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Characteristics and treatment of wastes from a confinement hog production unit

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CHARACTERISTICS AND TREATMENT OF WASTES FROM A CONFINEMENT HOG PRODUCTION UNIT

by

Eliseos Paul Taiganides

A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of The Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major Subjects: Agricultural Engineering Sanitary Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

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Signature was redacted for privacy.

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1963
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The trend in agriculture is to automation. This is particularly exemplified by the recent history of turkey and poultry production and by the rapidly increasing number of large animal production units. In the past 5 years, many of the problems associated with livestock production within a closely confined area have been satisfactorily solved. Many of the livestock producers, particularly the swine producers, consequently have changed from pasture to pen confinement production. Today, hogs are commonly placed in either totally enclosed or partially open sheds where they remain from early age (40 lbs) to market weight (200 lbs). In this manner, the full advantages of central feeding, better feed conversion and small land area use for the animals can be fully utilized.

The trend to confinement production is firmly established. Those who are close to the swine industry indicate that in the near future by far the majority of hogs will be raised in confinement units, each capable of marketing from 1,000 to 100,000 hogs per year. For example, in Red Oak, Iowa, a pilot unit designed to market 10,000 hogs per year is now in operation and anticipates a 10-year expansion to 100,000 hogs per year.

Manure handling and disposal is already the largest single problem in confinement production. Manure cannot be left on the pen floors. It is a health hazard to both man and animal, a breeding ground for the common fly and a source of objectionable odors. Furthermore, the large quantities of manure produced daily, and its relatively low income value
to the swine producer, complicate the problem. About 22 million hogs (20 percent of total U.S. production) are raised annually in Iowa. It takes about 5 months to bring hogs to market weight in confinement production; 9 million hogs are in production at any one time. Since the strength of manure from the pig is four to five times that of human sewage, the hog wastes are equivalent to at least 12 times the wastes from the human population of Iowa. In other words, hog manure from the state of Iowa alone presents a problem of disposing of wastes equivalent to that which would result from a human population of about 36 million people. If the wastes from all the other livestock and the nation as a whole are considered, the figures become astronomical.

Serious dangers to public and animal health result from the increasing rate of pollution of national surface and underground water resources by livestock wastes. Little basic or applied research has been done on methods of manure disposal. Virtually no information on manure disposal is found other than in the popular press. Technical papers based on research are practically nonexistent. Recognizing this deficiency, the NCA-16* Research Advisory Committee recently established a high priority on initiating research in this area.

Although many of the problems associated with the control of the environment of the animals in a confinement unit have been solved satisfactorily, no really satisfactory method of manure treatment and disposal has been advanced. The methods of manure disposal which are practiced in

* NCA - North Central Association.
Iowa and other states include spreading the manure on the fields in liquid or dry form, lagooning and composting. In other parts of the world, and particularly in Germany, anaerobic digestion of animal manures with methane recovery has been and is being practiced.

The method of manure disposal that is predominant in Iowa and in the Midwest is field spreading. Field spreading of manure has several limitations. With the increasing popularity of confinement production units, less land is needed for raising the animals and correspondingly less land is available for the disposal of the manure. Furthermore, the large confinement units are expected to be developed near the hog markets; i.e., near cities and towns. In such cases, land available for spreading will be limited.

A 10,000-hog production unit will produce annually about 17,000 tons of manure (Eby 1961). The maximum amount of manure that can be spread on an acre used for corn production is 15 tons per year (Morris and Robinson 1961). Thus, the farmer would need at least 1,100 acres of land for manure spreading every year. Furthermore, the land must be available for spreading throughout the year. Another limiting factor is the condition of the fields, i.e. the producer will be limited by the weather in his field-spreading operations.

Much has been written in the popular press about anaerobic lagoons, but both lagoons and composting have several limitations. They are not applicable where land is porous, water is scarce, or near cities where the odor could become a nuisance to the nearby dwellers. Furthermore, no design criteria for lagoons have been developed from actual experimenta-
tion. Most lagoons have been constructed to make use of the land available with no consideration given to the characteristics of the animal wastes. More basic information on the properties of the manure is needed before methods of treatment can be formulated.

The use of slotted floors in confinement production units is increasing in popularity. The floors of the pens are slotted and the excreta are collected in a 4- to 6-foot deep water pool underneath the pen floors. The water pool is emptied periodically. According to the proponents of slotted floors, no objectionable odors are present. Although the slotted-floor idea is relatively new in the U.S.A., it has been practiced in Europe for many years.

In municipal sewage treatment plants, the sewage solids are frequently treated by means of anaerobic sludge digestion. Digestion is used not only because it reduces the sludge to a stable and innocuous product, but also because it produces a valuable by-product, methane gas. The gas recovered from the anaerobic digestion of sewage sludge is used in heating the digesters and the plant buildings and as a fuel in internal combustion engines.

In Europe and other parts of the world, digestion of manure is used as effective treatment and a good source of power for the farm. Today, large confinement production units must treat the wastes before disposal since they can be penalized by local and state health department officials because of the pollution potential and odor nuisance from the wastes. Digestion of the wastes and utilization of the methane gas produced may offer a satisfactory solution to the problem of hog manure disposal.
Objectives

The objectives of this study were:

1) to determine qualitatively and quantitatively the physical and chemical characteristics of wastes from a hog confinement production unit, and

2) to evaluate the feasibility of using anaerobic digestion methods for the treatment of said wastes prior to ultimate disposal on land.
HOG MANURE PROPERTIES

General Introduction

The physical and chemical properties of hog wastes are affected by the characteristics of the hogs, their feed ration and environment. The size of the hog as measured by its weight is the most important parameter. The sex and breed of the hog affect the manure properties to the extent that they determine to some degree the feed conversion efficiency under a given environment. The quality of the feed influences not only the amount the hog eats daily which will be reflected in the quantity of manure produced, but also influences the chemical composition of the manure. The environment as measured by the air temperature and humidity, and the type and amount of bedding affect the growth rate of the pig and the quantity and quality of manure. Temperature perhaps is the most important of the environment factors. Data on the growth rate of the hogs, the quantity and composition of the feed and the air temperature were collected during the experimental investigations of this study. The other factors such as breed, sex, and bedding were kept constant throughout the investigations.

As in the design of municipal and industrial waste treatment plants, the physical and chemical characteristics of the wastes from a hog production unit had to be evaluated before a treatment could be described to render the wastes safe for subsequent disposal. Since the study was concerned with the treatment of hog wastes from a confinement hog production unit, all studies were made at the growing-finishing hog confinement
building at the Iowa State University Swine Nutrition Farm.

As a first step, the volume and strength of the manure produced at the growing-finishing confinement building were determined during three separate periods: Winter 1961, Summer 1961 and Spring 1962. During these periods, all of the manure from one-half of the confinement building was collected in a metering pit, measured and sampled. The waste samples were then analyzed for pollutional strength in the Sanitary Engineering Laboratories of the Civil Engineering Department, Iowa State University.

At the same time that manure production was studied, simultaneous studies were made of water and feed consumption, hog growth and air temperature so that their effect on manure quantity could be evaluated.

Collection of Data

Physical facilities

Hog manure was measured and sampled at the growing-finishing building (Figure 1) of the Iowa State University Swine Nutrition Farm. This farm is located 2 miles southwest of the city of Ames. The growing-finishing building is located on the southwest corner of the farm and has a maximum capacity of approximately 800 hogs. The building is a clear span, pre-fabricated steel frame structure with insulated sidewalls and roof. The lower portion of the building walls are insulated concrete. The upper portion has exposed insulation with an exterior metal lining. It is a total confinement production unit in which the pigs are placed at an early age (40 lbs) and remain in the unit for about 3 months until they reach market weight. The building was designed on the basis of providing
6 square feet of floor area per hog. The total floor area of the building is about 6,000 square feet. The space that is actually occupied by the pigs in the north half of the building is 2,800 square feet. The pen floors are concrete. Pipes carrying hot water were installed under the concrete floors for heating the floors during the cold months of the year. No bedding is used at any time on the pen floors.

The storage, grinding and mixing of the feed are done in the feed unit attached to the building (Figure 1). The feed unit is equipped with scales which weigh the feed automatically before it is conveyed to each of the feeders. The confinement building is divided lengthwise by a double row of self-feeders into north and south wings. All of the manure samplings for this study were made in the north wing of the building. Mechanical feed conveying tubes are installed directly above the feeders (Figure 2). Feed is conveyed along horizontal tubing and flows by gravity through T-connections into the feeders. Flexible shut-offs permit feed to be distributed to any pen or pens. As soon as one feeder is filled, feed is carried to the next feeder until all selected feeders are filled with the desired weight of feed.

Each side of the building is compartmented into pens with steel removable hinged partitions. Ventilation is provided by 12 fans and 12 ventilation tubes. A hydraulically-operated manure removal mechanism in each dunging alley carries the dung to a small sampling pit at the end of the building (Figure 3). From the sampling pit, the waste flows by gravity into 2,500-gallon underground storage tanks. A diaphragm pump at the south wing and an auger at the north wing elevate the manure from the
Figure 1. Exterior of the growing-finishing hog confinement building showing the feed storage and grinding unit attached to the hog unit

Figure 2. Interior of the confinement building showing the self-feeders, feed conveyors, overhead ventilation tubes and the hog pens of the north wing
respective underground storage tanks into a tank truck for final disposal in the field (Figure 4).

Each pen is equipped with an automatic waterer which is suspended on the pen frame (Figure 3) and is connected directly to the water line. The north wing main water line, which supplies drinking water for the pigs and water for hosing down the pens, is metered. Another water line which supplies the overhead sprinklers across the north wing is also equipped with a water meter so the water consumption by the pigs and water used for the cleaning of the pen floors can be measured. In addition, the building is equipped with livestock scales. Thus, individual or group hog weights can be determined.

The number of hogs grown in the north wing was not constant during these studies. The pens were occupied to full capacity during January 1961 (first sampling period) when 410 pigs were being fed. In the summer of 1961 and spring of 1962, the number of hogs in the north wing of the building did not exceed 350. Thus, the ratio of floor space to hogs was over 7 square feet per hog.

No attempt was made to control the size of the hogs in each pen. The pigs were brought into the building at about 7 to 9 weeks of age when they weighed between 35 and 45 pounds each. The pigs were left in the pens approximately 3 months until they reached 200 pounds and were sold when they reached a weight of over 200 pounds.

A hog production unit on a commercial farm is expected to operate much the same as this University confinement operation. The number of hogs in the building and their weight distribution will not be the same
Figure 3. North dunging alley in the confinement building showing manure removal mechanism and automatic waterer.

Figure 4. Tank truck and auger used to load the truck with manure from the underground storage tank.
at all times of the year. In an actual operation, a complete turnover of the hogs should be expected every 3 to 4 months, with the production unit running at 70 to 100 percent capacity at all times.

It is believed that the operational procedures and the facilities of the confinement unit at the ISU Swine Nutrition Farm are typical of the type of confinement production units that will be used in the future by private and commercial enterprises for the production of hogs. Therefore, the data collected by the use of the facilities of the confinement unit should be applicable to most hog confinement production operations of the future.

**Sampling procedure**

The sampling pit and the underground storage tank were calibrated both by measuring their dimensions, and by putting in known amounts of water and noting the level of the water surface above the bottom of the pit. The sampling pit was of small capacity (106 gallons) and gave more accurate results than the storage tank. Furthermore, if the manure were left in the underground storage tank over a period of days, it frequently foamed and the level of the manure could not be determined accurately. To avoid inaccuracies in the recordings taken in the underground tank, the level of the manure was measured just before and just after the day's manure was dumped into the tank. During the summer months of 1961 when personnel of this project were in complete charge of the north wing, a complete record was made of the amount of manure dumped into the underground tank and taken out with the truck for final disposal. This was not possible during the other periods of sampling when personnel of the
Swine Nutrition Farm were doing most of the work. However, the data taken on the underground tank were found to be inconsistent and were discarded in favor of measurements from the sampling pit.

The manure sampling procedure was as follows: After the pens were cleaned and all the day's manure was conveyed into the underground storage tank, the gates of the sampling pit were closed. The level of the manure in the storage tank and the readings of the water meters were recorded. Also, the time of closing the gates and of making the other observations were recorded. During the rest of the day and night, most of the urine and some of the water which pigs will spill out of the automatic waterers would flow into the sampling pit. Since the waterers supply fresh water only as needed and operate without floats or tanks, it was assumed that the amount of water spilled daily by the hogs was negligible.

Next day, usually about 8 A.M., the manure on the pen floors was scraped into the dunging alley and the manure removal mechanism was put into operation (Figure 3). When the manure filled the sampling pit, the manure removal mechanism was stopped and a reading of the level of the manure in the pit was taken. After the reading was taken, the contents of the pit were mixed until a uniform slurry was observed. At that time, a number of aliquot scoopfuls of manure were taken from the pit and emptied into a 5-gallon bucket. One scoopful was taken for each 2- or 3-inch depth of manure in the pit. After a sample was taken, the gates were opened and the manure was pushed out of the pit and into the underground tank. Then, the gates were closed and the same procedure was followed when the pit refilled.
After a representative sample of the day's manure was taken, the contents of the 5-gallon bucket were stirred vigorously until a uniform slurry was formed. A 1-gallon bottle was filled with the well-mixed contents of the bucket and taken to the Sanitary Engineering Laboratories for analysis.

If the pen floors were hosed on that day, both the amount of water used and the time it took for hosing were recorded. By taking a reading of the water meter after the pen floor scraping was finished and before the hosing began the next day, it was possible to compute the amount of water drank by the pigs.

The total weight of the pigs in each pen of the north wing was determined every 2 weeks. Any pigs removed from or placed in the pens were weighed. The feed conveyed to each pen was automatically weighed and recorded by the person in charge of feeding the pigs. Every 2 weeks when the pigs were weighed, the amount of feed left in the feeders of each pen was determined by recording the level of the feed surface in each feeder. The feeders had been calibrated previously. A hygrothermograph recorded the temperature variations within the building.

During the summer of 1961 when personnel of this project were responsible for cleaning the north wing, it was possible to determine the time required for each cleaning operation of the pens. During that period, the pen floors were scraped and hosed daily except on Sunday. Thus, on Monday the manure scraped from the floors was a 2-day accumulation. The manure was scraped with snow shovels into the dunging alley and was conveyed to the storage tank by the gutter cleaner. After the pens were scraped,
they were flushed with water under 80 psi pressure. The pen floor area to be cleaned was approximately 2,000 square feet.

When two men were cleaning, the average time required to scrape and hose down the pens was 23 and 86 minutes per man per day, respectively. The average time required to scrape the floors on Mondays was about 26 minutes per man and the time required to hose the floors on Mondays was 135 minutes per man. When one man was working, the time required for scraping and hosing the pens was 36 and 121 minutes per man per day, respectively.

Feed characteristics

The feed was a ration of ground yellow corn and soybean oil meal with vitamin and mineral additives. When the pigs were young, 40 to 100 pounds in weight, a 14 percent protein ration was fed. After the hogs reached a weight of about 100 pounds a 12 percent protein ration was fed. Tables 1, 2 and 3 show the composition of the feed fed to the pigs during all the manure sampling periods.

Table 1. Main ingredients of the feed rations for the pigs in the north wing

<table>
<thead>
<tr>
<th>Ingredients, in %</th>
<th>Protein content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12%</td>
</tr>
<tr>
<td>Ground yellow corn</td>
<td>82.5</td>
</tr>
<tr>
<td>Soybean meal (44% solvent)</td>
<td>10.0</td>
</tr>
<tr>
<td>Premix No. 1</td>
<td>--</td>
</tr>
<tr>
<td>Premix No. 2</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Table 2. Ingredients of premix No. 1

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium carbonate</td>
<td>15.00 lbs</td>
</tr>
<tr>
<td>Dicalcium phosphate</td>
<td>26.00 lbs</td>
</tr>
<tr>
<td>Iodized salt</td>
<td>10.00 lbs</td>
</tr>
<tr>
<td>Trace mineral premix*</td>
<td>2.00 lbs</td>
</tr>
<tr>
<td>Merck premix No. 84</td>
<td>0.75 lbs</td>
</tr>
<tr>
<td>Merck B₁₂ premix &quot;20&quot;</td>
<td>0.50 lbs</td>
</tr>
<tr>
<td>Aurofac - 10</td>
<td>2.00 lbs</td>
</tr>
<tr>
<td>Copper oxide</td>
<td>0.62 lbs</td>
</tr>
<tr>
<td>Vitamin D₂</td>
<td>3.00 grams</td>
</tr>
<tr>
<td>Ground yellow corn</td>
<td>43.13 lbs</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100.00 lbs</td>
</tr>
</tbody>
</table>

*The trace elements in the 14 percent protein ration are (based on ppm in total feed): iron (70.4 ppm); copper (4.8 ppm); cobalt (1.6 ppm); zinc (81.6 ppm); manganese (57.8 ppm). To find the mineral content of the 12 percent protein ration, multiply the figures in parenthesis by 0.75.

Table 3. Calculated analysis of the feed rations

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>Protein content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>12%</td>
</tr>
<tr>
<td>Protein</td>
<td>%</td>
<td>12.06</td>
</tr>
<tr>
<td>Fat</td>
<td>%</td>
<td>3.39</td>
</tr>
<tr>
<td>Fiber</td>
<td>%</td>
<td>2.89</td>
</tr>
<tr>
<td>Calcium</td>
<td>%</td>
<td>0.505</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>%</td>
<td>0.455</td>
</tr>
<tr>
<td>Vitamin A</td>
<td>I U/lb</td>
<td>878.7</td>
</tr>
<tr>
<td>Vitamin D₂</td>
<td>I U/lb</td>
<td>159.8</td>
</tr>
<tr>
<td>Riboflavin</td>
<td>mg/lb</td>
<td>1.69</td>
</tr>
<tr>
<td>Pantothenic acid</td>
<td>mg/lb</td>
<td>4.79</td>
</tr>
<tr>
<td>Niacin</td>
<td>mg/lb</td>
<td>14.78</td>
</tr>
<tr>
<td>Choline</td>
<td>mg/lb</td>
<td>296.7</td>
</tr>
<tr>
<td>Vitamin B₁₂</td>
<td>Meg/lb</td>
<td>3.75</td>
</tr>
<tr>
<td>Autofac</td>
<td>mg/lb</td>
<td>7.5</td>
</tr>
<tr>
<td>Copper oxide</td>
<td>ppm</td>
<td>187.5</td>
</tr>
</tbody>
</table>
To make 100 pounds of premix No. 2, 50 pounds of premix No. 1 were mixed with 50 pounds of ground yellow corn.

The constituents of the feed undergo highly complex chemical changes as they pass through the digestive tract of the hog. These changes are brought about by the enzymes of the digestive fluid and the bacteria which inhabit the intestinal tract of the hog. The degree of digestion of the feed constituents in the digestive tract of the animal varies with the chemical composition of the materials. Starch and sugars are highly digestible, hemicelluloses and celluloses are somewhat less digestible, while the lignins are highly resistant and hence tend to be accumulated unaltered in the feces. Proteins, which contain most of the nitrogen of the feed, vary in digestibility. However, most of the nitrogen of the proteins is excreted in the hog wastes. The nitrogen of the undigested proteins is excreted in the solid feces of the pig, whereas the nitrogen of the digested proteins is absorbed and is later excreted in the urine of the animal, except for a small portion which is used to build flesh in the hog. The potassium in the feed is absorbed during digestion but practically all of it is excreted in the urine and in the fecal matter. Part of the phosphorus constituent of the feed is absorbed, but most of it is excreted. Some of the feed is spilled on the pen floors and is included in the manure collected from the pens. Therefore, the wastes from the hogs in the confinement building should contain all the ingredients of the feed, some of them in their original form, others in a chemically simpler form. Moreover, the manure should be rich in bacteria which inhabit the digestive tract of the animal and are excreted in the
Hog growth characteristics

The hogs grown in the north wing were crossbred pigs (50 percent Poland China X 25 percent Yorkshire X 25 percent Landrace). They were weaned early (2 to 3 weeks) and were brought to the confinement unit when they weighed 35 to 45 pounds.

Table 4 shows the typical rate of growth of the hogs in the north wing of the confinement building during the 12-week period, June 6 to August 31, 1962. The average daily gain for the 12-week period was 1.41 pounds per pig, the maximum for a 2-week period being 1.56 pounds per pig per day. Table 4 indicates that the pigs gained somewhat faster at the

Table 4. Growth rate and feed conversion data of the hogs during the summer of 1961

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of pigs</th>
<th>Total weight, lbs</th>
<th>Average weight, lb/pig</th>
<th>Average gain, lb/pig</th>
<th>Average gain,* lb/pig/day</th>
<th>Feed efficiency* lb/lb gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-6-61</td>
<td>338</td>
<td>19,956</td>
<td>59.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-20-61</td>
<td>336</td>
<td>26,948</td>
<td>79.7</td>
<td>21.3</td>
<td>1.56</td>
<td>2.21</td>
</tr>
<tr>
<td>7-6-61</td>
<td>328</td>
<td>33,522</td>
<td>102.2</td>
<td>43.5</td>
<td>1.47</td>
<td>2.92</td>
</tr>
<tr>
<td>7-20-61</td>
<td>325</td>
<td>40,204</td>
<td>123.7</td>
<td>64.8</td>
<td>1.49</td>
<td>3.03</td>
</tr>
<tr>
<td>8-3-61</td>
<td>324</td>
<td>46,403</td>
<td>143.2</td>
<td>84.3</td>
<td>1.46</td>
<td>3.23</td>
</tr>
<tr>
<td>8-17-61</td>
<td>314</td>
<td>50,674</td>
<td>161.4</td>
<td>104.4</td>
<td>1.44</td>
<td>3.33</td>
</tr>
<tr>
<td>8-31-61</td>
<td>279</td>
<td>48,197</td>
<td>172.7</td>
<td>118.4</td>
<td>1.41</td>
<td>3.44</td>
</tr>
</tbody>
</table>

*All values based on gain from 6-6-61.
beginning of the period when they averaged 70 pounds than at the end of
the period when they averaged near their market weight. During the last
2 weeks the pigs that had reached 200 pounds were marketed.

