DEPARTMENT OF ENERGY

Office of Conservation and Solar Applications
Urban Waste and Municipal Systems Branch

Project Officer:

Donald K. Walter, Chief

Contract No. E(40-1)-5175

EVALUATION OF MIXING SYSTEMS FOR BIOGASIFICATION OF MUNICIPAL SOLID WASTE

SYSTEMS TECHNOLOGY CORPORATION
245 North Valley Road
Xenia, Ohio 45385

Authors:

Dr. Joseph T. Swartzbaugh
Ralph B. Smith

DISCLAIMER

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This study was conducted
in cooperation with the
U.S. Environmental Protection Agency

OFFICE OF CONSERVATION AND SOLAR APPLICATIONS
DEPARTMENT OF ENERGY
WASHINGTON, D.C.

NOTICE

ABSTRACT

Two specially selected mixing systems were tested and evaluated to determine how effectively they could prevent the formation of fibrous mats and stringers during the anaerobic digestion of a slurried mixture of preprocessed municipal solid waste and sewage sludge to produce methane gas. The tests were conducted in a modified 10.7-m (35-ft) diameter, nominal 378,000-liter (100,000-gal) capacity concrete vessel in the Franklin, Ohio, environmental complex. This complex included two plants that collectively provided the solid waste/sewage sludge feedstock. One of the two mixing systems was a mechanical agitator--a vessel-centered rotary shaft with four blades at each of two levels to drive the slurry downward. The second system included three equidistantly placed gas gun assemblies that each produced bubbles at a constant rate to draw the slurry upward.

Between August 1977 and September 1978, nine tests were conducted with 3:1 and 9:1 solid waste/sewage sludge ratios and with 4, 7, and 10 percent total solids in the feedstock. Though the microbial culture was healthy in most tests, the mixing systems were not effective in preventing excessive fibrous mat and stringer formations. These formations occurred because of the high cellulosic content of the feedstock. The test with the best energy recovery had a gas production of 805 liters/kg of volatile solids destroyed. However, the energy recovered was only 50 percent of the energy available in the solid waste, and only four times greater than the mixing energy expended for that test.

The solids accumulations were generally the same for the two mixing systems when they had common test conditions. In all tests, the percent solids for the top level were higher than those for the middle and bottom levels. As the feed ratio and the percent solids in the feedstock were increased, this differential became progressively more pronounced. Moreover, the percent of volatile solids (in a given amount of total solids) for the top level became disproportionately higher than those for the other two levels.

This report was submitted in partial fulfillment of Contract Number E(40-1)-5175 by Systems Technology Corporation (SYSTECH) under the sponsorship of the U.S. Department of Energy. This report covers the period September 22, 1976, to April 30, 1979.

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Assistance in installation and helpful input on evaluation procedures was supplied by the mixer manufacturers--Chemineer, Inc., for the mechanical agitator, and Aero-Hydraulics Corporation for the gas mixer. This assistance is greatly appreciated.

The authors are greatly indebted to the following SYSTECH personnel, without whom the successful completion of the project would have been impossible: Catherine Jarvis, John Miller, Robert Griffin, Gerald Ellis, and James Thomas.

SECTION 1

EXECUTIVE SUMMARY

The bioconversion of municipal solid waste through anaerobic digestion has been considered promising for energy recovery. The prime product is a medium-Btu gas consisting of methane and carbon dioxide which can readily be cleaned and upgraded to a pipeline quality. By-products can be cattle feed, soil amendment materials, or a dry refuse-derived fuel.

Researchers have concluded that before the anaerobic digestion can function adequately, three waste preprocessing steps are required: (1) The separation of inert materials such as metals and glass from the waste, (2) the shredding or milling of the remaining waste, and (3) the slurrying of the shredded waste in water to produce a suitable medium for the growth of the mixed bacterial culture that will convert the organic materials into methane.

Even with such a preprocessed waste, a major problem remains; namely, the tendency of the solids to coalesce into floating fibrous mats. Since the microbes that perform the anaerobic digestion can live only in a liquid medium, any solids entrapped in a dry part of the mat cannot be subject to bioconversion.

A prime cause of solids coalescing and accumulation is the high cellulose content of municipal solid waste. Cellulose is the main part of the cell walls of plants. The disintegration of the cellulose fibers requires first the separation and exposure of their fibrils; second, attack the fibrils to break their molecular bonds; and third, the digestion of the resulting short-chain molecules by the microbes. Though the mixing of a slurried, preprocessed municipal solid waste may promote these operations, it also has the opposing effect of causing separated fibrils to coalesce into stringers and mats. The mats rise to the fluid surface in the form of large scum accumulations, and the stringers interfere with the mixing equipment and retard the slurry mixing, and consequently, the enzyme and bacterial contact with the substrate.

To investigate how specially selected slurry mixing could prevent the formation of the fibrous mats and stringers and thereby ensure the desirable conditions for methane production, the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE) jointly funded Systems Technology Corporation (SYSTECH) to test and evaluate two mixing systems in an available digester vessel. One system was a mechanical agitator--that is, a vessel-centered rotary shaft with four blades at each of two levels. The second system was made up of three equidistantly placed gas gun assemblies that each produced bubbles at a constant rate to draw the slurry upward.

The available digester was a 10.7-m(35-ft) diameter concrete vessel whose floating roof was secured at the mid height of its 7.6-m (25-ft) high sidewalls to provide a nominal 378,000-liter (100,000-gal) capacity. Situated in Franklin, Ohio, the digester was in an environmental complex that included two public waste treatment plants. One plant supplied the preprocessed solid waste having the characteristics (a low solids content slurry of small, relatively inert-free particles) suitable for a municipal solid waste anaerobic digester. The other plant produced a sewage sludge. Both waste streams had about 4 percent total solids. Since the sewage sludge had a much higher nutrient and microbial content than the solid waste, the two waste streams were mixed to provide a better feedstock.

As prescribed by the EPA and the DOE, each mixing system was to be tested under a common set of six conditions, with the variables being 3:1 and 9:1 solid waste-sewage sludge ratios; 4, 7, and 10 percent total solids; and 11- and 22 1/2-day hydraulic retention times (HRT). The loading rate was a function of the total solids percentage and the HRT. Four of the six conditions were the 3:1 and 9:1 ratios with the 4 percent total solids and with both the 11- and the 22 1/2-day HRT. The remaining two conditions were the 9:1 ratio with the 7 and 10 percent total solids, but with only the 22 1/2-day HRT.

To provide the 7 and 10 percent total solids, a screw dewaterer (hydrodensor) was installed beside the digester vessel. When the 4 percent total solids of the feedstock was fed to the hydrodensor, the output was a constant 18 percent total solids. Consequently, the hydrodensor and original feedstock streams were proportioned to yield the 7 and 10 percent total solids.

Earlier studies performed by SYSTECH had shown that once a healthy culture of microbes is established, their health can be retained through changes in mechanical operating conditions (e.g., mixing type or total solids content) with very minimal acclimation periods. The test schedule thus was planned based on this knowledge.

Of 12 tests planned, only 9 were performed because of the poor results from test 3, the first test with an 11-day HRT. In this test, the total solids accumulations at the top level of the vessel were excessive, and the microbial culture throughout the vessel was not healthy, as indicated by the high ratio of volatile acids to alkalinity and the gas composition data. Consequently, the remaining three tests with the lower HRT were cancelled. Table 1 summarizes in chronological order the operating conditions for the nine tests.

TABLE 1. OPERATING CONDITIONS FOR THE NINE TESTS PERFORMED

Test Number	Mixing mode	Feed ratio (MSW:sewage sludge)	Hydraulic retention time (days)	Loading rate (g of volatile solids/ℓ per day)	Total solids in feed (%)
1	Gas	3:1	22.5	1.25	4
2	Mechanical	3:1	22.5	1.25	4
3	Gas	3:1	11	2.35	4
4	Gas	9:1	22.5	1.25	4
5	Mechanical	9:1	22.5	1.25	4
6	Mechanical	9:1	22.5	2.19	7
7	Gas	9:1	22.5	2.19	7
8	Gas	9:1	22.5	3.13	10
9	Mechanical	9:1	22.5	3.13	10

SECTION 2

SUMMARY AND CONCLUSIONS

A summary of the most significant findings is given in this section.

MIXING PHENOMENA

With both the gas and the mechanical mixing system, solids accumulated and scum formed in all nine tests. The solids accumulations and scum formation developed more rapidly and extensively as (1) the ratio of solid waste to sewage sludge increased, (2) the hydraulic retention time decreased, and (3) the percent of total solids increased. Of these variables, the ratio increase was the most significant.

In the first two tests with the lowest feed ratio, volatile solids loading rate, and total solids percentage for each of the two mixing modes, the contents were less viscous, had better pumping and handling qualities, and coalesced less than the contents in the later tests. Though the better mixing performance during these tests was attributed primarily to the lower solid waste content, it was also due to the operation of the scum breaker pump during the test periods. In the third test, which was in the gas mixing mode, the feed ratio and percent total solids remained the same as in the first two tests, but the HRT was reduced from 22 1/2 to 11 days. Note that at a constant total and volatile solids content, this results in a concommitant increase in volatile solids loading rate. The results of this test indicated that the bacterial culture health, as measured both by the ratio of volatile acids to alkalinity and the ratio of methane to carbon dioxide, had so deteriorated and the digester fluid/solids mixing was so poor that the mechanical mixing system was not tested at the shorter HRT. The original 22 1/2-day HRT was resumed after the third test and maintained throughout the remaining six tests.

As the samples taken from the top level increased in total solids concentrations, they had a disproportionately higher volatile solids percentage compared with those for the samples taken at the lower levels. Consequently, as more solids accumulated at the top and still more volatile solids became entrapped, a progressively lesser amount of solids were subject to degradation since the volatile solids are the substrate for the microorganisms.

The amounts of the solids accumulations and scum formations were generally the same for the two mixing systems in the successive paired tests with the common set of variables for the two systems. The gas mixing mode caused the cellulosic materials to rise and coalesce uniformly over the surface area, while the mechanical mixing mode produced a toroidal flow pattern (downward flow in center and then out along the floor and upward near the walls) so that the material accumulations were toward the digester sidewalls. Consequently, the solids/scum configurations in the gas mixing mode were generally constant depth layers, and those in the mechanical mixing mode were generally characterized by an evenly distributed floating mass whose depth formed an arc extending downward from near the top of the vessel center to the sidewalls. Figure 1 depicts the two configurations.

In all tests in the mechanical mixing mode, the mechanical agitator became imbalanced as cellulosic stringers formed on its shaft. In the later tests, the increased shaft imbalance caused the shaft to bend. In addition, the shaft blades became twisted and some of their attachment bolts broke. Also, in the later tests, solids accumulations in the gas gun assemblies progressively diminished the bubbles to the extent that they no longer produced the mixing effect.

ENERGY PRODUCTION

Of the nine tests, the best mixed and the one whose mass balance indicated almost no solids accumulation and best gas production was the second test. In this test, the gas production per kilogram of volatile solids destroyed was 805 liters, which is very reasonable for a healthy digester. However, the total energy in the methane produced was only 1200 kW-hr per day. The mixing equipment utilized in this particular test (assuming full load operation, but ignoring power generation efficiencies) was 300 kW-hr or one-fourth of the energy produced. Considering the additional energy required for preprocessing the municipal solid waste and for pumping and heating the digester contents (as well as the additional energy required to truly mix the digester contents), even a well mixed anaerobic digester with current technology would not be economically viable as a means of recovering energy from municipal solid waste.

HEALTH OF MICROBIAL CULTURE

Except for the third test, the ratio of the volatile acids to alkalinity in the digester samples and the ratio of methane to carbon dioxide in the product gas throughout the test period indicated that the microbial cultures in the solid waste-sewage sludge mixtures were healthy with a good balance of acid and methane formers. Therefore, the difficulty in degrading the municipal solid waste in the current study was due to the physical characteristics of its cellulose content and the inadequate mixing and consequent entrapment of much of the volatile solids, and not to any failure in establishing a healthy microbial culture.

GRIT-INDUCED FAILURES

Although a liquid cyclone purportedly removed the metals and grit fraction from the slurried solid waste during its processing, the as-received solid waste still had a grit content that severely abraded and eroded the moving parts of equipment in the digester processing stream. This

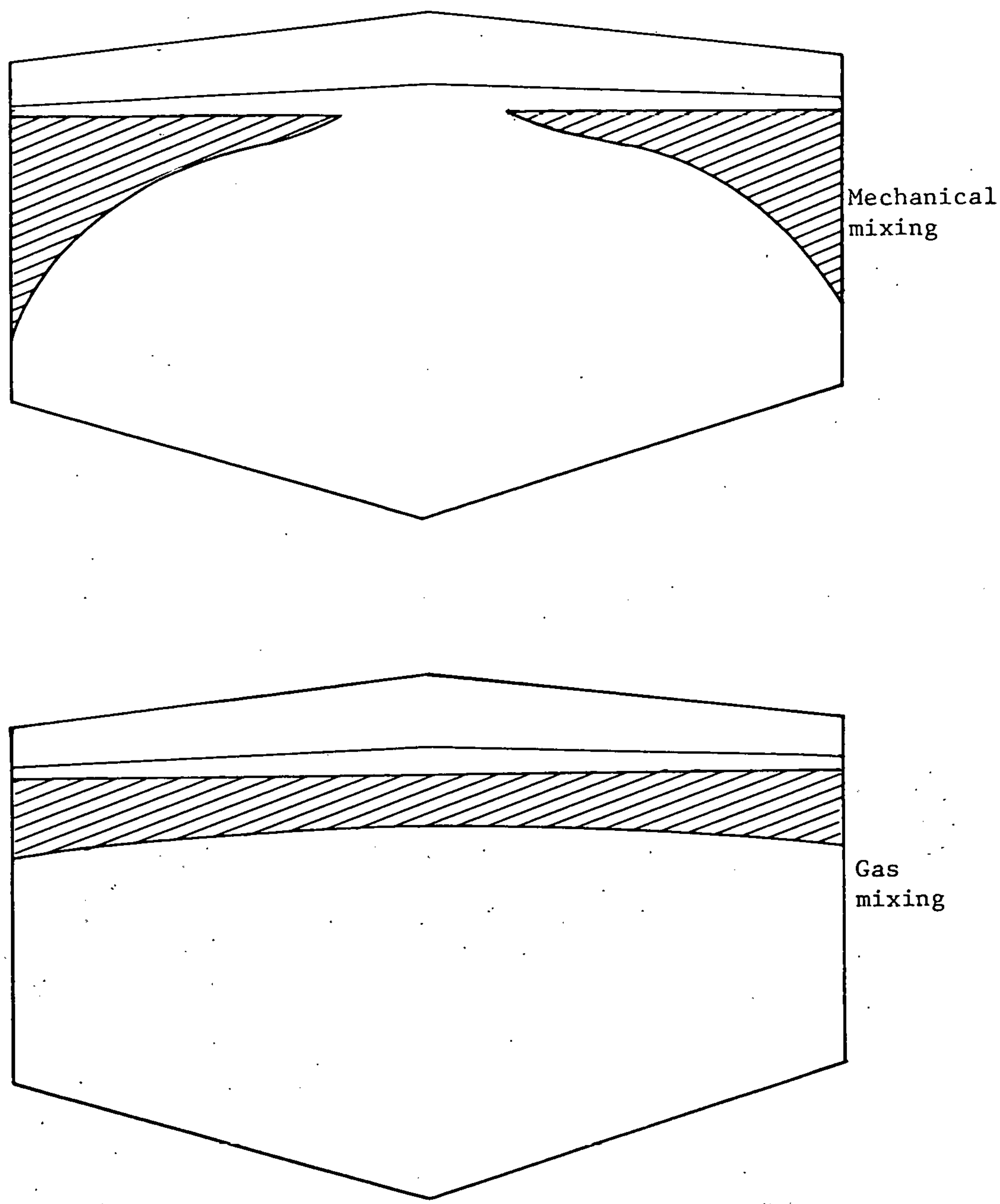

Figure 1. Scum layer solids configurations in mechanical and gas mixing modes.

deterioration was particularly evidenced by the scum breaker pump in the digester and the Moyno pump in the manifold within the control building.

