8-1969

A laboratory investigation of anaerobic sludge digestion for dairy manure

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Recommended Citation

Branch, John William, "A laboratory investigation of anaerobic sludge digestion for dairy manure. " Master's Thesis, University of Tennessee, 1969.
https://trace.tennessee.edu/utk_gradthes/8434

To the Graduate Council:

I am submitting herewith a thesis written by John William Branch entitled "A laboratory investigation of anaerobic sludge digestion for dairy manure." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

John I. Sewell, Major Professor

We have read this thesis and recommend its acceptance:

John J. McDow, James D. Womack, Curtis H. Shelton

Accepted for the Council:
Carolyn R. Hodges

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(Original signatures are on file with official student records.)

June 9, 1969

To the Graduate Council:

I am submitting herewith a thesis written by John William Branch, Jr., entitled "A Laboratory Investigation of Anaerobic Sludge Digestion for Dairy Manure." I recommend that it be accepted for nine quarter hours of credit in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering.

John I Sewell
Major Professor

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A LABORATORY INVESTIGATION OF ANAEROBIC SLUDGE DIGESTION FOR DAIRY MANURE

A Thesis
Presented to
the Graduate Council of
The University of Tennessee

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
John William Branch, Jr.
August 1969

ACKNOWLEDGMENTS

The author is deeply indebted to his major professor, Dr. John I. Sewell, and the other members of his committee, Dr. John J. McDow, Professor James D. Womack, and Professor Curtis H. Shelton, for their invaluable assistance in the preparation of this thesis.

The author is also deeply indebted to Dr. William A. Drewry for his excellent advice and help in the conduct of this study, and to Mr. William Johnson and Mr. Jodie Millward for their assistance in the fabrication of the experimental apparatus.

The author is especially indebted to his wife, Patricia, for her patience and encouragement throughout his graduate program.

ABSTRACT

An increasing trend toward total confinement of dairy herds as well as livestock being fed for marketing has resulted in farmers having large volumes of manure produced in small areas. The encroachment of suburbia into farming areas has added new problems to the burden of manure disposal. Efficient, economical methods of stabilizing large volumes of manure and rendering it free from odor while reducing its potential as a pollutant are necessary.

Anaerobic sludge digestion is one possible method of stabilizing manure and eliminating odor with a minimum of labor and with possible valuable by-products to help offset its cost. The purpose of this study was to design and build laboratory equipment with which to investigate anaerobic sludge digestion of dairy manure, and to investigate the effects of sludge mixing on reduction of total volume, total solids, volatile solids and on gas production.

The laboratory equipment was built and was operated continuously for three months. The data collected indicated that continuously mixed digesters were considerably more effective than unmixed or partially mixed digesters. Increasing the speed of mixing had little effect on total or volatile solids content of the settled sludge. Increased mixing speed significantly increased the total and volatile solids content of the supernatant. An optimum mixing speed for maximum gas production was observed, above or below which gas production decreased.

The author concluded that anaerobic sludge digesters may play an important role in agricultural waste disposal and that gas mixing should be preferred to mechanical mixing.

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CHAPTER I

INTRODUCTION

The Problem

Waste disposal and pollution control are beginning to receive the attention and respect that they have long deserved. Man is rapidly and painfully becoming aware of the results of his disregard for the condition of his environment. The spread of pollution-borne diseases, rapid deterioration of water quality, and frequent occurrences of nuisance causing odors and sights serve to remind the public that, in many instances, nature has been pushed beyond her capacity to quickly dispose of wastes.

Agriculture is one of many industries faced with the problem of waste disposal. Because of the competition for land demanded by urban expansion and transportation, the farmer has been forced to produce more crops and livestock from fewer acres. With more people moving into farm areas, the farmer is becoming more cautious that his operations do not offend his neighbors by sight or odor. A number of cases have been reported where farmers have been forced out of business or to great expense because of lawsuits successfully brought against them by neighbors who were offended by the sight or odor of animal wastes (1,2).

The high cost of labor required to spread manure on fields makes spreading no longer economically feasible. Approximately 2,000,000 tons of manure are produced in the United States each year (3). Each of the

14,662,000 dairy cattle kept for milking purposes in 1968 (4) produced an average of 72 pounds of manure per day (5). This means that every day dairymen in the United States accumulate over 1,000,000 pounds of manure. With such large volumes involved, spreading on the land would require tremendous expenditures in time and money.

Spreading does not eliminate the problem. Once it is on the field, manure requires time to decompose. Prior to its decomposition it has ample opportunity to pollute streams and water supplies by being washed into them during rainstorms. In Kansas, during 1964, it was determined that 15 of 27 major fish-kills were caused by runoff carrying manure into streams (6). The manure produced from a 1000-pound cow has approximately five times as much biochemical oxygen demand (BOD), eighteen times as much total dry solids, and five times as much nitrogen as the wastes from one human (3). These characteristics of high polutional strength greatly increase the waste load placed on the environment.

Compounding the problem is the fact that the cost-price squeeze has forced livestock producers to concentrate large numbers of animals on small areas of concrete in order to reduce labor and operating costs. More than one-half of our laying hens and broilers are now produced in confinement. Most units can handle up to 100,000 birds, and some have over 1,000,000 birds per operation (3). Dairy herds are often confined to small areas, and 200- to 400-cow herds are not uncommon. Feedlots with capacities for 10,000 cattle occur frequently in the West (3).

In these highly concentrated operations, manure disposal becomes an even greater problem.

The value of the manure to the land does not make up for the cost of spreading or the potential for stream pollution. One ton of average manure has approximately the same amount of plant nutrients available as 100 pounds of 10-5-10 commercial fertilizer which can be bought for about $2.50 (7). Manure does have the advantage of adding organic matter to the soil and increasing soil tilth, but one ton of manure requires more labor to spread than does the 100 pounds of commercial fertilizer.

Methods of Disposal

Land spreading. To reduce labor requirements for spreading manure on the land, many operators have installed liquid manure systems. This involves scraping or flushing the manure into a concrete storage tank which has sufficient capacity to hold 30 to 90 days accumulation of manure. When the tank is full, the contents are agitated until they form a slurry which is then pumped into a trailer-mounted tank for field spreading. Labor is thus reduced to a few days per year, and it can be scheduled to coincide with slack periods in the farm operation. Although some decomposition occurs in the pit, the manure may be considered raw when it is spread; thus, the pollution potential is not appreciably reduced.

Natural treatment. Lagoons have been used extensively for manure disposal for several years. Manure and water are pumped into a large pit where the bacteria which are naturally present in the manure decompose it. Lagoons are considered aerobic when they are shallow (up to five feet deep) and lightly loaded so that the dissolved oxygen content of the liquid is high enough to support aerobic bacteria. When the lagoons are built deeper (eight to ten feet) and loaded more heavily, the oxygen is consumed faster than it can diffuse into the liquid from the air so that anaerobic bacteria must accomplish the organic matter reduction. When the upper layer of the lagoon is aerobic and the lower layer is anaerobic, the lagoon is termed facultative. If the lagoon is anaerobic from top to bottom, it is termed anaerobic.

Aerobic lagoons are often preferred because they usually do not have foul odors and the floating scum layer which are characteristic of anaerobic lagoons. In order to maintain an adequate oxygen concentration for the aerobic bacteria it is necessary to provide a large surface area for diffusion of air into the liquid. This requirement for a large surface area is the primary disadvantage of aerobic lagoons. Twenty acres of land would be required for an aerobic lagoon for treatment of manure from a 1000-head cattle feedlot (3). In addition to the hydraulic problems of attempting to distribute 36 tons of manure per day (5) over 20 acres, few farmers can afford to invest that much land in manure disposal. In dry areas, the water loss by evaporation from a 20-acre pond would be an added burden. The wastes must be kept covered with water for an optimum bacterial environment.

Concentrated treatment. The bacterial reduction of organic matter is a natural phenomenon. Man, with his high concentrations of wastes in limited areas, has found it necessary to speed up the natural process. This is done by determining the optimum environmental requirements for the bacteria and then providing the most suitable environment for their growth. Sanitary engineers are directly concerned with the development and maintenance of such an environment for waste disposal. Many of their methods have been adapted to agricultural use.

Several variations of the activated sludge process have been successful in stabilizing manure. Extended aeration systems consist of a reinforced concrete pit into which the manure and water are pumped and facilities for forcing air into the wastes to provide oxygen for aerobic digestion. Several types of fixed-in-place or floating aerators are available. These are usually large rotors which are driven by an axially connected electric motor. The rotors turn in a plane which is parallel to the liquid surface and the blades extend into the liquid. The speed of rotation is high enough that the waste is forced into the air in a spray. This increases the oxygen content of the liquid and thus speeds aerobic digestion. The action of the rotor also provides mixing of the tank contents, which increases exposure of the bacteria to the substrate.

The oxidation ditch also operates on the principle of aerobic digestion. It consists of a shallow ditch laid out in an oval shape. One or more multi-bladed paddle wheels are installed transversely across the ditch with the axle just above the liquid surface. When the paddle wheels rotate, they cause the slurry to flow around the oval ditch, thus increasing exposure to the air. The action of the rotating paddle wheel also adds oxygen to the wastes.