Figures on pig growth characteristics in each of the six pens of the
north wing were used to arrive at the figures shown in Table 4. The
variation in weight, daily gains and feed conversion values was consider­
able between pens and within pens. For example, on July 20, 1961, the
average pig in the north wing weighed 123.7 pounds, the pigs in one of
the pens averaged 94.1 pounds and in another pen averaged 166.5 pounds.
Thus, during the same period of time, some of the pigs were being fed 12
percent protein rations while others were being fed 14 percent protein
rations.

The average weight of the pigs during the sampling period from
January 18 to February 2, 1961 was 106 pounds. The average daily gain
was 1.31 pounds per pig. No data were collected on feed conversion. Dur­
ing the Spring of 1962, April 4 to May 3, the pigs averaged 100 pounds at
the beginning and 150 pounds at the end of the 4-week period. The average
daily gain and the feed conversion rate for this period were 1.54 pounds
per pig and 3.89 pounds of feed per pound of gain, respectively.

The pigs drank, on the average, 1.10 gallons of water per day during
the period from July 20 to August 8, 1961 when the inside temperature
ranged from 66°F to 93°F with an average temperature of 80°F. During
the period from April 11 to May 3, 1962, the daily water consumption per
pig was 1.31 gallons and the temperature averaged 64°F. It would seem
that the figures for water consumption for the two periods should be the
other way around. However, during the period from July 20 to August 8, the pen floors were hosed down daily. During the time it took to hose down the pens, the pigs would drink some non-metered amount of water from the floor or as the water came out of the nozzles of the hose. In April of 1962, the pens were hosed only once a week, so the pigs had to drink the water from the waterers which were metered.

**Manure Quantity**

The quantity and chemical characteristics of hog wastes depend so much on the feed ration and the environment in which the animals grow that it is difficult to evaluate figures given in the literature for the quantity and composition of hog manure unless the feed ration and the environmental conditions are given. Furthermore, most of the figures on manure found in the literature include bedding. Bedding was not used in the confinement building and it is not expected that bedding will be used in future confinement production units. The values of manure production reported here do not include bedding.

Ames and Gaither (1912) reported the average daily production of manure (including urine) of four farm animals to be as follows: hogs, 9.3 pounds; cattle, 71.4 pounds; horses, 43.5 pounds; and sheep, 3.8 pounds per animal. Salter and Schollenberger (1939) and Anderson (1957) published figures that are similar to those given by Ames and Gaither.

Hazen and Mangold (1960), using data on the environmental conditions of confinement production units and feed rations, estimated (Table 5) the variations in the daily manure production to be expected with the growth
Table 5. Variation in the daily manure production with increase in weight of swine*

<table>
<thead>
<tr>
<th>Hog weight range, lbs</th>
<th>Total manure, lbs/day</th>
<th>Feces, lbs/day</th>
<th>% of total</th>
<th>Urine, lbs/day</th>
<th>% of total</th>
<th>Ratio to hog weight, lbs/lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-80</td>
<td>5.6</td>
<td>2.7</td>
<td>48</td>
<td>2.9</td>
<td>52</td>
<td>1:11</td>
</tr>
<tr>
<td>80-120</td>
<td>11.5</td>
<td>5.4</td>
<td>47</td>
<td>6.1</td>
<td>53</td>
<td>1:9</td>
</tr>
<tr>
<td>120-160</td>
<td>14.6</td>
<td>6.5</td>
<td>44</td>
<td>8.1</td>
<td>56</td>
<td>1:10</td>
</tr>
<tr>
<td>160-200</td>
<td>17.6</td>
<td>8.5</td>
<td>48</td>
<td>9.1</td>
<td>52</td>
<td>1:10</td>
</tr>
</tbody>
</table>

*The data for this table were taken from Hazen and Mangold (1960).

of the animals. They calculated the average total daily manure production per hog to be one-tenth the live weight of the animal. It is interesting to note in Table 5 that the amount of manure increases as the weight of the pig increases and the urine production of the animal is always more than 50 percent of the total. The average urine content of manure is about 53 percent of the total. According to Hazen and Mangold (1960) during hot weather the urine production is expected to increase by 30 percent. For the design of liquid manure collection pits, Jedele (1959) recommended a minimum value of 2 gallons per day per hog, of which one-fourth is cleaning water; i.e., Jedele estimated the daily manure production to be about 1.5 gallons per hog.

**Theoretical estimation of manure quantity**

The two primary factors affecting the quantity of manure excreted by the hog are the quantity of the feed and water intake, and the environ-
ment. The best measure of the effect of the environment can be given by the air temperature. Thus, an attempt was made to estimate the quantity of manure production from data on feed and water consumption and the air temperature.

A total mass balance to estimate manure production from a growing pig in a confinement unit may be expressed in the form of Equation 1:

\[ M_{f_i} + M_{w_i} + M_{a_i} + M_{v_i} = M_g + M_m + M_{a_o} + M_{f_h} + M_{v_o} + M_{w_e} \]  

(1)

where:
- \( M_{f_i} \) = mass of daily feed intake in lbs/day,
- \( M_{w_i} \) = mass of daily water intake in lbs/day,
- \( M_{a_i} \) = mass of dry air inhaled in lbs/day,
- \( M_{v_i} \) = mass of water vapor inhaled in lbs/day,
- \( M_g \) = mass of daily gain in weight in lbs/day,
- \( M_m \) = mass of manure excreted minus the amount evaporated in lbs/day
- \( M_{a_o} \) = mass of dry air exhaled in lbs/day,
- \( M_{f_h} \) = portion of \( M_{f_i} \) dissipated as heat in lbs/day,
- \( M_{v_o} \) = mass of water vapor exhaled in lbs/day, and
- \( M_{w_e} \) = mass of water evaporated from and around the pig in lbs/day.

The difference in mass between the weight of the dry air inhaled and the dry air exhaled was assumed negligible because it was small in comparison to the other components of Equation 1. Then Equation 1 can be written as follows:
where: \( M_{w_r} = M_{w_e} + M_{v_o} - M_{v_i} \) = mass of water vapor removed from the confinement unit by the ventilating air in lbs/day.

The values for \( M_{f_i} \), \( M_{v_i} \) and \( M_g \) were determined from data collected during the second and third sampling periods. Values for \( M_{w_r} \) were taken from Bond et al. (1959) who measured the amount of water removed by the air ventilating a test hog confinement chamber. The moisture removed by the ventilating air included the water evaporated from the feed, feces, urine, drinking fountain and the pigs. Bond et al. (1959) found that the moisture removed by the ventilating air correlated well with the pig weight and the air temperature. Thus, values for \( M_{w_r} \) were obtained from the data on average pig weights and air temperature by using the graphs of Bond et al. (1959).

Before a value could be substituted in Equation 2 for the term, \( M_{f_h} \), the total heat loss from the animal and the gross energy of the feed had to be determined. The total heat loss, \( Q_T \), represents the heat loss from the animal by each of the four methods of heat transfer; i.e., convection, conduction, radiation and evaporation. Again, the total heat loss was obtained from graphs of Bond et al. (1959). Through the use of values for the average pig weight and air temperature, the total heat loss was obtained in BTU's per pig per day. The heat loss was converted to mass units by dividing its value by the gross energy per unit mass of the feed.
In computing the value of the feed energy used in the calculation of the term, $M_{fh}$, the following assumptions were made: all the digestible ingredients of the feed were used by the animal for the production of heat and, except for ash and water, no other matter was excreted nor was it used for weight gain by the pig. Table 6 shows the procedure for the calculation of the gross energy of the feed.

Table 6. Calculation of the gross energy per unit mass of feed

<table>
<thead>
<tr>
<th>Energy ingredients</th>
<th>Percent in feed, $^a$</th>
<th>Gross energy of feed ingredients $^b$</th>
<th>Feed gross energy Kcal/ gr protein level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12%</td>
<td>14%</td>
<td>Kcal/ gr</td>
</tr>
<tr>
<td>Carbohydrates</td>
<td>65.09</td>
<td>62.40</td>
<td>4.15</td>
</tr>
<tr>
<td>Fat</td>
<td>3.39</td>
<td>3.18</td>
<td>9.40</td>
</tr>
<tr>
<td>Protein</td>
<td>12.06</td>
<td>14.01</td>
<td>5.65</td>
</tr>
<tr>
<td>Total</td>
<td>80.54</td>
<td>81.59</td>
<td>3.70</td>
</tr>
<tr>
<td>Average</td>
<td>81.06</td>
<td></td>
<td>3.69</td>
</tr>
</tbody>
</table>

$^a$These values were calculated from data given in Tables 1 and 3; data on NFE (Nitrogen Free Extract) given by Morrison (1954).

$^b$These values were taken from Maynard and Loosli (1956).

The ash content for the 12- and 14 percent protein feed was calculated to be 4.11 and 5.12 percent respectively. The ash content for the feed fed to the pigs in the confinement building was assumed to be the average of the values for the two types of feed; i.e., 4.61 percent. The water content of the feed was assumed to be 15 percent. Therefore, the portion
of the feed mass intake converted into heat is the total mass intake minus the water and ash content; i.e., 100.00 - 19.61 = 80.39 percent. This value of the feed converted to heat agrees well with the value of 81.06 given in Table 6. The value of Table 6 was used in the calculations of the term $M_{f_h}$.

The gross energy of the feed was found to be 3.69 Kcal per gram of feed or, expressed in equivalent terms, 6.672 BTU's per pound. Dividing the gross energy value by the percent of the feed which converts into heat, 81.06, gave a value of 8,231 BTU's per pound of feed. The value of 8,231 BTU's per pound was used in the determination of the term $M_{f_h}$ in Equation 2.

For the period between July 20 and August 31, 1961, the data necessary to solve Equation 2 were as follows: $M_{f_i} = 4.85$, $M_{w_i} = 9.20$, $M_g = 1.41$, and for average pig weight and air temperature of 149 pounds and 80° F, respectively, $M_{w_r} = 7.44$, $Q_t = 12,000$ BTU's per day and $M_{f_h} = 1.46$. Substituting the above values in Equation 2 and solving for $M_m$, the value obtained was 3.74 pounds of manure per pig per day. For the same period, the actual value measured was 3.92 pounds of manure per pig per day.

For the period between April 4 and May 3, 1962, the values for the terms of Equation 2 were found to be as follows: $M_{f_i} = 6.0$, $M_{w_i} = 10.93$, $M_g = 1.54$, and for average pig weight and air temperature of 125 pounds and 64° F, respectively, $M_{w_r} = 4.8$, $Q_t = 12,000$ BTU's per day and $M_{f_h} = 1.46$. Substituting the above values in Equation 2, the value obtained for $M_m$ was 9.13 pounds per day. The actual value obtained for the same period was 6.34 pounds of manure per pig per day.
Although for the summer of 1961 period the theoretical and the actual values of daily manure quantity agree well, the error in the actual value for the spring of 1962 period is 30 percent. Even so, it is hard to say, on the basis of the theoretical values, whether the actual value measured in the summer of 1961 is more accurate than that obtained in the spring of 1962 because of the inconsistency of the water intake figures for the two periods. This inconsistency has been discussed in a previous section of the thesis. However, from the theoretical analysis presented above, the following conclusion can be made: 1) Equation 2 can be used to estimate the daily manure quantities to be removed from a confinement unit when the air temperature, the feed conversion, the daily gain and the water intake values are known. The air temperature, the feed consumption and the pig gain can be routine procedures in an actual operation. The installation of a water meter to measure the water consumption can be easily facilitated. 2) A large error in the calculation of the water intake results in a similarly large error in the estimation of the theoretical value for the quantity of manure.

**Observed manure quantity**

Tables 7, 8 and 9 show the quantities of manure measured in the north wing of the confinement building during the three sampling periods. During the winter of 1961 and spring of 1962, the pens were not hosed, therefore, the quantities in Tables 7 and 9 are raw wastes minus some evaporation and manure which could not be scraped from the pen floors. During the summer of 1961 the pens were scraped daily, and after scraping and measuring the manure (Table 8), the pen floors were hosed daily. The
Table 7. Daily hog manure quantities collected in the north wing in winter of 1961\(^a\)

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of pigs</th>
<th>Manure gal</th>
<th>gal/pig</th>
<th>Mean temperature, °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-18</td>
<td>411</td>
<td>189</td>
<td>0.46</td>
<td>56</td>
</tr>
<tr>
<td>1-19</td>
<td>411</td>
<td>251</td>
<td>0.61</td>
<td>52</td>
</tr>
<tr>
<td>1-20</td>
<td>410</td>
<td>271</td>
<td>0.66</td>
<td>47</td>
</tr>
<tr>
<td>1-21</td>
<td>410</td>
<td>283</td>
<td>0.69</td>
<td>48</td>
</tr>
<tr>
<td>1-22</td>
<td>409</td>
<td>283</td>
<td>0.76</td>
<td>49</td>
</tr>
<tr>
<td>1-23</td>
<td>409</td>
<td>311</td>
<td>0.68</td>
<td>52</td>
</tr>
<tr>
<td>1-25</td>
<td>409</td>
<td>278</td>
<td>0.73</td>
<td>53</td>
</tr>
<tr>
<td>1-26</td>
<td>409</td>
<td>325</td>
<td>0.79</td>
<td>53</td>
</tr>
<tr>
<td>1-27</td>
<td>409</td>
<td>304</td>
<td>0.74</td>
<td>53</td>
</tr>
<tr>
<td>1-28</td>
<td>409</td>
<td>323</td>
<td>0.79</td>
<td>54</td>
</tr>
<tr>
<td>1-29</td>
<td>409</td>
<td>318</td>
<td>0.78</td>
<td>54</td>
</tr>
<tr>
<td>1-30</td>
<td>409</td>
<td>308</td>
<td>0.75</td>
<td>56</td>
</tr>
<tr>
<td>1-31</td>
<td>409</td>
<td>309</td>
<td>0.76</td>
<td>58</td>
</tr>
<tr>
<td>2-1</td>
<td>400</td>
<td>339</td>
<td>0.85</td>
<td>56</td>
</tr>
<tr>
<td>2-2</td>
<td>400</td>
<td>335</td>
<td>0.84</td>
<td>52</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.71</td>
<td></td>
<td>53</td>
</tr>
</tbody>
</table>

\(^a\)The data for this period were collected and analyzed by C. Schertz. During this period, the pen floors were hosed only once. No data were taken on water consumption.

Summer measurements showed only about 60 percent of the manure quantities measured in the other periods. This difference may be in large part due to the loss each day of that manure sticking on the floor and the higher evaporation losses during the summer when the average air temperature was 20° F higher.

The effect of the difference in evaporation losses on the manure quantities measured during the sampling periods is considerable. Assuming a specific gravity of 1 (actual measurements showed a specific gravity of 0.98 to 1.06), the average measured daily manure production during the
Table 8. Daily hog manure quantities collected in the north wing in summer 1961a

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of pigs</th>
<th>Manure gal</th>
<th>Manure gal/pig</th>
<th>Water gal</th>
<th>Water gal/pig</th>
<th>Mean temp, °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-21</td>
<td>325</td>
<td>213</td>
<td>0.66</td>
<td>316</td>
<td>0.97</td>
<td>76</td>
</tr>
<tr>
<td>7-22</td>
<td>325</td>
<td>177</td>
<td>0.55</td>
<td>350</td>
<td>1.08</td>
<td>75</td>
</tr>
<tr>
<td>7-25</td>
<td>325</td>
<td>168</td>
<td>0.52</td>
<td>359</td>
<td>1.10</td>
<td>82</td>
</tr>
<tr>
<td>7-26</td>
<td>325</td>
<td>120</td>
<td>0.37</td>
<td>368</td>
<td>1.13</td>
<td>78</td>
</tr>
<tr>
<td>7-27</td>
<td>324</td>
<td>221</td>
<td>0.68</td>
<td>386</td>
<td>1.19</td>
<td>82</td>
</tr>
<tr>
<td>7-28</td>
<td>324</td>
<td>160</td>
<td>0.49</td>
<td>351</td>
<td>1.08</td>
<td>84</td>
</tr>
<tr>
<td>7-29</td>
<td>324</td>
<td>214</td>
<td>0.66</td>
<td>352</td>
<td>1.09</td>
<td>83</td>
</tr>
<tr>
<td>8-1</td>
<td>324</td>
<td>149</td>
<td>0.46</td>
<td>389</td>
<td>1.20</td>
<td>82</td>
</tr>
<tr>
<td>8-2</td>
<td>324</td>
<td>147</td>
<td>0.45</td>
<td>356</td>
<td>1.10</td>
<td>83</td>
</tr>
<tr>
<td>8-3</td>
<td>324</td>
<td>161</td>
<td>0.50</td>
<td>380</td>
<td>1.17</td>
<td>83</td>
</tr>
<tr>
<td>8-4</td>
<td>320</td>
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<td>0.53</td>
<td>428</td>
<td>1.34</td>
<td>83</td>
</tr>
<tr>
<td>8-5</td>
<td>320</td>
<td>155</td>
<td>0.48</td>
<td>408</td>
<td>1.27</td>
<td>79</td>
</tr>
<tr>
<td>8-8</td>
<td>318</td>
<td>126</td>
<td>0.40</td>
<td>540</td>
<td>1.70</td>
<td>81</td>
</tr>
<tr>
<td>8-9</td>
<td>318</td>
<td>133</td>
<td>0.42</td>
<td>234</td>
<td>0.74</td>
<td>81</td>
</tr>
<tr>
<td>8-10</td>
<td>317</td>
<td>120</td>
<td>0.38</td>
<td>384</td>
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<td>83</td>
</tr>
<tr>
<td>8-11</td>
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<td>0.41</td>
<td>350</td>
<td>1.10</td>
<td>80</td>
</tr>
<tr>
<td>8-12</td>
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<td>124</td>
<td>0.39</td>
<td>366</td>
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<td>80</td>
</tr>
<tr>
<td>8-15</td>
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<td>0.52</td>
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<td>0.95</td>
<td>80</td>
</tr>
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<td>8-16</td>
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<td>80</td>
</tr>
<tr>
<td>8-17</td>
<td>314</td>
<td>101</td>
<td>0.32</td>
<td>333</td>
<td>1.06</td>
<td>81</td>
</tr>
<tr>
<td>8-18</td>
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<td>146</td>
<td>0.52</td>
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<td>1.05</td>
<td>81</td>
</tr>
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<td>8-19</td>
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<td>179</td>
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<td>76</td>
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<tr>
<td>8-22</td>
<td>281</td>
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<td>0.52</td>
<td>263</td>
<td>0.94</td>
<td>75</td>
</tr>
<tr>
<td>8-23</td>
<td>281</td>
<td>115</td>
<td>0.41</td>
<td>396</td>
<td>1.41</td>
<td>74</td>
</tr>
<tr>
<td>8-24</td>
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<td>1.17</td>
<td>74</td>
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<tr>
<td>8-25</td>
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<td>0.59</td>
<td>204</td>
<td>0.73</td>
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</tr>
<tr>
<td>8-26</td>
<td>280</td>
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<td>82</td>
</tr>
<tr>
<td>8-29</td>
<td>278</td>
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<td>0.45</td>
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<td>0.92</td>
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</tr>
<tr>
<td>8-30</td>
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<td>0.35</td>
<td>317</td>
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<td>82</td>
</tr>
<tr>
<td>8-31</td>
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<td>126</td>
<td>0.45</td>
<td>362</td>
<td>1.31</td>
<td>82</td>
</tr>
<tr>
<td>9-1</td>
<td>278</td>
<td>122</td>
<td>0.44</td>
<td>304</td>
<td>1.10</td>
<td>82</td>
</tr>
<tr>
<td>9-2</td>
<td>278</td>
<td>100</td>
<td>0.36</td>
<td>300</td>
<td>1.08</td>
<td>82</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.47</td>
<td></td>
<td>1.10</td>
<td>80</td>
</tr>
<tr>
<td>9-5</td>
<td>278</td>
<td>145</td>
<td>0.52</td>
<td>315</td>
<td>1.14</td>
<td>80</td>
</tr>
<tr>
<td>9-6</td>
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<td>158</td>
<td>0.57</td>
<td>357</td>
<td>1.29</td>
<td>82</td>
</tr>
<tr>
<td>9-7</td>
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<td>92</td>
<td>0.33</td>
<td>315</td>
<td>1.14</td>
<td>82</td>
</tr>
<tr>
<td>9-8</td>
<td>278</td>
<td>115</td>
<td>0.41</td>
<td>222</td>
<td>0.80</td>
<td>82</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.46</td>
<td></td>
<td>1.09</td>
<td>82</td>
</tr>
</tbody>
</table>

The pens were hosed daily except Sundays from 7-21 through 9-2. Pens were not hosed from 9-4 through 9-8. Data for Monday collections were not included.
Table 9. Daily hog manure quantities collected in the north wing in spring 1962

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of pigs</th>
<th>Manure gal</th>
<th>Manure gal/pig</th>
<th>Water gal</th>
<th>Water gal/pig</th>
<th>Mean temp, °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-22</td>
<td>267</td>
<td>233</td>
<td>0.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-23</td>
<td>267</td>
<td>223</td>
<td>0.84</td>
<td>356</td>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td>3-30</td>
<td>250</td>
<td>228</td>
<td>0.91</td>
<td></td>
<td></td>
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<td>1.01^c</td>
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<tr>
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<td>0.76</td>
<td>1.31</td>
<td></td>
<td></td>
<td>64</td>
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</table>

^a The pens were not hosed except Mondays.

^b First hot day. Considerable amount of water spilled. These values were not included in the calculation of the mean.

^c A water hose leaked. These figures were not included in the calculation of the mean.

The summer of 1961 was 3.92 pounds per pig per day, or 2.42 pounds less than the value measured in the spring of 1962, 6.84 pounds per pig per day. However, during the summer the moisture removed by the ventilating air was 7.44 pounds per pig per day, or 2.64 pounds greater than the value calculated for the spring of 1962 period, 4.80 pounds of water per pig per day. The value for the moisture removed includes water vapor exhaled by the animal. However, the major portion of the water removed by the
ventilating air is the water evaporated from the feces, urine and pen floors. Thus, it may be concluded that the daily manure production measured during the hot months of the year was less than that measured during the cold months of the year mainly because of the higher evaporation losses per pig per day during the hot months of the year.

