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BIOLOGICAL CONVERSION OF BIOMASS TO METHANE

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John T. Pfeffer

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Department of Civil Engineering
University of Illinois
Urbana, Illinois 61801

INTRODUCTION

Recovery of energy from residual organic materials and from crops grown specifically for their energy content is part of ERDA's Fuels from Biomass Program. One of the processes for energy recovery is the methane fermentation system. In order to evaluate the methane yields from various organic materials a small pilot scale experimental system has been established. Constructions of this facility was initiated in June of 1976, and it became operational in October 1976.

After the initial shakedown period, tests were conducted on the methane yields from animal manure. This initial substrate was selected to complement the work being conducted on other ERDA projects.

The effect of the type of reactor on methane fermentation has been discussed extensively in the literature. An addendum to the initial proposal provided for the evaluation of methane fermentation in complete mixed, two-stage and plug flow reactors. The objective of this phase of the present study is to determine the desired reactor type to maximize gas production.

One objective of the proposed research is to provide data on the methane yield for various operating conditions. This data will provide the necessary base from which economic feasibility studies can be conducted. Since a major factor in the economic evaluation is the yield of methane per unit of material processed, this data is essential for the above studies. Additional objectives include the evaluation of the benefits of various substrate pretreatment and the evaluation of potential systems for processing and disposing of the fermentor slurry.

DESCRIPTION OF EXPERIMENTAL SYSTEM

The experimental reactors are housed in the Department of Civil Engineering's Dynamic Testing Lab. This building is located on the south campus of the University of Illinois in Urbana. In addition to a large test bay in which the reactors are housed, this facility contains adequate laboratory and office space for the research staff. The experimental units consist of four completely mixed stainless steel reactors having an operating volume of 750 liters. The reactors are heated so that temperatures can be maintained from ambient to 60°C. Heating is provided by circulating hot water through the external jackets of the reactors. Figure 1 shows a schematic of the processing system.

The reactors are mixed with a variable speed turbine mixer. The speed range can be varied from 20 to 120 rpm. The mixing power input can be varied from approximately .1 kw to 1.0 kw. This is equivalent to a mixing power input of from .13 kw/m^3 to 1.3 kw/m^3. Figure 2 shows the dimensions of the reactor and the associated mixer.

The feed slurry is pumped into the reactors with a progressing cavity pump. This pump is connected to a timer to allow for the approximation of a continuous feed system by pumping a percentage of each hour. Effluent from the reactors is pumped by a similar type pump that is actuated by a level controller. The effluent is collected in a holding tank for additional processing. Gas from the reactors is passed through wet test gas meters for determining gas flow rate. The gas can then be sampled for gas analysis with a Fisher Gas Partitioner.

