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THE BIOLOGIC DIGESTION OF GARBAGE WITH SEWAGE SLUDGE

BY

HAROLD E. BABBITT

BENN J. LELAND

AND

FENNER H. WHITLEY, JR.

BULLETIN No. 287

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THE BIOLOGIC DIGESTION OF GARBAGE WITH SEWAGE SLUDGE

BY

HAROLD E. BABBITT
PROFESSOR OF SANITARY ENGINEERING

BENN J. LELAND
SPECIAL RESEARCH GRADUATE ASSISTANT IN CIVIL ENGINEERING

AND

FENNER H. WHITLEY, JR.
RESEARCH GRADUATE ASSISTANT IN CIVIL ENGINEERING

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THE BIOLOGIC DIGESTION OF GARBAGE WITH SEWAGE SLUDGE

I. Introduction

1. *Objects of Tests.*—The water carriage method of garbage collection may be expected to place an added load upon sewage treatment plants, to increase stream pollution, and possibly to offer a new and satisfactory method for the collection and disposal of garbage. The problems thus created will affect the work of sewage treatment plant operators, public officials, authorities responsible for the protection of the purity of natural water courses, and others. These problems involve the capacity and ability of plumbing systems and sewers to convey ground garbage suspended in water, the nature of the load placed upon sewage treatment plants and water courses, and the economics of the method.

The objects of these tests were to study the nature and intensity of the load placed upon sewage treatment plants and water courses, the capacity of digestion tanks to carry this load, and the division of the load between primary and secondary forms of treatment in a sewage treatment plant. Studies were restricted principally to the digestion of garbage with fresh sewage sludge, and to methods for the dosing of digestion tanks.

2. *History and Experience.*—Probably the earliest serious attempt to dispose of garbage through a sewage treatment plant was made by C. R. Fox and W. S. Davis at Lebanon, Pa., in 1923.[1, 2*] United States patent Number 1 543 154, filed July 28, 1923, has been granted on the process. So little attention was paid to the process at the time of its introduction that no mention of it is made in the exhaustive discussion of methods of garbage disposal[3] in the Transactions of the American Society of Civil Engineers in 1927.

In 1928 Rudolfs and Heukelekian working[4] with vegetable wastes resulting from the screening of sewage concluded that "the digestion of vegetable waste in treatment plants receiving domestic sewage is possible, but that it will require not only an increase in digestion capacity equivalent to the increase in weight of solids to be handled, but also a larger digestion capacity on account of the slower rate of digestion. Anaerobic digestion of vegetable wastes and possibly of garbage is possible, but takes a longer time, probably due to the fact that the amounts of nitrogenous substances are low and the produc-

*These numerical indices on this and following pages refer to the correspondingly numbered references in the List of References, Appendix F, p. 106.

tion of acid substances is great. The low quantity of nitrogenous substances results in a poor nitrogen-carbon relation which affects the proper growth of organisms responsible for decomposition. Ordinarily organisms active in the decomposition of mixed organic substances, like sewage solids, are depressed by acid conditions. An incorrect N-C ratio results in an acid medium and odors are intensified. The acidity can be corrected by the addition of lime, but the quantities required are large. At present it does not seem that separate digestion of mixed carbonaceous vegetable matter is economical. But, if sufficient sludge digestion capacity is available, such vegetable waste can be decomposed readily in plants treating domestic sewage, without upsetting the digestion activities. There is no doubt that, with intelligent control and sufficient capacity, vegetable waste can be handled, but further experiments will have to show the limit of such addition. Vegetable wastes, high in N content, as bean and pea waste, may digest quicker than low N content vegetables."

Studies of the digestion of garbage with sewage sludge were commenced by Fair[5] in 1928, but the results were not published until 1934. The thermophilic digestion of garbage with sewage solids, principally in connection with the Becarri process of garbage disposal, is discussed by Hyde[6] in 1932.

In 1931 the Massachusetts Institute of Technology Division of Municipal and Industrial Research stated[7] concerning disposal of garbage with sewage: "This method is applicable to garbage, but only where a satisfactory treatment plant is available. The garbage is ground up and fed into the municipal sewage supply, in amounts insufficient to interfere with the efficiency of the sewage treatment plant. The process has only a limited application at the present time." The American Reduction Corporation was organized in 1931 "and acquired from Dr. G. H. Earp-Thomas the rights to the use of his patented process for the depuration of garbage, sewage, and tankage and the manufacture of fertilizer therefrom." The process is covered by the Earp-Thomas patent application Serial No. 570 757.

A report of the practical application of the water carriage method for the collection of garbage on a large scale was made by Keefer[8] as a result of experience with a 100-ton garbage grinding unit in Baltimore in 1933. The possible effect of placing this load upon the Baltimore sewage treatment plant had previously been studied by Keefer and Kratz.[9] Cohn,[10] in Schenectady, reported upon the presence of waste food on the screens, and suggested the possibility of the digestion of greater loads of such material if seeded with digested sludge and maintained with a neutral reaction.

Investigations of the possibilities of the disposal of garbage through sewage treatment plants were commenced at the Engineering Experiment Station of the University of Illinois in March 1934.

Calvert and Bloodgood have carried on laboratory tests on the digestion of garbage and Calvert has disposed of ground garbage on a large scale into the sewers of Indianapolis which lead to the aeration plant of the Sanitary District of Indianapolis. Results of these tests and experiences were reported before the Central States Sewage Works Association in Urbana, Illinois, in October 1935.[11] Recent experience in the disposal of garbage with sewage has been reported from Durham, N. C.[12] and Baltimore, Md.;[8, 13] Bloodgood,[14] in 1936, reported the results of an investigation of the digestion of garbage with activated sludge at Indianapolis.

In 1935 the city of St. Louis, Mo., installed a garbage grinding plant to deposit 300 tons of ground garbage daily into the Mill Creek sewer.[15, 16] This mixture of garbage and sewage is discharged, untreated, into the Mississippi River.

The amount of attention given to the water carriage method for the collection of garbage has been progressively increasing, as evidenced by the articles appearing in the technical press. Interest upon the part of the public has been aroused through the introduction, in 1934, of an electrically operated device known as a waste food grinder, which makes possible the disposal of waste food (garbage) through the kitchen sink and the house plumbing. Results of more than a year of experience with these devices in twenty different homes are reported by Cohn.[17]

The disposal of garbage into sewers has not yet become popular abroad. An intensive review of French, German, and Italian technical literature has revealed no description of an investigation of, nor practice of, the water-carriage method of garbage collection, nor of the disposal of garbage by anaerobic digestion with sewage sludge.

Keefer[13] summarizes the status of the procedure of the disposal of garbage into sewers with the statement:

"It is difficult to predict whether there will be a general tendency in the future to adopt such methods as those described here. It is advisable that laboratory work be continued, and its results be checked more extensively on a plant scale. However attractive the combined treatment of garbage and sewage may appear in certain instances, it should be adopted only after the most careful study."

3. *Other Investigations.*—Early investigations, the results of which are useful in the study of the disposal of garbage in sewage treatment

plants, were directed mainly towards the recovery of by-products from industries producing organic wastes, or methods for the disposal of such wastes. Probably the earliest studies of which record is available are those of Popoff[18] who, in 1875, showed that methane, carbon dioxide, and sometimes hydrogen arise from sewage sludge diluted with water. Popoff is credited also[18] with the earliest work on the digestion of cellulose with sewage sludge. In spite of Popoff's early work little or no progress was made until the past decade in the utilization of biological processes in the recovery of by-products from organic wastes or the disposal of such wastes.

In 1923, the same year that the first recorded attempts were made to dispose of garbage with sewage, Bach and Sierp[18] studied the decomposition of a variety of typical food substances such as are likely to be present in domestic wastes. Rudolf and associates,[19, 20] in 1927 and 1929, and Heukelekian[21] reported upon the digestion of pure food substances with sewage sludge, finding marked differences in the characteristics of the digesting mixtures which contained dissimilar food materials.

4. *Testing Plant and Equipment.*—The Sewage Testing Plant of the University of Illinois is located on the campus and is so situated as to take its supply of sewage from the 30-in. main outfall sewer of the city of Champaign. A low dam in a manhole in the outfall sewer diverts a portion of the sewage into a 4-in. and a 6-in. vitrified clay pipe, each about 240 feet long, terminating in a sump in the main building of the testing plant. The sump into which these two sewers discharge was made as small as possible, by means of partitions, to reduce to a minimum the settling of sewage at this point. Two 2-in. electrically-driven centrifugal pumps distribute the sewage through black iron and galvanized pipes, 2-in. and smaller, to the various devices throughout the plant. All effluents and drainage from the plant are returned to the Champaign outfall sewer. A plan of those parts of the testing plant used in these tests is shown in Fig. 1.

5. *Tanks.*—Four circular wooden tanks, each approximately 10 ft. in diameter, with conical bottoms, were used for the principal large-scale tests. These tanks are marked A, B, C, and D on Fig. 1. Tanks A and B are approximately 28 feet deep, and tanks C and D are approximately 17 feet deep. The two deeper tanks are equipped and operated as Imhoff tanks. Dimensions and details of these tanks are shown in Figs. 1 and 2. A small amount of fresh sludge was sometimes collected in tank F and in 50-gallon, metal oil drums. Modifications

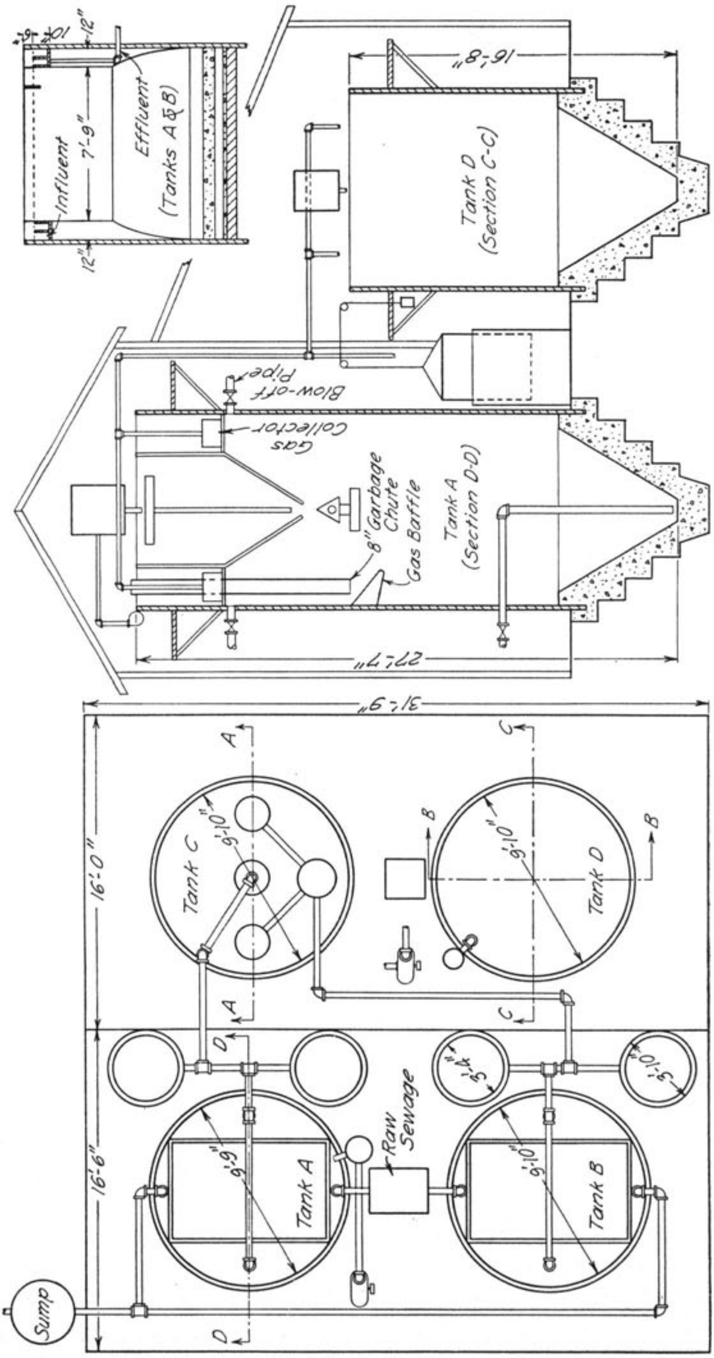

Fig. 1. Plan of East Building Showing Tanks A, B, C, and D

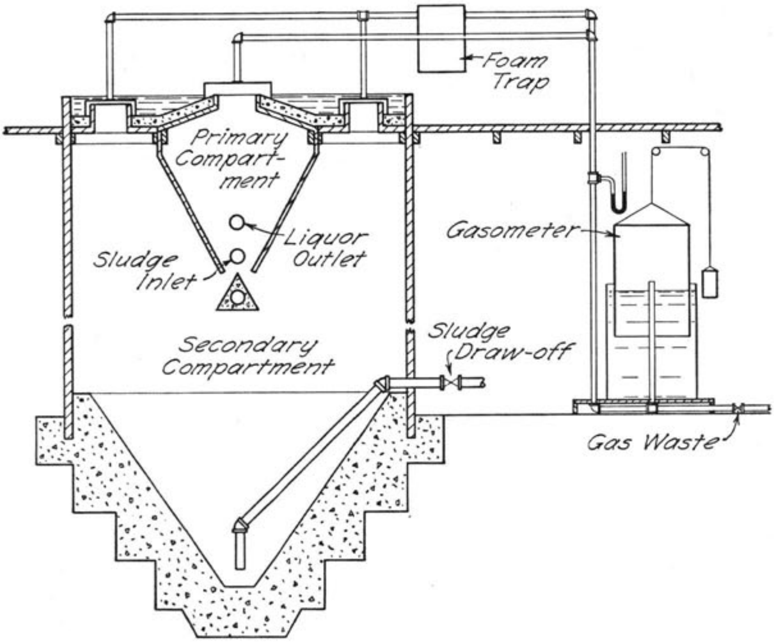

FIG. 2. ARRANGEMENT OF TANK C FOR TWO-STAGE DIGESTION

which were made of the arrangements of the interior of tanks A, B, and C for the various tests are described in conjunction with the discussion of each test series. Tank D was used at all times as a plain sedimentation tank, arranged as shown in Fig. 3.

Small-scale digestion tests were made in 50-gallon oil drums, in 5-gallon glass carboys, and in one-gallon and two-gallon glass bottles.

6. *Garbage Grinding.*—Garbage was ground in a farm-type grain grinder, using roughened, flat steel plates between which the particles were partly cut and partly crushed. The device, driven by a one h.p. motor, was capable of grinding about 100 pounds of garbage per hour, exclusive of large bones and other large objects which were picked out by hand. During the operation of the grinder the full time of a man was required to hand-pick the garbage and feed it into the machine.

The sizes of the ground particles were such that practically all particles could be washed through a ½-in. mesh sieve, and approximately 50 per cent, by weight, of the dry solids were retained on a ¹⁄₁₀-in. mesh sieve when an attempt was made to wash the ground

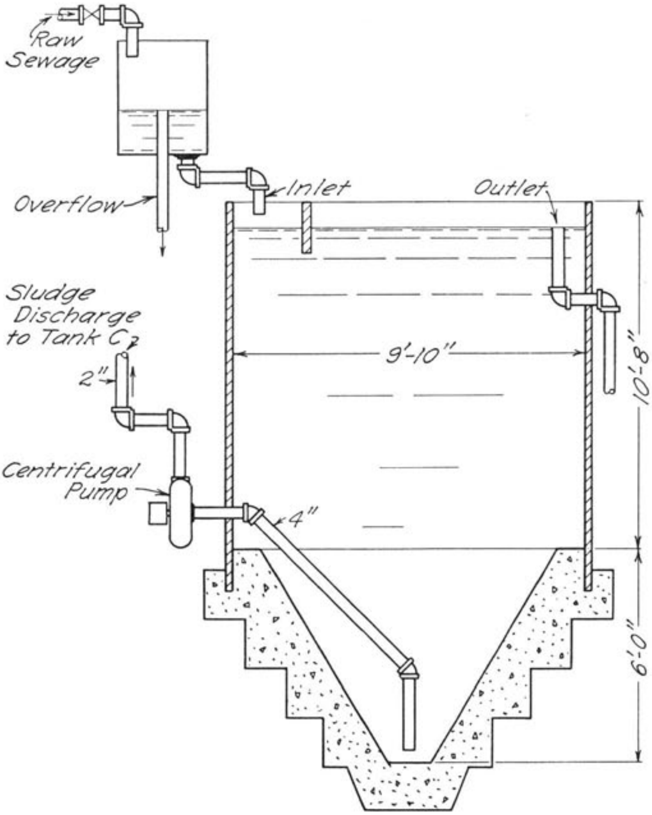

FIG. 3. DETAILS OF TANK D

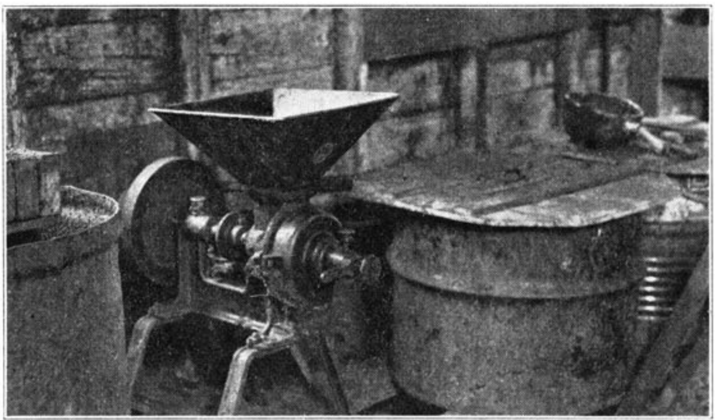

FIG. 4. GRAIN GRINDER USED FOR GRINDING GARBAGE

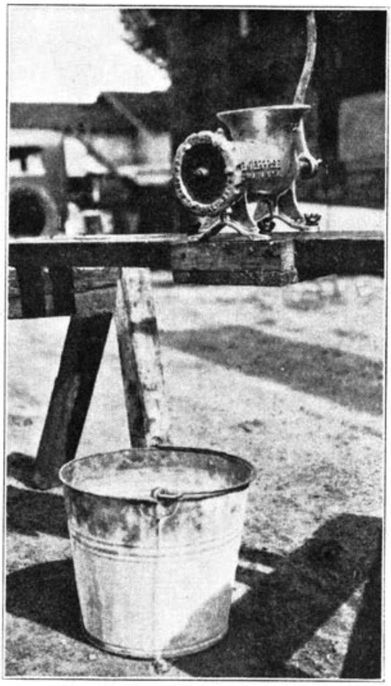

FIG. 5. MEAT GRINDER USED FOR GRINDING GARBAGE

garbage through the sieve. An illustration of the garbage grinder is shown in Fig. 4. In a few instances in which finer grinding was desired the material from the large grinder was put through a domestic meat grinder of the type illustrated in Fig. 5. The material passing through this grinder was pushed through a steel plate containing circular holes $3/16$-in. in diameter.

7. *Gas Collection Equipment.*—In some of the tests tanks A and B were roofed for the collection of gas, as illustrated in Fig. 1, and in all of the tests tank C was so equipped that gas could be collected separately from the primary and from the secondary compartments, as illustrated in Fig. 2. The gas was collected in batteries of galvanized iron gasometers as shown in the figure. The gasometer domes were counter-balanced so that they would move up or down with a gas pressure of less than $1/4$-in. of water. For a few days towards the end of the tests the gasometers were supplemented by a standard type of wet gas meter.[22] The brine solution used to seal the gasometers

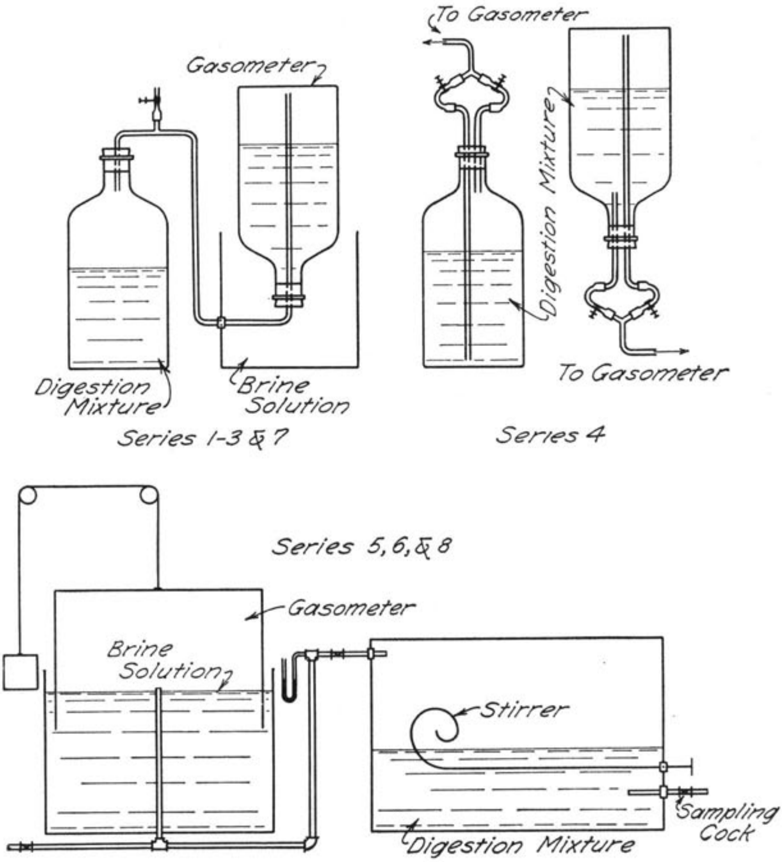

FIG. 6. DETAILS OF DIGESTERS USED IN SERIES 1-8 OF DIGESTION OF GROUND GARBAGE WITH FRESH SEWAGE SLUDGE

and the meter was never changed, small quantities being added as needed to maintain the seal. As shown by the test reported on page 78 the loss of methane through this seal was insignificant, and when the gasometers were emptied daily the loss of gas was insufficient to affect the interpretation of the results.

Galvanized iron and black iron piping were used for conveying gas from the tank to the gasometers. It was found that ½-in. piping was inadequate in capacity to carry the sudden bursts of gas coming from the tanks. A back pressure resulted on the gas domes which occasionally confined the gas under them to such a degree that some escaped until the difficulty was remedied. The situation was aggra-

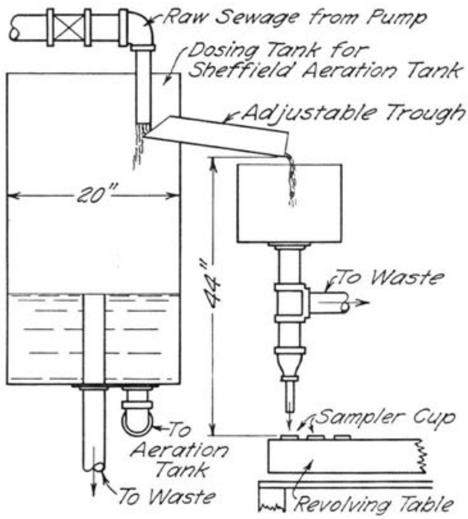

FIG. 7. DEVICE FOR DIVERTING SAMPLES OF RAW SEWAGE

vated through the clogging or even stoppage of the gas pipes by froth or scum which was blown into them during periods of violent ebullition. The difficulty was overcome by using larger gas piping, up to 1½ inches in diameter, and by placing a foam trap in the gas line from the most troublesome points.

Gases were collected from the cask, carboy, and bottle experiments in a similar manner, as illustrated in Fig. 6. Glass tubing and rubber hose were used for the collecting pipes, and either metal or glass gasometers for temporary storage.