The power consumption by the electric motors required is one disadvantage of aerated systems. Using oxygen requirements and transfer rates presented by Taiganides (8), approximately 6300 kilowatt-hours of electricity per month would be necessary for a system using floating aerators to treat wastes from a 200-head dairy herd.

The use of anaerobic systems for manure stabilization has not been as widespread as has the use of aerobic systems, even though anaerobic sludge digestion is the most commonly used method of solids stabilization in cities (9). Anaerobic systems are built so as to exclude or minimize contact with the atmosphere. The common septic tank is an example of an anaerobic system. Johnson (10) has reported success in using large septic tanks for poultry manure.

Anaerobic sludge digesters are large, cylindrical, reinforced concrete tanks into which the waste material is pumped. The tanks are covered with a fixed or floating cover which seals them and prevents exposure to oxygen. The tanks are heated to about 35°C and agitated so as to provide maximum exposure of the bacteria to the substrate and to reduce concentrations of toxic materials. The bacteria digest the organic matter, with large quantities of methane and carbon dioxide being given off as the end products of digestion.

The major disadvantage of anaerobic digestion is that the bacteria which produce the gas are very sensitive to environmental changes. If they are inhibited for some reason, digestion rate decreases rapidly. Another disadvantage is the cost of the system. Taiganides (11) estimates the cost for a system to treat the wastes from a 3000-hog per year feeding operation to be approximately $10,000 and the cost per pound of meat marketed as 0.13¢.

In all of the above-mentioned systems some sludge build up occurs, and the digesters must be cleaned out periodically. In adequately designed lagoons, this period might be a number of years. In the aerated systems, cleanout may be required every few months. The anaerobic systems are flow-through processes where sludge is continually discharged. The sludge removed from these systems is generally innocuous and does not cause odor and fly problems when spread on the land. Dried sludge from municipal anaerobic digesters is frequently sold to organic gardeners for use as a soil tilth improving additive. The sludge from these systems retains much of the original plant nutrients which were in the manure (12).

Because anaerobic sludge digestion is the most often used method for biological stabilization of organic matter, and because it has considerable potential for producing valuable by-products, this study was designed to further investigate the potential of anaerobic sludge digestion for manure stabilization.

CHAPTER II

THEORY OF ANAEROBIC SLUDGE DIGESTION

Sanitary Application

Anaerobic sludge digestion has long been used by municipalities for stabilization of solids. The principles of operation are basically the same regardless of the substrate. The primary difference between manure and sewage as substrates is the solids content. Manure is normally about 15 percent solids. Sewage is less than 0.5 percent solids. As compared to other industrial wastes, manure may be considered a better substrate because of the abundant supply of the nutrients needed by the bacteria.

Digesters are used to decompose the solids which have been removed from the liquid portion of the sewage by other sanitary processes. The sludge from the digesters is usually dried by some means and sold or dumped in a sanitary landfill. It may be used in land reclamation projects. The principles and theory of operation of the process as used in sanitary applications can be applied to the digestion of manure or other agricultural wastes.

Microbes Involved

Anaerobic sludge digestion occurs in two steps. A different group of anaerobic bacteria is responsible for each step. The first group are commonly called "acid formers" and are facultative anaerobes. These bacteria do not stabilize the solids. They change the carbohydrates, proteins, and fats into simple fatty acids which must be further stabilized. The second group of bacteria are obligate anaerobes, referred to as "methane formers," which attack the simple acids and reduce them to gaseous end products. The gas is primarily methane and carbon dioxide with small amounts of hydrogen sulfide and ammonia included, depending on the composition of the substrate. Although the methane has a high energy content, it is easily removed from the system and reduced to carbon dioxide and water by burning with oxygen.

The high energy content of the methane indicates that the anaerobic bacteria obtain less energy from the substrate than do the aerobic bacteria. Thus anaerobic bacteria must consume more of the substrate for energy than would an equal number of aerobic bacteria. Based on this comparison, anaerobic bacteria are often considered more efficient than aerobic bacteria for waste stabilization (13).

The lack of knowledge of how to maintain an optimum anaerobic environment at high loading rates causes most sanitary applications to use low feed rates for continuous operations. This forces the bacteria to operate in the endogenous metabolic zone with a small population. As a result, the small population is extremely sensitive to sudden changes in environmental conditions such as temperature, feeding rate, and concentration of toxic materials.

Metabolic Reactions

Acid formers. The substrate must be soluble for use by the microbes. Thus the first step is the liquefaction of the solid material which is done by extracellular enzymes. The ability of the anaerobes to use the substrate as both their oxygen donor and hydrogen acceptor differentiates them from the aerobes which must have a supply of dissolved oxygen. Carbohydrates such as starch and cellulose are first converted into hexoses and glycerol. Fats and oils are converted into glycerol and simple fatty acids. The hexoses, glycerol, and fatty acids are converted into pyruvic acid and then into the simple acids such as acetic, formic, butyric, and propionic. Long-chain fatty acids are not affected by the acid formers because of lack of an adequate hydrogen acceptor (13). Proteins are first reduced to amino acids which may go through the pyruvic acid cycle and then be converted into the simple acids, or they may be deaminated into fatty acids.

Methane formers. The methane formers act on the simple acids and convert them into methane and carbon dioxide. Acetic acid is the most important of the simple acids because approximately 70 percent of the methane produced comes from the direct cleavage of the acetic acid molecule into methane and carbon dioxide. The rest of the methane produced comes from the reduction of carbon dioxide. McCarty (14) gives the following reactions for methane production:

1. Acetic acid cleavage: $CH_3COOH \rightarrow CH_4 + CO_2$

2. Carbon dioxide reduction: $CO_2 + 8H \rightarrow CH_4 + 2H_2O$

The ability of methane bacteria to use carbon dioxide as a hydrogen acceptor, as indicated in the reaction for carbon dioxide reduction noted above, is unique in microbiology (13).

Long-chain fatty acids are metabolized by the Beta oxidation cycle (13). Molecules which have an even number of carbon atoms are first converted to acetate and then into acetic acid. Molecules with an odd number of carbon atoms are converted into two-carbon molecules of acetate until a single-carbon fragment remains. This last fragment is hydrolized to formic acid and then oxidized to carbon dioxide and water.

Environmental Requirements

The first requirement for an anaerobic environment is the exclusive of oxygen or air. Small amounts of oxygen have an inhibitory effect on the methanogenic bacteria, and the addition of oxygen to an atmosphere which has a high methane content would create a potential safety hazard. The methane is collected and stored. It may provide a source of fuel for heating the digesters or for power requirements of the system.

Temperature is one of the most important environmental variables to control from a standpoint of digestion rate. It is usually stated that "the rate of microbial growth doubles with each 10°C increase in temperature" (13). Microbial growth is not the ultimate objective in organic waste disposal; however, the rate of growth is determined by the rate of substrate metabolism or solids stabilization. Two temperature ranges have been used for sewage digestion. The mesophillic zone is most frequently used and has a range of 29-40°C. The thermophillic zone has a range of 50-57°C. While the thermophiles stabilize organic matter at a much higher rate than do the mesophiles, the physical problems of maintaining a constant temperature in the thermophillic range have generally discouraged its use.

While the bacteria can adapt to slowly changing temperatures, they are inhibited by sudden changes of only a few degrees. The optimum range for stabilization must be determined for each waste. Once this range is selected, caution must be exercised to hold the temperature constant.

Another very important consideration in maintaining the proper digester environment is the mixing of the digester contents. Mixing accomplishes several important functions. Bacteria must be in contact with the substrate for metabolism to take place because its feed must diffuse through the cell walls. Mixing insures maximum exposure of the organisms to the substrate. This is particularly important in anaerobic digesters because of the small bacterial population present.

By moving the bacteria and substrate throughout the entire tank, mixing serves to increase the effective size of the tank. Without mixing, some solids would settle while others would float to the top, forming a scum layer or crust which would decrease the effective volume of the digester. Mixing also serves to dilute toxic materials which may be introduced in the feed by reducing localized concentrations and spreading the material throughout the tank.

Mixing is usually accomplished by rotating devices inside the digester or by recirculation of digester gas through the digester contents. Gas recirculation is more popular because of the increased rate of agitation available and because of reduced maintenance requirements. Most digesters are under-agitated. McKinney (13) states that commercially available equipment is "not capable of furnishing the type of mixing required for rapid digestion."

Digester Control

Detention time. Detention time can be defined as the ratio of effective digester volume to daily discharge volume. It is the most important design criterion in determining both the amount of reduction of the volatile content of the wastes and the required size of the digester. Detention time ranges from 6-60 days for high-rate digesters. Optimum detention time appears to be about 30 days. Efficiency of operation becomes marginal when detention time is increased above 30 days (15).

Feed rate. Feed rate and detention time determine the amount of solids stabilization which will be effected in the digester. Feed rate is usually given in pounds of volatile solids added per day per cubic foot of digester volume (lb VS/day cu ft). Loading rates for high-rate digesters range from 0.1-0.4 lb VS/day cu ft. At lower feed rates, volatile solids reduction is more complete because the bacteria are operating further into the endogenous zone. At higher feed rates, volatile solids reduction begins to decrease as exposure of the bacteria to the substrate decreases.