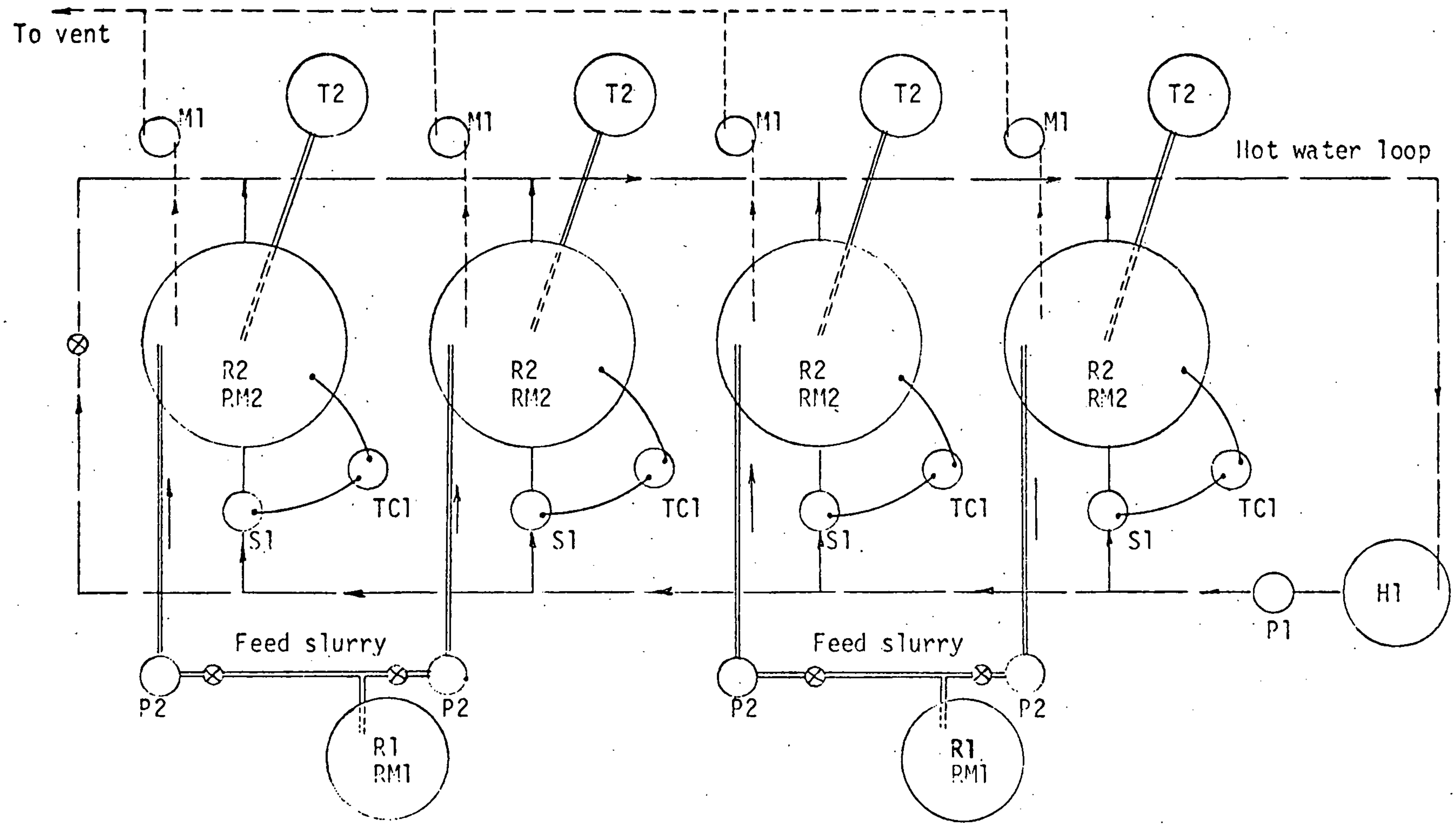

Figure 1. Schematic of experimental processing system

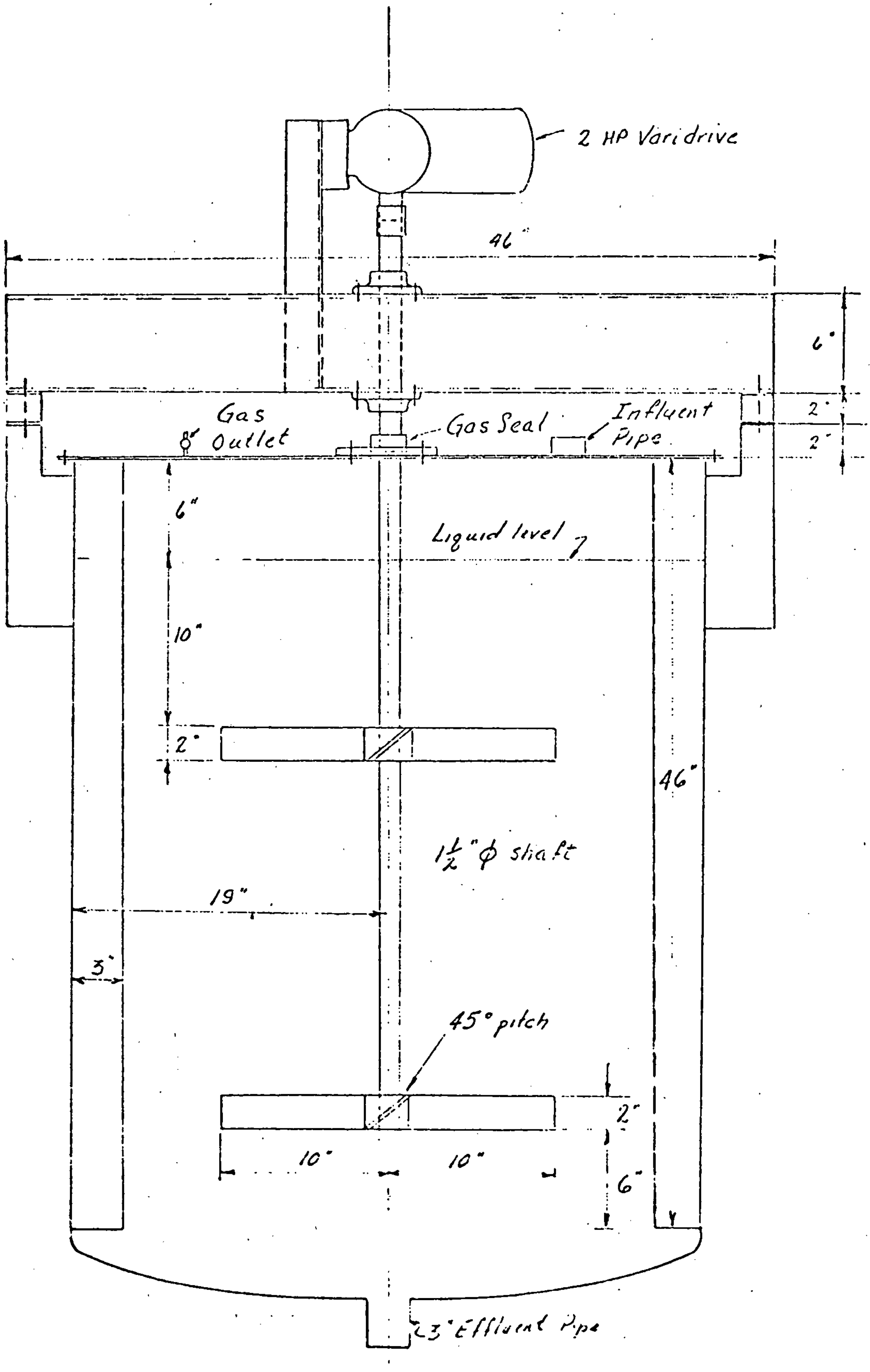

Figure 2. Details of Reactor and Variable Speed Mixer

A. Feed Preparation

The organic materials used in this process must be prepared for feed into the system. The initial step is one of size reduction. This is accomplished by a "granulator" manufactured by H. C. Davis Sons, Inc. This unit is equipped with three screens, 1/4", 3/4" and 1-1/2". The organic material can be ground to either of these three desired sizes. In order to effectively grind this material it must be relatively dry. This also assists in storage of significant quantities of feed material. The dry material does not decompose.

After shredding, a predetermined weight of the feed material is added to mix tanks. The dry feed is slurried with the desired amount of water. Either recycled liquor or fresh water can be used in the slurry tanks. After completely wetting the organic material, it is then discharged into holding tanks. This provides for storage of the slurry prior to pumping into the reactors. The mixed storage tanks also provide for a relative uniform feeding of material into the reactors since they contain approximately two days supply of feed slurry. These tanks are covered primarily for odor control.