8. *Sampling.*—Samples of raw sewage and effluents from tanks A and B were collected hourly by an automatic device. Twenty-four equally-sized samples were mixed to represent a composite sample of the day's flow. The automatic sampler operated as follows:

Twenty-four tin containers, each with a capacity of about 200 cc. were equally spaced on the perimeter of a circle on a table driven by a mechanism which caused it to move intermittently $\frac{1}{24}$th of a revolution every hour. Glass containers were found unsuitable because of breakage due to freezing. The motion of the table was controlled by an escapement rachet, similar to a clock mechanism, in such a manner that each hourly movement of the table was completed in about 30 seconds, one-half of the distance being moved suddenly; then there was

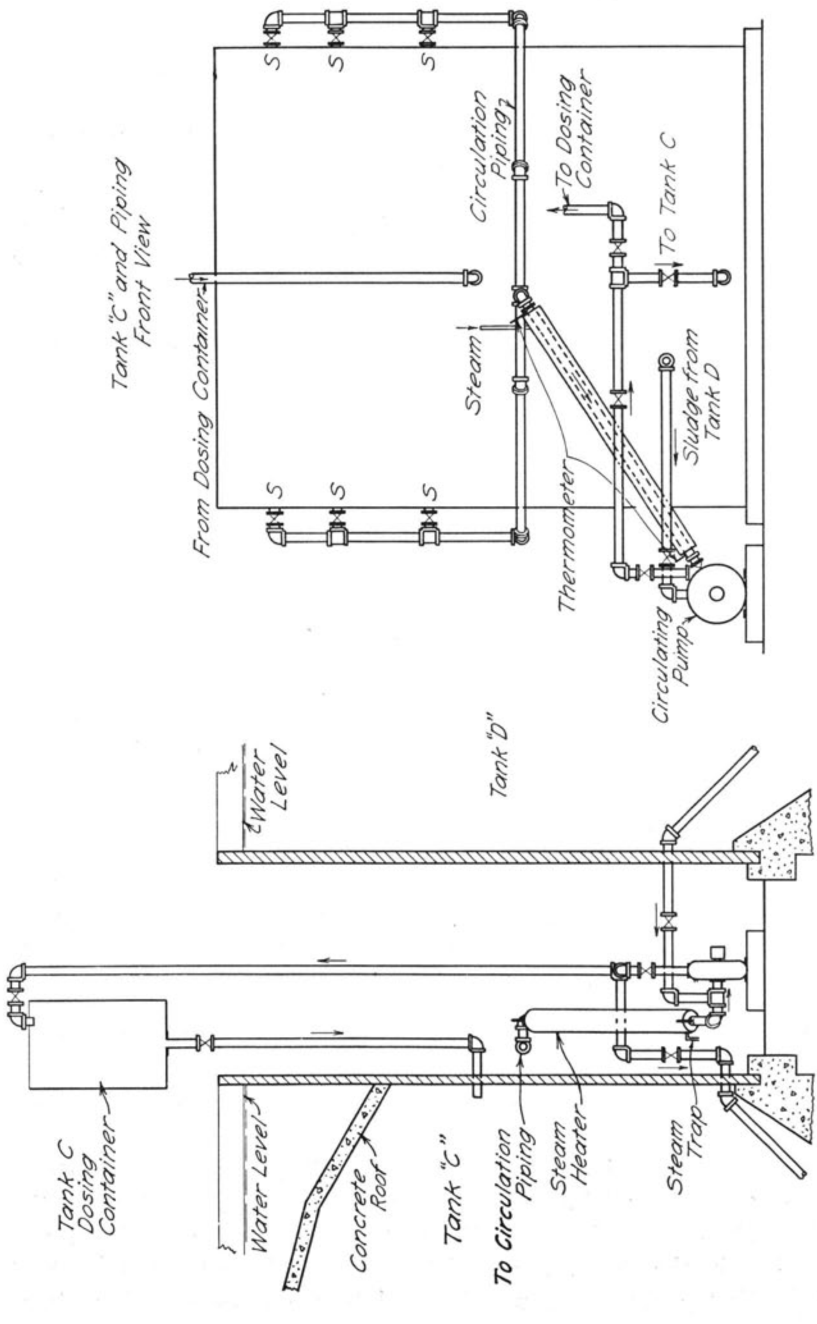

FIG. 8. PIPING ARRANGEMENT FOR CHARGING TANK C AND SAMPLING SLUDGE FROM TANK D

a pause for 30 seconds, followed by a quick jerk to complete the movement. This liquid to be sampled was allowed to run continuously from the pipe, the end of the pipe being so fixed that for 59½ minutes the liquid fell directly upon the table, between two sample containers, and wasted away through the drain. During the half minute of interruption of the hourly movement of the table, a container came directly under this stream and was filled to overflowing. The table was sufficiently large to permit the collection of three samples simultaneously. The streams of raw sewage and tank effluents were diverted to the automatic sampler, as illustrated in Fig. 7.

In the routine sampling of other materials the procedure was as follows: Supernatant liquor and digested sludge were sampled from the sludge compartments of tanks A and B by inserting the end of a suction hose from a pitcher pump to the desired depth in the tank, and pumping until a flow of the representative material came from the pump. The material was caught in a glass or metal container and taken to the laboratory within an hour after collection. Samples of the liquor in the secondary compartment of tank C and of the sludge from tank D were taken from the discharge pipe of the circulating pump, shown in Fig. 8. Samples of the primary compartment of tank C were drawn from a pipe shown at *A* in Fig. 9. The pipe was well cleaned before the sample was drawn.

Gas samples were collected by displacing the water, previously saturated with gas, from 250 cc. gas pipettes inserted in the discharge line from the gasometers.

When samples of garbage were taken, a large tub of ground garbage was mixed thoroughly by turning with a spade until the contents were uniformly mixed. Then a small sample of about one-half pound was taken to the laboratory. A representative portion of this sample was taken in the laboratory for the determination of solids and of grease, or ether soluble matter.

9. *Source and Quality of Sewage.*—The sewage used in these tests is characteristic of a strong domestic sewage, free from industrial wastes, and receiving large quantities of ground water in wet seasons. It is diverted from the 30-in. Champaign outfall sewer by means of a low dam in the bottom of the sewer. This tends to concentrate settleable solids and inorganic matter in the sewage received at the testing plant, as such material cannot easily escape over the diversion dam in the sewer. Some of the suspended matter and most of the floating particles are not diverted to the sewage testing plant,

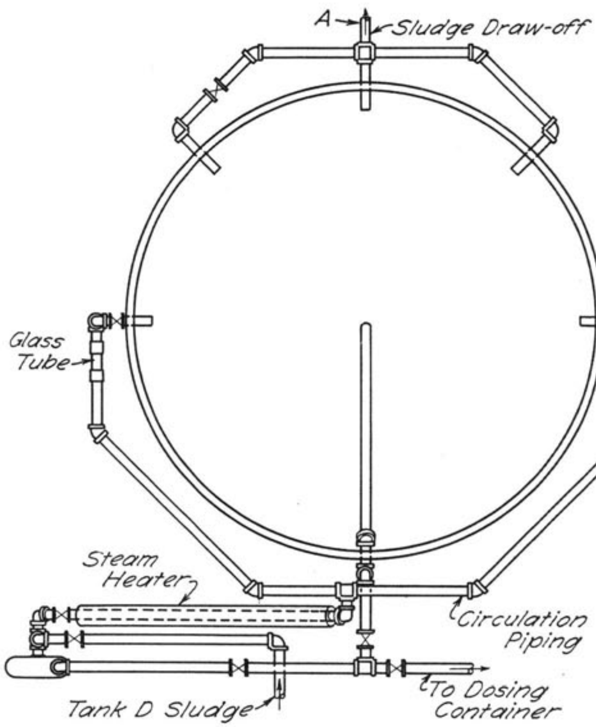

FIG. 9. PLAN OF TANK C SHOWING PIPING ARRANGEMENT

particularly during high flows, as they escape over the diversion dam. In pumping the sewage through the plant, large solids are broken up and the settleable solids content is reduced. Analyses of 32 composite samples of sewage taken during the period Feb. 6 through April 15, 1936, are averaged in Table 1. The composite samples were collected by taking hourly samples of equal volume and combining the 24 samples to represent the quality of the sewage entering the plant.

TABLE 1
QUALITY OF SEWAGE USED IN TESTS
32 composite samples

	Average	Maximum	Minimum
Total solids, p.p.m.	1200	3100	610
Volatile solids, p.p.m.	646	1765	208
B.O.D. 5-day 20 degree	312	650	100
pH	....	7.6	7.1

TABLE 2
TYPICAL ANALYSES OF GROUND GARBAGE AND OF FRESH SLUDGE USED IN INVESTIGATION

	Garbage			Sludge		
	Av.	Max.	Min.	Av.	Max.	Min.
Total solids, per cent	30.4	36.4	24.2	1.7	4.3	0.4
Volatile solids, per cent	28.5	33.8	22.4	1.2	2.7	0.25
Dry weight ether soluble, per cent	28.4	54.3	16.4	23.8	37.7	6.2
Total Nitrogen, per cent dry basis	2.21	....	....	2.10	....	....

As a rule the strongest sewage reaches the experimental plant from about 10 a.m. to 1 p.m., and the weakest between 3 a.m. and 6 a.m. During the latter period the sewage is largely ground water which has filtered into the sewer.

Although there is a marked fluctuation of the rate of flow in the sewer during any 24-hour period, no allowance was made for this variation in the rate of dosing the various tanks. It was felt that such a refinement in the rates of dosing of the tanks was unnecessary, as the purpose of the tests was to find the effect of the addition of waste food to tanks dosed with sewage. Variation of the rate of flow of sewage would result only in changing the strength of the sewage added to the tanks.

10. *Source and Quality of Garbage.*—Garbage for the tests was collected by private scavengers from restaurants, boarding houses, residences, and similar establishments in the University district. It might be classified as "clean" garbage in that it was free from any materials other than waste food. The specifications were that the material must be "fit to be fed to a hog." This waste food was delivered daily to the testing plant. It was usually delivered the same day as collected and, except in extremely inclement weather, was comparatively fresh.

The garbage, as received in galvanized iron barrels, was dumped into a container with a perforated bottom, which permitted excess moisture to drain away from it before the material was hand-picked to remove inorganic and inedible materials and large lumpy objects that would not go through the grinder. One result of this procedure was that the material put through the grinder and used for subsequent digestion tests was probably richer in putrescible organic matter than the average municipal garbage. Analyses of the ground garbage are given in Table 2.

11. *Source and Quality of Sludge.*—Fresh sludge was collected in tank D, a plain sedimentation tank equipped as shown in Fig. 3. The rate of flow of sewage into the tank was controlled by an orifice upon which a constant head was maintained. The retention period, as computed on the basis of the time to displace the full volume of the tank, was normally about 4½ hours. The sludge was removed from the tank by hydrostatic pressure aided by pumping, and was forced through pipes into the control box used to regulate the dosing of the separate sludge digestion tank, tank C.

Sludge was never allowed to remain in tank D longer than three days, and additional fresh sludge, collected by plain sedimentation in other small containers, was never more than three days old when put into tank C. Some typical analyses of fresh sludge are shown in Table 2.

12. *Acknowledgments.*—These tests have been conducted by the authors as a regular part of the work of the Engineering Experiment Station of the University of Illinois, of which DEAN M. L. ENGER, is the Director, and of the Department of Civil Engineering, of which W. C. HUNTINGTON is the Head. Routine laboratory tests and other activities in connection with the investigation which have not been performed by the authors have been carried on under their supervision by undergraduates and graduate students employed for the purpose, and paid principally from National Youth Administration funds. The principal microscopical and bacteriological work, and the search of foreign literature were done by DR. MAX SUTER. The authors are indebted to DR. F. W. MOHLMAN, Chief Chemist of the Sanitary District of Chicago and Editor of "Sewage Works Journal," for his review of the manuscript.

II. DIGESTION OF GARBAGE SOLIDS SEEDED WITH SEWAGE SLUDGE

A. Batch Digestion of Ground Garbage with Sewage Sludge

13. *Purpose.*—Preliminary batch tests were conducted in a study of the following: suitable types of digestion equipment for use in the laboratory and in the experimental plant; desirable routine observations; the best ratio of garbage and sewage solids in a mixture; and to develop such other conditions as might affect the final tests.

14. *Procedure.*—The preliminary tests were conducted on mixtures of garbage and sewage sludge made up in batches and allowed to

stand in the digester, without the addition of fresh solids, until the completion of the observations. These have been called "batch" tests, to distinguish them from the more practical tests in which periodic feeding of the digesters was practiced. After the batches had been made up and put into the digesters the temperature of the surrounding atmosphere and the volume of gas produced were observed periodically for all of the containers, and the small samples of material withdrawn from a few of the containers were analyzed periodically for the total and volatile solids, pH, and physical characteristics such as color and odor.

Different preliminary batch tests were made as follows:

Series 1. In this series approximately 1.5 liters of a mixture of garbage and sewage sludge were placed in white glass bottles, each with a capacity of 2.5 liters. The following percentages of total garbage solids were placed in the respective digesters: 92.3, 78.3, 65.5, 47.3, and 37.6. The bottles were connected with gasometers, as illustrated in Fig. 6, and were allowed to stand undisturbed for 55 days from May 3 to June 27, 1934.

(Bottles 12-15)

Series 1a. Similar to Series 1. Period of digestion, 32 days, from May 22 to June 23, 1934.

(Bottles 31-35)

Series 2. Similar to Series 1. The percentages of garbage volatile solids in the respective digesters were 94.3, 85.5, 81.1, 68.1, and 43.8. The bottles were allowed to stand undisturbed for 39 days, from May 15 to June 23, 1934.

(Bottles 21-25)

*Series 3.** Similar to Series 1. The bottles were allowed to stand undisturbed for 106 days from Dec. 12, 1934, to March 28, 1935.

(Bottles 13-18)

*Series 4.** Similar to Series 2, except that the bottles were inverted, i.e. turned through 180 degrees, twice daily. Observations were made over a period of 106 days, from Dec. 12, 1934, to March 28, 1935.

(Bottles 19-24)

*Series 5.** Similar to Series 2, except that the volume of the batch used was 20 liters and the digestion tanks were 208-liter metal soap or oil drums placed on their sides. Observations were made over a period of 303 days, from Dec. 11, 1934, to Oct. 10, 1935.

(Barrels 1-6)

*Series 6.** Similar to Series 4, except that the material within the digesters was stirred frequently (except when frozen) by means of the device illustrated in Fig. 6. Samples were withdrawn weekly, after a thorough stirring of the tank

*The mixtures in Series 3, 4, 5, and 6 were charged with the same materials from the same batch.

contents. Observations were made over a period of 303 days, from Dec. 11, 1934, to Oct. 10, 1935.

(Barrels 7-12)

Series 7. Similar to Series 1, except that a mixture of garbage and well-digested Imhoff sludge was used, and the bottles were well shaken frequently, each time preceding a reading of the volume of gas generated. The period of observations was 83 days, from April 20 to July 12, 1935. (Bottles 31-40, second time these numbers were used).

Series 8. Similar to Series 6, except that the garbage was seeded with various kinds of sludge. The period of digestion was 196 days, from April 3, 1935, to Oct. 16, 1935.

(Barrels 25-30)

The atmospheric temperatures experienced in Series 1, 2, 7, and 8, which were conducted during warm weather, seldom fell below 70 deg. F. In Series 3 and 4 freezing temperatures were approached, and during the greater portion of the period temperatures below 60 deg. F. were experienced. In Series 5 and 6, which were started in the winter, cold and freezing temperatures were common, the material in the digestion container being frozen solid for four to six weeks. During the latter part of the test, however, temperatures between 70 and 100 deg. F. prevailed. No conclusions have been drawn from the results of Series 3, 4, 5, and 6 because of the low temperatures to which they were subjected.

All of the garbage in the batches was ground in the domestic food grinder, shown in Fig. 5, the material being forced through a steel plate with $3/16$-in. circular perforations.

Gas was led through glass and rubber tubing to inverted glass bottles or steel drums, used as gasometers. These gasometers were filled with and immersed in a saturated brine solution which acted as a gas seal. The equipment is illustrated in Fig. 6. Routine procedure during the progress of the test included:

(1) The measurement of the rise of each gasometer
(2) The release of the gas and replenishing of the gasometer with brine
(3) The observation of the atmospheric temperature in the room
(4) Inverting the bottles of Series 4, twice daily
(5) Frequent stirring of the digesters of Series 6 and 8
(6) Weekly sampling and analyzing of the contents of the digesters of Series 6 and 8
(7) Frequent shaking and observation of gas produced in Series 7

TABLE 3
BATCH TESTS—SUMMARY OF OBSERVATIONS

Series 1.—Bottle Numbers	12	11	13	14	15
Total weight of mixture in grams	810.9	1211.6	873.3	1038.7	1042.2
Total weight of dry solids in mixture at start, grams	115.2	129.8	76.1	71.9	64.9
Garbage solids, percentage of total solids in mixture	92.3	78.3	65.5	47.3	37.6
Total solids in mixture, percentage at start	14.20	10.62	8.72	6.92	5.68
Total solids in mixture, percentage at end	9.20	6.97	7.25	9.72	12.92
Reduction of total solids, approximate percentage on dry basis	35	35	17	.....	.....
pH at start	6.0	6.0	5.8	5.4	4.8
pH at end	5.2	.....	5.0	5.4	5.4
Volume of gas per gram total solids at start, cc	0	68	61	0	36
Series 1a.—Bottle Numbers	31	32	33	34	35
Total weight of mixture in grams	1018.1	993.9	1029.0	1018.1	1010.5
Total weight of dry solids in mixture at start, grams	172.3	143.4	134.5	121.1	105.2
Total solids in mixture, percentage at start	17.0	14.6	13.1	11.9	10.4
Garbage volatile solids in mixture at start, per cent, dry basis	94.3	85.5	80.1	69.9	55.1
Volatile solids in mixture at start, grams	153.4	120.3	117.5	92.0	73.4
pH at start	.....	.....	4.2	4.2	4.4
Volume of gas per gram of volatile solids at start, cc	trace	72	63	84	63
Series 2.—Bottle Numbers	21	22	23	24	25
Total weight of mixture in grams	1060.8	1030.8	1075.9	1111.0	1034.3
Total weight of dry solids in mixture at start, grams	181.8	157.5	152.0	134.0	100.0
Total solids in mixture, percentage at start, wet basis	17.1	15.3	14.1	12.0	9.7
Garbage volatile solids in mixture at start, per cent, dry basis	94.3	85.5	81.1	68.1	43.8
Volatile solids in mixture at start, grams	151.5	126.9	118.5	99.6	67.1
Volume of gas per gram of volatile solids at start, cc	trace	40	trace	45	31
Total weight of dry solids at end, grams (approx.)	146.3	84.0	62.4	104.3	137.3
pH at end	.....	5.0	.....	5.0	5.2
Reduction of total solids, per cent (approx.)	20	47	59	22	.....

15. *Results and Conclusions.*—A summary of the results of Series 1, 2, 7, and 8 is shown in Table 3, and a graphical record of gas production in Series 7 is given in Fig. 10. Although the results appear anomalous the purposes of the tests were accomplished.

The results of Series 8 demonstrated the lack of correlation between pH and volatile acids, and the fact that either index might indicate unsatisfactory conditions of digestion. It was assumed that one of the principal causes of the acid digestion experienced in these tests was the relatively high concentration of solids in all of the batches and, as a result, this concentration was generally held lower in subsequent tests.

It was concluded that the seeding of the garbage with sludge could be satisfactorily accomplished if 10 per cent or more of the volatile solids in the mixture represented sludge volatile solids. In subsequent tests the percentage of sludge volatile solids used was more nearly 40

TABLE 3—(*Concluded*)

Series 7.—Bottle Numbers	31	32	33	34	35
Total weight of mixture in grams	3230	2985	3176	2705	3052
Total weight of dry solids in mixture at start, grams	293	271	288	246	323
Total solids in mixture, percentage at start	9.07	9.07	9.09	9.09	10.56
Garbage volatile solids in mixture at start, per cent, dry basis	0	0	12.8	12.8	25.0
Volatile solids in mixture at start, grams	185	171	189	166	220
Volatile solids in mixture at end, grams	34	39	36	37	57
Reduction of volatile solids, per cent	81.6	77.2	81.0	77.7	74.1
Volume of gas per gram of volatile solids digested, cc	357	187	304	345	124
pH at start	.....	.....	.....	.....	.....
pH at end	7.6	7.6	7.6	7.6	7.4

Series 7.—Bottle Numbers	36	37	38	39	40
Total weight of mixture in grams	2945	3340	3252	3162	2755
Total weight of dry solids in mixture at start, grams	311	420	408	480	418
Total solids in mixture, percentage at start	10.56	12.58	12.58	15.20	15.20
Garbage volatile solids in mixture at start, per cent, dry basis	25.0	45.0	45.0	67.5	67.5
Volatile solids in mixture at start, grams	212	310	302	384	335
Volatile solids in mixture at end, grams	69	238	203	278	232
Reduction of volatile solids, per cent	67.4	22.4	32.7	27.6	30.9
Volume of gas per gram of volatile solids digested, cc	103	34	35	38.5	23.7
pH at start	.....	.....	.....	.....	.....
pH at end	7.4	5.0	4.8	4.6	4.7

Series 8.—Barrel Numbers	25	26	27	28	29	30
Kind of sludge used for seeding	(1)*	(1)*	(2)*	(2)*	(3)*	(3)*
Total weight of mixture, kilograms	77.1	77.1	77.1	77.1	77.1	77.1
Total weight of dry solids in mixture at start, grams	4920	4920	5940	5940	1700	1700
Total solids in mixture, percentage at start	6.36	6.36	7.70	7.70	2.20	2.20
Garbage volatile solids in mixture at start, per cent, dry basis	71.0	71.0	73.5	73.5	65.7	65.7
Volatile solids in mixture at start, grams	4000	4000	5020	5020	1400	1400
Volatile solids in mixture at end, grams	1620	880	1120	1320	....	....
Reduction of volatile solids, per cent	59.5	78.0	77.7	73.7	....	....
Volume of gas per gram of volatile solids digested, cc	....	....	....	....	....	....
pH at start	....	....	....	....	....	....
pH at end	7.8	8.4	7.4	7.8	8.0	7.8
Volatile acids at start, p.p.m.	3000	2640	2500	2400	1670	2310
Volatile acids at end, p.p.m.	450	1160	2810	3160	430	220
Volatile acids, maximum observed, p.p.m.	3120	3260	3900	4280	1680	2330
Grease, percentage of dry samples at end	12.1	18.0	....	7.15	7.92	6.82

*(1) is digested sludge, (2) is fresh sludge, (3) is activated sludge.

to 50 per cent, approximating conditions to be expected in the operation of a sewage treatment plant receiving garbage.

The impracticability of digesting organic solids by batch digestion was emphatically demonstrated by the results of these preliminary tests. It was not always certain that the proper seeding of the batch was accomplished; some batches were slower in digesting, the reduction of volatile solids was low, and the volume of gas generated was low. Acid conditions, once established, were slow to change. The break in the curves in Fig. 10 between 20 and 30 days indicates that, when good digestion was possible, digestion approached completion in this period.

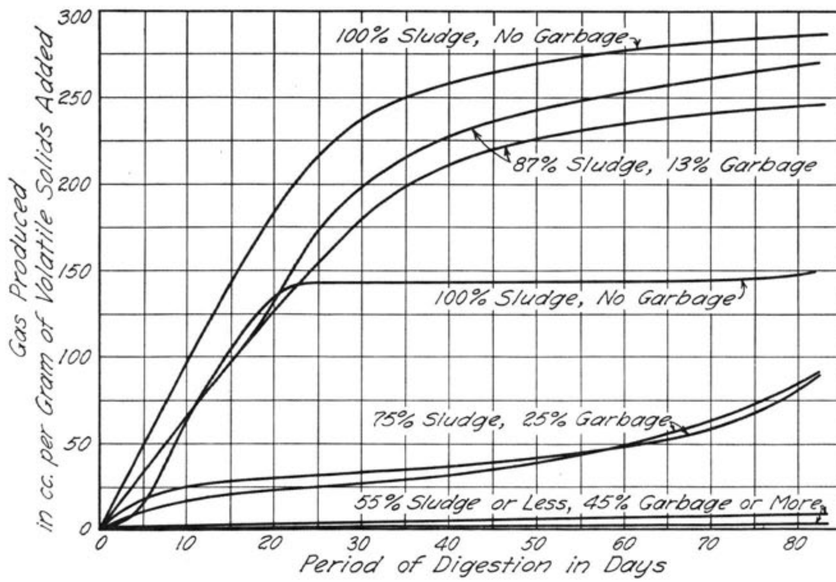

FIG. 10. RESULTS OF SERIES 7. RATE OF GAS PRODUCTION IN BATCH DIGESTION OF GARBAGE SEEDED WITH WELL-DIGESTED IMHOFF TANK SLUDGE

TABLE 4
OPERATING DATA ON TANKS A AND B DURING PERIOD OF APPLICATION OF GARBAGE TO DIGESTION COMPARTMENT OF TANK A, SERIES 2

Rate of flow of sewage through Tank A and Tank B......................	31 700 gal. per day
Period of retention in flowing-through compartments of each tank.........	2 hours
Velocity of flow in flowing-through compartment.........................	5 ft. per hr.
Capacity of sludge digestion compartments of each tank..................	40 cu. yd.
Sludge storage capacity of each tank, basis of 6 months between cleanings....	9½ cu. yd. per mill. gal.
Rate of addition of garbage to Tank A:	
Wet garbage added per day..	105 pounds
Wet garbage per mill. gal. of sewage................................	1.65 tons
Wet garbage per day per cu. yd. of sludge storage capacity.............	2.6 pounds
Duration of test, from Nov. 27, 1934 to April 29, 1935...................	154 days

B. Dosing of Imhoff Tanks with Ground Garbage

16. *Procedure.*—Tanks A and B, which are illustrated in Fig. 1 and are identical in construction, were used in this test. The procedure followed was to dose both of these tanks with the same quality and quantity of sewage, and to apply the garbage dose to one of the tanks in addition to the sewage. Through this procedure the difference between the results observed from the tank receiving garbage and the tank not receiving garbage could be attributed to the effect of the garbage. Tests were made of each method of dosing.