At least three times during each of the nine tests, the grit so severely damaged the scum breaker pump that bearings or moving parts failed. Similarly, the grit so damaged the rotor and stator in the Moyno pump that they generally had to be replaced within 30 days. Although several materials were substituted for the pump parts, they proved unsuccessful and the rotor and stator lives continued to be only about 30 days.

Therefore, even if the energy production became economically feasible with respect to the energy input, either the grit would have to be minimized or the digester processing equipment would require abrasion resistant slurry pumps.

SECTION 3

RECOMMENDATIONS

Before anaerobic digestion may become economically viable as a means for recovering energy from municipal solid waste, the energy output must be greater and the energy input must be less than those in the current test program. The crux of the problem is the difficulty in degrading the cellulosic materials.

When the slurried solid waste/sewage sludge combination was mixed to separate and expose the cellulosic fibrils to enzymatic attack, the mixing also produced the contradictory effect of coalescing, rather than separating, the detached fibrils. Therefore, to approach the economic viability of recovering energy from municipal solid waste by anaerobic digestion, two methods are proposed:

1. Operate a digester without mixing in a mode similar to the plug flow digesters currently being evaluated in DOE-sponsored programs that utilize cow manure as a feedstock.

2. Before subjecting the waste to microbial digestion, hydrolyze the cellulose content of the feedstock by an acid pretreatment as described by Brenner, et al.[1] or by an enzyme pretreatment as described by Gaden, et al.[2] The latter pretreatment is similar to the process now being evaluated as a posttreatment by SYSTECH under a DOE contract. These pretreatments would also allow screening the feedstock to remove the abrasive grit in the feedstock slurry that proved so damaging to the moving parts in the equipment used during the current study.

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[1] Brenner, W., B. Rugg, C. Rogers. Utilization of Waste Cellulose for Production of Chemical Feedstocks via Acid Hydrolysis. In: Symposium Papers, Clean Fuels from Biomass and Wastes, Institute of Gas Technology, January 25-28, 1977.

[2] Gaden, E. L., Jr., M. H. Mandels, E. T. Reese, L. A. Spano, editors. Enzymatic Conversion of Cellulosic Materials: Technology and Applications. John Wiley and Sons, New York 1976.

SECTION 4

PROJECT BACKGROUND AND RATIONALE

Previous research[3,4,5] has indicated that anaerobic digestion as used for treating wastewater may be used for recovering energy from municipal solid waste. The prime product from the latter processing is a medium Btu gas which can be readily cleaned and upgraded to a pipeline quality. In addition, potential by-products are cattle feed, soil amendment materials, and dry refuse-derived fuel.

There is general agreement that the refuse should be processed before anaerobic digestion is allowed to start. The processing would include separating the inert materials, such as metals and glass, from the waste; shredding or milling the remaining refuse; and slurrying the shredded refuse in water to produce a suitable medium for the growth of the mixed bacterial culture that will convert the organic materials into methane.

For the reasons detailed below, SYSTECH proposed to the EPA the establishment and operation of a pilot plant to investigate the bioconversion of municipal solid waste and to evaluate the dewaterability of mixtures of pulped municipal solid waste and sewage sludge before and after anaerobic digestion.

SYSTECH operated a liquid industrial waste treatment facility within the Franklin, Ohio, Environmental Complex. The aerial view of this complex in Figure 2 shows in the foreground the SYSTECH facility and from left to right in the immediate background the Regional Wastewater Treatment Plant of the Miami Conservancy District and the Solid Waste Processing Plant of the City of Franklin. The SYSTECH facility is an abandoned municipal wastewater plant which contains an unused 662,000 liter (175,000 gal) concrete, floating cover, wastewater digester. The Solid Waste Processing Plant was funded partly by the EPA to demonstrate the feasibility of recovering cellulose fiber and other materials from municipal solid waste. Using the technology employed in the pulp and paper industry, the Solid Waste Processing Plant

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[3] Klass, D. L., and S. Ghosh. Fuel Gas from Organic Wastes. Chem. Tech. J.:689-98, November 1973.

[4] Wise, D. L., S. E. Sadek, and R. G. Kispert. Fuel Gas Production from Solid Waste. Progress Report No. 1207, NSF/RANN/SE/C-827/PR/74/2. Dynatech R/D Company, Cambridge, Massachusetts, 1974. 184 pp.

[5] Pfeffer, J. T. Reclamation of Energy from Organic Waste. EPA Report No. 670/2-74-016. University of Illinois, Urbana, Illinois, March 1974.

Figure 2. Aerial view of Franklin, Ohio, environmental complex with SYSTECH facility in foreground.

employed in the pulp and paper industry, the Solid Waste Processing Plant first pulps the refuse into a finely milled material in a water slurry and then removes the metals and grit fraction from the slurried material in a liquid cyclone. The output of the liquid cyclone is a stream of cleaned organic material in a water slurry with about 4 percent of total solids. The sewage sludge output from the wastewater treatment plant has virtually the same total solids percentage but a much higher nutrient and microbe content than the foregoing processed solid waste stream. Although the organic material stream has the feedstock characteristics that make it physically suitable for a municipal solid waste anaerobic digester, its mixture with the sewage sludge would obviously improve the anaerobic digestion. Now while the two streams ultimately join and are dewatered for burning in the incinerator of the solid waste processing plant, each can be extracted through bypass valves. Therefore, both a digester and the desirable anaerobic digester feedstocks, namely, the processed solid waste and the sewage sludge, were close together and available for the proposed study.

After the project was funded, it was initiated as a laboratory-scale study to determine the optimum feeding conditions for the available feedstock and to familiarize the SYSTECH staff with some of the operational problems that might be anticipated during full-scale anaerobic digestion. As evidenced in this study and then confirmed in a following short-term pilot program, slurried municipal solid waste readily forms into a fibrous mat which floats at the top of the digester. Consequently, much of the organic material is removed from the slurry and therefore cannot be subjected to hydrolysis and biological conversion. Obviously, to make the anaerobic digestion a viable process for treating municipal solid waste, some method of agitating the slurry had to be developed to keep the slurry well mixed and to prevent the formation of the floating mat.

As a result, the EPA and DOE jointly funded SYSTECH to investigate and evaluate two systems of mixing the slurry at three percentages of total solid concentrations.

SECTION 5

CHARACTERISTICS OF CELLULOSIC MATERIALS

Cellulose constitutes the main part of the cell walls of plants. Consequently, plant fibers are commonly called cellulosic materials. Such materials are generally composed of cellulose, hemicellulose, and lignin. Cellulose molecules consist of linear chains of glucose molecules, and cellulosic fibers consist of several of these chains generally in a common alignment with all covered by a lignin sheath. The lignin is a relatively insoluble polymeric substance that is not readily degraded by natural causes. The only known enzymes which will attack lignin require several weeks to effect a measurable degradation of the lignin.

Cellulose fibers, especially those in woody cellulose, are typically long and relatively thick with minute hairlike fibrils distributed along the length and at the ends of the fibers. Only a few cellulose molecules thick, the fibrils are covered with a relatively thin, partially solubilized lignin sheath. Since the lignin is partially solubilized and the fibrils form a relatively hairlike mass, the cellulose fibers readily coalesce as their fibrils come in contact with one another.

Because of this coalescing characteristic of cellulose fibers, the pulp and paper industry grinds the fibers to separate and expose more of the liquified fibrils and then agitates the particles in a water slurry to promote their coalescing and consequently the optimum adhesive strength in the resultant paper. Obviously this characteristic severely hampers the mixing of slurried refuse for anaerobic digestion since the agitation increases the fibrilation of the cellulosic materials and consequently promotes the coalescing of the fiber particles into stringers and mats which retard the material flow in the digester. Moreover, when fibrous mats are formed from the cellulosic materials, rising microbubbles of the refuse gas carry them to the top of the digester where they progressively accumulate and float at the top of the water. Those floating materials which dry out cannot be subject to bioconversion since the microbes can live only in a liquid medium.

While the cellulose is subject to enzymatic attack, their molecular degradation requires energetic enzymes since the successive polymerized glucose molecules are connected by a moderately strong bond. Moreover, the degradation time is long because (1) enzymatic hydrolysis of cellulose is a relatively slow process; (2) the cellulose molecules of each fiber particle are so numerous; (3) the stringers and mats retard the mixing and consequently the movement of the enzymes; and (4) the mixing itself promotes the coalescence, rather than the separation, of the fiber particles. Moreover, the optimum temperature for cellulase is approximately 45°C which is just between the optimum temperatures for mesophilic and thermophilic methanobactors. In addition, the optimum pH for cellulase is between 4 and 5 while that for both types of methanobacters is about 7. Furthermore, the slow enzymatic hydrolysis of the cellulose allows more time for the fibrilation of the fibers and the formation of the stringers and mats.

In view of the foregoing conditions for normal cellulose degradation and the large amount of cellulosic materials in the waste stream, the adequate mixing of refuse for anaerobic digestion requires refuse pretreatment to either destroy the lignin or hydrolyze the cellulose.

SECTION 6

ANAEROBIC DIGESTION AS AN ENERGY RECOVERY PROCESS

As a means of energy recovery, the anaerobic digestion of the organic part of municipal solid waste is performed by a combination of physical, biochemical, and microbial processes. All researchers state that the waste must first be physically processed before anaerobic digestion may be reasonably completed.

As the first of four stages in the anaerobic digestion process, the physical processing includes separating the organic material from the waste, shredding the organic material so that microbes and enzymes can have better access to it, and slurrying the shredded material in water to provide a growth medium or habitat for the microbial cultures. Since this processing requires complicated trade-offs between the cost and the efficiency of the processing equipment, it has never been firmly defined. For example, Ghosh and Klass,[6] who researched biogasification variables, demonstrated that the gas production rate increases as the refuse particle size decreases from one inch to particulates passing through a 30-mesh screen. Consequently, they would recommend grinding the refuse to this screen size. Other researchers engaged in the enzymatic hydrolysis of cellulose[7,2] have recommended ballmilling or rollmilling the refuse to destroy the lignin sheathing and powder the cellulose. Others suggest that even larger particles sizes will suffice.[5]

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6 Ghosh, S., J. R. Conrad, and D. L. Klass. Materials and Energy Reclamation from Municipal Solid Waste, IGT Internal Report, Institute of Gas Technology, Chicago, Illinois, October 1974. 33 pp.

7 Millett, M. A., A. J. Baker, and L. D. Saltes. Physical and Chemical Pretreatments for Enhancing Cellulose Saccharification. In: Enzymatic Conversion of Cellulosic Materials: Technology and Applications, E. L. Gaden et al., eds. John Wiley & Sons, New York City, 1976. pp. 125-154.

2 Gaden, E. L., et al., eds. Enzymatic Conversion of Cellulosic Materials: Technology and Applications. John Wiley and Sons, New York 1976.

5 Pfeffer, J. T. Reclamation of Energy from Organic Waste. EPA Report No. 670/2-74-016. University of Illinois, Urbana, Illinois, March 1974.

While the amount of organic material separated from the refuse varies with the type of equipment used, the separation of such material can never be complete. Also a variable is the degree to which the organic material should be slurried. While some researchers state that a slurry can be well mixed only when it has less than 5 percent total solids, others maintain that the slurry still can be well mixed when it has up to 20 percent total solids.

The following is a very simplified description of the biological conversion processes taking place. The second stage in the anaerobic digestion process is the hydrolysis or solubilizing of the organic materials, that is, the breakdown of their molecular structures until they are sufficiently soluble to be digested by the microbes. Normally, the extracellular enzymes secreted by the microbes and contained in the as-received solid waste perform the hydrolysis. Of primary importance in the hydrolysis is the presence of cellulase and cellobiase (B glucosidase). While cellulase complexes apparently cannot be readily produced by the microbes in municipal solid waste, they can be readily obtained from various fungi and ruminant digestive systems. To hydrolyze the refuse, some researchers suggest adding cellulase from fungi or rumen to the digester; others recommend an enzyme pretreatment with cellulase; and still others favor an acid hydrolysis preprocessing.

The third stage in the process is the conversion of the hydrolyzed organics to organic acids, primarily acetic acid with some propionic and butyric acid. This conversion is performed by the numerous facultative and anaerobic organisms.

The fourth stage in the process is the production of gas; typically half carbon dioxide (CO_2) and half methane (CH_4). The strict anaerobes, the methanogens which consume the organic acids, free hydrogen and carbon dioxide, produce this gas as part of their digestive process. The methane is the prime energy product. Whether or not the resultant gas requires cleaning depends on its usage. Ashare et al.[8] detail the processes for the various methods of cleaning.

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8 Ashare, E., D. C. Augenstein, J. C. Yeung, R. J. Hossan, G. L. Duret. Evaluation of Systems for Purification of Fuel Gas from Anaerobic Digestion. Report on Contract No. EY-76-C-D2-2991 for the U.S. Department of Energy. Dynatech R/D Company, Cambridge, Massachusetts, July 1978.

SECTION 7

EQUIPMENT DESCRIPTION

The unused digester in the SYSTECH facility in Franklin, Ohio, that was adapted as a pilot digester for the current study was built by the Public Works Administration for the City of Franklin. The digester is a 10.7-m (35-ft) diameter concrete vessel with 7.6-m (25-ft) high sidewalls, a floating cover that serves as a roof, and a floor whose slope from wall to center is about 0.75 m. The roof sits at its lowest position, namely at the mid height (3.8 m) along the sidewalls, when the digester is empty. With the roof at this position, the digester has a nominal 378,000-liter (100,000-gal) capacity. Except for the following pilot test modifications, the digester was basically the same as originally built.

For the purposes of the current study, the roof was rigidly positioned at its lowest level and sealed around its edges to prevent rainwater infiltration. In addition, the roof was repaired to ensure water and gas tightness. The following paragraphs detail the digester modifications to accommodate the test equipment. The top- and side-view digester drawings in Figure 3 indicate the relative locations of the principal test equipment.

A Chemineer mechanical mixer with a 15.2-cm (6-in.) diameter, 6.4-m (21-ft) long shaft was mounted directly above the roof center on two parallel 45-cm I beams that extended across the diameter of the digester and rested on top of the walls. At the roof center was a 90-cm diameter manhole cover with two ports which were used as described later. To accommodate the shaft, the original gas collecting dome in this cover was removed and a lantern bearing was installed to provide a gastight seal around the shaft. The motor driving the mechanical mixer was a 7.5-kW (10-hp), totally enclosed, fan-cooled unit with a gear box that governed the 45-rpm rotation of the mixer blades. As shown in Figure 4, four 137-cm diameter blades at each of two levels on the mixer shaft were mounted at a 45°C attack angle to force the digester liquid from the top to the bottom of the vessel. The manufacturer stated that this system would result in a downward flow at the axis with an outward radial component at the blade levels and a slow centerward surface motion without uniform solids lifting to the top layer. According to the manufacturer, a solids distribution approaching uniformity would have required installing a 56-kW (75-hp), rather than the actual 7.5-kW (10-hp), motor. However, the smaller motor was chosen since it would be more compatible with the 3.7-kW (5-hp) gas mixer compressor and to match the mixing system that we understood was at that time intended for installation at the Pompano Beach pilot facility.