B. Fermenter Operation

The loading rate on the reactors is determined by the concentration of organic solids in the feed slurry and the volume of feed slurry pumped per unit time. The predetermined loading rates are set by controlling the feed slurry concentration and varying the pumping time.

The performance of the fermentation system is analyzed on the basis of gas production. This is augmented with analysis of the reactor contents for total and volatile total solids, pH, alkalinity and volatile acids. These data provide basis for calculating the conversion efficiencies and methane yields.

Since each reactor is on an independent mixing system, the mixing power can be varied. This will permit evaluation of the effect of mixing intensity on the methane yields. Also each reactor is on an independent temperature control system so that the fermentation temperature can be varied as desired.

There are only two feed slurry storage tanks so two reactors are fed from each tank. However, by varying the throughput, the loading rate and retention time of each reactor can be varied. This arrangement essentially allows each reactor to operate independent of the others. Therefore, it is possible to evaluate four variables at one time.

C. Residue Processing and Disposal

The effluent from the reactors is collected in an effluent storage tank. This storage tank is connected to a progressing cavity pump that feeds the centrifuge. The effluent is dewatered by passing it through a centrifuge. The resulting cake is collected for either further processing or disposal by landfill. The centrate is discharged into a holding tank. When centrate recycle is employed this liquor is used to make up the feed slurry. Without recycle this material is allowed to flow to the drain.

The centrifuge currently in use is a Fletcher Mark IV. This is a solid bowl basket centrifuge. Unfortunately, the solids handling capacity of this unit severely limits its use. It is not possible to continuously dewater the effluent, but it is necessary to shutdown the system and to remove the solids from the bowl at relatively short intervals.

This unit is being replaced with a horizontal solid bowl conveyor centrifuge that can be operated continuously. This will result in a substantial savings of time required for dewatering the effluent slurry.

Provisions have been made for applying a thermochemical treatment process for either the residue or the feed material. A mixed reactor capable of withstanding an internal pressure of 125 psi is connected to a stream generator. By adding the fibers to this reactor along with an appropriate amount of caustic and water it is possible to heat treat this material prior to fermentation. This permits evaluation of the effect of thermo chemical pretreatment or posttreatment of the residual solids on the fermentation characteristics.

In addition to the dewatering by centrifugation the effluent is available for additional tests. This material can be dewatered by vacuum filtration and filter test leaf studies are available to evaluate its filtration characteristics. Also, the quality of the effluent liquid and solids can be evaluated with respect to its nutrient value both as a possible refeed material or as a soil additive. These evaluations are made with laboratory analyses rather than having actual field tests.

SUMMARY OF PROGRESS TO DATE

The following is a summary of the results of the experimental program that have been obtained to date. In addition to completion of the installation of the experimental systems, studies using cattle manure as substrate have been undertaken. This substrate selection was made to provide additional data on manure fermentation to complement other studies that ERDA has on recovery of methane from feed lot manure. Studies are continuing on this substrate.

A. System Installation

The fermentation system as previously discussed has been completely installed. The installation was delayed for some time due to purchasing problems. Requests for prices for the reactors were placed in early May, 1976. There was a 60 day delay in issuing these requests. With the lead time necessary for fabrication of these tanks, they did not arrive on site until September 3, 1976. A contract modification to include variable speed mixers was made in August, 1976. This required redesign of the mixer drives to allow for variable speed operation. Because of the previous delays in the reactor acquisitions, this modification did not cause any additional delays in start-up.

The problem encountered with the plugging of the reactor effluent lines has been corrected by the installation of pumps in the effluent lines from the reactors. These pumps are activated by level control switches so that a constant level is maintained in the reactors. When the feed pumps are activated by the time switch, the increase in level in the reactor will activate the effluent pumps. This pump will continue until the tank is returned to the original level. The effluent pump rate is approximately 2 ℓ/min, or 120 ℓ/hr. The gas production rates are generally 50 to 100 ℓ/hr. Therefore, the effluent pumping will not produce a significant negative pressure on the fermentor since they will only operate for one to two minutes after the influent pumps stop.

The effluent accumulates in 300 liter storage tanks. This effluent can be subjected to further study or dewatered by centrifugation. The centrate is discharged to the sewer. The high ammonia nitrogen obtained with the fermentation of cattle manure precludes recycle of the liquid.

B. Substrate Selection

The original proposal was to investigate the application of the methane fermentation process to various crop residues and crops grown specifically for biomass production. The actual substrate to be tested was to be selected in consultation with the ERDA Program Manager. After discussion of the current program activities, it was decided that additional information was needed to complement the research on cattle feed lot manure fermentation. Therefore, manure from the College of Agriculture beef cattle feed lots was obtained for the initial substrate investigation.

The manure was scraped from the lots with a front end loader and hauled by truck to the laboratory. The manure was dumped on the floor of the test bay and a fraction of the pile was spread to allow for drying. Since the moisture content of the manure was reasonably high, the large pile was compact and, except for the surface, was anaerobic. Until the surface dried, there was some aerobic decomposition. However, the bulk of the pile was biologically stable due to the high ammonia content in the manure. After the spread material was sufficiently dried, it was passed through the mill and stored in containers.

The characteristics of the manure after it was slurried with water are shown in Table 1. A more detailed discussion of the manure characteristics will be given in the Final Report. This slurry served as the feed to the fermenters.