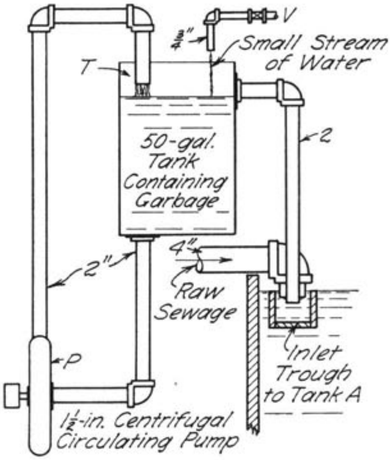

FIG. 11. DOSING TANK FOR TANK A

(1) In the first series of tests, made to determine the practicability of dumping ground garbage into the influent end of the flowing through compartment, 50 to 100 pounds of ground garbage were applied once daily, in three or four 20 to 25 pound lumps. Only the physical effects on the effluent and the appearance of the tanks thus dosed were observed. No chemical tests or gas measurements were made.

(2) In the second series of tests, made to determine the practicability of putting the ground garbage into the sludge digestion compartment of the tank, a charge of about 100 to 150 pounds of wet ground garbage was pushed into the digestion compartment of the tank through the 8-in. steel pipe illustrated in Fig. 1. Routine observations were made of physical and chemical characteristics of the sludge and of the influent and effluent of both the control tank and the dosed tank, and the rate of gas production in each tank was recorded. Operating data on tanks A and B during the conduct of this series of tests are shown in Table 4.

(3) In the third series of tests, made to determine the practicability of mixing the garbage thoroughly with the sewage entering the flowing-through compartment of the tank, a batch of ground garbage was placed in the dosing tank, shown at *T* in Fig. 11, which had previously been partly filled with water, so that nothing overflowed when the garbage was added to the dosing tank. The centrifugal pump shown at *P* circulated the material rapidly, making an intimate

mixture of the garbage with the contained water. A small stream of water was allowed to fall into the dosing tank, from the valve shown at *V*, and the overflow from the dosing tank was discharged, with the incoming sewage, into the Imhoff tank. The rate of flow of water into the dosing tank was controlled so that from four to eight hours were required for traces of garbage to disappear from the water circulating in the dosing tank. It was customary to divide the daily dose of garbage into from two to four batches, applying a batch to the dosing tank every two to four hours during the day. Operating data on tanks A and B during the period of the conduct of this series of tests, except for the rate of addition of garbage, are shown in Table 4. Routine observations were made of physical and chemical characteristics of the sludge, of the influent, and of the effluent from both the control tank and the dosed tank, and the composition of gas from each tank was determined periodically.

17. *Results and Conclusions.*—In the first series of tests no laboratory observations were necessary to demonstrate the futility of this method of dosing an Imhoff tank with garbage. Quantities of solid matter floated across the tank to be discharged with the effluent. The interposition of scum boards or hanging baffles served to collect scum behind the baffles without making any apparent improvement in the character of the effluent, which continued to be choked with solid particles sucked under the surface baffle.

Some results of the second series of tests in which ground garbage was added to the digestion compartment of tank A, are shown in Table 5. Shortly after the commencement of the operation of the tank it became evident that measurements of the volume of accumulated sludge were meaningless because of the tendency of the sludge to rise into the scum compartment. This condition was accompanied by a decrease of the pH in the digestion compartment.

Some time before the conclusion of the test all but a small portion of the sludge rose into the scum compartment to produce a 10-ft. thickness of scum. The gas vents became clogged, and the unbalanced pressures of the liquids and gas resulted in the collapse of the sides of the flowing-through compartment. Upon draining the tanks after five months of operation very little sludge was found in the digestion compartment of the garbage-dosed tank. The compartment was filled with a sour, vile-smelling, milky liquid. The scum in the scum chamber had the consistency of slush, and contained recognizable particles of undigested garbage, particularly citrus fruit and potato skins. The

TABLE 5

RESULTS OF ADDITION OF GARBAGE TO DIGESTION COMPARTMENT OF AN IMHOFF TANK; WEEKLY OBSERVATIONS IN DIGESTION COMPARTMENTS

Week of Obser-vations	Tank A					Tank B				
		With Garbage				Without Garbage				
	pH of Sludge	Sludge Solids		Volume Gas per Million Gallons Sewage cu. ft.	Tem-pera-ture of Sludge deg. F.	pH of Sludge	Sludge Solids		Volume Gas per Million Gallons Sewage cu. ft.	Tem-pera-ture of Sludge deg. F.
		Total per cent	Volatile per cent				Total per cent	Volatile per cent		
1	6.8	6.43	4.63	358	...	7.0	5.23	3.44	1380	...
2	6.2	6.77	4.72	341	59	6.8	5.75	3.77	716	59
3	5.8	5.10	3.33	381	59	6.8	6.74	4.30	503	...
4	5.8	....	....	326	...	6.8	5.95	3.77	422	...
5	5.4	4.99	3.68	291	...	6.8	4.38	2.91	362	...
6	5.3	3.07	2.28	286	55	6.6	5.09	3.17	376	58
7	5.3	3.62	2.77	286	58	6.9	6.88	4.99	414	59
8	5.2	11.75	7.73	252	55	7.0	9.71	5.28	376	56
9	5.2	17.3	14.18	246	...	7.0	7.85	4.73	466	...
10	5.6	3.03	2.39	242	54	...	9.33	5.49	525	57
11	5.2	11.48	10.03	245	...	7.0	8.14	5.29	563	...
12	5.3	13.45	11.36	264	57	6.8	10.80	6.92	563	56
13	5.2	7.21	6.48	280	55	6.7	9.60	6.45	578	57
14	...	8.02	6.99	304	54	...	6.40	3.74	631	55
15	5.2	12.87	11.12	302	...	7.0	4.78	3.10	613	...
16	...	4.00	3.41	288	54	...	10.68	5.94	618	55
17	...	....	....	276	...	...	....	....	629	...
18	...	....	....	264	...	...	....	....	656	...
19	...	....	....	250	...	...	....	....	656	...
20	...	....	....	238	...	...	....	....	657	...
21	...	....	....	226	...	...	....	....	635	...
22	...	....	....	216	...	...	....	....	613	...

sludge in the control tank had the appearance of normal, moderately-well-digested Imhoff sludge, indicating that the difficulty with the test tank was due to the addition of garbage.

Gas measurements from both tanks were difficult because of frequent leaks which occurred in the collection equipment. Until the complete break-down of the collectors in tank A, however, the measurements were such as to give a fair indication of the results being secured, and toward the latter part of the test the measurements of gas from the control tank were satisfactory. No analyses were made of the gas, but at no time could the gas from the test tank be ignited, whereas that from the control tank burned readily.

It is concluded from a study of the results of this series of tests, as well as from the results of the preliminary batch tests and the batch tests in which attempts were made to digest lumps of ground garbage, that it is not practicable to attempt to digest garbage in any digestion tank without intimately mixing the material with the liquid in the digestion compartment. The lumps of garbage are not broken

TABLE 6

RATES OF ADDITION OF GARBAGE WELL MIXED WITH SEWAGE ENTERING IMHOFF TANKS

Tank	Period Covered	Days	Garbage Added		
			Pounds per Day	Tons per Million Gallons	Pounds per Day per Cubic Yard of Sludge Storage
A....................	5- 6-35 to 11- 3-35	172	47.4	0.74	1.2
A....................	11- 4-35 to 12-21-35	47	94.5	1.48	2.4
B....................	12-26-35 to 1-16-36	21	61.4	0.96	1.5
A....................	1-17-36 to 3-17-36*	60	25.0	0.39	0.62
A....................	3-18-36 to 4-21-36	35	93.2	1.46	2.3
		351			

*During this period sub-zero weather sometimes prevented the grinding of garbage; hence the low average rate of application. The normal rate of dosing was about one ton of garbage per million gallons of sewage.

up and, as a result, produce the acid stage of digestion which is detrimental to rapid hydrolysis and gasification.

In the third series of tests, in which ground garbage was well mixed with the sewage entering tank A, the operating data shown in Table 4 are applicable, except for the rate of addition of garbage. This was added to either tank A or to tank B as shown in Table 6. It was never added to both tanks at the same time.

During the period of the test, 17 352 pounds of garbage were put into tank A and 1290 pounds into tank B. Each tank received 11 million gallons of sewage. Tank A accumulated 34.5 cu. yd. of thick sludge and tank B accumulated 6.4 cu. yd. No determination was made of the moisture content of this sludge. It would not be correct to assume that the difference between these quantities of sludge represents the amount due to the garbage added to tank A, because experience has shown that even when both tanks received sewage alone, the accumulation of sludge was more rapid in tank A than in tank B. The temperatures in the unheated digestion compartments varied between 50 and 72 deg. F., the tanks having passed through one of the coldest seasons on record. The action in tank B differed from that in tank A to such an extent as to cause the occasional discharge of larger quantities of sludge and scum in the effluent from B than in the effluent from A. Analyses which were made of 24-hour composite samples of the effluents from each tank are unsatisfactory, therefore, in studying the effect on the effluent from A resulting from the addition of garbage to the tank.

Sludge, when allowed to stand for a year in the digestion compartment, was thick and well digested. It accumulated at a rate of about 3.1 cu. yd. per million gallons of sewage receiving 1.5 tons of garbage. This is equivalent to 2.1 cu. yd. per million gallons of sewage per ton of garbage added. The efficiency of the removal of solids and of the reduction of B.O.D. were about the same in each tank. Solids were reduced from 1230 to an average of about 950 p.p.m. and B.O.D. was reduced from 300 to about 225 p.p.m.; pH was practically unchanged by either tank.

This series of tests indicated that the addition of ground garbage to the influent of an Imhoff tank did not interfere with the digestion in the tank, provided the rate did not exceed 1.5 tons of garbage per million gallons of sewage. The volume of sludge accumulated after a digestion period of one year was approximately 2 cu. yd. per million gallons of sewage per ton of garbage added to the sewage. It is probable that much more sludge was accumulated during the normal digestion periods allowed in full size sewage treatment plants.

Successful operation at higher rates of garbage addition is indicated, but no tests at higher rates were attempted in this investigation.

C. Digestion of Garbage in a Two-story, Separate Digestion Tank

18. *Purpose.*—The purpose of the test was to determine the capacity of a 2-story, temperature-controlled, separate digestion tank to digest ground garbage with fresh sewage sludge. It was expected that information might be obtained upon the quality and quantity of gas generated, the amount of sludge produced, and other factors of value in the design and operation of such a tank.

19. *Procedure.*—A 2-story tank, with temperature control, as illustrated in Fig. 2, with a primary compartment capacity of 1290 gallons and a secondary compartment capacity of 4770 gallons, was constructed. The temperature was controlled by circulating the contents of the secondary compartment through a steam-jacketed pipe placed outside of the digestion tank, as shown in Fig. 8. Automatic control was tried for about three weeks at the start of the test. Because of unsatisfactory operation of the automatic device the temperatures during this period fluctuated between 70 and 120 deg. F. Manual control was thereafter depended upon, with resulting extremes of temperature varying between 88 and 92 deg. F.

In dosing the tank, fresh sludge was drawn through the pump, shown in Fig. 8, and discharged into the dosing tank. Ground garbage was then added to the sludge in the dosing tank and the mixture brought to the required volume by the addition of sludge. Until January 2, 1936, the inlet valve to the primary compartment of the digestion tank was opened to allow the dose to enter the tank, at the same time that an equal volume of liquor was drawn from the outlet pipe at the other side of the primary compartment. After this date the outlet was changed to the secondary compartment.

Sedimentation in the tank was prevented by the continuous circulation of the liquor in the secondary compartment. In order to prevent clogging the small circulating pipes used, the pump was operated at a rate which resulted in turning over the contents of the secondary compartment 14 times daily. Such a rapid rate of turnover is higher than practicable for larger digestion tanks, and may be higher than is necessary to secure satisfactory results from the tank. Investigations of the effect of the rate of turnover of the tank contents upon the action of the tank are being continued.

The suction side of the pump was connected to pipes drawing liquor at different elevations near the top of the secondary compartment, as shown at *S* in Fig. 8, and discharging at the lower portion of the conical bottom of the secondary compartment. Sections of glass pipe were installed in the suction pipe to permit the observation of the quality of circulated liquor drawn from different elevations in the tank, in the belief that thick scum might accumulate at the top of the tank, necessitating the drawing of liquor from progressively lower elevations. At no time was this difficulty encountered, and circulating liquor was taken from the highest possible elevation in the secondary compartment. No mechanical circulation was provided in the primary compartment.

The possibility of the clogging of the gas collection grids by scum was anticipated by the installation of circular paddles, revolving in a vertical plane, placed immediately below the grids. Facilities were also provided for the pumping of liquor on to the top of the gas grids in order to soften scum and thereby to free them from clogging. The paddles were turned by hand through five or six revolutions at irregular intervals throughout the day, and were found to be effective in keeping the gas grids clear. One attempt to circulate liquor on to the top of the gas grids proved disastrous, as the suspended matter in the circulated liquor taken from the secondary compartment clogged the small openings in the grids, necessitating their removal for cleaning.

Gas was collected separately from the primary and secondary compartments and was measured, for a time in gasometers, as shown in Fig. 2. Towards the end of the tests the quantity of gas generated taxed the capacity of the gasometers to such an extent that all of the gas from the primary compartment was measured in the gasometers, and a wet meter[22] was used for the measurement of the gas from the secondary compartment. But few gas leaks occurred, such leaks as did occur being promptly discovered and stopped, and corrections for them made in the observations. Some early troubles were encountered from the clogging of the gas lines, resulting from the blowing into them of foam by the violent, intermittent ebullition of gas. This difficulty was overcome by the installation of 1½-in. gas lines, and the insertion of a foam trap through which all gas passed before going into the gasometers.

Routine procedure in the operation of the tank involved:

(1) Periodic dosing of the tank
(2) Adjustment of temperature
(3) Turning of scum paddles
(4) Wasting of gas from gasometers

Observations of data taken at the tank once, or more frequently, a day included the temperature of the tank contents and the volume of gas accumulated. Samples were taken of the sludge and the mixture added at each dose, of the liquor in the primary and secondary compartments, and of the gas generated in each compartment. The analysis of the liquid samples included pH, ether soluble matter, total and volatile solids, B.O.D., volatile acids, and physical characteristics, such as odor and color. The gas was analysed for carbon dioxide, methane, hydrogen, and occasionally for hydrogen sulphide.

All conditions in the operation of the tank were held constant except the rate of the application of garbage and sludge. Four different rates of feeding the tank were studied, data on the rates being given in Table 7. Further data concerning the total solids and volatile solids added to the tank during the various periods of feeding are given in Table 8. It is to be noted that two periods of digestion were studied: approximately a sixty-day period for eleven months, and approximately a thirty-day period for eight weeks. The charges of garbage and sludge were so proportioned that the ratio of garbage volatile solids to sludge volatile solids was never greater than 60:40, well within the safe limits found in the preliminary batch tests. The rate of charging the digestion tank with combined sludge and garbage varied between 0.34 and 1.67 lb. of volatile solids daily per cu. yd. of digestion capacity. This is equivalent to 0.38 to 1.85 lb. of volatile solids monthly per cu. ft. of digestion capacity. On the basis that

TABLE 7
RATE OF FEEDING SEPARATE DIGESTION TANK

Series	Period Covered			Size of One Charge		Number of Times Charged	Diges-tion Period—Days	Pounds Garbage Daily per Cu. Yd. Tank Capacity	Gallons Sludge Daily per Cu. Yd. Tank Capacity
	From	To	Days	Garb. lb.	Mixture gal.				
1	3-29-35	10-25-35	211	33	254	79	64	0.41	3.18
2	10-25-35	12- 4-36	40	66	258	17	55	0.94	3.65
3	12- 4-35	2-24-36	82	132	266	31	60	1.67	3.35
4	2-24-36	4-18-36	54	132	266	40	31	3.26	6.56

200 p.p.m. of solids are removed from sewage by plain sedimentation, the ratio of wet garbage per million gallons of sewage varied between one and three tons per million gallons of sewage treated.

20. *Results and Conclusions.*—A summary of analyses of the contents of the digestion tank, during various stages of operation, is given in Table 9, and of the rate of digestion of volatile solids in Table 10. Routine observations of volatile acids were made, but are not reported in the table, as at no time did they rise above 80 p.p.m., well below the danger limit of 2000 p.p.m.[23] The range of pH, between 6.6 and 7.8, and the percentage of methane produced at all stages, indicated optimum digestion conditions in the tank. The concentration of volatile solids in the secondary compartment served as a significant

TABLE 8
CHARGES OF SOLIDS ADDED TO SEPARATE DIGESTION TANK

Series	Pounds of Volatile Solids Added Daily per Cubic Yard of Tank Capacity			Volatile Garbage Solids percent-age of mixture	Pounds of Garbage per Cu. Yd. Sludge	Total Solids in Sludge per cent	Pounds of Wet Garbage Added to Sewage per 1,000 Pounds Solids Removed from Sewage	Tons of Garbage per Million Gallons Sewage (on basis of re-moval of 200 p.p.m. suspended matter)
	Garbage	Sludge	Total					
1.............	0.110	0.234	0.344	32.0	27	1.4	1130	0.95
2.............	0.267	0.174	0.441	60.5	54	0.85	3760	3.13
3.............	0.470	0.448	0.918	51.2	108	2.47	2590	2.16
4.............	0.931	0.743	1.674	55.7	108	2.06	3090	2.58

TABLE 9
SUMMARY OF ANALYSES OF CONTENTS OF SEPARATE DIGESTION TANK

Series	Primary Compartment						Secondary Compartment						
	pH		Gas Av. for Period per cent		Solids Av. for Last Week* p.p.m.		pH		Gas Av. for Period per cent		Solids Av. for Last Week p.p.m.		B.O.D. During Last Seven Days of Period
	Min.	Max.	CO_2	CH_4	Total	Volatile	Min.	Max.	CO_2	CH_4	Total	Volatile	p.p.m.
1..........	6.6	7.8	25.4	....	3380	1950	6.8	7.6	24.8	....	1890	915	750
2..........	7.0	7.6	31.2	60.6	8740	6100	7.2	7.5	29.8	61.8	4870	2500	1470
3..........	6.8	7.4	34.4	55.3	8780	5150	6.9	7.5	36.4	54.5	8210	4670	1240
4..........	6.6	7.4	32.6	59.9	6160	4010	6.7	7.4	34.8	58.2	7270	4730	1380

*This represents the quality of the liquid effluent from the tank.

TABLE 10
SUMMARY OF RESULTS OF VOLATILE SOLIDS DIGESTED IN SEPARATE DIGESTION TANK

Period	Pounds of Volatile Solids Added			Pounds of Volatile Solids				Volatile Solids Digested	
	Garbage	Sludge	Total	In Tank at Start	In Tank at End	Withdrawn During Test	Digested	per cent	Lb. per Cu. Yd. Digestion Capacity per Day
Last 146 days of series 1...............	555	1096	1651	35	47	216	1423	86.2	0.326
Last 9 days of series 2................	56	45	101	130	150	29	52	51.5	0.192
Last 24 days of series 3................	263	222	485	275	225	91	444	91.5	0.615
Last 23 days of series 4................	564	495	1059	215	250	133	891	84.1	1.292

indication of the approach of the tank to the limit of its capacity. As the load of volatile solids added to the tank increased from 0.34 to 1.67 lb. per day per cu. yd. of digestion capacity, the volatile solids concentration in the digestion compartment rose from 9.5 to 8000 p.p.m. The approximate safe limit of the concentration of total solids to permit satisfactory digestion has been variously stated. Bach[24] has fixed the value at 60 000 p.p.m., and Rudolfs[25] has fixed it at 150 000 p.p.m. It is probable, therefore, that a considerable addition of solids to the tank will be permissible without unfavorably affecting the digestion process.

The reduction of the period of digestion from 60 to 30 days apparently had no unfavorable effect upon the operation of the tank, as there was no change in volatile acids or pH, and the volatile solids remained practically constant, although the rate of charging with volatile solids was almost doubled.

All indications are, therefore, that the tank can digest successfully more than 1.67 lb. of volatile solids per day per cu. yd. of digestion capacity with a period of retention of 30 days, or possibly less.

Gas collection results and a comparison of the effectiveness of the gas production in the primary and secondary compartments are presented in Table 11. The volumes of gas shown in this table, if in error, are too low because of losses through leaks, except the figure noted in the second line of Table 11, which might be lowered noticeably by a relatively small variation in the results shown in the second line of Table 10.

The daily rate of gas production per unit volume of the primary compartment was about 150 per cent of the secondary compartment rate during the first two periods. During the third and fourth periods, the primary compartment rate was 56 per cent and 66 per cent of the secondary compartment rate. These figures would seem to indicate a higher rate of gasification from the grease floating in the primary compartment than from the heavier material that dropped into the secondary compartment. The higher secondary rate during the third and fourth periods would seem to indicate that the primary compartment was not of sufficient size to accommodate the material high in grease content.

A rapid increase in the rate of gas production was observed following the feeding of the tank. This is shown by typical data for a two-week period, presented in Fig. 12. The effect of the stirring of the scum in the tank on the rate of gas production is shown by the day-time increase in the volume of gas collected. The increase in the

TABLE 11
GAS COLLECTION FROM TANK C

Period	Volume of Gas Generated							
	Total During Period 1000 cu. ft.	Per Pound of Volatile Solids Added cu. ft.	Per Pound of Volatile Solids Digested cu. ft.	Per Cu. Yd. of Tank Capacity per Day cu. ft.	Per Pound of Volatile Solids Added		Per Cu. Yd. of Compartment Capacity per Day	
					Compartment		Compartment	
					Primary	Secondary	Primary	Secondary
					cu. ft.	cu. ft.	cu. ft.	cu. ft.
Last 146 days of series 1	17.9	10.8	12.6	4.1	3.22	7.62	5.7	3.7
Last 9 days of series 2	1.25	12.3	24.0*	4.6	3.54	8.80	6.2	4.1
Last 24 days of series 3	3.78	7.8	8.5	5.25	1.32	6.48	4.1	5.5
Last 23 days of series 4	8.90	8.4	10.0	12.9	1.28	7.12	9.1	13.8

*This figure may be too high on account of the relatively short period of observation and the small number of measurements of solids made.

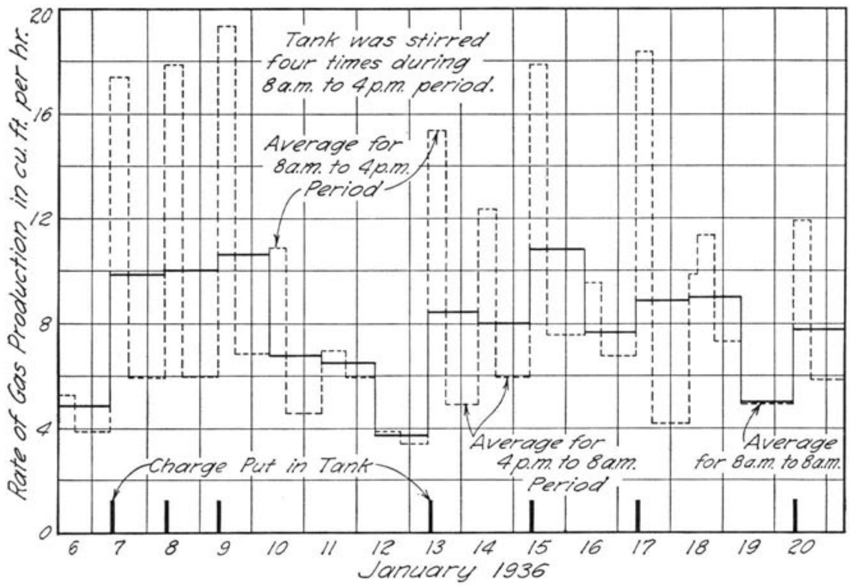

FIG. 12. GRAPH SHOWING HOURLY RATE OF GAS PRODUCTION IN TWO-STAGE DIGESTION TANK

rate of gas production following feeding indicates a rapid digestion of the volatile solids, and points to a possible shortening of the period of digestion and a permissible increase in the rate at which the tank can be fed.

III. EFFECT ON DIGESTION OF GARBAGE OF ITS ELUTRIATION WITH SEWAGE

21. *Purpose.*—When ground garbage is disposed of into sewers, soluble garbage solids are dissolved, insoluble garbage solids are intimately mixed with the sewage, and some of the insoluble solids are comminuted so finely as to settle less rapidly or to increase the colloidal content of the sewage. When such material enters a treatment plant much of the soluble and non-settleable solids pass through the primary settling tanks to increase the organic load on the secondary treatment devices or, if none exist, on the stream receiving the plant effluent. If the material which settles in the primary sedimentation tank is transferred to a separate digestion tank it is probable that the character of its digestion will differ from that of the ground garbage which has not been elutriated before being put into the digestion tank.

