ANAEROBIC DIGESTION OF MUNICIPAL SOLID WASTE

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ABSTRACT: Anaerobic digestion of classified municipal solid waste is a proposed disposal method for the mushrooming quantities of solid waste. To determine the suitability of anaerobic digestion to Los Angeles area wastes, a two-year pilot-scale study was conducted. A survey of a Southern California community was made to determine typical municipal waste composition. Municipal solid waste with characteristics conforming to survey results was classified using the Cal Recovery Process to provide a feedstock for digestion. Four 50-gal (0.19-m^3) digesters were operated at organic loading rates from 0.065 lb VS/cu ft-day–0.25 lb VS/cu ft-day (1.04 kg/m^3·day). Feed concentration ranged from 2.6%–8% VS and hydraulic retention time ranged from 15–30 days. Feed solids were composed of 80% classified municipal solid waste and 20% primary sludge. Results of the experimental investigation showed that gas containing 55%–60% methane can be produced at a rate of 7.0 cu ft–9.0 cu ft gas/lb-VS applied (0.44 m^3–0.56 m^3/kg·VS applied). The highest gas production rate was obtained at the lowest digester loading rates. Digester mixing ability appeared to be the controlling process variable. No chemicals for pH control or nutrients were required to maintain normal process operation.

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, ranging from well-known methods such as passive solar heating, to poorly understood methods such as wave energy generation. Energy production from biomass has also 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 yr.

Application of anaerobic digestion to other wastes has not found widespread commercial acceptance. A number of farm wastes, such as cow

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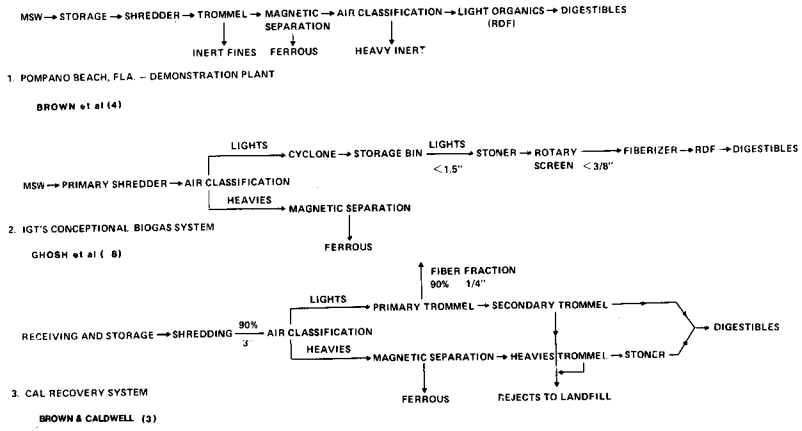

FIG. 1.—Anaerobic Digestion Classification Systems (1 in. = 25.4 mm)

manure, have been treated in anaerobic lagoons for many years. This application was originally developed as a disposal technique, but now has become an important energy production technique. One application of anaerobic digestion which appears attractive is the anaerobic digestion of classified municipal solid waste (MSW, i.e., garbage and refuse which has been shredded and sorted). Anaerobic digestion is a promising alternative due to the need for waste disposal as well as energy production.

Solid waste production is an increasingly more important problem in urban areas. The volume of waste produced is increasing rapidly, while the availability of landfill sites and other conventional disposal methods 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 classified MSW is attractive since it could potentially produce a medium Btu gas (550 Btu/cu ft–650 Btu/cu ft or 4,800 K cal/m^3–5,800 K cal/m^3) without creating the air pollution concerns associated with incineration. In many urban areas, especially in areas like Los Angeles with air pollution concerns, the production of a clean fuel is 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 difficulty in larger scale studies is partly attributed to insufficient classification and pretreatment, and partly to mixing problems.

The earliest reference to digestion of MSW is the work of Babitt, et al. (1), in 1936. Since that time others have investigated MSW digestion, including Brown et al. (4), Golueke et al. (7), Klein (9), and McFarland et al. (10). Various levels of volatile solid (VS) destruction efficiencies and gas production rates have been noted, ranging from 40%–60% and from 3.75 cu ft CH_4/lb–5.33 cu ft CH_4/lb VS applied (0.23 m^3CH_4 kg VS–0.33 m^3CH_4 kg VS applied) respectively. Gas composition range 50% CH_4–60% CH_4 on a dry volumetric basis. The CH_4 percentage was consistently lower for classified MSW digesters than for wastewater-derived

sludge digesters (60%–65%). Reviews of these results and other findings have been presented by Brown and Caldwell (2,3), Ng, et al. (11), the MITRE Corporation (12), Stenstrom (15), Vesilind and Reiner (16) and Wilson (17).