Table 1. Feed Slurry Characteristics

	Mix Tank 1		Mix Tank 2	
Manure Source	Tot. Sol.-%	Vol. Sol.-%	Tot. Sol.-%	Vol. Sol.-%
Beef 1	5.96	3.74	6.74	4.10
Dairy 1	5.45	3.81	5.12	3.84
Beef 2	5.00	3.42	4.80	3.35

Mix tank 1 supplied reactors 3 and 4 while mix tank 2 supplied reactor 1 and 2.

The organic content of the manure used to date has been relatively high. The beef manure was obtained from open lots. The second source did contain a small amount of bedding. The volatile solids content of the manure ranged from 63 to 70 percent with the dairy manure producing the highest volatile solids.

The nitrogen content in the feed slurry is given in Table 2. These data represent only one set of analyses. The TKN does not exhibit much variation for the three different manures. However, there is a

Table 2. Nitrogen Content in the Feed Slurry

	Vol. Solids - %	TKN - mg/ℓ N	NH_3 - mg/ℓ N
	Beef Lot Manure 1		
Mix tank 1	3.67	1679	1180
Mix tank 2	3.95	2001	1008
	Dairy Manure		
Mix tank 1	3.38	1134	280
Mix tank 2	3.54	1652	454
	Beef Lot Manure 2		
Mix tank 1	3.06	1624	353
Mix tank 2	3.38	1736	302

substantial variation in the ammonia content. This variation was also observed by the intense ammonia odor associated with the first beef lot manure stored in the test bay.

C. Fermenter Operating Parameters

The performance of the fermentation process as measured by the standard operating parameters is shown in Table 3. The fermentation temperature for these tests was 58 ± 1°C. After the initial start-up period, the pH of the fermenters was always in excess of 7.0. This would be expected with the high alkalinities and low volatile acids. The average retention time for these tests are also given in Table 3.

The nitrogen content in the reactors was determined at the same time the feed slurry was analyzed. These data are shown in Table 4 and represent the results of only one analysis on each reactor.

Table 3. Average Fermenter Operating Parameters

	Reactor 1	Reactor 2	Reactor 3	Reactor 4
	Test Condition 1 - Beef Lot Manure (11/15/76 - 12/11/76)			
pH	7.20	7.18	7.20	7.24
Alkalinity[1]	4.18	4.04	4.00	4.40
Vol. Acids[2]	0.20	0.18	0.18	0.19
Retention Time[3]	10.6	10.7	11.0	11.2
	Test Condition 2 - Dairy Manure (12/11/76 - 12/30/76)			
pH	7.20*	7.29	7.29	7.30
Alkalinity[1]	6.74	6.24	5.94	6.21
Vol. Acids[2]	0.28	0.19	0.30	0.19
Retention Time[3]	7.7	8.3	8.6	8.0
	Test Condition 3 - Beef Lot Manure (2/21/77 - 3/12/77)			
pH	7.29	7.26	7.31	7.29
Alkalinity[1]	5.28	5.19	5.37	6.98
Vol. Acids[2]	0.28	0.39	0.30	0.64
Retention Time[3]	9.0	6.7	6.7	6.3

[1] g/ℓ as $CaCO_3$, [2] g/ℓ as acetic acid, [3] days

* Belt on mixer drive failed on 12/21/76. No data collected after this date.

Table 4. Nitrogen Content in Fermenter

Fermenter	Vol. Solids-%	TKN-mg/ℓ N	NH_3-mg/ℓ N
	Beef Lot Manure 1		
1	2.56	1548	1054
2	2.24	1666	850
3	2.18	1694	848
4	2.12	1409	731
	Dairy Manure		
1	2.51	1680	920
2	2.39	1666	1025
3	2.03	1554	781
4	2.40	1638	645

Nitrogen analyses have not yet been conducted for test condition 3. The TKN of the feed slurry is essentially equal to the TKN in the fermenters. In the first beef lot manure tested, the high ammonia in the feed slurry did not change significantly in the fermenter. This would suggest that a substantial portion of the organic nitrogen had been hydrolyzed to ammonia before the manure was fed to the fermentation system. The converse was true for the dairy manure. A significant amount of TKN was organic nitrogen. The dairy manure was freshly collected and processed.

D. Gas Production Rates

The loading rates, retention time and gas production rates are shown in Table 5. All test temperatures are at 58°C ± 1°C. This temperature was selected to insure that normal temperature variations would not elevate the fermenter temperature into the inhibitory range. For the initial test run on beef lot manure, the retention times varied from

Table 5. Loading and Gas Production Rates

	Reactor 1	Reactor 2	Reactor 3	Reactor 4
	Beef Lot Manure (11/15/76 - 12/11/76)			
Loading-kg V.S./m^3-day	3.86	3.86	3.40	3.34
Gas-m^3/kg V.S. Add	0.260	0.234	0.307*	0.275
Gas-m^3/day-m^3	1.00	0.90	1.04	0.92
Retention time-days	10.6	10.7	11.0	11.2
	Dairy Manure (12/11/76 - 12/30/76)			
Loading-kg V.S./m^3-day	4.99	4.63	4.43	4.76
Gas-m^3/kg V.S. Add	0.403	0.419	0.412	0.401
Gas-m^3/day-m^3	2.01	1.49	1.82	1.91
Retention time-days	7.7	8.3	8.6	8.0
	Beef Lot Manure (2/26/77 - 3/13/77)			
Loading-kg V.S./m^3-day	3.72	5.00	5.10	5.43
Gas-m^3/kg V.S. Add	0.288	0.267	0.272	0.266
Gas-m^3/day-m^3	1.07	1.34	1.39	1.44
Retention time-days	9.0	6.7	6.7	6.3

* Due to faulty gas seal, gas data collected on 12/7 through 12/11/76

10.6 days in fermenter 1 to 11.2 days in fermenter 4. With a total feed solids of about 6 percent, the loading ranged from 3.34 to 3.87 kg volatile solids/m^3-day (0.21 to 0.24 lb V.S./ft^3-day). The gas production ranged from 0.234 to 0.275 m^3/kg V.S. added (3.76 to 4.4 ft^3/lb V.S. added). Fermenter 3 indicated a gas production of 0.307 m^3/kg V.S. added. However, because of a problem with gas seal, these gas data are based on only four readings. The methane content of this gas produced in each fermenter was measured to be between 58 and 59 percent.