Both the theoretical and observed values for the daily manure quantity from the confinement unit are less than the values reported in the literature. The difference is mainly due to the fact that the values obtained in this thesis are for actual quantities of manure collected daily from the confinement building while the values in the literature cited are for the total daily manure production.

The average daily manure quantity, both estimated and observed, when divided by the average weight of the pigs gives an overall average of 4.7 pounds of manure per 100 pounds of live weight. For design purposes a figure of 5 pounds of manure per 100 pounds of live weight is recommended.

Manure Composition

The composition of hog manure depends primarily on the feed ration. The feces in manure are composed of the undigested portion of the feed intake, bacteria carried from the digestive tract, digestive liquids and water. Since the digestion coefficient of the feed ingredients may vary from 0.57 (fiber) to 0.93 (carbohydrate) (Morrison 1954), the fecal portion of the manure contains a large number of the feed ingredients in their original form. Fecal excreta also contain substances which were changed by the metabolic activities of the bacteria in the alimentary
tract and the enzymatic action of the digestive juices. The urine is composed mainly of the end product of the protein catabolism, urea, and a varying percent of the mineral and vitamin additives of the feed and water.

The total and organic solids content of the manure depends on the type of feed and partly on the environment which influences the water intake of the animals. According to Reinhold and Noak (1956), the total-solids content of pig manure was 26.2 percent during the wintertime when the pigs were raised in confinement and were fed on grain rations and 18.7 percent during summer months when grain feeding was supplemented with pasturing of the pigs. They found the volatile-solids content to be 16.2 (62.0 percent on dry basis) and 15.2 (81.4 percent on dry basis) percent of the solids during winter and summer periods, respectively. Apparently the percentage of the volatile solids (wet basis) did not change as much as the total solids did with change in the feed. Table 10 taken from Salter and Schollenberger (1939) shows the average daily production and composition of different animal manures. The manure was analyzed only for its fertilizing constituents. The figures for nitrogen, phosphoric acid and potash for the hog manure represent recoveries of 72, 83 and 90 percent of the constituents present in the feed ration intake, respectively. For the other animals, the percent recovery of these feed nutrients are similar to the values given for hogs. For hogs, 21 percent of the nitrogen, 60 percent of the phosphoric acid and 35 percent of the potash intake are recovered in the feces and the rest in the urine of the animal. These recovery figures are based on manure from a young growing
Table 10. Average daily production and composition of fresh manure of mature animals

<table>
<thead>
<tr>
<th>Animal</th>
<th>Hogs</th>
<th>Cattle</th>
<th>Sheep</th>
<th>Hens</th>
<th>Horses</th>
</tr>
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<tr>
<td>Excreta per animal</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Solid, lbs/day</td>
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<td>52.0</td>
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<td>0.1</td>
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</tr>
<tr>
<td>Liquid, lbs/day</td>
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<td>20.0</td>
<td>1.5</td>
<td>--</td>
<td>8.0</td>
</tr>
<tr>
<td>Total solids, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid portion</td>
<td>18.0</td>
<td>16.2</td>
<td>34.5</td>
<td>35.0</td>
<td>24.3</td>
</tr>
<tr>
<td>Liquid portion</td>
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<td>6.2</td>
<td>12.8</td>
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<td>9.9</td>
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<tr>
<td>Total</td>
<td>12.4</td>
<td>13.3</td>
<td>22.1</td>
<td>35.0</td>
<td>21.6</td>
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<tr>
<td>Total N, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid portion</td>
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<td>0.32</td>
<td>0.60</td>
<td>1.00</td>
<td>0.50</td>
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<tr>
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<td>0.95</td>
<td>0.30</td>
<td>--</td>
<td>1.20</td>
</tr>
<tr>
<td>P2O5, %</td>
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<tr>
<td>Solid portion</td>
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<td>0.21</td>
<td>0.46</td>
<td>0.80</td>
<td>0.30</td>
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<tr>
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<td>0.03</td>
<td>0.12</td>
<td>--</td>
<td>trace</td>
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<tr>
<td>K2O, %</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid portion</td>
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<td>0.16</td>
<td>0.44</td>
<td>0.40</td>
<td>0.24</td>
</tr>
<tr>
<td>Liquid portion</td>
<td>1.00</td>
<td>0.95</td>
<td>1.00</td>
<td>--</td>
<td>1.50</td>
</tr>
</tbody>
</table>

*Modified from data by Salter and Schollenberger (1939).*

The percent recovery of the feed ingredients is higher from mature hogs which are neither gaining nor decreasing in weight. Salter and Schollenberger (1939) suggested a recovery value of 40 percent of the organic matter of the feed for mixed classes of livestock.

Values similar to those in Table 10 were reported by Anderson (1957) and Feldmann (1956). Eby (1961) reported the strength of hog and other farm animal wastes as a population equivalent. Eby (1961) compared values of the carbon-nitrogen (C/N) ratio of the different wastes and arrived at the following population equivalents: 1.9 humans to one hog,
16.4 to one dairy cow, 11.3 to one horse, 2.45 to one sheep and 0.014 to one chicken.

According to Eby (1961), lagoons for animal wastes can be designed by taking the organic loading criteria found in the rules and regulations of the public health departments in most states for the lagooning of human sewage and modifying them by the population equivalents. Eby assumed, of course, that the C/N ratio is a sufficient index of strength and that the animal and human wastes are similar in the other characteristics which affect the biological processes of decomposition. This assumption may not be true for all animal wastes.

**Laboratory analyses**

The manure samples collected at the confinement building were brought to the Sanitary Engineering Laboratory around 10 A.M. every day. By 12 noon, all the tests which were to be performed on the manure were completed. The time elapsed between collection of the sample and the performance of the analyses did not exceed 2 hours. Thus, the use of manure preservatives to stop biological decomposition was not necessary.

During the first and second sampling periods, only the total and volatile solids content of the manure were determined. During the third sampling period, the solids content, the nitrogen content, the pH, the biochemical oxygen demand (BOD) and the chemical oxygen demand (COD) of the manure were determined. These tests include all of the applicable procedures recommended in the Standard Methods (1960) for the examination of sludge and mud samples. Hog manure, being high in total solids content,
is considered sludge. Sludge is defined as the solids portion of the waste water which results from the separation of the settleable solids that are naturally present in waste water.

**Total and volatile solids** The total and volatile solids determinations are important in the analyses of raw and digested manure. They are important as an index of the strength of the manure, the amount of treatment required, or as a measure of the efficiency of a treatment process. The volatile solids determinations are considered to constitute the organic matter content of the sample. In any biological treatment of a waste, the quality and quantity of the organic matter is of primary importance because the microorganisms can attack and decompose only the organic matter in the waste.

The methods employed in the solids determinations of the manure deviated somewhat from those in American Public Health Association (APHA) (1960). Approximately 20 grams of manure were weighed to the nearest 0.001 gram in a tared porcelain evaporating dish. The analytical balances in the weighing room of the laboratory were used for all the weighings. The manure was evaporated to dryness by placing the dishes under infrared heat lamps for about an hour. Prolonged exposure of the manure to the heat lamps resulted in loss of organic matter due to burning. The dishes were then further dried in a drying oven at 103 ± 2° C for about 20 to 24 hours. The procedure in the standard methods of APHA (1960) was followed for the remainder of the total and volatile solids determinations except for the accuracy with which weighings were made; i.e., to the nearest 0.001 gram and not 0.01 gram. The determination of both the total and
volatile solids of manure is subject to error due to the loss of ammonium carbonate and volatile organic matter while drying, making the results lower than they should be.

Twelve manure samples were analyzed for solids during the first sampling period, winter 1961. The average total solids content was 14.8 percent with 75.0 percent of the solids being volatile; i.e., the volatile solids of the manure constituted 11.1 percent of the total manure. These solids determinations are not accurate and, thus, are not offered as representative values. They were made by a laboratory assistant who did not use the analytical balance in the weight measurements but used scales which were accurate only to the nearest 0.1 gram. The solids determinations during the rest of the sampling periods were made under the supervision of the author and were more accurately weighed.

Both the total and volatile solids content of 12 manure samples tested during the summer of 1961 increased. The total solids increased to 18.5 percent and the volatile solids to 15.5 (83.5 percent on a dry basis) percent. The results of the solids content analyses of samples collected in the spring of 1962 are shown in Table 11. The average total and volatile solids content of the manure was lower during the third sampling period than in the summer of 1961. The average total solids in the manure collected from February 8 until May 3 was 15.6 percent with the volatile solids being 82.9 percent of the total solids or 12.9 percent of the manure. It is interesting to note that the percent of the total solids which were volatile remained approximately the same in both periods.
The percent of fixed and organic solids excreted by the hogs was calculated from data on the composition of the feed and the hog manure. The ash and organic content (fixed solids) of the feed were calculated to be 4.61 and 81.06 percent, respectively. Therefore, during the summer of 1961 when the average daily feed intake was 4.85 lbs/pig, the total daily intake per pig was 0.224 lbs of fixed solids and 3.96 lbs of organic matter. For the same period, the average daily manure production was found to be 3.92 lbs per pig. The fixed solids constituted 3 percent of the manure; i.e., 0.118 lbs, and the organic solids constituted 15.5 percent of the manure; i.e., 0.607 lbs. Thus, the percent of the feed fixed solids excreted by the hogs was 52.2, and 47.8 percent was retained. The percent of the feed organic matter excreted was 15.3, and 84.7 percent was retained by the animals. For the spring of 1962, the values for the percent of fixed and organic solids excreted by the hogs were calculated in the same manner and found to be 62.0 and 16.8, respectively. On the average, 57 percent of the fixed and 16 percent of the organic solids intake were excreted by the hogs.

The moisture content of the manure was estimated theoretically using a total water mass balance on a growing pig. A total water mass balance was derived in the same manner as the total mass balance presented in a previous section of this thesis. The water mass balance is more complicated than the total mass balance due mainly to the difficulty in estimating the quantity of the metabolic water produced. Metabolic water is the end product of the metabolism of the carbohydrates, fats and proteins of the feed. For example, when the carbohydrate glucose is
burned to furnish energy for body processes, carbon dioxide and water result as shown by the following chemical equation:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O$$

Generally the amount of metabolic water produced in an animal is 60 percent of the weight of the digested carbohydrates, over 100 percent of the weight of the digested fat and 42 percent of the weight of the digested proteins of the feed (Babcock, 1912).

A total water mass balance can be expressed in the form of Equation 3:

$$W_f + W_i + W_m = W_g + W_r + W_w$$

where:

- $W_f$ = mass of the water content of the feed in lbs/day,
- $W_i$ = mass of the daily water intake in lbs/day,
- $W_m$ = mass of the metabolic water in lbs/day,
- $W_g$ = mass of the water in the daily mass gain of the pig in lbs/day,
- $W_r$ = mass of the water removed by the ventilating air in lbs/day, and
- $W_w$ = mass of the water in the feces and urine of the pig in lbs/day.

In a previous section of the thesis, the values of $W_f$, $W_i$ and $W_r$ were found to be as follows: $W_f = 0.15 M_{f_1} = 0.73$ for the summer and 0.90 for the spring period; $W_i = M_{w_1} = 9.20$ for the summer and 10.93 for the spring period; $W_r = M_{w_r} = 7.44$ for the summer and 4.80 for the spring period.

The term $W_g$ is equal to 75 percent of the total daily gain of the pig (Maynard and Loosli, 1956); i.e., $W_g = 0.75 M_g = 1.06$ for the summer and 1.15 for the spring.
The amount of metabolic water was estimated as follows: The metabolic water yielding components of the feed (Table 6) were multiplied by their respective conversion factors as given by Babcock (1912), and it was found that if the water yielding components of the feed were digested completely to carbon dioxide and water, 47 percent of the feed intake was converted to metabolic water. However, only a percent of the feed ingredients is digested by the animal and, therefore, the percent of feed converted to water is less than 47. The laboratory analyses indicated that approximately 84 percent of the volatile matter of the feed was retained by the animal. Assuming that 90 percent of the retained volatile matter was digested completely by the animal, the percent of feed converted to metabolic water is about 36 (47 X 0.84 X 0.90). Thus

\[ W_m = 0.36 \times M_f_i = 1.75 \] for the summer and 2.22 for the spring period.

After substitution of the values obtained for the components of Equation 3, the value for \( W_w \) was calculated to be 3.18 lbs/day for the summer and 8.10 lbs/day for the spring period. The total manure for the summer and spring periods was estimated theoretically at 3.74 and 9.13 lbs/day, respectively. Therefore, the water content of the hog manure produced during the summer period is 85.0 percent and 88.7 percent during the spring period. These theoretical estimates of the water content are within 5 percent of the values found in the laboratory analyses. The total solids content of the manure is obtained by subtraction; i.e.,

\[ 100.0 - 85.0 = 15.0 \] percent for the summer and 11.3 percent for the spring period.
**pH** The logarithm of the reciprocal of the hydrogen ion concentration in the sample in moles per liter is the pH of the manure. It has little bearing on the strength of the manure but is of considerable importance in its biological treatment. The pH values express the intensity of the acid or alkaline conditions of the sample. For raw manure, a high pH value indicated a relatively fresh manure, while a low pH value indicated that the manure in the sample had begun to deteriorate and turn septic.

Measurements of pH were made as soon as the sample was brought into the laboratory. The pH of the raw manure was determined in accordance with the glass electrode procedure described in APHA (1960). A Beckman Zeromatic pH meter, Model 9600, was used. The pH range of the manure tabulated in Table 11, is favorable for biological treatment since the optimum pH range for the anaerobic bacterial decomposition of organic matter is from a pH of 6.5 to a pH of 8.0. A pH of fresh manure between 7 and 8 favors the hydrolization of the urea of the urine and, through bacterial action, the formation of ammonia as shown in the following equation:

\[
\text{CO(NH}_2\text{)}_2 + \text{H}_2\text{O} \rightarrow (\text{NH}_4\text{)}_2\text{CO}_3 \rightarrow 2\text{NH}_3 + \text{CO}_2 + \text{H}_2\text{O}
\]

The ammonia formed enters the atmosphere as gas giving rise to an objectionable odor along with other odor-producing substances such as sulfides and mercaptans. Besides the odor-producing characteristics of ammonia, which are not as objectionable as those from the sulfides, the escape of ammonia represents a loss in the fertilizing value of the manure.
The decomposition of urea is inhibited if the pH is below 7.0. However, the rate of ammonia formation from urea is proportional to the concentration of \((\text{NH}_4\text{)}_2\text{CO}_3\) in the manure and the manure temperature. Therefore, during the warm months of the year when the temperature and the water evaporation losses are high, the loss of nitrogen as ammonia gas from the floor is considerably greater than during the cold periods of the year.

**Total nitrogen**  
Nitrogen data are extremely important in connection with waste treatment. If an aerobic treatment is to be used for the waste, such as aerobic lagoons, ammonia and organic nitrogen determinations are important in evaluating whether sufficient available nitrogen is present for optimum bacterial action. If the manure is to be used as a fertilizer, the nitrogen content of the manure is a major factor in determining its value for such a purpose.

The chemistry of nitrogen is complex because of the several valences that nitrogen can assume and the fact that living organisms can bring about changes in the valence state of the nitrogen. Nitrogen can be found in manure in several forms; i.e., as ammonia, as organic nitrogen, and nitrites and as nitrates. Tests have been devised for determinations of nitrogen in all its forms. The Kjeldahl total nitrogen test was used in this study. The total Kjeldahl nitrogen includes both ammonia and organic nitrogen, but does not include nitrite and nitrate nitrogen. However, no nitrite or nitrate nitrogen is present in fresh manure and, therefore, the Kjeldahl test results include all the nitrogen content of the manure samples tested. The total nitrogen of the manure was determined by testing 5 or 10 grams of manure in accordance with the total...
Kjeldahl nitrogen test described in APHA (1960). Because of the solids content of the manure, it was easier to use a sample of known weight rather than a sample of known volume.

The analysis of manure for total nitrogen indicated that on the average the total nitrogen was 1.12 percent of the manure, and 7.02 percent of the solid matter in the manure (Table 11). The corresponding values for domestic sludge sampled from the bottom of the primary digester of the Ames Treatment Plant are 0.32 and 4.52 percent, respectively. The total nitrogen content of the raw domestic sludge can be assumed to be the same as that of the partially digested sludge. If anything, the nitrogen content of the raw sludge would be lower than that of the digested sludge. Considering total nitrogen content as an index of the fertilizing value of a waste, the fertilizing value of hog manure was found to be 3.5 times more than that of domestic sludge on the basis of equal total volumes, and 1.6 times more valuable on the basis of equal dry matter volumes.

A theoretical estimate of total nitrogen in hog manure was made. Practically all of the nitrogen intake of the pigs was in the form of protein nitrogen. Since the pigs were fed a 12- and 14-percent protein ration and, on the average, 16 percent of the protein is nitrogen, the total nitrogen intake of the pigs was 2.08 percent of their feed intake or 0.125 pounds of nitrogen per day. According to Thorne (1930), the recovery in the wastes of the nitrogen intake of a growing pig is 72 percent; i.e., 0.09 pounds of nitrogen are excreted daily. The daily manure production averaged 6.34 pounds, of which 0.09 pound is estimated
to be nitrogen. Therefore, the total nitrogen content of manure should be 1.40 percent. The experimental analysis showed a total nitrogen content of 1.12 percent. The difference in the estimated and measured values is due mainly to the loss of nitrogen from the pen floors as ammonia gas. This loss of nitrogen was discussed in a previous section of the thesis.

During the summer of 1962, analyses of manure for total and ammonia nitrogen were made periodically. The results of these analyses showed that the total nitrogen content of the manure was 0.90 percent and 5.62 percent of the total solids in the manure. These summer nitrogen values are lower than those obtained in the spring indicating that there are higher nitrogen losses during the summer mainly because of the higher air temperatures. The ammonia nitrogen content of the manure averaged 44 percent of the total nitrogen. This percentage of ammonia found in the total manure nitrogen indicates the high rate of urea breakdown since almost all the nitrogen at the time of its excretion from the animal is in the form of organic nitrogen. Thus, if the fertilizing value of manure is to be conserved, the manure should not be left on the pen floors for any length of time.

**COD** The chemical oxygen demand (COD) test is widely used as an index of the strength of sewage. It is of particular use to the operator of a sewage treatment plant because it takes only 3 hours to run the test and is a good indicator of the change in strength of the sewage with time. The COD test represents a wet chemical oxidation of all the carbon present in the sample tested because the sample is boiled with a strong
oxidizing agent such as potassium dichromate under acid conditions. Although the results of the test can be taken to be equivalent to the amount of organic matter present in the sample, no predictable differentiation can be made between biologically oxidizable and biologically inert organic matter. Neither does it indicate the rate at which the biologically active material would be stabilized under conditions that exist in nature. During the COD test, all the organic matter of the sample is converted to carbon dioxide and water. The BOD test, which is discussed later in this thesis, measures the oxygen required to stabilize the decomposable organic matter in the sample by aerobic biological activity while the COD test measures the oxygen required for the chemical oxidation of all the organic matter. As a result, the COD values for a waste are greater than the BOD values.

The COD test was performed in accordance with the procedure outlined in APHA (1960) except that no corrections were made for the chloride content of the samples. The chloride correction was considered negligible because of the small size of manure samples used, 0.15 to 0.20 grams of manure in 50 grams of distilled water, and the high COD values of manure. The result of the analyses are tabulated in Table 11. The average COD value of the manure was found to be 159,000 mg/l of manure, or 1.20 parts of oxygen per part of volatile matter. The latter units of value are more useful in that they express the amount of oxygen required to oxidize chemically the organic matter of the manure; i.e., 1.20 pounds of $O_2$ are required to oxidize 1 pound of the organic matter of hog manure under the conditions that exist in the COD test.
<table>
<thead>
<tr>
<th>Date, 1962</th>
<th>Total solids (%)</th>
<th>Volatile solids (%)</th>
<th>pH</th>
<th>Total nitrogen (%)</th>
<th>COD $10^3$ mg liter</th>
<th>BOD $10^3$ mg liter</th>
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<td>12.9</td>
<td>1.18</td>
<td>7.02</td>
<td>159</td>
</tr>
</tbody>
</table>

aParts of oxygen required per 1 part of volatile matter.

bThese values were not used in the calculation of their respective means. See Table 8.
The biochemical oxygen demand (BOD) of a waste is the amount of oxygen required by bacteria for the biological decomposition of the decomposable organic matter of the waste under aerobic conditions and at a standardized time and temperature. The standardized time and temperature are 5 days and 20° C, respectively. The amount of oxygen that the bacteria use during the decomposition period is determined by the BOD test. It follows that the higher the organic matter content of the waste, the higher will be the BOD value.

The BOD test is widely used to determine the pollutional strength of a waste in terms of the oxygen demand that the waste will exert on the water if discharged into a natural water course in which aerobic conditions prevail. It is a highly informative test. Information concerning the BOD of a waste is an important consideration in the choice of the method of treatment and the design of treatment facilities. The design of a sewage treatment plant is based primarily on the BOD values of the waste to be treated. The units of the plant are designed for the maximum removal of BOD for minimum cost. The efficiency of a treatment is usually measured by the relative BOD values of the waste before and after treatment.

The BOD determinations were performed in accordance with the procedures outlined in APHA (1960). Because of the high organic matter content of the hog manure, high dilutions of the samples had to be made for the BOD test. A sample of 20 grams of manure was weighed to the nearest 0.1 gram and was diluted with distilled water to 2,000 ml giving a 1 percent dilution of the manure. Aliquot samples were taken from the
1 percent dilution and were diluted further to give dilutions of 0.01, 0.0075, 0.005 and 0.0025 percent. The initial and final dissolved oxygen was determined on these four dilutions. The BOD value was calculated according to the procedure outlined by Sawyer (1960). However, because of the high dilution of the manure, the BOD results are subject to error.