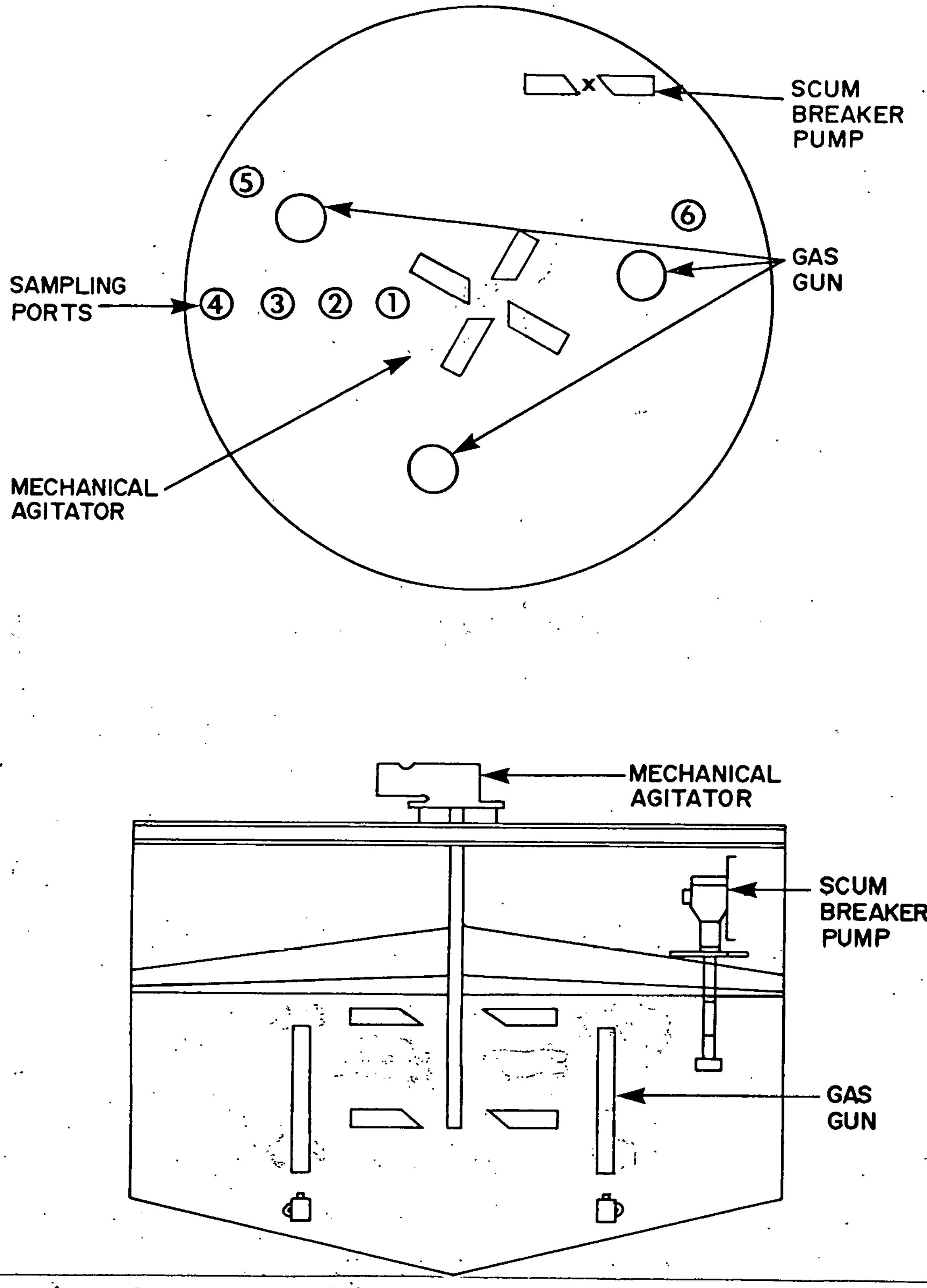


Figure 3. Top- and side-view digester drawings indicating relative locations of test equipment and sampling ports.

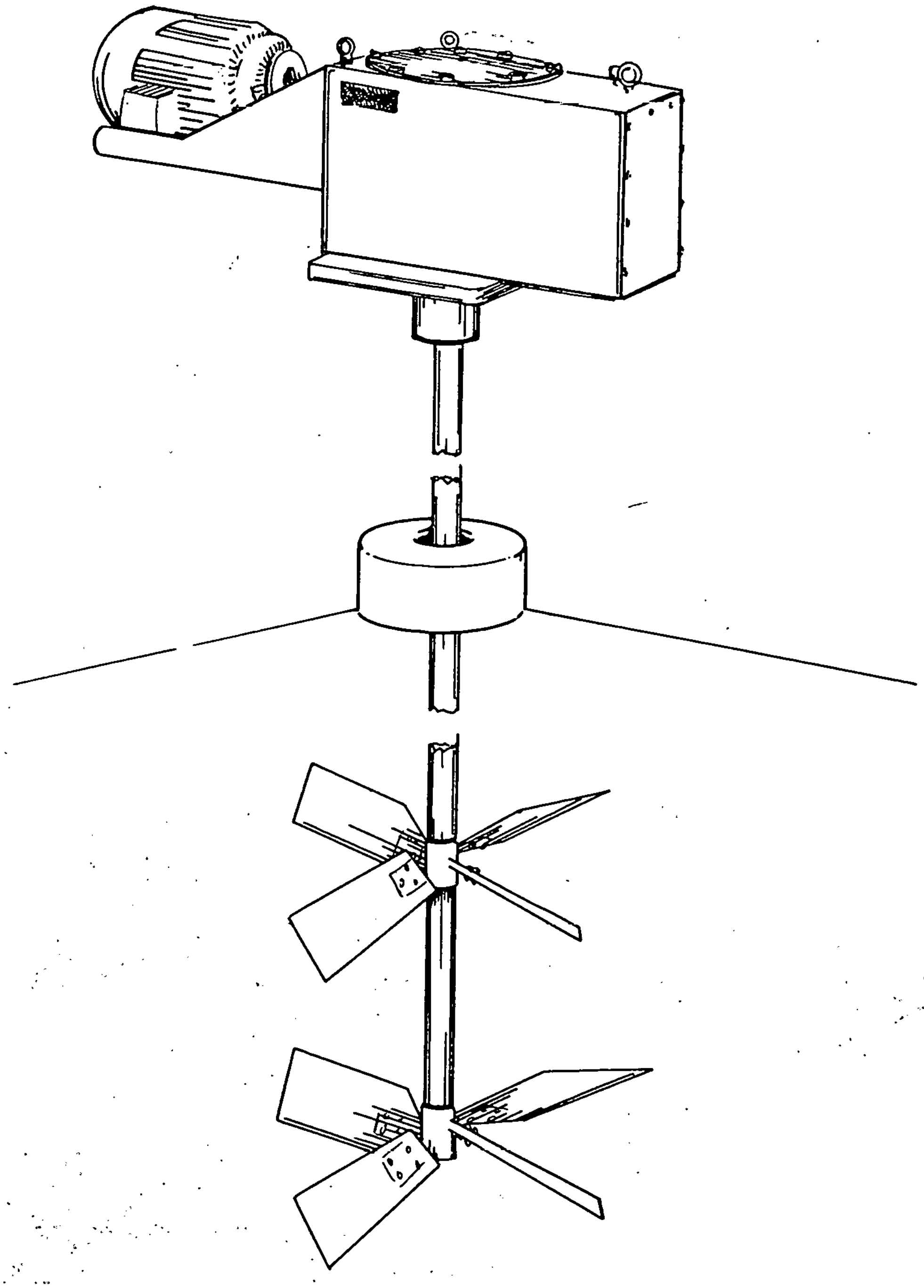


Figure 4. Chemineer mechanical agitator with shaft and blades.

An existing 60-cm diameter manhole was used to install a Vaughn scum breaker pump. Then a second 60-cm diameter manhole was installed to provide access to the digester interior. The pump assembly included a 30-kW (40-hp), 1200-rpm, 3-phase, explosion proof, vertically mounted motor that rotated the pump shaft. The pump itself was a reverse-slinger impeller constructed of tempered cast steel with the lower edges of the impeller segments sharpened on the leading edge. Bolted to the bottom of the shaft assembly was a circular tempered cast steel plate with two openings whose sharpened sides served as cutter bars. Therefore, as the shaft rotated, the combined impeller-bar effect produced a scissors-like operation to cut any stringy material that entered the pump through the plate holes. Figure 5 shows the installation of the scum breaker pump.

Material entering the pump was centrifugally lifted through a 10-cm pipe and exhausted through a deflector nozzle that could be manipulated from a position above the roof. The nozzle could be rotated through 270° in the horizontal plane with a ±35° vertical movement to permit aiming the high velocity exit stream at practically any part of the fluid surface.

Since the test requirements called for six sampling ports in addition to an existing one, the roof was further modified as follows. Five 20-cm diameter 1- to 1.5-m long pipes were installed with their lower ends flush with the bottom surface of the roof and their upper ends capped by threaded covers. The sixth new port, a 15-cm pipe, was installed in the manhole cover of the newly installed 60-cm diameter manhole. The existing port was a 15-cm diameter, 2.5-m long pipe whose lower end extended 1.25-m into the digester and therefore well below the liquid level. Besides the provisions for the six new sampling ports, three pairs of holes were made in the roof to insert the lines for the ATARA gas gun system described in the next paragraphs.

As installed, the ATARA system consisted of three equidistant assemblies mounted on the digester floor with each half way between the floor center and the sidewalls. As shown in Figure 6, each assembly consisted of a floor-bolted tripod which supported a vertical 0.3-m diameter, 2.75-m long draft tube whose bottom had an outward funnel. Centered below the funnel and attached to the tube by three elbows was a bubble-forming chamber whose bottom was about a foot above the floor level.

As illustrated in Figure 7, the chamber assembly consisted of a cylinder, closed at the top and open at the bottom, that formed the outer part of the chamber and a pipe that was partially inside and concentric with the cylinder. With its upper end open and above the outer cylinder, the pipe was a cylinder until it formed a curve to exit the lower part of the chamber and then enter the upper part of the outer cylinder. Two lines were coupled to the external part of the pipe: one to supply gas to the chamber and the other to permit cleaning the pipe.

Mounted outside and above the digester walls, a gas compression pump with a 3.7-kW (5-hp) motor drew gas from the digester through one of the two ports available in the center 90-cm diameter manhole cover and pumped it to a manifold. From the manifold, the gas flowed to the gas inlet on the external

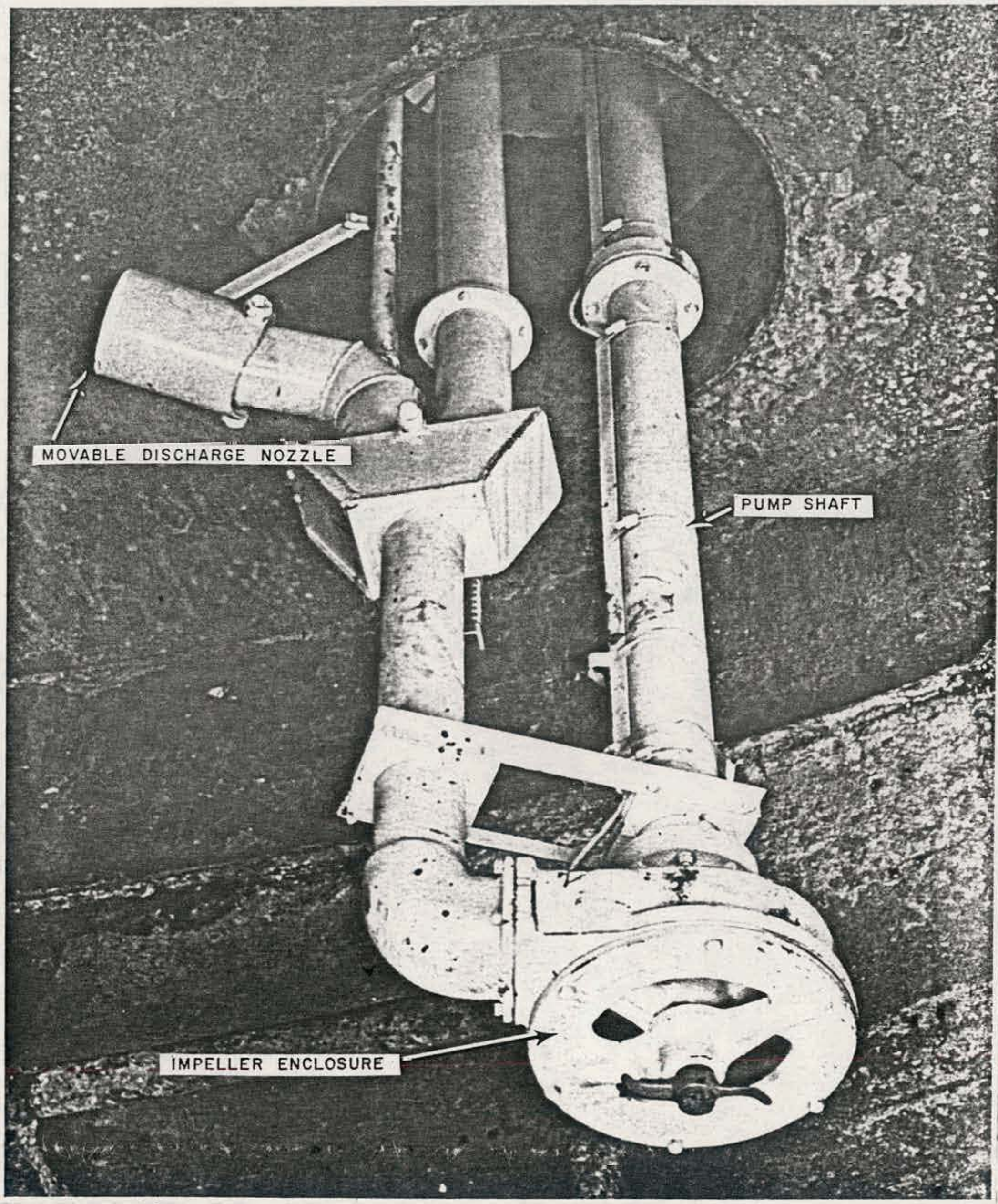


Figure 5. Vaughn scum breaker pump installation.