The objective of this study is to evaluate the Cal Recovery classification technique in 50-gal (0.19-m^3) pilot scale digesters to determine if economical gas production and solid destruction rates could be obtained. The Cal Recovery Process shown in Fig. 1 with two alternative processes has the unique feature of separating digestibles from both the heavy and light MSW fractions. The effect of organic loading rate, influent solids concentration, and hydraulic retention time were also evaluated. It was hoped that the successful results of this study could be used for the development of a demonstration-scale resource recovery plant in a Los Angeles area.

Experimental Procedures

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 assess 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. The truck was dumped while jogging forward to distribute the waste over a 25-ft (7.6-m) section. Next, a 10-ft by 25-ft (3-m × 7.6-m) sheet of plastic was spread next to the column of waste and a garden rake was used to transfer between 250 lb and 300 lb (113 kg–136 kg) to the sheet, by raking 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 twelve categories.

Cal Recovery Systems used the survey information to select waste from areas adjacent to University of California Berkeley Richmond Field Station which would be similar in composition to the Santa Monica Waste. Cal Recovery Systems classified the waste and shipped the digestible fraction to UCLA in 40-lb–70-lb (18-kg–32-kg) cardboard drums. The waste was refrigerated at 4° C until used.

Experimental Apparatus.—Experiments were carried out with four 50-gal (0.19-m^3) cylindrical stainless steel digesters, each with a working volume of approximately 45 gal (0.17 m^3). The details of the digester design and external apparatus are shown in Fig. 2. Briefly, each digester was constructed with a sloping bottom and a 2-in. (50-mm) exit port for sludge withdrawal. The top flange of the digesters had entry ports and fittings for the gas outlet, pH sensor, liquid level sensor, thermometer, RDT temperature sensor, and feeding port. Mixing was accomplished by a top mounted, directly coupled 1/4-hp-DC motor with a two impeller vertical shaft extending approximately 5/6 the distance to the bottom of the digester. The digester temperature was controlled at 37° C ±

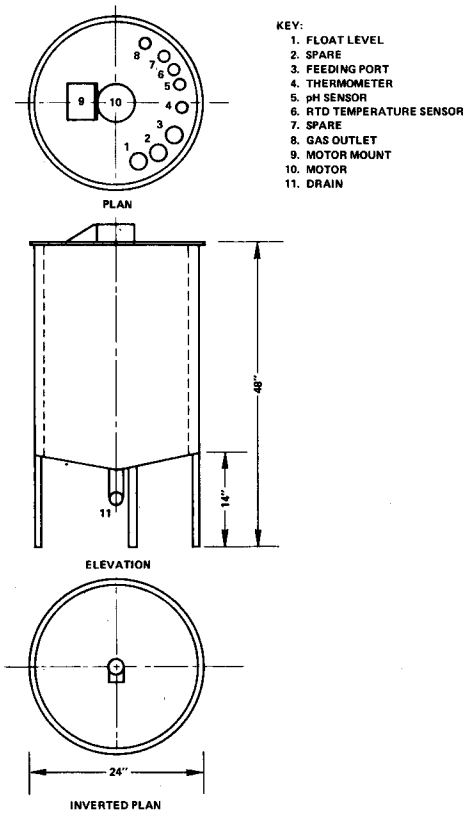

FIG. 2.—Pilot Scale Digester (1 in. = 25.4 mm)

1° C with an automatic portional-integral controller using externally wrapped heating tapes and fiberglass insulation. Gas measurements were taken by bubbling the biogas into a 2% solution of H_2SO_4 in a closed flask connected to a wet test meter. The pH control, which was occasionally necessary in the start-up stage of the experiments, was accomplished by the manual addition of NA_2CO_3.

Digester Start-Up Procedure.—Each digester was initially seeded 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 0.04 lb VS/cu ft day (0.64 kg/m^3 day, equaling approximately 1 gal or 3.78 L of raw sludge per 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/cu ft day (1.6 kg/m^3 day) until a new level of stable gas production and acids concentration were obtained. Following this initial period of acclimation, experiments with MSW began in three of the digesters, with the fourth digester retained as a control (fed with raw primary sludge only). The conversion of the feed from 100% raw sludge

to 80% MSW and 20% raw sludge was made gradually while monitoring gas production and composition and volatile acids concentration. When overloading occurred as indicated by a decline in CH_4 production or an increase in volatile acids concentration, feeding rate was temporarily reduced in order to allow the digester to restabilize. Also pH control was used when needed. The acclimation period to MSW required approximately 60 days. After acclimation at each value of influent volatile solids or hydraulic retention time, the digester was operated for at least 30 days to obtain representative values of gas production and other operating parameters.