Volatile acids. Total volatile acids (TVA) is a measure of the amount of organic acids present in the digester. It is usually expressed in milligrams per liter (mg/l) as acetic acid. Organic acids produced by the acid-forming bacteria are normally present in the digester at levels of 500-2000 mg/l. If the methane bacteria are operating effectively, the TVA concentration will remain fairly constant. However, if some environmental condition inhibits the methane bacteria so that they cannot convert the acids into methane and carbon dioxide as rapidly as the acid-formers produce the acid, then the acid content of the digester will increase. Thus TVA is a good indicator of digester conditions. It has been demonstrated by McCarty and Brosseau (16) that high concentrations of TVA are not the cause, but the result of digester imbalance.

Alkalinity. Alkalinity is primarily a measure of the bicarbonate content of the digester, and it is reported as mg/l $CaCO_3$. Alkalinity normally exists in one or two of three possible forms. Hydroxide and carbonate alkalinity do not exist at the normal digester pH. Thus total alkalinity in a digester usually exists as bicarbonate (HCO_3^-) alkalinity. Sawyer and McCarty (17) presented the following equations to illustrate the interrelationship between carbon dioxide (CO_2) concentration and bicarbonate alkalinity (BA):

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightleftharpoons HCO_3^- + H^+ .$$

From the above it can be seen that the relationship between the CO_2 content of the system and the BA is closely related to the hydrogen ion $[H^+]$ concentration,

At low loading rates, the BA is approximately equal to the total alkalinity (TA). As the loading rate increases, the volatile acids increase, and some of the BA is required to neutralize the excess acids, which increases the CO_2 content. The following equation represents this reaction:

$$R—COOH + HCO_3^- \rightarrow R—COO^- + H_2O + CO_2 .$$

The ionized acid combines with the cation from the HCO_3^- to form an acid salt which no longer enters into the reaction. The acid salt is measured as part of TA. In order to determine the amount of buffer ability remaining in the form of BA, subtracting the volatile acids alkalinity from the TA is necessary. Because alkalinity is given as calcium carbonate and the acids as acetic acid, it is necessary to include a factor of 0.833 in the equation. This is the ratio of the equivalent weight of the calcium carbonate to the equivalent weight of acetic acid. McCarty (18) states that an added factor of 0.85 should be included since the determination of TA (19) only measures 85 percent of the volatile acid alkalinity. Inclusion of these two factors gives the following equation for determination of the buffering capacity of the system:

$$BA = TA - (0.85)(0.833)TVA .$$

Hydrogen ion concentration. Hydrogen ion concentration determines pH, which normally ranges from 6.6 to 7.5 in digester operation. Control of pH is essential because the methane bacteria are seriously inhibited at pH values above or below the range of 6.6 to 7.4. The hydrogen ion concentration $[H^+]$ of the system is controlled by the relationship between the content of CO_2 in the digester gas and the concentration of BA in solution. McCarty (18) indicates that the content of CO_2 in the digester gas is a function of the carbonic acid (H_2CO_3) concentration and the ionization constant for H_2CO_3 (K_1), and that this concentration determines $[H^+]$ by the following equilibrium equation:

$$[H^+] = K_1 \frac{(H_2CO_3)}{(HCO_3^-)} .$$

Thus for an increasing CO_2 content, adding BA to the system to maintain the pH at a desired point becomes necessary. Conversely, if the BA reaches too high a level without a corresponding increase in the CO_2 content of the digester gas, the pH will increase to a point where the methane bacteria will be inhibited. If the resultant increase in volatile acids does not lower the pH sufficiently, it may be necessary to add an inorganic acid such as hydrochloric acid (HCl) to lower the pH. Albertson (20) found that ammonium bicarbonate (NH_4HCO_3) alkalinity could reach very high levels when nitrogenous wastes were fed into a digester at high loading rates. The high alkalinity content drove the pH high enough to inhibit the methane bacteria. Addition of HCl neutralized the excess alkalinity and allowed recovery. The reaction may be represented as:

$$NH_4HCO_3 + HCl \rightarrow NH_4Cl + H_2CO_3 \rightleftharpoons CO_2 + H_2O \; .$$

The most common additive for increasing pH is slaked lime ($Ca(OH)_2$). Caution must be exercised when adding lime because it combines with the CO_2 in the digester gas to form BA which goes into solution. This removal of a portion of the digester gas volume may create a partial vacuum which could draw in air and create a hazardous condition. Lime should be added when the pH is between 6.4 and 6.7. If lime is added when the pH is above 6.7, insoluble calcium carbonate ($CaCO_3$) is formed which does not contribute to the BA and precipitates out of solution.

Although control of pH is essential to proper digester performance, it is not a good indicator of the balance between TVA and TA in the system. With increasing TVA in relation to TA, the pH will decrease very slowly until the buffer ability of the BA is reduced. When this occurs, the pH will drop sharply; but by this time it may be too late to do anything to prevent digester failure.

Gas analysis. Total gas production from digesters is erratic, varying by 10 percent to 50 percent on a daily basis (21). However, if a continual plot of gas production against time is maintained, any long-range decrease in gas production can be observed. Such a long-range decrease would indicate some stress in the system. A more reliable estimate of digester performance is the methane content of the gas. When the methane bacteria are inhibited, the methane content of the gas will decrease. This may not be detected from observation of the total gas production because of its erratic behavior.

Toxic Materials

Heavy metals such as copper, nickel, zinc, or cadmium in waste feed are toxic to the methane bacteria. Sulfides and the cations of ammonium, potassium, sodium, magnesium, and calcium salts are also toxic at certain concentrations. At low concentrations some of these substances are stimulatory. Sodium is stimulatory up to concentrations of 200 mg/l, inhibitory up to 5500 mg/l, and toxic at 8000 mg/l (22). Toxicity of materials varies with pH. At low pH, the ammonium ion concentration is toxic. When the pH increases to 7.4 or higher, the ammonia gas concentration becomes toxic (20).

Toxicity control can be accomplished by several methods. The simplest method is to remove the toxic material from the feed. The toxic effect can also be reduced by dilution. The effect of some toxic materials can be removed by addition of substances which react with the toxic material to reduce its effect or to precipitate it out of solution. McCarty (22) reports that some cations appear to be antagonistic to others, thereby reducing the effect of their toxicity. He reports that the addition of 300 mg/l of potassium has reduced the toxicity of 7000 mg/l of sodium by 80 percent, and that the further addition of 150 mg/l of calcium may completely eliminate the toxicity. Sulfides, which are quite toxic to the anaerobic system when introduced by themselves, may be added to a system which is suffering from heavy metal toxicity. The sulfides will cause the heavy metals to precipitate out of solution, thus removing the toxicity.

Process Variations

Conventional process. Most digesters in use today are concrete tanks with floating or fixed tops. They are usually agitated by gas recirculation and heated to the mesophillic range. Loading rates range from 0.1 to 0.4 lb VS/day cu ft, and detention times vary from 6 to 30 days. The digester may be completely mixed with a secondary digester for sedimentation, or sedimentation may occur in the lower part of the primary digester. Supernatant is frequently recirculated because it has a high volatile solids content.

Contact systems. When input feed is less than one percent solids, digester efficiency is very low because of the low loading rate. In order to increase solids retention time without requiring a larger volume for the digester, the effluent is allowed to settle, and the solids are recycled through the digester. This increases solids retention time without increasing liquid detention time. It also reduces the loss of bacteria which flow out with the effluent. The sedimentation tank is usually preceded by a vacuum degassifier which removes gas from the effluent. Without this intermediate step, the gassified solids would float to the top of the sedimentation tank and be discharged with the supernatant. Liquid retention time may be as low as one to six days, and the solids retention time may be two to four times that, depending upon the recycle ratio (23).

CHAPTER III

REVIEW OF LITERATURE

Physical Properties of Dairy Manure

Loehr (3) has summarized the results of a number of investigators who were studying various aspects of manure disposal. Reports included in his summary give manure production as 73 to 143 pounds per cow per day, moisture content as 79 percent to 87.5 percent, volatile solids as 80 percent to 84 percent of total dry solids, and density as 62 pounds per cubic foot. Webster _et al._ (5) reported, from the work of several earlier investigators, average values of manure production as 72 pounds per day, moisture content as 86.8 percent, and volatile solids content as 80.6 percent of total dry solids. Webster estimated that 40.6 gallons of manure slurry per cow would be produced in a flush system of twice-daily cleaning. The slurry would contain 9.56 pounds of dry matter which would indicate a moisture content of 97.17 percent or a total solids content of 2.83 percent. Taiganides (24) separately reported manure production of 71 pounds per cow per day at a moisture content of 84 percent and a volatile solids content of 71 percent of total dry solids.

Loehr (3) reported BOD/COD ratios of 0.08 to 0.23. Definitions and explanations of tests are given in the Appendix. Hart (12) found BOD/COD ratios of 0.098. Jex (25) summarized a number of reported

BOD/COD ratios and found an average value of 0.161. Jex studied cattle feedlot wastes and found that the nitrogenous stage in BOD tests appeared to start at about three days and represented 20 percent to 30 percent of the total demand at five days. He concluded that BOD as usually reported is of dubious value for characterizing animal wastes. He also found that feed ration has no significant effect on BOD.