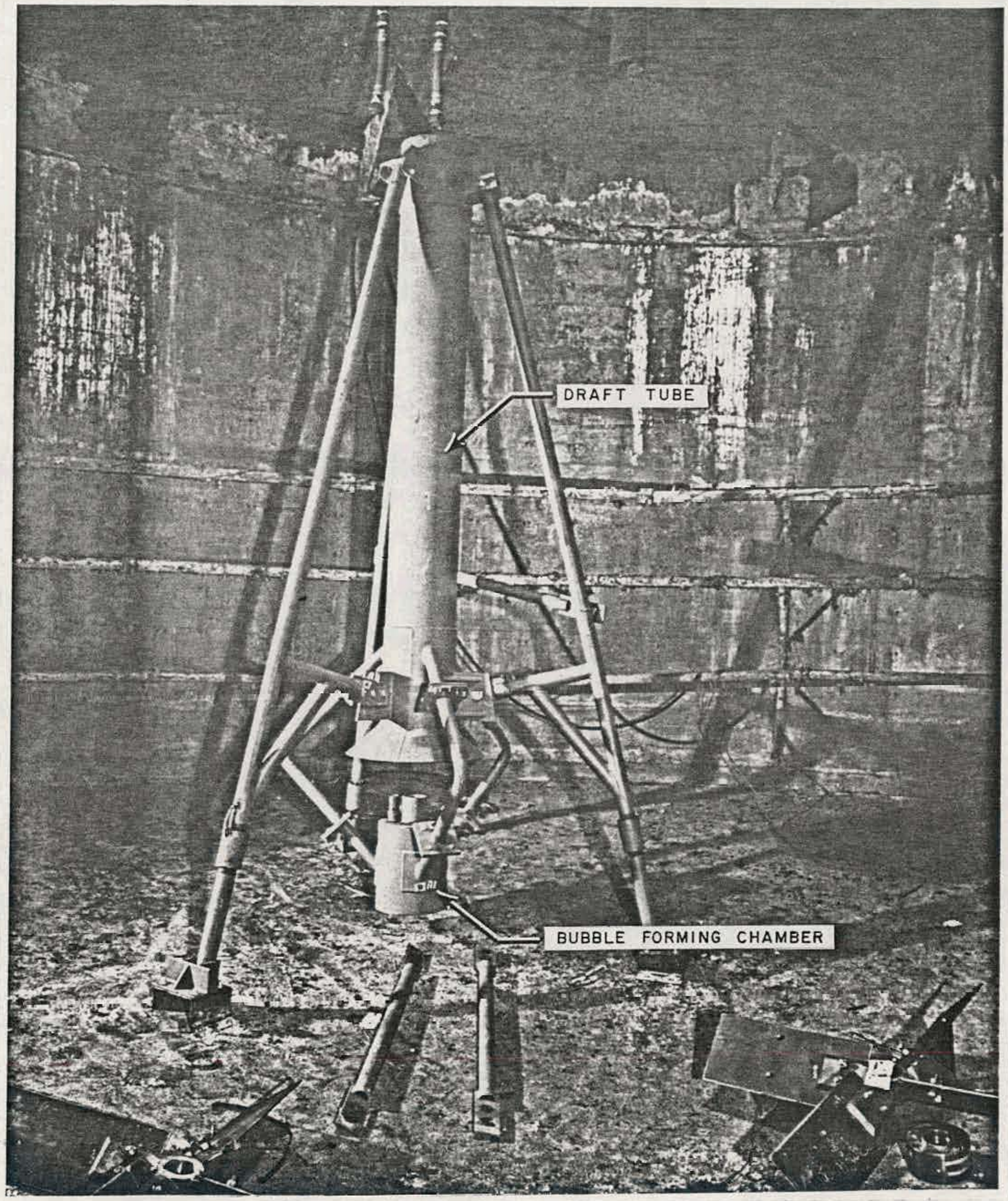
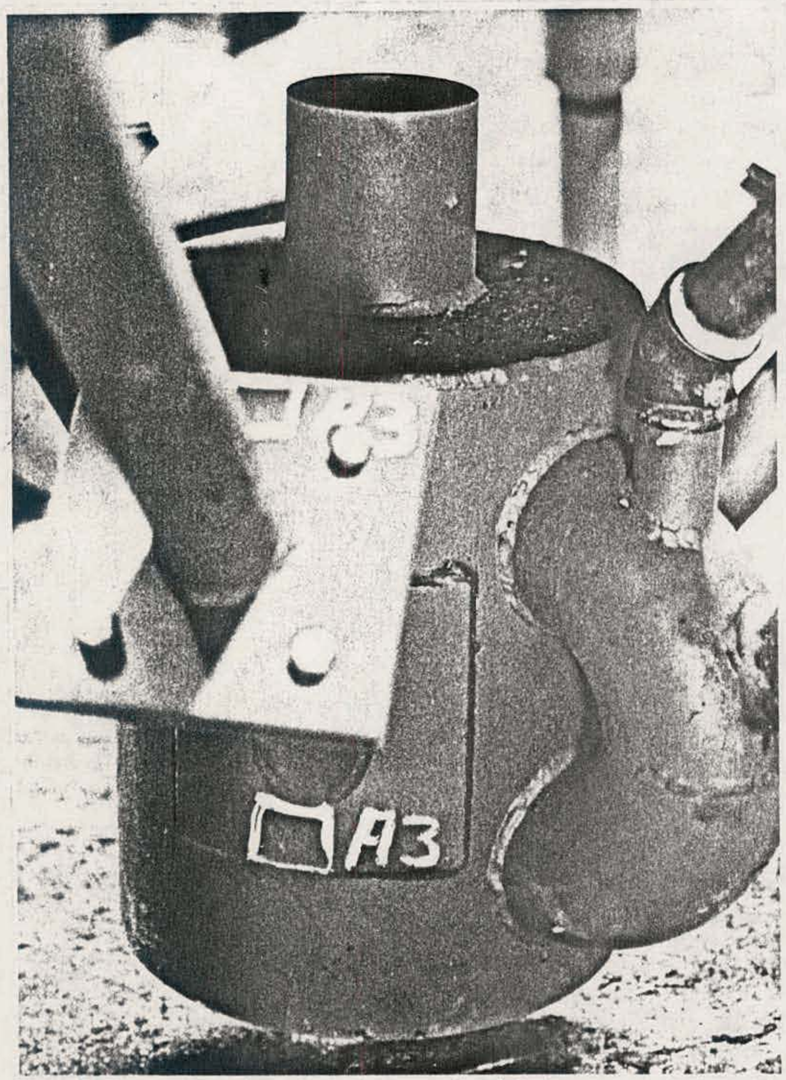


Figure 6. ATARA gas gun system installation.



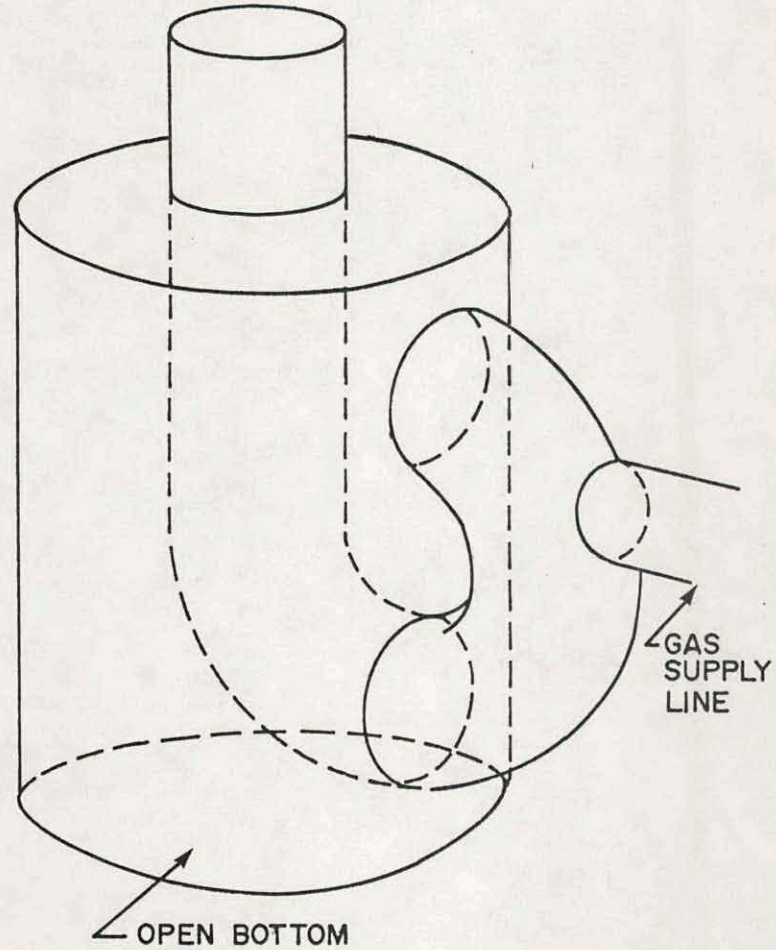


Figure 7. Bubble-forming chamber assembly in gas gun system.

part of each pipe in the three chamber assemblies. As the gas pressure built up in the pipe, the water level in the chamber progressively decreased until the gas pressure was greater than the water pressure. Then some of the gas passed through the rest of the pipe and formed a bubble which rose into the funnel of the draft tube.

Since the bubble entering the tube was large enough to completely fill the cross-sectional area of the tube, it acted as a rising piston or gun to force out the water in the tube as it traveled upward. The pumping rate of the gas compressor was adjusted to develop bubbles at a rate such that there were always two bubbles in each tube at one time or such that a bubble was produced about every 4 seconds in each tube.

In addition to the three gas gun assemblies and the gas compressor, the ATARA system included (1) valving to cut off the gas flow to the guns by recirculating the gas through a gun by-pass line from the pump outlet to the pump inlet, (2) pressure relief valves that automatically shut off the pump motor whenever the pressure in the supply line to the compressor dropped too low or the pressure in the output line from the compressor became too high, (3) a vacuum filter, (4) a flame arrestor, (5) a water trap, (6) gages to indicate the pressures in the compressor supply and output lines, and (7) a drip trap to permit removing fluids from the output line. Except for the piping, the entire system was supplied by the ATARA Corporation.

The other of the two ports in the 90-cm (36-in.) diameter manhole cover was used to pass the digester gas through a Singer dry gas meter installed on the digester roof. Although the meter operated sporadically, especially during cold weather, it provided accurate gas measurements over short time intervals for the periodic test readings. While the meter provided the means for evaluating the gas produced by the digester, its primary function was to allow pressurized gas to escape into the atmosphere.

To supply the digester with the 4 percent total solids refuse, the following existing equipment was utilized: the influent and effluent lines between the digester and the control building some 15 m away from the digester, the equipment in the control building, and the influent-effluent line between the control building and an auxiliary manifold. Figure 8, an aerial view of the SYSTECH facility, indicates the locations of the digester, control building and auxiliary manifold. Lying between the control building and the wastewater treatment plant, the auxiliary manifold also had an effluent line extending to this plant. The control building equipment included a manifold which was modified for the current study, a pump driven by a 3.7-kW (5-hp) Westinghouse motor, and valving for pumping (1) the feedstock into the digester and (2) digested material out of the digester to be either returned to the digester or deposited in the municipal sewage line.

For the current study, the original pump in the control building was replaced by a Robins & Myers Moyno traveling cavity type of unit. The 15-kW (20-hp) Westinghouse motor procured for the new pump provided more power than was needed. The Moyno pump served the threefold function of (1) drawing the feedstock from the auxiliary manifold and pumping it into the digester, (2) discharging the digester effluent to the wastewater treatment plant, and

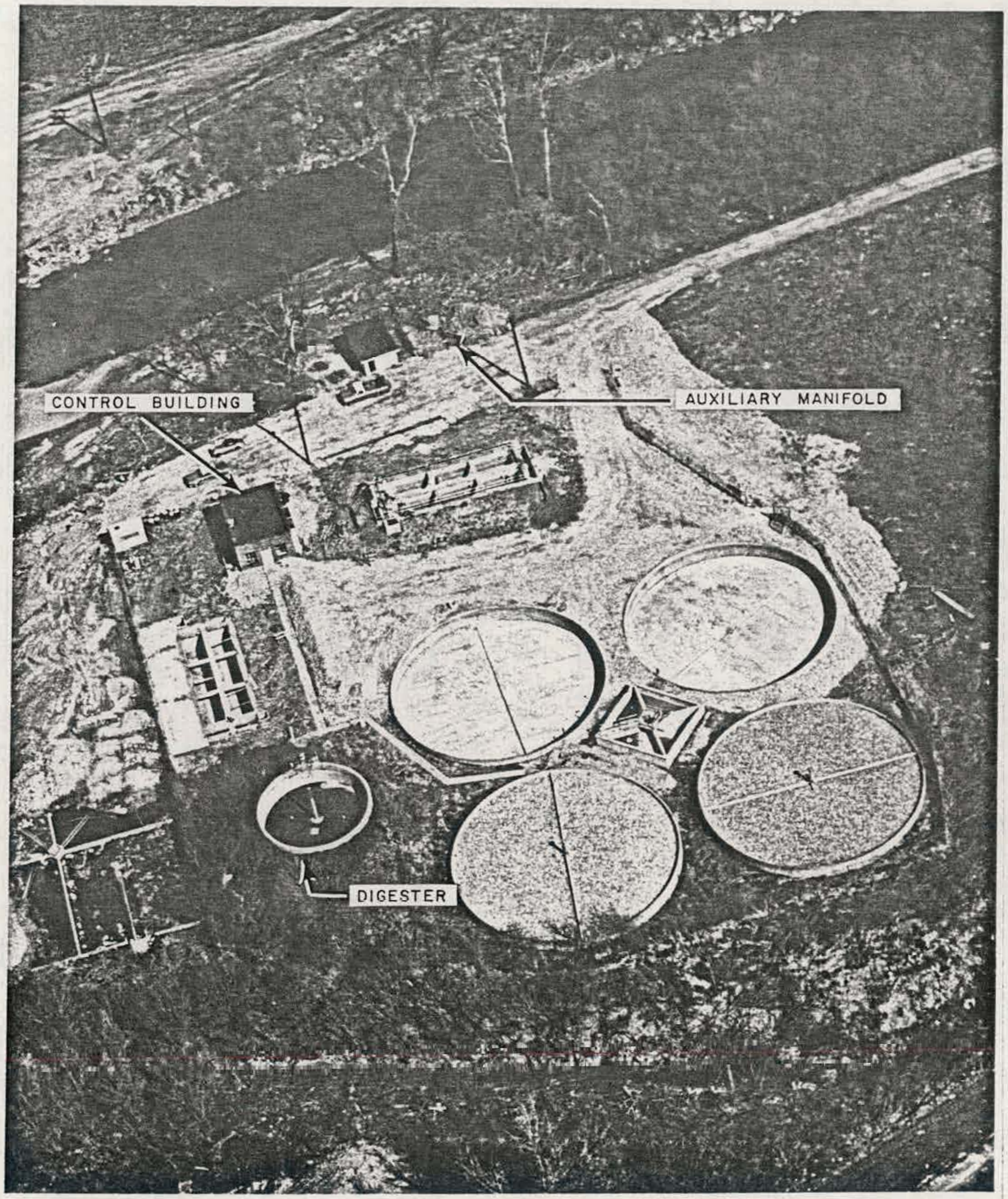


Figure 8. Aerial view of SYSTECH facility with digester vessel, control building, and auxiliary manifold indicated.

(3) circulating the digester contents by drawing refuse from the bottom and injecting it slightly below the surface of the fluid. During the test period, combinations of various stator and rotor materials were substituted in the pump in unsuccessful attempts to improve its wear resistance.

To supply the digester with the 7 and 10 percent total solids refuse, a hydrodensor was used in conjunction with the foregoing equipment supplying the 4 percent total solids refuse. Since the hydrodensor so dewatered the original feedstock that its output was an 18 percent total solids refuse, this output had to be proportioned with the 4 percent total solids supply to yield the 7 and 10 percent total solids inputs into the digester.

Mounted on a concrete pad beside the digester walls as shown in Figure 9, the hydrodensor was inclined so that it discharged the refuse over the walls and onto a trough extending to the existing 15-cm diameter, 2.5-m long pipe in the digester roof. However, when this pipe proved impractical because of its narrowness and length, the refuse was transported to and force-fed through one of the new 20-cm diameter, 1- to 1.5-m long pipes.

The hydrodensor was a pilot size stainless steel screw-thickener with two 23 cm barrels. Each barrel was a cylindrical screen in which a screw was driven independently by its own 3.7-kW (5-hp) motor. Each screen was formed from a stainless steel plate with numerous perforations. Attached along the entire length of the leading edge of each screw was a heavy bristled brush which served the twofold purpose of making the spiraling contact with the screen without metal abrasion and of brushing away material clogged in the screen holes. As water squeezed through the screen and flowed into a tank below the barrels, a Deming pump driven by a 5.6-kW (7.5-hp) motor pumped the water to a disposal facility.

A 7000-liter tank diesel truck equipped with a vacuum pump was acquired to transport the feedstock from the solid waste and wastewater treatment plants to both the auxiliary manifold between the control building and the wastewater plant and the hydrodensor beside the digester. Hoses and connectors for loading and discharging the tank were purchased separately. When the hydrodensor was operated, a locally leased trash pump was used to transport the feedstock up the approximate 5-m height to the hydrodensor.

The digester fluid was sampled by a uniquely designed assembly. The sampler consisted of a remotely openable/closable sample container which could be inserted into the digester from the top to remove samples at several depths. The exploded-view drawing in Figure 10 illustrates the mounting of the sample container and its holder in the block of the sampling assembly.

Three sampling assemblies were fabricated: one with a 2-m long tube for samples at the top level, the second with a 4-m long tube for samples at the middle level, and the third with a 5.5-m long tube for samples at the bottom level. When a sample was to be taken, the appropriate assembly was first lowered about a quarter meter below the desired level with the sampler closed. Next the sampler was opened, and the assembly was jerked upward a little more than a quarter meter so that the digester fluid would be forced into and fill

Figure 9. Hydrodensor installation.

