of a portion of the organic materials in the waste. Anaerobic digestion has the advantage of producing a medium BTU gas which can be used for electric power production or can be upgraded to produce home heating fuel.

This report discusses the results of a two-year investigation to determine the suitability of Los Angeles area municipal solid waste for producing digester gas. An experimental study was conducted using four 50 gallon pilot-scale digesters. The digesters were operated at organic loading rates ranging from 0.10 lb VS/ft^3 day to 0.25 lb VS/ft^3 day and over hydraulic retention times ranging from 15 to 30 days. Feed solids concentration ranged from 3.1 to 10.1% VS. In all cases the municipal solid waste was blended with raw, primary sludge obtained from the Hyperion Treatment Plant in a ratio of 80% waste to 20% sludge, on a volatile solids mass basis.

The results of the experimental investigation show that a medium BTU gas (55-60% methane) can be produced at a rate of 6.5 to 7.5 ft^3 gas/lb VS applied. The highest gas productions were obtained at the lowest loading rate. At higher loading rates reduced gas productions were observed, and this reduction is attributed to the inability to adequately mix the digesters.

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INTRODUCTION

The recent upward trend in energy costs has created renewed interest in novel, or heretofore uneconomical energy production techniques. A number of alternate technologies have been evaluated, including well-known methods such as passive solar heating, to poorly understood methods such as wave energy generation.

Energy production from biomass has become an important research topic. Many methods are being developed, including fermentation techniques to produce alcohols, combustion of waste biomass, and novel pyrolysis techniques. Anaerobic digestion of wastewater derived sludges is a particularly well-known biomass energy production technique, and has been used extensively at wastewater treatment plants to reduce mass and volume of waste sludges. Anaerobic digestion of waste sludges with energy recovery has been a commercially viable energy production technology for over 50 years.

Application of anaerobic digestion to other wastes has not found widespread commercial acceptance. A number of farm wastes, such as cow manure, have been treated in anaerobic lagoons for many years, but this application is primarily a waste disposal technique, rather than an energy production technique. One application of anaerobic digestion which appears attractive is the anaerobic digestion of classified municipal waste (MSW, garbage and refuse which has been shredded and sorted).

Solid waste production is an increasingly more important problem in urban areas. The volume of waste production is increasing rapidly, while the availability of landfill sites is declining. Existing landfills are being exhausted and the legal and financial problems of opening new landfills are causing delays which severely limit the availability of disposal sites. Anaerobic digestion of municipal solid waste is finding renewed interest due to this shortage.

Anaerobic digestion of classified MSW is attractive since it produces a medium BTU gas (550-650 BTU/ft^3) without producing the air pollution associated with incineration. In many urban areas, especially areas with air pollution problems like Los Angeles, this can be a major advantage. Unfortunately, much of the pilot scale experience with digestion of classified MSW has been poor, in direct contrast with bench scale studies. The difficulties with larger scale devices is partly attributed to insufficient classification and pretreatment, and partly due to mixing problems. It appears that many of the pretreatment techniques do not remove a sufficient portion of the indigestibles.

The objective of the study herein was to evaluate the Cal Recovery preprocessing technique in medium scale pilot (50 gallon) digesters to determine if economical gas production rates could be obtained. The effect of organic loading rate, influent solids concentration and retention time were also evaluated.

LITERATURE REVIEW

I. BACKGROUND

Anaerobic digestion has been used as a means of wastewater sludge volume reduction and stabilization for many years. The low-to-medium BTU gas generated from the process provides a portion of heat and power requirements to treatment plants. The successful application of anaerobic digestion in wastewater treatment plants led to the attempt by Babitt (1936) to treat domestic solid wastes by the anaerobic digestion process; however, these early results were generally unsuccessful and consequently the feasibility of the concept was not pursued for many years.

Interest in the digestion of municipal solid waste (MSW) was revived in the late 1960's principally by its potential for energy recovery. The thrust of research was initiated by Golueke and co-workers at the University of California, Berkeley. As part of a five-year comprehensive study on solid waste management, Golueke, et al. (1971) examined the feasibility of digesting "synthetic" MSW with sewage sludge and animal manure. Their results showed that a high percentage of the organic refuse could be anaerobically digested to form methane and carbon dioxide gases. In line with Golueke's preliminary work, Klein (1972) and McFarland, et al. (1972) investigated the technical feasibility of digesting "as received" MSW with minimal pretreatment (shredding only). In these studies, a 400 gallon pilot-scale digester was operated to determine the effect of the solid wastes on the digestion process and its potential for reducing the bulk of the input material. Their 18-week results 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. Brown, Pfeffer and Liebman (1976) at the University of Illinois conducted a major study investigating the economic feasibility of digesting processed MSW with limited addition of sewage sludge. The main objective of their four-year program was to determine the cost of methane production through a multi-step process which included pretreatment of the MSW, digestion, gas separation, sludge dewatering and residue disposal. Using a 100-gallon pilot plant operated at thermophillic temperatures and processed MSW from three geographical locations, the investigators examined the effects of recycling, nutrient addition and caustic pretreatment on MSW digestion, and the settability and dewatering characteristics of the resulting sludge. Computer simulation of their results showed that the overall process is economically sound with the economics being most sensitive to the credit allowed for refuse disposal.

Ongoing research in this field includes work from private business and Governmental agencies. Among the most active are 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 Refuse Conversion to Methane (RefCom) facility in Pompano Beach, Florida. This process, now sponsored by the DOE, includes primary shredding followed by ferrous metals recovery, secondary shredding, trommeling, and air classification. The resulting material is then introduced to a pre-mix tank, where it is blended with raw sludge, nutrients, and water and subsequently transported pneumatically into two mechanically agitated anaerobic digesters. The RefCom facility is designed to process up to 100 tons of MSW per day, and its primary technical objective is the demonstration of long-term and economically attractive gas production rates. The experimental program is divided into three phases including start-up, experimental programs and steady-state operation at optimum conditions. The independent variables to be evaluated are temperature, solids loading, feed slurry concentration and solid size. A final report to DOE is scheduled to be submitted in late 1981.

II. THE ANAEROBIC DIGESTION PROCESS

The anaerobic digestion process is a biological process used in waste treatment for the controlled destruction of biodegradable organic material. This process is currently applied at most major municipal wastewater treatment plants and less frequently for the treatment of several types of industrial and agricultural wastes. As a result of its widespread use for treating municipal sewage sludge, an abundance of literature exists for its practical application. However, despite the availability of the voluminous information, development of process control parameters have been largely emphirical due primarily to the extreme complexities in elucidating the microbial metabolic pathways involved in the process. Much of the current research in anaerobic digestion is directed towards understanding the complex ecosystem in the digester with the objective of securing a more confident and reliable design of the overall process. In this respect, reference is made to reviews by Mah, et al. (1977), Zehnder (1978), Wolfe et al. (1979), and Zeikus (1980) for a comprehensive microbiological and biochemical analysis of anaerobic processes.

Anaerobic digestion commonly takes place in a closed reactor (i.e., concrete or steel tank) under controlled conditions. Two types of digestion processes are now in common use: standard-rate and high-rate. In the standard rate digestion process, the contents of the digester are usually unheated and unmixed. Retention times for this process vary from 30 to 60 days. In the high-rate digestion process, the contents of the digester are heated and completely mixed. The required retention time is usually 10 days or more. A combination of these two basic processes is known as the two-stage digestion process. The primary function of second stage (standard rate digester) is to separate the digested solids from the supernantant liquor.

To facilitate a basic understanding of anaerobic digestion, the digestion process can be considered to be accomplished in two distinct phases: acid fermentation and gas formation. In the first phase, the organic matter to be digested is in solid form and, in order to become available to bacteria, it is hydrolyzed by external enzymes produced by the bacteria and dissolved in the liquid medium which surrounds them. The acid-forming bacteria then take these dissolved compounds (simple sugars, long chained fatty acids, etc.) and metabolize them into various volatile acids (acetic, butyric, etc.) which serve as a source of food for the methane producing bacteria in the second phase of methanogenesis. Certain species of the methane-producing bacteria (methanogens) are also capable of reducing carbon dioxide to form methane gas. In the overall process, the final end products of the complete conversion of organic matter under anaerobic conditions will be methane and carbon dioxide gas.

The two phases appear to involve at least two physiological different groups of bacteria. It also appears that the acid-forming bacteria possesses a much higher growth rate and are fairly resillient,making them better able to withstand sudden changes in environmental conditions than their counterparts, the methanogens. In this sense, the conversion of volatile acids (principally acetic acid) by the methanogens to methane is considered the rate-limiting step in the digestion process. In a properly operating digester, the two groups of bacteria reach an equilibrium at steady state conditions. Careful control of the digestive process is required to maintain proper population balance between the acid-forming and methane producing bacteria. Control of the process is currently accomplished by maintaining favorable environment conditions for balanced microbial growth. Control parameters include organic loading rate, feed quality, temperature, pH, and solids retention time. Current design procedures for sewage sludge digesters are shown in Table 1.

III. TECHNICAL EVALUATION

Much of the current knowledge and technology of MSW digestion is drawn from the substantial amount of literature and field experience accrued through years of digesting wastewater derived sludges. As such, most of the process parameters describing digestion of sewage sludge and MSW are identical. In general, MSW digestion for the volume reduction and the production of methane involves four major elements: preprocessing, digestion, gas recovery, and residue disposal. In the following sections, the more important considerations for establishing MSW digestion process design criteria will be discussed. These include the sources and characteristics of MSW; MSW preprocessing and pretreatment; digester performance parameters such as nutrient requirements, organic loading rate, retention time; feed slurry concentration, temperature, and mixing; gas quantity and quality; residue dewatering characteristics and ultimate disposal, and reactor design.

Table 1. Typical Operational Criteria for the Anaerobic Digestion Process Mesophilic Range

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

(after U.S. EPA, 1979)

A. Sources, Quantity, and Characteristics of MSW

MSW characteristics can vary significantly with respect to geographical location and time of year. Depending on the source of the MSW and its characteristics, one of several configurations can be developed to preprocess and/or pretreat the MSW to meet the requirements of the digestion process. In this regard, evaluation of the characteristics of MSW from site-specific sources is a critical factor in the determination of potential MSW to methane applicability.

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

In 1975 the Environmental Protection Agency (EPA), 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 United States. This is equivalent to 3.4 lb. of solid waste/capita/day. The EPA then projected the solid waste generation for the years 1980, 1985, and 1990 using the data generated by specialized agencies that routinely collect data. This data is summarized in Table 2.

The composition of MSW varies with time, location and local conditions. For example, the amount of yard waste is very sensitive to geographical location, seasons and type of dwelling. In Table 3, MSW composition data

Table 2. Projection of Municipal Solid Waste Generation Rates

Year	Million Tons/Year		lbs/Capita/Day
	Total Gross Discard[a]	Net Waste[b]	
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.

(after EPA-OSWMP, 1975)

Table 3. Refuse-Composition Data

Location	Notes	Food Wastes	Yard Wastes	Misc.	Ceramics	Metal	Paper Products	Leather, Plastics & Rubber	Textiles	Wood	Oil, Paint Chemicals	Total	References
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	—	100.0	Daniels (1970a)
Delaware County Broomal, PA	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	—	100.0	Hahn (1970a)
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	—	100.0	Hahn (1970b)
City of Memphis, TN	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	—	100.0	Achinger (1970)
Fulty County, GA Altanta 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	—	100.0	Daniels (1970b)
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	—	100.0	Niessen (1970)
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	—	100.0	Niessen (1970)
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	—	100.0	Niessen (1970)
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	—	100.0	Niessen (1970)
Long Island, NY Town of Babylon	Predominantly household minor quantities commercial & industrial	10.0	5.0	6.0	12.0	10.0	47.0	3.00 (4.0) 1.0	3.0	3.0	—	100.0	Kaiser, et al. (1971)
City of Berkeley, CA	Residential, Commercial 1967-as received basis	20.06	5.02	7.10	11.33	8.71	44.61	1.85(2.11)0.26	1.06	—	—	100.0	Golueke et al. (1970)

Table 3 (continued)

Location	Notes	Food Wastes	Yard Wastes	Misc.	Glass Ceramics	Metal	Paper Products	Leather, Plastics & Rubber		Textiles	Wood	Oil, Paint Chemicals	Total	References
Long Island, NY	Household-June 1966	9.89	26.17	9.62		8.05	36.26	2.95		3.16	3.90	–	100.0	Mear Symposium (1967)
	Household-Feb. 1967	16.70	0.26	11.37		10.60	53.33	3.54		2.24	1.46	–	100.0	" " "
City of New Orleans LA	Household Average- [illegible]9) May 15, 1978	18.90	9.20	–	16.2	12.2	39.4	1.5		2.6	–	–	100.0	Switzger (1969)
4-City, NJ 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	Ingram, et al. (1968)
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	Kaiser (1968a)
Hempstead, Long Island, NY	Predominantly Residential-as received	10.9	17.6^a	–	9.6	8.5	42.6	4.6		3.1 3.0	3.2	– –		Kaiser et al. (1968b)
	Residential and Commercial excluding bulky & industrial	12.0		20		8	46.0	4			7.0	–	100.0	Kaiser et al. (1967)
Johnson City, TN	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	Willson (1977)
	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, UT	Residential & Commercial, 4/68	8.5	4.2	5.9	4.6	8.4	61.8	2.5		2.0	2.2	–	100.1	" "
Cincinnati, OH	Residential, 10/66	28.0	6.4	–	7.5	8.7	42.0	1.6	1.0	1.4	2.7	–	99.3	U.S. PHS (1966)
Alexandria, VA	Residential & Commercial, 5/68	7.5	9.5	3.4	7.5	8.2	55.3	3.1		3.7	1.7	–	99.9	Willson (1977)
San Diego, CA	Residential & Commercial, 1967	0.8	21.1	–	8.3	7.7	46.1	0.3	4.7	3.5	7.5	–	100.0	U.S. PHS (1967)
Genesee County, NY	As collected, includes commercial, industrial, domestic, & demolition wastes	7.11	1.99	23.62	3.34	4.64	20.39	1.49		3.01	22.41	12.00	100.0	U.S. DHEW (1968a)
Flint, MI	Annual Average	32.	13.5	0.3	17.9	14.5	17.5	2.3		0.5	0.9	–	100.0	U.S. DHEW (1968)

Table 3 (continued)

Location	Notes	Food Wastes	Yard Wastes	Misc.	Glass Ceramics	Metal	Paper Products	Leather, Plastics & Rubber		Textiles	Wood	Oil, Paint Chemicals	Total	References
Genesee County, MI	Domestic	26.0	10.8	0.2	14.3	11.8	34.0	1.8		0.4	0.7	—	100.0	U.S. DHEW (1968b)
Santa Clara, CA	collected, domestic, average	2.3	23.8	—	12.7	7.6	47.5	1.0	1 (ave.)	1.2	1 (ave.)	–	100.0	FMC Corporation (1968)
Philadelphia, PA	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	—	100.0	Purdom (1966)
Jefferson County, KY	As collected, residential; average 66/67	19.8	—	1.3	10.5	9.3	59.1	—		—	—	—	100.0	U.S. DHEW (1967)
New Jersey	As collected	10.0	—	—	4.0	8.0	51.0	———— 4.0 ————			4.0	—	81.0	Hickman (1968)
Ohio	As collected	28.0	—	—	8.0	9.0	42.0	———— 3.0 ————			3.0	—	93.50	" "
Arizona	As collected	22.0	—	—	8.0	10.0	43.0	———— 1.0 ————			2.0	—	86.0	" "
California	As collected	15.0	—	—	2.0	7.0	54.0	———— 2.0 ————			2.0	—	82.0	" "
Tennessee	As collected	26.0	—	—	11.0	11.0	46.0	———— 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	100.0	U.S. DHEW (1968c)
Hamilton, Canada	June 28-July 26	31.0	13.0	—	7.0	5.0	33.0	1.3	1.0	2.0	6.0	–	99.0	Willson (1977)

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[a] Average of four 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.

are shown for various geographical locations within the United States as presented by Wilson (1977). 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 parts of the United States. The results in Table 4 have been adjusted, category by category, to a moisture level basis corresponding to the manufactured state of the material entering the refuse storage bins on an "as discarded" basis. The discarded solid waste mixed with other refuse materials may either lose or gain moisture. For example, food wastes transfer significant amounts of moisture to paper and textiles. The "as discarded" basis is useful for true relative magnitude of waste generation of various categories, for estimating garbage potential and forecasting refuse generation rates.

Brown and Caldwell (1979) presented data on the composition and projected quantities of MSW generated in Southern California. This is shown in Table 5 and 6. The composition data for Los Angeles County was developed by a weight averaging survey from the City of Los Angeles with an estimate of the commercial waste generated in the county. The national average composition of MSW prepared from surveys reported between 1968 and 1972 is also included in Table 6.

From Table 6, Brown and Caldwell (1979) reported the following trends for the composition of MSW in Los Angeles:

- Over a six-year period, there was a substantial decline in the proportion of mixed paper in MSW. This was accomplished by a small reduction in the newspaper component and an increase in yard trimmings. The net effect is that total digestible organics have declined by almost 20 percent within six years.

Table 4. Estimated Average Municipal Solid Waste Composition, 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	44.0
Yard Waste	27.1	6.2	0.4	14.4	13.9	9.4
Food Waste	17.7	22.7	24.1	20.8	20.0	17.1
Glass	7.5	9.6	10.2	8.8	9.8	8.8
Metal	7.0	9.1	9.7	8.2	8.4	8.6
Wood	2.6	3.4	3.6	3.1	3.1	3.0
Textiles	1.8	2.5	2.7	2.2	2.2	2.6
Leather & 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	4.0	4.2	3.7	3.4	3.6
Total	100.0	100.0	100.0	100.0	100.0	100.0

a: The refuse composition in winter in southern states is similar to that shown in fall.