Manure Digester Applications

Taiganides (26) reported on several thousand small digesters in use in India. They were cylindrical concrete tanks with floating metal gas collectors for covers. They were fed with the wastes from a few families and their cows, and they provided gas for cooking, lighting, and heating purposes. He reported that in Germany, after World War II, a number of large concrete manure digesters were built to provide a fuel supply. He indicated that one of the digesters was still operational, and that it provided gas for the cooking needs of several hundred persons. In addition, he reported a digester built to handle the manure from a 1000-head hog feeding operation in California. The gas production was used to power a gasoline engine and a war surplus generator which provided some electricity for the farm.

Fry (27) reported on a digester used for the disposal of the manure production from a 900-head hog feeding operation in South Africa. He indicated that the digester was operated successfully for six years.

Laboratory Studies

Jeffrey (21) used eight-liter jars which were heated to 35°C and batch-fed to study anaerobic digestion of several types of manure. He used a sludge volume of five liters without agitation. Volatile solids loading rates of 0.15 to 0.218 lb/day cu ft were used at a detention time of 16.6 days. Average gas production was 2.07 to 3.05 cu ft/lb VS added. Carbon dioxide content of the gas was 35 percent and a volatile solids reduction rate of 50 percent was effected. Jeffrey concluded that higher loading rates were feasible.

Hart (12) used 3.8-liter bottles with 3.41 liters of sludge on a twice-weekly feeding schedule to study the effects of loading rate and temperature on rate of manure stabilization. The bottles were mixed twice daily by shaking. A detention time of 25 days was maintained, and loading rates of 0.132 to 0.215 lb VS/day cu ft were used. One-half of the digesters were run at 23.4°C, and the other half were run at 35°C. Volatile solids reduction was found to be 10 percent to 16 percent and gas production was 0.13 to 0.34 cu ft/cu ft of digester capacity. The reduction rates at the higher temperature were greater. Hart concluded that dairy manure can be digested anaerobically, but that it would be impractical to do so because of the low reduction rate of organic matter.

Dalrymple and Proctor (28) conducted dairy manure stabilization studies at two loading rates and two detention times. They used 14-liter rectangular digesters which were filled with 10 liters of sludge and maintained at 35°C. Loading rates of 0.1 and 0.18 lb VS/day cu ft and detention times of 12 and 20 days were used. The digesters were fed once daily and mixed 15 minutes every two hours with a 3/4 in by 2 in propeller driven at 200 rpm. Proctor (29) suggests that continuous agitation was "far in excess" of requirements. Total solids reduction was 30 percent to 42 percent; volatile solids reduction was 37 percent to 53 percent. Gas production was 1.5 to 2.0 cu ft/lb VS destroyed. The gas was 75 percent to 80 percent methane, and the alkalinity ranged from 5000 to 7500 mg/l. Volatile acids ranged from 90 to 600 mg/l, giving a volatile acids to alkalinity ratio of 0.02 to 0.08. The shorter detention time digesters had a greater rate of volatile solids reduction. The pH for the digesters ranged from 7.4 to 7.55.

Johnson (10) reported use of a 50,000-gallon septic tank for disposal of the manure from 7000 chickens. The tank was divided into an anaerobic compartment with a 16-day detention time and an aerobic compartment also with a 16-day detention time. Overflow from the anaerobic tank flowed into the aerobic compartment, which used compressed air outlets in the bottom of the tank to aid aerobic stabilization. The supernatant from the aerobic tank was recirculated through the barn for flushing manure into the anaerobic tank. The owner calculated operating costs as $260 per year and the cost of the system at $700.

Webster and Clayton (5) investigated the use of two aerobic-anaerobic dairy manure treatment systems. The first involved a 750-gallon primary anaerobic settling tank followed by a 500-gallon secondary aeration tank. The second system included a 1000-gallon primary aeration tank followed by a 300-gallon secondary settling tank. Both systems were loaded at a rate of 0.044 lb VS/day cu ft. The first system was more effective than the second, and it was concluded that the addition of a secondary settling tank after the aeration tank would improve the quality of the effluent.

Agnew and Loehr (6) tested anaerobic sludge digestion of beef cattle feedlot wastes in the laboratory. They used mixed and heated digesters at 10-days detention time and loading rates of 0.1 to 0.4 lb total solids/day cu ft. At the lower loading rates, they found 42 percent to 55 percent total solids reduction. For the higher loading rates, they found total solids reductions of 31 percent to 36 percent. Considering that the higher loading rates were four times as great as the lower rates, almost twice as much total solids was reduced at the higher loading rates. Gas production in cu ft/lb VS added ranged from 8.7 to 11.9.

Agnew and Loehr also studied laboratory models of an anaerobic lagoon followed by an aeration tank. The lagoons were loaded at a rate of 0.1 lb total solids/day cu ft and maintained at room temperature. Loading rates were increased to 0.4 lb/day cu ft with no difficulties experienced. Odors from the lagoons were minimal, which could be expected as long as the lagoons were operating properly. A complete-mix activated-sludge system was fed the effluent from one of the lagoons. BOD, COD, and total nitrogen were reduced, but the effluent was turbid and the turbidity could not be removed by filtering. The authors concluded that a series of lagoons should be able to remove 97 percent of the BOD from feedlot run-off. The system proposed included a primary anaerobic lagoon with a 10-day detention time and loaded at a rate of 0.2 lb total solids/day cu ft, followed by an aeration unit with a five-day detention time, and then by a polishing unit with a five-day detention time.

CHAPTER IV

DESIGN OF THE EXPERIMENT

Objective

Although anaerobic sludge digestion is in common use, it is not very well understood (30). Because of the need in agriculture for more efficient and economical methods of stabilizing large quantities of strong waste material, this study was intended to investigate some of the characteristics of anaerobic sludge digestion as applied to animal wastes.

The substrate used was dairy manure. It was selected because it appears to be the most difficult to digest. Volatile solids reduction rates and gas production rates reported are low as compared with other manures and municipal sewage (3,5,12,21,28). If anaerobic sludge digestion proves effective for dairy manure, it should be even more effective for manure from other animals.

The laboratory apparatus was designed to provide the conditions used in high-rate digester designs. The temperature was maintained at 35°C. Facilities for gas collection and analysis as well as for continuous mixing and twice-daily feeding and sludge withdrawal were included. The size and number of the digesters were as large as practical in the laboratory.

Of the many variables that need to be investigated concerning the digestion of manure, only a few have been studied. The effects of loading rate and detention time have been studied at levels which correspond to current practices (5,12,21,28), and the effect of temperature has been studied in one case (12).

Only one brief reference (6) was found for a continuously-mixed system. No reference on the effect of levels of mixing on solids reduction rate and gas production rate was found. Because mixing plays such an important part in the performance of high-rate digesters, this study was designed to investigate the effect of varying degrees of mixing in a continuously-mixed system.

Thus the objective of this experiment was to design and build laboratory digesters which could be used to study the effects of continuous mixing at various levels on the anaerobic sludge digestion of dairy manure. The parameters used to measure digester effectiveness were total volume, total and volatile solids, and gas production. The Appendix gives an explanation of these tests.

Equipment Design

Twenty-liter glass bottles were used for digesters. A 14-liter sludge volume was maintained which represented a compromise between the greater reproducibility of data from a large sludge volume and the size restrictions imposed by laboratory conditions.

Figure 1 shows the experimental equipment. Figures 2 and 3 give details of the digesters. A 10-mm glass tube was inserted through the shoulder of the jar for feeding and extended two inches below the liquid level of the digester to minimize exposure to air during feeding. The