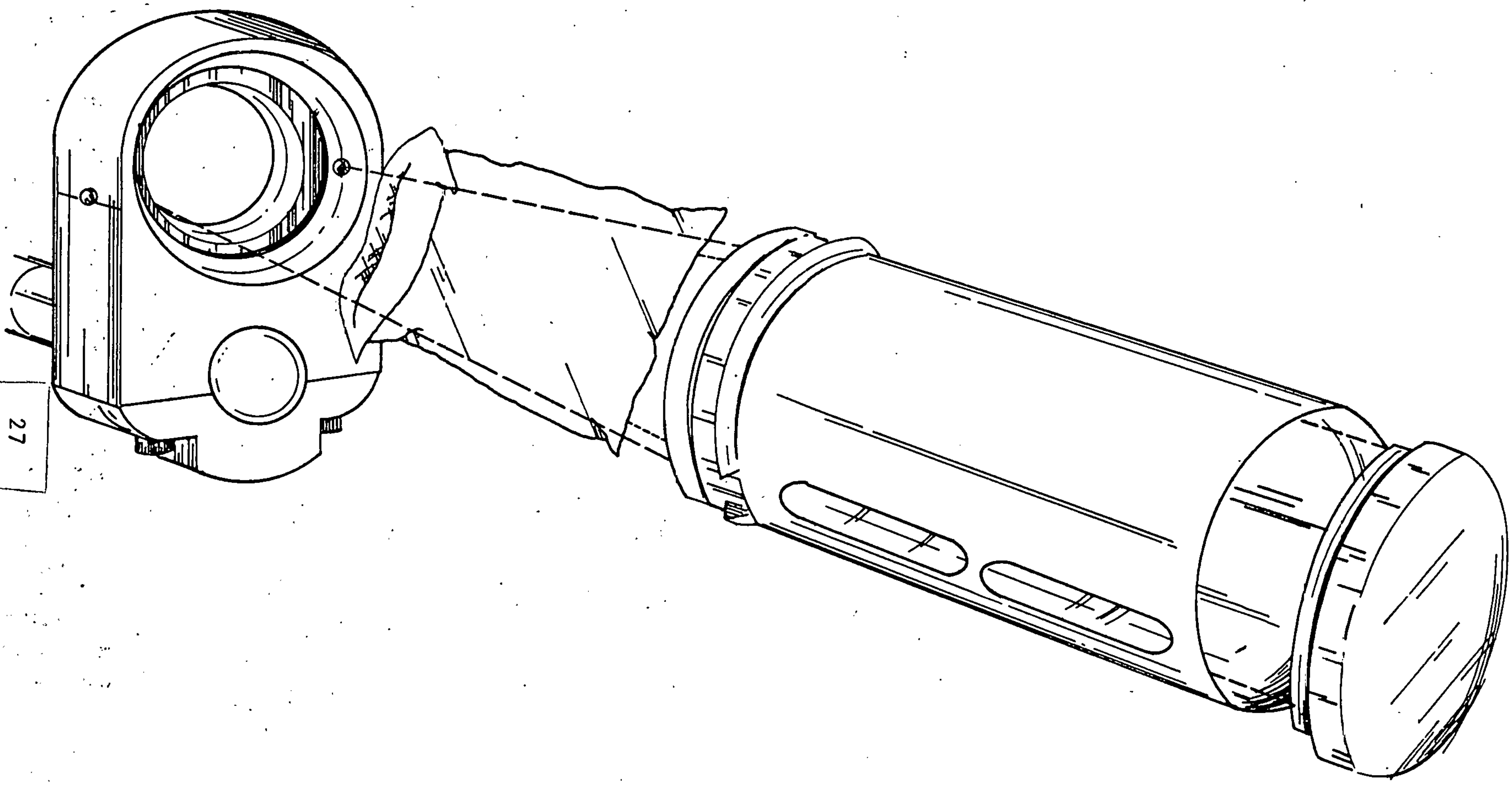


Figure 10. Exploded-view of sampling assembly.

the bag. Then after the sampler was again closed, the assembly was withdrawn and, the filled bag was removed for total and volatile solids analyses.

To track the digester health as well as to take solids distribution measurements that enabled determining the effectiveness of the various mixing modes required such laboratory equipment as a pH meter, a centrifuge, and much glassware. In addition, the system operation required such items as reagents, greases and oils, safety equipment, insulating materials, mechanical supplies, and repair materials.

SECTION 8

OPERATION OF THE TEST DIGESTER

The experimental operation of the pilot digester began after the modified digester vessel and the newly installed equipment had been dry-tested.

To preclude any solids accumulation at initiation and to speed the establishment and acclimation of a healthy anaerobic culture, the digester filling and start-up was very carefully controlled.

Specifically, after the water filled the vessel, it was heated to mesophilic temperatures (32° to 35°C) using the existing perimeter heating pipes. Next to provide a healthy, well-established microbial culture for the digester, digested municipal wastewater sludge was fed into the water at a constant rate until its total solids content was 2 percent. Then a mixture of hydropulped municipal solid waste and digested sewage was added until the total solids content was approximately 3 1/2 percent. Finally, on the basis of the measured values of the total and volatile solids in the two feed streams, the daily amounts of the material to be removed by the Moyno pump and of the feedstock to be added were calculated to establish the 7-day week feeding-removing schedule throughout the period of the first test.

The test plan called for the performance of the digester tests at specific hydraulic retention times. The hydraulic retention time is defined as the fixed volume of a digester vessel divided by the volume of the feedstock added daily which must equal the volume of the digested waste removed daily. At a given HRT, the total solids content of the feedstock and the percentage of volatile solids in the total solids determine the specific volatile solids loading rate.

As the material was withdrawn each day, a sample of it was analyzed to determine the health of the microbial cultures and the total and volatile solids remaining in the digester. Also twice a week but before adding feedstock or removing effluent, solids samples were taken at three fluid levels through each of the sampling ports in the digester roof. While these ports were open, the valves in the gas meter line were closed to minimize air infiltration into the digester dome. After the samples were analyzed to determine the percentage of total solids in each sample and the volatile solids as a percentage of the total solids content of each sample, the data for both the total and the volatile solids concentrations were arranged tabularly as shown in the next section. For each of three sampling levels (top, middle, and bottom) with the data for each grouped separately in this order, the tabular arrangement was prepared to permit comparing laterally the percentages for the samples from each of five ports on each sampling date and then vertically the percentages for the samples from the same port at the successive sampling dates. The comparisons of the data within each sampling-level group and then between the groups enabled (1) evaluating the effectiveness of the particular mixing mode, (2) identifying the well-mixed regions, and (3) determining the extent and amount of the solids accumulated in the poorly mixed regions.

During the test period, gas meter readings were taken daily to compute the gas production. Whenever the solids were sampled in the twice weekly schedule, gas meter readings were taken before and after the sampling period to interpolate the gas production during the sampling period, and the results were extrapolated to compute the total gas production for 24 hours.

As detailed in Table 1, each mixing mode had a single set of operational conditions. Throughout each test, all indicators of digester health were continually monitored to ensure that the digester operated under healthy conditions. Between tests, the scum buster was used to break up and disperse any scum that had formed during the previous test. Although the scum buster did not completely eliminate the scum (as detailed in Section 7), the residual scum at the start of any test did not seriously affect the interpretation or the validity of the data since the results of each test were markedly different.

SECTION 9

PILOT MIXING SYSTEM TESTS

The two mixing systems, the Chemineer mechanical mixer and the ATARA gas gun system, were each to be tested with a 3:1 feed ratio and a 4 percent total solids and then with a 9:1 feed ratio and a 4, 7, and 10 percent total solids. Each of these eight tests was to be performed with a 22 1/2-day hydraulic retention time. In addition, the four tests with the 4 percent total solids were each to be conducted with an 11-day HRT, as well as the 22 1/2-day HRT, to study the feasibility of using shorter retention times. Thus 12 tests in all were planned. Since the percentage of the volatile solids in the total solids of the feedstock was virtually constant in any test period, the volatile solids loading rate was a function of the total solids percentage and the HRT.

As described later, the poor results during the third test, the first to be conducted at the lower HRT, precluded further tests with an 11-day HRT. Consequently, only nine tests were conducted. Table 1 summarizes in chronological order the operating conditions for the nine tests.

Two tables, one for the total solids percentages and the second for the volatile solids percentages, are presented for each of the nine tests. Each of the paired tables lists in the chronological order of sampling the percentages for each of the samples taken through each of five ports (see Figure 2) at each of three levels. Under the "Level" heading, "top" denotes a level about a quarter of a meter below the fluid surface, "middle" denotes a level about 2 m below the surface, and "bottom" denotes a level about 3 1/2 m below the surface.

Also presented in tabular form for each test is a mass balance for the total and volatile solids. The mass of the discharged solids was obtained by calculating the mass of the measured product gas and adding it to the mass of the solids in the effluent. If the digester is mixed sufficiently to prevent any solids accumulations, this mass should equal the mass of the solids entering the digester.

FIRST TEST

The conditions for this test were as follows: (1) gas mixing mode, (2) 3:1 ratio of municipal solid waste to sewage sludge, (3) 4 percent total solids, and (4) volatile solids loading rate of 1.25 grams per liter per day. The data samples for this test were taken between August 1 and 25 of 1977.

In all tests except the first two, the scum buster was operated only between test periods. The operation during the first test was intermittent whereas that in the second test had a planned variation as detailed later. The apparent retardation of the scum formation during the first test was attributed partly to the scum buster effects.

As indicated in Table 2, the total solids percentages at the top level are higher than those at the other two levels. In addition, the percentages for the top level at each date have a greater variation than those for the percentages at the other two levels. The markedly higher values for the top level data are explained as follows. Table 3 shows a relatively uniform volatility solids distribution. Although the uniform scum characteristic of the following tests did not form, a large clump of scum developed and floated randomly throughout the digester.

On the average, the gas production was about 76,500 liters per day, and the ratio of volatile acids to alkalinity was 0.7 on the average. The gas composition was generally 71 percent methane and 23 percent carbon dioxide. While the feed blend contained 4.3 percent total solids, the effluent had 3.3 percent total solids.

As shown in Table 4, the mass of the gas and solids effluent was less than the mass of the feedstock solids. Some solids, therefore, had accumulated during this test, even though the solids sampling indicated that the digester contents were usually well mixed.

No data related to volatile solids destruction could be presented for the nine tests except for the second test. The calculation of the volatile solids destruction is based on the difference between the volatile solids content of the influent and the effluent. Any solids accumulation would decrease the effluent content and therefore invalidate the calculation. Consequently, unless the mass balance indicates little or no solids accumulation, as in the mass balance for the second test only, neither the percentage of the volatile solids destruction nor the gas production per kilogram of volatile solids destroyed can be validly determined.

SECOND TEST

Except for the change to the mechanical mixing mode, the test conditions for this test were the same as those for the first test. The data samples for this test were taken between August 29 and September 29 of 1977.

As seen in Table 5, the total solids percentages for the top level at the beginning of the test were relatively uniform and averaged 4.5 percent. After 1 week, the sample from Port 1 had a 10.11 percent total solids. Then after 2 weeks, the sample from Port 4 had a 11.35 percent total solids. Except for the sample from Port 3 whose percentage remained fairly consistent with the preceeding sampling values, the samples from the other ports compared closely in percentage with the samples from the same ports at the middle and bottom levels. Then within 3 weeks as reflected in the data for the top level, an extensive 3/4-m thick scum with an average 25 percent total solids developed. By 4 weeks, the scum at Ports 5 and 6 (the ports closest to the

TABLE 2. LEVEL-PORT NUMBER DISTRIBUTION OF TOTAL SOLIDS PERCENTAGES FOR TEST 1*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	8/01	6.14	8.68	3.87	7.15	1.93
	8/04	6.01	6.29	4.38	4.35	3.23
	8/08	3.92	3.88	3.16	4.73	3.04
	8/11	2.48	10.29	5.55	2.54	2.04
	8/15	9.52	3.21	4.21	3.25	2.83
	8/18	12.52	3.45	3.27	4.20	2.66
	8/22	9.62	13.21	10.44	6.59	5.26
	8/25	5.55	5.50	5.56	7.94	11.41
Middle	8/01	2.98	2.69	2.99	2.92	2.62
	8/04	3.64	3.84	6.40	3.93	2.43
	8/08	2.81	3.29	4.83	3.23	3.00
	8/11	3.48	3.65	2.19	2.30	2.53
	8/15	3.25	2.76	2.76	2.65	2.80
	8/18	2.41	2.54	2.47	2.30	2.58
	8/22	3.47	5.30	4.55	2.83	3.57
	8/25	2.64	3.36	2.80	3.21	3.08
Bottom	8/01	2.40	2.54	1.82	2.77	2.92
	8/04	5.28	4.20	--	4.43	3.75
	8/08	3.72	4.84	3.94	3.06	3.30
	8/11	0.93	1.62	3.11	2.89	6.02
	8/15	--	5.00	3.48	3.77	3.46
	8/18	3.60	4.69	2.50	3.88	2.80
	8/22	4.13	3.35	3.14	5.42	3.37
	8/25	3.12	2.91	3.27	3.63	3.14

* Gas mixing, 3:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

TABLE 3. LEVEL-PORT NUMBER OF VOLATILE SOLIDS PERCENTAGES FOR TEST 1*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	8/01	63.1	64.1	64.0	65.7	83.7
	8/04	57.4	55.0	49.1	47.4	54.7
	8/08	53.3	51.5	52.6	59.8	48.7
	8/11	53.7	62.5	58.4	57.9	54.0
	8/15	61.0	52.8	60.6	51.9	56.0
	8/18	62.1	56.7	56.2	55.9	52.0
	8/22	62.3	61.0	54.9	61.7	55.6
	8/25	54.3	56.6	56.7	59.3	56.2
Middle	8/01	76.2	60.4	59.1	61.6	56.6
	8/04	50.0	53.5	54.5	53.2	56.5
	8/08	67.7	53.1	55.4	52.2	48.4
	8/11	51.9	47.6	44.4	48.5	51.0
	8/15	51.6	53.2	50.9	48.0	52.1
	8/18	51.5	52.4	52.5	52.5	51.4
	8/22	56.2	57.3	52.6	48.6	54.7
	8/25	48.8	47.4	52.2	47.8	50.0
Bottom	8/01	75.0	58.6	79.6	57.7	69.4
	8/04	56.2	54.6	--	48.8	47.4
	8/08	61.7	57.1	53.0	42.4	47.5
	8/11	66.1	60.0	48.0	51.4	50.5
	8/15	--	52.2	50.0	52.1	51.6
	8/18	50.5	58.4	50.6	52.0	50.0
	8/22	51.0	54.2	58.9	49.3	50.5
	8/25	49.3	53.4	58.5	51.6	52.9

* Gas mixing, 3:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

TABLE 4. AVERAGE DAILY MASS FLOWS FOR TEST 1*

Item	Total solids (kg/day)		Volatile solids (kg/day)	
Feed blend	754		485	
Effluent liquid	580		295	
Product gas †	77		77	
Mass out / Mass in		0.871		0.767
Apparent accumulation **	97		113	

* Gas mixing, 3:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

† The mass total gas produced was calculated from the total gas production and the average gas composition as measured. It is presented here in units of kg/day to allow the reader to visualize the system mass balance.

** Apparent accumulation is calculated as total mass input per day minus total mass output per day (effluent and gas). This remainder is assumed to represent the solids accumulating within the digester vessel.