(after Wilson, 1977)

Table 5. Quantities and Percentages of Municipal Refuse

County	1980		1990		2000	
	Quantity tons/day	Percent of total	Quantity tons/day	Percent of total	Quantity tons/day	Percent of total
Los Angeles	17,000	61	18,200	54	19,000	50
Orange	5,700	20	7,300	22	8,600	23
Riverside[a]	1,800	6	2,600	8	3,200	8
San Bernardino[a]	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

(After Brown and Caldwell, 1979)

Table 6. Municipal Refuse Composition, Percent by Weight

Item	City of Los Angeles			Commercial[d]	Los Angeles Country Average	National Average 1968-72[f]
	1971-72[a]	1973-74[b]	1976-77[c]			
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 Waste	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 & 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 & Stone	0.7	1.9	2.5	0.1	1.7	NA
Dirt & 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, Robert M. 1974. 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, Robert M. Interdepartmental Correspondence to Mr. William Guber, Assist. Director, Bureau of Sanitation, City of Los Angeles. July 1977.

[d] Source: Huitric, Ray. 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.

(After Brown and Caldwell, 1979)

- Plastics have increased by about 50 percent, textiles by more than 80 percent, and lumber by more than 200 percent. Overall total undigestible organics have increased by more than 120 percent.
- A threefold increase in ceramics and stone and a doubling of the dirt and miscellaneous category are evident. Total inorganics have increased by about 10 percent.

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

- Total digestible organics for the county, 50.5 percent, are significantly less than the national average of 69.6 percent.
- Total indigestible organics for the county, 24.3 percent, are greater than the national average of 8.4 percent.
- Total inorganics for the county, 25.1 percent, are slightly higher than the national average of 22.8 percent.

The data presented here on generation rate and composition of MSW within Los Angeles County and the nation are indicative of MSW variability in time and location. As such, care should be exercised before extrapolating results from one source of MSW to a new source of MSW. Because of the great variability of generation rate and composition, the design of solid waste management systems must provide high safety factors for the capacity and flexibility of operation, and must be designed for extraordinary contingencies. This requirement often results in overdesign, and under-utilization, in order to be able to process all refuse material. For the design of resource recovery equipment and control of processes, knowledge of the physical, chemical and biological properties of mixed refuse and its components is essential. The characteristics which are of most interest are moisture content, particle size, particle density, chemical composition and mechanical properties.

i) Moisture content:

Moisture content of various components of refuse changes with time because the transfer of moisture occurs at storage tanks and at the time of transport of mixed refuse. According to Hickman (1976) the moisture content is very important for the design of storage and conveying equipment because changes in moisture content alters the material characteristics such as size, density, and abrasiveness. Trezek and Savage (1975) have shown that moisture content in the feed has a significant influence on shredding energy requirements with energy requirements being minimum for moisture content in the range of 35 to 40 percent. In the case of permanent magnet systems for ferrous recovery, Blayden (1976) reported that the moisture content has an effect on recovery and purity, both decreasing with an increase in moisture content; however, for electronic separators Blayden found that recovery increases with increases in moisture content. For pyrolysis, Sullivan, et al. (1972) determined that the moisture content of the feed has an influence on end product formation and that lower moisture content requires less heat to reach operating temperatures, thereby reducing the overall energy requirements in pyrolysis operation.

ii) Particle size

Particle size is an important parameter in resource recovery operation because most separation processes require specific and relatively uniform size for efficient operation. The measurement of particle size of municipal solid waste (MSW) is difficult because of its odd shape. The common procedure for measurement of particle size is by sieving. Particle size has a significant effect on all eddy current processes in resource recovery (Vesilind & Reimer, 1981). Particle size also has a significant effect on landfill gas production in that smaller particles produce more gas. Dewalle, et al., (1978) proposed that a decrease in size of refuse particles by a factor of 10 increases landfill gas production by a factor of 4.4. It also appears that digester efficiency and mixing requirements are a function of particle size. Unfortunately, the energy consumption of MSW preprocessing systems is inversely related to particle size.

iii) Particle Density

Material densities have a strong effect on disposal as well as resource recovery operation. The low initial density and poor compaction property (at moderate pressures) of municipal solid waste decreases carrying capacity and contributes to high-cost collection and hauling. Density of shredded refuse is also important for the design of storage tanks and retrieval systems because of its changes with time due to gravity. Chain, et al. (1977) has reported that the density of refuse has an effect on landfill gas production with greater densities decreasing gas production. Dewalle, et al. (1976) proposed that this effect may be due to the reduction of exposed surface area available for enzymatic hydroloysis.

iv) Chemical Composition

The economic recovery of materials and/or energy depends on the chemical composition of the refuse and its heating value. The chemical composition of the refuse changes with both time and location. The presence of toxic substances and caustic materials in municipal refuse enhances corrosion in refuse processing equipment; can be a potential source of air and/or water pollution; and can inhibit digester performance. Wilson (1977) reported that hydrocholoric acid is formed from plastics (i.e., polyvinyl chloride and vinylidene chloride) commonly found in refuse, when burned in air. Other chemical characteristics of MSW such as its carbon/nitrogen ratio can have a detrimental effect on the digestion process since many sources of MSW are nitrogen poor.

v) Mechanical Properties

Information on mechanical properties of material is important for the identification and quantification of the parameters governing the comminution of heterogeneous material such as municipal solid waste. Stress strain data is especially important for the design of shredding equipment.

B. Preprocessing Unit Operations for Resource Recovery

Various systems have been attempted on a commercial scale for the processing of MSW to recover valuable materials (aluminum, glass, etc.) and to produce an organic fraction commonly referred to as refuse derived fuel (RDF). The types of systems developed and employed are largely determined by specific requirements, market conditions, and other constraints depending on any particular project. However, despite the commercial availability of unit processing modules, a universally accepted preprocessing system does not yet exist (Wright, 1978). Lack of sufficient operating information and experience; the heterogeneous characteristics of MSW, and diverse site-specific objectives have caused this void.

Although there are a number of possible arrangements of unit modules for a given system, a typical material processing system will employ common units such as shredders, trommels, air classifiers, magnetic separators and glass extractors. The RDF production plants presently in operation are representative of first-generation facilities whose processes have and are continuing to undergo extensive modifications. The MITRE Corporation (1979), under a DOE contract, has summarized existing RDF facilities. A number of these facilities are operational and others are evolving process configurations. For the purposes of this report, the following sections will 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 & Reimer (1981).

i) Shredders

Size reduction of MSW is important and required for the conversion of solid waste to a source of energy. The objective of shredding is volume and particle size reduction. According to Ham (1975) shredded refuse is more uniform in size, closer to homogeneity, and more compacted than unshredded refuse. Shredding also reduces landfill volume requirements and is sometimes justified solely on this basis. Shredding technology, borrowed largely from mining industries, is difficult to apply in resource recovery because of the non-homogeneity of MSW. Most of the machines used for shredding MSW are generally of the hammermill type. These include vertical axis hammermills (Tolle-Mache Ltd.; London, England and Heil Inc.; Milwaukee, Wisconsin), horizontal axis hammermills (Broyeurs Gonard; Paris, France and Jeffrey Manufacturing Co.; Pennsylvania), vertical axis grinders (Eidal-International Corp.) and horizontal axis impactors (Hazernag Co.; New York, NY).

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

The parameters controlling the size reduction of refuse are flow rate, refuse moisture content, amount of material held within the shredder, residence time, and physical size of the shredder. According to Shiflett and Trezek (1979) 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. Trezek and Savage (1975) proposed that higher speeds produce finer particle sizes, but require more energy. The authors also state that the energy consumption increases with higher feed flow rate and decreases with increasing moisture content, with a minimum energy requirement at a moisture content range of 35 to 40 percent.

ii) Screens

The objective of screening is separation of material by size. Screens used at the beginning of a resource recovery facility are for the rough sorting of the refuse and screens used towards the end of the processing system are for reclaiming organic materials and glass from shredded refuse. There are basically two types of screens used for resource recovery: 1) reciprricating screens and 2) revolving screens (also refererd to as trommels).

According to Savage and Trezek (1976) trommel screens are superior to reciprocating screens because of lower capital cost and lower power consumption. They reported that high flow rate reduces the efficiency of screens and the rate of reduction is higher for vibrating screens than for trommels. They also found that a trommel screen requires about 12 percent of the energy required for a comparable vibrating screen and that trommels operate at an overall efficiency of about 90 percent compared to 72 percent for the vibrating screens.

iii) Air Classification

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

Worsel and Vesilind (1979) introduced a "total efficiency" parameter (the product of light and heavy fraction recovered under a specific set of conditions) for the evaluation of air classifier performance. They reported that this parameter is an acceptable indicator of performance which can be used to facilitate the evaluation and specification of air classifiers. They also demonstrated that recovery of material is a function of air speed, and that recovery appears to be maximum at an air speed of 1500 ft/min. Murry and Liddel (1977) proposed that moisture content has little effect in the recovery of light products, and that efficiency decreases by about 5 percent if moisture content is doubled. They also report a deterioration in the recovery of lights with higher feed rates.

iv) Magnetic Separation

Magnetic separators are used primarily for the separation of ferrous naterial from MSW. In a resource recovery system, magnetic separators are used with two objectives: 1) the recovery of saleable material and, 2) to increase the heat content and purity of RDF for energy recovery by combustion methods or digestion. Magnetic separators also reduce the wear on downstream processing equipment by reducing the amount of abrasive ferrous material. The magnetic separator is usually located after the primary shredder and sometimes following air classification.

Two types of magnetic separators frequently used for resource recovery are 1) holding type separators and 2) suspended type separators. In the case of holding type separators, the shredded MSW is fed directly onto the collecting surface, whereas in suspended type separators, the collecting surface moves above a conveyor belt loaded with shredded MSW.

C. Preprocessing Systems for Energy Recovery

Technology for the extraction of energy from MSW can be categorized into two conversion processes: physiocochemical and biological. The physicochemical process involves various types of combustion methods and incineration while the biological processes include anaerobic digestion and fermentation schemes for alcohol production. The practical application to either process requires preliminary separation into combustible-noncombustible and fermentable nonfermentable fractions of MSW for efficient conversion.

The MITRE Corporation (1979) has categorized preprocessing sysetms into five categories according to their product: coarse RDF, fine RDF, densified RDF, powdered RDF and wet pulped RDF. Briefly, coarse RDF is produced by a single pass through a shredding device that reduces MSW particle size and homogenizes the combustible elements. Fine RDF is produced by adding a second grinding or a shredding process to reduce the particle size even further. Densified RDF is the product that results from processing fine RDF through pellet mills commonly employed in the animal feed industry. Powdered RDF is

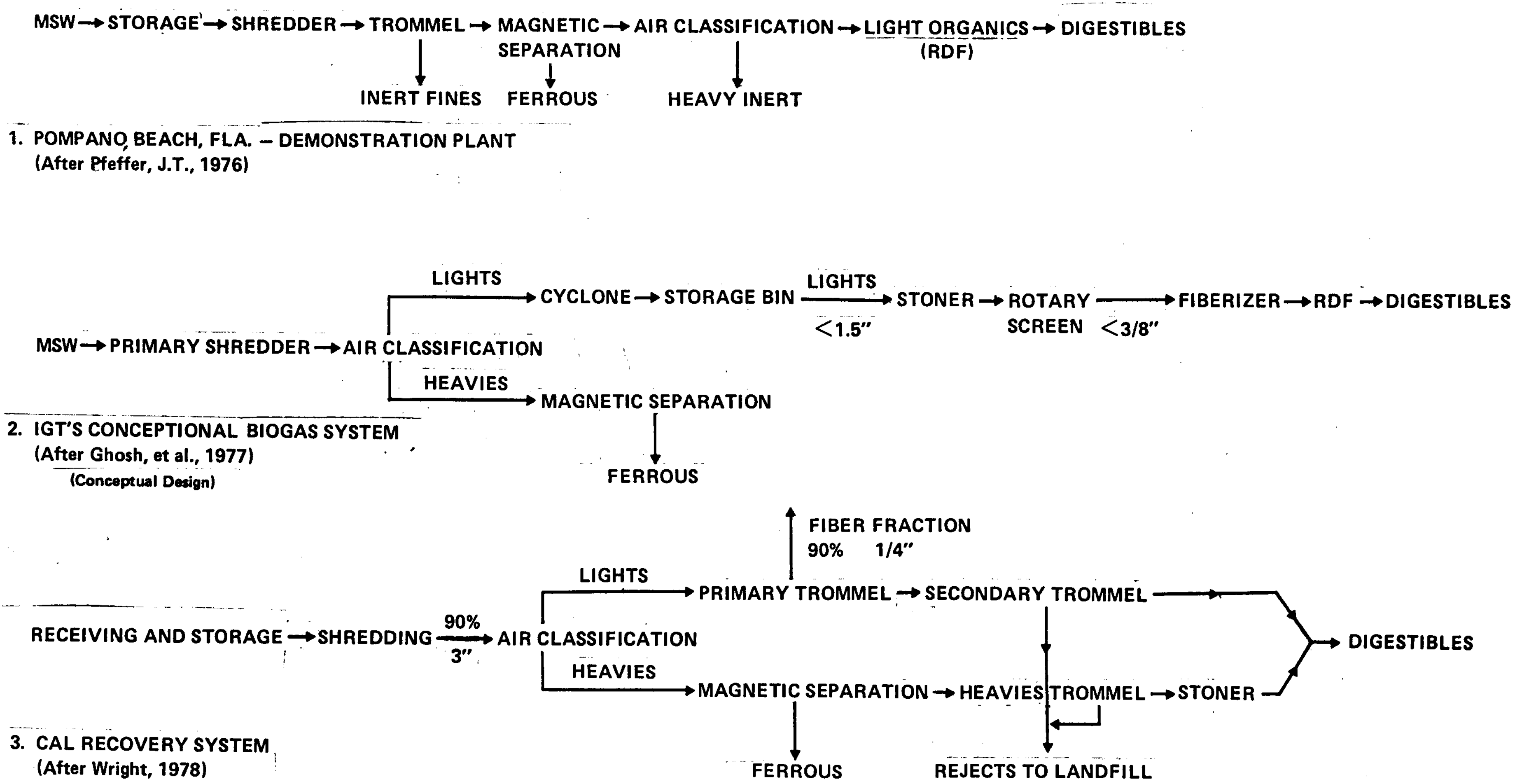
MSW turned into powder by a combination of mechanical, chemical and thermal action. The resulting product is dry and free flowing. In wet pulping, water is used as a medium for size reduction, inert separation, surge storage and conveyance. Size reduction is accomplished by a wet pulper that grinds MSW in a water medium into particles one inch or less in size while all other material is rejected. Comparative RDF characteristics are shown in Table 7.

Several patented preprocessing systems presently exist: Combustion Equipment Associates (Bridgeport, Conn.) market powdered RDF known as Eco-Fuel II while the Black Clawson process developed by Parsons and Whittermore, Inc. (Hempstead, NY) produces a pulped fiber RDF. The systems mentioned above produce a RDF compatible with physiochemical methods for energy recovery. Some preprocessing systems as applied to physiochemical processes will not necessarily yield a readily digestible fraction for biological energy conversion. As such, several preprocessing systems have been attempted to produce a RDF specifically for digestion. These are shown in Figure 1.

The Cal Recovery System appears to hold the most promise of the schemes shown in Figure 1, as it provides a means of separating a highly organic or digestible portion from the fiber portion of RDF. Cal Recovery's innovative features may be a key determinant of economic feasibility of methane gas production from anaerobic digestion. A description of the Cal Recovery System may be reviewed from the work of Savage, Diaz and Trezek (1975).

D. Pretreatment

Review of pretreatment technologies as applied to anaerobic digestion processes include those in the preprocessing steps described in the last section. Rationale for most types of pretreatment methods lies in the fact



1. POMPANO BEACH, FLA. – DEMONSTRATION PLANT
(After Pfeffer, J.T., 1976)

2. IGT'S CONCEPTIONAL BIOGAS SYSTEM
(After Ghosh, et al., 1977)
(Conceptual Design)

3. CAL RECOVERY SYSTEM
(After Wright, 1978)

Figure 1. Anaerobic Digestion Preprocessing Systems

Table 7

Comparative RDF Characterists

	Coarse[a]	Fine[b]	Densified[c]	Powdered[d]	Wet-Pulped[e]
Higher Heating Value as Received (BTU/lb)	5,319	5,610	6,000	7,740	3,600
Ash (percent)	15-17	17	25	15-25[f]	25
Moisture (percent	NA	23	10-16	2.0	55
Nominal Particle Size (in.)	4-6	1.5	0.5 x 1.25	0.015	NA (<1)
Bulk Density (lb/ft^3)	4-6 (est.)	8	28	30-34	NA
Handling/Storage Characteristics	Poor	Poor	Good	Good	NA

(After Mitre Corp., 1974)

NA: Not Available

a: Mitre Corp. (1979)
b: Even (1977)
c: Systems Technology Corp. (1977)
d: Beningson (1975)
e: U.S. EPA (1975)
f: Mitre Corp. (1979)

that the digestible portion of MSW consists primarily of paper products containing about 75 percent carbohydrates, mostly in the form of cellulose. Although cellulose is readily digestible, the portion that is tied up in the lignin/cellular matrix is probably less than 50 percent degradable. Since lignin is not fermentable under anaerobic conditions, it is probable that more than 50 percent of the apparently digestible portion of MSW remains undigested over an extended period of time (Brown-Caldwell, 1978). In addition, the undigested lignin/cellulal material tends to build up in the digester, creating mixing and scum problems. These problems will be discussed further in the section entitled Mixing.

Pretreatment of the MSW or removal of a substantial portion of the cellulose material from the MSW prior to digestion (as in the Cal Recovery process) are two possible alternatives to deal with this problem). In general, pretreatment of MSW prior to biological conversion processes can be classified into three methods; physical, chemical-thermal or a combination of both. Various methods of the pretreatment of cellulose to increase digestibility are listed in Table 8.