The BOD results are tabulated in Table 11. The average BOD of the hog manure was found to be 68,000 mg/l, or expressed in more meaningful terms, the average BOD was 0.54 part of oxygen per part of volatile matter of the manure. Since the daily volatile matter production was measured to be 0.82 pound per pig, the average daily BOD production is 0.44 pound per pig. Fair and Geyer (1954) reported that, on an average, humans produce daily 0.32 pound of organic solids with 0.37 part of oxygen required per part of volatile matter as BOD.

A comparison of the average BOD values for human and hog wastes shows that under the conditions that exist during a BOD test (5 days at 20° C), a pound of hog manure requires 1.5 times as much oxygen as human waste for aerobic decomposition, and each pig will produce 2.6 times as much organic waste; therefore, the pollutional load of 1 pig would be equivalent to the pollutional load of (2.6 X 1.5) 3.85 humans. In other words, the population equivalent of hog manure is about 4 humans.

**Miscellaneous ingredients of manure**

In a previous section of the thesis, a complete list of all the feed ingredients was given. It was also pointed out that research on animal nutrition has shown that practically all the feed constituents appear in
the fecal and urine excreta of the animal. The hog is not able to digest all of the digestible portion of the feed nor is it able to utilize the mineral and vitamin intake. Therefore, if the degree of utilization of the feed ingredients by the animal is known, the quantity of these ingredients in the manure can be approximated without actual measurements.

Furthermore, feed is invariably spilled on the floor and is included in the manure scraped from the pens. This feed which finds its way to the manure insures the presence of practically all of the feed ingredients in the animal excretions.

The pig ration contained, on the average, 0.5 percent phosphorus (Table 3). Assuming an 83 percent recovery in the excreta of the phosphorus intake (Thorne 1930), the phosphorus content of the manure is estimated to range between 0.4 and 0.5 percent, or about 2.5 to 3.2 percent of the dry matter of the manure. Most of the phosphorus is in the form of phosphoric acid, $P_2O_5$. The manure should contain 50 to 100 percent of the amounts of the mineral and vitamin feed additives; i.e., iron, zinc, manganese, calcium, copper, sodium, vitamins A, D$_2$ and B$_{12}$. These elements are added in the feed in small quantities and, thus, they represent a small percentage of the total dry matter content of the manure. However, most all of them are required in minute amounts for the metabolic activities of the bacterial population of manure. The presence of these elements in the manure in small quantities will not inhibit the growth of the microscopic organism but will enhance and support it.

Some substances, when present in large quantities, are toxic to bacteria. One such substance is copper. The copper content of the feed
is only about 4.2 ppm. However, copper oxide to the amount of about 220 ppm are also added to the feed. Copper exerts a definite influence on iron metabolism at the cellular level. It is also a constituent or activator of several enzymes. On the other hand, copper oxide is added to the feed as an antibiotic and its influence on the bacterial population of the manure might be inhibitory to some degree.

Conclusions

The following conclusions are based on the analysis and interpretation of the data on feed and growth characteristics of hogs in confinement and the results of the laboratory analyses of hog manure. The manure was obtained from growing hogs which during this study ranged in size from 35 to 200 pounds.

1. The daily quantity and quality of the manure are affected primarily by the size of the hogs, the type and quantity of the feed intake, the quantity of the water intake and the air temperature.

2. The quantity and, to a considerable extent, the composition of manure can be estimated from data on the daily quantity and composition of the feed intake, the water intake, the size of the hog and the air temperature within the confinement building. Measured and theoretical data on the independent factors are available in many research papers on hog nutrition and housing.

3. The daily quantity of manure varies with the time of year. It is lower during the hot months than during the cold months of the year mainly because of higher evaporation losses of water at higher air
temperatures. For design purposes, a value of 5 pounds of manure per 100 pounds of live weight is suggested as a daily average the year around.

4. The solids content of the manure varies with the time of year mainly because of the variation in the quantity of water in the manure. The average total solids content of the manure is 18.5 percent (83.5 percent volatile) and 15.6 percent (82.9 percent volatile) during the hot and cold months of the year, respectively.

5. The pH of fresh hog manure is favorable for biological decomposition of the manure. It ranges from 7.6 to 8.5.

6. Hog manure is rich in nitrogen. The total nitrogen of the manure is 7 percent of the dry matter.

7. The 5-day BOD of hog manure is 68,000 mg/l; i.e., 0.54 mg of oxygen are required to decompose 1 mg of volatile matter under aerobic conditions and at 20° C. This is equivalent to 0.35 pound of BOD per 100 pounds of live weight.

8. The COD of manure is 159,000 mg/l; i.e., 1.20 mg of oxygen per mg of volatile matter. The COD:BOD ratio is 2.2.

9. Hog manure contains sufficient quantities of carbon, nitrogen, phosphorus and other elements necessary to support bacterial decomposition of the manure under both aerobic and anaerobic conditions.

10. For purposes of estimating the design requirements of a confinement unit manure treatment plant, the following values for the given variables are recommended:
Manure quantity: -- 5.0 lb/100 lb live weight

Manure composition
Total solids -- 17 percent
Volatile solids -- 83 percent (dry basis)
Nitrogen -- 14 percent (wet basis)
BOD -- 7 percent (dry basis)

Population equivalent -- 4 people/pig
HOG MANURE DIGESTION

General Introduction

Untreated hog manure from large units should not be spread on fields and allowed to drain into the underground and surface water resources. It is a pollutant of great magnitude. The water resources of Iowa and the nation already are being polluted at an alarming rate by industrial and domestic wastes. Farm animal wastes allowed to enter the streams of Iowa untreated will accentuate an already serious problem. The wastes must be treated so that their pollutional properties are removed or reduced to a reasonably safe level.

One of the methods of treatment of concentrated organic wastes that has been found satisfactory in municipal and industrial wastes is the process of anaerobic digestion. In some parts of the world the process of digestion of farm wastes has met with success. In Europe, Africa and Asia the digestion of farm animal and plant wastes is being practiced as a means of conserving the fertilizer value of the wastes and recovering valuable methane gas as a source of power for the farm. However, commercial fertilizers and power are relatively more expensive in those parts of the world than in the United States.

The advantages of anaerobic digestion are several: 1) The organic content of the waste is reduced and stabilized so that it is a lesser pollutional hazard. 2) The end products are inoffensive, are soupy in texture and free flowing. 3) Rodents and flies are not attracted to the end products of digestion. 4) The fertilizing constituents of the raw
waste are conserved and, even more, the fertilizer value of the digested materials is higher than in the raw waste. 5) The dewatering characteristics of the digested waste are better than those of the raw waste. 6) Combustible gases are evolved during digestion and these gases have commercial value when sufficiently high volumes of gas can be recovered.

On the other hand, anaerobic digestion as a method of treatment of animal wastes has several limitations: 1) The initial investment for equipment is high. 2) Daily feeding of the digester with the proper amount of waste is required. 3) Care must be taken to store safely the gas which is not being used and avoid explosions by preventing the escape of the digester gas products to the atmosphere. 4) The disposal of the digested materials is a problem even though not as large as the problem of raw waste disposal.

Anaerobic digestion of hog manure was investigated with laboratory-size digesters. These investigations began in January, 1961 and were completed in November, 1962. Preliminary tests were made to determine whether hog manure was digestible. Once the digestibility of the manure was established, further studies were made to determine maximum rates of digestion and the quantity and quality of the gas evolved. The current economic feasibility of anaerobic digestion as a method of treatment for hog wastes was evaluated on the basis of the laboratory findings.

Literature Review

Anaerobic digestion of the settleable solids of municipal wastes has been in practice for over 50 years. No attempt was made to review all
that has been published on the digestion process. The literature, though voluminous, is irrelevant to our studies since the main purpose of this part of the study is the application of the principles of digestion to hog manure and not the exploration of the process itself. Therefore, only the general theory of digestion as it affects the operation of a digester is reported. The information on the general theory of digestion presented here was taken primarily from class lectures attended by the author and from the following references: Buswell and Neave (1930), Buswell and Hatfield (1939), Fair and Geyer (1954) and Babbitt and Baumann (1958). A complete review of the published information on the digestion of animal wastes was made and is also presented in this section of the thesis.

**General theory of anaerobic digestion**

In most sewage treatment plants, the solids separated from the liquid waste are fed to an anaerobic flora which converts them into inoffensive end products. The process is termed sludge digestion. Commercially valued combustible gases are evolved during the digestion of the organic matter of the sludge. These gases are mainly methane and carbon dioxide.

The anaerobic degradation process is a highly complex series of reactions brought about by a mixed culture of bacteria. It differs in many respects from other types of fermentations. The most important difference is that it is neither necessary to use a pure culture of bacteria nor to maintain such a culture for inoculation or reinoculation. The bacteria that are capable of decomposing organic substances and of
producing methane gas are found almost universally in nature, but particularly in decaying matter. They are found in abundant numbers in human and animal excreta. Under proper conditions these bacteria can be cultivated to a high degree of activity within a few weeks. This bacterial flora can then be maintained at this high level of activity indefinitely provided their environment is kept favorable.

Sludge digestion, in contrast to most fermentations, is a continuous process. Once the process starts, it is possible to feed continuously the substrate at one point and withdraw continuously residue from another, while methane and carbon dioxide are given off at a steady rate. Furthermore, there is no limit to the size of the digestion apparatus. This latter characteristic is of considerable significance in that laboratory-size digesters can be used to evaluate the digestive characteristics of a substrate without too much concern about scaling effects. Thus, laboratory data can be used to evaluate the design and formulate the operational procedures of much larger digestion plants.

A third characteristic of sludge digestion is that the organic substrate does not need to be pure. Any kind of pure and/or mixture of organic substances are decomposed and the end products are always methane and carbon dioxide. The latter is somewhat unique in anaerobic digestion. The entire substrate - cellulose, fats and proteins - with the possible exception of a small amount of fiber, is converted during the digestion process to methane and carbon dioxide. A fourth characteristic of the anaerobic digestion process is that it can be carried out within a wide range of temperature, provided the temperature is
maintained at a constant level. The rate of digestion increases with increase of temperature from 32°F to 140°F.

Two phases of decomposition occur in the digestion of organic matter: the liquefaction stage and the gasification stage. The first stage is brought about by a highly mixed culture of bacteria, the majority of which are saprophytes. These bacteria are capable of rapid reproduction and are not as sensitive to changes in environmental conditions as the bacteria which are responsible for the gasification stage. Extracellular enzymes excreted by the saprophytes bring about the liquefaction of the organic matter. Complex carbohydrates are converted to simple sugars and alcohols, lipids to glycerol and fatty acids and proteins to peptides and amino acids. The first culture of bacteria carries the decarboxylation even further by converting all the alcohols, fatty acids and amino acids to volatile acids and water. The two stages of degradation and the main intermediate products are shown in Figure 5.

Although the controlling factor in digestion is the liquefaction phase (without liquefaction of the solid particles no gasification can proceed), in the operation of an actual digester, the establishment and maintenance of proper growth conditions for the gasifying bacteria is the limiting factor. The gasifying organisms are again a mixed culture of bacteria called methane formers. They are capable of utilizing the end products of the acid-producing bacteria and convert the acids to methane and carbon dioxide. The methane bacteria are strict anaerobes, the majority of them are nonmotile, have low rates of reproduction, are extremely sensitive to pH and temperature changes and require carbon
Figure 5. Schematic diagram of the pathways and stages of decomposition of organic matter under anaerobic digestion conditions
HOG MANURE

INORGANIC

NITROGENOUS

PROTEINS

PEPTIDES

AMINO ACIDS

COMPOUNDS OF

Cu, P, K, Zn, Mn
Ca, Co, Fe, H, O

H2O

CH4

CO2

CELLULOSE LIGNIN

SULFIDES

ACID-PRODUCING BACTERIA

MAIN ANAEROBIC DIGESTION END PRODUCTS

ORGANIC

CARBONACEOUS

LIPIDS

GLYCEROL

FATTY ACIDS

ALCOHOLS

VOLATILE ACIDS

SULFURESous

FIBER

CARBOHYDRATES

MAIN ANAEROBIC DIGESTION END PRODUCTS
dioxide for the reduction of the volatile acids to methane.

The conversion of acids to methane is accomplished with intracellular enzymes secreted by the methane bacteria. In the absence of methane bacteria, the digestion process succeeds only in liquefying the sludge, often rendering it more offensive than the raw sludge. On the other hand, if under certain conditions liquefaction proceeds at a faster rate than gasification, the resultant accumulation of acids inhibits further the methane bacteria and the digestion process malfunctions. Thus, both the acid- and methane-producing bacteria must be in proper balance in a properly functioning digester. However, the optimum conditions for the gasifying bacteria are also satisfactory for the liquefying bacteria because the latter group of microorganisms is not as sensitive to environmental changes.

**Principles of digester operation**

The main factors that are of importance in the operation of anaerobic digesters are: 1) pH, 2) temperature, 3) loading rate, 4) volatile acids concentration, 5) detention period, 6) scum formation, 7) solids concentration, 8) toxic substances, and 9) essential nutrients.

The optimum pH range for digestion is from 7 to 8. Digestion is inhibited below a pH of 6.5 and ceases below a pH of 4.5. Once digestion is established, the pH reaches about 7 and the sludge becomes well-buffered; i.e., its hydrogen ion concentration remains unchanged even when relatively large amounts of acid or alkali are added. If the buffering capacity of the sludge is destroyed, the pH declines and the digester ceases to function properly and eventually goes "sour."
The temperature range for digestion is from 32°F to 140°F. However, the two optimum temperature ranges are the mesophilic, 85 to 105°F, and the thermophylic range, 120 to 140°F. Most digesters operate in the mesophilic range where optimum digestion is attained at about 95°F. The rate of digestion at temperatures above 120°F is higher than the digestion rate at any other temperature range. However, few digesters are operated at the thermophilic range because of the high sensitivity of bacteria to environmental changes at that range, the poor quality of the supernatant liquor and the difficulty in maintaining such high temperatures, particularly in northern climates.

Digestion is not affected by an increase in temperature of a few degrees. However, a decrease of only 5°F from that at which the bacteria had been working will arrest the production of methane by the methane bacteria without materially affecting the acid-producing bacteria. Thus, a small drop in temperature may result in an excessive accumulation of acids and in digester failure.

The loading rate of a digester commonly is expressed as the weight of volatile solids fed per day per cubic foot of digester capacity. Most conventional digesters operate at loading rates ranging from 0.06 to 0.15 lb of volatile solids per day per cubic foot of digester capacity (lb/d/ft³). Mueller, et al. (1959), reported that the maximum gas production, 8.0 ft³/lb of volatile solids fed, was attained at a loading rate of 0.1 lb/d/ft³ of digester. He and his co-workers, using 10-liter laboratory digesters, found that at loadings higher than 0.1 lb/d/ft³ the gas production decreased and the volatile acids increased. Their
findings on single stage digester agree with results obtained by others (Etzel and Pohland, 1960; Hindin and Dunstan, 1960). In recent years, work with high-rate digestion has shown that digester loadings of up to \(0.345 \text{ lb/d/ft}^3\) of digester and detention times as low as 7.2 days are possible (Morgan, 1954). However, high-rate digestion requires continuous mixing of the sludge, preferably by gas recirculation, and frequent feeding.

The concentration of the volatile acids normally should not exceed a predetermined value usually 2,000 to 3,000 mg/l expressed as acetic acid. If the volatile acids concentration rises much over 2,000 mg/l, methane gas formation drops, the acids increase rapidly because the methane-producing bacteria cannot utilize them at the rate the acids are produced, and digestion ceases within 2 to 3 days. The main causes of acid digestion are high loading rates, drop in temperature and scum formation. Decrease of loading rates and dilution have sometimes been found to be effective remedies for sour digesters. For normal operation the volatile acids in the digester should be maintained below 300 mg/l (Backmeyer, 1955).

The optimum detention period or time is the digestion time required to obtain maximum gas production and volatile solids destruction. It is the hydraulic loading of the digester expressed in days of average displacement of the digesting sludge. A detention time of 30 days is used frequently in conventional digesters maintained at 95°F. However, laboratory and pilot plant studies with high rate digesters have demonstrated that detention periods of less than 10 days are possible.
A condition that should be avoided in digester operation is the formation of a considerable amount of scum and the accumulation of fibrous material. The objection to scum is that it constitutes a zone of high substrate concentration in which a high concentration of acids develops. Scum formation must be avoided by mixing the digester contents continuously if possible. Mixing of the digester contents aids the digestion process in that it establishes uniform conditions within the digester. Fibrous materials are liquefied at much slower rates than most other organic substances. An accumulation of fibrous material favors the accumulation of large amounts of acid (Buswell and Hatfield, 1939).

Satisfactory digestion at solids concentrations of 15 percent and more has been attained. However, the practical range of solids concentration is below 10 percent (Liebmann, 1956). Presence of toxic substances in excessive amounts is detrimental in that the growth of the bacteria is inhibited. Copper in small quantities is a stimulator to the enzymatic activity of bacteria but is toxic in high concentrations. Other substances which have been found to adversely affect digestion when in high concentrations are: cyanides, phenols, detergents, free acids, alkalies and trivalent chromium (Lohmeyer, 1959). The concentrations at which these substances become toxic have not been established clearly. Most of these substances are found in industrial wastes; rarely are they found in toxic concentrations in human or animal wastes. However, copper is included in the hog feed and, thus, is present in hog manure. The essential elements for the bacterial metabolism such as carbon, nitrogen...
and phosphorus must be present in sufficient amounts and easily available to the bacteria.

**Digestion of farm wastes**

Fry in South Africa and a number of German investigators have recently conducted research on digestion of farm wastes and have published their results. In Germany, a firm is designing, manufacturing and selling digestion units under the trade name of Bihugas Plants. Buswell and Hatfield (1939) reported numerous batch and continuous feeding digestion experiments with paunch manure and cornstalks.

Fry (1961a, b, c) began experimenting with digestion of pig wastes during the middle 50's and by 1957 had installed a digestion unit on his farm which unit has been in continuous operation ever since. His unit consists of a collection pit, a digester, a gas holder and an engine room. Since his 500 pigs are scattered in small units, he brings the daily dung to the collection pit, dilutes it with water and then introduces it into the heated digester. The digester roof is made of concrete. The gas is collected into a fixed roof container and from there it is used to run a converted diesel engine. The engine runs a generator which produces ample electricity for his farm.

The gas production from Fry's system is 10 cubic feet per day per "average size" pig with a heating value of 711 BTU per cubic foot. The fertilizer value of the effluent sludge is reported to be 10 percent dry matter containing 6 percent nitrogen, 5 percent phosphates and 1 percent potash [on dry basis]. No other details were given by Fry primarily because he is hoping to sell his idea commercially.
Reinhold and Noak (1956) conducted batch digestion studies using 2-liter bottles to determine the time required for digestion of animal wastes and vegetable refuse. They filled each bottle to the 1-liter mark with the waste diluted with water to a total solids concentration of 1.6 percent and placed the airtight bottles in an incubator. Each bottle was shaken daily by hand to provide some mixing of the contents. The temperature of digestion and the results are shown in Table 12.

Assuming that digestion is completed when 90 percent of the gas evolved has been produced (Keefer, 1959), it is noted in Table 12 that while all the farm crops digest in less than 20 days, the animal wastes require more than 30 days. The table also shows that pig manure digests at a faster rate than the cow or horse manure. Moreover, the production of gas per gram of organic matter is highest for pig manure when compared with other animal wastes tested by Reinhold and Noak (1956). However, it is interesting to note that the production of gas per unit weight of seeds, green grass and potato tops is greater than the gas produced from animal wastes. This is the reason the units built to digest animal wastes from a farm in Germany also utilize plant materials. In this way not only higher gas yields are obtained but also the fertilizer value of the plant wastes is conserved. At times of low manure production, green plants can be used to keep the digesters in operation. Although more manure is produced daily from cows, Table 12 indicates that the gas production per unit weight of cow manure is less than that of hog or horse manure because of the "double chewing" of food by cows. Reinhold and Noak (1956) concluded that the specific gas yield from farm animals
Table 12. Results of batch digestion studies of animal wastes and vegetable refuse

<table>
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<tr>
<th>Item</th>
<th>Winter feeding</th>
<th></th>
<th>Summer feeding</th>
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<th>Green grass</th>
<th>Plant seeds</th>
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<td>Horse</td>
<td>Cow</td>
<td>Pig</td>
<td>Horse</td>
<td>Cow</td>
<td></td>
</tr>
<tr>
<td>Temperature of digestion, °C</td>
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<td>30</td>
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<tr>
<td>Days of digestion</td>
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<td>112</td>
<td>117</td>
<td>119</td>
<td>119</td>
<td>100</td>
<td>53</td>
</tr>
<tr>
<td>Gas, ft³/lb</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile solids</td>
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<td>6.89</td>
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<td>6.74</td>
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<td>9.71</td>
</tr>
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<td>3.80</td>
<td>6.20</td>
<td>5.86</td>
<td>3.52</td>
<td>8.43</td>
</tr>
<tr>
<td>CH₄ content, %</td>
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<td>75.7</td>
<td>80.2</td>
<td>81.1</td>
<td>71.0</td>
<td>85.4</td>
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<td>771</td>
<td>780</td>
<td>682</td>
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<td>718</td>
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<td>% gas produced in</td>
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</tr>
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<td>5 days</td>
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<td>21.1</td>
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<td>23.6</td>
<td>45.9</td>
<td>31.5</td>
<td>30.5</td>
<td>85.0</td>
</tr>
<tr>
<td>15 days</td>
<td>57.2</td>
<td>47.0</td>
<td>36.3</td>
<td>61.9</td>
<td>52.1</td>
<td>51.2</td>
<td>89.5</td>
</tr>
<tr>
<td>20 days</td>
<td>67.6</td>
<td>60.7</td>
<td>48.5</td>
<td>71.4</td>
<td>66.1</td>
<td>64.1</td>
<td>91.7</td>
</tr>
<tr>
<td>25 days</td>
<td>74.4</td>
<td>70.4</td>
<td>59.4</td>
<td>76.9</td>
<td>74.3</td>
<td>71.0</td>
<td>93.4</td>
</tr>
<tr>
<td>30 days</td>
<td>80.0</td>
<td>76.6</td>
<td>66.7</td>
<td>80.5</td>
<td>80.0</td>
<td>77.3</td>
<td>94.7</td>
</tr>
</tbody>
</table>

aData for this table were taken from Reinhold and Noak (1956). The Metric System units in which some of the results were reported were changed to British System units.

bWinter feeding consists mainly of grain rations; summer feeding includes pasturing of the animals.
depends primarily on the quantity of the feed intake, the composition of the feed and the age and race of the animal.