The manure used in the second test was obtained fresh from a dairy herd. The manure was removed from the buildings on a daily basis. It was stockpiled outside. Because of the cold temperatures, the manure was frozen. This manure contained about 90 percent water. After it thawed, it was quite fluid and had to be stored in barrels. Because of this high moisture content, only enough solids were obtained to provide feed to the fermentation system for 19 days. Consequently, this manure was fresh and contained more unstable organics than the beef manure. The beef manure was obtained from an open lot where it was partially stabilized by natural processes.

The gas production from the dairy manure was substantially greater than from the beef lot manure. Even though the retention times were approximately 8 days, the gas production varied from 0.401 to 0.419 m^3/kg V.S. added (6.44 to 6.73 ft^3/lb V.S. added). At the shorter retention times, loadings approaching 5 kg V.S./m^3-day (0.31 lb V.S./ft^3-day) were obtained. This resulted in gas production of 2.0 m^3/m^3-day.

A return to beef feed lot manure produced essentially the same results as in the first test. The second batch of beef manure contained some straw that was used as bedding during the winter. With retention times ranging from 6.3 to 9.0 days, the gas production varied from 0.266 to 0.288 m^3/kg V.S. added (4.30 to 4.62 ft^3/lb V.S. added). At the 6.3 day retention time, the loading was 5.43 kg V.S./m^3 (0.34 lb V.S./ft^3-day). The gas production ranged from 1.07 to 1.44 m^3/m^3-day.

E. Operational Problems and Delays

Several delays resulted from problems with equipment acquisition. Problems in obtaining the stainless steel reactors caused an unexpected 30 to 45 day delay in completing the installation of the experimental system. The initial manure samples that were obtained did not require shredding since bedding was not used. The bedding in the second batch of beef lot manure required purchasing a knife mill to chop this straw. A 30 day delay in obtaining this equipment was encountered. This delay was due in part to the Christmas holidays as well as failure of the supplier to meet promised delivery dates. Without the knife mill it was not possible to process feed for the fermenters. Therefore, the system was in standby status during the month of January.

In a way this was fortunate since a severe winter storm in late January isolated the lab for a period of four days. Had the system been operational, the test run would have been interrupted by the inability to service the system during this period. Additional power failures in March caused disruption of the system due to shut down of the pumps, mixers and heating system. This resulted in some process disruption.

The installation of the laboratory hood and sink has been delayed. Delivery time for the hood was approximately 120 days. The schedule called for installation in January, but the severe weather during this month caused the University Physical Plant to delay all but emergency work until they were able to repair the damage caused by the extreme cold weather.

In addition to the above problems, the manure has caused some problems within the system. The manure contains a limited quantity of stones, sand and soil. Since the system was originally designed to handle only crop residues and other vegetation, these materials have caused problems in the pumps and pipes. Some modifications were necessary. Effluent pumps had to be installed because of the clogging of the effluent overflow pipes. Also problems in maintaining flow in the influent pumping systems has prevented use of the time cycle pumping to maintain semi-continuous feeding. This problem still has not been resolved.

Failures of the variable speed drives has been very disappointing. To date, all four vari-drives have failed. Delivery of repair parts is extremely slow, so that at times, the vari-drive is removed. A direct hook-up of the motor to the gear reducer allows for mixing at 60 rpm, which is more than adequate to keep the reactor homogeneous.

F. Results of Plug-Flow vs. Complete-Mix Reactors

Three laboratory scale reactors with a volume of 43 liters have been constructed for this phase of the study. One reactor (A) is completely mixed. The second reactor (B) is a two stage system with the first stage accounting for one-third of the total reactor volume. Both stages are completely mixed. The third reactor (C) consists of four complete mixed compartments in series.

Substrate for this study is shredded computer paper plus a small quantity of sewage sludge added for microorganism seed and micronutrients. Additional nitrogen and phosphorus are added to provide a balanced substrate. An appropriate quantity of base is added to the substrate to maintain the pH at 6.8 to 7.0 in the completely mixed reactor. The reactors were initially seeded with cultures from the larger manure fermentation system. The initial pH in all reactor stages was in the 7.2 to 7.5 range. The alkalinity was approximately 2700 to 2800 mg/ℓ and the volatile acids were approximately 300 mg/ℓ. This run was initiated on January 15, 1977. Table 6 shows the change in pH, alkalinity and volatile acids with time. The total retention time in all three reactors was 10 days with a fermentation temperature of 60°C.

The amount of caustic added to the substrate was sufficient to maintain the pH in Reactor A at 6.7 or greater. While this caustic was adequate to maintain the pH in Reactor A, the pH in all other reactors eventually dropped to inhibitory levels. These data are shown in Figure 3. Reactor C failed in a short period due to these inhibitory pH levels. The pH in the first stage of Reactor B dropped to low levels, but it was only after about 30 days that pH in the second stage began to drop. The associated alkalinity and volatile acids are shown in Figure 4.