In regard to physical pretreatment, size reduction and separation of inorganics appears to have the most significant impact on the economics of biological conversion processes. Studies conducted by Ghosh, et al. (1976) at the Institute of Gas Technology have shown that refuse particle size has a significant effect on refuse digestibility. Their laboratory experiments using refuse having median sizes of 10.1 to 5.1 mm demonstrated that lower gas yields and gas production rates were obtained with the coarser refuse. Unfortunately, the cost-effectiveness of various degrees of size reduction and separation efficiencies for anaerobic digestion is not well established.

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	

(After Brown and Caldwell, 1978)

Waste-Management, Inc., is currently investigating the effect of particle size and separation efficiency of the material handling and mixing systems at the Pompano Beach facility. Results from this study should yield valuable information concerning the relationship between particle size and biodegradibility and the amount of size reduction and separation necessary to facilitate material handling and mixing of solid waste slurries.

Several methods of chemical and thermal pretreatment for the bioconversion of MSW to methane have been investigated at the bench scale. At present, the most promising appears to be heat treatment under alkaline condition. It has been reported that the mechanism by which alkali pretreatment increases digestibility involves a swelling of the substrate resulting in an increase in the size of pore spaces. Lignin is solubilized to phenols, isolating the carbohydrate fraction and allowing greater accessability to microbial enzymes. Elevated temperature and pressure aid in breaking down chemical bonds to yield a product which is more susceptible to hydrolytic activity during anaerobic digestion. McCarty (1976) has shown that peak biodegradability of alkaline heated MSW occurs at pH 13 and 480°F. Further work (1977) demonstrated that heat pretreatment of newspapers and alkaline conditions increased methane production by 25 percent to 70 percent. Brown et al. (1976) showed that for a caustic dose of 3g/100g of refuse and heating at 130°C for one hour, an increase of over 30 percent in biogas production is observed in laboratory digesters. In addition, it was discovered that the rate of substrate utilization is increased therefore implying that the treatment could be effective at shorter retention times.

The various experimental results cited indicate that alkali pretreatment at elevated temperatures is an effective method to increase digestibility of MSW; however, there are unanswered questions with respect to scale-up potential, disposal of the non-biodegradable, solubilized lignins in the digester effluent and the cost effectiveness of such treatment.

E. MSW Digestion Performance Parameters

After the source of MSW has been carefully quantified, characterized, and preprocessed (which may include various degrees of physical, chemical/thermal pretreatment) to yield a rich organic fraction of MSW, it is ready for digestion. Several parameters are important for the design and control of MSW digestion with respect to the objective of achieving optimal performance in terms of gas production and volatile solid destruction. Among these are nutrient requirements; organic loading rate and hydraulic retention time; feed slurry concentration; temperature, and mixing.

i) Nutrient requirements:

Typical MSW is deficient in both nitrogen and phosphorus with respect to microbial growth requirements in anaerobic digesters. Based on typical refuse characteristics, Pfeffer, et al. (1976) performed a nitrogen balance on an anerobic digester system and determined that the amount of supplemental nitrogen required per pound of volatile solids fed to the system is 19.32 lbs/ton of volatile solids fed. Less information is available on phosphorus requirement although it is generally considered to be much less than nitrogen. Nutrient requirements can be satisfied by chemical addition or by introduction of organic materials rich in the needed nutrients such as sewage sludge or animal waste. Chemical addition of nutrients can become a significant cost factor in the overall process economics, and it appears that nutrient supplementation from organic residue is a preferred approach at this time. Mah, et al. (1980) at UCLA conducted a series of laboratory digestion studies to assess the effect of nutrient addition to MSW digestibility and gas production by adding various levels of animal manure, sewage sludge, or a combination of both. Results indicated that while a highly processed MSW (obtained from the Cal Recovery System) could be digested without nutrient supplementation up to a loading rate of 0.1625 lb VS/ft^3 day at an efficiency of 4.17 ft^3 day/lb VS added, sufficient enhancement of gas production and a more stable process could be achieved under conditions of nutrient addition. MSW supplemented with 35 percent raw sludge at a loading rate of 0.12 lb VS/ft^3 day yielded 6.10 ft^3 methane day/lb VS added. Digestion of raw sludge, feedlot waste, and MSW in the proportion of .14/.6/.70 respectively at an organic loading rate of 0.23 lb VS/ft^3 day gave an optimal yield of 6.42 ft^3 methane/lb VS added.

Ghosh and Klass (1977), Diaz, et al. (1974,1977), Klein (1972), Pfeffer and Liebman (1976) all investigated the digestion of MSW supplemented with raw sewage sludge. Diaz and Trezek (1978) and Mah, et al. (1980) showed that optimum gas production could be achieved with a mixture of 80 percent refuse and 20 percent sludge.

ii) Organic Loading Rate and Hydraulic Retention Time

The rate at which organic matter is introduced into the digester has a strong influence on the stability of the process. One main effect of an increased feeding rate is the rapid increase in the population of the acid-forming bacteria relative to the slower growing methanogenic bacteria. If continued, overloading occurs, causing unstable conditions which may eventually lead to process failure if not corrected in time. The organic loading rate (OLR) and the hydraulic retention time (defined as the theoretical time that a given input volume remains in the digester) are mutually dependable variables. They are interrelated in that the OLR and the solid feed concentration define the retention time for a given volume. Therefore, for a given OLR, retention time can only be increased by decreasing the feed solids concentration. At long retention times, the conversion of biodegradible organic solids will be essentially complete; however, retention times are usually shorter to affect the most cost efficient and economical design. Typical OLRs and retention times for the design of sewage sludge digesters are 0.2 to 0.4 lb VS/ft^3 day and 10 to 15 days, respectively.

OLR and retention times reported in the various studies on MSW digestion have ranged from 0.07 to 0.35 lb VS/ft^3 day and from 10 to 30 days, respectively. Most of these studies have included co-digestion with raw sewage sludge. Ghosh and Klass (1977) reported OLRs of 0.07 to 0.14 lb VS/ft^3 day with a retention time of 12 days. Diaz, et al. (1974,1977) reported using OLRs from 0.07 to 0.4 lb/VS/ft^3 at retention times of 15 and 30 days. Results from Diaz, et al. (1977) indicated that at a 15-day retention time, loadings higher than 0.3 lb VS/ft^3 day did not perform well. Mah, et al. (1980) reported optimal digestion of Cal Recovery RFD supplemented with 15 percent raw sludge and 15 percent feedlot wastes at an OLR of 0.35 lb VS/ft^3 day and a retention time of 10 days.

There is little doubt that optimal loading rates and retention time for methanogenic digestion will depend upon the quality of the feedstock and on the desired efficiency of the overall process. For the most cost effective operations, it is important to operate at the highest loading rate possible within the process constraints, in order to achieve the least investment cost.

iii) MSW Feed Slurry Concentration

MSW feed slurry concentration is important in many respects for the operational design and performance of anaerobic digesters. It determines the handling and pumping properties of the influent feed and influences the degree of mixing required for efficient operation. Little information is available for determining the optimal MSW feed slurry concentration; therefore, it has been largely determined by the constraints of organic loading rate, retention time and physical processing limitations. According to values reported in the literature, a reasonable upper limit of the range of total solids content appears to be about 8 percent, based on pumping and mixing limitations.

iv) Temperature

The rate of anaerobic digestion of organic waste is influenced by temperature. Digester operations fall into two temperature ranges: mesophillic and thermophillic. Thermophillic digesters are operated in the range of $100^{o}F$ to $140^{o}F$ with the optimum at about $130^{o}F$ while mesophillic digestion occurs between $80^{o}F$ to $110^{o}F$ with the optimum at approximately $95^{o}F$. Although thermophillic digestion usually results in higher gas yeilds and production rates, it is rarely applied to the municipal sludge digestion facilities primarily due to inexperience with the process and increased heating requirements.

In contrast to sewage sludge digestion, little information is available for determining optimal temperatures for large scale MSW digestion. Pfeffer (1974) conducted a series of laboratory digester experiments at various retention times employing shredded MSW to study the effect of temperature on the rate of methane production. His results showed that the optimum mesophillic temperature is 107°F, while the optimum thermophillic temperature is at least 140°F. He also observed that thermophillic digestion yielded higher rates of gas production although increases between the two optimum temperatures generally inhibited rather than enhanced gas production. Ghosh et al. (1977) reported slightly different results using laboratory digesters at a retention time of 12 days. Data from their runs show that the optimum mesophillic digestion of refuse-sludge mixtures occur in the temperature range of 95°F to 104°F when using a low loading rate (0.07 lb VS/ft^3 day). However, at a higher loading rate (0.14 lb VS/ft^3 day) the optimum mesophillic temperature was 95°F. Optimum thermophillic temperature for the digestion of MSW was observed to be 131°F. Their study also indicated that, for a given loading and detention time, a higher gas yield and a better effluent quality are obtained from MSW digestion at the optimum mesophillic temperature, than at the optimum thermophillic temperature. Both Pfeffer and Ghosh observed that the carbon dioxide content increased with digester temperature.

v) Mixing

Adequate mixing of digester contents is essential in order to achieve proper digestion performance. Experience with sewage sludge digesters in optimization of digester rates and gas production has shown that high-volume mixing is definitely beneficial in the overall digestion process (Torpey; 1954.

1955). Most mixed digesters have the mixing energy provided by gas recirculation. Other means available are mechanical mixing and liquid recirculation.

One major problem consistently reported in MSW digestion literature is inadequate mixing, resulting in the formation of thick scum layers which reduce the efficiency of digester operation. McFarland (1972) and Diaz, et al. (1978) reported mixing problems in their MSW pilot studies using the recirculation mode of mixing. Jarvis, et al. (1978) encountered similar problems in laboratory studies conducted at the Franklin, Ohio Environmental Complex. Using hydropulped MSW as substrate in 55 gallon digesters, Jarvis observed that the material accumulated as a fibrous mat on the uppermost part of the reactor with cellulosic fibers tending to float on the surface of the liquid, adhering to one another on contact during mixing, forming increasingly larger mats of fibrous scum. Following these laboratory observations, Swartzbaugh, et al. (1979) conducted a pilot study (100,000 gallons) to test and compare two methods of mixing, a mechanical agitator mounted in the center of the digester, and three gas mixing units located inside the digester in a equilateral triangle at approximately half the radius of the vessel. The investigators examined the effect of various feed ratios of MSW to sewage sludge, organic loading rates and feed solid concentrations on the efficiency of digester performance as related to the two modes of mixing and the resulting solids distribution in the digester. They concluded the folowing:

- A 4 percent total solids slurry can be satisfactorily digested on a short term basis.
- Both the gas mixing system and the mechanical agitator maintain fairly uniform solids distribution in the lower and middle level of the vessel.

- Both mixing systems tested allow the build-up of a 1- to 3-foot fibrous scum layer of 20 to 25 percent total solids within a month of operation.
- Grit content in the feedstock must be minimized to avoid using abrasion resistant slurry pumps.
- The properties of MSW are sufficiently different from sewage sludge that direct application of wastwater treatment practice to the anaerobic digestion of MSW is not feasible.

The results of the Franklin, Ohio facility and the preliminary problems encountered at the ReCom facility in Pompano Beach, Florida indicate that mixing of RDF slurries still remains a significant operational problem in terms of matting on the surface and cellulosic stringers binding mixing shafts and impellers. It appears that this is the major operational difficulty that needs to be addressed prior to any further large-scale undertakings in MSW digestion.

Factors influencing mixing such as the degree of feedstock preparation, MSW size, impeller and reactor design, and shaft speed need to be examined with respect to achieving acceptable mixing.

vi) Gas Quality and Quantity

Several important technical and economic considerations are related to the gaseous end products of anaerobic digestion. These include gas quantity, gas quality, gas processing and the potential market for gas utilization.

In general, the volume of gas produced in a digester will depend on the feedstock characteristics and digester operational parameters. For mesophillic domestic sewage sludge digesters, the gas produced should average between 16 and 18 cu ft/lb VS destroyed (about 10 cu.ft/lb VS added). Gas yields for MSW digestion are substantially less. Mah, et al. (1980) determined that RDF from preprocessing systems at San Diego and Berkeley produced 3.9 and 7.2 cu/ ft/lb VS added respectively when digested without nutrient supplements. These results confirm Pfeffer's earlier work (1974) in that MSW sources and preprocessing schemes can account for large differences in gas yields. Moreover, Pfeffer (1974), Brown et al. (1976), and Ghosh (1977) demonstrated that MSW gas production rates are strongly influenced by temperature, retention time and loading rate.

There is little doubt that the addition of nutrients in the form of sewage sludge or animal wastes enhances the organic destruction and gas production rates in MSW digestion. Diaz, Kurtz, Trezek (1974); Diaz, Trezek (1978); and Mah (1980) reported gas yields using various ratios of highly processed MSW and raw sludge. Their average results were about 7.8, 9.3, and 8.8 cu. ft/ lb VS added respectively. Differences in the reported values may be attributed to a number of variables including consistency of feedstock quality, MSW/ raw sludge ratio, retention time and organic loading rate. An upper limit of gas production from MSW has not yet been determined, although Mah (1980) has reported that an optimal yield of 10.2 cu/ft/lb VS added (18.5 cu. ft/lb VS destroyed) can be achieved using a feedstock blend of 70 percent MSW, 15 percent raw sludge, 15 percent feedlot waste at an organic loading rate of 0.35 lb VS/ cu ft day and a 10-day retention time.

The gas produced by the anaerobic digestion process consists primarily of methane and carbon dioxide with trace amounts of hydrogen sulfide and nitrogen. Typical gas composition for domestic sewage sludge digesters range from 60 to 70 percent methane and 30 to 35 percent carbon dioxide with a heating value of approximately 600 BTU/ft^3 (Metcalf & Eddy, 1979). In contrast, results from various studies indicate that gas composition from MSW digestion typically range from 50 to 60 percent methane and 40 to 45 percent carbon dioxide with a heating value of about 550 BTU/ft^3.

Digester gas without scrubbing is wet and mildly corrosive with about half the heating value of natural gas. Treatment 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 to be 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 in large sedimentation traps while water can be removed with strategically placed traps along the pipeline. A recent review of available gas purification systems (Ashare et al. 1978) indicated that commercially available methods for treatment of digester gas include physical absorption; chemical absorption, adsorption, and membrane separation processes. Large scale experience with MSW digester gas treatment is limited at this time; however, problems of applying current gas purification processes to MSW product gas are not anticipated.

vii) Dewatering Characteristics and Residue Disposal

The dewatering characteristics of MSW digester effluent is a critical consideration from the standpoint of the economics in the overall MSW to methane process. As in the case of sewage sludge digester effluent, the solid residue must be separated and dewatered to the maximum extent for economical disposal. Low moisture content in the residue is desirable to accomplish the following objectives:

- Rendering the sludges odorless and less putrescible.
- Reduction of fuel requirements if incineration is used as a means of final disposal.
- Reduction of hauling costs to landfills or drying fields.
- Reduction of leachate production at the landfill site.

Various technologies and alternatives have emerged for the processing of digester effluent and for the ultimate disposal of the material resulting from processing. These are discussed in a comprehensive report prepared by LA/OMA (1979). For digested sewage sludges, available dewatering processes include vacuum filtration, centrifugation, filter presses, horizontal belt filtration, sand drying beds, and lagoons.

Pfeffer et al. (1974) has conducted extensive laboratory studies on the dewatering characterisitcs of MSW digested sludge. He tested the applicability of vacuum filtration and centrifugation as a means of dewatering and also examined the effects of recycling and chemical conditioning prior to the dewatering step. Tests using Buckner funnels and filter test leaf technique demonstrated that vacuum filtration digested MSW sludge (5 to 6 % TS) can result in a 20 to 25 percent solid cake with a solids capture of 90 to 95 percent. Cake solid could be increased to an excess of 30 percent with a solid capture of 95 to 95 percent if chemical pretreatment is applied; however, Pfeffer noted that the cost of the polymer is not offset by the savings in the overall processing costs. Recycling of filtrate to the process resulted in a buildup of fine particles that eventually reduced the filter rate and solid cake content. In centrifugation tests, cake solid concentrations varying between 27 and 40 percent and 4 solids capture of 61 to 88 percent was observed depending largely on the type of centrifugation vessel used. Based on these results, Pfeffer concluded that centrifugation is a lower total cost system than vacuum filtration, provided the solids lost in the centrate are not important and that incineration of the resulting cake solid is used. Pfeffer's overall work supports the contention that existing technologies for dewatering domestic sludges can be successfully applied to digested MSW sludge without significant modifications. Brown and Caldwell (1978) have suggested the use of filter presses to dewater high solids concentration MSW slurries having sizable quantities of fine particles; however, supporting experimental evidence for their conclusion is not yet available.

The method used for the ultimate disposal of digested sludge after treatment depends on site-specific economics and governmental regulations. Common disposal methods include landfilling, incineration, pyrolysis, solar drying fields, and sludge storage basins. Information relating the advantages and disadvantages of various disposal methods to MSW sludges is lacking; however, it appears now that combustion methods with heat recovery will provide more beneficial effects than landfilling, especially since acceptable landfilling sites are becoming very scarce in major parts of the country (Brown and Caldwell, 1978).

viii) Reactor Design

One major drawback of conventional digester design is the large volume required. Several variations in digester design have been proposed with the objective of reducing capital and operating costs through digester volume reduction. The success of an innovative design could have a significant impact on the economics of a MSW-to-methane process since it is estimated that the digestion steps represent 28 percent of the process energy consumption and 35 percent of the capital cost in the overall conversion process (Kispert, et al., 1974).

Alternate design concepts have been reviewed and discussed in a report by MITRE Corporation (1979). They are summarized here in Table 9.