Schmidt (1951), in 1950, built a digestion unit for agricultural materials. Because Schmidt used vegetable refuse and animal bedding in addition to dung and urine, a floating scum of considerable magnitude tended to form in the digesters and thus inhibit the proper functioning of the unit. Stirring mechanisms such as the ones used in municipal sewage treatment plants were found ineffective in the destruction of the scum cover. The destruction of the floating sludge cover was accomplished by circulating the contents of the digesters by means of a pump and a set of nozzles. A pump sucks the thin sludge from the bottom of the digester and discharges it through a pipeline into a jet nozzle. The jet nozzle can be moved up and down by a telescoping pipe. The destruction of the floating sludge cover is done three times a day taking about 15 minutes each time. The mixing operation is reversible. When the digester is overfilled, the upper layers of sludge are sucked in through the nozzles and are pumped to unheated storage silos. The withdrawn sludge remains in the storage silos up to the time of field distribution.

The procedure for feeding the digesters includes premixing of supernatant sludge with the raw materials. The raw materials (dung, urine, chopped hay, bedding, potato tops, weeds, etc.) are brought to the mixing tank and are stirred mechanically. Part of the resulting magma is pumped into the full digesters. Thin sludge from the bottom of the digesters overflows into the mixing tank where it is mixed with the raw materials and pumped back into the digesters. The quantity and ratio of mixing is
not stated by Schmidt (1951).

According to Schmidt (1951), the chief value of the plant is the preservation of the humus and fertilizing components of the manure and vegetable refuse. The gas is only a by-product of the process. Thus, it was interesting to note in Schmidt's data that to avoid, so far as possible, any nitrogen losses from the manure, the stables were cleaned daily and the manure was not left exposed to air. The manure was collected and pumped into a covered pit three times daily taking 10 minutes each time.

In 1954 Schmidt and Eggergluus (1954) built another large plant in Breitenburg, Germany. The plant consisted of four digesters, two storage tanks for manure and one tank for gas storage. The average daily output of gas in this plant was 23,000 cubic feet. The gas was 62 percent methane and about 38 percent carbon dioxide with a gross heating value of 660 BTU/cu ft. The octane figure for this gas was 115. It contained less H₂S, 200 grams per 100 cubic meters (88 grains per 100 cu ft), than diesel oil which in Germany has a sulfur content of 0.5 to 1.0 percent on a weight basis.

Farm tractors capable of 28 B.H.P. were powered from the gas produced from the digestion of farm organic wastes. The gas was first compressed by a compressor into large high-pressure storage tanks up to 350 atmospheres (5,000 psi), and from there it was placed in two steel cylinders fitted on each tractor. These cylinders had a pressure of 200 atmospheres (2,840 psi). In some plants, the CO₂ content of the gas was washed out and the gross heating value increased up to about 1,000 BTU/ft³.
Other uses for the gas included heating of farm buildings, drying, refrigeration, and production of electricity. In Bavaria, a generator powered from the gas produced from a Bihugas plant provided enough electricity to even out the peaks in the consumption of electricity during working hours.

According to Schmidt and Eggergluess (1954), the main advantages of a Bihugas plant are: 1) mechanization of manure handling, 2) prevention of loss of nitrogen from raw manure thus increasing the fertilizer value of manure, 3) control of the loss of organic matter from manure, and 4) destruction of weed seeds during digestion. These advantages appeared to the above authors to be sufficient to recover the total cost of a Bihugas plant within a short time, about 10 years.

Buswell and Hatfield (1939) reported the work of C. S. Boruff on the stabilization of animal paunch manures and packing house screenings. Boruff investigated the digestion of hog and cow paunch manure with 10-liter laboratory digesters. The digesters were fed at the monthly average rate of 0.38 lb of total solids per day per cubic foot of digester capacity. The main difficulties encountered were control of loading rates to assure the presence of sufficient material undergoing the desired fermentation in the digester at all times and the formation of a scum layer from the fibrous matter of the manure. Mixing of the digester contents by inverting the bottles a few times a day alleviated the problem of fibrous mat formation. When the volatile acids indicated that the proper fermentation was not taking place, the feeding of the digesters was reduced or stopped completely for a few days.
The digesters were operated at room temperature; i.e., 77° to 85°F. The average volatile acids concentration was 1,400 mg/l. The gas yield was 9.0 ft^3/lb of volatile matter added. An average of 72 percent of the weight of volatile matter added to the digester was recovered as gas. Gas analysis showed a methane content of 53.3 percent by volume. The carbon dioxide content was 45.4 percent and the rest of the gas consisted of nitrogen (1.0 percent) and hydrogen (0.3 percent). Cow paunch manure yielded only 4.9 ft^3/lb of volatile matter. Only 35 percent of the volatile matter was recovered as gas, but the methane content of the gas from cow paunch manure was 61.2 percent by volume giving this gas a higher heat value per cubic foot (600 BTU/ft^3) than hog paunch manure (520 BTU/ft^3).

Hart (1960) studied the digestion of cow and chicken manure with eight 1-gallon laboratory digesters. The digesters were fed every 2 weeks with sufficient quantities of manure to give loading rates which ranged from 0.122 to 0.305 lb of organic matter per day per cubic foot of digester capacity. Two different digestion temperatures were investigated. Hart concluded that a temperature of 95°F was more advantageous than 74°F. Hart's data indicated that cow manure was easier to digest than chicken manure. The volatile acids tended to increase to high concentrations in digesters operating with chicken manure. However, Hart concluded that anaerobic digestion was a feasible method of stabilizing both cow and chicken wastes.
Experimental Investigations

Laboratory bottle digesters were used in the experimental investigation of the anaerobic digestion of hog manure. The main aims of the investigations were: 1) to establish the digestibility of hog manure, 2) to determine the maximum rate of digester loadings, and 3) to measure the quantity and quality of the gas yields. It was pointed out in a previous section of the thesis that the hog excreta contained copper oxide which is included in the hog feed as an antibiotic. It was suspected that the copper oxide might prevent the manure from digesting properly. However, the preliminary investigations showed that the manure was digestible under properly controlled conditions.

Once the digestibility of manure was established, experiments were made to determine the maximum loading rates and minimum detention periods with which the digester could be operated. The criteria used to evaluate how well the digesters functioned were: the volatile acids test, the ammonia nitrogen concentration, total and volatile solids content, and the quantity and quality of the gas produced. The gas yields were measured daily and analyses with a chromatography column were made periodically to determine the quality of the gas by measuring its methane and carbon dioxide content.

The procedures and results of the laboratory investigations can be applied to design and formulate the operational procedures of an actual hog manure digestion plant since, as was pointed out previously, a unique characteristic of the anaerobic digestion process is that the size of the digester does not affect the process.
Preliminary investigations

Four 5-gallon bottle digesters were used during the preliminary investigations. The bottles were tightly stoppered with rubber stoppers which were held in place by a steel plate. Two glass tubes, one for withdrawal of sludge and another for gas release, were inserted into the bottle digesters through holes bored in the rubber stoppers. The withdrawal tube extended inside the digester to about 3 inches from the bottom of the bottle and, on the outside, protruded about 2 inches above the rubber stopper. The gas release tube extended only 3 inches below the top of the digester and, on the outside, connected to a wet test meter. To protect the wet test meters from corrosion, the gas was put through a flask containing a saturated solution of copper sulfate before it entered the gas meters.

Partially digested sludge from the primary digester of the Ames Sewage Treatment Plant was used to seed the laboratory digesters. The digesters were fed by removing the rubber stopper and pouring the raw sludge into the digester. Digested sludge was withdrawn from the digester with the aid of a vacuum pump. The gas was discharged into the atmosphere after it had been measured by a wet test meter.

Experiments with the four digester bottles were carried out during three periods, each time the procedure of feeding being different. During the first period\textsuperscript{a}, March 7 to May 3, 1961, the seeded digesters were operated in the Engineering Annex. The digester temperature varied

\textsuperscript{a}During this period Clinton J. Edmonds operated the digesters because the author was in the midst of his Ph.D. preliminary examinations.
varied between 84° and 88°F. Two of the digesters were fed domestic sludge throughout the period. Two digesters were fed a mixture of raw domestic sludge from the Ames Sewage Treatment Plant and hog manure from the confinement building. Eventually, the latter two digesters were fed only hog manure. However, before hog manure feeding was initiated, the digesters had already gone sour presumably from lack of temperature control.

The second period of experiments lasted from June 1 until July 19, 1961. The same four digesters were used. Fourteen liters (about 0.5 ft$^3$) of partially digested sludge from the primary digester of the Ames Sewage Treatment Plant were placed in each digester.

The detention time was maintained at 28 days; i.e., each day 500 ml of raw sludge were added and an equal or less amount was pumped out. Up until June 21 the digesters were fed only raw domestic sludge. Between June 21 and June 26, a mixture of hog manure and domestic sludge at a ratio of 3:2, 300 ml of hog manure and 200 ml of domestic sludge, were fed to each digester. During the next week the ratio of hog to domestic sludge was raised to 4:1. During this period the gas production from each digester reached its maximum, about 0.8 ft$^3$ of gas per day. On July 3 the raw sludge fed to the digesters was all pig manure. However, soon thereafter the gas production began declining and the digesters never recovered. On July 5, the digesters were moved into a constant temperature room in the Agricultural Engineering Building. For a few days the digesters were not fed in an attempt to get them to function properly. Instead, the volatile acids in the digesters reached a level of 12,000
mg/l as acetic acid. Therefore, the digesters were emptied and restarted.

The next period of experimentation began July 19 and extended through September 18, 1961. Fourteen liters of partially digested domestic sludge were placed in each digester in the same constant temperature room of the Agricultural Engineering Building. The temperature was maintained at 93° ± 1°F. The detention time and organic loading of each digester was strictly controlled. The detention time was maintained at 28 days for all digesters. Three of the digesters were fed at the rate of 0.1 lb/d/ft³. The fourth digester was fed at the rate of 0.15 lb/d/ft³. The fourth digester and two of the other three digesters were shaken by hand twice daily; before digesting sludge was withdrawn and after raw sludge was fed.

From July 19 until July 28 raw domestic sludge was fed to the digesters. After July 28, hog manure was used. Within 5 days, the daily gas production reached a plateau which the digesters maintained until August 16 when the temperature in the room was allowed accidentally to drop to 85°F for 8 hours. This drop of 8°F in the room temperature resulted in the digesters going sour. Attempts to recover the digesters by lowering the loadings at first and later by dilution failed. The gas production from the digester which was operated at the loading rate of 0.15 lb/d/ft³ began to decline 2 days before the drop in temperature occurred. The volatile acids in this digester had reached and exceeded 2,000 mg/l by August 15 while the volatile acids in the other digester averaged about 1,000 mg/l on that day. At first the gas production from the digester that was not being shaken remained equal to that from the
digesters which were fed at the same loading rate but were shaken daily. However, its gas production rate began to decline after 13 days.

The gas production from the digesters which were fed 0.1 lb/d/ft$^3$ averaged 6.3 ft$^3$ per day per lb of volatile solids fed. The average gas production from the digester fed 0.15 lb/d/ft$^3$ was 5.7 ft$^3$ per day per lb of volatile solids fed.

The experimental data obtained from the operation of the four digesters during the period between July 19 and September 18, 1961, indicated that hog manure at loadings of 0.1 lb/d/ft$^3$ can be digested. They also indicated how critical temperature control and rate of mixing of the digester contents are in the anaerobic digestion process.

**Main test program**

The main experiments were conducted from March through November, 1962. In March 1962, the digestion cabinet of the Sanitary Engineering Laboratory became available for the experimental phase of this study. This apparatus was used for the rest of the experiments.

**Apparatus**

Six bottle digesters were used in this phase of the study. The digesters were 5-gallon pyrex bottles which were sealed at the top with No. 12 rubber stoppers. The stoppers were held in place by a steel plate which was held tightly to the bottle neck by two bolts. Three holes were bored through each stopper and one glass tube of 1/2-inch diameter and two tubes of approximately 1/8-inch diameter were placed in the three holes (Figure 6). The large tube extended to the center of the digester and on the outside protruded from the stopper.
Figure 6. Schematic diagram of a bottle digester at erect and reclining positions
GAS SAMPLING TUBE

GAS PRESSURE RELEASE TUBE

1/2" DIAMETER SLUDGE FEED TUBE

LEVEL OF SLUDGE

1/4" PLEXIGLASS MIXING PADDLE

LEVEL OF SLUDGE
about 2 inches. Rubber tubing 1/2 inch in diameter was placed at both ends of this large tube. The rubber tubing inside the digester was bent so that its end was submerged about 1 inch below the surface of the sludge when the digester containing 7 liters of sludge was tipped on its side (Figure 6, bottom). The rubber tubing on the outside end of the glass tube was clamped so that no gas could escape nor air enter the digester. Both the feeding of raw sludge and the withdrawal of digesting sludge was done through the 1/2-inch tube. Figure 6 illustrates a bottle digester in upright position and when tipped on its side.

Both of the small glass tubes extended about 2 inches inside the digester and protruded about 1 inch above the surface of the steel plate. Both tubes were sealed at their outside end, one with a short length of rubber tubing and a pinch clamp and the other with a self-sealing rubber serum stopper. The tube sealed with the rubber serum stopper was used to sample the digester gas for chromatographic analysis and the other was used to release gas to relieve the pressure inside the digester.

A paddle was placed inside each digester. The paddles were made of 1/4-inch plexiglass and were hinged at all joints so that they could be passed through the neck of the digesters. The purpose of the paddles was to aid in the mixing of the contents of the digesters. Mixing of the contents of the digesters was achieved by placing the digester bottles on rubber rollers which rotated around their horizontal axis. The rollers were made of 2-inch diameter steel tubing covered with a rubber-like material (Figure 7). The rollers were supported at each end by self-aligning ball bearings. A 1 HP, 1700 rpm, electric motor accompanied by
a gear reduction box was used to drive one of the rollers. The rest of
the rollers were connected to the drive roller by a drive chain. As the
rollers rotated, the bottles revolved at a rate of seven revolutions per
minute.

Both the mixing mechanism and the digesters were placed inside a
well-insulated wooden digestion cabinet (Figure 8). The temperature in
the digestion cabinet was maintained at 95° ± 1°F. A blower and two 20-
watt heating coils were used. The blower ran continuously while the
heating coils were thermostatically controlled. Both the blower and the
heaters were of high capacity. Unless the doors of the cabinet were
opened, the heaters were never in operation for more than 2 or 3 minutes
at a time. After the doors were opened and the temperature was allowed to
drop, the temperature would again reach 95°F in less than 5 minutes after
the doors were closed. The turbulence created by the blower was suffi­
cient to maintain uniform temperature conditions throughout the interior
of the cabinet. Thermometers placed at various locations within the
cabinet indicated uniform temperature conditions throughout.

The digestion cabinet became available to the author on March 26,
1962. At that time the cabinet was located in the small room underneath
the north stairway of Engineering Annex. On March 29, six bottle
digesters were seeded with digesting sludge and placed inside the cabinet.
The digesters were fed for a week on domestic sludge at an average rate
of 0.05 lb/d/ft³ and then hog manure for 30 days at an average rate of
about 0.08 lb/d/ft³. However, during this month-long period, many diffi­
culties were experienced.
Figure 7. The bottle digesters resting on rubber rollers are driven by a drive chain seen in the background.

Figure 8. Exterior of the digestion cabinet showing the double doors and the mercury manometer mounted on the right side wall of the cabinet.
The major difficulties were: the lack of space in the room, excessive wear of the drive sprocket teeth which permitted the chain to come off the sprockets, the vibration of the steel frame (not secured tightly) which resulted in misalignment of the power chain, and the wear of the screw clamps of the feed tube.

When the drive chain broke and damaged the electric motor on April 22, the cabinet was moved to a large room of the Sanitary Engineering Laboratory, larger size sprockets were attached to the rollers, the steel frame of the mixing mechanism was secured to the cabinet floor, new heavy pinch clamps were used on the feed tube in place of the screw clamps and the electric motor was overhauled. In the meantime, the digesters became sour because their temperature could not be maintained at 95°F during the 10 days it took to repair the mixing apparatus and relocate the digestion cabinet. The digesters were emptied and reseeded on May 10, 1962. Thereafter, no major trouble with the mixing mechanism or the digestion cabinet was encountered. The procedures and results of the operation of the six bottle digesters from May 10 through November 1962 are reported in detail in following sections of the thesis.

Feeding procedure The six bottle digesters were designated as digesters I, II, III, IV, V and VI. Each digester was seeded with 7,080 (+10) grams (equivalent to 0.25 ft³ in volume) of partially digested sludge. The seed sludge was taken from the bottom of the primary digester of the Ames Sewage Treatment Plant to insure a high solids content and an active flora of methane bacteria. Once the digesters were seeded, the rubber stoppers were inserted and clamped onto the bottles with the steel
plate. Sealer ("Permatex") was placed around the edges of the stoppers and the glass tubes to prevent gas leaks. Each digester was weighed before it was placed on the rollers inside the digestion cabinet in which the temperature had already been brought to 95°F. The rollers then were set in motion.

During the first 4 days, neither raw sludge was fed nor was digested sludge withdrawn from the digester to allow time for the organisms in the seed sludge to acclimate themselves to the new environment. On the fourth day, a program of daily feeding was initiated. The sludge fed to the digesters was collected in large quantities from the confinement hog building. Because only small amounts were required for the daily feeding of the digesters, aliquot portions of the manure, 300 to 400 grams in size, were placed inside individual quart-size ice cream containers. The containers were stored in a freezer (Figure 9) where the temperature was maintained below -10°F. At such temperature, all bacterial activity was stopped and, thus, the raw manure characteristics were preserved during the course of the experiments. When sludge was needed for feeding a container was removed from the freezer and thawed inside the digestion cabinet. The sludge temperature was raised to 95°F before it was fed to the digesters.

The daily operating procedure for feeding the digesters and making the necessary readings to determine the course of digestion was as follows:

1) Each morning, including Saturday and Sunday, one carton containing sufficient amounts of sludge for that day's feeding was removed from
the freezer and placed in the digestion cabinet to defrost.

2) At 1 PM, the motor driving the rollers was turned off, and gas pressure readings from each digester were taken. The gas pressures were measured by connecting the gas release tube (Figure 6) of each digester to one end of the 7-foot mercury manometer mounted on the side wall of the digestion cabinet (Figure 8). The gas pressure was read to the nearest 0.1 cm of mercury. Routine readings of the barometric pressure and temperature inside the digestion cabinet also were taken daily at 1 PM.

3) Each digester was weighed to determine any loss in weight during the preceding 24 hours. The digesters were brought to their original weight by withdrawing less sludge than the amount fed on that day if the weight of the digester was less than its original weight. In this way, it was possible to keep the amount of digesting sludge inside the digester constant; i.e., 7,080 (±10) grams.

4) Sludge was withdrawn from each digester. A short glass tube was inserted into the rubber tube extension of the feed tube. The digester was rotated until the rubber tube on the other end of the feed tube was below the surface of the sludge. As the clamp on the feed tube was slowly opened, the gas pressure inside the digester forced out sludge through the tube and into a beaker. The quantity of sludge withdrawn was in excess of the amount of raw sludge which was to be fed that day. The amount of sludge to be discarded was weighed out into another beaker. If no tests were to be made on the digested sludge that day, the excess sludge was discharged into the sewer.
5) The quantity of raw sludge which was to be fed to each digester that day was weighed and tap water added to give the desired volume rate of feeding. Then it was mixed with the digested sludge which had been withdrawn from the digester in excess of the amount discarded.

6) The gas pressure from each digester was released. This was done by connecting the gas pressure release tube to a long rubber tube which carried the gas and released it outside the building.

7) The digesters were fed the mixture of raw and digested sludge prepared in Step 5. The sludge was fed to the digester with the sludge gun (Figure 10). The gun was made of a brass tube, 14 inches in length and 2-3/4 inches in diameter. A 1/2-inch nozzle had been brazed to one end of the tube. The nozzle was stoppered and the sludge to be fed to the digester was poured into the gun. A watertight piston was placed at the other end of the gun. Holding the gun in a vertical position with the nozzle on top, the stopper was removed, the air was forced out, and the nozzle was inserted into the feeding tube. Then the clamp on the feeding tube was opened and the sludge was forced into the digester by pushing in the piston. Air was prevented from entering the digester by raising the piston end of the tube, as shown in Figure 10. In this manner, the air trapped between the nozzle and the valve bubbled up through the feed sludge. After all the contents of the gun were forced out into the digester, the clamp on the feeding tube was shut.

8) The gas pressure release tube was shut.

9) Gas pressure readings were again taken and recorded on the next day's data sheet. These readings were to be subtracted from the gas
Figure 9. Ice cream quart containers filled with manure were stored in freezer at -10°F.

Figure 10. Sludge gun used in feeding digesters.
pressure readings of the next day to determine the amount of gas produced during the day.

10) The drive motor was restarted as soon as all digesters were fed.

**Loading rates and detention period**  Loading rate, detention period and concentration of solids are interrelated. Only two of these three parameters can be varied independently from each other. Once the level of two of these parameters is fixed, the level of the third parameter is also fixed. The relationship between these three digestion parameters is shown in Figure 11. Since all three factors affect the anaerobic digestion process, some decision had to be made as to which two of the three factors to control.