After about 30 days after start-up, the pH in both reactors A and B-2 began to decrease. Apparently some micronutrient was missing in the feed slurry. Additional caustic was required to maintain the pH in Reactor A. As a result of the increased caustic addition, the pH in reactors B-1 and C-1 increased significantly. The volatile acids are shown in Figures 4 and 5. Also, Table 6 shows the pH, alkalinity and volatile acid for the first 30 days of this run.

The volatile acids in Reactor A increased slightly during this period. In reactors B-1 and B-2, there was a significant increase in

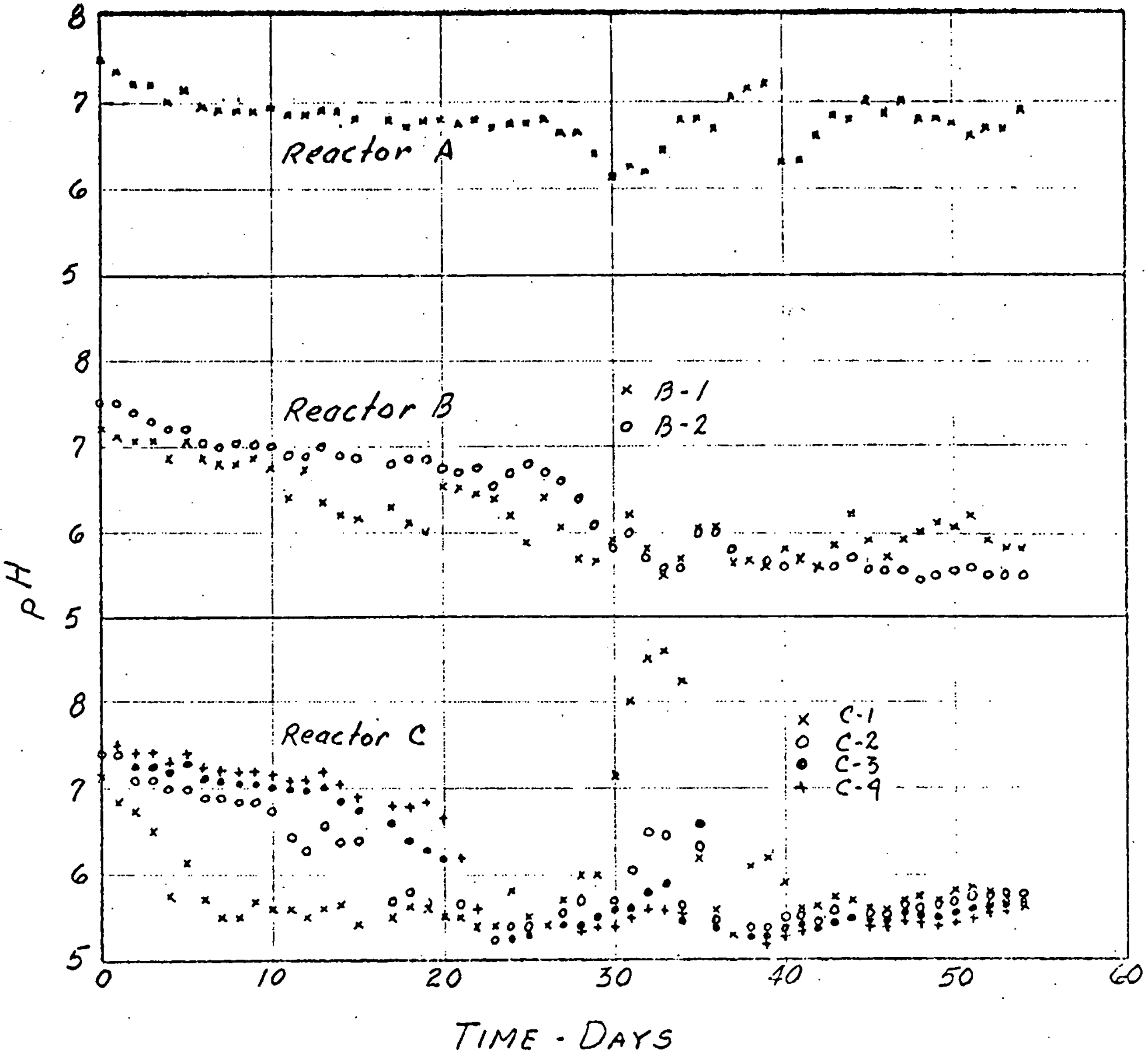

Figure 3. Variation in pH in Reactors A, B and C.