TABLE 5. LEVEL-PORT NUMBER DISTRIBUTION OF TOTAL SOLIDS PERCENTAGES FOR TEST 2*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	8/29	4.80	3.94	5.62	3.77	4.22
	9/01	8.07	3.37	3.98	6.51	3.95
	9/05	3.79	4.81	5.63	5.00	10.11
	9/08	4.70	4.14	4.01	4.17	3.57
	9/12	4.61	11.35	5.03	3.62	3.51
	9/15	16.02	13.77	11.87	8.74	7.99
	9/19	27.13	24.62	24.20	20.49	27.67
	9/22	26.56	23.05	14.26	23.19	22.51
	9/26	27.31	18.54	19.06	11.36	7.77
	9/29	21.49	25.03	31.05	22.09	19.94
Middle	8/29	3.08	4.57	3.44	3.91	2.00
	9/01	3.25	4.26	3.39	3.32	1.95
	9/05	4.85	3.45	4.12	5.18	5.56
	9/08	3.79	3.87	3.82	3.78	3.85
	9/12	4.52	3.70	3.87	3.33	3.67
	9/15	3.75	3.34	3.44	3.83	3.42
	9/19	3.41	3.10	2.36	2.92	3.17
	9/22	3.55	3.51	3.46	3.97	3.74
	9/26	4.23	2.86	3.15	3.46	2.94
	9/29	3.16	3.20	3.73	3.25	3.31
Bottom	8/29	3.46	3.56	3.18	3.62	3.61
	9/01	3.34	6.27	--	3.64	3.49
	9/05	4.61	3.85	3.18	3.60	3.26
	9/08	3.83	3.23	3.82	3.62	4.72
	9/12	4.58	3.29	3.45	3.70	3.69
	9/15	3.82	3.39	3.36	5.17	3.23
	9/19	3.12	3.91	3.40	3.91	3.40
	9/22	3.22	3.26	4.00	3.27	3.23
	9/26	3.03	3.16	3.00	2.26	3.95
	9/29	2.96	3.30	3.13	3.38	3.26

* Mechanical mixing, 3:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

TABLE 6. LEVEL-PORT NUMBER DISTRIBUTION OF VOLATILE SOLIDS PERCENTAGES FOR TEST 2*

Level	Date	Port number				
		5 (wall)	4	3	2	1 (center)
Top	8/29	55.6	55.3	57.4	54.6	55.7
	9/01	68.5	50.9	56.0	61.0	58.0
	9/05	55.1	55.5	56.2	55.9	59.8
	9/08	60.7	57.6	58.3	55.5	52.1
	9/12	53.7	63.7	54.0	50.5	--
	9/15	73.1	78.3	71.0	65.5	69.1
	9/19	67.3	71.2	69.7	70.0	71.1
	9/22	67.5	75.7	73.1	68.3	76.8
	9/26	72.0	75.3	78.9	71.4	68.9
	9/29	71.0	75.0	76.3	74.5	75.4
Middle	8/29	53.9	57.3	48.8	51.0	50.0
	9/01	50.9	61.3	51.8	46.9	46.1
	9/05	53.2	49.5	50.9	53.2	53.9
	9/08	55.5	54.8	56.0	51.5	53.8
	9/12	51.8	46.7	51.9	54.6	46.8
	9/15	50.5	50.6	49.4	50.9	46.0
	9/19	47.7	42.0	43.2	47.0	48.5
	9/22	51.7	59.1	55.4	43.1	42.3
	9/26	53.7	50.0	51.4	50.5	52.6
	9/29	53.9	47.4	45.7	47.1	48.8
Bottom	8/29	52.4	50.0	49.4	48.8	50.6
	9/01	54.7	75.6	41.1	51.0	54.2
	9/05	50.9	47.5	51.1	52.4	50.6
	9/08	54.2	54.2	55.2	56.9	53.3
	9/12	52.8	48.6	46.8	52.6	52.5
	9/15	52.3	52.7	47.8	71.7	48.9
	9/19	45.0	49.0	41.7	48.0	50.0
	9/22	51.2	52.7	58.4	41.6	40.9
	9/26	43.0	51.1	50.5	21.1	42.2
	9/29	46.7	46.0	45.0	47.6	45.8

* Mechanical mixing, 3:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

walls) was 1 to 1.5-m thick and dry and hard at the top. At Port 4, the scum was a quarter meter thick and partially dry; and at Ports 1 and 2 (the ports nearest the mechanical agitator), the scum was also about a quarter meter thick but soft.

In this and the following tests, the differential between the higher total solids percentages for the top level and the lower total solids percentage for the middle and bottom levels increased. Moreover, the volatile solids percentages for the top level generally became much higher than those for the other two levels. Therefore, since a higher total solids concentration occurred at the top level, as well as a higher volatile solids concentration, the result is that a disproportionately higher entrapment of volatile solids took place in the scum layer.

As viewed through the sampling ports, the top layer of the digester fluid rotated around the shaft of the center-mounted agitator with the rotation ranging from turbulence near the shaft to markedly slower movement near the vessel walls. This observation along with the data trends confirmed the manufacturer's statement of the mixing characteristics to be expected with the power of the motor, the size of the blades, and the length of the shaft selected for the mechanical agitator; namely, a downward flow at the axis with an outward radial component at the blade levels and a slow centerward surface motion without uniform solids lifting to the top layer. According to the manufacturer, a solids distribution approaching uniformity would have required installing a 56-kW (75-hp), rather than the actual 7.5-kW (10-hp), motor. However, the smaller motor was chosen since it would be more compatible with the 3.7-kW (5-hp) gas mixer compressor and with an energy-recovery concept wherein the energy expended for processing should be minimized.

On the average, the gas production was about 187,000 liters per day. The gas composition was generally 62 percent methane and 33 percent carbon dioxide. The ratio of volatile acids to alkalinity was 0.1. While the feed blend contained 4.5 percent total solids, the effluent had 3.3 percent total solids. The calculated volatiles solids destruction was 49 percent. On the average, the gas production per kilogram of volatile solids destroyed was 805 liters.

Compared with the results of the first test, those of the second test indicate a better digester performance, perhaps due to the digester having sufficient time to adapt to the feedstock and become more stable.

The best methane production of any test was observed in this test wherein 187,000 ℓ/day (6,600 ft^3/day) of biogas were measured at an average composition of 62 percent methane. Comparing this with the daily volatile solids destruction during the test gives 805 liters (16 ft^3) of gas produced per kilogram of volatile solids destroyed, a reasonable rate for a healthy digester. An overall system mass balance in Table 7 shows no solids accumulation taking place. The volatile solids destruction observed was 38 percent.

TABLE 7. AVERAGE DAILY MASS FLOWS FOR TEST 2*

Item	Total solids (kg/day)	Volatile solids (kg/day)
Feed blend	870	485
Effluent liquid	608	299
Product gas †	207	207
Mass out / Mass in	0.937	1.04
Apparent accumulation **	55	-21

* Gas mixing, 3:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

† The mass total gas produced was calculated from the total gas production and the average gas composition as measured. It is presented here in units of kg/day to allow the reader to visualize the system mass balance.

** Apparent accumulation is calculated as total mass input per day minus total mass output per day (effluent and gas). This remainder is assumed to represent the solids accumulating within the digester vessel.

Mixing employed throughout this test was a 24-hr/day operation of the 7.5-kW mixer and a 4-hr/day operation of the 30-kW scumbuster. Assuming full-load operation for both, but ignoring power generation efficiencies, this is an energy usage for mixing of 300 kWh/day. The methane produced was 115,000 ℓ/day, having an energy content of 1,200 kWh which is only four times greater than the direct energy usage of our admittedly underpowered mixing system.

After the second test, the digester vessel had to be emptied to repair the gas supply line to one of the gas mixing guns. The photograph of the emptied vessel in Figure 11 shows how the cellulosic materials had coalesced into stringers around the shaft of the mechanical agitator. These stringers were quite dense and as the shaft rotated, their irregular distribution could have imbalanced the agitator.

In addition to the repair of the gas supply line, the stringers were removed from the shaft, and grit deposits along with the fallen scum were removed from the vessel floor. Then the digester vessel was refilled and seeded for the resumption of the tests.

THIRD TEST

Except for an increased loading rate from 1.25 to 2.35 grams of volatile solids per liter per day to establish the 11-day HRT, the test conditions for this test were the same as those for the first test. The data samples for this test were taken between November 28, 1977, and January 23, 1978.

Within a short time, the scum with an average 20 percent total solids developed. Consisting mostly of fibrous materials, the scum was about a quarter meter thick after a few weeks and about half a meter thick after 2 months. At the end of the test, most of the scum was dry which indicated little, if any, turnover.

Although the digester was relatively well mixed at the middle and bottom levels, as indicated in Table 8, it had excessively high total solids percentages and consequently large solids accumulations at the top level. Therefore, as further evidenced by the relatively low volatile solids percentages for the middle and bottom levels in Table 9, most of the substrate for the microorganisms was contained in the scum.

At the beginning of this test, the ratio of volatile acids to alkalinity was 0.6. This relatively high ratio was likely due to the digester difficulty in handling the higher loading rate. It's later rise to 1.0 would indicate that the digester could not easily adapt to the high loading. During the early stage of the test, the gas production increased to 227,000 liters per day. Thereafter, however, the gas production could not be computed since the line to the gas meter had frozen. The gas composition was generally 35 percent methane and 62 percent carbon dioxide.

The feed blend contained 4.5 percent total solids, and the effluent contained only 2.9 percent total solids, so that the mass balance in Table 10 shows a large daily accumulation of solids within the digester vessel.

Figure 11. View of mechanical agitator shaft showing the stringer accumulations that ultimately caused the shaft to bend.

TABLE 8. LEVEL-PORT NUMBER DISTRIBUTION OF TOTAL SOLIDS PERCENTAGES FOR TEST 3*

Level	Date	Port number				
		5 (wall)	4	3	2	1 (center)
Top	11/28	5.4	5.0	4.1	3.1	3.9
	01/16	22.8	--	26.7	22.0	21.8
	01/19	22.1	23.8	22.3	18.3	16.5
	01/23	19.7	17.7	21.7	22.2	18.9
Middle	11/28	3.9	3.5	4.7	2.1	3.4
	01/16	4.5	--	4.4	9.3	7.3
	01/19	1.6	1.9	5.7	2.5	5.3
	01/23	1.7	1.8	2.0	1.8	2.5
Bottom	11/28	3.9	3.4	3.4	3.8	5.0
	01/16	7.3	--	4.3	10.4	3.7
	01/19	1.3	3.1	2.0	4.3	1.2
	01/23	2.9	1.6	3.4	3.0	3.4

* Gas mixing, 3:1 feed ratio, 11-day HRT, and 4% total solids in feed.

TABLE 9. LEVEL-PORT NUMBER DISTRIBUTION OF VOLATILE SOLIDS PERCENTAGES FOR TEST 3*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	1/16	61.6	--	65.9	56.8	56.7
	1/19	65.7	60.8	62.6	59.8	68.9
	1/23	83.7	68.4	66.7	67.1	73.4
Middle	1/16	48.1	--	52.5	49.5	44.0
	1/19	46.7	45.8	53.8	43.1	51.8
	1/23	48.1	53.1	53.2	50.0	54.0
Bottom	1/16	48.1	--	49.6	49.5	--
	1/19	44.4	50.0	45.9	49.5	43.3
	1/23	44.2	51.1	43.9	48.2	46.7

* Gas mixing, 3:1 feed ratio, 11-day HRT, and 4% total solids in feed.

TABLE 10. AVERAGE DAILY MASS FLOWS FOR TEST 3*

Item	Total solids (kg/day)	Volatile solids (kg/day)
Feed blend	1547	909
Effluent liquid †	975	449
Product gas	306	306
Mass out / Mass in	0.828	0.831
Apparent accumulation **	266	154

* Gas mixing, 3:1 feed ratio, 11-day HRT, and 4% total solids in feed.

† The mass total gas produced was calculated from the total gas production and the average gas composition as measured. It is presented here in units of kg/day to allow the reader to visualize the system mass balance.

** Apparent accumulation is calculated as total mass input per day minus total mass output per day (effluent and gas). This remainder is assumed to represent the solids accumulating within the digester vessel.

Along with the high ratio of volatile acids to alkalinity, the gas composition data indicated that a healthy microbial culture could not be maintained with an 11-day HRT. Therefore, only the 22 1/2-day HRT was used in the following tests.

FOURTH TEST

The conditions for this test were as follows: (1) gas mixing mode, (2) 9:1 ratio of municipal solid waste to sewage sludge, (3) 4 percent total solids, and (4) volatile solids loading rate of 1.25 grams per liter per day. The data samples for this test were taken between March 23 and April 13 of 1978.

In Table 11, the data reflect the rapid solids buildup. Except for the sample taken from Port 5 (the port closest to the wall), the samples at the start had relatively uniform total solids percentages. Then as evidenced by the top level data for the next few sampling dates, the percentages for the samples from Ports 1 through 4 generally increased progressively with the scum apparently spreading from the walls toward the center. Within a week, the scum extended over virtually all the surface and had an average 18 percent total solids. Although the digester was obviously not well mixed, the microbes were apparently healthy.

On the average, the gas production was about 34,000 liters per day. The 0.3 average for the ratios of the volatile acid to alkalinity indicated that the acid and methane forming groups were favorably balanced. The gas composition was generally 61 percent methane and 35 percent carbon dioxide. While the feed blend contained 3.5 percent total solids, the effluent had 1.8 percent total solids.

The mass balance in Table 13 shows that about half of the solids fed to the digester were entrapped within the scum and therefore not reacted.

FIFTH TEST

Except for the change to the mechanical mixing mode, the conditions for this test were the same as those for the fourth test. The data samples for this test were taken between April 20 and May 4 of 1978.

As evidenced by the top level data in Table 14, the high total solids concentrations and scum near the walls gradually spread to Port 3 but did not reach Ports 1 and 2. The very low percentages for the samples at the middle and bottom levels corroborated the previous suppositions that the cellulosics in the well-mixed regions are rapidly removed and captured in the top layer and therefore not available for degradation.

Gas volume data for this test were suspect because of low readings. This suspicion was confirmed in the next test when on inspection it was found that the gas meter had been malfunctioning. The invalidity of the gas meter data, therefore, precluded computing the gas production rates for the fifth and sixth tests.

TABLE 11. LEVEL-PORT NUMBER DISTRIBUTION OF TOTAL SOLIDS PERCENTAGES FOR TEST 4*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	3/23	21.5	1.3	2.0	2.0	1.9
	3/27	19.0	17.8	3.6	2.3	18.6
	3/30	15.2	22.7	14.8	15.6	17.1
	4/03	18.9	17.7	20.1	14.2	19.4
	4/06	18.5	13.8	21.2	17.6	18.1
	4/10	15.1	16.1	15.0	20.0	15.2
	4/13	12.6	13.4	14.6	16.5	16.6
Middle	3/23	2.5	1.9	1.9	1.9	1.8
	3/27	1.7	1.4	1.7	1.5	1.8
	3/30	1.6	1.6	1.3	1.3	1.7
	4/03	0.9	0.9	1.1	1.5	1.7
	4/06	1.3	1.1	1.1	1.0	1.1
	4/10	0.9	0.9	0.4	0.8	0.5
	4/13	0.6	0.5	0.7	0.7	0.6
Bottom	3/23	3.2	1.9	1.9	2.4	2.2
	3/27	1.7	1.6	1.8	2.0	3.3
	3/30	1.5	1.5	1.3	1.6	1.8
	4/03	1.1	0.9	1.3	1.4	2.3
	4/06	1.0	0.9	1.2	1.0	1.2
	4/10	0.5	2.4	0.9	1.7	0.5
	4/13	0.8	0.5	0.8	1.9	1.1

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

TABLE 12. LEVEL-PORT NUMBER DISTRIBUTION OF VOLATILE SOLIDS PERCENTAGES FOR TEST 4*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	3/23	71.3	36.4	53.6	56.0	53.1
	3/27	70.6	61.3	59.7	58.9	71.1
	3/30	61.3	64.3	79.3	67.8	76.2
	4/03	59.0	72.3	71.5	74.0	78.2
	4/06	65.5	68.6	68.3	70.8	--
	4/10	64.7	69.5	65.0	79.0	73.3
	4/13	68.9	68.5	68.7	79.5	78.6
Middle	3/23	51.1	53.1	52.9	51.9	51.2
	3/27	45.1	50.0	45.9	41.9	45.7
	3/30	48.8	52.2	57.9	50.0	48.2
	4/03	45.0	36.8	34.5	42.4	45.7
	4/06	52.5	50.0	40.7	46.2	42.9
	4/10	62.5	55.6	70.0	53.3	53.9
	4/13	65.0	--	72.7	63.0	66.7
Bottom	3/23	55.8	53.6	54.7	63.8	50.0
	3/27	51.0	52.8	41.7	44.2	47.9
	3/30	51.1	57.1	61.8	50.0	50.9
	4/03	40.6	42.3	35.3	37.5	49.1
	4/06	43.2	37.0	46.7	41.4	43.3
	4/10	50.0	72.2	47.1	52.3	50.0
	4/13	60.1	64.7	60.9	61.3	41.7

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

TABLE 13. AVERAGE DAILY MASS FLOWS FOR TEST 4*

Item	Total solids (kg/day)		Volatile solids (kg/day)	
Feed blend	724		485	
Effluent liquid †	369		176	
Product gas	40		40	
Mass out / Mass in		0.565		0.445
Apparent accumulation **	315		269	

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

† The mass total gas produced was calculated from the total gas production and the average gas composition as measured. It is presented here in units of kg/day to allow the reader to visualize the system mass balance.