There appear to be several concepts that may well be superior to the conventional digester for the efficient production of methane gas. However, the technology of these novel concepts are at a formative stage of development and are unproved at the practical level. Detailed studies, including economic analysis of these concepts should be made in order to incorporate any of the advantages into what appears to be the "established," conventional system.

IV. ECONOMIC STUDIES

A number of studies on the projected economics of specific MSW to methane processes have been undertaken. Kispert, Sadek and Wise (1974) developed a computer model with the objective of sizing the processing equipment required for producing methane gas at the lowest cost based on the 1000 ton/day Dynatech system shown in Figure 2. The model provided for the analysis of capital and operating costs, credits for handling MSW (tipping fee) and sewage sludge, and penalties for the disposal of the effluent. To account for uncertainties in the values used in their analytical description of the system, the investigators also conducted a sensitivity study to evaluate the impact of technological advances or economical changes on the process. Their results indicated that the process economics are most sensitive to the digestible fraction of MSW and tipping fees. Other major factors relating to the overall economics of the process included digester

Table 9. Alternate Reactor Designs

Process Description	Potential Advantages over Conventional Design	Terminal 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. 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 of 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.

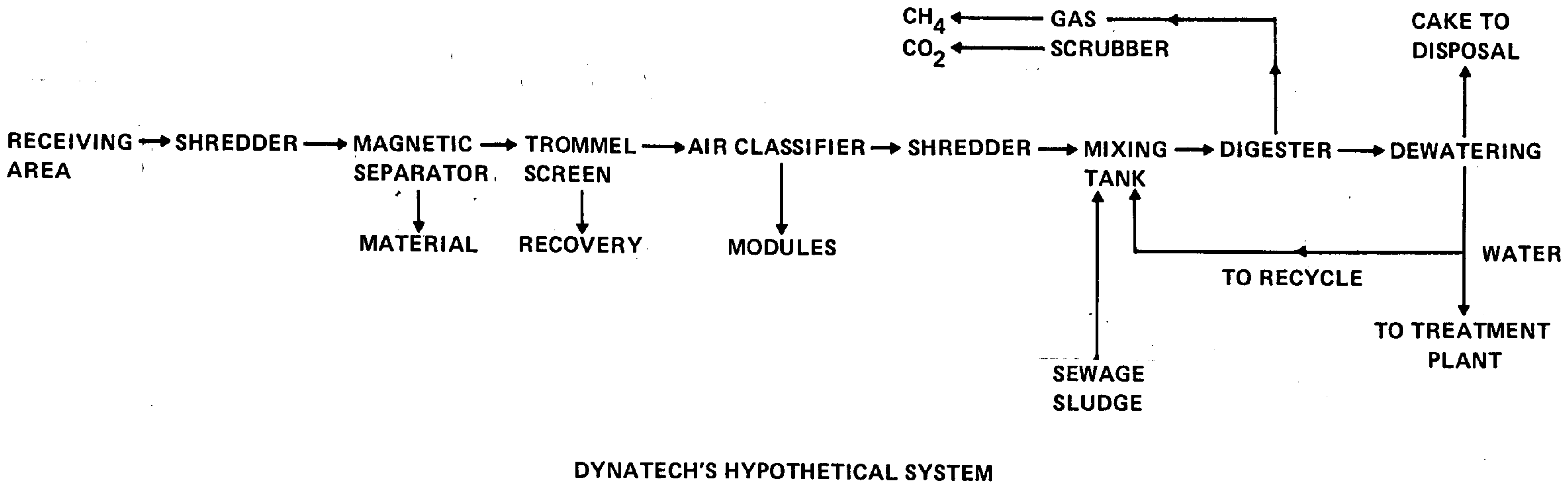


Figure 2. Flow Process Diagram of Anaerobic Digestion Used for Dynatech Economic Analysis

operating conditions, dewatering costs and financing options (i.e., public vs. private). The authors concluded that the cost of methane production is economically acceptable when compared with projected costs of natural or synthetic gas. The MITRE Corporation (1979) reviewed and updated Kispert's original report incorporating additional considerations such as the cost of disposal facilities for trommel screen unders, air calssification of heavies, dewatered cake, increased electric power requirements, and operating personnel. Their analysis indicated that the economic feasibility of the process was not encouraging and that a tipping fee of $15.60/ton (without incinceration) to $19 to $22/ton (with incineration) would be required as the major source of revenue to offset costs.

Brown and Caldwell (1978) examined the technical and ecomomic feasibility for various MSW to methane processes based on four major process steps: feedstock preparation; feedstock pretreatment; digestion and gas production; and residue disposal. After detailed screening of candidate processes, four alternatives were identified and cost estimates were prepared for production plants with the capacity to use 1000, 2000, and 3000 tons per day of MSW. Their analysis demonstrated that a number of process variables affect the cost of gas production for the four alternative processes. Among the more influential variables are the manner of financing, feedstock prepration costs and tipping fees. The following conclusions were reached in the analysis:

- Minimum cost gas would be produced from MSW which has undergone only shredding with ferrous metals removed prior to digestion at maximum possible loading rates.
- Feed concentration should be as high as possible, consistent with mixing availability.

- The residue, after dewatering, should be thermally processed, and the recovered heat used to operate the plant; excess steam should be sold.
- The Cal Recovery process appears to be the most cost-effective above 1000 tons/day if all excess steam can be sold and if organic loading rates are restricted to the lower range.
- 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.

Brown and Caldwell (1979) later conducted site-specific economic studies on the digestion of MSW with thermal processing of the residue. They identified five general factors that are important in establishing the economic feasibility of any energy from a refuse project:

- Facility's capital cost,
- Facility's operation and maintenance cost,
- Market for steam from thermal processing of non-digestible fraction or demonstration of feasible pyrolytic thermal processing unt for non-digestible fraction,
- Land acquisition and development cost,
- Tipping fee revenue expected.

The first three factors are a function of process selection and facility design, while the remaining two are site specific. Among the major conclusions reached in the study are:

- A facility designed for anaerobic digestion and thermal processing of MSW in Southern California can produce a medium Btu and/or steam

steam product at a cost as low as $\$6.00/10^6$ BTU.

- The apparent most cost-effective option involves mesophillic digestion of the non-cellulose organic fraction, with thermal processing of the non-digestible fraction.
- Energy recovery from the thermal processing step is necessary for the economic feasibility of the process.

Waste and Water International (1981), under contract by the EPA recently completed a general cost evaluation of the co-digestion of MSW and sewage sludge based on certain assumptions. Their major assumptions included a resource recovery plant sized at 2500 metric tons MSW/day; use of Cal Recovery feedstock; digester operating conditions as specified by Pfeffer and Liebmann (1976); vacuum filtration for dewatering; and landfilling for the residue disposal. According to their analysis, the largest expense will be incurred by the vacuum filter dewatering equipment. They calculated that the difference in costs between the system with and without dewatering is $25.7 million per year not taking the tipping fee into account. The authors concluded that although lower disposal fees are expected for dewatered solids, the savings are not substantial enough to augment the capital and operating costs of the filtering equipment.

V. SUMMARY

Technology for MSW digestion is at a formative stage of development. The technical and economic feasibility of the overall process is dependent on a number of factors that are external to and within the process itself. The most important of these factors includes the site-specific sources and characteristics of MSW; land availability; local economics and potential market for recovered material; and development of "optimal" preprocessing configuration and methods of pretreatment for increased feedstock digestibility.

Evaluation of work related to MSW digestion performance parameters has revealed that much research remains undone, especially in the areas of optimum particle sizes, feed slurry concentration and acceptable mixing. Anaerobic digestion of MSW has been demonstrated to be a viable alternative for the volume reduction of solid waste and for energy recovery from otherwise useless material. However, continued research is required to "optimize" such a process into an economically attractive one.

In general, the best economical process-design criteria for MSW digestion can be established from existing knowledge and experience. This is shown in Table 10.

Table 10. State-of-the-Art Design Criteria for MSW Digester

MSW Moisture Content:	35-40% (after Ferrous removal)
Preprocessing System:	Designed specifically to remove fiber portion of MSW yielding a highly organic fraction (as in Cal Recovery System)
Pretreatment:	None
Particle Size:	0.5 in. or less
Nutrient Addition:	Municipal primary sludge
Ratio of MSW to Sludge:	5.1
Organic Loading Rate:	0.25 lb VS/ft^3 day
Retention Time:	10-15 days
Feed Slurry Concentration:	4-8% total solids
Temperature of Operation	Mesophillic at ~ 95°F
Mixing Mode:	Mechanical agitation
Reactor Design:	"Conventional" municipal sewage sludge digesters
Dewatering:	None or centrifugation
Residue Disposal:	Sludge drying beds or incineration
Gas Treatment:	Degree dependent on subsequent use

EXPERIMENTAL PROCEDURES

I. FEEDSTOCK

The feedstock used in this study was selected to simulate municipal waste from Santa Monica, California. A survey was made of the Santa Monica waste on three separate occasions, in order to determine the seasonal variability. The survey procedure was supplied by Cal Recovery Systems.

Each survey was conducted over a one-week period with two truck samplings per day. Trucks were selected from specific routes in the city in order to quantify the waste from the specific areas in the city. Each truck to be sampled was routed to an isolated point at the Santa Monica transfer station and the contents were dumped onto the concrete transfer station's foundation. The truck was dumped while jogging in forward in order to distribute the waste over a 25-foot section. Next, a 10-foot by 25-foot sheet of plastic was spread next to the column of waste. A garden rake was used to transfer between 250 and 300 pounds to the sheet. Waste was raked from the pile to the sheet along the entire length of the pile. An effort was made to rake a representative sample from the pile. Finally, the sample was hand sorted into the categories shown in Table 11 and weighed. Weight percentages were then calculated.

Cal Recovery Systems used the survey information to select areas adjacent to U.C. Berkeley Richmond Field Station similar in composition to the Santa Monica Waste. Cal Recovery Systems shipped the waste to UCLA in 40 to 70 lb cardboard drums. The waste was refrigerated at 4°C until used.

Table 11. Survey Categories for Santa Monica Municipal Solid Waste

Mixed Paper
Newsprint
Corrugated
Plastic
Yard Waste
Food Waste
Other Combustibles
Ferrous Metals
Aluminum
Other Non-Combustibles
Glass
Miscellaneous

II. EXPERIMENTAL APPARATUS

Experiments were carried out with four 50-gallon cylindrical stainless steel digesters (alloy 304), each with a working volume of approximately 45 gallons. The details of the digester design and external apparatus are shown in Figure 3. Briefly, each digester was constructed with a sloping bottom and a 2-inch exit port for sludge withdrawal. The top plate of the digesters had entry ports and fittings for the gas outlet, pH sensor; float level; thermometer; RDF temperature sensor and feeding. Mixing was accomplished by a top mounted 1/4 hp Bodine motor with a 2-impeller vertical shaft extending approximately 5/6 the distance to the bottom of the digester. The digester temperature was controlled at 37°C by an automatic temperature sensor having externally wrapped heating tapes and fiberglass insulation. Gas measurements were taken by bubbling the product gas into a 2 percent solution of sulfuric acid in a closed flask connected to a Precision Wet Test Meter. PH control, which was occasionally necessary in the start-up stage of the experiments , was accomplished by the manual addition of a solution of sodium carbonate.

III. DIGESTER START-UP PROCEDURE

Seeding was accomplished by filling each digester with mesophillic digested sewage sludge from the Los Angeles Hyperion Treatment Plant to full working volume. Initially, raw sewage sludge was fed at an organic loading rate of .04 lb VS/ft^3 day (~ 1 gal. raw sludge/day) until the gas production rate and volatile fatty acid concentration in each digester stabilized (approximately 2 weeks). The feedrate was increased to 0.1 lb VS/ft^3 day (~ 2 gal. raw sludge/day) until a new level of stable

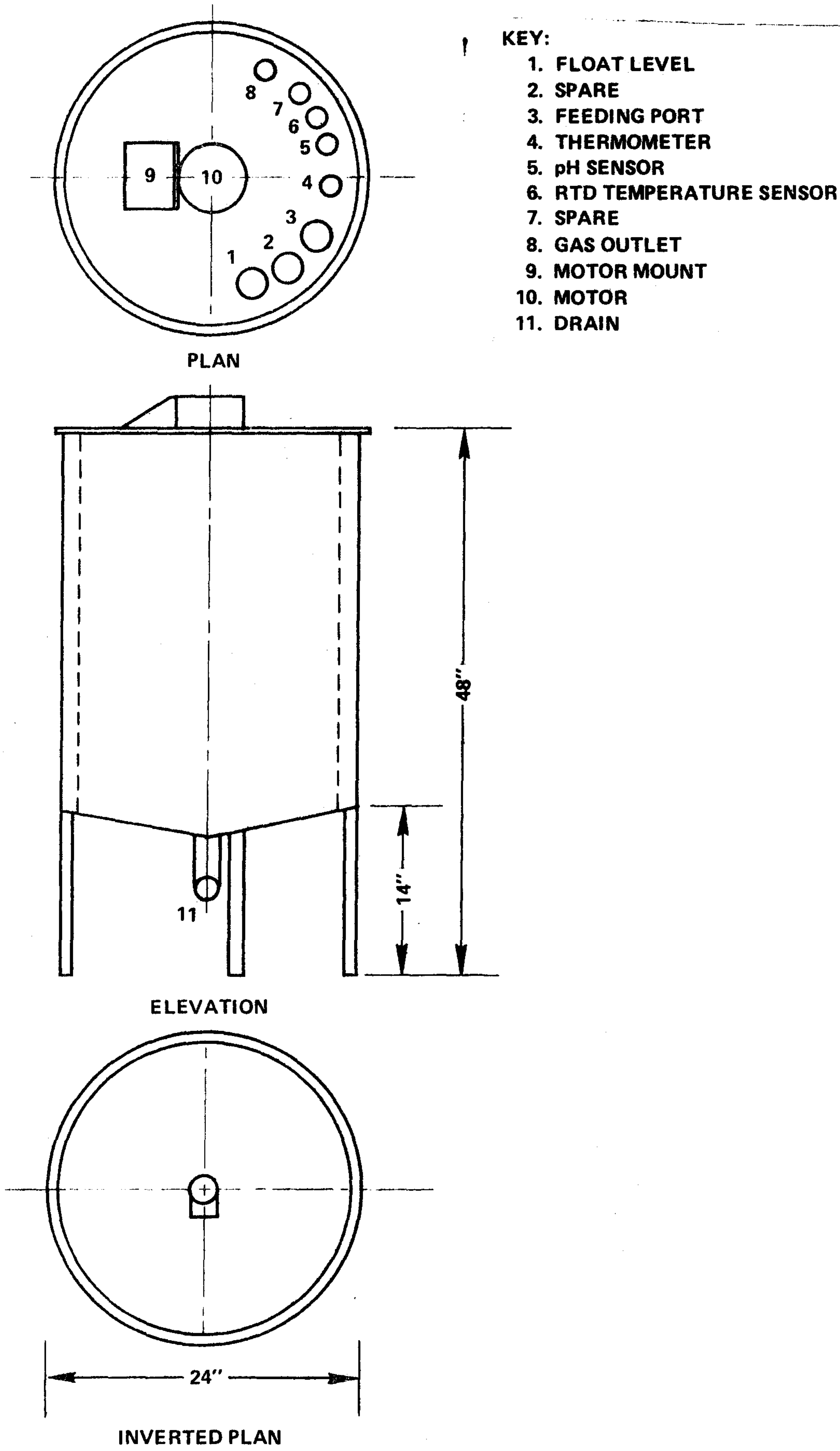


Figure 3. Pilot Scale Digester

gas production and acids concentration was obtained. Following this initial period of acclimination, experiments with MSW began in three of the digesters, with the fourth digester retained as a control (fed with raw sludge only).

IV. FEEDING PROCEDURE

The following procedure was developed to load the digester:

- Based on the organic loading rate (OLR) the amount of refrigerated MSW for each digester was weighed on a Mettler Gray balance and placed into wide mouth 1 gallon jars (~300 gms/jar).
- Based on hydraulic retention time, the appropriate volume of sludge was withdrawn and wasted. An excess volume of approximately 1 gallon of digested sludge per 0.25 Kilogram of MSW to be fed was then withdrawn for loading purposes.
- Tap water was added to the dry MSW to bring the total weight of MSW plus tap water to equal the weight of the feed volume, assuming specific gravity of 1.0. Excess withdrawn digested sludge was added to top off the jars and then the resulting mixture of MSW, tap water and digested sludge was vigorously shaken into a slurry that could be poured easily into the feeding port of the digester.
- Supplemental raw sludge (20 percent of OLR) was measured in premarked gallon containers and fed accordingly.

V. ANALYTIC METHODS

Alkalinity, Ammonia, pH: Alkalinity and ammonia determinations were made at least once a week. Ammonia was measured by an Orion Research 407A meter with a specific ion electrode. The meter was calibrated by standard solutions prepared in the laboratory. Alkalinity determinations were made in accordance to the procedure (sec. 405) described in Standard Methods (1). PH data was collected daily using a Corning Model 12 meter.

Analysis of Organic Acids: Samples to be analyzed for volatile fatty acids were acified to pH 3 with concentrated ortho-phosphoric acid and centrifuged. A Hamilton 7105 syringe was used to inject 2-ul supernatant samples into a Varian (Series 1400) gas chromatograph equipped with a flame ionization detector and a 1-mV Varian recorder. A 6-foot glass column (OD, 1/4", ID, 2 mm) was packed with 15 percent SP-1220 chromosorb AW with 1 percent phosphoric acid and mesh size 100/120 + conditioned overnight at 160°C. Operating conditions were: Column temperature, 130°C; Injector temperature, 160°C; Carrier gas; Helium at a flow rate of 30 ml/min., H_2 at 30 ml/min., and Oxygen at 300 ml/min. Analysis for volatile fatty acids (VFAS), including acetic, propionic, butyric, iso-butyric, valeric and iso-valeric acids, were made at least once a week.