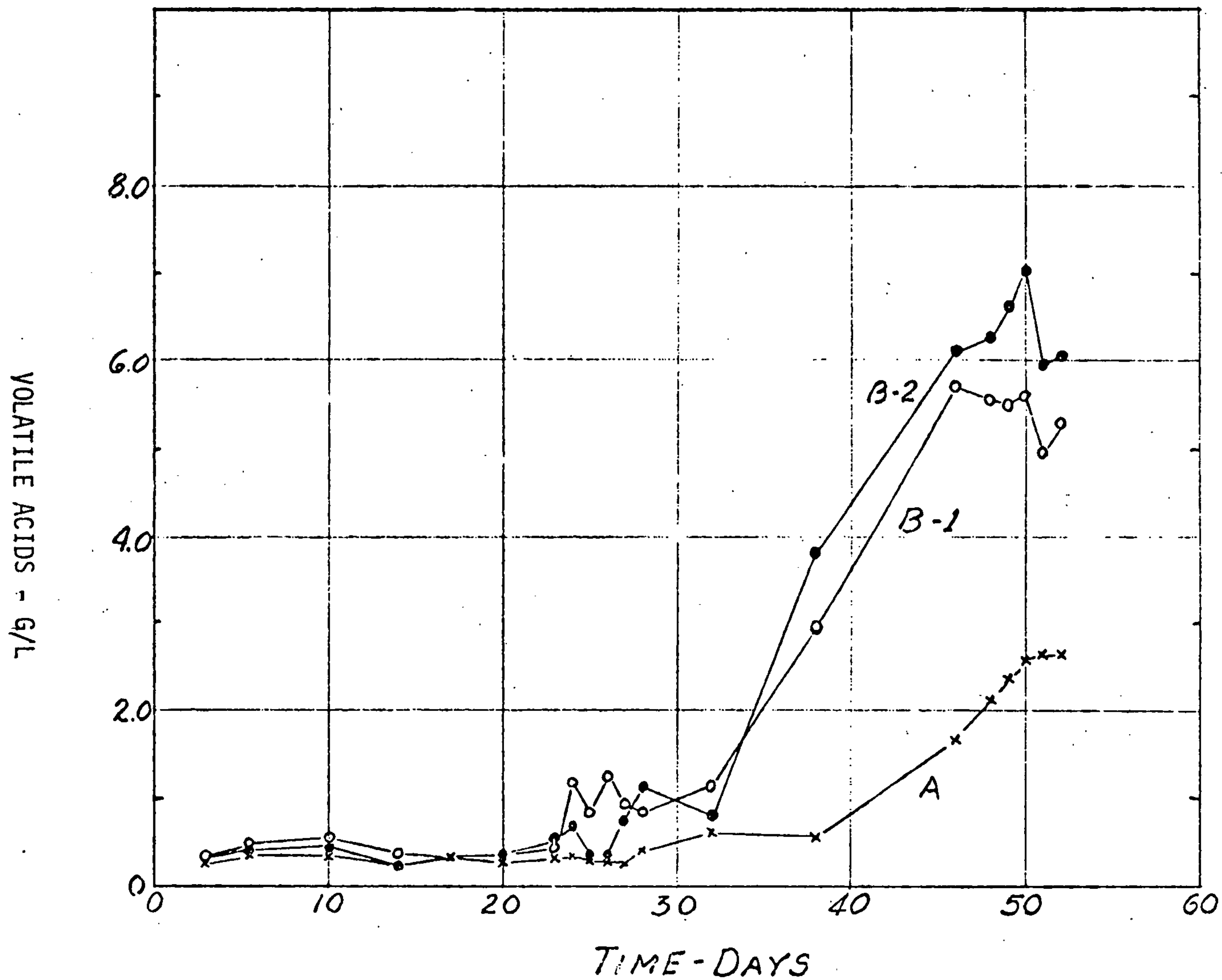

Figure 4. Volatile acids concentration in Reactor A and Reactors B-1 and B-2

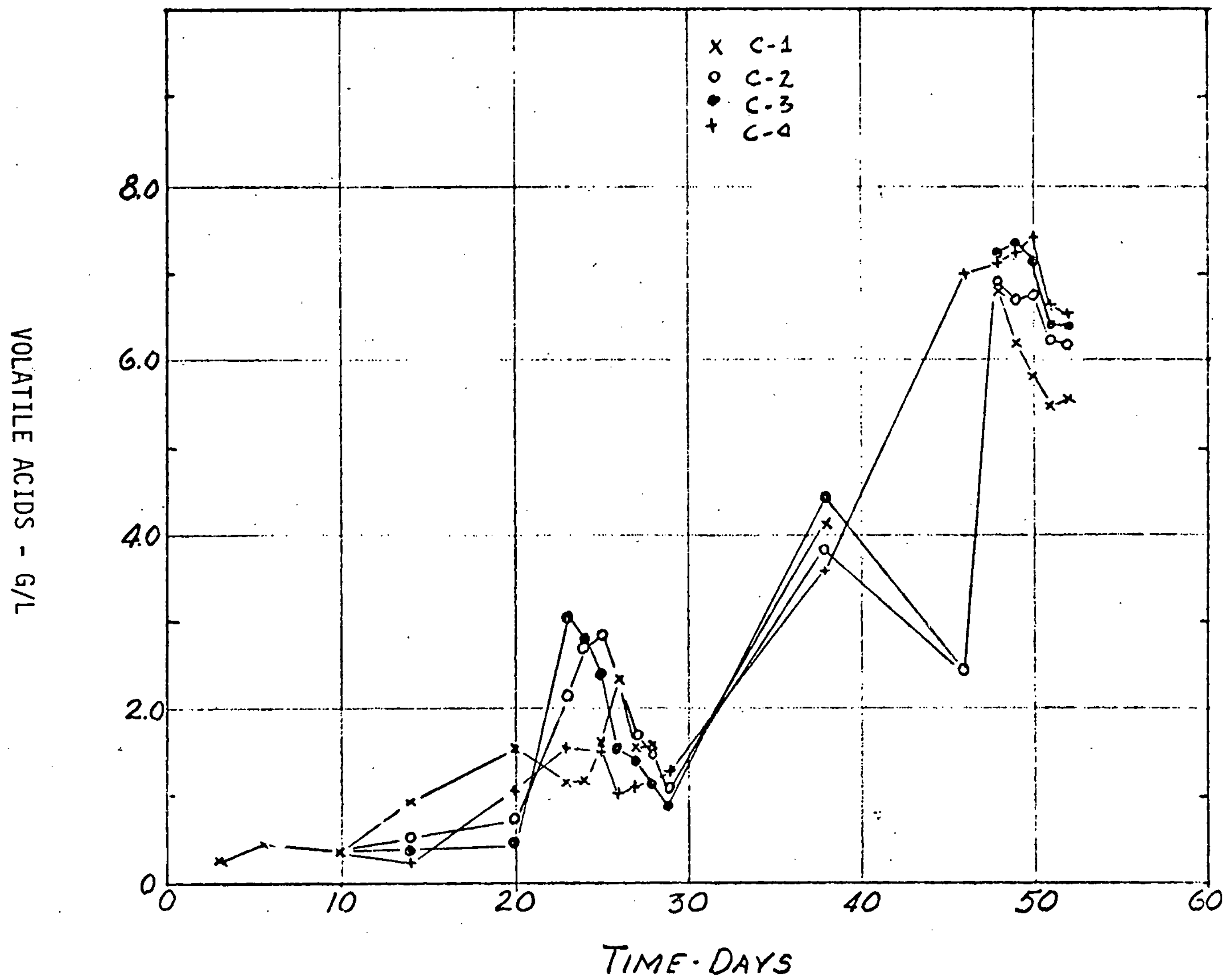

Figure 5. Volatile acids concentration in Reactors C-1, C-2, C-3 and C-4.

Table 6. Variation in pH, Alkalinity and Volatile Acids

Reactor		Date										
		1/25	1/29	2/1	2/4	2/7	2/8	2/9	2/10	2/11	2/12	2/13
A	pH	6.95	6.95	6.8	6.8	6.7	6.75	6.75	6.8	6.65	6.65	-
	Alkalinity	1570	1405	1100	1251	1170	1220	1312	1400	1335	1213	1151
	Vol. Acids	342	294	310	289	326	364	290	288	234	400	389
B-1	pH	6.75	6.4	6.6	6.55	6.4	6.2	5.9	6.4	6.05	5.7	5.65
	Alkalinity	1363	962	947	1335	1033	1068	1092	1306	1124	1201	-
	Vol. Acids	564	432	310	469	469	1171	838	1251	954	870	836
B-2	pH	7.0	6.9	6.8	6.75	6.6	6.7	6.8	6.7	6.6	6.4	6.2
	Alkalinity	1583	1358	1256	1236	1109	1232	1335	1225	1335	1239	1271
	Vol. Acids	348	288	387	387	571	337	337	414	774	1147	677
C-1	pH	5.1	5.75	5.5	5.5	5.4	5.8	5.5	5.4	5.7	6.0	6.0
	Alkalinity	1210	1246	1144	1690	1082	1150	1481	1290	1590	1684	1751
	Vol. Acids	360	924	-	3570	2102	3168	1591	2340	1512	1578	1121
C-2	pH	6.75	6.4	5.7	5.5	5.25	5.4	5.4	5.4	5.55	5.7	6.0
	Alkalinity	1384	1151	1082	1335	1162	1335	1314	1335	1478	1780	1592
	Vol. Acids	282	528	255	775	2162	2688	2840	-	1674	1526	1104
C-3	pH	7.0	6.85	6.6	6.4	5.25	5.25	5.3	5.4	5.4	5.4	5.5
	Alkalinity	1710	1507	1246	1140	1256	1168	1263	1335	1430	1412	1434
	Vol. Acids	372	384	370	490	3039	2726	2378	1566	1395	1158	895
C-4	pH	7 15	7.05	6.8	6.65	5.3	5.25	5.3	5.4	5.4	5.35	5.4
	Alkalinity	1870	1557	1335	1277	1060	1130	1191	1335	1335	1408	-
	Vol. Acids	400	264	310	1060	1550		2566	1008	1170	1158	1301

volatile acids. In Reactor C, the volatile acids started to increase in stage 1 after about 10 da A continued increase was observed in all stages during the balance of the run, reaching levels in excess of 6000 mg/ℓ as acetic acid.