Feeding Procedure.—The following procedure evolved over the first year of operation, since it was found that feeding technique greatly affected the mixing ability of the digesters. Based upon organic loading rate (OLR) the amount of refrigerated MSW for each digester was weighed using a gram balance, and placed into wide-mouth, 4 L plastic jars at approximately 300 g/jar. Tap water was added to the jars to bring the weight and volume of feed to the appropriate level, assuming the mixture had a specific gravity of 1.0. Based upon hydraulic retention time, the appropriate volume of waste sludge was withdrawn from the digester and wasted. An excess volume of digested sludge was withdrawn and mixed with the feed MSW and tap water in the wide mouth jars at a ratio of approximately 4 L of digested sludge per 250 g of dry MSW. This mixture was thoroughly blended by shaking so that it could be poured easily into the digester. Finally the supplemental raw sludge (20% by volatile mass) was measured and fed to the digesters.

Analytical Methods.—A number of analyses were routinely performed. Alkalinity, pH and NH_3 (specific ion electrode method) were performed at least once, and usually three times per week. Organic acids (acetic, propionic, butyric, iso-butyric, valeric, and iso-valeric) were made once or twice weekly, using a Varian series 1400 gas chromatograph equipped with an FI detector and a 1.8 m long, 6.25 mm OD glass column packed with 15% SP-1220 chromosorb AW with 1% H_3PO_4 (mesh size 100/120). The column was operated at a temperature of 130° C with an injector temperature of 160° C. The carrier gas was composed of He (30 ml/min), H_2 (30 ml/min) and O_2 (300 ml/min). Biogas analyses were also made once per week with a Varian 920 series chromatograph, equipped with a thermal conductivity detector, using a 3.6 m long stainless steel column packed with activated carbon. Solids analyses were performed at least twice per week according to methods 208A and 208E of *Standard Methods* (13) with the exception that volatile solids were determined on a g/g basis as opposed to a g/volume basis. This modification was required because it was not possible to accurately measure sludge volume.

Statistical Design.—A factorial design was developed which required that three of the digesters be operated at 30, 20 and 15 days hydraulic retention time, with feed concentrations ranging from 2.5%–10% volatile solids. This provided a range of organic loading rates from 0.05 lb VS/cu ft–0.42 lb VS/cu ft day (0.80 kg VS/m^3 day–6.7 kg VS/m^3 day). The fourth digester functioned as a control digester, treating 100% raw primary sludge. During the period of the study not all positions in the factorial design could be obtained due to limitations of the process and

equipment. The digesters were first operated at the lowest organic loading rate (OLR) and greatest hydraulic retention time, and as the experimental phase continued the OLR was increased. It was necessary to increase loading rates very gradually. Often volatile acid concentration would quickly increase to a high value, indicating that the OLR was being increased too quickly. To control these upsets the feeding rate was temporarily reduced, and in severe cases the pH was neutralized with Na_2CO_3.

Results and Discussion

Santa Monica Survey.—Municipal solid waste was surveyed three times at the Santa Monica transfer station during the periods of August 11, 1980–August 15, 1980, December 16, 1980–December 22, 1980, and February 17, 1981–February 23, 1981. The survey results are shown in Table 1. The results for the various categories are remarkably consistent for the three sampling periods, and show no significant difference at the 5% level of confidence ($\alpha = 0.05$).

Digestion Results.—The initial experimental procedure was to produce a series of digester experiments which could be analyzed as a factorial design. Hydraulic retention time and influent suspended solids concentration were to be used as blocking factors. Three levels of hydraulic retention time, corresponding to 15, 20, and 30 days were selected. Influent volatile solids ranged from 2.75%–10%. This provided a range of organic loading rates (OLR) from 0.065 lb VS/cu ft–0.42 lb VS/cu ft day (1.04 kg/m^3 day–6.7 kg/m^3 day). Originally it was hoped to achieve OLR's in the high end of this range, but this was not possible due to process instability, and no OLR over 0.25 lb VS/cu ft day (4.0 kg/m^3 day) was obtainable.