After operating all six digesters for a few weeks at the same detention time, loading rate and solids concentration, the author found that the digester performance as measured by gas production and other criteria was the same for all digesters. Thus, the loading rate, detention time and solids concentration were varied between digesters at different times during the course of the subsequent experiments. For example, from June 3 to August 3, the detention time in Digester VI was maintained constant at 40 days; i.e., 175 grams of total volume were added to the digester daily while the loading rate was varied from 0.08 to 0.026 lb/d/ft³. During the same period, the volatile solids concentration of the sludge fed varied from 5.2 to 1.7 percent. From August 3 to October 3, the loading rate was kept constant at 0.031 lb/d/ft³; the detention time was varied from 100 to 20 days. For other digesters, the solids concentration was maintained constant and the other factors were allowed to vary.
Figure 11. Relationship between three anaerobic digestion parameters: loading rate, detention time and solids concentration
MARKED POINTS INDICATE LEVELS AT WHICH ONE OR MORE OF THE DIGESTERS OPERATED

• • MAY - SEPTEMBER, 1962
++ SEPTEMBER - NOVEMBER, 1962
Figure 11 shows the relationship between the three digestion parameters: loading rate, detention time and solids concentration. The solids concentration lines represent the concentration of the total solids in the raw sludge that is added to the digester. The volatile solids are assumed to constitute 83 percent of the total solids. The solids concentration of the digesting sludge is lower since a part of the solids is destroyed during digestion. The points marked on Figure 11 represent the levels of the three parameters at which one or all of the digesters operated for two or more days during the course of the experiments.

Because of the high sensitivity of the bacterial flora in the digesters to abrupt environmental changes, changes in any of the three digestion factors had to be made slowly to give the bacteria the opportunity to make the necessary adjustments. The digesters were more sensitive to changes in loading rate than to changes in the other two factors. Therefore, rarely was the loading rate increased by more than 0.015 lb/d/ft\(^3\). The detention time was not decreased by more than 1 day once the detention time was 20 days or less. Changes of five to ten or even more days in detention time did not affect the digester performance if the digestion time was 20 days or more. One digester was operated at a total solids concentration level of 8.5 percent. All other digesters were operated at solids concentrations less than 8.5 percent.

**Routine analyses**  The raw manure fed to the digesters was analyzed for total and volatile solids, ammonia and organic nitrogen content, pH and COD. The procedures used for these analyses were in accordance with
standard methods recommended by APHA (1960) and have been described in previous sections of the thesis. The same tests were made on the digested manure to determine the changes in the raw manure brought about by digestion. Tests to determine the volatile acids and the filterability or dewatering properties of the digested sludge were occasionally made on the digested sludge.

The volatile acids test is generally accepted as a criterion of anaerobic digestion. It measures the concentration of volatile acids which, as was pointed out previously, are intermediate products of the anaerobic digestion process. A high volatile acids concentration indicates that the acid-forming bacteria produce acids at a faster rate than the methane formers can utilize. When the volatile acids in a digester exceed 2,000 mg/l for a few days, the digester will not consistently function properly.

These figures might be valid for some sludges but are dependent on the available alkalinity of the sludge. A high alkalinity indicates a large buffering capacity which neutralizes some of the excess acids formed. More important than the actual volatile acids level is the constancy of the value. A rapid increase in volatile acids, even with proportional increase in alkalinity, means that the methane bacteria are not keeping pace with the acid producers. This unequal rate of activity by the two groups of bacteria will lead to digester failure unless measures are taken to balance them out.

The tentative procedure described in APHA (1960) was followed when testing for volatile acids. This method is not an exact test. However,
since changes in volatile acids are of more value than the exact acids concentration in digester operation, the method was considered adequate. A major difficulty with the test was the securing of a stable titration end point. Use of the pH meter instead of the penolthalein indicator failed to give consistent results. The author found that heating the distillate to 60°C gave consistently stable end points. Thus, the distillate was heated to about 60°C before it was titrated with 0.1N NaOH solution. The results of the volatile acids tests were expressed in mg/l as acetic acid. For the most part, volatile acids were determined three times a week.

Periodic tests were made to determine the alkalinity of the digesting sludge. The tests were run in accordance with the procedure described in APHA (1960) except that 1.0N H₂SO₄ was used for titration instead of 0.02N H₂SO₄. The higher normality of the titrant became necessary because of the high alkalinity of the sludge. Also, color change indicators could not be used because of the turbidity of the sludge. Thus, the end point of the titration was set at a pH of 4.5 and was determined with a pH meter.

The ease with which water could be removed from the digested sludge from the different digesters was determined occasionally with the apparatus shown in Figure 12. For these tests, 50 ml of sludge were poured onto a Whatam No. 4 filter paper placed at the bottom of a Buchner funnel (A in Figure 12). The filtrate volume was collected and measured in a 100-ml buret (B in Figure 12) in which a vacuum of 41 cm of mercury was applied and maintained throughout the test. The vacuum was applied with
Figure 12. Apparatus used in filterability tests
A. Buchner funnel
B. Buret
C. Mercury manometer
D. Stabilizing tank
E. Vacuum pump

Figure 13. Digestion cabinet and components of the gas chromatography apparatus
A. Helium gas cylinder
B. Partition column
C. Thermal conductivity cell
D. Power supply unit
E. Recording potentiometer
F. Carrier gas line
G. Blower
H. Thermostat
I. Bottle digester
a vacuum pump (E in Figure 12) and was stabilized by a large tank (D in Figure 12). The relationship between volume of filtrate and time was expressed graphically.

**Gas production** The gas production rates were determined from pressure measurements made daily at 1 PM, the total volume of the digester, the volume of the digesting sludge, and the digestion temperature.

The total volume of each digester was determined by weighing each empty and then filled with water. The volume of the digesting sludge in each digester was 0.25 cubic feet and was maintained at that level by bringing the weight of the digesting sludge to 7080 grams daily. The volume occupied by the gas was the difference between the total digester volume and the volume of the digesting sludge. The digestion temperature was kept constant at 95°F. The solubility of the gases in the liquid was neglected because it did not affect the pressure measurements.

The gas production readings were reduced to standard conditions; i.e., 76 cm Hg pressure and 0°C temperature. The usual formula of the gas law was applied; i.e.,

\[ V_g = V \frac{T_a P_g}{T_g P_a} \]  \hspace{1cm} (4)

and

\[ P_g = P_m + P - P_v \]  \hspace{1cm} (5)

where: \( V_g \) = volume of dry gas at standard conditions, 
\( V \) = volume occupied by the gas in the digester, constant,
\( T_a = \) absolute temperature at standard conditions, 273°K,
\( T_g = \) absolute temperature of the gas, 308°K,
\( P_g = \) absolute pressure of dry gas in digester,
\( P_a = \) absolute pressure at standard conditions, 76 cm Hg,
\( P_m = \) pressure of gas in digester as read from the mercury manometer, cm Hg,
\( P = \) atmospheric pressure, and
\( P_v = \) water vapor pressure at the digestion temperature.

Since the terms \( V, T_a, T_g \) and \( P_a \) were constant, Equation 4 may be written as follows:

\[
V_g = C P_g 
\]

(5)

where: \( C = \) constant.

As was pointed out in a previous section, the recorded gas pressure readings, \( P_m \), were the increases in pressures each day. Therefore, the volume of gas produced per day, \( V_g \), is equal to the difference of the gas volumes computed for the end and the beginning of the day; i.e.,

\[
V_g = V_{g1} - V_{g2} = C (P_{g1} - P_{g2}), \text{ or}
\]

\[
V_g = C (P_m + P_2 - P_v - P_m - P_1 + P_v), \text{ or}
\]

\[
V_g = C (P_m - P_m + P_2 - P_1)
\]

(6)

where the subscripts 1 and 2 designate the beginning and the end of the time interval, one day.
Barometric pressure readings were taken daily during the course of the experiments. However, the average variation in atmospheric pressure was about 3 mm of mercury. This variation in atmospheric pressures from day to day was considered negligible. Therefore, Equation 6 can be written as follows:

\[ V_g = C (P_{m_2} - P_m), \text{ or} \]
\[ V_g = CP_m, \]  

or for the conditions of these experiments

\[ V_g = 0.0055 P_m. \]  

The value of the constant \( C \) was computed by substituting the values given above for \( T_a, T_g \) and \( P_a \) and 0.469 cubic feet for \( V \). The value for \( V \) was the average of the values for each digester. The maximum error in using the average \( V \) value for all digesters was less than 1 percent and, thus, was considered negligible.

All daily gas production rates were calculated from Equation 8 and are, thus, expressed in cubic feet of dry gas at standard pressure and temperature conditions.

Gas analysis Gas chromatography was used for the analysis of the digester gas. The various components of this gas were separated by helium elution from an adsorption column packed with silicone-grease coated firebrick. The detection of the gas components was achieved by a thermal conductivity cell and was recorded with a recording potentiometer.
The apparatus used for gas analysis was built and described in detail by Edmonds (1962). The literature on gas-liquid partition chromatography is voluminous and is beyond the scope of this thesis. The reader is referred to Grune (1960) and Grune, et al. (1956) for a detailed discussion of the use of gas chromatography for digester gas analysis.

The components of the gas chromatography apparatus pictured in Figure 13 and shown schematically in Figure 14 were the following:

A. Helium gas cylinder equipped with pressure controls.

B. Partition column packed with Dow-Corning silicone stop-cock grease coated firebrick. The silicone grease was dissolved in carbon tetrachloride and mixed with C22, 28-40 mesh, crushed firebrick at the ratio of 40 parts of grease to 100 parts of firebrick on weight basis. The grease coated brick was dried and then packed in 50 feet of 1/4-inch O.D. copper refrigeration tube.

C. Thermal conductivity cell. This cell was a Cow-Mac Model TR-11-B. The temperature in the cell was maintained at 260°F. The thermal conductivity cell consisted of two heated sources arranged in a Wheatstone bridge circuit. As the digester gas sample passed over the heated sources, the circuit would become unbalanced due to the heat conductivity of the gas components and a signal would be sent through the power supply unit to the recorder.

D. Power supply unit, Cow-Mac Model 9999-D. This unit supplied and

These capitalized letters correspond to the letter appearing in Figure 13.
Figure 14. Schematic diagram of the components of the gas analysis chromatography apparatus (taken from Edmonds, 1962, p. 52)
HELIUM VALVE
HELIUM GAS CYLINDER
TWO-STAGE CYLINDER REGULATOR
INJECTION ASSEMBLY
PARTITION COLUMN
FLOW CONTROL NEEDLE VALVE
FLOWRATOR
TO ATMOSPHERE
RECORDING POTentiOMETER
POWER CONTROL UNIT
THERMAL CONDUCTIVITY CELL
controlled the power requirement of the thermal conductivity cell and transmitted the signals of the conductivity cell to the recorder.

E. Recording potentiometer. The recorder used was a Sargent recording potentiometer, Model MR.

F. Flow control valve. The flow control valve was situated in the gas line and was used to regulate the flow rate of the carrier gas. The carrier gas was released to the atmosphere.

The sample injection assembly is not pictured in Figure 13, but is shown in Figure 14. It was located immediately before the partition column. The digestion gas samples were injected into the chromatography apparatus at the injection point by a syringe. The syringe was a Hamilton Model 1001 gastight hypodermic syringe accurate to the nearest 5 μl of gas volume.

Gas analyses began in the middle of July 1962 when the chromatography apparatus became operational. Calibration curves were developed by injecting measured volumes of pure methane, carbon dioxide and air into the chromatography column and recording the corresponding peak heights on the recorder. Gas analyses were made before 1 PM. To analyze the digester gas, the hypodermic syringe was inserted into the gas analysis tube (Figure 6) of the digester, and a gas sample of 300 μl was extracted.

The sample was injected into the carrier gas stream at the beginning of the partition column. The increase of gas pressure in the system resulting from the injection of the sample caused a blip on the recorder charts (see Figure 15). As the component gases of the sample passed through the partition column, they were adsorbed by the column and were
Figure 15. Chart recordings by the potentiometer of a typical digester gas analysis
later released to the thermal conductivity cell, each component being released at different rates. The arrival and departure of each of the gas components was recorded on the chart of the potentiometer as shown in Figure 15. Figure 15 shows a typical gas analysis chart. The peak heights produced by each of the components of the gas sample were converted to actual volumes through the use of the calibration curves.

Only three gas components were separated by the chromatography apparatus: air (mostly nitrogen gas), methane and carbon dioxide. Apparently, the hydrogen sulfide content of the digester gas was too small to be detected by the chromatography apparatus. The three digester gas components were expressed in percent of the digester gas.

Analysis and Discussion of Experimental Results

In this part of the study, the experimental procedures and the data collected were designed to fulfill the following objectives: 1) to determine the maximum volatile solids loading rate and the minimum detention period which could be used as criteria in the design of a field digester and 2) to determine the typical gas and manure characteristics that would be produced during the digestion process. To accomplish these objectives, the six laboratory-size digesters and the test procedures described previously were used to collect information concerning the following:

1. Design criteria
   a. Volatile solids loading rate
   b. Detention period
   c. Solids concentration
2. Product evaluation criteria
   a. Quantity of gas yields
   b. Quality of gas yields
   c. Volatile matter reduction
   d. Physical and chemical characteristics of digested manure

Schedule of work

The main test program began on May 15 and was terminated on November 26, 1962.

From June through August 1962, two students, one on full time and the other on a part-time basis, assisted the author in the performance of the routine analyses of digester performance. With the opening of the 1962-1963 academic year on September 12, the services of these students were no longer available. During the period from September 13 to November 26, 1962 the analyses for nitrogen, solids and gas were discontinued, and only the volatile acids test was performed periodically to evaluate the state of digestion. Consequently, the test results have been tabulated and graphed separately for each of the two periods.

The average operating conditions and digestion results for all digesters from May 10 to September 12, 1962 are shown in Table 13. Digesters I and IIIB were abandoned on September 12. Table 14 shows the average operating conditions and results obtained from Digesters II, IV, V and VI during the period from September 12 to November 26, 1962. The daily observations and results from Digester V for the two periods are shown in Figures 16 and 16a and the figures for the other digesters are presented in the Appendix of the thesis.
Table 13. Summary of laboratory results of the anaerobic digestion of hog manure during the period between May 10 and September 12, 1962

<table>
<thead>
<tr>
<th>Seed sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
</tr>
<tr>
<td>Total solids, %</td>
</tr>
<tr>
<td>Volatile solids, % (dry basis)</td>
</tr>
<tr>
<td>Volatile acids(^b), mg/l</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials fed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days fed(^c)</td>
</tr>
<tr>
<td>Total solids, total, gr.</td>
</tr>
<tr>
<td>&quot; &quot; , daily mean, lb/d/ft(^3)</td>
</tr>
<tr>
<td>&quot; &quot; , daily max.(^d), lb/d/ft(^3)</td>
</tr>
<tr>
<td>Volatile solids, total, gr.</td>
</tr>
<tr>
<td>&quot; &quot; , daily mean, lb/d/ft(^3)</td>
</tr>
<tr>
<td>&quot; &quot; , daily max.(^d), lb/d/ft(^3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solids concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total, daily mean, %</td>
</tr>
<tr>
<td>&quot; &quot; , daily max.(^d), %</td>
</tr>
<tr>
<td>Volatile, daily mean, % (wet basis)</td>
</tr>
<tr>
<td>&quot; &quot; , daily max.(^d), % &quot; &quot;</td>
</tr>
<tr>
<td>COD, mean, mg O(_2)/mg V(_m)</td>
</tr>
</tbody>
</table>

\(^a\)Digester IIIA exploded on July 10 and was replaced by Digester IIIB.

\(^b\)The volatile acids were determined 6 days after the digesters were seeded.

\(^c\)The digesters were not fed for 4 days after they were seeded with partially digested sludge.

\(^d\)Values for the first 10 days of feeding were not considered.
Table 13. (Continued)

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>IIIA</th>
<th>IIIB</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Digested sludge</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH, max.</td>
<td>7.4</td>
<td>7.5</td>
<td>7.3</td>
<td>7.5</td>
<td>7.4</td>
<td>7.4</td>
<td>7.5</td>
</tr>
<tr>
<td>pH, min.</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Ammonia nitrogen, mean, mg/l</td>
<td>1467</td>
<td>1523</td>
<td>1040</td>
<td>1326</td>
<td>1240</td>
<td>1199</td>
<td>1285</td>
</tr>
<tr>
<td></td>
<td>2100</td>
<td>2010</td>
<td>1220</td>
<td>2110</td>
<td>1590</td>
<td>1870</td>
<td>1620</td>
</tr>
<tr>
<td>Total nitrogen, mean, % (dry basis)</td>
<td>8.66</td>
<td>9.14</td>
<td>6.70</td>
<td>6.11</td>
<td>8.42</td>
<td>8.47</td>
<td>8.61</td>
</tr>
<tr>
<td></td>
<td>1350</td>
<td>1640</td>
<td>810</td>
<td>1950</td>
<td>1310</td>
<td>1280</td>
<td>1130</td>
</tr>
<tr>
<td>Volatile acids, mean, mg/l</td>
<td>4430</td>
<td>3640</td>
<td>1280</td>
<td>4740</td>
<td>2400</td>
<td>2800</td>
<td>1830</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>2.2</td>
<td>1.9</td>
<td>2.6</td>
<td>1.8</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Volatile solids, mean, % (wet basis)</td>
<td>54</td>
<td>52</td>
<td>41</td>
<td>34</td>
<td>47</td>
<td>54</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>79</td>
<td>46</td>
<td>50</td>
<td>75</td>
<td>70</td>
<td>62</td>
</tr>
<tr>
<td><strong>Gas production</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total volume, ft³</td>
<td>21.44</td>
<td>19.76</td>
<td>8.99</td>
<td>10.77</td>
<td>18.68</td>
<td>20.44</td>
<td>15.74</td>
</tr>
<tr>
<td>Ft³/lb Vm fed, mean</td>
<td>9.08</td>
<td>9.23</td>
<td>9.27</td>
<td>9.70</td>
<td>9.20</td>
<td>9.04</td>
<td>10.09</td>
</tr>
<tr>
<td>Ft³/lb Vm destroyed, mean</td>
<td>16.11</td>
<td>17.50</td>
<td>22.61</td>
<td>27.72</td>
<td>19.58</td>
<td>16.75</td>
<td>23.49</td>
</tr>
<tr>
<td>Ft³/lb Ts fed, mean</td>
<td>7.68</td>
<td>7.84</td>
<td>7.96</td>
<td>8.10</td>
<td>7.82</td>
<td>7.68</td>
<td>8.60</td>
</tr>
<tr>
<td><strong>Gas composition, mean</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane, %</td>
<td>58.6</td>
<td>58.7</td>
<td>--</td>
<td>58.8</td>
<td>59.2</td>
<td>58.5</td>
<td>59.6</td>
</tr>
<tr>
<td>Carbon dioxide, %</td>
<td>40.7</td>
<td>40.6</td>
<td>--</td>
<td>40.6</td>
<td>40.2</td>
<td>41.1</td>
<td>39.7</td>
</tr>
<tr>
<td>Heating value, mean, BTU/ft³</td>
<td>564</td>
<td>565</td>
<td>--</td>
<td>565</td>
<td>570</td>
<td>563</td>
<td>574</td>
</tr>
</tbody>
</table>
Table 14. Summary of results of the anaerobic digestion of hog manure during the period between September 13 and November 26, 1962

<table>
<thead>
<tr>
<th></th>
<th>Digestera</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>II</td>
<td>IV</td>
<td>V</td>
<td>VI</td>
</tr>
<tr>
<td>Days fed</td>
<td>74</td>
<td>74</td>
<td>74</td>
<td>74</td>
</tr>
<tr>
<td>Loading rate, lb/d/ft^3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.079</td>
<td>0.107</td>
<td>0.100</td>
<td>0.077</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.121</td>
<td>0.202</td>
<td>0.168</td>
<td>0.243</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.036</td>
<td>0.064</td>
<td>0.064</td>
<td>0.031</td>
</tr>
<tr>
<td>Detention period, days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>8.8</td>
<td>15.0</td>
<td>9.1</td>
<td>16.0</td>
</tr>
<tr>
<td>Maximum</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>Minimum</td>
<td>7.9</td>
<td>8.7</td>
<td>7.9</td>
<td>7.9</td>
</tr>
<tr>
<td>Volatile solids in raw sludge, % (wet basis)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.12</td>
<td>2.65</td>
<td>1.43</td>
<td>1.95</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.53</td>
<td>2.82</td>
<td>2.12</td>
<td>3.06</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.73</td>
<td>2.01</td>
<td>1.07</td>
<td>1.10</td>
</tr>
<tr>
<td>Total solids in raw sludge, %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.30</td>
<td>3.07</td>
<td>1.66</td>
<td>2.26</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.80</td>
<td>3.32</td>
<td>2.50</td>
<td>3.60</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.84</td>
<td>2.32</td>
<td>1.23</td>
<td>1.26</td>
</tr>
<tr>
<td>Volatile solids destruction, %</td>
<td>59</td>
<td>66</td>
<td>64</td>
<td>68</td>
</tr>
<tr>
<td>Gas production, ft^3/d/lb V_m fed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>7.75</td>
<td>8.96</td>
<td>7.77</td>
<td>9.35</td>
</tr>
<tr>
<td>Volatile acids, mg/l</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>880</td>
<td>1000</td>
<td>840</td>
<td>1000</td>
</tr>
<tr>
<td>Maximum</td>
<td>1220</td>
<td>1600</td>
<td>1350</td>
<td>2370</td>
</tr>
</tbody>
</table>

aDigester I and IIIIB were abandoned September 12.

bVolatile solids destruction is based on solids content of digesters on November 9.
Figure 16. Performance of Digester V during the period from May 10 to September 12, 1962
PERFORMANCE OF DIGESTER V

VOLATILE ACIDS

Volatile Acids and NH₃-N, 10² mg/l.