Analysis of Gases: CH_4 and CO_2 were analyzed at least once a week by gas chromotography using a Varian Aerograph 920 gas chromatograph equipped with thermal conductivity detector. Gas samples were collected in a vacuumed bottle and injected (5 ml sample) into the Varian gas chromatograph with a hypodermic needle. Separation of constituent gases was achieved by using a 12-foot stainless steel column of 1/4" OD packed with activated charcoal. The injector, detector, column temperatures were operated at 60°C, 60°C, and 180°C respectively. The filament current was set at 190 mA. Helium was used as the carrier gas at a flow rate of of 60 ml/min.

Solids Analysis

Digester effluent total and volatile solids were analyzed according to the procedures described in Sections 208A and 208E of Standard Methods (1975); however, determinations of percent total solids and percent volatile solids were based on a gram/gram sample rather than on a volumetric basis (as precribed by Standard Methods). This was done because an accurate volumetric measure was sometimes not possible due to the digester effluent bulky characteristics.

Digester influent total and volatile solids were calculated based on the following formula:

$$\frac{\text{Volume Fed}}{\text{day}} \times \text{gm} \frac{\text{Total Solids}}{\text{Volume Fed}} \times \%\ \text{Volatility} = \%\ \text{VS}$$

Calculations were based on the assumption of 5.5 % total solids for raw sludge. Percent volatility of raw sludge and the MSW were experimentally determined according to Standard Methods (1975). Volume fed/day and total solids/volume fed was predetermined by organic loading rate and hydraulic retention time.

Percent volatile solids destruction was calculated by the following formula:

$$\frac{\%\ \text{VS Influent} - \%\ \text{VS Effluent}}{\%\ \text{VS Influent}} \text{X } 100 = \%\ \text{VS Destroyed}$$

RESULTS AND DISCUSSION

I. Santa Monica Survey

Municipal solid waste was surveyed three times at the Santa Monica transfer station during the periods of August 11, 1980 to August 15, 1980, December 16, 1980 to December 22, 1980 and February 17, 1981 to February 23, 1981. The survey results are shown in Table 12. The results for the various categories are remarkably consistent for the three sampling periods. The greatest variability is for the yard waste category which shows an increase of almost four percentage points between the August and December surveys. One would expect a large variability in yard waste, since the season was changing between surveys; however, one normally expects to find the greatest yard waste in the summer, during the growing season. The opposite trend was observed here, but this might be explained by the rainfall pattern in Southern California, where August is the driest month. The news print category shows a large increase through survey, but there is no explanation for this at present.

Cal Recovery Systems selected an MSW similar to the Santa Monica Waste for digester feed preparation. The Cal Recovery feed material average 80% solids (20% moisture) and the dry solids averaged 60% volatile matter, by weight.

II. Digestion Results

Figures 4, 5, 6 and 7 show daily gas production for the stable periods of operation. The horizontal axis shows the day of the year. The day begins at 270, which corresponds to September 26, 1980. Days numbered greater than 365 correspond to days in 1981, and continues to the end of the project. The straight lines between groups of data points correspond

Table 12. Results of the Santa Monica Municipal Solid Waste Survey

Category	Survey 8/11/80-8/15/80		Survey 12/16/80-12/22/80		Survey 2/17/81-2/23/81		3 Period Average
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	
Mixed Paper	10.40	5.38	9.94	4.8	10.6	5.81	10.31
News Print	12.10	4.01	13.76	4.7	15.3	4.98	13.72
Corrugated Paper	19.30	5.28	19.49	6.6	18.6	7.41	19.13
Plastics	7.94	2.26	6.15	2.06	6.19	2.20	6.96
Yard Waste	16.2	12.0	20.03	17.9	17.77	15.58	18.0
Food Waste	7.07	2.73	1.46	2.37	9.88	3.88	8.14
Other Combustibles	5.88	5.30	5.65	7.12	4.95	3.44	5.49
Ferrous Metals	5.12	2.61	3.62	1.50	4.44	3.51	4.39
Aluminum	0.961	0.25	1.22	2.43	0.751	0.45	0.978
Other Non-Combustibles	0.709	1.09	1.43	2.62	0.28	0.72	0.806
Glass	11.96	4.2	10.63	4.86	9.29	4.86	10.62
Miscellaneous	1.16	0.65	0.85	0.24	1.84	2.18	1.28
TOTAL	98.8	99.96		99.95			99.57

Numbers denote weight percents

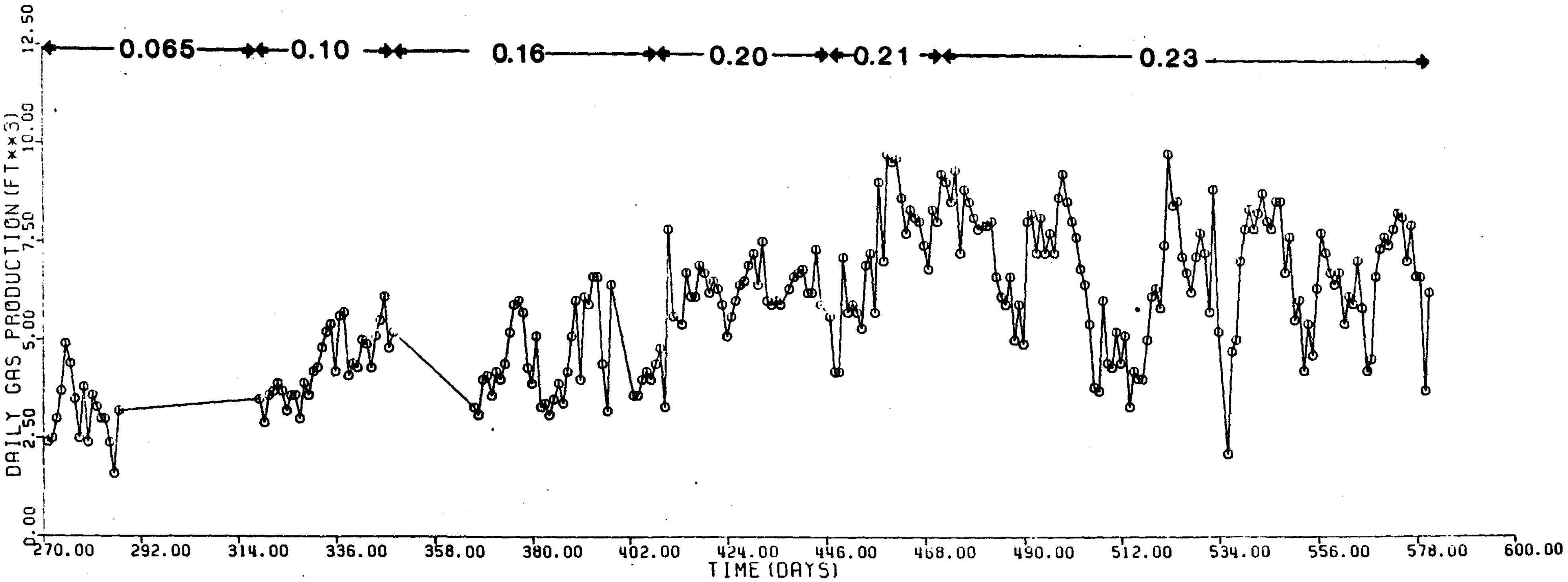


Figure 4. Gas Production for Digester Number 1

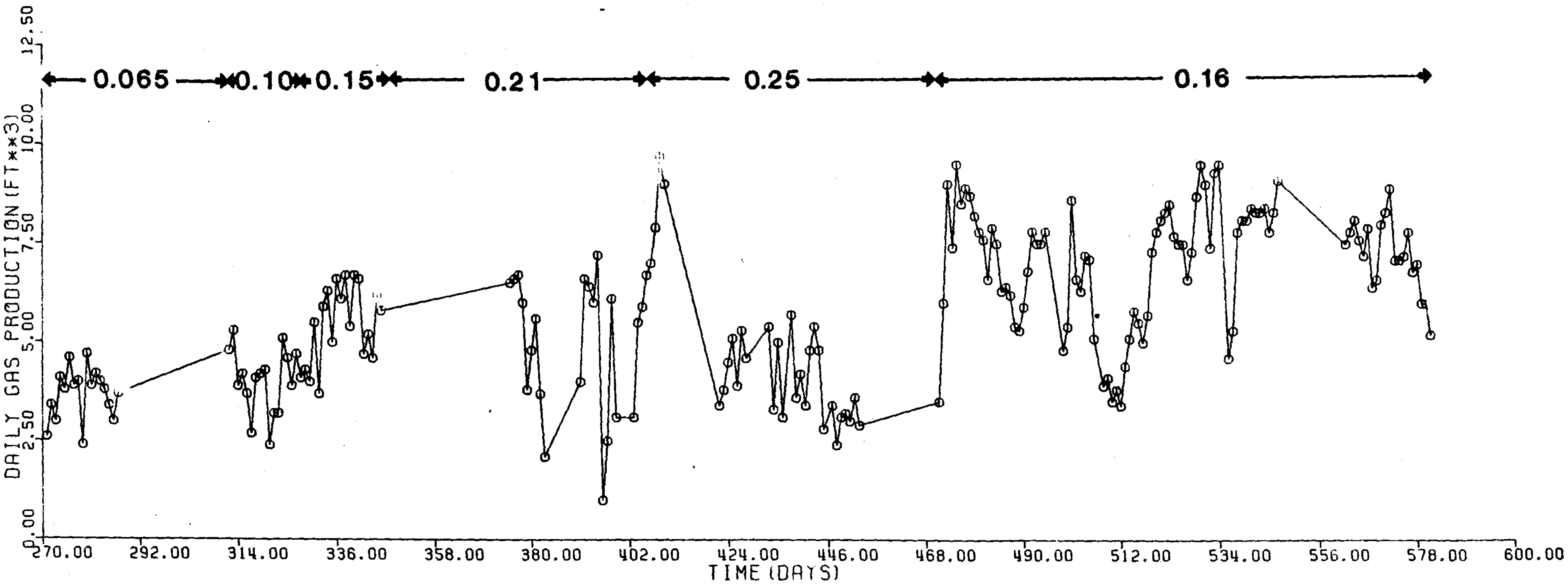


Figure 5. Gas Production for Digester Number 2

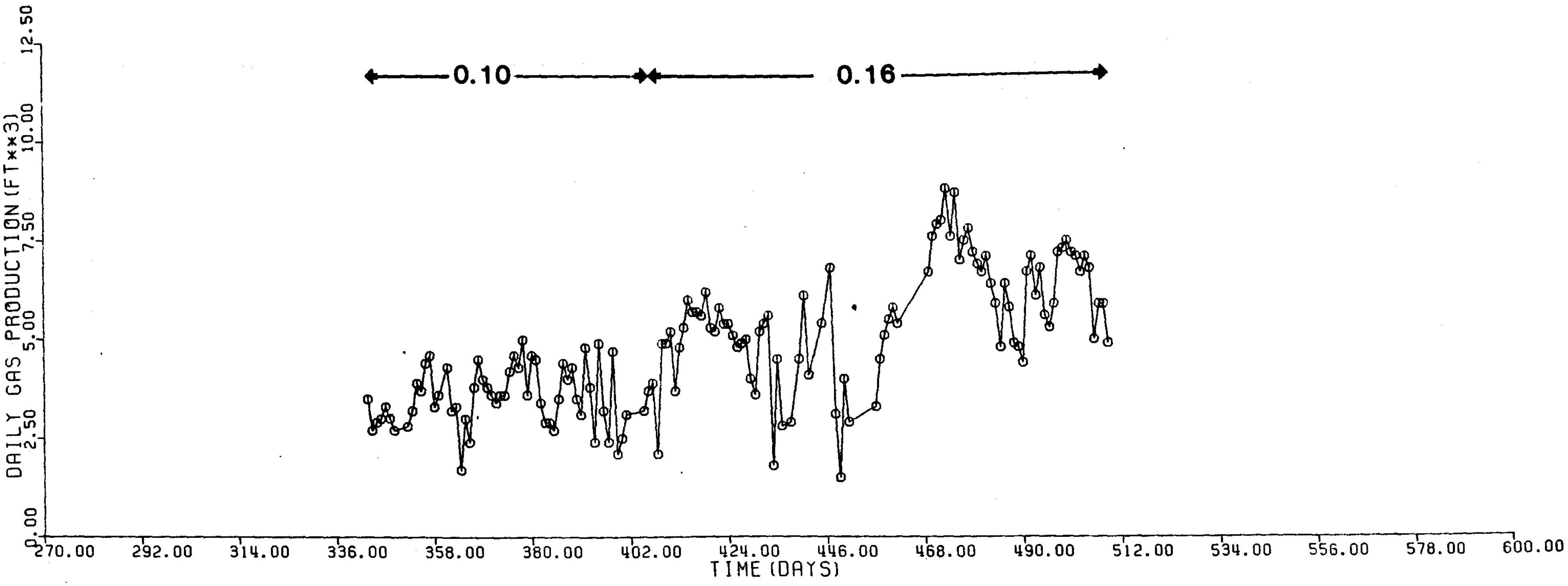


Figure 6. Gas Production for Digester Number 3

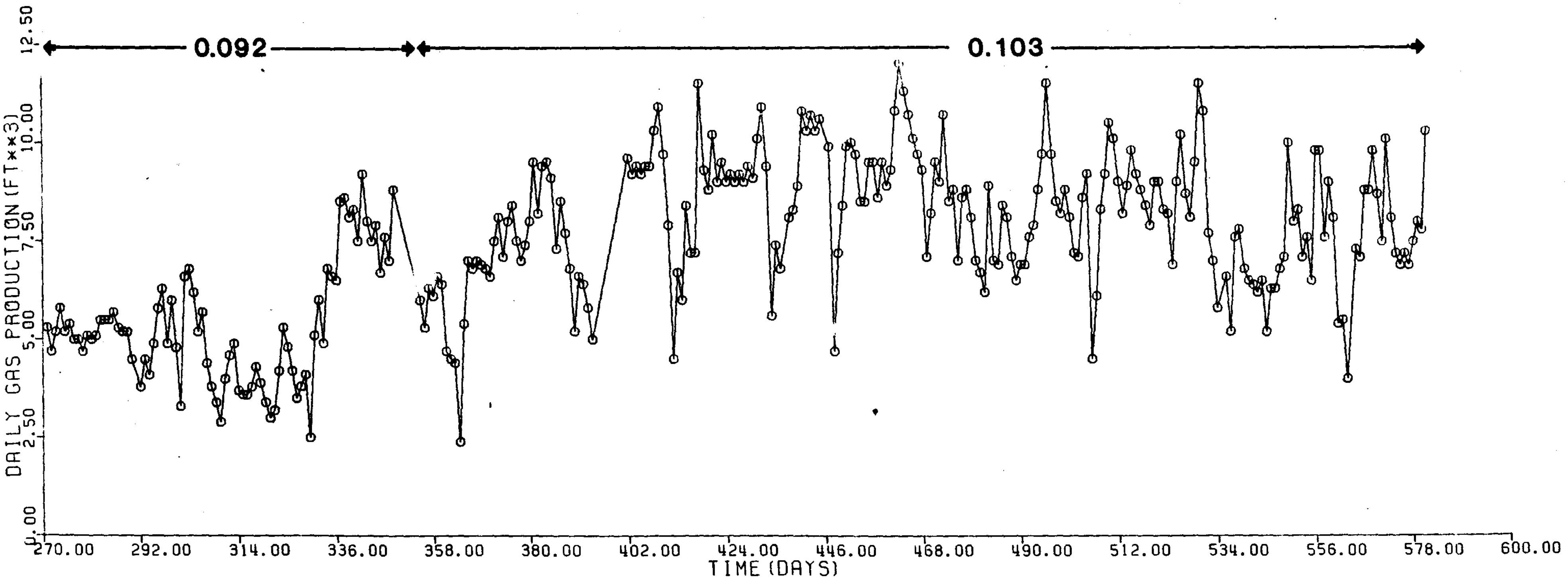


Figure 7. Gas Production for Digester Number 4

to periods when operational problems existed. The primary operational problems were gas leaks o faults in the metering system, lack of municipal solid waste for feed, and upsets due to scum blanket accumulations. Figure 7 shows the control digester (Number 4) which was operating entirely on raw primary sludge obtained from the Hyperion treatment plant. Figures 4, 5, 6 correspond to digesters one, two and three, respectively which were operated on MSW and raw sludge. Gas composition for the MSW digesters ranged between 55% and 60% methane during stable operation.

Table 13 show the gas production rates per unit mass of volatile solids applied. The table is arranged to show the effect of organic loading rate and hydraulic retention time. Table 14 shows the remaining parameters for the stable periods of operation. The number shown in Tables 13 and 14 represent the mean parameter values for the stable periods shown in Figures 4 through 7.