TABLE 12
DATA CONCERNING CHARACTERISTICS OF MATERIALS USED IN PERIODIC FEEDING OF DIGESTERS AND SOME EFFECTS OF ELUTRIATION OF GARBAGE

Feeding Schedule Number	Period		Percentage of Total Solids Which Is Garbage Solids		Percentage of Volatile Solids Which Is Garbage Volatile Solids		Digesters Receiving Mixture with Garbage Before Elutriation	Digesters Receiving Mixture with Garbage After Elutriation
	From	To	Mixture with Non-elutriated Garbage	Mixture with Elutriated Garbage	Mixture with Non-elutriated Garbage	Mixture with Elutriated Garbage		
1...........	11-17-35	1-20-36	49.0	18.2	54.7	25.6	74-76	71-73
2...........	1-20-36	4-22-36	74.9	58.0	80.2	59.4	74-76	71-73

The principal purposes of this investigation were, first, to measure the load upon the secondary treatment devices in a sewage treatment plant resulting from the intimate mixing of garbage and sewage before passing into the primary sedimentation tanks from which the secondary devices are fed; second, to observe the characteristics of the digestion of garbages which have been elutriated and garbages which have not been elutriated before addition to a separate digestion tank; and, third, to determine the requisite capacity of digestion tanks to receive elutriated or non-elutriated garbage.

22. *Procedure.*—Samples of elutriated and non-elutriated garbage were digested under identical conditions, in 5-gallon clear glass containers.

Elutriation was accomplished by placing the required quantity of ground garbage in a mixing bucket together with 15 liters of sewage, and violently agitating the mixture, with power-driven paddles, for approximately one hour. The contents of the bucket were then allowed to stand quiescent for an hour after which they were poured on a 16-mesh screen and allowed to drain. After most of the water had passed through the screen the garbage particles, which had settled to the bottom of the bucket, formed a "soupy" blanket on the screen, effectively preventing thorough drainage of the solids on the screen. Additional moisture was removed from this mass by stirring and gentle pressure.

In the preparation of the charges for the digestion containers, garbage, either before or after elutriation, and fresh sewage sludge, collected from a plain sedimentation tank, were mixed in proportions shown in Table 12. Two different ratios of garbage to sludge

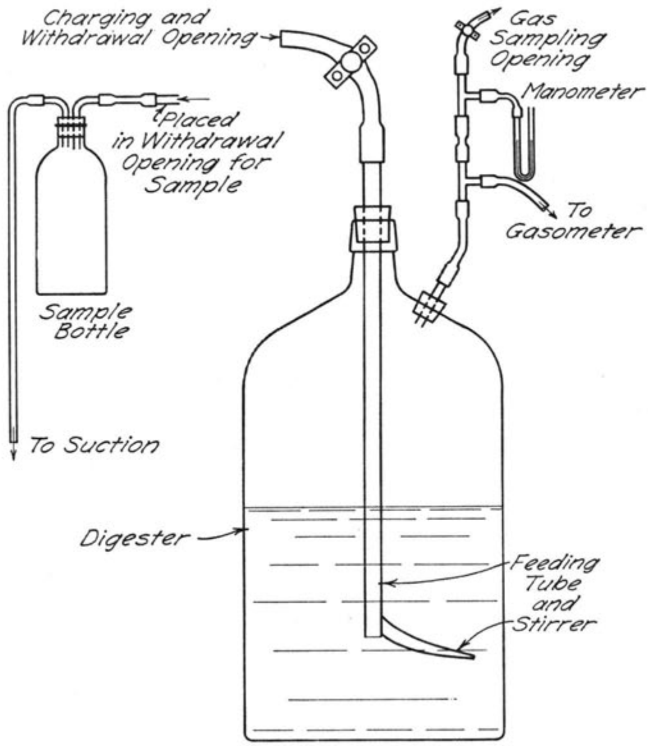

FIG. 13. APPARATUS FOR DIGESTERS 71-76

solids were selected for the investigation, one containing about 55 per cent and the other about 80 per cent garbage volatile solids. The former ratio represents approximately the normal solids load which might be expected at a sewage treatment plant receiving all of the garbage from a community.[26] The 80 per cent concentration of garbage volatile solids was used to test the possible maximum limit of garbage load in relation to sewage load on a digestion tank. The digesters receiving the garbage which had not been elutriated were charged with volatile solids on these two approximate ratios. After elutriation of the garbage, which had been weighed out to approximate these two ratios before washing, it was found that the ratios of garbage volatile solids to sludge volatile solids were quite different, as shown in Table 12. The tendency of the digestible garbage solids to go into solution or colloidal suspension is indicated by the reduction of the percentage of garbage volatile solids as a result of elutriation.

Since the control of the ratio of garbage to sewage solids in these

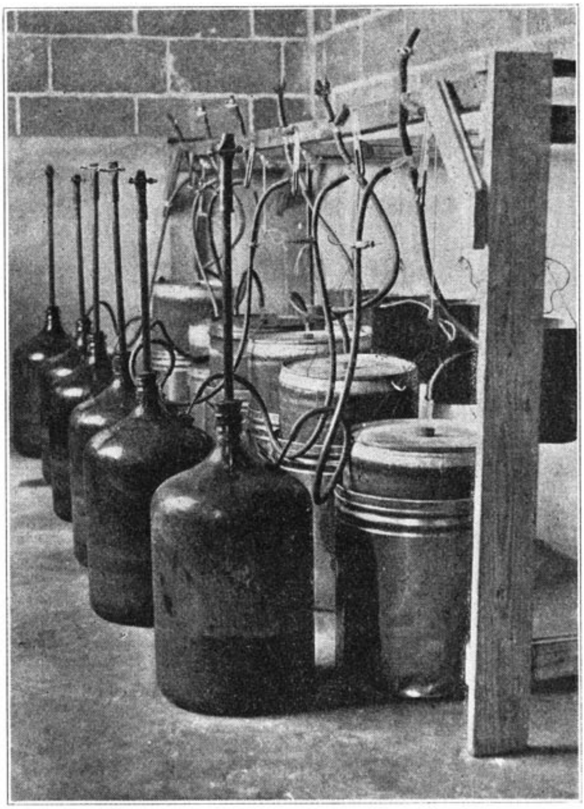

FIG. 14. CARBOY DIGESTERS

mixtures was desirable, it was customary to prepare them by assuming the solids content of the garbage and of the sludge and to mix the materials in a ratio which, based upon the assumed solids content of the two constituents, would give the ratio desired. The exact ratio was determined later by an analysis of the garbage and sewage solids which had been mixed. The charges were then introduced directly into the digestion containers equipped as illustrated in Figs. 13 and 14.

On Nov. 1, 1935, six 5-gallon clear glass containers were each seeded with 8.5 kilograms of partially digested Imhoff sludge, some characteristics of which are shown in Table 13. The digesters were allowed to stand for fourteen days without addition of sludge or garbage, and during this time observations of the digestion characteristics were made, the apparatus was checked for gas leaks, and otherwise prepared for periodic feeding.

TABLE 13
CHARACTER OF SLUDGE USED FOR SEEDING DIGESTERS

Total solids	6.65 per cent
Volatile solids	4.41 per cent
pH	7.8
Volatile acids	227 p.p.m.

Periodic feeding of the tanks with fresh sludge and ground garbage, and the withdrawal of material were commenced on Nov. 15, 1935. The volumes of the charges were based on a thirty-day retention period, the digesters being charged and samples being withdrawn on 96 days of the 127-day period of the investigation. The actual retention period was later calculated to be 33.2 days. The contents of the digesters were thoroughly stirred and a sample of material was withdrawn, equal in volume to the charge which was then inserted into the digester.

23. *Results and Conclusions.*—The *first* purpose of this investigation was to measure the load upon the secondary treatment devices in a sewage treatment plant resulting from the intimate mixing of garbage and sewage before passing into the primary sedimentation tanks from which the secondary devices are fed. If this load may be measured in terms of the B.O.D. resulting from the elutriation of the garbage, then it may be expressed for these tests as ranging from between 27 and 110 p.p.m., 5-day, 20-degree B.O.D., averaging about 55 p.p.m. This is about half of the normal load placed upon the secondary devices by sewage alone passing through primary sedimentation tanks.

The results from which the preceding conclusion was drawn are shown in Table 12 and in Fig. 15. A high correlation is to be noted in the figure between the B.O.D. and the volatile solids in the sewage before its use in the elutriation of garbage. The approximately one hundred per cent variations of the individual observations above and below the average line shown in the figure may have been due both to the lack of precision in the B.O.D. determination and the variations in the strength of the sewage. It may be assumed that the B.O.D., expressed in p.p.m., was equal to one-half of the volatile solids in the sewage, expressed in p.p.m. This relation would apparently hold only so long as the volatile solids are in the same stage of decomposition, which was the condition in these tests, and would be the condition in a sewage treatment plant.

It was found in the elutriation of 95 samples of garbage that the

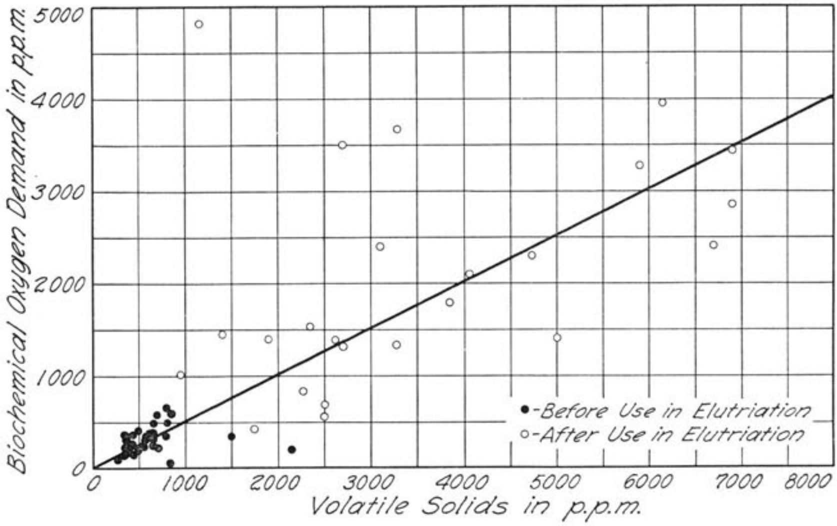

FIG. 15. RELATION BETWEEN VOLATILE SOLIDS AND B.O.D. IN SEWAGE BEFORE AND AFTER ITS USE IN THE ELUTRIATION OF GARBAGE

volatile solids in the elutriated garbage varied between 63 per cent and 23 per cent of the original dry weight of the volatile solids in the non-elutriated garbage, averaging about 34 per cent. The total solids in the elutriated garbage varied between 66 per cent and 27 per cent of the original dry weight of total solids in the non-elutriated garbage, averaging about 41 per cent. On this basis, if it is assumed that the ratio of wet garbage to sewage in a normal American city is 2½ tons per million gallons of sewage, and that the quality of the garbage is as shown in Table 2, then the dumping of this garbage into the sewage will increase the total and volatile solids in the primary settling tank effluent by 110 p.p.m.

Since the B.O.D. may be assumed to be equal to one-half of the volatile solids, both expressed in p.p.m., it may be estimated that the elutriation of all of the garbage in the sewage of a normal American city may increase the 5-day, 20-degree B.O.D. of the primary settling tank effluent about 55 p.p.m., with possible variations between 27 and 110 p.p.m. This average increase is equivalent to a first-stage, 20-degree B.O.D. of 80 p.p.m. The normal population equivalent of B.O.D. is 0.244 pound per day per capita. This is equivalent to a first-stage B.O.D. of 290 p.p.m. on the basis of the production of 100 gallons of sewage per day per capita. With a 35 per cent removal of B.O.D. of the sewage by preliminary sedimentation,[27] the first stage

TABLE 14
CHARACTER OF MATERIAL FED TO DIGESTERS AND EFFECT OF GARBAGE ELUTRIATION UPON SOLIDS IN MIXTURES

Feeding Schedule Number	Period		Solids Added to Digesters in Grams per Day per Liter of Digesting Mixture				Percentage Reduction of Solids in Mixture Resulting from Elutriation of Garbage	
			Mixture of Sludge and Garbage Before Elutriation		Mixture of Sludge and Garbage After Elutriation			
	From	To	Total Solids	Volatile Solids	Total Solids	Volatile Solids	Total Solids	Volatile Solids
	(1)		(2)	(3)	(4)	(5)	(6)	(7)
1..........	11-17-35	12-15-35	1.99	1.60	1.43	1.10	28.2	31.2
1..........	12-15-35	1-20-36	1.68	1.38	1.30	0.95	22.8	31.1
2..........	1-20-36	2-16-36	2.63	2.31	1.46	1.22	44.5	47.2
2..........	2-16-36	3-22-36	2.83	2.44	1.67	1.39	40.7	43.1

B.O.D. of the sewage going to the secondary unit would be 188 p.p.m., without garbage, or 268 p.p.m. with garbage. The increased load on the secondary treatment devices resulting from the elutriation of garbage by sewage is, therefore, about 43 per cent. The increase in the B.O.D. may, under some circumstances, be as high as 100 per cent or as low as 25 per cent. In other words, the average load on the secondary oxidizing devices in a sewage treatment plant resulting from the dumping of 2½ tons of garbage into each million gallons of normal domestic sewage, will be about 1.5 times the load before the garbage was dumped into the sewers, and it may vary between 1.25 and 2.0 times the normal B.O.D. load of the sewage before it is used in elutriation of garbage.

The *second* purpose of this investigation was to observe the characteristics of the digestion of garbages which have been elutriated, and of garbages which have not been elutriated, before addition to a separate digestion tank. Results of tests on the digestion of both kinds of garbages are shown in Tables 14 and 15 and in Fig. 16. The data in Fig. 16 are representative of the characteristics of only two of the six digesters operated, and the data in Table 14 are representative of the averages of three digesters operated under similar conditions. The results observed in all of the digesters, operated under similar conditions, never varied significantly from the average.

TABLE 15

SUMMARY OF ANALYSES OF SLUDGES IN DIGESTERS CONTAINING GARBAGE BEFORE OR AFTER ELUTRIATION†

Line No.	Digester Number	Character of Garbage in Mixture	Percentage of Garbage Volatile Solids in Mixture	Time in Digester Since Start of Feeding, Days	Sludge Solids in Mixture at Start of Feeding, Grams per Liter of Digesting Mixture		Solids Fed During Period, Grams per Day per Liter of Digesting Mixture		Solids in Mixture at End of Feeding, Grams per Liter of Digesting Mixture		Digestion of Solids, Grams per Day per Liter of Digesting Mixture		Reduction of Solids per cent		Remarks
					Total	Volatile	Total	Volatile	Total	Volatile	Total	Volatile	Total	Volatile	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	71–73	E*	25	35	30.4	18.6	1.29	0.95	21.6	12.7	0.765	0.652	59.0	68.8	Period of Light Feeding
2	74–76	N*	55	35	33.0	20.8	1.67	1.38	23.6	14.9	1.06	0.991	63.5	71.7	
3	71–73	E	59	35	20.9	13.5	1.69	1.39	18.0	10.8	1.04	1.01	61.4	72.4	Period of Heavy Feeding
4	74–76	N	80	35	30.0	21.4	2.83	2.48	37.0	16.6	1.90	1.84	69.5	74.3	

*E = elutriated; N = non-elutriated.
†The figures shown are the observations made only during the routine periods of feeding, and not during the transition periods shown in Fig. 18.

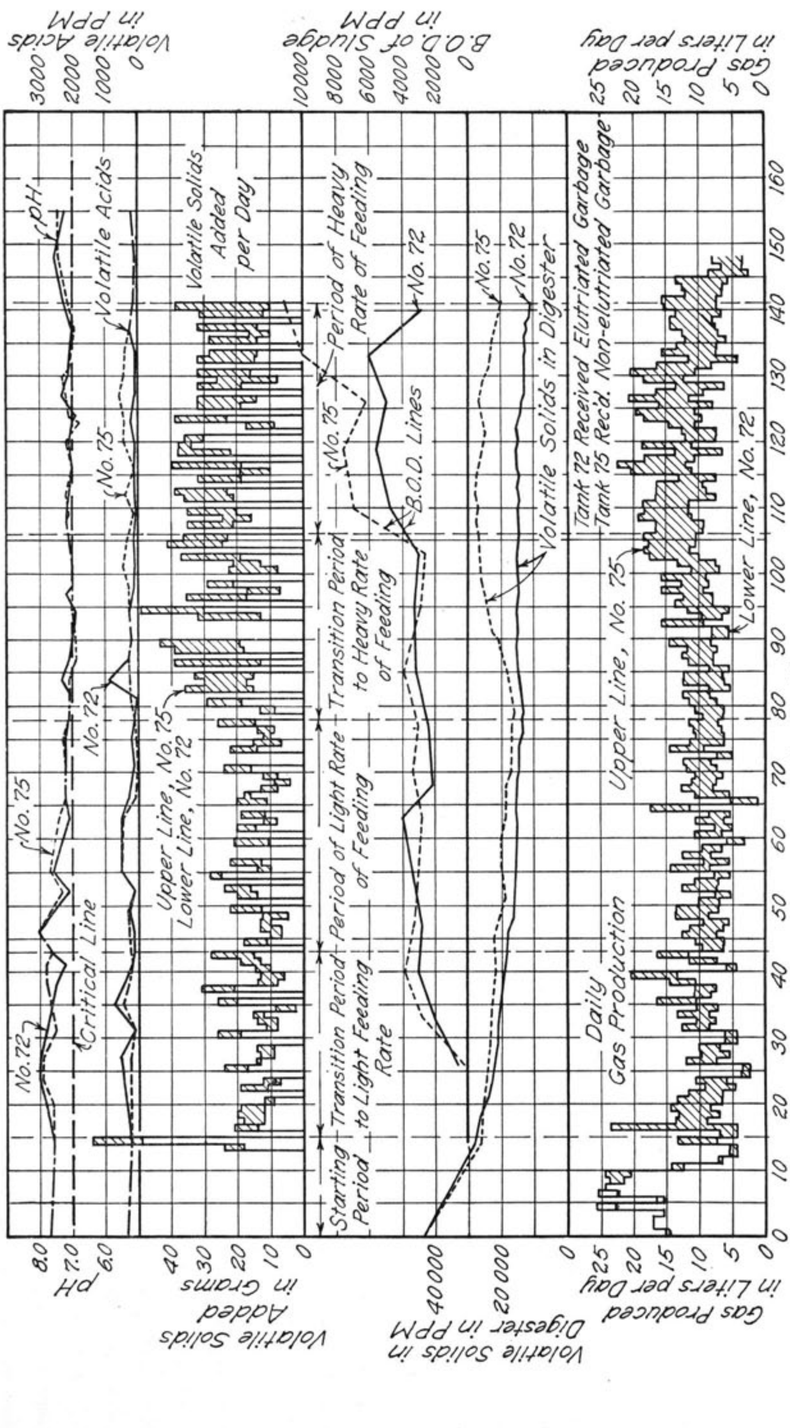

FIG. 16. CHARACTERISTICS OF DIGESTION OF TYPICAL MIXTURES OF SEWAGE SLUDGE WITH ELUTRIATED AND WITH NON-ELUTRIATED GARBAGE

A study of the data in the tables and the figure will make possible many conclusions, among which are the following:

(a) The conditions of digestion were not affected by the elutriation of the garbage; this is shown by the pH and volatile acid results at the top of Fig. 16.

(b) The pH of the sewage was not significantly reduced by the elutriation of the normal amount of garbage. Other tests, the results of which are not shown in the figure or tables, caused the pH, upon the elutriation of 30 to 175 tons of garbage per million gallons of sewage, to drop from 7.2-7.8 to 6.6-7.4.

(c) The amount of volatile solids handled in the separate digestion tank receiving the elutriated garbage was from 60 to 70 per cent of the volatile solids it would have received had it been fed with the sludge collected from the same amount of sewage passing through a plain sedimentation tank; this conclusion is drawn from the figures in column 7 of Table 14.

(d) The concentration of the volatile solids in the separate digestion tanks fed with a mixture of sludge and elutriated garbage was, at the end of the period of digestion, from 65 to 85 per cent of the concentration of volatile solids in the tanks fed with a mixture of the same amount of fresh sludge and the same amount of non-elutriated garbage; this conclusion is drawn from the figures in column 10 of Table 15.

(e) The digestion of solids was not affected by the elutriation of the garbage before being fed into the tank; this is shown by a comparison of lines 2 and 3 in column 12, Table 15, with due consideration for the approximately constant conditions shown in lines 2 and 3, columns 3 and 8.

It is to be noted that the reduction of solids (column 14) and the rate of digestion (column 12) may be functions of either the percentage of garbage volatile solids in the mixture (column 3), or the rate of feeding (column 8), or of both. Further tests are required to determine this point.

(f) The volatile solids in mixtures with elutriated garbage and with non-elutriated garbage were reduced approximately 70 per cent by digestion; this is shown by the figures in column 14 of Table 15.

(g) The volatile solids in the mixture of elutriated garbage and sewage sludge had a higher B.O.D., per unit of weight, than those in the mixture of non-elutriated garbage and sewage sludge; this is shown by the relation between the B.O.D. lines in Fig. 16.

TABLE 16

GAS PRODUCTION FROM DIGESTERS CONTAINING GARBAGE BEFORE OR AFTER ELUTRIATION†

Line No.	Character of Garbage Added	Percentage of Garbage Volatile Solids in Mixture	Volume of Gas Produced per Gram of Volatile Solids cc.				Percentage CO_2 in Gas[3]	Percentage CH_4 in Gas	Gas Produced per Gram of Volatile Solids Digested[3, 4] gm.
			Added Total	Added CH_4	Digested Total	Digested CH_4			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	E*	25[1]	709	417	1030	606	29.1	58.9	1.16
2	N*	55[1]	747	422	1032	582	33.8	56.6	1.28
3	E	59[2]	647	405	895	560	32.2	62.6	1.03
4	N	80[2]	645	378	882	516	35.4	58.5	1.07

*E = elutriated; N = non-elutriated.
Note 1.—The same amount of non-elutriated garbage was used in the preparation of these two mixtures.
Note 2.—Same as note 1.
Note 3.—Not corrected for loss of CO_2 through the water-seal in the gasometer.
Note 4.—Weight corrected to 32 deg. F., but not corrected for barometric pressures.
†The figures shown are the observations made only during the routine periods of feeding and not during the transition periods shown in Fig. 18.

(h) The B.O.D. of the sludge formed of a mixture of non-elutriated garbage and sewage sludge was greater than that from a sludge formed of a mixture of an equal amount of garbage which had been elutriated and the same amount of sewage sludge, so long as the ratio of garbage volatile solids to sewage volatile solids in the mixture was greater than 55:45.

(i) The volume of gas produced by the digestion of a mixture of sludge and elutriated garbage was less than that produced by the digestion of a mixture of sludge and non-elutriated garbage, other things being equal. This conclusion is based upon the fact that the rate of gas generation, resulting from the digestion of either elutriated or non-elutriated garbage, was the same per unit weight of volatile solids in the digesting mixture, as shown in columns 3 and 5 of Table 16, and upon the fact, shown in column 8 of Table 15, that the weight of volatile solids in the mixture of sewage sludge and non-elutriated garbage is 1.45 to 1.8 times the weight of volatile solids in the mixture of sewage sludge plus elutriated garbage formed from an equal amount of non-elutriated garbage. In other words, the amount of gas generated depends upon the weight of volatile solids present, and there are less volatile solids in elutriated garbage than in a corresponding weight of non-elutriated garbage.

TABLE 17

CHANGES IN GREASE CONTENT OF DIGESTED MIXTURES OF SEWAGE SLUDGE WITH ELUTRIATED AND NON-ELUTRIATED GARBAGES

Average of results from 3 different digesters.

Line No.	Character of Garbage in Mixture	Percentage of Garbage Volatile Solids in the Mixture	Grease in Tank Feedings, Percentage of Total Dry Weight of Sample	Grease in Sludge Withdrawn, Percentage of Total Dry Weight of Sample	Grease Reduction, Percentage by Weight of Grease Fed	Remarks
	(1)	(2)	(3)	(4)	(5)	(6)
1	E*	25	25.7	10.2	72.3	Contains insoluble grease
2	N*	55	32.2	10.1	82.0	Contains soluble and insoluble grease
3	E	59	21.8	8.6	82.9	Contains insoluble grease
4	N	80	26.8	9.7	86.3	Contains soluble and insoluble grease

*E = elutriated; N = non-elutriated.

(j) The percentage of methane in the gas produced was not affected by the elutriation of garbage; this is shown in column 8 of Table 16.

(k) The percentage of carbon dioxide in the gas increased slightly with an increase in the percentage of garbage volatile solids in the digestion mixture; this is shown in column 7 of Table 16. This is corroborated by the figures in column 9 which show the effect of the increased percentage of carbon dioxide on the unit weight of the gas. This may be explained by the removal of soluble sugars, starches, and salts by elutriation, leaving protein, cellulose, and grease. The digestion of cellulose and grease will produce weights of gas greater than the weight of material decomposed. Elutriation alters the garbage quality so that the less soluble protein matter plays a predominant part in the production of methane in the gas from the non-elutriated garbage.

(l) The limit of the rate of the feeding of a heat-controlled, separate digestion tank was approached under the conditions of the second series of tests in this investigation; this was indicated by the qualities of the sludges withdrawn from the digesters. During the period of feeding at the lower rate* during which the digesters

*From the 43rd to the 78th day shown in Fig. 16, and in lines 1 and 2 in Table 15.