Table 2 summarizes the analytical results for the stable operating periods. Each period corresponds to a minimum of 30 days stable operation. Total volatile acids concentration ranged from less than 100 mg/L to over 1,400 mg/L (as acetic). Gas production ranged from 9.4 cu ft/lb VS added to 3.07 cu ft/lb VS (0.59 m^3/kg VS–0.19 m^3/kg VS). In all cases methane content of the biogas ranged from 55%–60%, except in the last case at 20 days hydraulic retention time and 8.0% influent volatile solids, when the methane content of the biogas ranged from 50%–55%. The remaining portion of the biogas was primarily CO_2, with only a trace of N_2. H_2 was not observed in the biogas, except in periods of extreme upsets, which are not reported herein. H_2S was not detected in the biogas but was obviously present from the gas odor. NH_3 and alkalinity concentrations ranged from 500 mg NH_4^+-N/L–800 mg NH_4^+-N/L and 3,200 $CaCO_3$/L–4,500 $CaCO_3$/L, respectively. During stable periods it was not necessary to add any pH control chemicals, and the digesters were self-regulating.

An analysis of variance of gas production using a factorial design with influent volatile solids concentration and hydraulic retention time as blocking factors revealed that the former is the more significant parameter. This was concluded from two methods of analysis with two types of errors considered, using Type I and Type IV sum of squares (14).

TABLE 1.—Results of the Santa Monica Municipal Solid Waste Survey

Category (1)	Period 1 8/11/80–8/15/80 Average (2)	Period 1 Standard deviation (3)	Period 2 12/16/80–12/22/80 Average (4)	Period 2 Standard deviation (5)	Period 3 2/17/81–2/13/81 Average (6)	Period 3 Standard deviation (7)	3 period average (8)
Mixed paper	10.4	5.38	9.94	4.8	10.6	5.81	10.3
News print	12.1	4.01	13.8	4.7	15.3	4.98	13.1
Corrugated paper	19.3	5.28	19.5	6.6	18.6	7.41	19.1
Plastics	7.94	2.26	6.15	2.06	6.19	2.20	6.96
Yard waste	16.2	12.0	20.0	17.9	17.8	15.6	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	12.0	4.2	10.6	4.86	9.29	4.86	10.6
Miscellaneous	1.16	0.65	0.85	0.24	1.84	2.18	1.28
TOTAL	98.8		99.96		99.95		99.57

Note: Numbers denote weight percents on an "as received basis."

TABLE 2.—Digestion Results

Influent VS, as a percentage (1)	θ_H, in days (2)	OLR,[a] in pounds per cubic foot day (3)	Gas production,[b] in cubic feet per pound VS added (4)	Total volatile acids, in milligrams per liter as HAC (5)	pH (6)
2.75	15	0.12	7.18	225	7.18
2.75	20	0.08	9.42	130	7.32
3.13	30	0.065	8.79	180	7.15
3.85	15	0.16	7.55	114	7.24
5.00	20	0.16	6.57	434	7.18
5.0	30	0.10	6.09	202	7.26
5.5	15	0.23	5.17	532	7.11
5.5	20	0.18	4.16	536	7.28
6.0	30	0.13	6.11	200	7.29
6.5	20	0.20	5.18	1,030	7.14
7.25	20	0.23	5.11	120	7.22
7.25	30	0.15	6.17	95	7.16
7.70	30	0.16	4.85	240	7.26
8.00	20	0.25	3.07	1,480	7.08

[a]To convert to kg/m^3 day, multiply by 16.04.
[b]To convert to m^3/kg, multiply by 0.0623.

Using influent volatile solids and hydraulic retention time as blocking factors, the null hypothesis (no effect) for gas production per unit volume of VS added is rejected for influent volatile solids at the 99.9% level of confidence, and is rejected for hydraulic retention time at the 83% level of confidence, using both Type I and Type IV sum of squares criteria. From this type of test it is obvious that gas production is much more strongly influenced by influent solids than by hydraulic retention time. If the effects of influent solids are neglected (blocking only using hydraulic retention time), the null hypothesis is rejected for hydraulic retention time at the 99.9% level of confidence using both Type I and Type IV error criteria. A factorial analysis also showed that influent volatile solids concentration is more significant than hydraulic retention time. If the results are analyzed using only organic loading rate as a blocking factor, the null hypothesis is also rejected; however, if influent volatile solids concentration and hydraulic retention time are added as blocking factors, the organic loading rate is no longer significant.