On about day 30, a small quantity of sewage sludge was added to the feed slurry to supplement the trace nutrients. Reactor A responded favorably for about 15 days. The volatile acids began to increase again. During this period, the volatile acids in Reactor B-1 increased to greater than 6000 mg/ℓ while B-2 increased to about 5500 mg/ℓ. These data show that the two-stage system functioned reasonably well when the system was not stressed. However, when a stress was applied, the two-stage system failed rapidly. The complete mix reactor was considerably more stable. Complete failure occurred in Reactor C in about 20 days.

The volatile solids destruction and gas production are shown in Table 7. The feed slurry to the reactors contained 29.9 g/ℓ total solids and 24.5 g/ℓ volatile solids. The COD of the feed slurry was 29.1 g/ℓ. These data clearly show that the complete mix reactor produces a higher gas production than either of the other two reactor designs. The methane production per kg of volatile solids added in Reactor A appears to be low. Based on a measured COD reduction of 73.8 percent in Reactor A, the calculated methane production is 0.306 m^3/kg V.S. added. In Reactor B, the calculated methane production based on COD reduction is 0.106 m^3/kg V.S. added. For Reaction C, this calculated methane production is 0.047 m^3/kg V.S. added.

Table 7. Volatile Solids Destruction and Gas Production

Reactor	Eff.V.S. g/ℓ	% V.S. Dest.	Eff. COD g/ℓ	COD Red. %	CH_4 Production* m^3/kg V.S. Add.
A	6.3	74.7	7.6	73.8	0.229
B-1	13.4	45.3	23.1	20.6	
B-2	7.8	22.4	21.7	4.8	
Total		68.2		25.4	0.126
C-1	20.1	18.0	26.9	7.6	
C-2	14.1	24.4	27.0	0	
C-3	12.9	5.9	26.9	0	
C-4	12.0	3.7	25.8	3.7	
Total		51.0		11.3	0.06

* Dry gas at 0°C and 1 atm.

This analysis does show that there is some variation in the data collected. However, in spite of these variations, the complete mix reactor exhibits better methane production than either of the other two reactor designs. Experiments at longer retention times are presently underway to further evaluate the effect of the reactor type on gas production.

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