The variability of the measured operating parameters is shown in Figures 8 through 13. The pH of all digesters is shown in Figure 8. The control digester, treating raw primary sludge, consistently had the highest pH, ranging in the 7.4 to 7.8 region. The high pH is partially attributed to the high ammonia concentration of the raw sludge. The pH of the urban solid waste digesters fluctuated more widely than the control digester. At one point during the study the pH dropped to below 6.8, near day 300. This drop was caused by increasing the organic loading rate too quickly. During this particular upset, sodium carbonate was added to increase alkalinity and pH which accounts for the rapid return of digesters to neutral pH. After the digesters were acclimated to the feed distribution and loading rate, no base additions were required. A similar drop in pH occured around day 450 and this pH drop was controlled

Table 13. Gas Production per Unit Volatile Solids Summary

ft^3/lb VS added / OLR 1b VS/ft^3

θ_H in DAYS	2.57	3.1	3.3 - 3.85	4.8	5.1 - 5.2	5.5 - 5.6	6 - 6.4	7 - 7.7	8.0	10.1
15			6.680 0.16 (3.85)			5.316 0.23 (5.53)				
20	9.421 0.080 (2.57)		13.146* 0.103 (3.3) 7.181 0.115 (3.7)		5.841 0.16 (5.1) 7.56 0.16 (5.13)	4.164 0.175 (5.6)	5.116 0.20 (6.4)	5.078 0.23 (7.378) 5.863 0.21 (7.4)	3.075 0.25 (8.0)	
30		8.793 0.065 (3.1)	9.70* 0.092 (3.3)	7.119 0.10 (4.8)			6.110 0.125 (6.0)	4.86 0.16 6.714 0.15 (7.2)		3.950 0.21 (10.1)

Feed Concentration (% VS)

*Raw Sludge Only

TABLE 14. DIGESTER PARAMETER SUMMARY

DIGESTER NUMBER	FEED CONCENTRATION (% VS)	EFFLUENT CONCENTRATION (% VS)	% VS DESTROYED	PERIOD OF OPERATION	VOLATILITY (% VS/TS)	pH	ALKALINITY (mg/ℓ AS Ca CO_3	AMMONIA NH_3-N (mg/ℓ)	AVERAGE DAILY GAS PRODUCTION (ft^3)	ORGANIC LOADING RATE (lb VS/ ft^3 day)	GAS PRODUCTION ft^3 lb VS day	TOTAL VOLATILE ACID (mg/ℓ)	HYDRAULIC RETENTION TIME (DAYS)	NUMBER OF DATA POINTS
1	3.1	0.869	71.97	271-287	65.00	7.173	3892.9	752.9	3.167	0.065	8.094	201.0	30	17
2	3.1	0.772	75.09	271-287	66.65	7.137	3317.9	634.3	3.714	0.065	9.492	159.0	30	17
2	2.57	--	--	510-516	62.77	7.320	3975.0	830.0	4.537	0.08	9.421	130.0	20	7
4	3.3	1.27	61.5	271-349	60.13	7.378	4561.0	1066.4	5.372	0.092	9.70	144.0	30	78
1	4.8	2.453	48.89	319-328	72.97	7.267	4068.75	578.5	5.221	0.10	8.674	205.0	30	24
2	4.8	3.682	23.29	312-328	72.54	7.290	3662.5	448.7	4.059	0.10	6.743	217.2	30	17
3	4.8	2.149	55.22	343-406	65.00	7.220	647.9	843.3	3.576	0.10	5.941	176.1	30	58
4	3.3	1.74	47.27	355-394 402-581	59.40	7.529	5896.0	1594.3	8.151	0.103	13.146	176.8	20	216
1	3.7	--	--	510-516 531-537	61.85	7.185	4500.0	815.0	4.972	0.115	7.181	225.0	20	13
1	6.0	2.612	56.46	367-372	71.25	7.293	3970.8	591.7	4.598	0.125	6.110	199.6	30	27
2	7.2	2.992	60.10	329-346	73.33	7.157	3550.0	527.5	5.575	0.15	6.174	92.8	30	18
1	7.7	3.069	60.14	373-406	67.34	7.264	4090.0	592.0	4.68	0.16	4.86	133.56	30	30
1	3.85	2.553	33.69	562-568	73.36	7.260	4375.0	825.0	5.60	0.16	5.81	1050.0	15	7
2	5.13	3.3 3	35.22	375-377 471-509 517-542	74.01	7.166	4376.8	829.1	7.282	0.16	7.56	370.6	20	68
2	3.85	2.04	47.01	562-581	72.05	7.246	3562.5	656.7	7.272	0.16	7.55	114.5	15	20
3	5.1	3.553	30.33	407-510	71.96	7.193	3526.7	707.3	5.626	0.16	5.841	493.4	20	87
2	5.6	4.842	13.54	378-383	80.17	7.295	4200.0	805.0	4.386	0.175	4.164	536.0	20	6
1	6.4	4.168	34.87	407-445	68.18	7.038	3650.0	646.0	6.159	0.20	5.116	1030.7	20	37
1	7.40	5.037	31.93	447-474	76.35	7.244	4055.0	770.0	7.411	0.21	5.863	1026.8	20	28
2	10.1	4.274	57.68	391-406	72.67	7.170	4250.0	1180.0	4.994	0.21	3.950	--	30	13
1	7.378	4.801	34.93	475-509 517-530	72.31	7.108	4541.67	793.33	7.031	0.23	5.078	532.5	20	49
1	5.53	3.00	45.75	538-547 569-581	74.97	7.196	3828.57	648.57	7.361	0.23	5.316	159.00	15	23
2	8.0	2.681	66.48	407-453	71.02	7.083	4081.3	767.50	4.628	0.25	3.075	1481.7	20	30

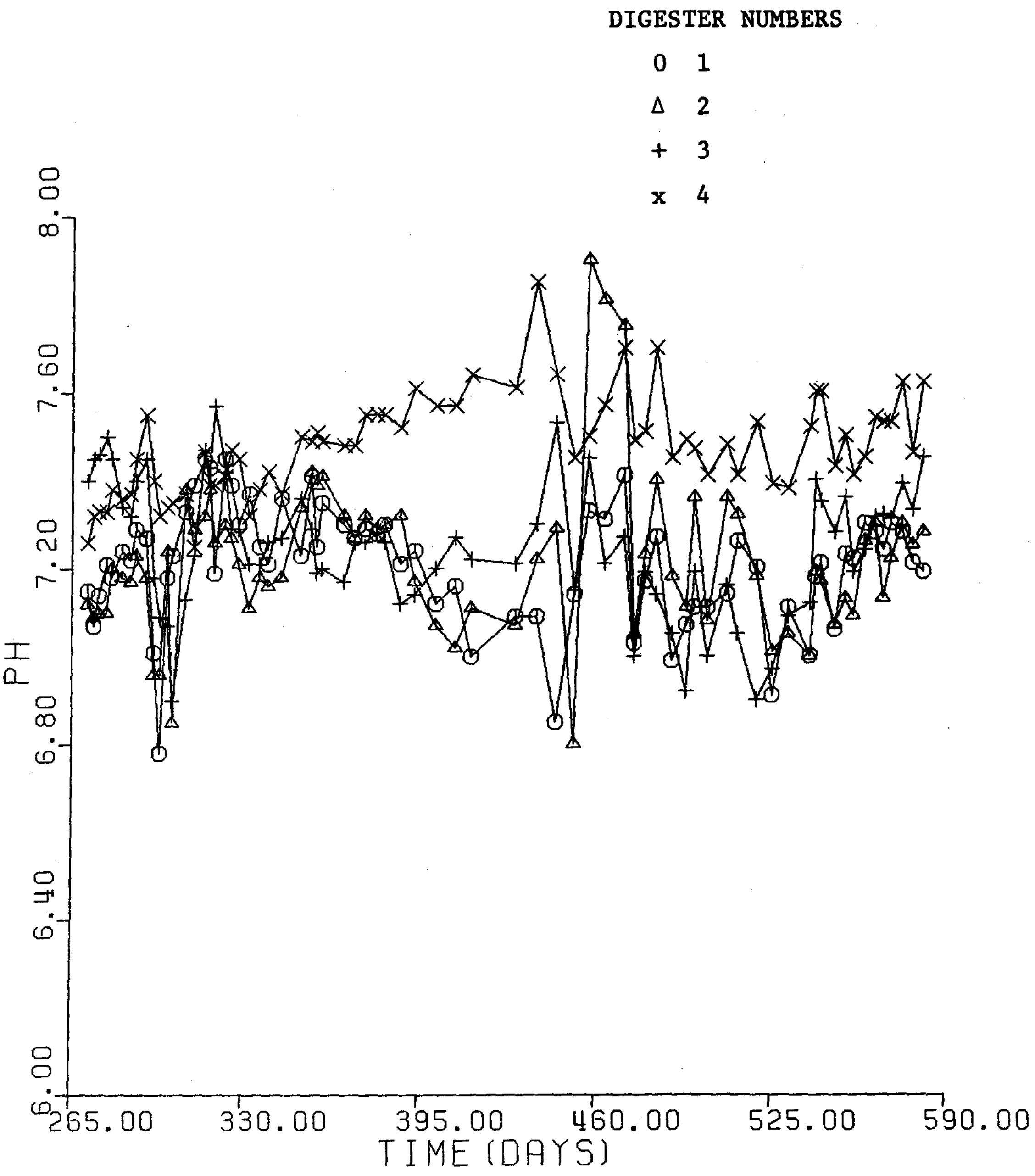


FIGURE 8. DIGESTED SLUDGE pH AS A FUNCTION OF TIME.

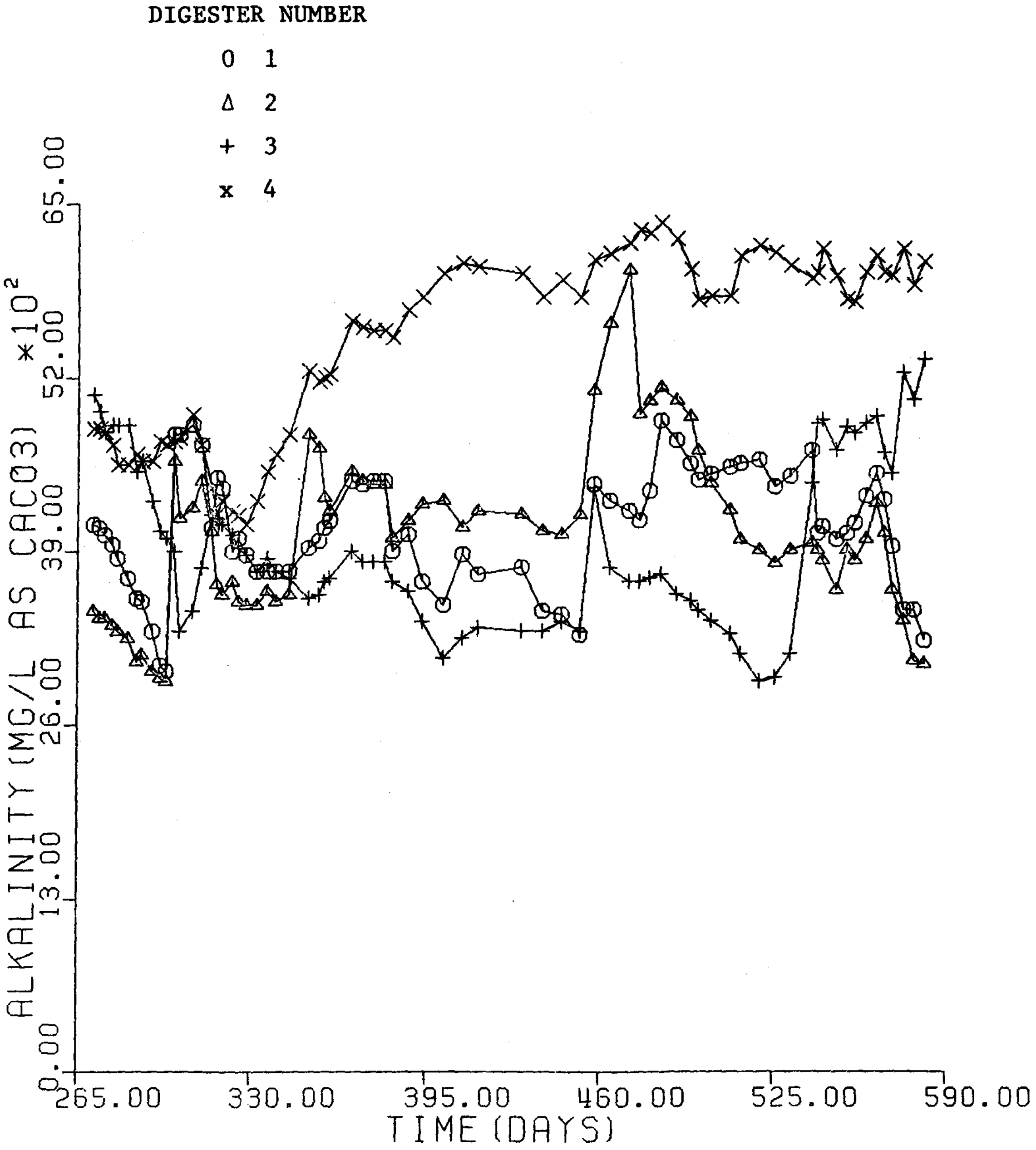


FIGURE 9. DIGESTED SLUDGE ALKALINITY.

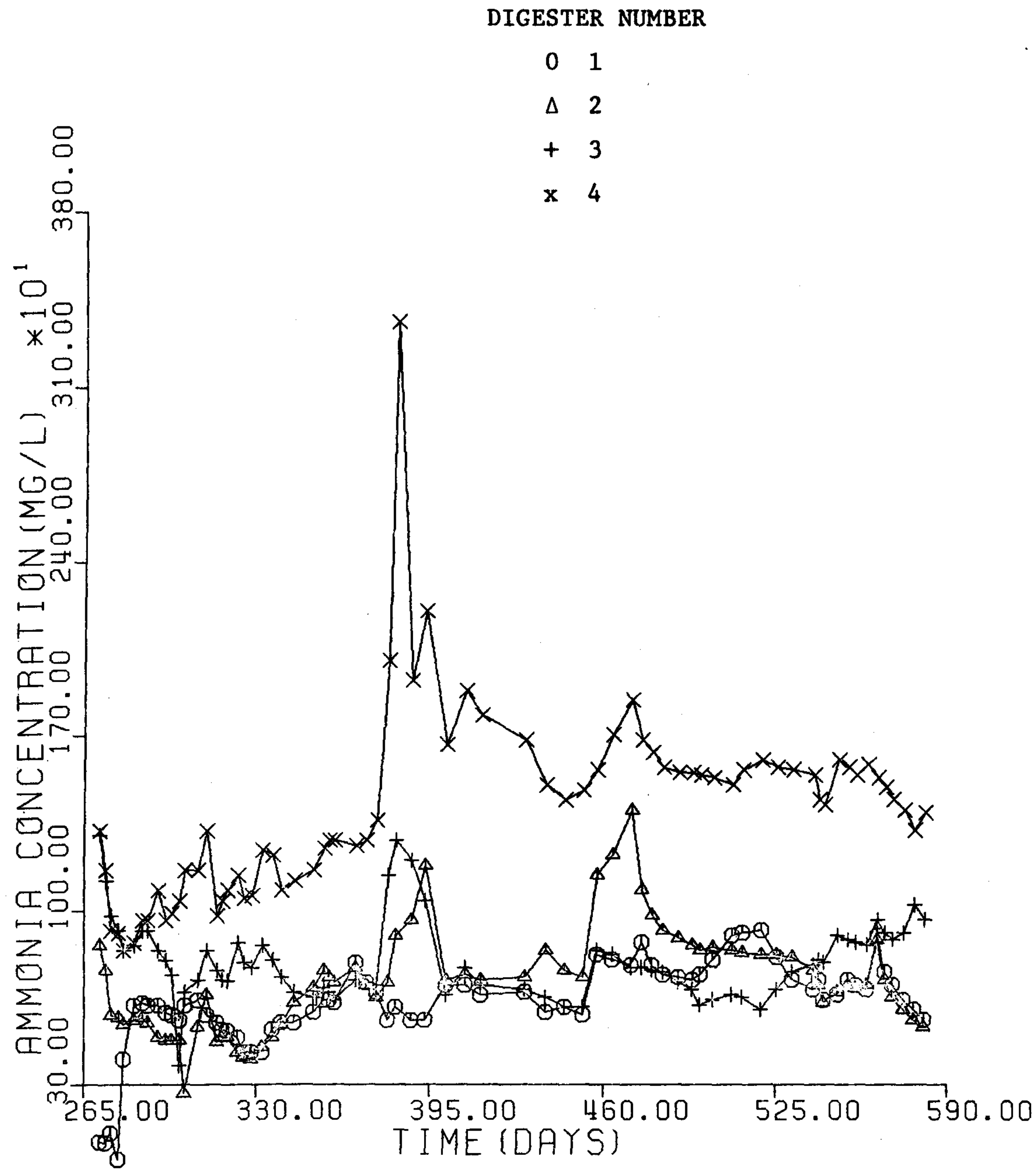


FIGURE 10. DIGESTED SLUDGE AMMONIA CONCENTRATION.