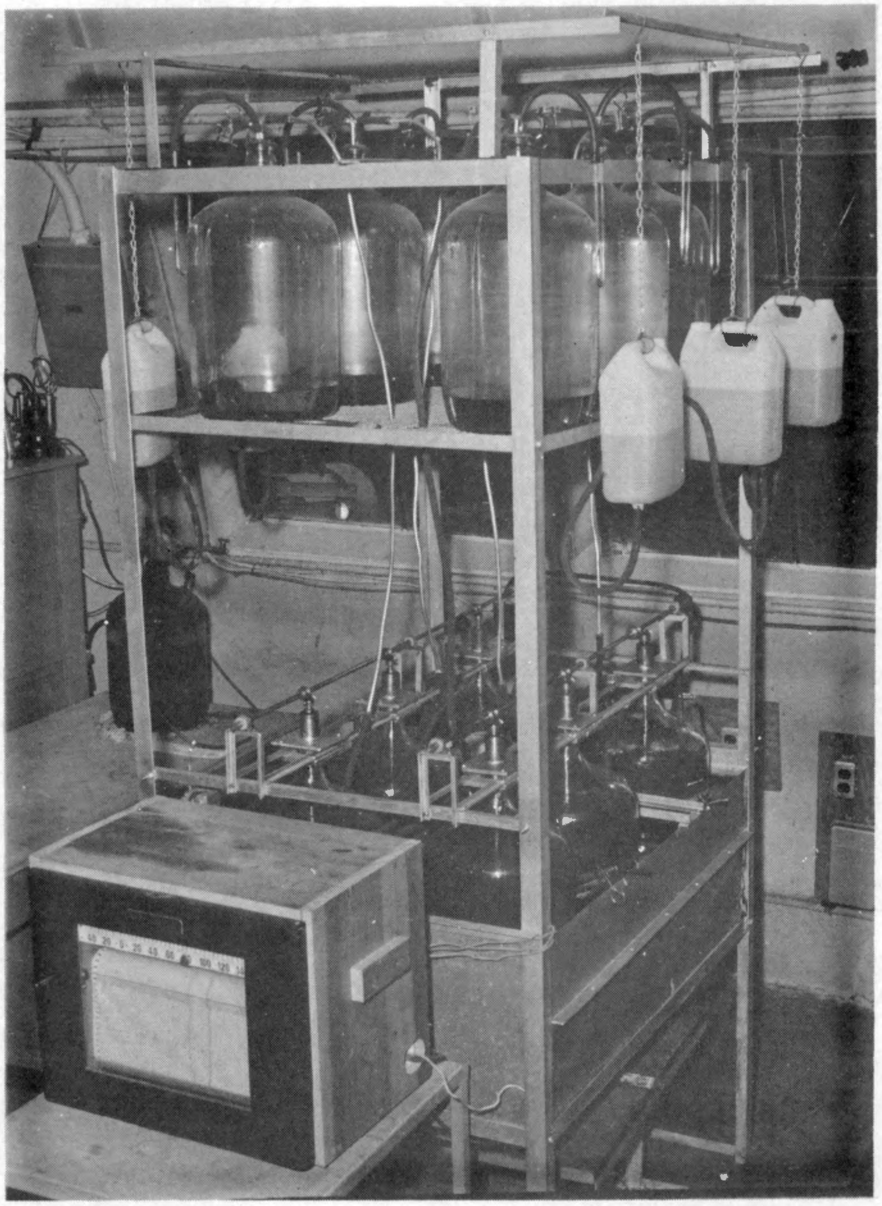

Figure 1

Experimental Equipment

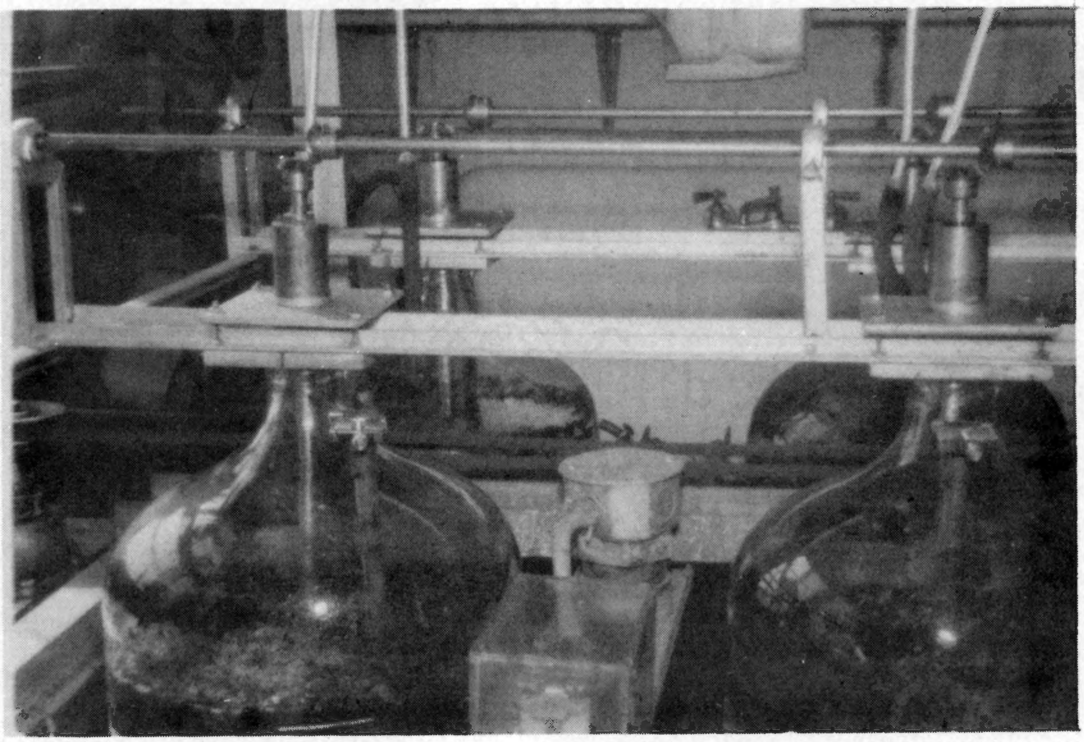

Figure 2

Arrangement of Digesters and Propeller Drive Train

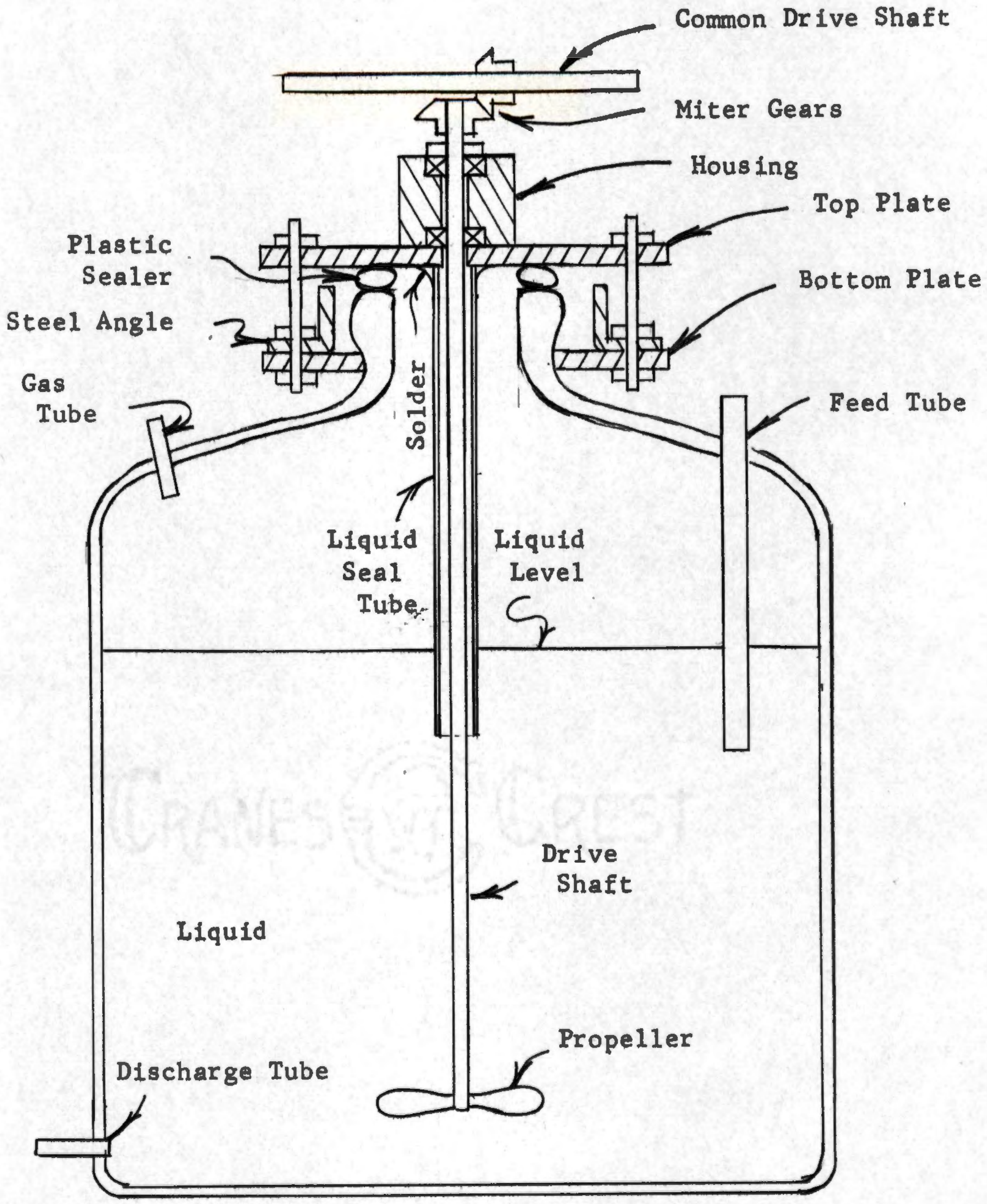

Figure 3

Diagram of Digester

tube was closed by means of a plastic tube and tubing clamp attached to the top end between feedings. On the opposite shoulder of the jar was inserted a 7-mm glass tube which served as a gas outlet to the gas collection jars located overhead. Discharge was effected via a 7-mm glass tube inserted in the bottom of the digester. An 18-in piece of rubber tubing was attached to the glass tube, and it carried the discharge to the outside of the water bath where the tubing could be closed with a tubing clamp when not in use.

The six digesters were arranged in two rows of three each and were supported three inches above the bottom of the water bath to allow for free circulation of the water under them. The water bath was a rectangular, galvanized, sheet metal tank of 60 gallons capacity. Temperature of the water bath was controlled by a thermostat which had a temperature range of ±1.8°F. The thermostat operated an 800-watt, immersion-type water heater element through a relay. The water heater was placed near the center of the water bath.

The water bath was stirred by two propellers located near the bottom of the tank. A 12-point recorder measured the temperature of the bath at several locations through copper-constantan thermocouples. The recorder also measured ambient air temperature. The recorder operated ten minutes of every hour.

Digester mixing was provided by a 3/4 in by 1-1/2 in propeller mounted 1 in above the bottom of the digester on a vertical drive shaft. All metallic components used in the digester were of stainless steel to reduce the possibility of heavy-metal toxicity.