GAS PRODUCTION

Gas Production, ft³/h lb VM FED.

pH

LOADING RATE, lb VM(d)/ft³

LOADING RATE

V/ₘ in Raw Sludge

V/ₘ in Digested Sludge

Days of Digestion

Days of Digestion
Figure 16a. Performance of Digester V during the period from September 13 to November 26, 1962
PERFORMANCE OF DIGESTER V

VOLATILE ACIDS

GAS PRODUCTION

LOADING RATE, lb/d/ft³

Vm IN RAW SLUDGE

LOADING RATE

DAYS OF DIGESTION

GAS PRODUCTION, ft³/d/lb Vm FED

VOLATILE ACIDS, 10² mg/l
The digesters, except IIIB, were seeded with partially digested sludge on May 10 and operated continuously for about 7 months. Digester IIIB was again seeded with new sludge on July 10 when Digester IIIA exploded. The seed sludge for Digester IIIB was taken also from the digesters of the Ames Sewage Treatment Plant. However, the plant operator, in pumping sludge out of the digester, drew sludge from the very bottom of the tank which was high in total solids and low in volatile solids (Table 13), indicating the sludge had been well digested. Because the bottle digester had to be sealed as soon as it was seeded so as not to allow exposure of the sludge to the oxygen of the atmosphere, the seed sludge characteristics were not known until after the digester was sealed and put into operation. For this and other reasons, Digester IIIB did not operate as well as the other digesters and was soon abandoned. Digester I was also abandoned when its volatile acids concentration reached over 4,000 mg/l (Table 13) and continued to remain high after feeding of the digester was stopped on August 28 (Figure 23).

Summary of results

The daily loading rates at which the digesters operated are presented graphically for each digester in Figures 16, 16a and in all the figures appearing in the Appendix. Each of the figures shows the daily volatile solids concentration of the raw sludge fed to the digesters. The detention period corresponding to any loading rate and any volatile solids concentration in the raw sludge fed can be obtained from Figure 11. This figure shows also the conditions under which one or more of the digesters operated during the course of the study. It was hypothesized that copper
toxicity limited digestion at loadings higher than 0.10 lb/d/ft$^3$ during the period from May 10 to September 12 (Figures 16 and 23 through 27). However, before the operation of the digesters was halted on November 26, 1962 (the digestion equipment was needed for another study), Digester VI was being operated at a loading rate of 0.243 lb/d/ft$^3$ and a detention period of 7.9 days (Figure 27a). These were the maximum loading rate and minimum detention time at which the digesters were operated. The effect of copper on the loading rates, solids concentration and detention time are discussed in detail in following sections of the thesis.

The digesters operated at a pH level which ranged from 7.0 to 7.5 (Table 13). The daily variation in pH was small and varied mostly between 7.2 and 7.5 (see Figures 16 and 23 through 27). The average total nitrogen content of the raw manure fed to the digesters during the period from May 10 to September 12 was 5.62 percent on a total solids basis. Table 13 indicates that the total nitrogen content of the manure increased from a low of 6.11 percent in Digester IIIB (further indication of failure of this digester to operate as well as the other digesters) to a high of 9.14 percent in Digester II. The mean ammonia nitrogen content of the digesting sludge in each digester is plotted in Figures 16 and 23 through 27. On the basis of the volatile acids test results, the digesters operated at a more favorable range after September 12 than before September 12 as is indicated by the volatile acids concentration values tabulated in Tables 13 and 14 and the daily observations shown in Figures 16, 16a and in the figures of the Appendix.

Nine determinations of total alkalinity of the digesting sludge were
made during the period from May 10 to September 12. Figure 17 shows
typical total alkalinity titration curves for five of the digesters. It
is noted in Figure 17 that the alkalinity of the digesting sludge is
bicarbonate alkalinity since the initial pH is below 8. The average
alkalinity of the sludge in all digesters was found to be about 6,800
mg/l as calcium carbonate; the maximum alkalinity, 12,500 mg/l, was
obtained from Digester II on August 17 when the volatile acids had
reached a level of 3,640 mg/l; the minimum alkalinity, 4,050 mg/l, was
obtained from Digester V on September 5 when the volatile acids of the
digester had decreased to about 1,100 mg/l.

The volatile matter, and thus the pollutional strength of the raw
manure, was reduced during digestion. Tables 13 and 14 show that the
mean volatile matter destruction ranged from a minimum of 34 percent in
Digester IIIb (another indication of failure of this digester to operate
as well as the other digesters) to a maximum of 75 percent in Digester IV.
This reduction in volatile matter produced a stable end product which was
inoffensive in odor, smooth in texture, high in nitrogen content and
repelled flies instead of attracting them as was the case with the raw
manure.

The gas evolved during digestion varied in quantity mainly with the
loading rate and the detention period at which the digesters were
operated. An apparent maximum gas production per unit of volatile matter
fed was obtained at a loading rate between 0.03 and 0.04 lb/d/ft$^3$ and a
detention time of 40 days. The gas contained approximately 59 percent
methane, 40 percent carbon dioxide and less than 1 percent nitrogen. The
Figure 17. Typical total alkalinity titration curves on supernatant sludge from 5 of the digesters
TOTAL ALKALINITY TITRATION CURVES

- DIGESTER II
- DIGESTER III A
- DIGESTER IV
- DIGESTER V
- DIGESTER VI

pH vs. 1.0 N H₂SO₄, ml.
hydrogen sulfide content of the gas was not detectable with the chromatography apparatus used for the gas analysis. The heating value of the gas was determined on the basis of its methane content and was found to be approximately 570 BTU/ft$^3$ (Table 13).

**Maximum loading rate**

As was pointed out in a previous section of the thesis, conventional digesters do not ordinarily operate at loadings much higher than 0.10 lb/d/ft$^3$. However, Morgan (1954) attained loading rates of 0.345 lb/d/ft$^3$ with high-rate laboratory and pilot plant digesters operating at 95°F and 7.2 days detention periods. His high-rate digestion process required the recirculation of diffused gas throughout the digester contents to bring the digesting sludge, the raw sludge, and the gas into intimate contact. Furthermore, the digesters were fed twice daily which is also the practice in conventional digestion. Digesters can operate at higher loadings with more frequent feeding. Continuous feeding is desirable but impractical.

The contents of the digesters used in this study were continuously mixed through the mechanical rotation of the bottles. In this respect, the digesters of this study approximated the action of high-rate digesters. The digesters of this study, however, were fed only once a day. Although more frequent feeding would have facilitated higher loadings than those achieved, such a practice cannot be expected on a farm; i.e., it is unlikely that the farmer would clean the pen floors twice daily including Sunday. Therefore, it was decided to establish the maximum
loading rate feasible with once-a-day feeding of the digesters.

During the period from May 10 to September 12, 1962 the loading rate to the laboratory digesters ranged from 0 to 0.124 lb/d/ft$^3$. The average loading rate attained was 0.072 lb/d/ft$^3$, while the maximum loading rate at which the digesters operated satisfactorily was 0.1 lb/d/ft$^3$. The loading rates to Digesters I and IIIB reached 0.122 and 0.124 lb/d/ft$^3$, respectively. Both digesters failed to maintain proper digestion conditions soon after the loading rate exceeded 0.1 lb/d/ft$^3$. The loading rate of Digesters II and V reached 0.108 lb/d/ft$^3$. At this loading rate, the gas production declined, the volatile acids surpassed 2,000 mg/l as acetic acid and the ammonia nitrogen content increased to a concentration higher than 1,250 mg/l which, according to Albertson (1961), indicates digester failure.

The inability to maintain proper digestion conditions at loading rates higher than 0.1 lb/d/ft$^3$ should not be due to an inadequate detention period. At the time the digesters failed, the detention periods for Digesters I, II, IIIB and V were 26, 38, 20 and 25 days, respectively. In subsequent periods, digestion proceeded satisfactorily at detention times as low as 7.9 days and with loading rates higher than 0.1 lb/d/ft$^3$ (Table 14). Furthermore, the digester failure could not be attributed to increasing the loading rate too fast because Digester II had been operating at 0.103 lb/d/ft$^3$ for 35 days previous to the day the volatile acids increased in an abnormal manner as shown in Figure 24.

Several hypotheses were advanced to explain why digestion was retarded at loadings higher than 0.10 lb/d/ft$^3$. It was hypothesized that
the failure of both Digesters II and V after many days of normal operation at a loading rate of 0.103 lb/d/ft$^3$ (Figures 16 and 24) might have been due to the cumulative effects of toxic substances. Toxicity could have been the result of excessive concentrations of ammonia nitrogen and/or copper. Both nitrogen and copper were present in the raw manure fed to the digesters. The nitrogen content of the raw and digested manure was measured; the copper content of the raw manure was approximated from the copper content of the feed.

Albertson (1961) reported that in his experiments with high-rate digestion of domestic sludge the loading rate was not directly associated with the cause of digester failure. He recorded digester failures at volatile matter loadings of 0.20, 0.27 and 0.44 lb/d/ft$^3$. All of these failures had one condition in common, a $\text{NH}_3$-N concentration of 1,200 to 1,400 mg/l. He also reported that a pH of 7.3 to 7.4 at a loading rate of 0.3 lb/d/ft$^3$ may be inhibitory to the methane producers. He found the optimum pH to be about 7.1 for high loading rates. Ammonium ion in the form of $\text{NH}_4\text{Cl}$ was not toxic or inhibitory. Albertson concluded that either high solids concentrations or an increase in the alkalinity to 5,000 mg/l or more through the formation of $\text{NH}_4\text{HCO}_3$ resulted in the digester failure by excess volatile acids. Therefore, $\text{NH}_3$-N concentration is at least an indicator of digester malfunction if not the actual cause.

The following conditions were common to all digester failures observed in this study: an $\text{NH}_3$-N concentration above 1,250 mg/l, an alkalinity well above 5,000 mg/l and a pH at 7.2 to 7.4 previous to
digester failure through excessive volatile acid formation (Figures 23-27). The NH₃-N concentration of Digester VI reached and surpassed 1,250 mg/l and the alkalinity level reached over 5,000 mg/l. However, Digester VI did not fail. The lower loading rates of Digester VI may have facilitated the tolerance of high NH₃-N concentrations (Albertson, 1961).

Partial retardation or complete inhibition of digestion also could have been caused by the accumulation of copper and/or fibrous materials. Although the exact toxic concentrations have not been established, Rudgal (1941) noted a gas production decrease with 150 to 250 ppm of copper in batch laboratory digestion studies of domestic sludge. With continuous digestion, daily additions of 50 to 100 ppm (wet basis) of copper to laboratory-size digesters accumulated to toxic concentrations which were estimated to be about 200 ppm. On the basis of experience with a municipal digester, Rudgal (1946) reported that 2,500 ppm (wet basis) of copper in the raw sludge interfered with gas production. The removal of the bottom sludge of the digester and of the source of copper brought the digester to normal operation.

A calculated analysis of the hog feed showed it contained, on the average, 224 ppm of copper, 98 percent of it as copper oxide. Since the pigs consumed 6 lbs of feed daily in the Spring of 1962, the total daily copper intake was 610 mgs per pig. Buescher, et al. (1961) reported that 64 percent of the copper fed as copper oxide to pigs averaging about 60 to 70 pounds in live weight was excreted in the feces of the animals. These animals were on a copper-free ration previous to the start of the experiments. Assuming that the percent of copper excreted by pigs
averaging above 100 pounds in weight and fed continuously on a copper-containing feed is 80, then the average quantity of copper excreted was 490 mgs/day. Since the daily manure quantity was 6.84 lbs per pig, the copper content of the manure would have been approximately 160 ppm on a wet basis (15.6 percent solids) or about 1,000 ppm (0.1 percent) on a dry solids basis.

At the time Digesters I, II, IIIB and V failed, the maximum daily additions of copper to these digesters were estimated to be approximately 60, 71, 48 and 85 ppm (wet basis), respectively. During this period, the procedure used in withdrawing sludge from the digesters aided the accumulations of solids and, thus, of copper also. Three to five times a week supernatant sludge was withdrawn for the volatile acids test from the top layer (after solids had settled to the bottom) of the digester contents. This procedure favored the accumulation of copper-forming concentrations higher than those fed to the digesters.

However, if the high copper doses limited the digester loading rate, then the reduction of the daily copper dose by dilution of manure and the daily removal of copper by withdrawal of representative samples from the digesters should facilitate operation at higher loading rates. Indeed, after the loading rate and the detention time were reduced (by an increase in the hydraulic loading) and representative samples were withdrawn daily, the volatile acids of Digesters II and V decreased from an average of 1,640 and 1,280 mg/l to 660 and 240 mg/l, respectively (Figures 16a and 24a). On November 9, the volatile acids of Digesters II and V were found to be 820 and 390 mg/l, respectively, even though at that time the load-
ing rate of these digesters had been increased to 0.090 and 0.104 lb/d/ft$^3$, respectively, and the detention time had been decreased to 7.9 and 8.4 days, respectively. However, the daily maximum doses of copper to these digesters were estimated to have been reduced to 13 and 16 ppm (wet basis), respectively, by the addition of dilution water to reduce the detention time in the digester.

It may be noted in Table 14 and Figure 26a that the loading rate of Digester IV was increased to 0.202 lb/d/ft$^3$ and the detention period was decreased to 8.7 days on November 17. Digestion proceeded satisfactorily for 10 days as was indicated by the volatile acids tests. Although the volatile acids increased at first, they remained well below 2,000 mg/1 throughout the 10-day period. During this period the estimated copper daily addition to Digester IV was 33 ppm (wet basis). Gas production in Digester VI was reduced by approximately 50 percent (Figure 27a) when its loading rate was increased from 0.121 to 0.243 lb/d/ft$^3$. The copper content of the raw sludge fed daily to this digester was estimated at 36 ppm (wet basis). The retardation of the gas production of Digester VI might have been due to copper toxicity or to the abrupt change in the loading rate. The volatile acids of Digester VI increased to about 2,300 mg/1; however, they remained at that level throughout the 10-day period. It is possible, therefore, that the gas inhibition was caused by the abrupt change in the loading rate and in the solids concentration at which the raw sludge was fed to Digester VI.

Buswell and Hatfield (1939) encountered a serious difficulty with fibrous materials. These substances formed a mat which favored the
accumulation of large amounts of acids unless broken up through stirring or other means. The hog manure fed to the digesters of this study contained fibrous matter and lignin which are decomposed slowly under anaerobic conditions. However, these materials were prevented from forming a mat by the action of the paddles inside the digesters and the continuous rotation of the bottles. Furthermore, because they tended to float, they were removed with the daily sludge withdrawals, thus their accumulation in the digester was prevented. Therefore, it seems unlikely that the fibrous materials of the manure were responsible for the digester failures.

On the basis of the results obtained from Digesters II, IV, V and VI during the period from September 13 to November 26, it can be concluded that satisfactory digestion of hog manure can proceed satisfactorily at volatile solids loading rates higher than 0.1 lb/d/ft\(^3\) provided the solids concentration and, thus, the copper content is not allowed to increase above the copper toxicity level. No attempt was made to establish the exact toxicity level of copper because it was felt that such a study was beyond the scope of the present study. However, there was no evidence of digestion retardation when copper was added at rates less than 33 ppm (wet basis). Digestion proceeded satisfactorily in Digester IV at a volatile solids loading rate of 0.202 lb/d/ft\(^3\) and once-a-day feeding (Figure 26a).
Detention period

All digesters were started with a detention time of 35 days; i.e., the total quantity of raw sludge and water added to each digester daily was 200 grams. Then the detention period was varied by changing the quantities of tap water added and sludge withdrawn from the digester. Figure 11 shows the levels of detention periods at which the digesters were operated.

The results obtained during the period from September 13 to November 26 indicated that digestion was satisfactory at detention periods as low as 7.9 days. However, on the basis of the filterability test results (Figure 21) and the volatile matter reduction results (Table 14), a detention period of 10 days may be more desirable than a 7.9-day detention. Chmielowski, et al. (1959), operating bottle digesters under similar conditions as in this study, concluded on the basis of their volatile matter reduction and filterability test results that a 10-day detention period when compared to 20- and 6.7-day detention periods was optimum for digester performance.

The digester volume needed is determined by the detention period which, as was pointed out previously, is defined as the average time in days required to replace the digester contents. Therefore, the detention period in Figure 11 can be replaced by digester capacity. Then the relationship between volatile solids concentration (wet basis), loading rate and digester capacity required per cubic foot of total daily waste to be digested can be shown as in Figure 18.

The use of Figure 18 is illustrated with the following example.
Figure 18. Relationship between volatile solids concentration loading rate and digester capacity requirements
DIGESTER CAPACITY REQUIRED, ft$^3$ PER ft$^3$ OF TOTAL WASTE, OR DETENTION PERIOD, DAYS

VOLATILE SOLIDS IN WASTES, % (WET BASIS)

LOADING RATE, lb/d/ft$^3$
Assume that a digester is to be constructed to treat the wastes from the hog confinement unit of the Iowa State University Swine Nutrition Farm. Assume, also, that the average number of pigs in the unit is 800, averaging 100 lbs in weight, and that the pen floors are hosed down daily. The daily manure production is estimated to be 4,000 lbs of which 560 lbs will be volatile solids. Since the daily average amount of water used for hosing the pens during the summer of 1961 was 21.7 lbs per pig, the total daily volume of the waste will be 342.3 cubic feet; volatile solids content will be 2.6 percent (wet basis). If the loading rate at which the digester is to be operated is 0.10 lb/d/ft$^3$, Figure 18 indicates that the detention time will be 16 days and the digester capacity will have to be 5,550 cubic feet. If hosing were not used and the manure was introduced to the digester undiluted, then the size of the digester required will still be 5,550 cubic feet. However, the detention time will be 87 days instead of 16 days. If the loading rate is maintained constant at 0.10 lb/d/ft$^3$, the digester capacity will remain the same. The only parameter changing will be the detention time. Since manure was found to be digestible at loading rates as high as 0.20 lb/d/ft$^3$, then the capacity of the digester required can be reduced to about 2,800 cubic feet.

Gas production and composition

Gas production was measured daily. Equation 8 was used to reduce the daily gas yield readings to standard pressure and temperature conditions. The rate of gas production was high immediately after the digesters were fed. About 50 percent of the day's gas yield was produced
within the first 8 hours of the day, while during the last 8 hours of the day only 25 percent of the gas was produced. The composition of the gas produced was determined periodically with the chromatography apparatus. The carbon dioxide content of the gas produced immediately after the feeding of the digesters was higher than that of the gas produced near the end of the day.

The average gas yields per pound of volatile matter fed to each of the digesters are shown in Tables 13 and 14. The average daily gas production from the four digesters operated for 200 days was approximately 9 cubic feet per pound of volatile solids added. The daily gas production readings are plotted in Figures 16 and 16a for Digester V. For the other digesters the gas data are shown in figures in the Appendix.

The optimum conditions for maximum gas production were investigated with Digester VI. There are statistical procedures for the determination of the point of maximum production. However, an attempt to use one of these methods failed because of the nature of the digestion process. The optimum detention period and loading rate for maximum gas production were not clearly established because of the residual effect observed when one or both of the digestion parameters was changed. This residual effect is clearly shown in the daily gas production data plotted in Figure 19.

Figure 19 shows the daily gas production with variations in the daily loading rate and detention time for Digester VI. A change in the daily loading rate brought a considerably larger change in the gas yield than a change in the detention time. Because of the residual effect of the previous conditions and the natural variation of the gas data, it was
Figure 19. Daily gas production variation with changes in the parameters of anaerobic digestion: loading rate and detention period. The data are from Digester VI.
not possible to establish the exact conditions for maximum gas production. Apparently, at a loading rate of 0.03 to 0.04 and a detention time of 40 days, the gas yields were maximum, 12 ft$^3$/d/lb V added (16-day average). However, the daily gas yields for those conditions were maximum when the loading rate was being decreased. When the loading rate was increased from 0.026 to 0.031 with detention period still at 40 days, the gas yields were not as high. During the period in which the loading rate is being decreased but the detention period is kept constant, the apparent effect is an increase in gas yield because gas is given off from the undigested volatile solids added the previous day. If the time required to completely digest the volatile matter added in the digester is 40 days, then the residual effect should persist for 40 days.

Both the loading rate and the detention period at which the digester operated affected slightly the average gas yields. It may be noted in Figures 16a and 26a that from September 13 until November 9 Digesters IV and V were being operated simultaneously at about the same loading rate, but the detention period of Digester IV was twice the detention time of Digester V. The average gas production from Digester IV was 1.16 times higher than that of Digester V. During the same period (September 13 to November 9), Digester VI was being operated at half the loading rate but the same detention period as Digester IV (Figures 26a and 27a). The average gas production from Digester VI was 1.13 times higher than that of Digester V. Therefore, it may be concluded that the average gas yield was a function of the detention period and loading rate, and increased slightly when the detention period was increased and/or the loading rate
was decreased.

The composition of the gas produced was determined periodically during the period from May 10 to September 12. The average methane and carbon dioxide content of the digester gas as determined chromatographically is shown in Table 13. There are no values given for Digester IIIA because it exploded before the chromatography apparatus became operational (July 14). The heating value of the gas was computed from its methane content.

The average methane content of the digester gas was about 59 percent by volume with an average net heating value of 570 BTU/ft³; the carbon dioxide was about 40 percent. Free nitrogen and other gases constituted less than 1 percent of the gas. Apparently the hydrogen sulfide content of the gas was quite small because it could not be detected by the chromatography apparatus. The daily variation in the content of the gas components was small. The average methane content of Digester VI, the only digester whose volatile acids did not exceed 2,000 mg/l, was 59.6; the maximum and minimum values recorded were 61.8 and 58.0 percent, respectively. During the time the volatile acids of Digester V increased beyond 2,000 mg/l, the methane content of its gas decreased to 56.0 percent. However, similar trends in methane content were not observed when the volatile acids of other digesters increased beyond 2,000 mg/l.

The methane content and, consequently, the heating value of the digester gas was lower than the values reported by Reinhold and Noak (1956), 80.5 percent, but higher than those reported by Buswell and Hatfield (1939) for hog paunch manure, 53.3 percent. However, Reinhold
and Noak obtained their results from batch and not continuous digestion experiments. Edmonds (1962), using the same chromatography apparatus and bottle digesters used in this study, reported an average methane content of 65 percent for domestic sludge being digested at a loading rate of 0.044 lb/d/ft³. Schmidt and Eggergluess (1954) reported a methane content of 62 percent for the gas produced from a field digester operating on animal and plant wastes.

**Digested manure characteristics**

The changes in the raw manure caused by the anaerobic digestion process were evaluated regularly during the period from May 10 to September 12, 1962. The results obtained during this period are summarized in Table 13. Except for the filterability test, the only test performed regularly after September 12 was the volatile acids test.