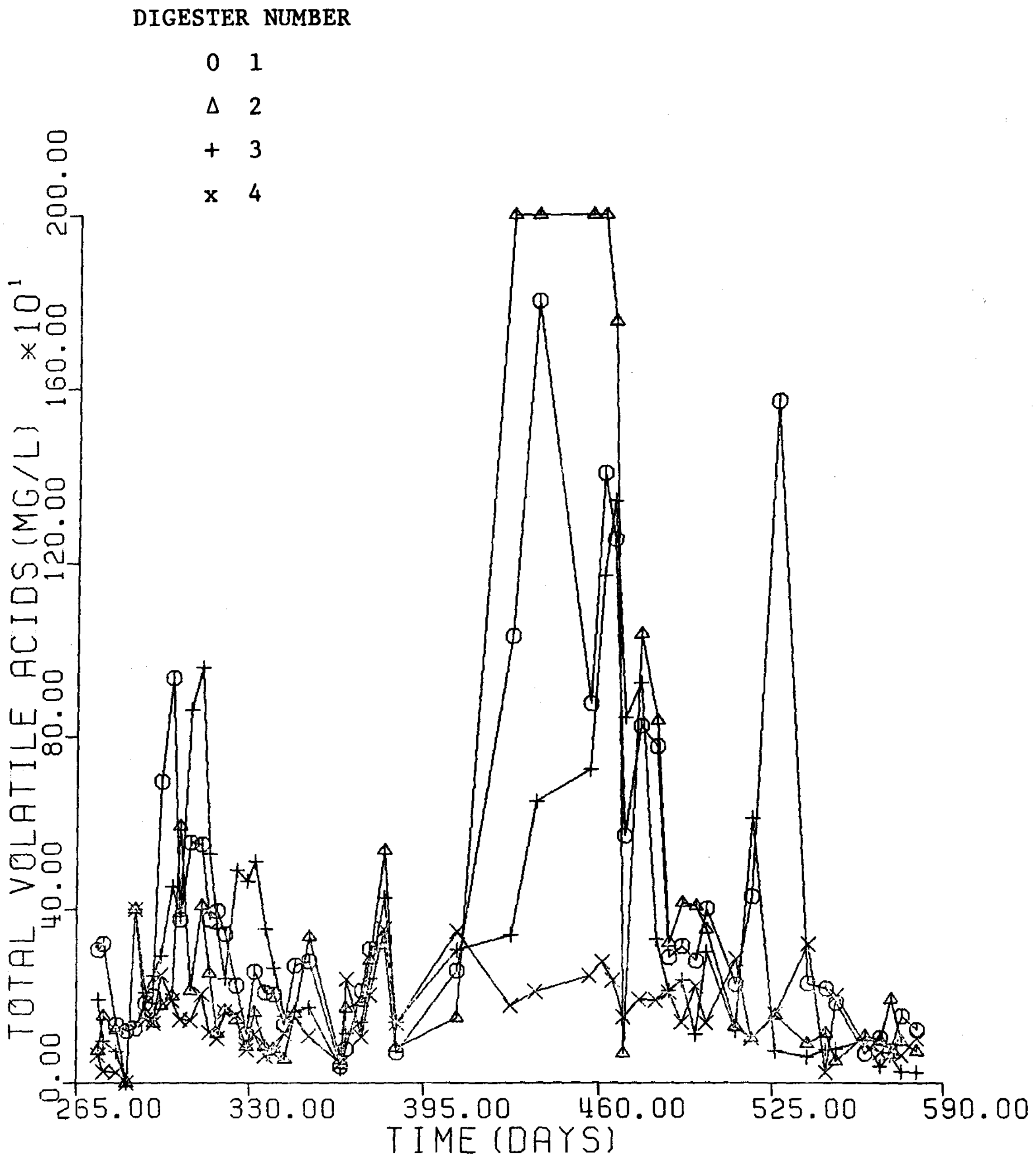


FIGURE 11. DIGESTED SLUDGE TOTAL VOLATILE ACIDS CONCENTRATION.

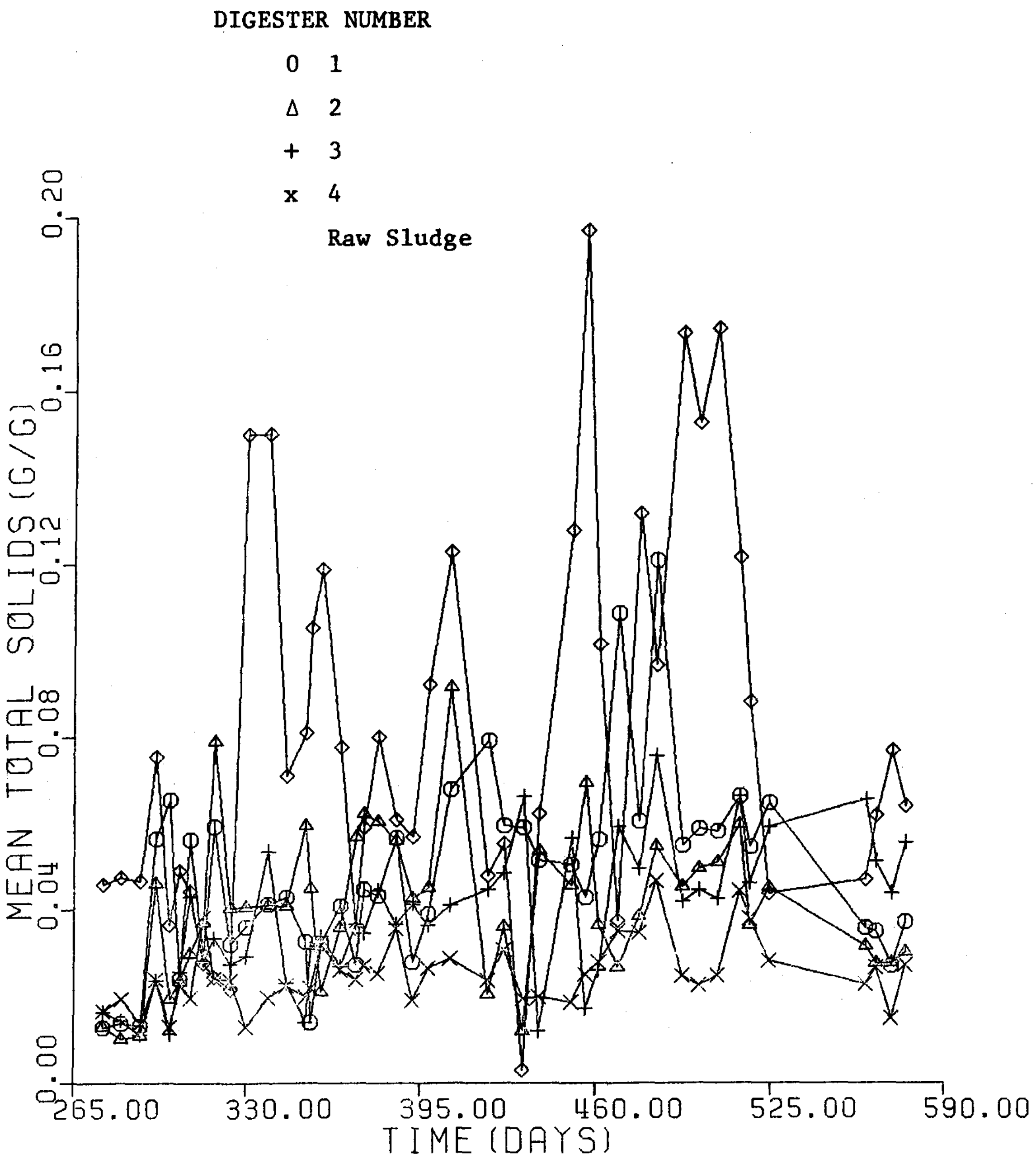


FIGURE 12. DIGESTED SLUDGE TOTAL SOLIDS CONCENTRATION.

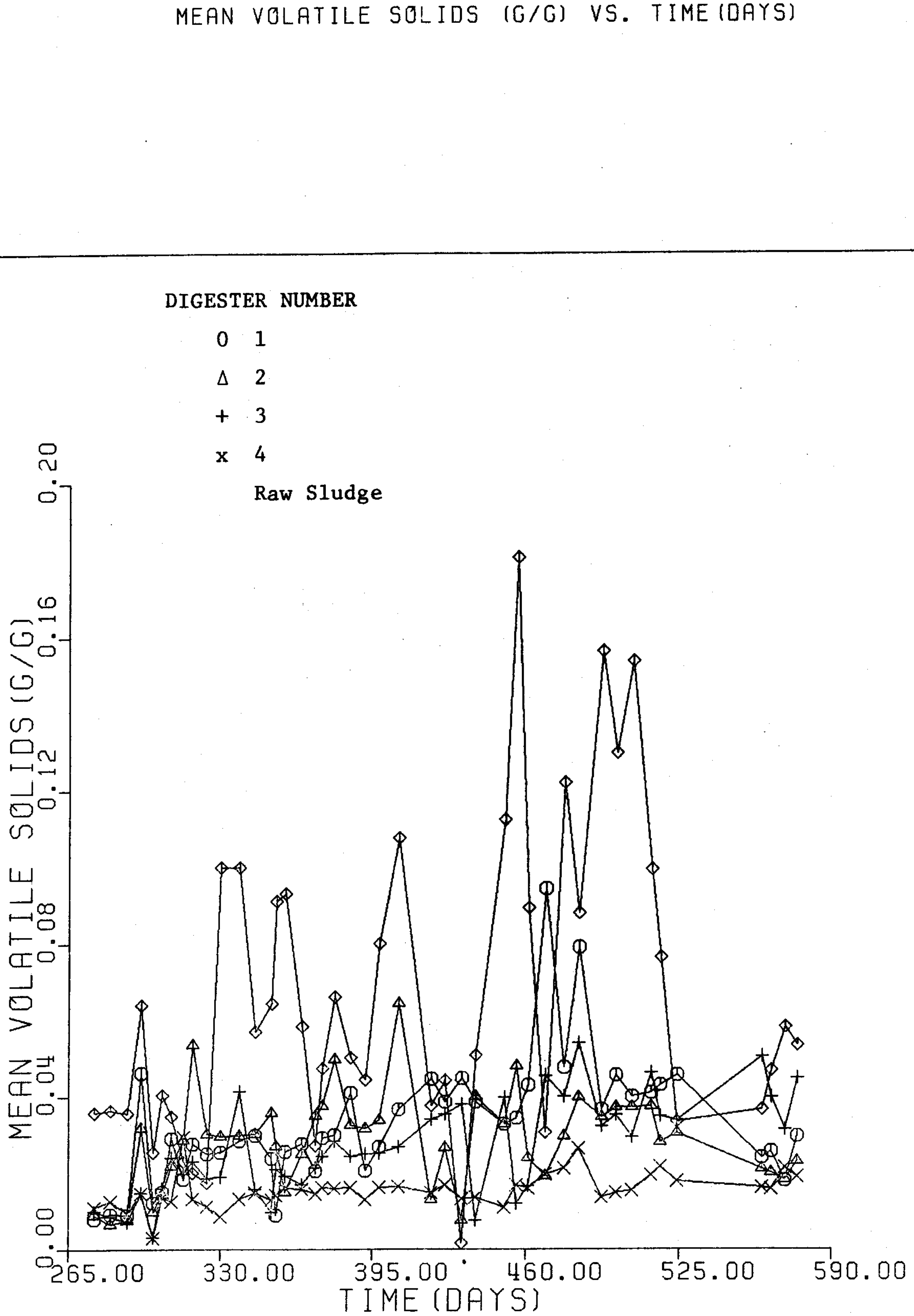


FIGURE 13. DIGESTED SLUDGE VOLATILE SOLIDS CONCENTRATION.

with sodium carbonate also. The downward trend in pH between days 350 and 450 occurred because the organic loading rate of the digesters were gradually being increased. The upward trend from day 520 to the end of the study occurred because the organic loading rate was being decreased.

The digested sludge alkalinity is shown in Figure 9. The trends are similar to the trends in pH, and the causes of the fluctuation are similar. The ammonia concentration of the digested sludge is shown in Figure 10. The control digester showed the highest alkalinity concentration, which is due to the unusually high organic nitrogen content of the raw sludge. The MSW digesters had much lower ammonia concentrations because the MSW is nitrogen poor. At one point in the study the nitrogen content of the raw sludge increased dramatically, and the cause of the increase was unknown. The total volatile acids concentration of the digested sludge is shown in Figure 11. In general the control digester had the lowest acids concentration, remaining well under the maximum accepted values for normal sludge digestion. The urban solid waste digesters had several upsets in acids concentration. The upsets correspond to the upsets in pH and alkalinity. When the volatile acids rapidly increased, digester feeding was halted in extreme cases, such as for digester number 2 in the 400 to 450 day range, digested sludge from a properly operating MSW digester was fed to the upset digester. This was done to promote recovery. The high acids period correspond to periods of low gas production and low solids destruction. The upset periods were deleted from the summary shown in Tables 13 and 14, because the upset conditions do not produce normal gas production.

Total and volatile solids concentrations of the digested sludge are shown in Figures 12 and 13. The solids concentration of the raw sludge fluctuated widely, and this was due largely to the operation of the Hyperion treatment plant. On several occasions raw sludge collection was suspended due to the low solids concentration. A second source of variability is the analytical procedure. It is extremely difficult to obtain representative samples of raw sludge. The scale of this operation also makes it difficult to obtain representative samples. At small, bench-top scale, it is possible to use inexpensive blending equipment to thoroughly mix the entire gravity of raw sludge to be fed to the digester, which makes sample collection much simpler. At very large scale and full scale operation, the volume of raw sludge to be fed to the digester is large enough to require sophisticated mixing and feeding equipment. At medium scale the volume of feed material is too large to use standard laboratory equipment, but too small to justify the expense of sophisticated, full scale equipment.

The mixture of urban solid waste and raw sludge was analyzed at the beginning of the sludge. It was impossible to obtain representative samples. The use of a blender to produce representative samples was precluded because a blender would have changed the particle size distribution of the MSW.

III. Effects of Organic Loading Rate and Hydraulic Retention Time on Digesters

A major objective of this research project was to determine the effect of organic loading rate and hydraulic retention time on digester performance. The experimental procedure was designed to provide a matrix of experimental results which could be used to evaluate the effects of these operating parameters. These results were shown previously in Table 13 for gas production per unit mass of volatile solids applied.

The table shows that gas production rapidly declines as organic loading rate is increased, and as hydraulic retention time is decreased. Generally one would expect performance to decline as the digesters are more heavily loaded, but the decline in performance is greater than was anticipated.

To further show the experimental results, gas production per unit mass of volatile solids applied is plotted as a function of organic loading rate in Figure 14. The figure shows a decline from approximately 9.0 ft^3/lbVS applied day at an organic loading rate of 0.07 lbVS/ft^3 day to less than 4.0 ft^3/lbVS applied day at 0.25 lbVS/ft^3 day. This reduction in gas production is in direct contrast to the results of Mah et al (1980) who found more sustained gas productions at higher loading rates. The difference in values is attributed to the difference in mixing regimes. The digesters used by Mah, et al.(1980) were bench scale units having volumes less than 10 liters. In a digester this small it is much easier to obtain adequate mixing.

The mixing observed in the 50 gallon digesters used in this study was often inadequate. On several occasions scum blankets were removed from the heavily loaded digesters. The scum layers were 8" to 12" thick which further reduced the mixing. The existence of a scum layer tends to create more mixing problems, resulting in more scum generation.

Figures 15 and 16 show volatile solids destruction and total volatile acids as a function of organic loading rate. The declining volatile solids destruction with increasing organic loading rate verifies the declining gas productions shown in Figure 15. Increasing total volatile acids concentration with increasing organic loading rate is to be expected. It should be noted however that the acids concentrations found in this study are generally lower than results for similarly sized equipment treating similar MSW.

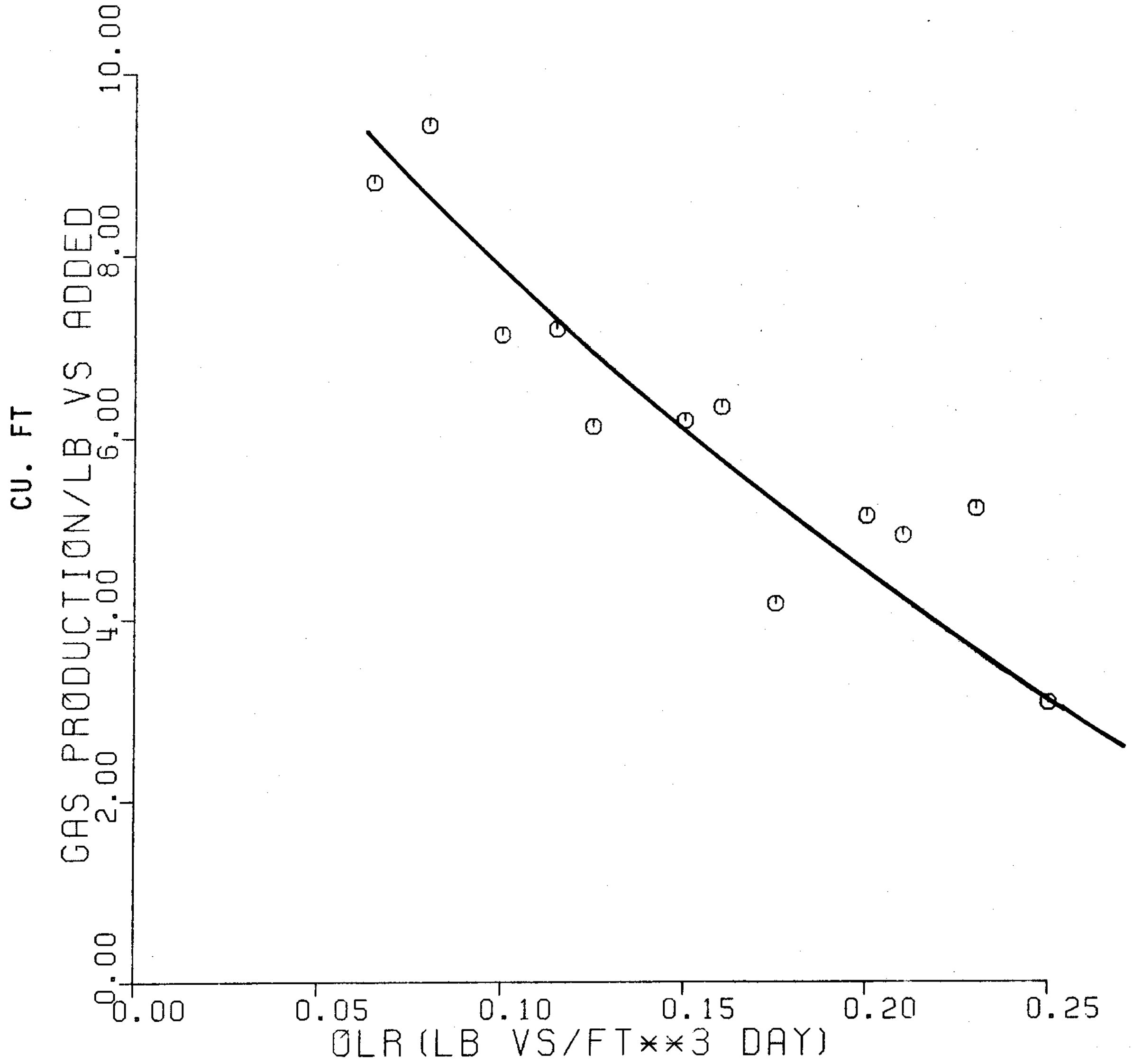


FIGURE 14. GAS PRODUCTION AS A FUNCTION OF ORGANIC LOADING RATE.