TABLE 18

COMPUTATIONS OF CAPACITIES OF HEAT-CONTROLLED SEPARATE DIGESTION TANKS REQUIRED TO DIGEST ELUTRIATED OR NON-ELUTRIATED GARBAGE

1	Specific gravity of normal mixture of sludge and ground garbage, (assumed)	1.0
2	Garbage production, pounds per capita per day, (assumed)	0.5
3	Garbage dry solids produced, pounds per capita per day, (assumed)	
	total	0.125
	volatile	0.115
4	Sewage dry solids collected in primary sedimentation tank receiving sewage alone, pounds per capita per day, (computed)	
	total	0.165
	volatile	0.115
5	Percentage total solids in material collected in primary sedimentation tank receiving sewage alone or sewage plus elutriated garbage, (assumed)	3.0
6	Percentage of garbage solids that will be added to sludge on basis of loss of garbage solids during elutriation procedure in this investigation	
	total	41.0
	volatile	34.0
7	Per capita volume of mixture from a sedimentation tank receiving sewage and elutriated garbage, cu. ft. per day	0.115
8	Per capita volume of mixture of non-elutriated garbage plus sludge collected in a sedimentation tank receiving sewage alone, cu. ft. per day	0.096

Note: Items 7 and 8 were computed as follows:

Sewage solids (item 4), = 0.165 lb., plus the garbage solids (item 3 times item 6), = 0.051 lb., total, 0.216 lb. dry weight. Assuming a moisture content of 97 per cent (item 5) and a specific gravity of 1.0, the volume of sludge containing 0.216 lb. of dry solids is $0.216 \div (0.03) \times (62.5) = 0.115$ cu. ft. (item 7).

The wet weight of sewage sludge produced per capita per day is 5.5 pounds (item 4 divided by item 5). The wet weight of garbage produced is 0.5 pound. The total wet weight of sewage sludge and garbage is, therefore, 6.0 pounds per capita per day. If its specific gravity is unity, its volume is $6.0 \div 62.5 = 0.096$ cu. ft. (item 8).

received 0.95 and 1.38 grams of volatile solids per day, the odor of the sludges drawn from all digesters was tarlike, typical of well-digested sludge. After three weeks of feeding the digesters at a higher rate,† with a higher proportion of garbage in the mixture, during which the digesters received 2.46 grams of volatile solids per day per liter of digesting mixture, the sludge from the digesters containing garbage which had not been elutriated had a slight odor of fermentation, associated with undigested sludge. The sludge was grey in color, and particles of undigested garbage were visible in it. The settleable solids could not be determined in either of the sludges, as no distinct sludge line was apparent, due probably, to the thorough stirring of the digester contents before the withdrawal of sludge.

(m) The elutriation of garbage decreased the percentage of grease to be digested; this is shown by the figures in column 3 of Table 17.

(n) The percentage reduction of grease by digestion was independent of the elutriation of the garbage; this is shown by a comparison of the figures in lines 2 and 3, column 5, of Table 17.

(o) The garbage greases were more digestible than the sewage greases; this is indicated by the data in Table 17. As the per cent of garbage volatile solids in the mixture was increased (column 2,

†From the 106th to the 141st day shown in Fig. 16, and in lines 3 and 4 in Table 15.

Table 17), the percentage reduction of grease increased (column 5, Table 17).

(p) About 66 per cent of the garbage volatile solids and 59 per cent of the garbage total solids went into solution or colloidal suspension when the garbage was elutriated; this is indicated by the figures in columns 6 and 7 of Table 14.

The *third* purpose of this investigation was to determine the requisite capacities of temperature-controlled separate digestion tanks receiving either elutriated or non-elutriated garbage, together with sewage sludge. Assumptions and computations upon which a conclusion was reached, based upon practice and upon the findings in this investigation, are shown in Table 18. The last two lines of the table indicate that the elutriation of garbage will require 20 per cent more capacity in a separate digestion tank than if the garbage fed to the tank were not elutriated. This is due to the increase in the bulk of the sludge due to higher moisture content and not to the change in the quality of the garbage. More digestion capacity is required per pound of solids fed to a digestion tank by feeding with a thin sludge than by feeding with a concentrated sludge, the retention period being the same under both conditions.

The requisite capacity of a digestion tank is dependent, in part, upon the retention period. If a 30-day period be assumed, the digestion tank receiving the elutriated garbage would require a capacity of 3.45 cu. ft. per capita whereas the digestion tank receiving non-elutriated garbage would require 2.88 cu. ft. per capita. From the figures in Table 18 it is shown that the tank receiving elutriated garbage is receiving 0.157 pound of volatile solids per capita per day, and the tank receiving non-elutriated garbage is receiving 0.230 pound of volatile solids per capita per day. The rates of feeding these tanks would be, therefore, 0.05 and 0.08, respectively, pound of volatile solids per day per cu. ft. of tank capacity.

IV. Effect of Chemicals on Digestion of Mixture of Garbage and Sewage Solids

24. *Purpose.*—The addition of garbage to sewage sludge in a digestion tank may result in the creation of acid conditions, unsatisfactory digestion, and foul odors. The object of this investigation was to study the effectiveness of certain chemicals in preventing or in overcoming such acid conditions, and in restoring satisfactory digestion.

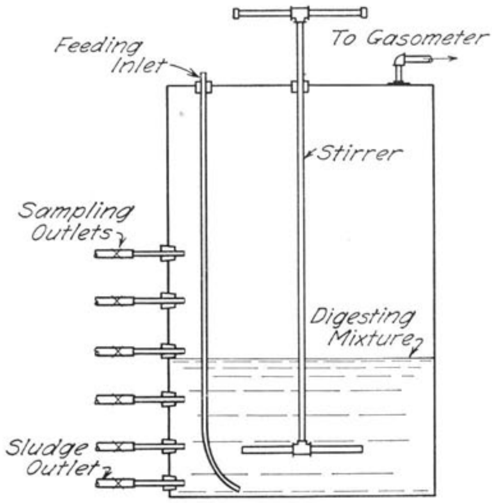

FIG. 17. DETAILS OF BARREL DIGESTER

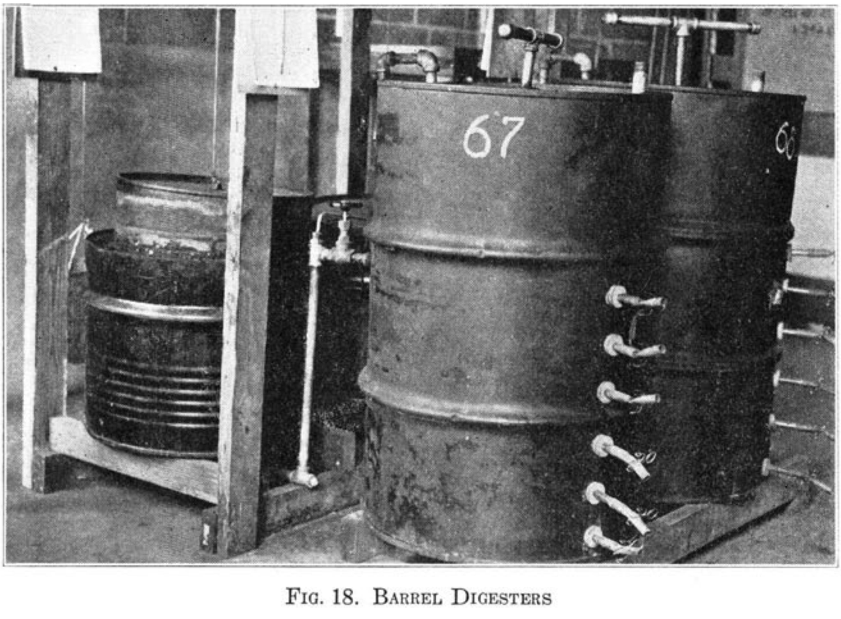

FIG. 18. BARREL DIGESTERS

TABLE 19
SUMMARY OF PROCEDURE IN INVESTIGATION OF EFFECT OF CHEMICALS ON DIGESTION OF MIXTURE OF GARBAGE AND SEWAGE SOLIDS

Series 1 Continuous Feeding Nov. 4, 1935 to March 28, 1936						Series 2 Batch Test Jan. 25, 1936 to March 28, 1936	
Digester	Chemical	Digester	Chemical	Digester	Chemical	Digester	Chemical
61	$Ca(OH)_2$	64	$Ca(OH)_2$	67	NaOH	84	Na_2CO_3
62	$Ca(OH)_2$	65	None	68	NaOH	85	Na_2CO_3
63	$Ca(OH)_2$	66	None	69	NaOH	86	None

25. *Procedure.*—Three alkaline chemicals, lime, sodium hydroxide, and sodium carbonate were studied. Steel oil drums, of 55-gallon capacity, were used in the investigation as digesters, with steel gasometers sealed with brine. They were set up as illustrated in Figs. 17 and 18. The temperature in the room was kept between 80 and 90 deg. F., with occasional lapses to about 70 deg. for not more than an hour once or twice a week.

Two series of tests were conducted. In the first series the initial mixtures used in the digesters consisted of ground garbage and Imhoff tank sludge, the periodic charges being made of ground garbage and fresh sewage sludge. The digesters were fed periodically on a routine schedule. In the second series, the digesting mixtures consisted of ground garbage, fresh sludge, and a seeding batch of the effluent from tank C, the temperature-controlled, two-stage, separate digestion tank. No digestible organic solids were added to the digesters after the first charge, the investigation being conducted on batch tests. A summary of the tests made in the two series is shown in Table 19.

To start the test, in the first series, each digestion tank was charged with a well-mixed batch composed of 35 pounds of ground garbage and 145 pounds of partially digested sludge from an Imhoff tank. All of the tanks were charged with the same mixture of material taken from one large batch prepared for the purpose. The bulk of each batch placed in a digester was about 20 gallons. The analyses of the components of this mixture are given in Table 20. After the mixture had been poured into the digester, the feeding tube was inserted into the proper opening, and the digestion tank was placed in operation.

TABLE 20
ANALYSES OF COMPONENTS OF ORIGINAL MIXTURE, SERIES 1; TESTS ON EFFECT OF CHEMICALS ON DIGESTION

	Percentage of Total Solids	Percentage of Volatile Solids	Percentage of Volatile Solids of Total Volatile Solids
Garbage	27.8	24.5	51.0
Tank B Sludge	7.72	5.72	49.0
Mixture	11.65	9.39	100.0

In the first series of tests the objective in feeding the tanks was to add to each tank an equal amount of dry volatile solids for each day of operation, the draw-and-fill schedule being arranged to displace the contents of each tank in thirty days. Each charge was made up in the ratio of 6 pounds of wet garbage to 50.5 pounds of wet sludge. The composition of the garbage and sludge used in the charges is shown in Table 21. The rate of charging of each tank for the feeding period was 0.0841 pound of volatile solids per day per cu. ft. of tank capacity. Daily additions and withdrawals were made when practicable. There were several times when three days elapsed between charges, and on one occasion there was a lapse of four days. At each charging operation an amount of material equal to one-thirtieth of the tank contents times the number of days since the last charge was withdrawn, and an equal amount was added. The contents of the tanks were thoroughly stirred immediately before any withdrawals and immediately after any additions were made.

When material was to be added to the tanks the correct proportions of fresh ground garbage and fresh sewage sludge were intimately mixed in a large container. After removing the desired amount of

TABLE 21
ANALYSES OF GARBAGE AND FRESH SLUDGE USED IN MIXTURES FOR PERIODIC FEEDING IN SERIES 1; TESTS ON EFFECT OF CHEMICALS ON DIGESTION

	Percentage of Total Solids			Percentage of Volatile Solids			Percentage of Ether Solubles in Dry Sample		
	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.
Garbage	31.45	45.40	22.50	29.50	43.50	20.90	28.53	46.60	23.20
Fresh Sludge	3.82	6.10	1.21	2.75	5.21	0.78	23.59	42.80	8.79

TABLE 22
ANALYSES OF COMPONENTS OF ORIGINAL MIXTURE, SERIES 2; TESTS ON EFFECT OF CHEMICALS ON DIGESTION

	Percentage of Total Solids	Percentage of Volatile Solids	Percentage of Ether Solubles in a Dry Sample
Garbage	22.2	19.6	29.0
Fresh Sludge	3.91	2.95	16.8
Tank C Effluent	0.783	0.444	6.74
Mixture	7.88	6.63	25.2

sludge from the digestion tanks the fresh mixture was stirred, and the required amount was poured into the digester through the charging tube. Records were kept of the weights of materials added and withdrawn in order to maintain a solids balance. Occasionally 50 cc. samples were withdrawn, between feedings, for the determination of pH and volatile acids. These small samples were withdrawn infrequently, and were ignored in making the solids balance.

At the beginning of the first series of tests no additions of materials were made during the first eight days, and only small samples were withdrawn for analyses. The purpose of this period, preceding the periodic feeding of the tanks, was to permit the contents to become acid. On the ninth day draw-and-fill operation was commenced, and observations were made on the acidity and other characteristics of the digesting mixtures. Chemical treatment was commenced sixteen days after the start of the test.

At the close of the first series of tests, which lasted for 145 days, the contents of each digester were weighed, sampled and discarded.

In starting Series 2, the batch for each digester was made up separately, and was composed of 45 pounds of ground garbage, 100 pounds of fresh sludge, and 35 pounds of tank C effluent, making a volume of about 20 gallons; results of analyses of the components and of the resulting mixtures are shown in Table 22. The series was run as a batch test, small samples of about 50 cc. being withdrawn periodically for analyses.

Chemicals were added in both series to neutralize the effect of acidity on digestion. The quantities of chemicals added were computed as equivalent to the acidity measured by the volatile acids determination, all acids being calculated as acetic acid. Lime quantities were computed on the basis of 75 per cent available calcium oxide in the hydrated lime; sodium hydroxide was assumed to be

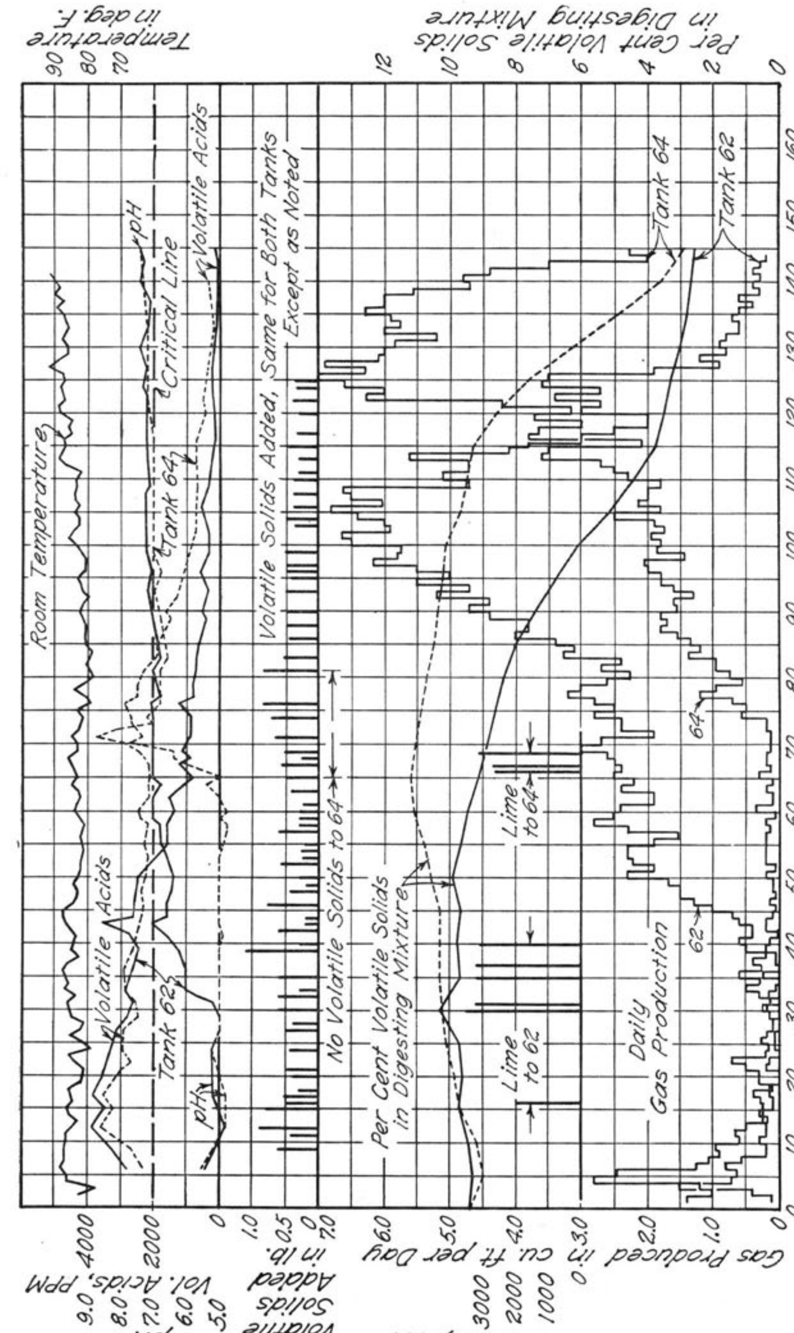

FIG. 19. CHARACTERISTICS OF DIGESTERS 62 AND 64

100 per cent available. When chemical treatment was started commercial hydrated lime was added to three digesters, commercial sodium hydroxide was added to three others, and the three remaining digesters were left untreated.

A period of two weeks was allowed to elapse after the first chemicals had been added in order to permit observation of any immediate or slow reaction affecting the acidity in the treated tanks. Chemicals were added thereafter at frequent intervals until six or more additions had been made.

Sodium hydroxide was added in the form of a solution. It was poured through the charging tube and washed down with about one gallon of supernatant liquor withdrawn from the digester. A solution of lime was tried for lime treatment, but it was found that too much water was required, so that the lime was added dry and washed into the digester with supernatant liquor. Sodium carbonate was added in the same manner as lime.

Results of the study of the control of digestion with lime are presented for digester 62 in Fig. 19. The results observed in the other two lime-controlled digesters varied but little from those shown in Fig. 19. All of the phenomena observed in this digester were repeated in numbers 61 and 63. To aid in the study of the effectiveness of digestion a line has been plotted, called the Critical Line, representing a concentration of 2000 p.p.m. of volatile acids and a pH of 7.0. Unsatisfactory digestion conditions are indicated when the concentration of volatile acids in the digester is above the critical line or when the pH is below it. In practice a slightly lower pH may be experienced without detrimental results.

Significant facts pointed to in Fig. 19 include the following:

(a) The rapid commencement of the generation of gas during the first three days of the test was followed by its immediate falling off after the first week. Although the volatile acids were too high and the pH was too low for good digestion, according to the critical line, it is possible that substances inhibitory to bacterial metabolism required time for their development. The diminution of gas generation after the first week may be due to the unfavorable factors of high concentration of volatile solids and the presence of inhibiting substances or organisms.

(b) At the start the volatile acids were well above the minimum concentration permissible for good digestion, and the pH was too low, with a decreasing trend.

(c) Lime was first added on the sixteenth day following the start of the test. A very slight effect was observed on all of the characteristics. The pH was immediately raised from 4.8 to 5.2, but it slowly dropped back to 5.0. Gas production showed a slight increase for the following week, but again dropped back to an almost negligible amount. Volatile acids were unaffected.

(d) Five doses of lime were added between the 30th and 40th days. The effect on all of the characteristics was marked. The addition of the lime tended to neutralize some of the acids, resulting in a marked increase of pH from 5.0 to 7.0. The preceding downward trend of volatile acids was temporarily halted due, probably, to the formation of acetates which are reported in the test as volatile acids. A most remarkable effect was produced upon the rate of gasification which increased, during the 40th to the 50th days, from an almost negligible value to the probable normal rate for the best digestion of the substances in the digesters. Volatile acids and the concentration of volatile solids diminished continuously, and the pH fluctuated between 6.4 and 7.0 until the 80th day.

(e) On the 80th day the volatile acids decreased to a concentration of slightly less than 1000 p.p.m., and the concentration of volatile solids to 84 100 p.p.m. Without other observable changes, the gas production increased steadily and rapidly until on the 100th day it had attained a computed rate of 24.8 cu. ft. per pound of volatile solids added that day to the tank. Such a rate of gas production is higher than would be possible from the solids added at the time. It is evident, therefore, that the volatile solids accumulated in the digester were being digested. This fact is borne out by the slope of the line showing the concentration of volatile solids in the tank. The maximum rate of gas production, shown in Fig. 19, is equivalent to 2.26 cu. ft. of gas per day per cu. ft. of digester contents. This high rate is a result of the digestion of accumulated solids. The maximum rate of gas production occurred in digester 63, and was equivalent to 3.0 cu. ft. per day per cu. ft. of tank contents. This occurred when the concentration of volatile solids in the digesting mixture was 45 000 p.p.m. Such a high rate of gas production and the rapid exhaustion of the accumulated volatile solids suggests the possibility of more rapidly charging the digesters and operating with a shorter retention period than the 30-day period tested. Further research is necessary to determine how much the digestion period can safely be shortened.

TABLE 23

SUMMARY OF RESULTS OF CHEMICAL TREATMENT, SERIES 1; TESTS ON EFFECT OF CHEMICALS ON DIGESTION

Digester No.	Chemical Treatment	Gas Produced per Pound of Volatile Solids Digested cu. ft.	Percentage Reduction of Volatile Solids	Percentage Reduction of Grease
61	Lime	12.86	51.6	69.9
62	Lime	12.56	51.3	69.1
63	Lime	13.12	53.0	73.5
64	Lime	10.78	54.5	61.7
65	None	6.06	41.5	40.3
66	None	9.82	59.8	70.6
67	NaOH	4.03	29.9	75.5
68	NaOH	4.32	30.9	62.0
69	NaOH	4.75	27.6	77.0

On or about the 105th to the 113th day, the excess accumulation of volatile solids in the tank having been digested, the rate of gas production decreased to normal and continued at a normal rate until feeding was stopped on the 125th day.

(f) The sag in the rate of gas production between the 115th and 122nd days may be explained, in part, by the slight decrease in the rate of feeding at a critical time when the biologic activity was great.

Additional information on the effect of lime in the control of digestion was secured from a fourth digester, number 64, which was charged and fed in the same manner as numbers 61, 62, and 63, but no lime was added until the 66th, 67th, and 69th days. The records of observations are shown graphically in Fig. 19. The results show the immediate effect of the addition of lime on the pH value, which rose from 5.0 to 8.8 within 5 days of the first addition of lime. It quickly fell to 7.0 and remained within 0.4 of this value until the end of the test. The rate of gas production increased the day after the pH reached 8.8, but the volatile acids did not begin to fall for five or six days thereafter, indicating that digestion, and not lime, was the proximate cause of the diminution of volatile acids. The character of the variations in the rate of gas production followed those in digesters 61, 62, and 63. In about 35 days the rate of production became approximately normal, that is, 11.0 cu. ft. per pound of volatile solids added, and remained at this figure until the concentration of volatile solids in the digester was reduced to 86 000 p.p.m. The rate of gas production then suddenly increased to about 2.5 cu. ft. of gas per day per cu. ft. of digesting material, and remained at that rate for nearly two weeks after the cessation of feeding the digester.

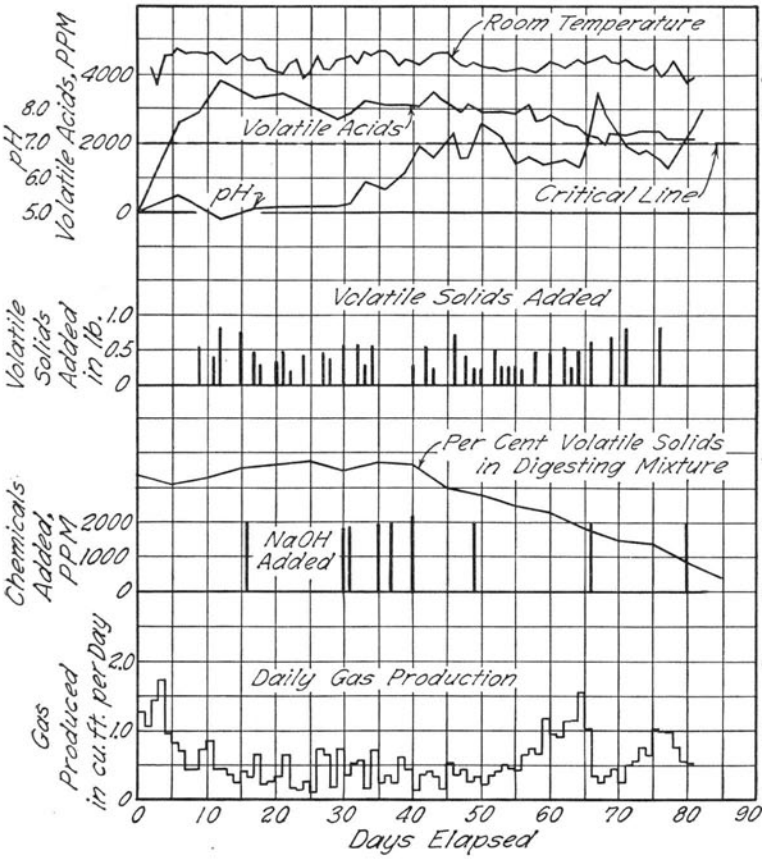

FIG. 20. AVERAGED CHARACTERISTICS OF DIGESTERS 67, 68, AND 69

The percentage reduction of volatile solids and of grease in the lime-treated tanks are shown in Table 23. More than 50 per cent of the volatile solids added were digested in each of these tanks. There was the greatest reduction of grease in tank 63, in which 73.5 per cent of the grease added was digested, and the least reduction in tank 64, in which 61.7 per cent was digested. The data in the table show good reduction of volatile solids and of grease in view of the long period of acid conditions during which undigested sludge was withdrawn.