** Apparent accumulation is calculated as total mass input per day minus total mass output per day (effluent and gas). This remainder is assumed to represent the solids accumulating within the digester vessel.

TABLE 14. LEVEL-PORT NUMBER DISTRIBUTION OF TOTAL SOLIDS PERCENTAGES FOR TEST 5*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	4/20	18.8	25.5	0.9	0.9	0.9
	4/24	17.6	27.4	0.8	0.7	1.0
	4/27	14.9	17.6	0.7	0.7	0.7
	5/02	16.9	21.0	14.8	0.4	0.5
	5/04	22.0	19.7	13.8	0.7	3.7
Middle	4/20	1.3	1.2	--	0.8	1.0
	4/24	1.3	1.7	0.6	0.6	0.5
	4/27	3.2	1.3	0.9	0.6	0.7
	5/02	0.6	0.6	0.4	0.3	0.6
	5/04	2.2	0.6	1.4	0.6	0.6
Bottom	4/20	1.5	1.3	1.3	1.3	1.0
	4/24	3.6	1.2	0.8	0.8	0.6
	4/27	1.2	2.1	0.9	0.8	0.9
	5/02	1.4	1.8	0.9	1.0	0.7
	5/04	1.3	0.9	1.4	1.7	0.8

* Mechanical mixing, 9:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

TABLE 15. LEVEL-PORT NUMBER DISTRIBUTION OF VOLATILE SOLIDS PERCENTAGES FOR TEST 5*

Level	Date	Port number				
		5 (wall)	4	3	2	1 (center)
Top	4/20	65.1	69.0	36.0	40.9	44.4
	4/24	68.3	67.8	42.9	47.6	48.2
	4/27	70.7	83.6	52.0	59.1	40.0
	5/02	72.0	76.1	76.6	75.0	75.0
	5/04	72.1	69.0	62.1	43.5	69.7
Middle	4/20	40.0	40.0	--	38.1	27.8
	4/24	57.1	63.6	66.7	62.5	73.3
	4/27	79.5	47.6	44.8	42.9	39.1
	5/02	52.9	64.3	70.0	70.0	66.7
	5/04	50.9	60.0	57.6	52.6	63.6
Bottom	4/20	47.9	46.7	43.8	36.7	47.8
	4/24	50.0	68.3	61.5	69.6	66.7
	4/27	50.0	52.3	52.6	68.0	61.1
	5/04	43.3	60.0	52.6	53.0	52.0

* Mechanical mixing, 9:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

The gas composition was generally 60 percent methane and 35 percent carbon dioxide. While the feed blend contained 4.0 percent total solids, the effluent had 1.2 percent total solids. The ratio of volatile acids to alkalinity was 0.1.

As shown in Table 16, the mass balance for the fifth test could not be completed because of the lack of valid gas meter data.

SIXTH TEST

The conditions for this test were as follows: (1) mechanical mixing mode, (2) 9:1 ratio of municipal solid waste to sewage sludge, (3) 7 percent total solids, and (4) volatile solids loading rate of 2.2 grams per liter per day. The data samples for this test were taken between June 5 and June 22 of 1978.

As evidenced by the data in Table 17, the top level samples from Ports 3, 4, and 5 had high total solids percentages whereas those from Ports 1 and 2 had generally very low percentages throughout the test period. The scum progressively dried until it was so hard that some samples could not be withdrawn from Ports 3 and 4. Although the feedstock had a 7 percent total solids, the samples taken at the well-mixed middle and bottom levels had total solids percentages ranging only from 0.7 to 3.8 with only 7 of the 50 samples having percentages above 2.0.

The gas composition was generally 60 percent methane and 35 percent carbon dioxide. While the feed blend contained 6.5 percent total solids, the effluent had 1.7 percent total solids. The ratio of volatile acids to alkalinity was 0.2.

As for the fifth test, the mass balance for the sixth test, as shown in Table 19, could not be completed because of the lack of valid gas meter data.

SEVENTH TEST

Except for the change to the gas mixing mode, the conditions for this test were the same as those for the sixth test. The data samples for this test were taken between July 3 and July 20 of 1978.

The data in Table 20 for the top level samples show a fairly constant solids accumulation throughout the top layer and the test period with only the percentages for the samples taken from Ports 1 and 2 being appreciably less than the average value. The scum was so dense and dry that no samples for the middle and bottom levels could be withdrawn from Ports 3 and 4. Again, the samples taken at the well-mixed middle and bottom levels had total solids percentages ranging from only 0.6 to 3.2 percent with only 3 of the 32 samples having percentages above 2.0.

The average gas production was about 40,000 liters per day. The gas composition was generally 72 percent methane and 24 percent carbon dioxide.

TABLE 16. AVERAGE DAILY MASS FLOWS FOR TEST 5*

Item	Total solids (kg/day)	Volatile solids (kg/day)
Feed blend	706	485
Effluent liquid †	212	104
Product gas	gas meter malfunction	
Mass out / Mass in	--	--
Apparent accumulation **	--	--

* Mechanical mixing, 9:1 feed ratio, 22.5-day HRT, and 4% total solids in feed.

† The mass total gas produced was calculated from the total gas production and the average gas composition as measured. It is presented here in units of kg/day to allow the reader to visualize the system mass balance.

** Apparent accumulation is calculated as total mass input per day minus total mass output per day (effluent and gas). This remainder is assumed to represent the solids accumulating within the digester vessel.

TABLE 17. LEVEL-PORT NUMBER DISTRIBUTION OF TOTAL SOLIDS PERCENTAGES FOR TEST 6*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	6/05	20.7	--	30.8	1.2	0.9
	6/08	34.6	34.2	25.6	2.6	1.7
	6/12	22.1	24.6	15.0	0.9	5.9
	6/15	17.8	--	23.7	15.7	0.9
	6/19	31.6	33.9	29.3	0.7	1.3
	6/22	36.0	27.2	31.3	1.2	2.1
Middle	6/05	1.5	--	2.1	0.7	0.7
	6/08	1.1	--	2.0	0.9	1.1
	6/12	1.8	1.7	1.1	0.9	1.2
	6/15	2.5	--	1.2	3.2	0.9
	6/19	1.5	1.5	--	1.0	1.0
	6/22	1.7	1.3	--	1.3	1.3
Bottom	6/05	1.0	--	1.3	1.2	1.0
	6/08	3.8	--	1.3	1.2	0.9
	6/12	1.9	1.6	1.3	1.5	1.0
	6/15	2.8	--	1.2	0.9	0.9
	6/19	1.1	2.5	--	1.2	1.7
	6/22	2.2	1.4	--	1.2	1.7

* Mechanical mixing, 9:1 feed ratio, 22.5-day HRT, and 7% total solids in feed.

TABLE 18. LEVEL-PORT NUMBER DISTRIBUTION OF VOLATILE SOLIDS PERCENTAGES FOR TEST 6*

Level	Date	Port number				
		5 (wall)	4	3	2	1 (center)
Top	6/05	74.5	--	64.6	71.4	46.6
	6/08	64.4	67.7	61.5	73.0	69.1
	6/12	60.8	66.0	65.5	63.3	--
	6/15	68.2	--	71.6	64.2	54.5
	6/19	56.8	66.4	59.5	60.6	59.6
	6/22	64.5	86.9	54.0	59.5	65.5
Middle	6/05	55.8	--	45.6	45.0	47.1
	6/08	65.7	--	58.0	67.8	63.1
	6/12	64.7	58.7	56.7	62.9	65.3
	6/15	54.8	--	54.5	51.4	49.4
	6/19	58.0	40.1	--	56.0	55.4
	6/22	61.7	59.0	--	57.7	56.8
Bottom	6/05	53.3	--	48.5	58.8	55.8
	6/08	39.8	--	71.4	68.6	78.9
	6/12	61.5	57.7	61.2	58.9	62.5
	6/15	57.5	--	54.8	48.8	52.0
	6/19	54.8	58.5	--	57.8	62.5
	6/22	62.3	58.3	--	58.8	60.3

*Mechanical mixing, 9:1 feed ratio, 22.5-day HRT, and 7% total solids in feed.

TABLE 19. AVERAGE DAILY MASS FLOWS FOR TEST 6*

Item	Total solids (kg/day)	Volatile solids (kg/day)
Feed blend	2629	1909
Effluent liquid †	680	401
Product gas	gas meter malfunction	
Mass out / Mass in	--	--
Apparent accumulation **	--	--

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 7% total solids in feed.

† The mass total gas produced was calculated from the total gas production and the average gas composition as measured. It is presented here in units of kg/day to allow the reader to visualize the system mass balance.

** Apparent accumulation is calculated as total mass input per day minus total mass output per day (effluent and gas). This remainder is assumed to represent the solids accumulating within the digester vessel.

TABLE 20. LEVEL-PORT NUMBER DISTRIBUTION OF TOTAL SOLIDS PERCENTAGES FOR TEST 7*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	7/03	25.7	29.5	30.6	13.5	--
	7/06	31.0	36.5	31.3	24.4	19.9
	7/10	26.6	21.5	29.4	17.2	17.3
	7/13	31.1	35.8	35.6	28.0	17.9
	7/17	26.2	--	31.3	22.9	15.6
	7/20	33.3	37.0	35.3	18.1	16.6
Middle	7/03	2.7	--	--	1.6	1.1
	7/06	1.5	--	--	1.2	1.0
	7/10	.6	--	--	.8	.8
	7/13	1.9	--	--	2.0	1.6
	7/17	--	--	--	1.5	.8
	7/20	--	--	--	.7	.8
Bottom	7/03	2.9	--	--	1.0	1.1
	7/06	3.2	--	--	1.2	1.0
	7/10	.8	--	--	.7	.7
	7/13	1.2	--	--	1.2	1.1
	7/17	--	--	--	.9	.7
	7/20	--	--	--	.7	.7

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 7% total solids in feed.

TABLE 21. LEVEL-PORT NUMBER DISTRIBUTION OF VOLATILE SOLIDS PERCENTAGES FOR TEST 7*

Level	Date	Port number				
		5 (wall)	4	3	2	1 (center)
Top	7/03	74.2	62.3	47.5	76.5	--
	7/06	70.7	62.4	53.8	74.2	79.6
	7/10	58.3	55.6	55.8	73.0	74.3
	7/13	72.1	61.8	60.4	72.3	66.5
	7/17	70.0	--	48.8	--	75.9
	7/20	69.4	57.5	57.4	71.3	74.6
Middle	7/03	64.0	--	--	50.9	53.6
	7/06	56.9	--	--	54.8	52.9
	7/10	52.6	--	--	55.1	50.4
	7/13	53.2	--	--	49.3	48.6
	7/17	--	--	--	52.6	49.6
	7/20	--	--	--	53.0	54.0
Bottom	7/03	63.7	--	--	63.0	53.7
	7/06	54.6	--	--	53.5	52.9
	7/10	49.7	--	--	48.9	52.7
	7/13	55.1	--	--	58.1	73.5
	7/17	--	--	--	59.1	52.7
	7/20	--	--	--	55.9	66.6

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 7% total solids in feed.

While the feed blend contained 6.2 percent total solids, the effluent had 1.3 percent total solids. The ratio of volatile acids to alkalinity was 0.5.

The mass balance in Table 22 also indicates the large solids accumulations. These accumulations with the 7 percent total solids feedstock are much greater than those in the tests with the 4 percent total solids feedstock.

EIGHTH TEST

The conditions for this test were as follows: (1) gas mixing, (2) 9:1 ratio of municipal solid waste to sewage sludge, (3) 10 percent total solids, and (4) volatile solids loading rate of 3.2 grams per day. The data samples for this test were taken between July 24 and August 8 of 1978.

As shown in Table 23, the data for the top level samples through the first four of the seven sampling dates are similar to those in the seventh test in that they show a fairly constant solids accumulation throughout the top layer with only the percentages for the samples taken from Ports 1 and 2 being appreciably less than the average value. While the data for the middle and bottom levels show that the lower regions were well mixed, these regions had total solids concentrations still lower then those in the seventh test with no sample having a percentage more than 1.7.

On the average, the gas production was about 82,000 liters per day. The gas composition was generally 65 percent methane and 31 percent carbon dioxide. While the feed blend contained 10.1 percent total solids, the effluent had 1.7 percent total solids. The ratio of volatile acids to alkalinity was 0.2.

The mass balance in Table 25 shows that most of the feedstock solids had accumulated in the vessel.

NINTH TEST

Except for the change to the mechanical mixing mode, the conditions for this test were the same as those for the eighth test. The data samples for this test were taken between August 17 and September 14 of 1978.

Although not as clearly defined nor as consistent as the data for the seventh and eighth tests, the data for the top level samples in Table 26 present a pattern similar to those in the preceding tests. In comparison with the very low total solids percentages for the samples at the middle and bottom levels in the eighth test, those in the ninth test are slightly higher.

On the average, the gas production was about 82,000 liters per day. The gas composition was generally 75 percent methane and 24 percent carbon dioxide. While the feed blend contained 10.9 percent total solids, the effluent had 1.3 percent total solids. The ratio of volatile acids to alkalinity was 0.5.

TABLE 22. AVERAGE DAILY MASS FLOWS FOR TEST 7*

Item	Total solids (kg/day)	Volatile solids (kg/day)
Feed blend	2508	1778
Effluent liquid †	514	296
Product gas	42	42
Mass out / Mass in	0.222	0.190
Apparent accumulation **	1952	1440

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 7% total solids in feed.

† The mass total gas produced was calculated from the total gas production and the average gas composition as measured. It is presented here in units of kg/day to allow the reader to visualize the system mass balance.

** Apparent accumulation is calculated as total mass input per day minus total mass output per day (effluent and gas). This remainder is assumed to represent the solids accumulating within the digester vessel.

TABLE 23. LEVEL-PORT NUMBER DISTRIBUTION OF TOTAL SOLIDS PERCENTAGES FOR TEST 8*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	7/24	35.5	--	--	1.4	--
	7/27	29.8	35.2	35.6	14.8	--
	7/31	27.3	34.0	36.1	13.8	1.1
	8/03	32.8	33.7	40.2	22.1	18.6
	8/07	29.1	36.7	43.3	13.4	14.0
	8/10	23.5	14.8	31.6	12.9	13.7
	8/14	15.6	14.8	16.3	23.5	22.3
Middle	7/24	--	--	--	1.7	--
	7/27	--	--	--	1.1	1.1
	7/31	--	--	--	--	--
	8/03	--	--	--	0.3	0.3
	8/07	--	--	--	1.0	1.1
	8/10	0.9	1.1	0.7	0.9	1.4
	8/14	1.0	1.0	1.2	0.8	0.7
Bottom	7/24	--	--	--	1.2	--
	7/27	--	--	--	1.5	1.7
	7/31	--	--	--	--	--
	8/03	--	--	--	0.4	0.3
	8/07	--	--	--	1.0	1.1
	8/10	1.0	1.0	0.8	1.2	1.2
	8/14	1.2	0.9	1.1	0.7	0.8

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 10% total solids in feed.