Power was transmitted to the propeller drive shafts through miter gears mounted on an overhead shaft common to three digesters. The two overhead shafts were driven at selected speeds through a gear reducer and belt drives. A 1/8-hp, 1725 rpm motor provided the power for both the water bath and digester propellers. The motor was cooled by an auxiliary fan to insure continuous operation for the planned three-month duration of the experiment.

A liquid seal was used to exclude air from the digester contents. A 1/2-in diameter steel tube enclosed the propeller drive shaft and extended two inches below the digester liquid level. The top end of the tube was soldered to the steel top plate which was sealed to the top of the jar with a plastic compound. The drive shaft extended through the top plate and was mounted in a bearing housing which was fastened to the top plate.

A second steel plate was shaped to fit around the neck of the jar and was clamped to the top plate. The plates were rigidly fastened to two steel angles which were connected to the water bath frame.

Each digester was connected to a gas collection jar of 20-liter capacity. The jars had fittings for mercury manometers, gas wasting valves, and an outlet at the bottom which was connected to an aspirator bottle. Liquid displacement was used to measure gas production, and an acidified, saturated brine solution was used in the gas collectors to reduce absorption of methane and carbon dioxide. Figure 4 illustrates the gas collection system.

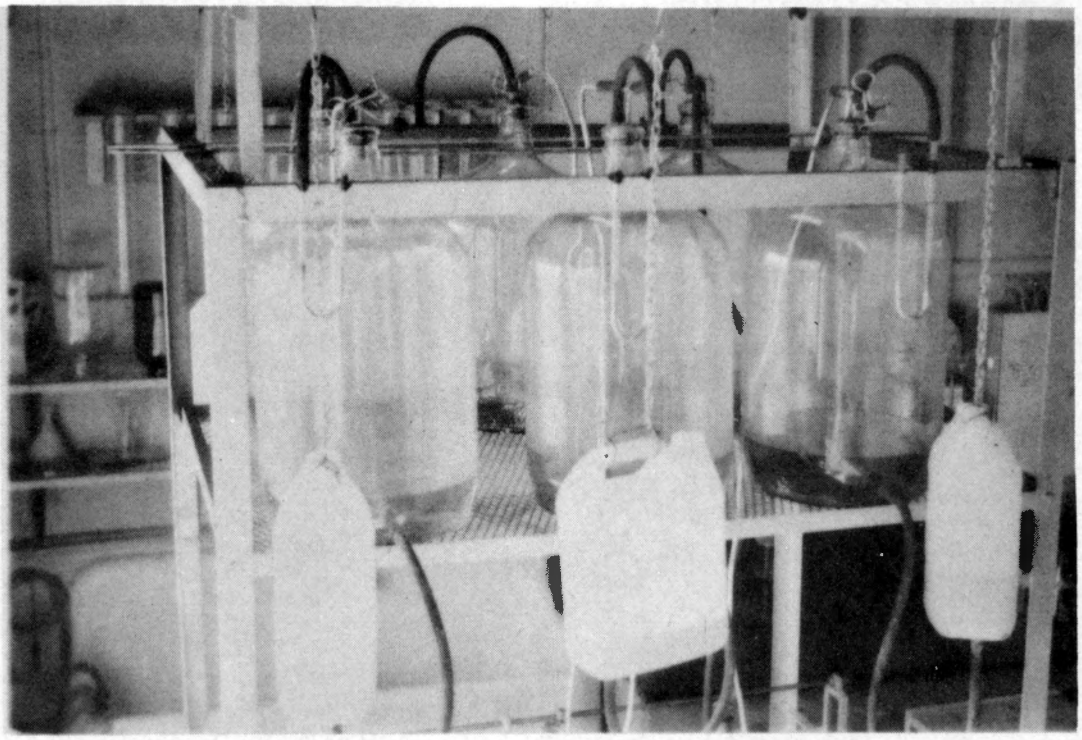

Figure 4

Gas Collection System

System Design

Additional laboratory apparatus was added to study settling properties of the digester effluent, aeration properties of the supernatant, and dewatering characteristics of the sludge. A 20-liter jar provided with a bottom discharge outlet was used for settling the effluent. A second 20-liter jar was used as an aerator for the supernatant. It was provided with a discharge outlet at the bottom of the jar and an air inlet four inches above the bottom. A drying bed was used to observe the dewatering characteristics of the settled sludge. It consisted of a rectangular box, 22 in by 32 in by 10 in, with a removable top and a wire screen bottom. The top was used during periods of rainfall.

Experimental Procedure

The feed rate and temperature were held constant throughout the test period. Five propeller speeds were used. All digesters were operated at 80 rpm for the first set of tests. Propeller speed was varied by changing the size of the pulleys on the common drive shafts and on the gear reducer. Since the pulleys on the drive shafts were not the same size, three of the digesters ran at one speed and three ran at a different speed. Speeds used were 80, 114, 176, 226, and 360 rpm. Each operating speed was maintained constant for a minimum of 15 days.

Tests were conducted for each speed. Total and volatile solids tests were used to measure reduction of organic matter, and total gas production was measured to indicate digestion rate. A gas column chromatograph was used to analyze the gas for methane content. Alkalinity and pH were also monitored. An explanation of applicable tests is given in the Appendix.

Digester Operation

The intent in operation of the digesters was to approach ideal conditions as closely as possible. The digesters were fed twice daily to approximate the optimum condition of continuous feeding. A feed rate of 500 ml per feeding or 1000 ml per day was used to give an apparent detention time of 14 days. The feed consisted of 89 gm of raw, fresh manure, 200 ml of aerator effluent, and enough tap water to give a 500-ml volume. This mixture provided a daily loading rate of approximately 0.1 lb VS/day cu ft. Use of the aerator effluent reduced water requirements and increased the effective solids content of the feed. It also provided some increase in digestion efficiency by providing recycle for the effluent supernatant. One important consideration was that aeration of the effluent supernatant raised its pH to 8.5 through combining oxygen with the carbon dioxide in the supernatant to form bicarbonate alkalinity. The increase in the pH of the feed may have helped maintain the pH of the digesters.

Manure was collected two or three times weekly from the loafing pen at The University of Tennessee Cherokee Dairy Farm. No effort was made to be selective in sampling other than to exclude straw and bedding. The samples were weighed and blended for each feeding.

Prior to feeding, the digesters were discharged to a premeasured level which indicated 13.5 liters. Since 0.5 liters were added with each feeding, the gross volume reduction could be observed. The aspirators were manipulated to apply pressure to the digester contents for discharge and to force liquid into the feed tube before feeding to minimize introduction of air bubbles with the feed.

Except for small amounts used for sampling, all of the aerator liquor was fed into the digesters, and all of the digester effluent went into the aerator or the drying bed. In this way an analysis of volume reduction at each stage could be made.

Digester Start-Up

The digesters were started by filling them with 15 liters of digesting sludge from the Fourth Creek Sewerage Treatment Plant in Knoxville. This plant was selected because it did not receive industrial wastes, was underloaded, and because the digesters were operating well. Manure was fed into the digesters at increasing rates until full feed was reached at six days. An equal amount of sludge was discharged at each feeding. Gas production and pH were monitored continuously. At 15 days, the effluent no longer had the odor or color of sewage sludge. At 40 days, gas production appeared to be good, and pH was steady at 7.0.

CHAPTER V

RESULTS

Performance of Equipment

Very few problems were experienced in the continuous operation of the laboratory equipment during the 100 days of the test. The only serious problem was the failure of the ball bearings used in the housing for the propeller shafts. After 60 days of operation the bearings on the sixth digester stopped turning. Efforts to free them failed, and at 70 days the digester was taken off feed. Apparently the corrosive nature of the digester liquid which was occasionally forced up through the liquid seal tube and into the bearings caused rusting and accelerated wear. The bearings in the first digester failed at 92 days for the same reason; but since the test was nearly concluded at that time, no serious consequences resulted.

The water-bath temperature was maintained between 94° and 96°F during the test. Temperature variation throughout the bath was less than 1°F. Ambient air temperature varied diurnally from 10° to 39°F below the water-bath temperature.

Total Volume, Total Solids, and Volatile Solids

Table I presents a summary of the characteristics of the feed to the digesters and the discharge at each stage on a per-feeding basis. The solids content of the feed was approximately 20 percent higher than

TABLE I

MEAN TOTAL AND VOLATILE SOLIDS FOR FEED AND DISCHARGE

Material	Total Solids Percent of Wet Weight	Volatile Solids Percent of Wet Weight
Feed[a]	3.47	2.59
Discharge		
Settled Sludge	3.84	2.69
Supernatant	1.08	0.59
Dried Sludge[b]	16.79	12.27

[a] Feed consisted of 89 gm raw manure, 200 ml aerator effluent and approximately 210 ml tap water.