Results of a study of the control of digestion with sodium hydroxide are presented in Fig. 20, which represents the average of the observations made on the three digesters, numbers 67, 68, and 69.

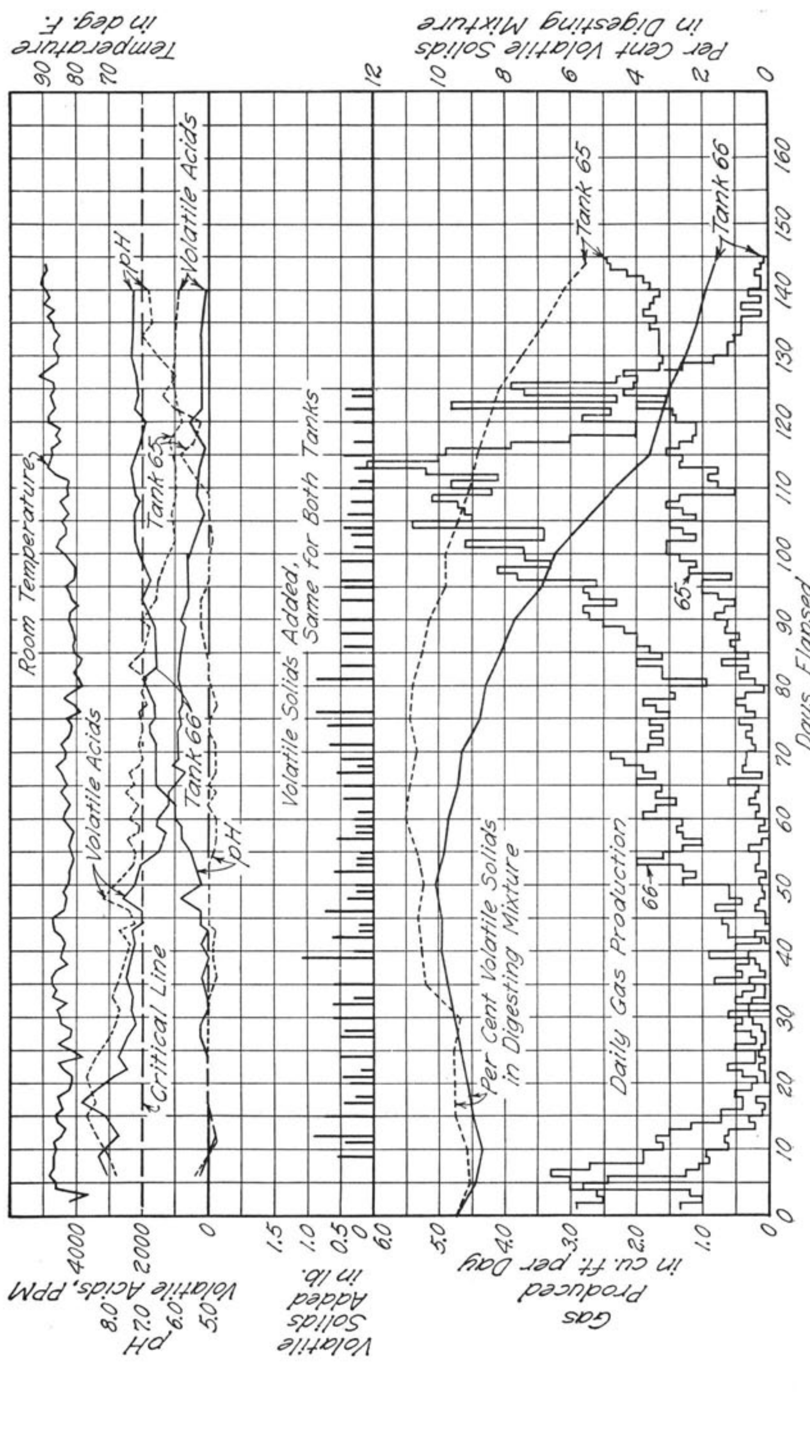

FIG. 21. CHARACTERISTICS OF DIGESTERS 65 AND 66

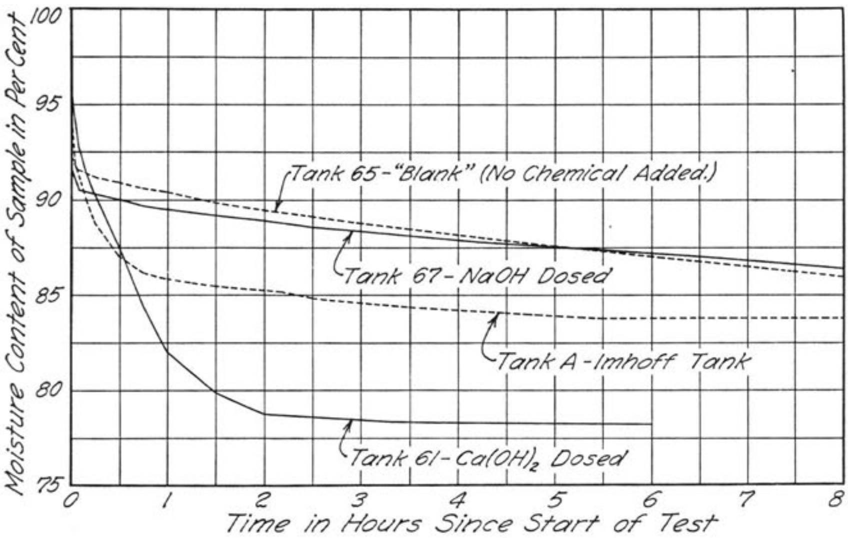

FIG. 22. TYPICAL DRAINABILITY CURVES

None of the observations on any of the three digesters tested under these conditions varied significantly from the average. The information in the figure shows that the addition of sodium hydroxide had no appreciable effect on the rate of gas production or on the reduction of the concentration of volatile solids. The addition of the chemical did increase the pH value to a slight extent, and the concentration of volatile acids slowly diminished to the critical maximum of 2000 p.p.m.

There was a low reduction of volatile solids in tanks 67-69, as shown in Table 23. The reduction of grease, as shown in Table 23, seems high when compared with the reduction of volatile solids, but possibly can be attributed to the action of sodium hydroxide, which saponified the grease to form sodium soaps.

Results of a study of digestion not controlled by chemicals are shown graphically in Fig. 21. All conditions in the operation of the two digesters in this test, numbers 65 and 66, were the same as in the tests on digesters numbered 61 to 64 and 67 to 69, except that the temperature in digester 66 was at all times about 3 degrees F. higher than that in any other digester. The characteristics of the digestion in digester 66 are similar to those of the lime-controlled digester, number 62, shown in Fig. 19, except that there was a lag of 10 to 15 days in the changes in digester 66 behind the changes in digester 62. The characteristics of digestion in digester 65 were markedly different from those in the warmer digester, or from those in the lime-controlled digesters. Acid conditions prevailed for the first 130 days, and volatile acids remained close to the critical concentration for good digestion. Gas production rose slowly, however, beginning with the 85th day, until it had attained a normal rate at about the 125th day, about the time that the pH increased to 6.5.

The percentage reductions of volatile solids and grease in the untreated tanks, numbers 65 and 66, are shown in Table 23. There was little reduction of volatile solids and grease in tank 65. There was a greater reduction of volatile solids in tank 66 than in any other tank. Grease was also digested readily, as shown by the 70.6 per cent reduction of the grease added.

Drainability curves for the sludges from the lime-treated and the sodium hydroxide-treated digesters, at the end of the test, are compared with the drainability curves for the sludge taken from the garbage-sludge-dosed Imhoff tank in Fig. 22. The better quality of the sludge from the lime-treated digester is clearly shown.

A comparison of the results of the batch digestion in digester 85, controlled with sodium carbonate, and those of the batch digestion in digester 86, not controlled with any chemical, is shown in Fig. 23. The conditions of operation of both digesters were identical, except for the addition of sodium carbonate to digester 85. The comparison indicates that the addition of sodium carbonate had no beneficial effect on the control of digestion.

In all of the tests of this investigation analyses were made of the gases generated. Averages of the analyses are summarized in Table 24. The results are of no great significance in the interpretation of the effects of added chemicals on digestion, except to show the relatively high concentration of methane under conditions of satisfactory digestion.

26. *Summary and Conclusions.*—During this investigation when the concentration of volatile solids in the digesting mixture of the temperature-controlled, separate digestion tank, number 63, was in the neighborhood of 90 000 p.p.m., the rate of gas production increased to 3 cu. ft. of gas per day per cu. ft. of digesting mixture, equivalent to 13.15 cu. ft. of gas, containing 60 per cent methane, per pound of volatile solids digested. This high rate continued for a short period of time only and depended, apparently, upon the accumulation of volatile solids in the tank. This rate is equivalent to the digestion of 0.228 lb. of volatile solids daily per cu. ft. of digesting mixture.

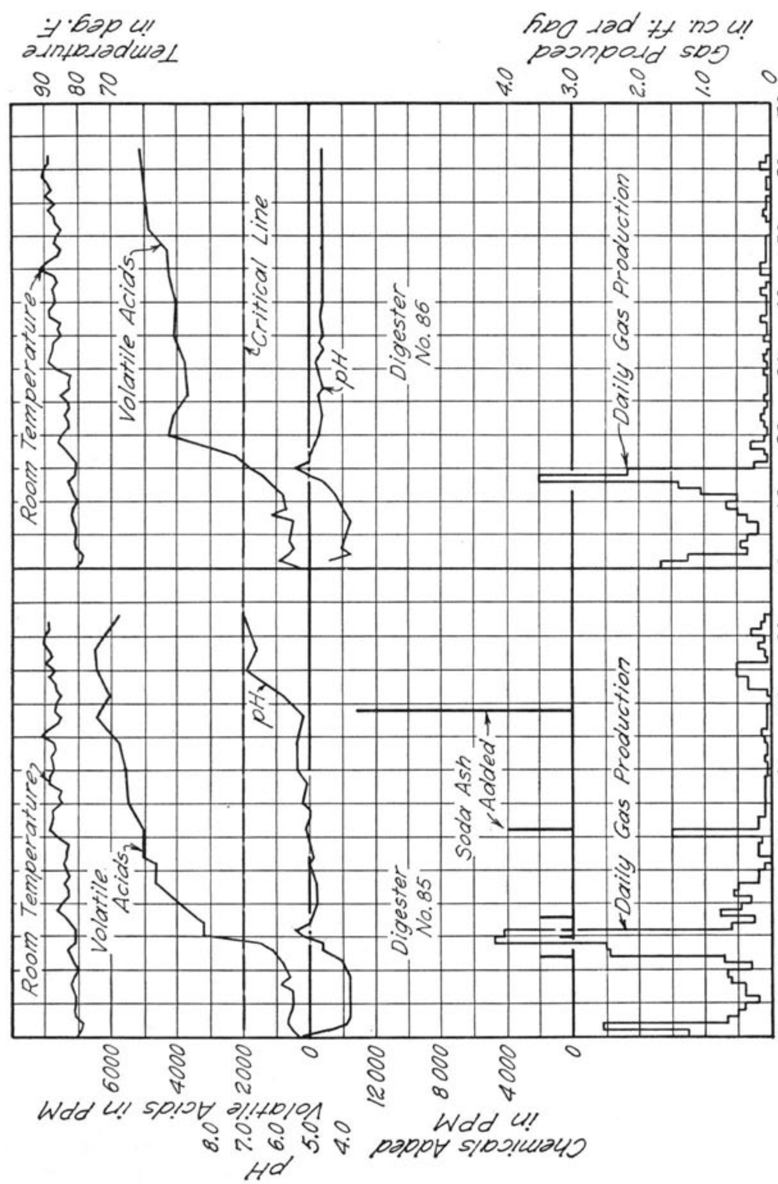

FIG. 23. CHARACTERISTICS OF DIGESTERS 85 AND 86

TABLE 24

QUALITY OF GAS GENERATED IN TESTS MADE TO STUDY EFFECT OF CHEMICALS ON DIGESTION

Samples were taken at irregular intervals, mostly towards the end of the period, when alkaline conditions prevailed in all digesters except 84, 85, and 86.

Digester Number	Chemical Added	Carbon Dioxide per cent (average)	Methane per cent (average)
61†	$Ca(OH)_2$	31.7	57.9
62†	$Ca(OH)_2$	31.3	57.6
63†	$Ca(OH)_2$	30.5	60.6
64†	$Ca(OH)_2$	30.6	63.2
65†	None	31.5	65.3
66†	None	31.9	60.6
67†	NaOH	43.0	45.3
68†	NaOH	44.5	37.5
69†	NaOH	35.3	49.8
84*	Na_2CO_3	67.7	....
85*	Na_2CO_3	64.0	....
86*	None	53.5	....

*Batch test.
†Periodic feeding.

Volatile solids, resulting from a mixture of garbage and sewage sludge, as shown in Table 21, were digested in the lime-controlled digesters at the rate of 0.06 lb. per day per cu. ft. of tank capacity with a 30-day retention period, resulting in the production of a well-digested sludge. This rate of gas production was computed from the results obtained throughout the entire period of the investigation. During the period of intense biologic activity volatile solids were digested at the rate of 0.228 lb. per day per cu. ft. of tank capacity. When the pH of the digesting contents of a tank was neutralized, either by the addition of lime or by the increase of biologic activity through the adjustment of temperature, the rate of gas production and the digestion of volatile solids was accelerated when the concentration of volatile solids in the digesting mixture was in the neighborhood of 80 000 to 90 000 p.p.m.

As a result of the investigation of the effect of lime, caustic soda, or soda ash on the digestion of a mixture of garbage and sewage sludge it is concluded that lime is beneficial as a means of overcoming acid digestion. Caustic soda and soda ash will have no beneficial effect when applied in amounts less than 2000 p.p.m. where the volatile solids in the digesting mixture are above 3000 p.p.m. No tests were made in which greater concentrations of caustic soda were added. The conclusion that sodium hydroxide is not effective in controlling digestion corroborates the report made by Rudolfs in 1928.[28] Unsatisfactory acid conditions of digestion may be corrected by the addition of an amount of lime computed as the equivalent of the volatile acids

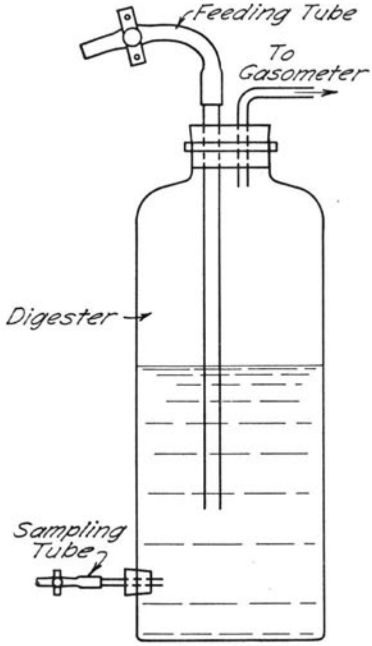

FIG. 24. APPARATUS FOR DIGESTERS 77-80

present where the volatile acids do not exceed 4000 p.p.m. No attempts were made to correct acid conditions where there were greater concentrations of volatile acids. It is possible that greater concentrations might be adjusted with lime to produce satisfactory digestion.

Under favorable conditions the adequate raising of the temperature of the contents of a digestion tank may be effective in the restoration of satisfactory digestion, but no quantitative measure of the amount of temperature rise required for this purpose was determined.

V. MISCELLANEOUS INVESTIGATIONS

A. Digestion of Lumps of Ground Garbage

27. *Purpose.*—This test was made in an effort to determine the cause of unsatisfactory conditions of digestion in an Imhoff tank fed by pushing lumps of ground garbage into the digestion compartment, as described in Chapter II, part B, page 28.

TABLE 25
MATERIALS PLACED IN FOUR-LITER DIGESTERS FOR LUMP DIGESTION TESTS

Material	Weight of Wet Mixture gm.	Dry Solids, Percentage of Wet Weight		Percentage of Weight of Dry Solids in Mixture Represented by Volatile Solids from Source Indicated	Percentage of Weight of Wet Mixture Represented by Volatile Solids from Source Indicated
		Total	Volatile		
Garbage	120	26.6	24.8	33.4	1.20
Fresh Sludge	1475	2.56	1.43	23.6	0.85
Digested Sludge	885	2.18	1.63	16.4	0.58
Total	2480	3.60	2.64	73.4	2.63

Ratio of dry weight of garbage volatile solids to dry weight of sludge volatile solids: = 45.6 : 54.5

28. *Procedure.*—Four four-liter brown glass bottles with gasometers, as illustrated in Fig. 24, were set up in a room in which the temperature was held between 80 and 90 deg. F. with occasional periods of less than an hour when it fell to 70 deg. These bottles were seeded and equipped to operate as "batch" digesters; that is, they were not fed after the original charging.

All of the digesters were charged with the same material, as shown in Table 25. The digested sludge was obtained from tank C, the heat-controlled separate digestion tank being fed with a mixture of fresh sludge and ground garbage. The ground garbage was introduced into two of the digesters, numbers 77 and 78, in the form of a lump, and the sludge was poured carefully into the digester so as not to break up the lump. The sludge and garbage were well mixed before being poured into the other two digesters, numbers 79 and 80.

Observations were recorded on the quantity and quality of gas produced, and small samples of the mixture were withdrawn periodically for determinations of odor and pH. The test was conducted as a batch digestion, no other materials being fed into the digesters during the investigation.

29. *Results and Conclusions.*—Results of the observations on the behavior of these digesters are presented in Fig. 25.

The favorable conditions of digestion in the lump digesters, high pH and rapid gasification, for the first 21 days, were apparently due to the digestion of the seeding material. The lump of garbage, exposing a minimum of surface to the sludge, did not greatly influence the rate of digestion of the sludge. After the twenty-first day, however,

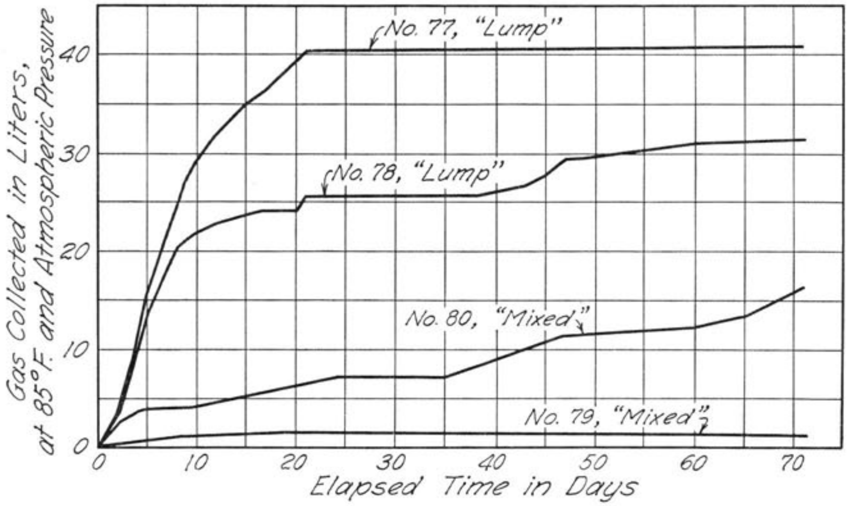

Fig. 25. Graph Showing Effect of Placing Garbage in Digester Mixed with Sludge or as a Lump

the pH dropped sharply to a low value, probably due to the disintegration of the lump of garbage, and gasification ceased. The pH then rose in the two lump digesters, until on the 71st day it had risen to 5.8 and 7.0, respectively.

The contents of the digesters containing a mixture of ground garbage and sludge turned acid immediately, and gasification continued to be sluggish throughout the period of observations. Satisfactory conditions of digestion did not get under way because of incomplete seeding at the start. It is concluded, because of the sudden cessation of the production of gas and the sudden establishment of very acid conditions in the lump digesters, that the unsatisfactory digestion characteristics of the Imhoff tank receiving lumps of ground garbage were due to the sudden and simultaneous breaking up of an accumulation of lumps of ground garbage in such a manner as to overload the tank with a mass of undigested volatile material, which could not be penetrated by the seeding material without stirring.

B. Digestion of Large Objects Suspended in Digestion Tanks

30. *Purpose.*—This investigation was made to determine the effect of dumping unground garbage into the digestion compartment of a tank.

TABLE 26

WEIGHTS OF LARGE OBJECTS AT VARIOUS PERIODS OF SUSPENSION IN DIGESTION TANK*

Weeks in Tank	Imhoff Tank								Separate Digestion Tank			
	Bread	Orange Peels	Rat	Bones	Cooked Potatoes	Meat	Paper	Rabbit	Rabbit	Orange Peels	Bread	Meat
1	A24	....	....	B33	F28	B21	B70	B46	B104	B32	C16	M36
2	A18	B38	F11	B30	....	....	B70	M47	K94	K16	E	B35
3	A30	B33	G8	....	A24	L18	B70	M56	B114	P5	....	B28
4	A31	B36	B8	B30	K19	B16	B70	B54	N82	P4	....	B28
5	A2	B29	B23	J30	K21	K16	B70	B54	N78	E	....	B27
6	E	K20	B11	B28	C14	C12	B70	B54	N78	....	....	B26
7	....	C16	C4	I36	....	....	B70	K44	N70	....	....	S
8	....	C10	C4	J26	D11	C12	B70	S	O	....	....	....
9	....	D9	Q4	B26	D10	D5	B70	....	S	....	....	....
10	....	D8	H4	B26	E	D4	B70	....	....	....	....	....
11	....	D6	R4	B25	....	D4	B70	....	....	....	....	....
12	....	P5	B4	B25	....	D2	B70	....	....	....	....	....
13	....	P4	E	B25	....	E	S	....	....	....	....	....
14	....	P4	....	....	....	....	....	....	....	....	....	....
15	....	P2	....	....	....	....	....	....	....	....	....	....
16	....	P2	....	....	....	....	....	....	....	....	....	....
17	....	P2	....	B25	....	....	....	....	....	....	....	....

A—Soggy Mass
B—Unchanged
C—Almost Gone
D—Trace Left
E—Gone

F—Burst Open
G—Skin Off Tail
H—Hide Alone Left
I—Meat Gone
J—Black

K—Broken Up
L—Slightly Moldy
M—Decaying
N—Compact Mass
O—Bones and Sludge

P—Few Left
Q—Decomposed
R—Sludge
S—No Further Observations

*The letters in the table refer to the corresponding letters in the list below the table. The numerals represent weights in ounces.

31. *Procedure.*—Various large objects were placed in wire cages and suspended in the sludge in the digestion compartments of the two Imhoff tanks and in the separate digestion tank. The objects were withdrawn from the compartments periodically and observed and weighed approximately. Exact weights were difficult to obtain because of the varying moisture content during weighing.

The results of the observations are presented in Table 26. A study of the data in the table indicates the futility of attempting to feed a digestion tank with unground garbage, although some of the objects were ultimately digested. The bones and the paper were unaffected, and some of the citrus fruit skins remained after more than 80 days in the sludge compartment. The small-boned animals, such as the rat and the rabbit, showed signs of complete digestion in 90 days. It is concluded that for satisfactory digestion in less than thirty days it is necessary to grind the garbage and mix it thoroughly and continuously with the digesting material.

C. Anaerobic Digestion of Some Pure Food Substances

32. *Purpose.*—In the anaerobic digestion of pure food substances considerable information, applicable to the digestion of garbage with sewage, has been made available by the work of other investigators.[18, 19, 21] Lack of adequate information on the effect of the concentration of solids in a digestion tank on the digestion of various kinds of foods, and on the quantity and quality of gas produced under different concentrations of various simple foods, pointed to the need of further tests to supply the required data. The development of other valuable data was anticipated, with the possibility that a prediction of the characteristics of the digestion of garbage might be based upon the results of its analysis and a knowledge of the method of digestion to be adopted.

33. *Procedure.*—Samples of cane sugar, powdered corn starch, ashless filter paper, cotton seed oil, casein, and blood fibrin were each divided into three batches weighing, respectively, 15, 35, and 100 grams, and each batch was added to 1.5 liters of digested sewage sludge. Ashless filter paper was used to represent cellulose, powdered corn starch and cane sugar for other carbohydrates, blood fibrin and casein for proteins, and cotton seed oil for fats. Each of the solid foods lost from ½ to 1½ per cent of their weight upon drying for 3 hours at 100 deg. C. Each of the smaller samples was placed in a 2.5 liter bottle, equipped for gas collection, similar to the arrangement illus-

TABLE 27
CHARACTERISTICS OF DIGESTED SLUDGE USED IN PURE FOOD DIGESTION TESTS

Nitrogen (ammonia), p.p.m.	204	B.O.D. (5-day 20 deg.), p.p.m.	2780
Nitrogen (Kjeldahl), p.p.m.	1100	Volatile acids, p.p.m.	20
Nitrites, p.p.m	1	Total solids, per cent	2.09
Nitrates, p.p.m.	3.66	Volatile solids, per cent	1.27
pH	7.3	Fats (ether solubles), per cent	4.87

trated in Fig. 24, and allowed to digest, with frequent shaking, as a "batch" test, under the conditions described for Series 7 on page 25. During the entire period of observation the bottles stood in the room under a temperature variation between 80 and 90 deg. F.