TABLE 24. LEVEL-PORT NUMBER DISTRIBUTION OF VOLATILE SOLIDS PERCENTAGES FOR TEST 8*

Level	Date	Port number				
		5 (wall)	4	3	2	1 (center)
Top	7/24	61.9	--	--	57.7	--
	7/27	60.4	61.6	51.5	74.8	--
	7/31	59.0	57.3	53.9	70.0	57.5
	8/03	58.8	63 7	58.2	63.2	57.4
	8/07	56.0	52.5	51.7	78.4	74.7
	8/10	69.3	76.8	61.7	73.5	81.5
	8/14	78.4	80.9	78.5	67.4	86.4
Middle	7/24	--	--	--	56.7	--
	7/27	--	--	--	54.7	53.9
	7/31	--	--	--	--	--
	8/03	--	--	--	27.9	27.3
	8/07	--	--	--	48.1	50.7
	8/10	48.3	49.5	46.1	49.3	67.6
	8/14	51.2	50.9	56.0	49.0	49.0
Bottom	7/24	--	--	--	54.0	--
	7/27	--	--	--	54.9	54.7
	7/31	--	--	--	--	--
	8/03	--	--	--	38.4	26.0
	8/07	--	--	--	49.1	49.9
	8/10	53.6	47.6	48.2	50.7	56.8
	8/14	56.3	52.6	54.3	50.2	55.7

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 10% total solids in feed.

TABLE 25. AVERAGE DAILY MASS FLOWS FOR TEST 8*

Item	Total solids (kg/day)	Volatile solids (kg/day)
Feed blend	3960	2840
Effluent liquid†	660	360
Product gas	80	80
Mass out / Mass in	0.187	0.155
Apparent accumulation**	3220	2400

* Gas mixing, 9:1 feed ratio, 22.5-day HRT, and 10% total solids in feed.

† The mass total gas produced was calculated from the total gas production and the average gas composition as measured. It is presented here in units of kg/day to allow the reader to visualize the system mass balance.

** Apparent accumulation is calculated as total mass input per day minus total mass output per day (effluent and gas). This remainder is assumed to represent the solids accumulating within the digester vessel.

TABLE 26. LEVEL-PORT NUMBER DISTRIBUTION OF TOTAL SOLIDS PERCENTAGES FOR TEST 9*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	8/17	22.6	14.5	15.7	16.9	22.0
	8/21	31.7	18.4	12.9	16.5	15.1
	8/24	26.6	24.2	15.5	20.0	13.5
	8/28	18.3	31.4	37.1	15.7	--
	8/31	25.9	20.1	24.2	0.6	0.9
	9/04	21.5	18.5	16.9	0.9	0.8
	9/07	15.6	17.5	14.2	10.2	1.1
	9/11	30.2	28.8	37.0	37.7	1.5
	9/14	19.8	22.9	13.8	31.3	1.3
Middle	8/17	0.7	1.5	0.5	0.4	0.5
	8/21	0.8	0.8	1.0	0.8	0.8
	8/24	0.4	0.9	0.7	0.7	0.8
	8/28	2.6	1.2	0.6	0.6	0.9
	8/31	1.7	2.3	1.2	0.2	0.9
	9/04	2.3	0.6	1.1	0.7	0.8
	9/07	1.9	1.4	1.2	1.2	1.0
	9/11	1.5	1.5	1.2	2.7	1.2
	9/14	1.3	2.0	1.2	1.2	1.0
Bottom	8/17	0.7	0.4	0.8	0.7	0.6
	8/21	0.8	1.0	1.0	1.3	0.9
	8/24	1.2	0.9	0.8	1.0	1.5
	8/28	2.2	1.1	1.2	1.5	2.1
	8/31	1.5	1.5	1.5	1.1	1.2
	9/04	1.2	1.7	1.3	1.1	0.3
	9/07	1.5	1.3	--	1.2	--
	9/11	1.5	1.7	0.9	1.7	1.3
	9/14	1.6	1.7	1.6	1.9	1.0

* Mechanical mixing, 9:1 feed ratio, 22.5-day HRT, and 10% total solids in feed.

TABLE 27. LEVEL-PORT NUMBER DISTRIBUTION OF VOLATILE SOLIDS PERCENTAGES FOR TEST 9*

Level	Date	Port number 5 (wall)	4	3	2	1 (center)
Top	8/17	89.8	82.6	80.7	74.5	80.7
	8/21	85.0	72.1	73.3	62.6	56.5
	8/24	88.9	75.5	89.2	--	69.0
	8/28	79.5	86.9	64.7	73.9	--
	8/31	83.6	72.8	61.2	43.6	51.7
	9/04	83.8	75.0	72.9	--	57.7
	9/07	85.1	78.4	74.4	70.9	60.0
	9/11	64.7	61.2	63.0	63.9	58.3
	9/14	77.9	78.1	73.7	67.7	55.2
Middle	8/17	48.0	56.0	39.7	35.0	38.2
	8/21	54.3	53.6	61.7	43.8	59.0
	8/24	48.0	52.5	48.6	50.3	51.1
	8/28	63.4	51.3	47.6	46.5	48.0
	8/31	55.6	57.8	83.0	65.1	45.4
	9/04	63.8	21.4	44.8	37.5	45.5
	9/07	64.7	53.8	65.0	55.6	71.4
	9/11	55.3	51.4	55.6	56.4	45.0
	9/14	55.2	55.8	44.4	50.0	52.6
Bottom	8/17	54.3	43.3	49.2	--	21.2
	8/21	51.5	56.7	54.5	48.2	55.7
	8/24	69.3	36.9	33.4	53.4	56.4
	8/28	62.3	53.8	56.3	50.8	55.3
	8/31	54.3	50.9	53.6	46.1	46.2
	9/04	44.0	85.3	47.1	18.5	41.7
	9/07	58.6	69.0	--	57.1	--
	9/11	53.3	58.5	54.2	63.9	43.9
	9/14	52.4	50.0	52.9	52.8	47.6

* Mechanical mixing, 9:1 feed ratio, 22.5-day HRT, and 10% total solids in feed.

Like the mass balance for the eighth test, that for the ninth test in Table 28 shows that most of the feedstock had accumulated in the digester vessel.

Table 29 summarizes the results of the nine tests. For convenience in comparing the data for the nine tests, this table includes the planned test conditions.

When the digester vessel was emptied again after the ninth test, the stringers around the shaft of the mechanical agitator were much greater than those observed after the first vessel emptying. In addition, the excessive and irregular forces caused by the stringers had twisted all impeller blades, broken the mounting bolts of some of the blades, and bent the shaft.

Also observed after the second vessel emptying was the unexpected large solids accumulation in the bubble-forming chamber of each gas gun assembly. The solids had accumulated so extensively that the chamber volume and the gas passage were drastically reduced. Consequently, at some time during the test period, the bubbles leaving the chamber were too small to completely fill the draft tube. When this condition prevailed, the bubbles would have ceased to promote the fluid mixing because they would no longer serve as pistons. Since the efforts to remove the solids through the pipecleaning line proved inadequate, the manufacturer of the gas mixing system offered suggestions to improve the cleaning. The letter presenting these suggestions is reproduced in the Appendix.

TABLE 28. AVERAGE DAILY MASS FLOWS FOR TEST 9*

Item	Total solids (kg/day)	Volatile solids (kg/day)
Feed blend	4272	3012
Effluent liquid †	510	261
Product gas	73	73
Mass out / Mass in	0.136	0.111
Apparent accumulation **	3689	2678

* Mechanical mixing, 9:1 feed ratio, 22.5-day HRT, and 10% total solids in feed.

† The mass total gas produced was calculated from the total gas production and the average gas composition as measured. It is presented here in units of kg/day to allow the reader to visualize the system mass balance.

** Apparent accumulation is calculated as total mass input per day minus total mass output per day (effluent and gas). This remainder is assumed to represent the solids accumulating within the digester vessel.

TABLE 29. SUMMARY OF TEST CONDITIONS AND RESULTS

Parameter	Test number 1	2	3	4	5	6	7	8	9	
Mixing Mode	G*	M*	G	G	M	M	G	G	M	test conditions
Feedstock ratio (MSW: sewage sludge)	3.1	3.1	3.1	9.1	9.1	9.1	9.1	9.1	9.1	test conditions
Hydraulic retention time (days)	22.5	22.5	11	22.5	22.5	22.5	22.5	22.5	22.5	test conditions
Planned feedstock total solid (%)	4	4	4	4	4	7	7	10	10	test conditions
Actual feedstock total solids (%)	4.3	4.5	4.5	3.5	4.0	6.5	6.2	10.1	10.9	measured results
Effluent total solids (%)	3.3	3.3	2.9	1.8	1.2	1.7	1.3	1.7	1.3	measured results
Gas production (ℓ per day)	76,500	187,000	204,000	34,000	---	---	40,000	82,000	85,000	measured results
Gas composition (of CH_4: of CO_2)	71:23	62:33	35:62	61:35	60:35	60:35	72:24	65:31	75.24	measured results
Volatile acid to alkalinity ratio	0.7	0.1	0.8	0.3	0.1	0.2	0.5	0.2	0.5	measured results

* G - Gas, M - Mechanical

APPENDIX

LETTER FROM AERO-HYDRAULICS CORPORATION

TELEPHONE: (514) 631-5548
TELEX: 05-821714

CABLE ADDRESS: AERHYD

RECEIVED ... 1979

AERO-HYDRAULICS
CORPORATION
10355 CÔTE DE LIESSE ROAD
DORVAL, QUÉBEC, CANADA
H9P 1A6

May 1st, 1979

Systems Technology Corporation,
245 N. Valley Road,
Xenia, Ohio 45385

Att. Dr. J.R. Swartzbaugh Ph.D/ Ms C.E. Jarvis

Subject: Biogasification Mixing Study

Dear Sirs,

We wish to thank you for the preliminary copy of your report on the above subject.

At the time of its receipt we had very little comment to make other than the fact that the mechanical end (blowers, pressure switches etc.) should have been more fool-proof than was fact. Also missing one-third of the mixing power when one of the "guns" was not functioning due to blocking, was quite a loss to the efficiency of the system.

In the light of your report it was decided that, with the noted characteristics of the sludge involved, we should review and research a "customized" solution to suit the conditions in which the unit would work.

The parameters to work to were roughly established as follows:

1.- Review the bubble generator design so that "dead" corners in the chambers would be all but totally eliminated. This would mean a continuous bend generator rather than the canister and pipe design which has been so successful in ordinary sludges.

2.- Develop an alternative method for introducing the bubble into the stack of the unit to reduce possible hang up areas and give a freer path for liquid movement though the stack.

3.- Consider suspending the units from the roof with a sealed manhole so that the unit could be removed without losing gas pressure.

4.- Consider using an 18" diameter unit to increase flow areas in both stack and generator and also to introduce heavier punching power to break down the scum layer.

5.- Increase stack length. This gives greater pumping power, but would only be possible in a digester with greater depth.

We have worked on items 1 and 2 and have succeeded in developing a new form of our patented bubble generator in which all sections are free flow pipes in continuous bends and all areas are self-scouring. We also have developed a method of side entry of the bubble into the stack. This allows us far greater flexibility in setting the level of the bottom end of the stack and depending on the job allows us to vary the level of the bubble generator in relation to the bottom of the stack. We have a U.S. patent pending on our new ideas.

This newer unit, as applied to unusual type wastes such as were involved at Franklin, is effective in providing continuous operation. Even the effect of the rodding line is increased because of the ability of the rod to absolutely scour all areas.

With reference to item 3, 4 and 5, hindsight would indicate that an 18" unit would have had much improved punching power at the surface and we believe this would have assisted much more in breaking up the scum layer experienced. Roof suspension may not have been possible due to strictures of the roof design. Stack length is related to side water depth so not too much could have been modified in this respect.

To conclude, the modifications outlined above in items 1, 2 & 4, would have materially increased the performance of our units, over that recorded in your report, with little increase in horsepower needs.

AERO-HYDRAULICS
CORPORATION

We were grateful to have been included in the experiments and, as a matter of interest, the three 45 gallon drums of the Franklin waste material which we had left over were of immense use in finalizing the continuous bend bubble generator.

Yours very truly,

D.S. Murphy, General Manager

DSM/ld

c.c. J. DeVos

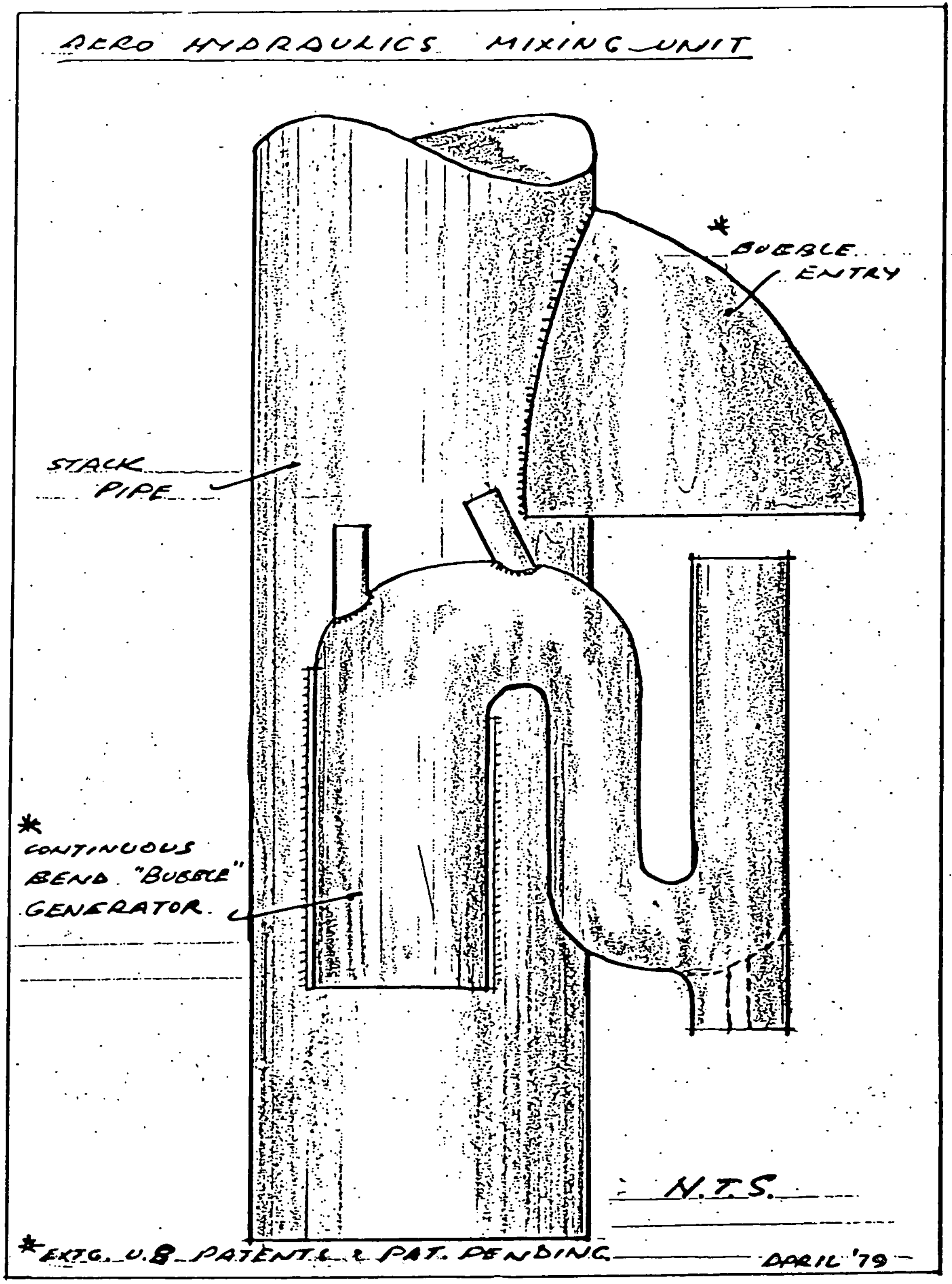


Figure A-1. Aero-Hydraulics mixing unit.