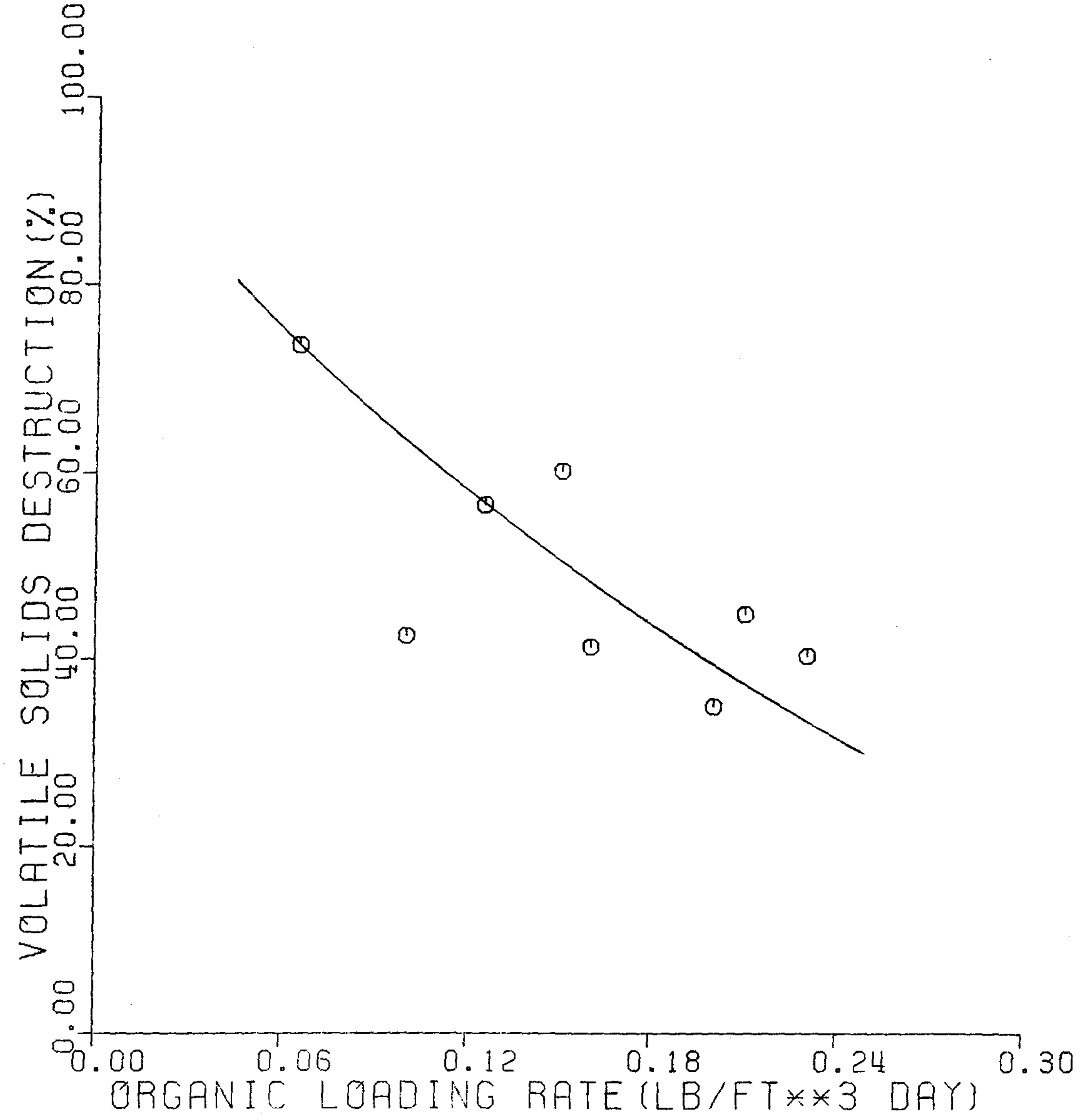


FIGURE 15. VOLATILE SOLIDS DESTRUCTION AS A FUNCTION OF ORGANIC LOADING RATE.

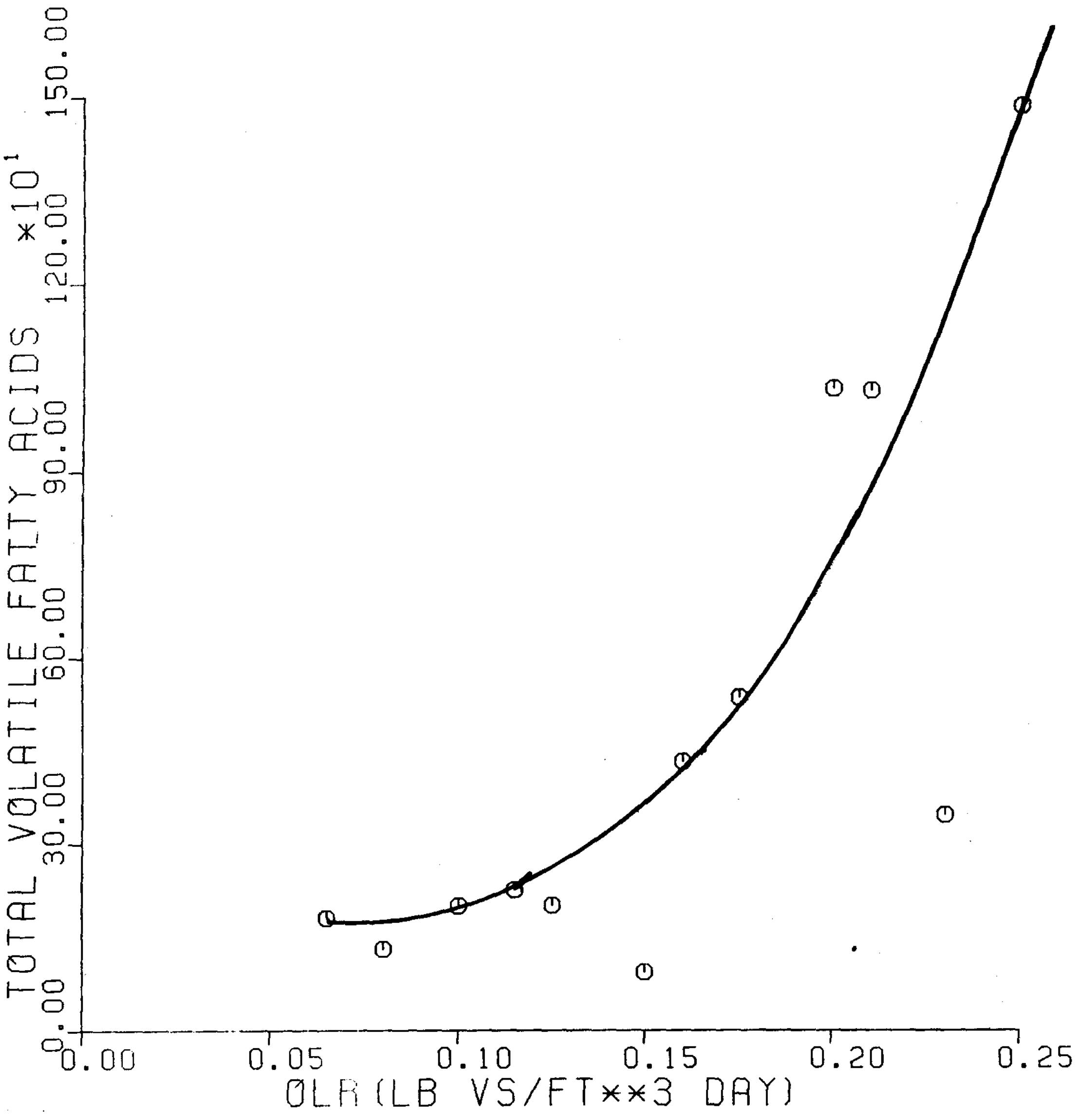


FIGURE 16. TOTAL VOLATILE ACIDS AS A FUNCTION OF ORGANIC LOADING RATE.

The effect of hydraulic retention time on digester performance is not clear. Figure 17 shows gas production as a function of hydraulic retention time. It is surprising to see the gas production increasing with decreasing retention time because the opposite trend usually occurs. One possible explanation of the reverse trend is the feed solids concentration and its effect on mixing. At the lower hydraulic retention time, the feed solids concentration is much lower, resulting in a thinner slurry which is easier to mix.

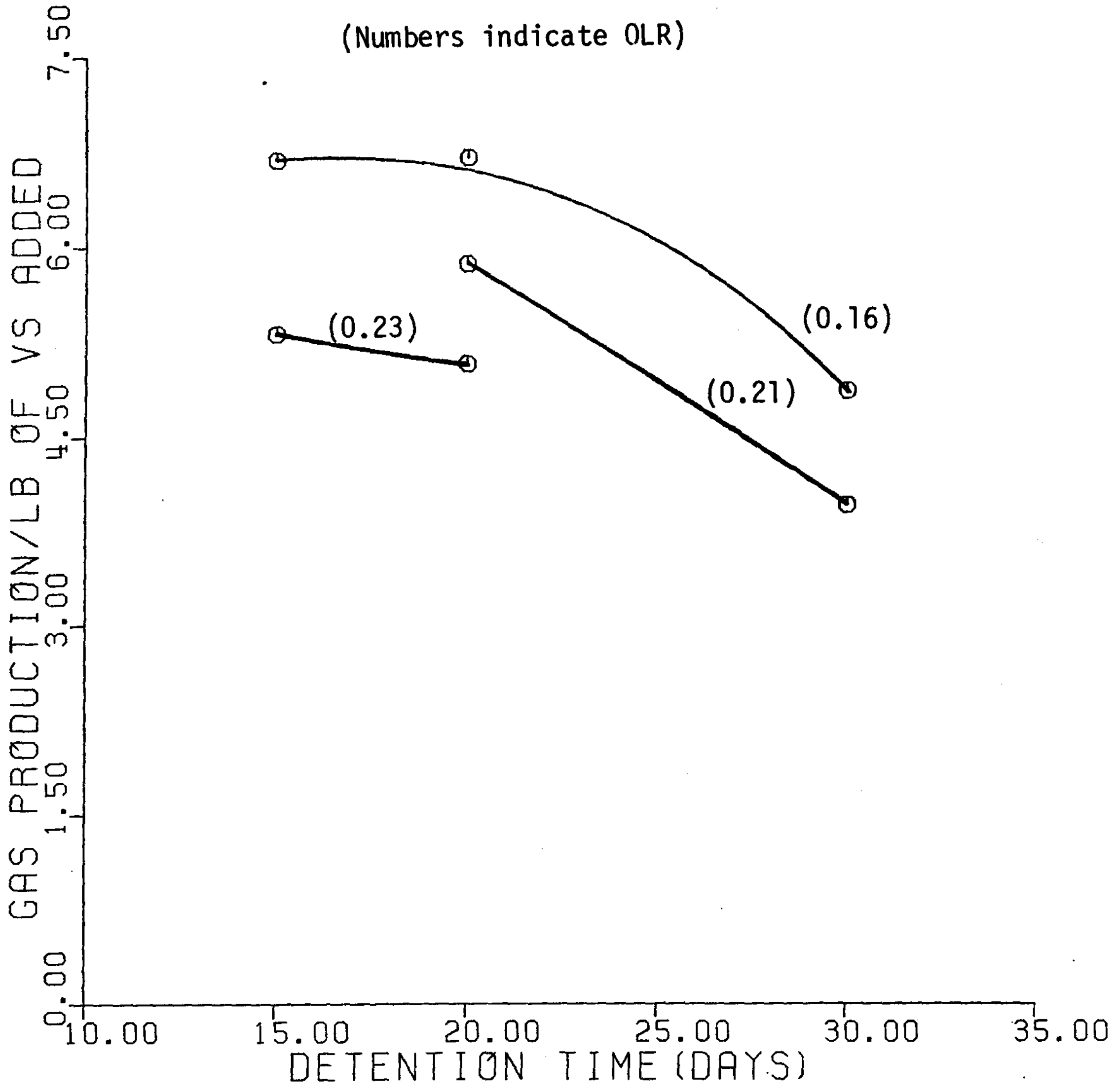


FIGURE 17. GAS PRODUCTION AS A FUNCTION OF HYDRAULIC RETENTION TIME.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study show that MSW, after classification with the Cal Recovery Process is a material suitable for anaerobic digestion in combination with a nutrient and alkalinity source, such as raw primary sludge. Gas productions ranged from a high of 9 ft^3/lbVS applied to 4 ft^3/lbVS applied. This corresponds to the range of 8 to 12 ft^3/lbVS applied for raw sludges alone. The major difficulty encounter in the study was mixing of the digester at high organic loading rates, which appears to be the main cause of poorer performance at the higher loading rates. The results of this study can be compared to other MSW-anaerobic digestion studies shown in Table 15.

The most reasonable interpretation of the experimental results indicates that approximately 6-8 ft^3/lbVS applied of medium BTU digester gas (55-60% methane) can be produced from MSW classified by the Cal Recovery Process. At present, this conclusion is restricted to loading rates less than 0.15 lbVS/ft^3 day. Higher loading rates are possible but this study indicates that mixing problems must be overcome before adequate gas productions will be obtained.

Anaerobic Digestion of MSW is a much more sensitive process than anaerobic digestion of raw sludge alone. The MSW digesters were easily overloaded, producing high volatile acids concentration. It was demonstrated that digester failure could be avoided by pH control using sodium carbonate and by temporarily reducing feeding rate. In extreme cases, feeding digested sludge was necessary to insure prompt recovery.

The pattern of impending upset was similar to the predictions made by Gray and Andrews (1974). The indicator responding most quickly to digester

TABLE 15. MUNICIPAL SOLID WASTE TO METHANE STUDIES

Feed	Source	RDF Size & Preprocessing Features	Exp. Scale (gallons)	Temp. °C	OLR (lb VS/ft^3 day)	R-T (days)	Mixing	Gas Conversion (ft^3/lb VS added)	% CH$_4$	% Dest.	Period of Operation	Major Problem	References
50% MSW 50% RS	New Mexico Oklahoma	B, (1/2-3/4")	400 gal	35°	0.077	30	Recirculation	7.0	55-60	64.5	18 weeks	Scum Layer	McFarland et al. 1972
MSW/RS	Illinois	A,B(1/2-1")	100 gal	60°	0.325*	10	Mechanical	6.28	53	57	3 months	Temp. Control	Brown, Pfeffer et al. 1976
	Wisconsin	A,B(1/2-1")				10	Paddle	5.22			7 months		
	Missouri	A,B(1")				50-80% Recycling Study	36 rpm	4.99			25 months		
MSW/RS (80/20)	Indianapolis IN	C,D	106 gal	35°	(0.1-0.2)		Mechanical continuous 200 rpm to intermittant (30 min/day)	5.8	58.6$^{\psi}$	50.5	123 days		Ghosh et al. 1977
MSW (80/20)	Indianapolis IN	C,D	5.0 1.5,2.5	35°	(0.14)	12-21							
MSW/RS (20-80)	Berkeley CA	E,F,H	2.4 gal	35°	0.062 to 0.068	30	Mechanical Sealed Stirrer	7.6		51.3	14 days		Diaz et al. 1974
MSW/RS	Berkeley CA	E,F,H						7.9		44.3	22 days		
MSW/RS (40-100)/(60-0)	Berkeley CA	B,F,I,H Material retained from 0.11" screens	1 gal	35°	(2.-.4)	30	Mechanical Sealed Stirrer (4x/day)	(8.2-5.4)	55-60^{+}	(35-77)	14 days		Diaz et al. 1978
(20-60)/(80-40)		After passing 0.5" screens	423 gal	35°	(0.07)	30	Recirculation	(6.25-12)	60-63	64	24 days	Scum Layer	
MSW^{a}(100%)	San Diego CA	B,F,J,H,G	1 gal	37°	(0.11)	15	Mechanical Scaled Mixer 1x15 min.	3.94	57	25	140 days		Mah, et al 1980
MSW^{b}(100%)	Berkeley CA	B,F,I,K,L	1 gal	37°	(0.12)	15		7.2	58	51	140 days		
MSW^{b}/KS (90-60)/(10-40)	Berkeley CA	B,F,I,K,L	1 gal	37°	(0.08)	15		(8.1-9.7)^{z}	(61-63)		140 days		
MSW^{b}/FLW/RS	Berkeley CA	B,F,I,K,L	1 gal	37°	(0.35)	10		10.2^{z}	61				

A - Handsorting
B - Shredding
C - Fiberized RDF
D - Tertiary Grading
E - Dry Milling
F - Air Classification
G - Fine Shred
H - Screening
I - Trommelling
J - Drying
K - 2nd Trommelling
L - Stoner
a - Garrett System
b - Cal Recovery
z - Calculated from CH$_4$ Conversion efficiencies
ψ - Averaged Values
* - Calculated from 4.35 lb VS/day input
\+ - Calculated from CH$_4$ Conversion efficiency of 3.4 and 3.8

upset was gas composition. Volatile acids concentration responded next, while pH and alkalinity showed the slowest response to upset.

Future work should be directed at obtaining better mixing. Novel techniques should be investigated to develop better mixing and scum blanket control. The mixing requirements of the MSW digesters were very different than the raw sludge digesters. For example, the raw sludge digester performed flawlessly during the entire period of operation, without any failures. The MSW digesters required occasional cleanings and frequent bearing and seal replacement, due to mixing difficulties.

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