[b] Dried sludge as taken from drying bed.

the solids content expected from a twice-daily manure-flush system (5). The solids content of the settled sludge was slightly higher than the solids content of the feed, and the solids content of the dried sludge was similar to that of raw manure,

Total volume reduction for the entire system was 87.8 percent. This is based on the 300-ml volume of raw manure and water fed into the system and the output of the drying bed. The values were determined for a total of 40 days operation, and the reduction represents the total volumetric reduction. Total and volatile solids reduction at the low and high speeds were:

	80 rpm	360 rpm
Total Solids	55.8 percent	49.3 percent
Volatile Solids	63.2 percent	69.4 percent

Table II presents mean values of total and volatile solids at each propeller speed. The Duncan multiple-range test was used to determine which means were significantly different. There was no significant difference at the 5 percent level in the sludge total solids content at any of the five propeller speeds. The mean value of the sludge volatile solids content for the 176-rpm propeller speed was significantly higher at the 5 percent level. There was a significant difference at the 5 percent level for every combination of three and four adjacent means of the supernatant total solids content. In addition there were significant differences at the 5 percent level for adjacent pairs of means at 80 and 114 rpm and at 176 and 226 rpm. For the supernatant volatile solids,

TABLE II

EFFECT OF PROPELLER SPEED ON TOTAL AND VOLATILE SOLIDS

Material	Propeller Speed (rpm) 80	114	176	226	360
Sludge					
Total Solids	3.50[a]	3.95	3.95	3.75	4.05
Volatile Solids	2.24	3.13	4.01	2.23	1.85
Supernatant					
Total Solids	0.75	1.00	1.05	1.25	1.35
Volatile Solids	0.44	0.39	0.67	0.69	0.77

[a] Percent solids of wet weight.

there was a significant difference at the 5 percent level for every possible combination of adjacent means except the adjacent means at 176 and 226 rpm.

Gas Production

Table III presents means of gas production for each digester and speed. Each mean was calculated from 15 observations of gas production over periods of 8-12 hours. No gas production is given for the sixth digester because of bearing failure as reported earlier. Results of the Duncan multiple-range test as used on the data in Table III indicate significant differences between successive means as noted.

Quadratic regression equations were developed for the regression of gas production on propeller speed. The resulting equations with data observations are plotted in Figure 5. The values plotted on the vertical scale are coded values of gas production, and they indicate magnitude rather than actual values of gas production. The regression equations were differentiated and set equal to zero in order to determine an optimum propeller speed. The equation developed for digesters 1, 2, and 3 operating at 80, 114, and 226 rpm is:

$$Y = 0.22 + 0.087\ X - 0.0003\ X^2$$

where

Y = (gas production in cu ft/day lb VS added) $\div$ 0.773

X = digester propeller speed in rpm.

TABLE III

EFFECT OF PROPELLER SPEED ON MEAN GAS PRODUCTION

Digester Number	Propeller Speed (rpm)				
	80	114	176	226	360
1	4.04[a]	4.80		3.93	
2	4.16	4.92[b]		3.13[c]	
3	4.15	4.62		3.55[c]	
4	4.01		4.65[b]		3.36[c]
5	3.52		4.99[c]		4.17[c]
6	3.57		4.82[c]		--[d]

[a] Units for gas production are cu ft/day lb VS added.

[b] Significantly different from the preceding mean at the 5 percent level.

[c] Significantly different from the preceding mean at the 1 percent level.

[d] No data because of bearing failure.

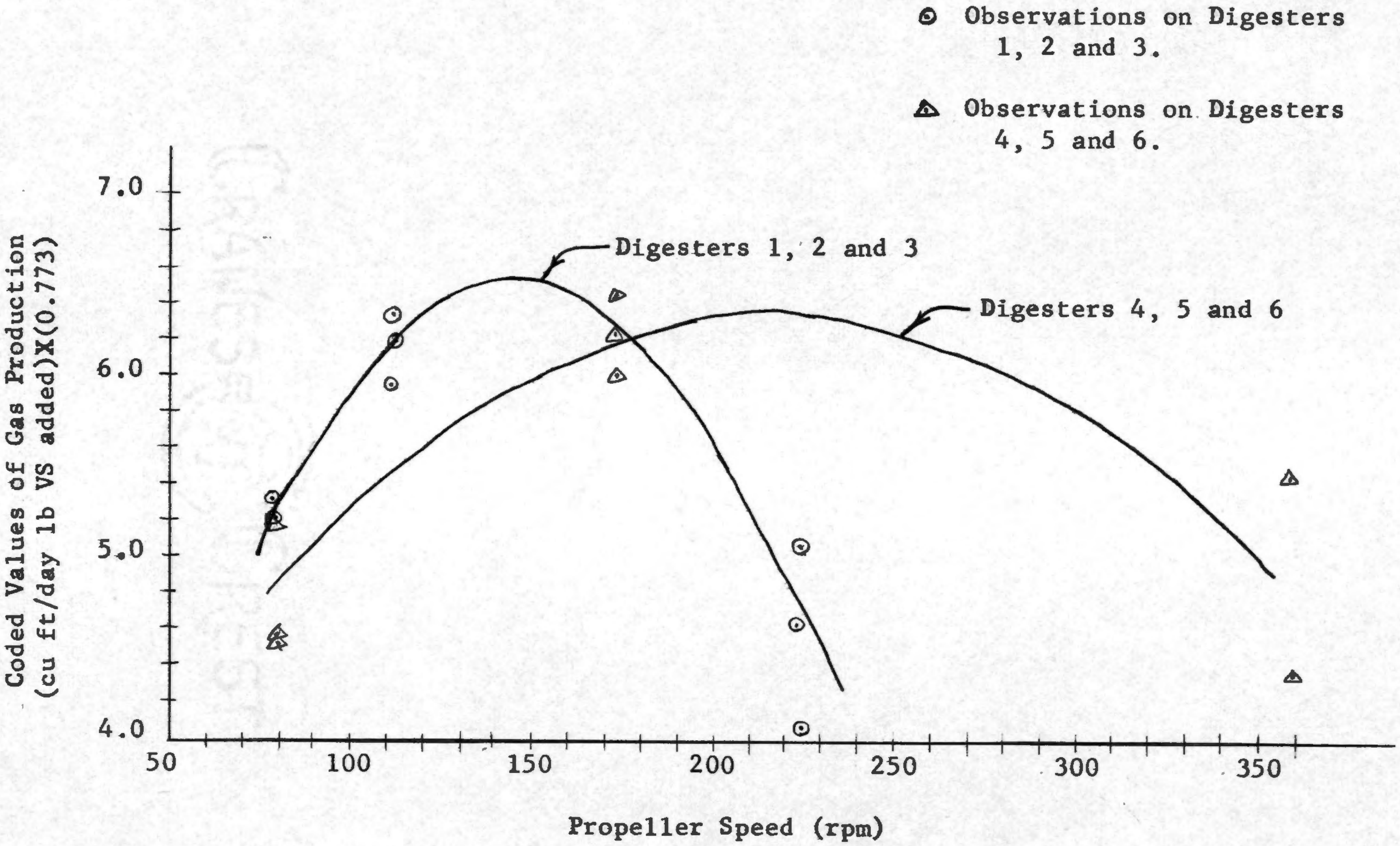

Figure 5

Regression of Gas Production on Propeller Speed

The equation developed for digesters 4 and 5 operating at 80, 176, and 360 rpm is:

$$Y = 2.64 + 0.034\ X - 0.000078\ X^2.$$

Indicated optimum digester propeller speed for the first equation is 145 rpm; and for the second equation it is 220 rpm.

System Observations

Samples of digester gas were analyzed on a gas column chromatograph. A standard gas mixture was not available with which to compare the results. However, for the same carrier gas flow rate and signal attenuation, the peak heights and locations as printed on the strip chart compared with those presented by Andrews (31) for digester gas with a methane content of 60 percent.

Measurements of alkalinity content of the digester effluent indicated an increase throughout the test period. Little vaiation was found between digesters. The average alkalinity at 30 days was 3000 mg/l and at 80 days was 3640 mg/l, which is a 21 percent increase. All digesters remained at pH 6.8 to 7.0 during the test. Aerator effluent pH ranged from 8.3 to 8.6.

A crust formed on the surface of the digester liquor within a few days after input of the seed sludge. The sludge built up to about one inch in thickness, and it remained throughout the experiment. Discharge of dry nitrogen under the crust destroyed it temporarily; however, it reformed in a few days.

Digester effluent settled in one hour so that the sludge occupied one-half of the total volume of a settling column. At four hours settling time, the sludge volume occupied 40 percent of the volume. Longer detention times did not improve the settling; and at eight hours, solids began floating to the top forming a scum layer. Increased settling time resulted in more solids floating to the top due to gassification.

Aerator effluent settled more slowly than did the digester effluent. The sludge occupied 25 percent of the settling column volume at 10-12 hours settling time. Little additional settling was noted after 10-12 hours. When the supernatant was decanted and settled for a longer period, no sedimentation was noted.

A layer of foam was continuously building up on the surface of the aerator liquor. The amount of foam appeared to increase directly with the amount of air being discharged beneath the surface.

CHAPTER VI

CONCLUSIONS

Effect of Mixing

Solids. Increasing the speed of rotation of the propeller appeared to have little effect upon the solids content of the settled sludge, but it did significantly increase the total and volatile solids content of the digester supernatant. The 49.25 percent to 55.8 percent total solids reduction found in this experiment was comparable with the 55.2 percent total solids reduction reported by Agnew and Loehr (6) for a continuously mixed system using beef cattle manure as substrate. The total solids reduction found in this experiment was 30 percent to 60 percent greater than that found by Dalrymple and Proctor (28) for a partially mixed system. The 60 percent to 70 percent volatile solids reduction found in this experiment was 30 percent to 100 percent greater than the reduction rates reported by Dalrymple and Proctor, and several hundred percent greater than the rates reported by Hart (12) for a partially mixed system.