The volatile matter and, thus, the pollutional potential of the raw hog manure was reduced by 60 to 70 percent through the action of the anaerobic digestion process. Furthermore, the digested manure was higher in total nitrogen content than the raw manure. When two open beakers, one containing raw and the other digested hog manure, were placed on a table in the laboratory, it was observed that no flies approached the beaker with the digested manure while flies covered the beaker with the raw manure. Digested manure, in contrast to raw manure, had no offensive odors, was soupy in texture and black in color. Figure 20 shows the difference in texture and color between the raw and digested manure. These characteristics make digested manure more suitable for disposal by field
spreading.

**Volatile matter destruction** The raw manure fed and the digested sludge withdrawn from the digesters were analyzed for total and volatile solids. The results obtained for the period from May 10 to September 12, 1962, are summarized in Table 13; the daily variations of the volatile solids concentrations for each of the digesters are shown in Figures 16, and 23 through 27. Table 14 shows the percent volatile matter reduction computed for the conditions under which the digesters were being operated on November 9.

The procedure used in the determination of the volatile solids destruction during the period from May 10 to September 12 was as follows: The areas underneath the curves for the volatile solids concentration in the digester and in the raw manure (Figures 16, and 23 through 27) were determined with a planimeter. The difference in the areas divided by the total area (volatile solids in raw manure) gave the average percent destruction of the volatile solids fed. If the feeding of the digesters was stopped temporarily or permanently before September 12, the data collected up to the last day the digesters were fed regular doses of solids were used; i.e., the data up to August 14 were used in the case of Digester II. The computation of the organic matter destruction did not give representative results for two reasons. 1) The solids content of the digesters was higher than it should be because the sludge withdrawn from the digesters was not always representative of the digester contents. Three to five times a week, after the rotation mechanism was halted, the
solids of the digester were allowed to settle to the bottom and then a sample was withdrawn from the upper layers which were low in solids. This procedure favored the accumulation of solids in the digester. 2) It may be noted in Figures 16 and 23 through 27 that the digesters did not reach steady conditions during the course of the experiments because of the frequent changes made in the digestion parameters. Furthermore, some of the digesters were overloaded which also favored solids accumulation. Therefore, the actual volatile solids destruction was considerably higher than that indicated in Table 13.

Under steady conditions, the volatile matter reduction would have approximated the maximum destruction figures given in Table 13; i.e., about 60 to 70 percent. Digester II might have reached steady conditions after operating for about 30 days at a loading rate of 0.10 lb/d/ft$^3$ and a detention time of 36 days (Figure 24). Starting July 18, the volatile solids of the raw manure added daily to Digester II were maintained at a constant level, 6.0 percent on a wet basis. Within 15 days, the volatile solids of the digesting sludge increased to 2.25 percent and remained at that level for the next 15 days. The volatile matter destruction during the latter 15 days was found to be 62 percent. The volatile matter would have been higher than 62 percent if, as mentioned above, the procedure for withdrawing sludge did not favor the accumulation of solids in the digester.

On November 9 the solids content of the four digesters still in operation was determined. From the results of the solids test, the percent volatile matter reduction was computed and found to range between
59 and 68 percent (Table 14). For 20 days previous to November 9, the volatile solids in the raw sludge fed to the digesters was kept at a constant level (Figures 16a, 24a, 26a and 27a) and the detention time for all digesters was lower than 20 days. Therefore, it may be assumed that steady conditions were attained in the digesters at the time their solids content and the percent volatile matter reduction were determined.

Digester V was being operated at a loading rate approximately equal to those of Digesters II and IV, but at a detention period of about 8.5 days as compared to 7.9 and 17 days for the other digesters, respectively.

The percent volatile matter reduction in Digester V was 8.5 percent greater than that of Digester II and only 3.0 percent smaller than that of Digester IV (Table 14). These results on volatile matter reduction and the curves of filterability characteristics of Figure 21 indicate that detention of 7.9 days might be low, and that detention at 8.5 to 10 days might be just as satisfactory as 17 or 20 days for the digestion of hog wastes. This conclusion agrees with the conclusions for digestion of domestic sludge reported by Chmielowski, et al. (1959) who obtained their data from bottle digesters operated under conditions similar to those of this study.

**Nitrogen content** The ammonia and the total nitrogen content of the digested sludge is shown in Table 13. The nitrogen content of the solid matter of the manure increased during digestion. The average total nitrogen content of the manure fed to the digesters during the period from May 10 to September 12, 1962 was 5.62 percent of the dry matter. The
Figure 20. Visual comparison of manure before and after anaerobic digestion
A. Raw manure
B. Digested manure

Figure 21. Filterability curves for three of the digesters
average total nitrogen in the dry matter after the manure was digested
was found to be 8.02 percent; i.e., the manure total nitrogen increased
43 percent through digestion. This increase in the nitrogen content of
the manure was due to the reduction in the volatile matter of the manure
during digestion. It was also observed that the ammonia nitrogen
constituted a higher percent of the total nitrogen content of the
digested manure, 61 percent (average for all digesters), than of the raw
manure, 44 percent. Therefore, on the basis of total nitrogen content
per pound of dry matter, digested manure was found to be about 1.4 times
greater in fertilizer value than raw hog manure. Moreover, since 61 per­
cent of the total nitrogen was in the form of ammonia, the nitrogen of
the digested manure would be more easily available to the plants if the
manure were used as a fertilizer.

Filterability  The relative ease with which the water content of
manure digested at different levels of loading rates and detention periods
might be expected to drain was determined by the filterability tests. The
procedure used for these tests has been described previously. Figure 21
shows a series of curves which may be considered representative. It may
be noted in Figure 21 that the filterability characteristics of the sludge
from Digester V appear to be better than those of Digesters IV and VI.
Digester V, as shown in Figure 21, operated at a detention time of 10
days as compared to 20 and 24 days for the other digesters at the time
the test was performed.

An attempt to compare the filterability characteristics of raw manure
diluted to concentrations equivalent to the digested manure with the
sludge withdrawn from the digesters gave erratic results. At times the raw manure filtered faster than the digested manure. The raw manure used in this study was stored in a frozen state and thawed before it was used. Thus, it may be assumed that its filterability was improved. However, the author believes the erratic results obtained were due mainly to the high dilution of the raw manure required to bring its solids to equal concentrations with the digested sludge and the difficulty of obtaining a representative sample after dilution.

Visual inspection of the solids retained on the filter paper after the completion of each filterability test of raw and digested manure revealed easily recognized parts of the ligneous portions of corn. The same phenomenon was observed in the sludge withdrawn daily from the digesters. Apparently, this fibrous portion of the manure is not changed during digestion.

Practical Conclusions

The following practical conclusions are based on the analysis and interpretation of the data and results obtained from the anaerobic digestion of manure collected from the confinement building at the Iowa State University Swine Nutrition Farm:

1. Hog manure is digestible.

2. At 95°F, hog manure can be digested satisfactorily at a volatile solids loading rate of 0.20 lb/d/ft³ with once-a-day feeding and a detention period of 10 days.

3. Hog manure must be diluted with added tap water or wash water
before it is digested because of its copper content. Since digestion was feasible at a total solids concentration in the raw sludge of 3.3 percent, 20 gallons of wash water per pig per day would suffice for the dilution.

4. The daily gas yield per pound of volatile matter fed to a digestion unit is approximately 9 cubic feet. This is equivalent to about 6.3 ft$^3$/d/pig.

5. The heating value of the digester gas is about 570 BTU/ft$^3$. This is equivalent to about 3,600 BTU/d/pig.

6. With the removal of the copper or the suppression of its toxicity and more than once-a-day feeding, volatile solids loading rates higher than 0.20 lb/d/ft$^3$ appear to be feasible. Furthermore, the removal of the copper or any other toxic substances would facilitate digestion at high solids concentrations and, thus, would lower the dilution water demands.

**Digester Design and Cost Considerations**

**Design considerations**

The results obtained in this study indicated that hog manure could be digested at 95°F at a volatile solids loading of 0.20 lb/d/ft$^3$ and a volatile solids content of about 3 percent. Figure 18 indicates that the digester capacity required is about 10 cubic feet per cubic foot of total daily volume of manure to be digested. On the basis of these digestion design criteria and the manure production values given in the first part of the thesis, approximately 3.74 cubic feet of digester volume are required per pig. Therefore, for a confinement production unit which has
a capacity of 1,000 hogs (about 3,500 to 4,500 hogs per year), the size of digester required is 3,740 cubic feet or roughly 1 cubic foot per pig per year.

A circular tank is preferred over a square tank from the standpoint of economy of construction and ease of digester mixing. The side depth of municipal sludge digestion tanks varies between 20 and 30 feet. Side depths higher than 30 feet should be avoided because they are liable to cause foaming due to rapid discharge of gas at the surface (Escritt, 1956). For small size digesters the depth of the tank can be made equal to its diameter. Digester diameter should be an even 2-foot intervals from 10 to 20 feet and 5-foot intervals thereafter. Unless sludge-removing mechanisms are provided, hopper bottoms with steep slopes of 3 to 4 feet horizontal to 1 foot vertical, or steeper, are preferred (Babbitt and Baumann, 1958). Two types of covers are commonly used for digestion tanks, fixed and floating. Although the floating cover is more expensive than the fixed cover, it has a number of advantages over the latter. For the particular application considered in this study, the floating cover is preferred because it minimizes the danger of mixing air with the digester gas to form an explosive mixture and provides storage for the daily gas production (Babbitt and Baumann, 1958).

The mixing and heating requirements of the digestion process can be met by gas diffusers and heat exchangers, respectively. Mixing of the digester contents by gas recirculation will assimilate the mixing conditions established in this study and, thus, make the results obtained in this study applicable. Heat is required to raise the incoming sludge to
95°F and to supply the loss of heat to the surrounding ground or air.

The heat required to raise the temperature of the incoming sludge can be expressed as follows:

\[
h_1 = \frac{w s (t_d - t_i)}{24}
\]  

(9)

where:  
- \( h_1 \) = heat required to raise the temperature of the incoming sludge, BTU/hour,
- \( w \) = weight of sludge entering the tank per day, lbs/day,
- \( s \) = specific heat of sludge, 1 BTU/lb/°F,
- \( t_d \) = temperature of digester contents, 95°F, and
- \( t_i \) = temperature of incoming sludge, °F.

Since the temperature in a confinement building is controlled so as not to allow the air temperature to go below 45 to 50°F, the temperature of the manure during the cold months of the year is assumed to be 45°F.

Through substitution of the above values in Equation 9, Equation 10 results.

\[
h_1 = 2.1w
\]  

(10)

The heat lost from the digestion tank can be expressed as

\[
h_2 = AC (t_d - t_o)
\]  

(11)

where:  
- \( h_2 \) = heat loss from the digester, BTU/hr,
- \( A \) = surface area of the digester, ft²,
- \( C \) = coefficient of thermal conductivity, BTU/°F-hr,
- \( t_o \) = temperature of incoming sludge, °F.
Assuming that the digester tank will be concrete surrounded by earth on the sides and exposed to the air at top, the value of C is about 0.10 (Babbitt and Baumann, 1958). The effective outside temperature of a partially covered digester tank may be assumed to be 35°F. Then Equation 11 can be written as follows:

$$h_2 = 6A$$  \hspace{2cm} (12)

The sum of $h_1$ and $h_2$ determine the maximum capacity of the heat exchanger because it represents the total heat required to heat and maintain the digester contents at 95°F during the cold months of the year.

The gas produced during digestion is combustible, explosive and asphyxiating. Therefore, provisions should be made to burn the waste gas in a waste gas burner and to prevent the passage of a flame along the inside of the gas pipes with a flame arrester. In addition to piping systems for the collection and utilization of the digester gas, at least two pumps are required, one to aid in the feeding of the raw manure and the other in the withdrawal of the digested manure.

**Digester costs**

Figure 22 shows estimates of the approximate cost of a digester for the treatment of hog manure and the estimated value of the excess combustible gas produced. The cost data used to develop Figure 22 were taken from Morgan (1962). These data are estimates of the current cost of purchasing equipment and erecting a concrete digester within the state of
Figure 22. Estimated total and net cost per pig for different size digesters to digest hog manure wastes
NOTE: TOTAL COST PER PIG IS BASED ON 10-YEAR AMORTIZATION OF INITIAL INVESTMENT AT 6% INTEREST, COMPOUNDED ANNUALLY.

TOTAL COST PER PIG

NET COST PER PIG

ESTIMATED VALUE OF GAS PRODUCED PER PIG

INCOME AND COST, DOLLARS PER PIG

ESTIMATED DIGESTER COST, 1,000 DOLLARS

TOTAL

EQUIPMENT

VOLUME OF DIGESTER, 1,000 ft³, OR THOUSANDS OF PIGS RAISED PER YEAR
Iowa. It was calculated that, on the average, one-third of the total gas produced would be required to maintain the digestion temperature at 95°F. The value of the excess gas was determined on the basis of $0.80 per million BTU's. At the end of 10 years, with annual deposits at 4 percent, the estimated income value of the gas from the digestion of the manure from each pig is approximately $0.22. This figure subtracted from the total cost per pig gives the net cost per pig as shown in Figure 22.

It may be noted in Figure 22 that the initial investment and, thus, the actual cost per pig for a digestion tank varies with the number of pigs being raised per year. For a confinement unit producing 10,000 hogs per year, the digester volume required is 10,000 cubic feet which will require an initial investment of approximately $33,000. The estimated net cost per pig with a 10-year amortization at 6 percent is $0.38. For a confinement unit four times as large, 40,000 hogs per year, the digester volume required will be 40,000 cubic feet; the total cost for the digester will be $66,000; but the net cost per pig will be about one-fourth, or $0.08.

The total cost for a digester to treat the wastes from the 800-hog capacity confinement production unit at the Iowa State University Swine Nutrition Farm is estimated from Figure 22 to be approximately $26,000. This will add approximately $1.10 to the cost of producing a market weight hog, or expressed in another way, $0.055 to the cost of producing one pound of pork.

It can be deduced from Figure 22 that the cost for equipment constitutes 87 percent of the total. The major items of expense are the
floating cover, the gas recirculation equipment and the heat exchanger. For a digester tank 30 feet in diameter and 20 feet deep; i.e., approximately 12,000 ft$^3$ in total capacity, the current prices for floating cover, gas recirculation apparatus and heat exchanger are $7,500, $6,000 and $5,000, respectively. The total cost of the digester can be reduced by the use of a fixed cover instead of a floating cover and the mixing of the digester contents by means other than gas recirculation. In all cases, however, the heat exchanger is necessary to keep the digestion temperature constant.
SUMMARY AND CONCLUSIONS

The purpose of this study was to determine the quantity and composition of wastes from a hog confinement production unit and to investigate the anaerobic digestion of hog wastes. The investigations began in January 1961 and were terminated in November 1962.

The properties of manure collected at the growing-finishing hog confinement building at the Iowa State University Swine Nutrition Farm were determined during three periods: Winter 1961, Summer 1961 and Spring 1962. The air temperature, the composition of the feed, the daily water and feed intake of the hogs and the size of the hogs were found to affect the quality and quantity of the hog manure. On the basis of the results obtained, the following values for the given variables are recommended:

1) daily volume, 5 lbs/d/100 lbs live weight;
2) total solids, 17 percent;
3) volatile solids, 14 percent (wet basis);
4) total nitrogen, 7 percent (dry basis);
5) pH, 7.5-8.5;
6) BOD, 0.35 lb/d/100 lbs live weight; and
7) COD, 1.20 mg O₂ per mg V_m.

The quantity and composition of manure can be estimated from data on the following factors: the daily quantity and composition of the feed intake, the water intake, the size of the hog and the air temperature within the confinement unit. Actual and theoretical data on these factors
are available in research papers on hog nutrition and housing.

Air temperature influenced the quantity, the solids content, and the fertilizer value of the manure. At high temperatures the manure quantity scraped from the pen floors was lower, the solids content was higher, and the nitrogen content was lower due to loss of nitrogen as ammonia gas.

Hog manure contains sufficient amounts of carbon, nitrogen, and phosphorus and other elements necessary to support the biological decomposition of the manure under aerobic and anaerobic conditions. From 60 to 70 percent of the original amount of the ingredients present in the feed appear eventually in the fecal and urine excreta of the animal. It was estimated that 80 percent of the copper content of the feed was excreted in the manure; i.e., the manure contained approximately 1,000 ppm (dry basis) of copper. Copper in the form of copper oxide was fed to the pigs as an antibiotic and, thus, can inhibit portions of the bacterial population of the manure.

The application of the anaerobic digestion process as a method of treatment of hog wastes was evaluated with laboratory-size digesters. The review of literature revealed that the anaerobic digestion process is not affected by the size of the digester and, therefore, the laboratory results obtained in this study can be used to evaluate the design and formulate the operational procedures of much larger digestion plants.

Hog manure is digestible. At 95°F, with once-a-day feeding and with continuous mixing of the contents of a single stage digester, hog manure could be digested at a loading rate of 0.2 lb of volatile solids per day per cubic foot of digester capacity and a detention period of less than 8
The copper content of the manure was found to limit the digestion process when copper was added at concentrations of 36 ppm. Therefore, it became necessary to dilute the manure with tap water to a total solids content of less than 3.6 percent before feeding the manure to the digesters. On the basis of a volatile solids loading rate of 0.2 lb/d/ft$^3$ and 10-day detention period, the digester capacity required is 3.74 cubic feet per cubic foot of manure to be digested or approximately 1 cubic foot of digester volume for every pig produced within one year; i.e., a confinement unit producing 10,000 hogs per year will require a digester with 10,000 ft$^3$ capacity.

The gas volume produced from each digester was measured daily. The average gas yield per day per pound of volatile solids ranged from 7.8 to 10.3 cubic feet. Analysis of the gas with a chromatography column showed a methane content of approximately 59 percent and a carbon dioxide content of about 40 percent. The rest of the gas was mostly free nitrogen. The heating value of the gas was estimated to be about 570 BTU/ft$^3$. On the basis of these data and the hog manure composition, about 3,600 BTU/day can be produced from the daily wastes of a pig.

The fertilizer value of manure as measured by its nitrogen content was increased through digestion. The digested manure was soupy in texture, black in color, had no offensive odors, and flies were not attracted to it. The organic matter of the raw manure and, thus, its potential pollutional strength was reduced from 60 to 70 percent through digestion.

Considerations for the design of a digestion plant were discussed.
and formulae for design were given. On the basis of estimation cost data given by Morgan (1962), the approximate total cost for different size digesters were presented. For the treatment by anaerobic digestion of the daily wastes collected at the confinement building of the Iowa State University Swine Nutrition Farm, a digester of about 3,200 ft$^3$ capacity is required. A digester of this size is estimated to cost about $26,000.


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APPENDIX
Figure 23. Performance of Digester I during the period from May 10 to September 12, 1962
PERFORMANCE OF DIGESTER I

VOLATILE ACIDS AND NH₃-N, 10² mg/l

GAS PRODUCTION

pH

Vm IN RAW SLUDGE

Vm IN DIGESTED SLUDGE

LOADING RATE, lb Vm/d/ft³

VOLATILE SOLIDS, % (WET BASIS)

DAYS OF DIGESTION
Figure 24. Performance of Digester II during the period from May 10 to September 12, 1962
PERFORMANCE OF DIGESTER II

VOLATILE ACIDS

NH₃-N

GAS PRODUCTION

pH

Vm IN RAW SLUDGE

Vm IN DIGESTED SLUDGE

LOADING RATE

VOLATILE SOLIDS, % (WET BASIS)

LOADING RATE, lb Vm/dt³

DAYS OF DIGESTION

Days of May, June, July, August, September

Perfomance values:

- Volatile Acids
- NH₃-N
- Gas Production
- pH
- Vm in Raw Sludge
- Vm in Digested Sludge
- Loading Rate
- Volatile Solids (% Wet Basis)
Figure 24a. Performance of Digester II during the period from September 13 to November 26, 1962
PERFORMANCE OF DIGESTER II

VOLATILE ACIDS

GAS PRODUCTION

Vm IN RAW SLUDGE

LOADING RATE
Figure 25. Performance of Digesters IIIA and IIIB during the period from May 10 to September 12, 1962
PERFORMANCE OF DIGESTER IIIA
NOTE: DIGESTER IIIA EXPLODED JUNE 10 AND WAS REPLACED WITH DIGESTER III B

PERFORMANCE OF DIGESTER IIIB

VOLATILE ACIDS

NH₃-N

GAS PRODUCTION

pH

LOADING RATE, lb Vm/d ft³

VOLATILE SOLIDS, % (WET BASIS)

DAYS OF DIGESTION
Figure 26. Performance of Digester IV during the period from May 10 to September 12, 1962
PERFORMANCE OF DIGESTER IV

VOLATILE ACIDS AND NH₃-N, 10³ mg/l

GAS PRODUCTION

pH

Vm in RAW SLUDGE

LOADING RATE, lb Vm/d ft³

Vm in DIGESTED SLUDGE

LOADING RATE

DAYS OF DIGESTION
Figure 26a. Performance of Digester IV during the period from September 13 to November 26, 1962
PERFORMANCE OF DIGESTER IV

VOLATILE ACIDS

GAS PRODUCTION

$V_m$ IN RAW SLUDGE

LOADING RATE, lb/d, ft$^3$/lb $V_m$ FED

LOADING RATE, lb/d, ft$^3$

$V_m$, % (WET BASIS)

DAYS OF DIGESTION
Figure 27. Performance of Digester VI during the period from May 10 to September 12, 1962
Figure 27a. Performance of Digester VI during the period from September 13 to November 26, 1962
PERFORMANCE OF DIGESTER VI

- VOLATILE ACIDS
- GAS PRODUCTION
- $V_m$ IN RAW SLUDGE
- LOADING RATE

LOADING RATE, lb/d | $V_m$ in RAW SLUDGE | GAS PRODUCTION, ft$^3$/d | VOLATILE ACIDS, $10^2$ mg/l

DAYS OF DIGESTION

SEPT. OCTOBER NOVEMBER