The sludge used in seeding the foods had the characteristics shown in Table 27. Two identical samples of this sludge were digested under the same conditions as the test batches of pure foods.

Periodic observations were made on the quantity and quality of gas produced, and analyses were made of the materials remaining in each bottle some time after gasification had ceased.

34. *Results.*—Records of the quantities and qualities of gas collected and solids digested during the tests are summarized in Table 28; information with regard to the rate of gas production is shown graphically in Fig. 26, and results of analyses of the materials remaining in the digesters after gasification had ceased are shown in Table 29. A study of Table 28 and of Fig. 26 shows that good digestion was indicated only in the lowest concentration of cellulose, sugar, and starch, and in the two lower concentrations of blood fibrin and casein.

No methane and only 4½ per cent CO_2 was present in the gas generated by the digestion of the sludge. The gas was mostly nitrogen, which may be accounted for partially by the reduction of nitrates and the presence of air. The small amount of carbon dioxide present in the gas generated by the digestion of the sludge, and the relatively high percentages of methane in the gases generated under conditions of good digestion may be explained, in part, by the loss of carbon dioxide through the brine seal in the gasometers. This loss was measured by a special test which corroborated this explanation of the loss of carbon dioxide.

Most, but not all, of the substances, even at the highest concentrations, digested better than the sludge alone. The results indicate that concentrations of less than 2 per cent solids are required for complete digestion. It is shown also that all food substances do not

TABLE 28

QUANTITIES AND QUALITIES OF GASES GENERATED AND SOLIDS CHANGED IN DIGESTION OF PURE FOOD SUBSTANCES

Test No.	Grams of Food Substance Added to 1.5 Liters of Digested Sludge	Gas Production											Days of Active Gasification	pH After 15 Days or at End of Gasification if Less Than 15 Days	Solids, Food Substance plus Volatile Sludge per cent			Remarks
		Theoretical			Observed													
		Kind and Volume liters		Percentage $CO_2 + CH_4$ Which Is CH_4	Kind and Volume liters				Percentage $CO_2 + CH_4$ Which Is CH_4	Ratio, Observed: Theoretical $CO_2 + CH_4$	$CO_2 + CH_4$ per Gram of Pure Food Substance						
		CO_2	CH_4		CO_2	CH_4	H_2	Total						Start	End	Reduction	
1	Cellulose—15	6.2	6.2	50	5.5	6.0	....	12.2	52	93	766	19	7.0	2.24	....	....	Completely digested
2	Cellulose—35	14.4	14.4	50	11.1	14.6	....	28.0	57	89	735	33	7.0	3.52	....	....	Completely digested
3	Cellulose—100	62.2	62.2	50	12.9	10.7	....	25.4	45	19	361	...	6.9	7.44	....	....	Gassing after 60 days
4	Sugar—15	6.2	6.2	50	4.8	6.2	....	11.0	56	89	733	19	7.4	2.24	....	....	Completely digested
5	Sugar—35	14.4	14.4	50	6.4	1.3	1.2	9.5	17	27	220	...	4.4	3.52	1.77	38.4	Sour, digestion ceased
6	Sugar—100	62.2	62.2	50	9.0	0	....	10.4	0	7	90	20	3.4	7.44	4.30	42.2	Sour, digestion ceased
7	Starch—15	6.2	6.2	50	4.3	5.4	....	11.4	56	62	514	10	7.0	2.24	....	....	Well digested
8	Starch—35	14.4	14.4	50	2.2	0	....	5.6	0	8	63	11	4.2	3.52	1.92	45.5	Sour, digestion ceased
9	Starch—100	62.2	62.2	50	2.8	1.3	....	7.1	32	3	41	11	4.0	7.44	2.33	68.8	Sour, digestion ceased
10	Cotton Seed Oil—15	....	....	...	3.3	5.2	0.32	10.2	61	...	567	...	7.0	2.24	....	....	Gassing after 60 days
11	Cotton Seed Oil—35	....	....	...	4.7	8.1	0.05	13.7	63	...	365	...	6.6	3.52	....	....	Gassing after 60 days
12	Cotton Seed Oil—100	....	....	...	1.6	1.2	....	4.8	43	...	28	16	4.8	7.44	....	....	Sour, digestion ceased
13	Blood Fibrin—15	....	....	...	2.2	8.2	....	10.5	79	...	694	17	7.4	2.24	....	....	Completely digested
14	Blood Fibrin—35	....	....	...	3.1	7.1	0.18	13.0	70	...	291	17	7.2	3.52	2.65	24.7	Not gassing
15	Blood Fibrin—100	....	....	...	7.7	5.3	....	16.5	41	...	130	16	7.0	7.44	4.81	35.4	Not gassing
16	Casein—15	....	....	...	2.2	8.1	....	10.4	79	...	687	18	7.8	2.24	....	....	Completely digested
17	Casein—35	....	....	...	3.2	5.6	tr.	10.0	64	...	252	17	7.6	3.52	1.68	52.3	Not gassing
18	Casein—100	....	....	...	5.1	1.7	....	8.4	25	...	68	13	7.2	7.44	3.71	50.3	Not gassing
19	Sludge Only	....	....	...	....	....	....	2.8	0	...	147	17	7.2	1.2	1.02	15.0	

TABLE 29

QUANTITIES OF DIGESTED PURE FOOD SUBSTANCES AFTER CESSATION OF GASIFICATION

Test No.	Grams of Food Substance Added to 1.5 Liters of Digested Sludge	pH	Volatile Acids p.p.m.	Total Solids per cent	Volatile Solids per cent	Ammonia Nitrogen p.p.m.	Organic Nitrogen p.p.m.	Total Nitrogen p.p.m.	B.O.D. p.p.m.
2	Cellulose—35	7.0	92	....	....	....	....	860	......
3	Cellulose—100	4.6	880	....	....	....	....	1123	......
5	Sugar—35	4.3	2080	2.59	1.77	337	888	1225	18 800
6	Sugar—100	2.8	6850	5.04	4.30	232	959	1191	20 000*
8	Starch—35	4.1	2340	2.69	1.92	250	1161	1411	17 600
9	Starch—100	4.0	6710	3.11	2.33	158	1030	1188	20 000*
10	Cotton Seed Oil—15	7.0	64	....	....	....	....	1168	......
11	Cotton Seed Oil—35	7.0	88	....	....	....	....	1144	......
12	Cotton Seed Oil—100	4.5	4910	6.60	5.82	432	828	1260	17 400
14	Blood Fibrin—35	4.9	2050	2.85	2.65	3960	718	4478	16 600
15	Blood Fibrin—100	5.0	7680	6.32	4.81	8980	1360	10340	20 000*
17	Casein—35	5.0	1400	2.50	1.68	3670	736	4406	17 000
18	Casein—100	5.0	7100	4.56	3.71	7240	2040	9280	20 000*
19	Sludge Only	7.0	126	1.82	1.02	526	615	1131	1 000

*Greater than 20 000.

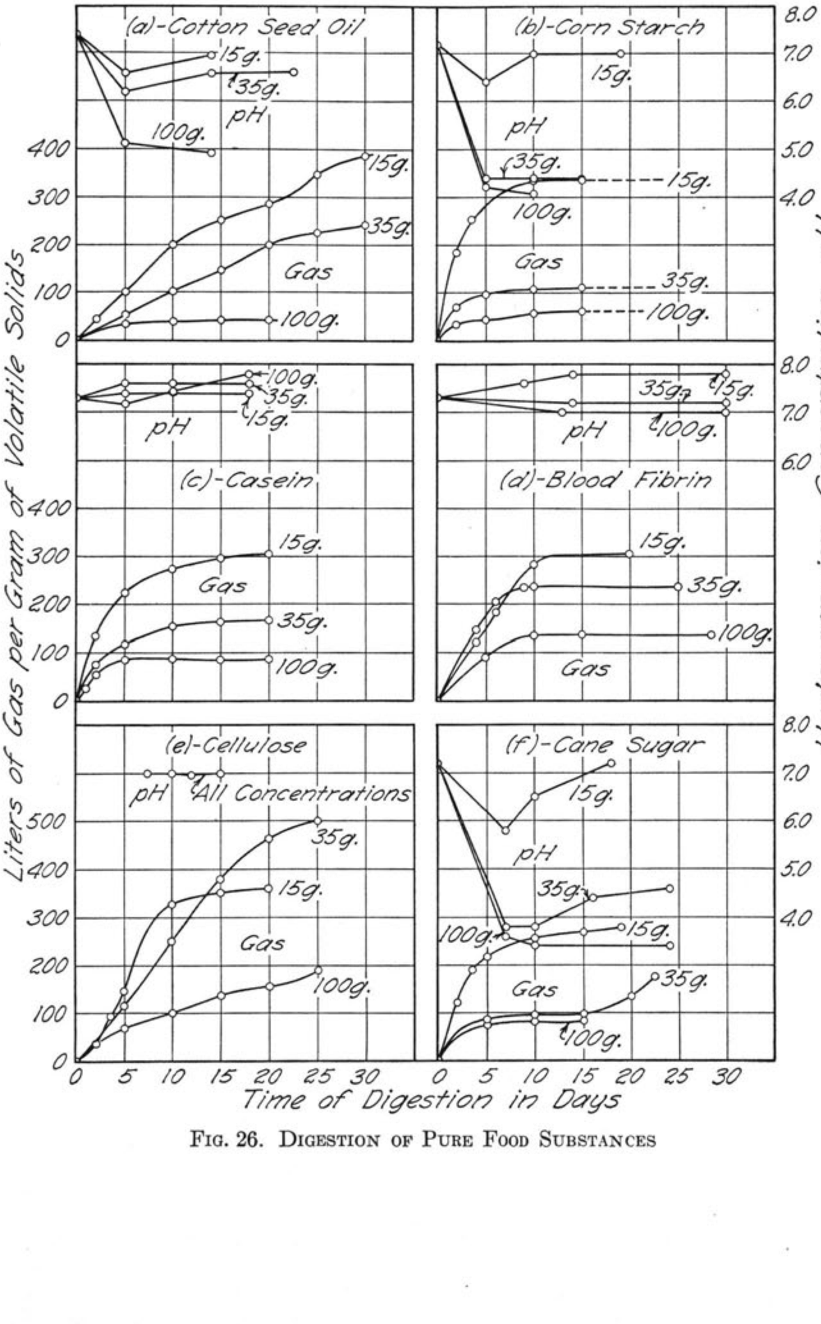

FIG. 26. DIGESTION OF PURE FOOD SUBSTANCES

digest at the same rate, and that some are more easily digested than others.

The substances tested may be placed in the following order of relative ease of digestion: (1) cellulose (carbohydrate), (2) sugar (carbohydrate), (3) blood fibrin (protein), (4) casein (protein), (5) cotton seed oil (fat), (6) starch (carbohydrate). The relative ease of the digestion of cellulose corroborates the work of Heukelekian.[19]

The cellulose produced little gas during the first two days. The lag was probably due to the time needed to hydrolyze the cellulose to start the slow production of sugar, only a small amount of which was present at any time. As a result no sour condition was produced and the concentration can be increased without detriment to the digestion so long as sufficient liquidity is maintained to permit good dispersion of the solids through the mixture. The principal difference between the digestion characteristics of the 15- and 35-gram samples was the time necessary for complete digestion. The 100-gram sample matted and produced more carbon dioxide than methane when the loss of CO_2 through the brine is considered.

The digestion of sugar also produced a 1:1 ratio of methane to carbon dioxide at the lowest concentration, but digestion of the more highly concentrated samples was unsatisfactory due to the production of acid conditions in the presence of too high a concentration of sugar. The 35-gram sample produced a highly explosive gas containing an appreciable quantity of hydrogen. The digestion of starch was similar to that of sugar.

The cotton seed oil rapidly produced a scum, and the reaction was soon retarded in the 15- and 35-gram samples, and stopped in the 100-gram sample, some hydrogen being produced at the lower concentrations.

The proteins behaved remarkably alike. The 15-gram samples digested completely, whereas the higher concentrations did not. A higher percentage of carbon dioxide was produced as the concentration of solids was increased. A trace of hydrogen sulphide was detected, and no gaseous nitrogen was formed. The digestion of the proteins was accompanied by the production of foul odors, due possibly to the presence of putrecine, cadavarine, and skatol.

The results of these tests indicate the need of further research to determine the proportions of sugars, starches, cellulose, proteins, etc. in garbage, the possible desirability of the addition of cellulose to improve the rapidity of gas production and stabilization in the diges-

TABLE 30
LOSS OF GAS THROUGH GASOMETER SEALS

Number of Days	Volume of Gas in Container liters	Percentage CO_2	Volume CO_2 cc.	Percentage CH_4	Volume CH_4 cc.
0	2.3	49.0	1130	43.1	992
1	2.2	....	....	....	...
2	2.1	....	....	....	...
7	1.9	....	....	....	...
10	1.8	42.1	758	52.8	952
Loss, cc.			372		40
Loss, per cent			33		4

tion of garbage, the possibility of beneficial or harmful effects on the digestion of one substance through the presence of other substances, and the determination of the optimum concentrations of the various substances for satisfactory digestion.

D. Loss of Gas through Gasometer Seals

35. *Procedure and Results.*—As the gasometers used in all investigations were sealed only with a strong brine solution it was felt that some of the gases might have been absorbed in this seal and diffused into the air. A test was made, therefore, to determine the rate of loss of gas. A sample of gas of average quality was removed from one of the digesters and stored in a gasometer. Periodic observations were made of the quantity and quality of the gas remaining in this gasometer. Results of these observations are given in Table 30. It is evident from a study of the figures in this table that very little methane is lost through the seal, but that the loss of carbon dioxide may be appreciable unless readings are taken at least daily and accumulated gas is discharged from the gasometers. The exact rate of loss of gas will depend upon such factors as the per cent saturation of brine in the solution, the temperature, the area of exposure of the surface of the brine solution to the gas and to the air, and the gas and barometric pressures. Numerical corrections for these losses have not been made in reporting observations on gas collection, but allowances therefor have been made, where necessary, in drawing conclusions. In general, the error is appreciable only when the rate of gas production is low, because of the relatively infrequent reading of the gasometers. At the highest rate of gas production gas volumes were measured and the gasometers were emptied two or three times daily.

VI. Observations on Biology of Anaerobic Stabilization of Garbage and Sewage Sludge

36. *Purpose.*—This investigation was made in the hope of finding an easily detectable biologic index of the progress of the anaerobic stabilization of organic matter. Such an index, if detectable by the microscope alone, might supply information more quickly and easily than the more cumbersome and time-consuming chemical tests now in use.

37. *Microscopical Examination.*—Samples of sludges taken from the various digesters were examined under the microscope, some with and some without the aid of dyes to accentuate the presence of various characteristics of the substances examined. Only weak solutions of the dyes were used in order to inhibit as little as possible the activities of the living organisms.

Four dyes were used: neutral red, methylene blue, congo red, and Lugol solution. Neutral red was used in an aqueous solution (1:20 000) to stain the nucleus of the organisms and to test the reaction of food vacuoles. The color change occurs at a pH of 6.8 to 8.0 and shows yellowish-red for alkalinity and cherry-red for acidity. Methylene blue was used in an aqueous solution (1:10 000). It stains practically everything in the field from deep blue to various shades of green. It has a tendency to concentrate in cytoplasmic granules, and to show structures in the nucleus. In the absence of oxygen it loses its color, but it cannot be used on microscope slides as an indicator of anaerobic conditions in the sample when withdrawn from the digestion tank because of the availability of oxygen to the slide. Congo red was used in aqueous solution (1:1000) as a test for alkalinity, which is indicated by a deep red color, or for the presence of organic acid, which is indicated by reddish to red orange to purple shades, or the presence of mineral acids, which is indicated by shades of blue, or to distinguish living from dead cells. It is stated by Heinrici[29] that this dye will stain only dead cells. Lugol solution was prepared with one gram of iodine and 5 grams of potassium iodide in 500 ml. of distilled water. This solution is highly poisonous to organisms, but stains them dark and facilitates recognition of number and arrangement of cilia or flagella.

In order to study the possible effect of the unavoidable exposure of the organisms to oxygen on the microscope slides, examinations were made of samples which had been exposed for various periods of time before being protected with a cover glass. The periods of uncovered exposure varied from the shortest possible time required to transfer a drop from the anaerobic sample taken from the digestion tank, to a prolonged exposure of five minutes. Direct observations were made upon unstained samples. The results showed that the number of motile ciliata was greatly reduced by the exposure to the air. This might indicate that the ciliata observed were obligate anaerobes. An increase in the number of organisms would have indicated that sufficient time had elapsed for the development of vegetative motile forms from the cysts of aerobes present in the digesting compartment. The failure of such forms to develop does not prove the absence of such cysts. However, all of the sludges studied, with one exception, came from digesters which had been under anaerobic conditions for a long period without the addition of fresh foods presumably saturated with oxygen. It is highly probable, therefore, that aerobic protozoa were not present in the samples. Such aerobic chance stragglers as are described by Lackey[30] in Imhoff tanks, could not well have survived so long under purely anaerobic conditions. Little is known of the etiology of anaerobic protozoa, although the various actions observed in the anaerobic digestion of organic matter indicate their presence.

Few protozoa were observed in this investigation. All of those observed were ciliata of the order of holotrichida. Neither mastigopohra nor sarcodina were observed on any slide, but it is possible that they were present and merely escaped detection. No typical organisms were detected in the sludges examined, although some samples of sludge showed a greater concentration of some unidentified organism.

An examination of the sludge from the periodically-fed digestion tank produced the most interesting results. This sludge was the richest in protozoa. Holotrichida were present on every slide. Some were large, about 30 μ in length, probably colpidium, and another species about 10 μ in length was observed. At one time an abundance of a threadlike organism, similar to sphaerotilus, was observed. It was noted that in those sludges in which an acid condition existed no motile protozoa were detected, but that in some of the sludges small organisms, similar to yeast, were present, sometimes budding. In one sample of sludge, in an acid condition and with an unpleasant odor, several sac-like structures about 6 μ in length, filled with various shaped particles were observed. They took no stain except from the congo red, which dyed them a brilliant red. These organisms showed no independent movement nor any arrangement of internal particles.

TABLE 31
NUMBER OF BACTERIA IN DIGESTING SLUDGE

Source of Sludge	Number of Bacteria thousands per cubic centimeter — Anaerobic Incubation: Sludge	Anaerobic Incubation: Super-natant	Anaerobic Incubation: Mixture	Aerobic Incubation: Sludge	Aerobic Incubation: Super-natant	Aerobic Incubation: Mixture	Date 1936	pH	Volatile Acids p.p.m.	Approximate Rate of Gasification; Gas Produced per Volatile Solids Added cc.
Fresh Sludge	....	....	12 000	....	....	47 600	Feb. 15	....	....	...
Tank C	520	60	150	850	30	480	Feb. 15	7.0	28	490
Tank C	....	....	910	....	....	200	Mar. 19	6.8	32	...
Barrel 61*	800	100	500	1580	151	1 130	Feb. 27	7.1	110	820
Barrel 66	4220	200	1 600	8400	730	4 360	Feb. 27	7.2	169	880
Barrel 85†	476	134	414	62	23	49	Feb. 27	5.0	5670	62
Barrel 86	100	16	55	30	20	20	Feb. 27	4.6	3950	31
Barrel 71‡	....	....	2 020	....	....	10 400	Mar. 19	7.0	308	645
Barrel 74¶	....	....	500	....	....	4 200	Mar. 19	7.0	318	647

*Treated with lime.
†Treated with soda ash.
‡Contains elutriated garbage.
¶Contains non-elutriated garbage.

They possessed no flagella nor cilia nor did they show a tendency to form pseudopodia.

38. *Bacteriological Examination.*—Some results of bacterial counts on various samples of sludges are presented in Table 31. All of the counts were made on nutrient agar incubated for 48 hours at 37 deg. C. The procedure was such as to make the preservation of anaerobic conditions impracticable during the preparation of the dilutions because of oxygen present in the diluting water and oxygen absorbed during the shaking of the samples to break up particles of sludge. During incubation, however, anaerobic conditions were maintained on the anaerobic samples.

It is probable that obligate anaerobes cannot survive the preparation period as they are in the vegetative state when drawn from the favorable environment of the digester, and, if spore-forming, they do not have time to form spores before a fatal quantity of oxygen is absorbed. The anaerobic counts on these sludges are, therefore, mainly of comparative value between the sludges examined under these special conditions. They do not represent the absolute number of all anaerobic bacteria present. Dilutions of 1:1000, 1:10 000 and 1:100 000 were used.

It is probable that the counts of bacteria in concentrated sludge, reported in Table 31, if in error, are low. This is due to difficulties in the handling of the thick sludge and in attempting to break it up into a uniform mixture. The resulting counts may probably, therefore, indicate aggregates of bacteria rather than individual organisms. Homogeneous samples of supernatant liquor could be collected so that the counts in the supernatant are probably more nearly representative of the number of individual bacteria present.

An attempt may be made to draw tentative conclusions from such data, however inconclusive, wherever the indications are in accord with a reasonable interpretation of the data. Because of the uniform presence of a larger number of bacteria in the sludge than in the supernatant liquor it may be concluded that sludge is more effective as a seeding material, being richer in bacteria.

Foul odors in sludge digestion are the product of obligate anaerobes. This conclusion is based on the fact that the anaerobic count is greater on all sludges except those taken from the foul-smelling, acid tanks. It is probable, therefore, that such conditions are detrimental to aerobes, either as cysts or as vegetable cells, and that obligate anaerobes existed to produce the foul odors.

Well-digested sludges showed lower bacterial counts than were shown by fresh sludges.

Insofar as the accomplishment of the purpose of the investigation is concerned, the results are negative. They do, however, serve to explain, in part, some of the biological activities in the anaerobic stabilization of organic matter.

VII. Discussion and Summary of Conclusions

39. *Discussion.*—Increasing public interest in the possibilities of the water carriage method for the collection of garbage points to an increasing load of pollution to be carried by natural bodies of water receiving municipal sewage, or by plants designed to treat such sewage before disposal. Knowledge of the effect of this load upon sewage treatment plants together with information on the proper design of treatment equipment to care for the load is, therefore, essential to the designer and to the operator.

The large amount of work done in the investigation of the anaerobic stabilization of organic wastes, particularly in the field of the disposal of industrial wastes, has been invaluable in the conduct of this investigation, which has been aimed towards securing data applicable in the design of sewage treatment equipment and in the operation of sewage treatment plants. The comparatively recent nature of the reports of experience with this method of garbage collection and disposal in the United States, and the lack of such reports in foreign literature, point to the slow adoption of the method since its introduction in the United States in 1923, and to the lack of its adoption abroad.

The anaerobic digestion of garbage under thermophilic conditions is said to be successful in stabilizing the organic matter in a few days. Some of the findings of this investigation have pointed to equal possibilities for the stabilization of sewage and garbage organic matter and point to the possibility of greatly decreasing the customary allowances for digestion tank capacities under current practice.

One of the most promising indications of such a desirable finding was given by the test on the control of digestion with chemicals. The concentration of volatile solids may be a valuable indicator of optimum digestion conditions. For example, when the concentrations of volatile solids in the digesting mixture in the temperature-controlled, separate digesters were in the neighborhood of 80 000 to 90 000 p.p.m., volatile solids were digesting at the rate of 0.23 lb. per day per cu. ft. of tank capacity. At this rate, if it can be assumed that 0.25 lb. of combined sewage and garbage volatile solids are produced per capita daily, it will be necessary to provide 1.1 cu. ft. of tank capacity per capita. In the tests on the elutriation of garbage, it was found that 2.5 to 4.5 cu. ft. of tank capacity was needed. The difference between the required capacity as found in these two tests may have been caused by a difference in the concentration of volatile solids in the test digesters. The loading of a digester depends on the concentration of solids in the mixture to be added, together with the nominal retention period in the tank.

If a very short retention period is possible, and the optimum concentration of volatile solids is 9.0 per cent, there will be required, for 0.25 lb. of combined garbage and sewage solids per capita daily, a digestion capacity of 0.1 to 0.2 cu. ft. per capita, dependent upon the retention period. If this figure be doubled to take care of daily variations from the average, the required digestion capacity will be 0.2 to 0.4 cu. ft. per capita. This indicates the possibility of designing controlled, separate digestion tanks with capacities of 10 per cent or possibly only 5 per cent of present requirements of capacity in the digestion compartment of an Imhoff tank, caring for sewage sludge alone. It is to be noted that the possibilities of using such reduced digestion capacities are only indicated by these tests. Further investigations are required to confirm the possibilities indicated.

The possibility of operating a tank with a very short digestion period is suggested as a result of the observations made during the lime-controlled tests and, because of the effectiveness of lime in controlling digestion, it may be possible, after good digestion has been established, to feed a temperature-controlled, separate digestion tank with any ratio of garbage to sewage volatile solids to the limit of 100 per cent of either of them. The volume of well-digested sludge produced may be expected to be somewhat less than twice the volume of the material resulting from the digestion of the sewage sludge alone.