Gas production. Gas production was significantly affected by the degree of mixing. The range observed between the two apparently optimum propeller speeds as obtained from the regression equations make them of questionable value. Little can be inferred from the results except that there apparently is an optimum value for propeller speed to obtain maximum gas production. The total gas production of 4 to 5 cu ft/lb VS added as found in this experiment was 60 percent to 100 percent greater than the values reported by Jeffrey (21), and several hundred percent greater than those values reported by Hart (12) for a partially mixed digester.

Anaerobic Sludge Digestion of Dairy Manure

Based on the results of this study, anaerobic sludge digestion appears to be feasible as a means of stabilizing dairy manure. The reduction of 88 percent in the volume of the water-manure slurry input to the system indicates substantial potential savings in handling costs, storage requirements, and stream pollution potential. The only odors observed during the entire experiment were from the gas being wasted and the fresh digester effluent. In a field system, these odors would not be noticeable in the opinion of the author.

From a standpoint of economic returns, sludge digestion offers as much as if not more than any other method of waste disposal. It is the only process which provides a source of fuel. The volume reduction effected is greater than that produced by other methods, and the sludge has fertilizer value as well.

Installation costs for a 15-day detention time digester would be less than for a 30-day covered liquid manure storage tank, or for a 60-day capacity aerated treatment system. Labor for monitoring system performance would probably be greater for the digester system. Some returns from excess gas production may be expected, particularly for manure from other than dairy cattle, due to the expected higher gas production rates.

In summary, anaerobic sludge digestion may be the best solution for the high-volume livestock producer who is located near urban areas without access to large open areas for spreading manure.

Recommendations for Further Study

Much work is required in many areas of manure disposal before firm design criteria can be established. Development of reliable tests for comparison studies is needed. Instrumentation to perform the tests is also needed. Optimum temperatures, detention times, and levels of agitation for gas recirculating systems must be determined. The upper limits of loading rates, ammonium bicarbonate concentration, and solids content of the digesters must also be determined.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Davis, Everett H. "Lawsuit Against a Dairy Operation by Urban Neighbors." American Society of Agricultural Engineers Paper No. 67-928, 1967.

2. Eby, Harry J. "Farm Wastes--A Legal, Psycho-Sociological Conundrum." American Society of Agricultural Engineers Paper No. 67-928-A, 1967.

3. Loehr, Raymond C. "Ahimal Wastes--A National Problem." Paper presented at the American Society of Civil Engineers Environmental Engineering Conference, Chattanooga, Tennessee, May, 1968.

4. U. S. Department of Agriculture. *Agricultural Statistics--1968*. Washington, D.C.: Government Printing Office, 1968.

5. Webster, N. W., and Clayton, J. T. "Operating Characteristics of Two Aerobic-Anaerobic Treatment Systems." *Management of Farm Animal Wastes*. American Society of Agricultural Engineers Publication No. SP-0366, 1966.

6. Agnew, R. W., and Loehr, R. C. "Cattle Manure Treatment Techniques." *Management of Farm Animal Wastes*. American Society of Agricultural Engineers Publication No. SP-0366, 1966.

7. U. S. Department of Agriculture. *Yearbook of Agriculture, 1957*. Washington, D.C.: Government Printing Office, 1957.

8. Taiganides, E. Paul. "Aeration of Animal Wastes." Paper presented at 1968 Farm Power Conference, Pittsburgh, Pennsylvania, August, 1968.

9. Water Pollution Control Federation. "Anaerobic Sludge Digestion." *Manual of Practice No. 16*. Washington, D.C.: Water Pollution Control Federation, 1967.

10. Johnson, Curtis A. "Septic Tanks Show Promise for Poultry Manure Disposal." *Electricity on the Farm*, 37:2, 14-16, 1964.

11. Taiganides, E. Paul. "Manure Gas Plants." *National Hog Farmer*, 8:5, 15-19, 1963.

12. Hart, Samuel A. "Digestion Tests of Livestock Wastes." *Journal Water Pollution Control Federation*, 35:6, 748-757, 1963.

13. McKinney, Ross E. Microbiology for Sanitary Engineers. New York: McGraw-Hill Book Co., Inc., 1962.

14. McCarty, Perry L. "Anaerobic Waste Treatment Fundamentals, Part I." Public Works, 95:9, 107-112, 1964.

15. Hindin, Ervin, and Dunstan, Gilbert H. "Effect of Detention Time on Anaerobic Digestion." Journal Water Pollution Control Federation, 32:9, 930-938, 1960.

16. McCarty, Perry L., and Brosseau, M. H. "Effect of High Concentrations of Individual Volatile Acids on Anaerobic Treatment." Proceedings of the 18th Industrial Wastes Conference, Purdue University, 1963.

17. Sawyer, Clair N., and McCarty, Perry L. Chemistry for Sanitary Engineers. New York: McGraw-Hill Book Co., Inc., 1967.

18. McCarty, Perry L. "Anaerobic Waste Treatment Fundamentals, Part II." Public Works, 95:10, 123-126, 1964.

19. American Public Health Association, Inc. Standard Methods for the Examination of Water and Wastewater. Twelfth Edition. New York: American Public Health Association, Inc., 1965.

20. Albertson, Orrid E. "Ammonia Nitrogen and the Anaerobic Environment." Journal Water Pollution Control Federation, 33:9, 978-995, 1961.

21. Jeffrey, Edgar A., Blackman, William C., and Ricketts, Ralph L. "Aerobic and Anaerobic Digestion Characteristics of Livestock Wastes." University of Missouri Engineering Experiment Station Bulletin No. 57, 1964.

22. McCarty, Perry L. "Anaerobic Waste Treatment Fundamentals, Part III." Public Works, 95:11, 91-94, 1964.

23. McCarty, Perry L. "Anaerobic Waste Treatment Fundamentals, Part IV." Public Works, 95:12, 95-99, 1964.

24. Taiganides, E. Paul, Bauman, E. Robert, and Hazen, Thamon E. "Sludge Digestion of Farm Animal Wastes." Compost Science, 4:2, 26-28, 1963.

25. Jex, Earl Morgan. "Cattle Feedlot Waste Characteristics." Unpublished Master's thesis, Colorado State University, Fort Collins, Colorado, January, 1969.

APPENDIX

EXPLANATION OF TESTS USED

Alkalinity. Total alkalinity (TA) is a measurement of the alkalinity content of the digester effluent. It is determined by titrating 50 ml of the effluent with 0.05N H_2SO_4 to the methyl orange end point (19). Alkalinity is expressed as mg/l $CaCO_3$.

Biochemical Oxygen Demand (BOD). BOD is a measure of the amount of oxygen required to biologically stabilize the organic matter found in one liter of the waste material. The oxygen content of a dilution of the waste material is determined by titration with 0.025N $Na_2S_2O_3 \cdot 5H_2O$ (19). The samples are then incubated at 20°C for five days at which time the dissolved oxygen content is again determined. The difference in dissolved oxygen content before and after incubation is reported in mg/l or parts per million (ppm) as oxygen.

Chemical Oxygen Demand (COD). COD is a measure of the amount of oxygen required to chemically oxidize the organic matter in the waste material. A portion of the waste is digested with heat by $K_2Cr_2O_7$ or $KMnO_4$ and titrated to determine the amount of oxygen consumed (19,32). COD is reported in mg/l or ppm as oxygen.

pH. pH is the negative reciprocal of the hydrogen ion concentration $[H^+]$. It is measured with a potentiometric indicating instrument and indicates the intensity of acidity or alkalinity rather than the amount of acidity or alkalinity. It may range between 0 and 14 for very acidic and very alkaline solutions respectively.

Total Solids. Total solids is the solids content of the waste on a wet basis. The waste is evaporated to dryness on a steam bath and dried at 103°C for one hour. Total solids are usually reported as percent of wet weight (32).

Volatile Acids. Total volatile acids (TVA) is a measure of the amount of organic acids present in the digester effluent. It is determined by separating the acids from the liquid phase of the sample in a silicic acid column and then removing them with a chloroform-butanol mixture. The separated acids are then titrated with 0.02N NaOH in methanol to determine their quantity which is reported in mg/l as acetic acid (19).

Volatile Solids. Volatile solids are determined by heating the residue from the total solids determination at 600°C for one hour. The residue is the ash content, and the loss in weight is usually reported as percent of total solids (32). Volatile solids represent the complete combustion of carbon from the organic matter as well as loss of minor quantities of inorganic salts and calcium carbonate. Thus volatile solids is the maximum amount of degradation that can take place.

VITA

John William Branch, Jr., was born in Brownsville, Tennessee, on September 8, 1941. He attended Dyersburg High School and graduated in 1959. In September of that year he enrolled in The University of Tennessee. He received the Bachelor of Science degree in Agricultural Engineering and was commissioned as a Second Lieutenant in the United States Army in 1964. After serving three and one-half years in the Army, he returned to The University of Tennessee where he expects to receive his Master of Science degree in Agricultural Engineering in August, 1969. He is a member of the American Society of Agricultural Engineers, Alpha Zeta and Gamma Sigma Delta.

He is married to the former Patricia Ann Craig of Ashland City, Tennessee.