An analysis of variance of total volatile acids' concentration was performed in a manner similar to the analysis for gas production. From the analysis it was concluded that only influent volatile solids concentration was significant; hydraulic retention time and organic loading rate were not significant. Figs. 3 and 4 show the effect of influent volatile solids concentration on gas production and total volatile fatty acids.

Other operating problems and observations should be noted. At high influent solids concentration it was very difficult to avoid forming a thick scum layer on the surface of the digesters. On two occasions the scum layer was so thick that the digester had to be disassembled in order to manually remove the scum layer. From these observations it appeared that the scum layer was formed from undigested solids which created a semi-dry mat, bridging the entire digester surface, which prevented mixing into the bulk of the digester. It is believed that the formation of the scum layer could be avoided by more effective mixing, which would force the digester surface to circulate through the lower sections of the digester.

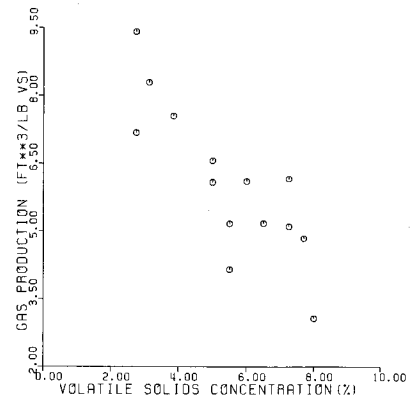

FIG. 3.—Biogas Production versus Influent Volatile Solids Concentration (1 cu ft/lb = 0.062 m³/kg)

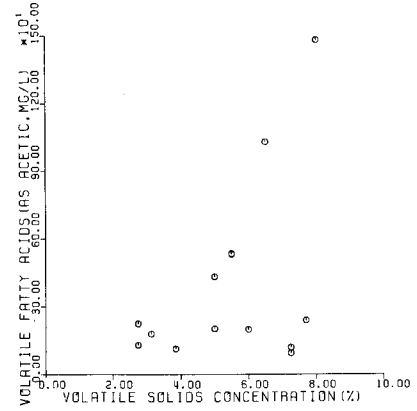

FIG. 4.—Total Volatile Acids Concentration (as HAC) versus Influent Volatile Solids Concentration

Upon disassembly and inspection the mixing impeller were usually coated with a large bundle of fibers. This was routinely observed when the digesters were disassembled for maintenance. The fibers appeared to be partially composed of recognizable influent materials, as well as long "strings" which appeared to be woven in the mixing process. The production of the bundles on the mixer was easily detected by changes in motor current and excessive bearing and seal wear. Reversing mixer direction was routinely performed and appeared to provide some relief from impeller clogging, but the relief was temporary. Eventually the bearings and seals on the mixer shaft failed, requiring replacement approximately every three months. The control digester, in contrast to the municipal solid waste digesters, performed flawlessly without a mixer or seal failure throughout the entire investigation.

The motors used for mixing were shunt-wound DC motors with a rated hp of 0.25 at 1,725 rpm (0.186 kW). Under severe conditions, the maximum rpm obtainable without exceeding maximum torque ratings, was approximately 250 rpm, indicating that the actual mixing energy transferred to the digester contents was approximately 0.04 hp (0.03 kW), or 6.0 hp/1,000 cu ft (0.157 kW/m³). The torque limits of the motors limited digester mixing.

Grit accumulation was not observed in the digester and it is hypothesized that this was due to the sloping tank bottom and the existence of a lower mixing impeller. Grit and broken glass were easily observed in the digested sludge, and flowed out of the digester almost immediately after the beginning of the feeding procedure. It was easy to observe the glass being removed from the digester by the sound it made as the digested sludge flowed into the sludge collection vessels.

Conclusions and Recommendations

From this investigation it is concluded that classified urban solid waste in combination with raw primary sludge can be anaerobically digested,

producing a biogas containing 55%–60% CH_4, at a rate of approximately 8–9 cu ft/lb VS (0.50–0.56 m^3/kg) applied. Analysis of variance using a factorial design revealed that influent volatile solids concentration was the most significant parameter affecting gas production rates. The rate of gas production observed in the pilot-scale digesters declined sharply with increasing influent volatile solids concentration, and this decline was due primarily to the limited ability of the digester to thoroughly mix the contents and thus avoid the production of a scum layer. The mixing capability of the pilot digesters far exceeded the mixing ability of commonly designed sludge digesters, indicating that new developments in digester mixing are needed for successful digestion of classified MSW.

The results of a survey performed at Santa Monica, California, indicated that municipal solid waste composition does not change with season.

Acknowledgments

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