40. *Summary of Conclusions.*—Conclusions resulting from this investigation are based upon observations made during the conduct of the tests. Reference is given to the page in this bulletin upon which each conclusion is explained. The following is a summary of some of the more important of the observations made:

(1) The digestion of a mixture of garbage and sewage sludge without frequent feeding and stirring of the mixture and without periodic

withdrawal of the products of digestion was impracticable. The acid phase of digestion developed and could not be corrected easily. Batch operation, as this may be called, was found to be impracticable except for special studies (page 27).

(2) The feeding of ground garbage in lumps into the influent end of an Imhoff tank was found to be impracticable. Lumps of ground garbage floated across the tank and were discharged, unchanged, with the effluent (page 30).

(3) The feeding of ground garbage in lumps into the digestion compartment of an Imhoff or separate digestion tank was found to be impracticable. The acid phase of digestion developed, with consequent deleterious results (page 31).

(4) The feeding of ground garbage, well-mixed with sewage, into the influent of an Imhoff tank was found to be successful when the rate of feeding did not exceed 1½ tons of wet garbage per million gallons of sewage. There is reason to believe that this rate could be materially increased. Further data on this point are desirable. Sludge accumulated at the rate of 2 cu. yd. per million gallons of sewage per ton of garbage added to the sewage when retained for one year in the digestion compartment. Higher rates of accumulation would result from a shorter period of sludge retention (page 33).

(5) Ground garbage, well mixed with sludge, was fed to a heat-controlled, two-stage separate digestion tank, with constant and rapid recirculation of the digesting mixture, in which the temperature was maintained close to 90 deg. F. The garbage and sewage volatile solids were equal in the mixture fed to the tank. The rate of feeding was equivalent to 1.67 lb. of volatile solids per day per cu. yd. of digestion capacity with a period of retention of 30 days. Such a rate of feeding calls for a digestion capacity of 3.75 cu. ft. per capita on the basis of the production of 0.115 lb. of garbage volatile solids and an equal weight of sewage volatile solids per day per capita. Since the capacity of the tank was not reached when fed at this rate, further research is necessary to determine the limit of the rate of feeding the tank. Indications are that a much shorter period of retention may be possible with digestion capacities as low as one-tenth of those used in the tests (pages 38 and 84).

(6) The concentration of volatile solids in the digestion tank was a good index of the behavior of the tank and its approach to the limit of its capacity. The permissible limit of this concentration was not reached at concentrations as high as 8000 p.p.m. Concentrations up to 80 000 p.p.m. were reached in smaller digesters, and were accompanied

by an increase in the rate of digestion of volatile solids (page 38).

(7) Two-stage digestion compartments in the tank revealed a higher rate of gas production in the primary compartment, presumably resulting from the greater accumulation of grease in this compartment (page 38).

(8) It was found that the water-carriage method of the collection of garbage added 25 to 100 per cent to the B.O.D. load on secondary treatment devices in a sewage treatment plant, and required 20 per cent more capacity in a heat-controlled separate digestion tank than if the same amount of garbage had been fed directly into the digestion tank, together with the sludge from the same amount of sewage (page 46).

(9) When garbage was washed (elutriated) with sewage, between 23 and 63 per cent of the garbage volatile solids, averaging 34 per cent, went into solution or suspension (page 45).

(10) Elutriated garbage digested as well as garbage which had not been elutriated (page 49).

(11) Garbage grease was somewhat more easily digested than sewage grease (page 52).

(12) Computations, based upon assumptions used in practice and upon observations made in the tests, indicated that temperature-controlled digesters may be operated successfully at a loading equivalent to 3.45 cu. ft. of digester capacity per capita when being fed with elutriated garbage with fresh sludge, and 2.88 cu. ft. per capita when being fed with non-elutriated garbage with fresh sludge. These figures are based on a retention period of 30 days (page 53).

(13) The control of digestion conditions with lime, in a temperature-controlled digester, with sludge recirculation, resulted in the peak production of 3.0 cu. ft. of gas per day per cu. ft. of tank capacity. This rate of gas production continued for only a few days during which the concentration of volatile solids in the tank was materially reduced. This rate is equivalent to the digestion of 0.23 lb. volatile solids per day per cu. ft. of tank capacity. The normal rate of operation was 0.06 lb. of volatile solids per day per cu. ft. of tank capacity. The sudden acceleration in the rate of digestion occurred when the concentration of volatile solids was about 90 000 p.p.m. (pages 65 and 67).

(14) Caustic soda and soda ash were found to be of no value in overcoming the acid phase of digestion (page 67).

(15) Unground garbage was not digested successfully. Indications were that the fineness of grinding is a factor in rapidity of digestion. Further information is desirable on this point (page 72).

(16) The pure food substances tested were digested in the following relative order of rate of digestion, beginning with the most digestible: filter paper, cane sugar, blood fibrin, casein, cotton seed oil, corn starch (page 77).

(17) The loss of carbon dioxide through the gasometer seals may be a source of error in the interpretation of the volume and quality of gas collected (page 78).

(18) No typical organisms indicative of particular stages in sludge digestion were found (page 83).

(19) Sludge is probably more effective than supernatant liquor as a seeding material because of the higher bacterial content of sludge (page 82).

(20) Well-digested sludge showed lower bacterial counts than were found in poorly-digested sludge (page 83).

(21) It is possible to measure the sizes of particles of ground garbage by means of the test described on page 90).

APPENDIX A

Laboratory Procedure

1. *Laboratory Procedure.*—Chemical control of the tests was maintained in the laboratory located about 1000 feet from the testing plant and contiguous to the warm room in which the small-scale digestion containers were stored. A few bacteriological and biological observations were made with the equipment available in the University bacteriological laboratory.

The chemical procedure followed in this investigation was in accord with standard methods[31] except as explained in the following paragraphs, unless otherwise stated in the description of any particular test.

2. *Total and Volatile Solids.*—Fifty grams of the sample were placed in a weighed porcelain evaporating dish, and dried on a sand bed at 103 to 105 deg. C. Occasionally as long as two days were required for the complete evaporation of moisture from garbage. After cooling, weighing, and determining the total solids the same sample, in the porcelain evaporating dish, was ignited in an electric muffle furnace at a temperature of 600 to 800 deg. C. Samples of sewage and of sludge were kept in the furnace for about thirty minutes, and samples of garbage were ignited for about two hours. An error in the determination of the total solids is possible, due to the loss of ammonium carbonate while the samples are drying on the sand bed.

3. *Biochemical Oxygen Demand.*—The dilution method was used. Distilled water, aerated by blowing through it air which had been passed through a soap solution to remove dust and grease, was used as dilution water. Immediately before use 300 p.p.m. of sodium bicarbonate ($NaHCO_3$) were added to the aerated distilled water. The permanganate modification of the Winkler method was used before and after incubation. The unmodified Winkler method was used to determine dissolved oxygen in the blanks. The initial dissolved oxygen in all dilutions greater than 1:100 was assumed to be the same as that in the blank.

Samples were usually incubated for five days in a 20-degree incubator which gave extremes of 2 degrees of temperature variations either above or below 20 deg. C. When other periods of incubation were used the B.O.D. was corrected to the 5-day basis by the method of Theriault.[32]

4. *pH.*—The pH was determined by means of a Sanitary District of Chicago colorimetric set which allowed readings from 1.6 to 9.6. This set provides compensation for turbidity in the samples. The pH on sludges was determined on the supernatant liquor. Concentrated samples were diluted with one to three volumes of distilled water.[33]

5. *Volatile Acids.*—Volatile acids were determined by the method recommended by Buswell.[34] The determination was made on a 200 ml. sample, or a sample diluted with distilled water to 200 ml., acidified with 2.0 ml. of concentrated sulphuric acid. The sample was then heated slowly until 150 ml. were distilled. The distillate was titrated with 0.1 N sodium hydroxide, using phenolphthalein as an indicator. The concentration of volatile acids, in p.p.m., as acetic acid, was calculated from the milliliters of sodium hydroxide solution used in the titration.

6. *Grease.*—Grease was determined by placing a known weight of a dried sample in a continuous extractor of the Soxhlet type and washing it with petroleum ether for six to eight hours. The sample was dried on a 105-deg. C. sand bed, and weighed. The loss in weight was considered to represent the grease present in the sample.

7. *Gas Analysis.*—Gas analyses were made in a Williams apparatus of the Orsat type. The sample was first passed through a strong solution of potassium hydroxide, the loss in volume being reported as carbon dioxide. The gas residue from the determination of carbon dioxide was passed through an alkaline solution of pyrogallol, the loss in volume being reported as oxygen (O_2). The gas residue was then stored in the pyrogallol tube, except for a measured portion of 8 to 9 cc., which was mixed with ten times its volume of air and exploded. The gas residue following the explosion was passed through the potassium hydroxide solution, and the loss in volume reported as the amount of methane present in the 8 to 9 cc. sample. Hydrogen was determined from the expression

$$\text{Hydrogen} = 2/3\ (C\text{-}2M)$$

in which

C is the volume of the contraction due to the explosion

M is the volume of methane

Nitrogen was reported as the difference between the volume of the original sample and the sum of the volumes of carbon dioxide, methane, and hydrogen present.

APPENDIX B

The Determination of Sizes of Particles in Ground Garbage

The sizes of the particles of garbage which passed through the grain grinder and through the meat grinder were determined in a manner similar to the standard sieve analysis of sand. In making the determination a number of sieves were tied together, open both top and bottom, and submerged in a metal container filled with distilled water, as shown in Fig. 27, with the rim of the top sieve protruding above the surface of the water. A kilogram of wet garbage was placed

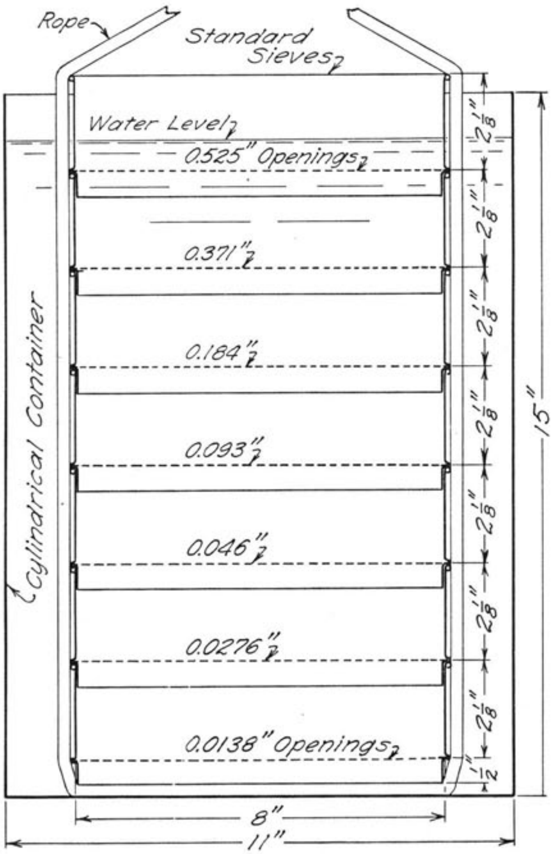

Fig. 27. Sieves Used to Determine Size of Garbage Particles

on the top sieve and the whole set moved up and down about two inches, in jerky, rotating movements, without submerging the rim of the top sieve. As each sieve was washed free of particles small enough to pass through it, the set was pulled up an amount equal to the height of one sieve, and the motion continued. When the screening was complete the sieves were separated and the solids retained were removed by a spatula and a small stream of wash water. These solids, together with the wash water, were dried at 100 deg. C. and the dry weight determined. The water remaining in the metal container was agitated violently and a liter sample taken to determine the percentage of solids passing through the finest screen. As a check on the dry solids in the sample taken for the screening test, a separate determination was made on a representative sample of garbage to learn the amount of dry solids in a kilogram of garbage. The sum of all solids determined in the screening test varied 1.6 per cent from the computed dry solids in a kilogram of garbage. The average results of two typical analyses of garbage ground in the grain grinder and garbage ground in the meat grinder are presented graphically in Fig. 28.

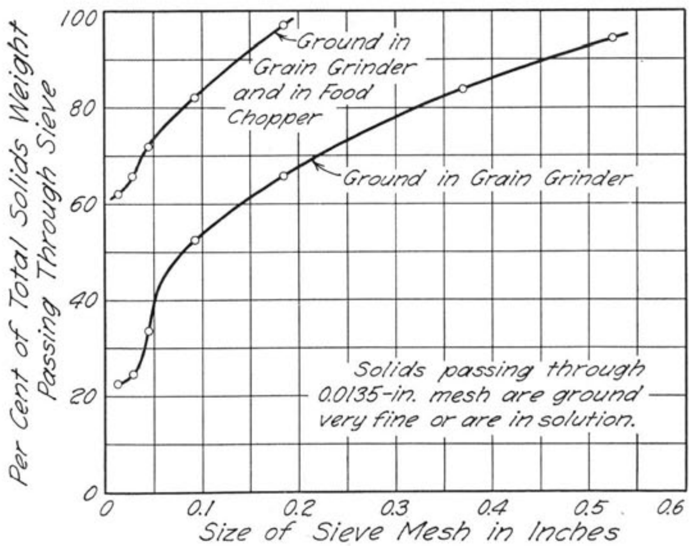

FIG. 28. GRAPH SHOWING SIEVE ANALYSIS OF GROUND GARBAGE

APPENDIX C

Conditions Affecting Digestion

1. *Test Procedure.*—In the conduct of these tests it has been attempted to observe all conditions which might affect the test, to observe and record the conditions which were not controllable, to hold constant all but one of the controllable conditions, and to record the results caused by the variation of the particular controllable conditions.

The number of recognized conditions affecting the digestion of sewage sludge and organic matter, such as waste food, is large. Among the conditions which were controlled in these tests, either closely or approximately, may be included

(1) The temperature of digestion
(2) The period of digestion
(3) Agitation of the contents of the digesting tanks
(4) The manner of dosing the tanks
(5) The source of the sludge
(6) The solids content of the digesting mixture (very limited control)
(7) The fineness of grinding of the garbage
(8) The ratio of garbage solids to sewage solids in the digesting mixture
(9) The concentration of solids in the digestion tank
(10) The amount and character of added chemicals

Among those conditions which were but slightly or not at all under control may be included

(1) The quality of the garbage
(2) The quality of the sludge
(3) Biological conditions
(4) The quantity and quality of sludges, liquors, gases, and effluents produced

2. *Temperature of Digestion.*—In most of the tests involving the digestion of sludge-garbage mixtures temperatures within a few degrees of 90 deg. F. have been maintained. This temperature was chosen on the basis of the results of previous investigations, particularly those reported by Fair and Moore[35] and by Heukelekian[36, 37] in which the optimum, non-thermophilic range of temperature is fixed as within a few degrees above or below 33 deg. C.

The control of the temperature of the contents of the largest separate digestion tank, tank C, has been maintained within two degrees of 90 deg. F., with but few brief periods above or below this point. A few times during the first few weeks of the investigation the temperature rose to a maximum of about 120 deg., and less frequently fell to 70 or 75 deg. During the last nine months of the investigation no appreciable variations of temperature above 92 deg. or below 88 deg. ever occurred in tank C.

During the first year of the period of investigations the tests in 55-gallon casks, 5-gallon carboys, and smaller bottles were conducted in rooms in which the temperature was not controllable. The temperatures in these rooms varied between about 20 deg. and 105 deg. F., commonly being in the range between 65 and 85 deg. For two or three months during the first winter, however, the contents of the digesters were below 50 deg. F. and were observed, at times, to be frozen solid. Results of these tests are, therefore, not reported.

During the last nine months of the investigation the smaller digesters were stored in a room in which the temperature was held between 80 and 90 deg. F. with occasional short periods of one-half hour to one or two hours when it was permitted to fall to 70 deg. F. It is thought that these brief periods of lower temperatures had no appreciable effect upon the results of the tests.

No attempt was made to control the temperatures in the digestion compartments of the Imhoff tanks. These temperatures were determined by the temperature of the incoming sewage, and by the surrounding atmospheric temperature, and were observed regularly. Records of the temperatures are reported in the discussion of the results of this phase of the investigation.

3. *Period of Digestion.*—Thirty days was taken as the standard digestion period for the separate sludge digestion experiments involving continuous feeding. Not all tests were run at this period, however, as experience has shown that garbage and sludge mixtures can be satisfactorily digested, under favorable circumstances, in less time.[11, 14] The period was controlled by feeding the digester with a charge, the volume of which was equal to the product of the volume of the container, the period between doses in days, and the reciprocal of the period of retention in days. In some tests one charge was placed in the digestion container and allowed to react without addition of other material throughout the duration of the test. Some of these batch dosing tests were continued for more than ten months.

The period of retention of sludge in the digestion compartments of the Imhoff tanks varied in accordance with the observations. The capacity of the compartments was sufficient to permit more than 12 months storage of the sludge accumulated.

4. *Agitation.*—Experience has shown that the mixing of the contents of a digestion tank is conducive to more rapid digestion. Agitation aids in maintaining an alkaline condition by mixing the incoming fresh solids with a well-buffered mixture in the tank. Stirring serves also to break up scum and to keep solids surrounded with liquid, thus enhancing digestion.

In this investigation the contents of the large digestion tank, tank C, were continuously circulated by means of a centrifugal pump, as described on page 34, the rate of circulation being such as to turn over the contents of the tank once in about 1¾ hours. In the preliminary tests, in which small containers were used without continuous feeding, the contents of one set of bottles was stirred by turning the bottle over daily, without violent agitation of the contents. As this method of stirring was not found to be altogether satisfactory the stirring was accomplished in subsequent small-container investigations by means of violent shaking or with bent stirring-rods inserted in the container. The straight portion of the rod passed through a packed joint in the container and the rod was pulled vigorously back and forth in the tanks at frequent intervals. These stirrers are illustrated in Fig. 6.

5. *Dosing.*—Three different methods were used for the dosing of the Imhoff tanks: In the first series of tests the ground garbage was thrown into the inlet end of the flowing-through compartment. The second series tests were made by pushing batches of ground garbage deep into the digestion compartment of the tank. In the third series of tests the tank was fed by mixing the ground garbage with the incoming sewage and applying it slowly so that about 8 hours were required for the application of the charge.

In dosing the periodically-fed separate digestion tanks the charge of ground garbage was mixed intimately with the desired amount of fresh sludge, and the batch introduced into the digestion container at one time, thereafter being well mixed with the material already in the container. Those digestion containers which received their charge only at the start of the series of observations received the desired amount of an intimate mixture of garbage and sludge, except in one series of observations, in which a lump of ground garbage was immersed in sludge in the container and allowed to digest without mixing.

In one series of tests large undisintegrated organic objects were suspended in the sludge digestion compartments of the Imhoff tanks and of tank C.

6. *Source of Sludge.*—Fresh sludge was collected by allowing sewage to flow through tank D, a plain sedimentation tank, illustrated in Fig. 3. The sludge was removed 2 to 3 times weekly by hydrostatic pressure and pumped directly into the separate digestion tank.

7. *Fineness of Garbage Particles.*—Although the fineness of the particles of organic matter to be digested might be expected to affect the characteristics of the digestion process, no reports of tests on this factor have been found in the literature. The sizes of the particles of ground garbage used in this investigation, unless otherwise described in the text, are shown by the curves in Fig. 28. No attempt was made to use particles of a size different from that shown in Fig. 28, except in one series of tests on the rate of digestion of unground particles.

8. *Ratio of Garbage to Sewage Solids.*—The proportions of garbage to sewage solids in the digestion mixtures were ordinarily based upon the volatile solids present and not upon the total solids. The principal mixtures tested in the preliminary observations were in the following proportions by weight of volatile garbage solids to volatile sewage solids:

Per cent weight of volatile garbage solids....	100	80	60	40	20	0
Per cent weight of volatile sewage solids....	0	20	40	60	80	100

As it was not feasible to determine the volatile solids in the garbage and sludge before making the mixture it was customary to mix those total weights of fresh garbage and sludge which it was expected would give approximately the desired proportion of volatile solids of each kind in the mixture. The exact ratio was determined after the mixture had been made. It was thus possible to prepare the mixture and to commence observations on its digestion while the materials were still fresh.

On the basis of the average figures in North American cities, given in Table 32, it was assumed that the average daily per capita production of dry volatile garbage solids is about 0.11 pound, and of dry volatile sewage solids about 0.115 pound. These amounts of dry volatile garbage solids and dry volatile sewage solids have been used in translating digestion tank capacities to population loads.

TABLE 32
ASSUMED AVERAGE QUANTITIES AND QUALITIES OF GARBAGE AND SEWAGE SOLIDS PRODUCED IN NORTH AMERICAN CITIES PER CAPITA PER DAY

Sewage	100 gallons
Plain sedimentation sludge	3.3 pounds
Dry solids in sludge	5 per cent
Volatile solids in dry sludge	70 per cent
Garbage	½ pound
Dry solids in garbage	25 per cent
Volatile solids in dry garbage	90 per cent

The data in Table 32 indicate that approximately 2½ tons of wet garbage may be collected daily per million gallons of sewage produced, and that if all of the garbage thus collected is put into a separate digestion tank with all of the sludge collected by plain sedimentation from this sewage, the volatile garbage solids in the digestion tank will exceed the volatile sewage solids in the tank, in a ratio of about 1.4:1.

9. *Solids Concentration in Digestion Tank.*—The concentration of solids in a digestion tank, above a high limit, has been found to affect materially the characteristics of the digestion. Rudolfs[25] has set the upper limit as 15 per cent. In this investigation no attempt has been made to study or control the solids content of the digesting mixtures except in one series of tests devoted to the digestion of simple organic compounds. In general, the procedure has been to prepare mixtures in which the concentration of solids was well below the maximum permissible for good digestion and to make periodic observations of this factor. In some of the preliminary batch tests and in some tests in which an attempt was made to overload the digester, the concentration of solids exceeded this limit.

10. *Added Chemicals.*—The effect of chemicals on the process of sludge digestion has been studied by a number of investigators. Weldert[38] in 1910, Guth and Keim[39] in 1912, and Bach[40, 41] in 1912 and 1924 reported that sodium nitrate will shorten the time required for the digestion of fresh sewage solids. Schaetzle[42] in 1924 reported that the use of lime would aid in more rapid digestion of fresh sewage sludge. Fair and Carlson[43] in 1927 studied the effect of lime, marble dust, soda ash, caustic soda (sodium hydroxide), and dolomite on the rate of digestion, and reported that calcium carbonate and lime reduce digestion time. Rudolfs and associates[44, 45, 46, 47] investigated the effect of lime, sodium nitrate, sodium hydroxide, calcium hypo-

phosphate, calcium carbonate, and sodium thiosulphate. They found that lime and sodium nitrate caused more rapid digestion of sludge.

Chemicals were used in the experimental digestion of food wastes by Rudolfs and Heukelekian[4] in 1928, when they added lime to digesting mixtures of kitchen wastes and sewage sludge, and by Keefer and Kratz[48] in 1934 when they controlled the pH of their mixtures of garbage and sewage sludge with lime.

In this investigation a series of tests was made to determine the effect produced on digestion by the addition of lime, soda ash, and sodium hydroxide.

11. *Quality of Garbage.*—The dry volatile solids in the garbage used in this investigation represented approximately 95 per cent of the total solids. Since the garbage used in this investigation was richer in organic matter, because of its careful selection, then normal municipal garbage, it has been assumed that the loads on the test digesting equipment were greater than those to be found in normal practice, and the conclusions based upon these loads are, therefore, conservative.

Other investigators have made tests of the digestion of simple organic substances[20, 21, 49, 50] such as casein, starch, cellulose, etc. as well as peas, carrots, beans, meat, and other substances. These tests have been supplemented in this investigation by studies of the digestion of cellulose, sugar, starch, cotton seed oil, blood fibrin, and casein; and an attempt has been made to correlate the findings therefrom with the results found in the digestion of garbage.

12. *Quality of Sludge.*—Measurable characteristics of sludge which may affect digestion include: pH, per cent of total and volatile solids, B.O.D., fats, and nitrogen content. Other characteristics which may affect digestion include the presence of industrial wastes or similar substances, as well as the kind of sludge, such as fresh material from a sedimentation tank, well digested sludge, activated sludge, and chemically precipitated sludge.

In this investigation only fresh sludge collected by plain sedimentation was used in practically all of the tests, and the measurable characteristics listed were determined. No information has been developed, therefore, on the effect of different qualities of sludge on the digestion of garbage.

APPENDIX D

Measures of Digestion

1. *Sludge Digestion.*—The digestion of organic matter, as observed in these tests, involves physical and chemical changes brought about by biological action in the material. The principal physical indices of digestion are the ebullition of gas and changes in the texture, color, and odor of the sludge. Laboratory tests show a great variety of chemical and biological changes. Various attempts have been made to select quantitative measures, or parameters, which would indicate the progress and the nature of the digestion. The following laboratory tests were used in this investigation to aid in the control of the digestion and some were used as parameters thereof:

(1) Gas production, quantity and quality
(2) Solids, volatile and fixed
(3) B.O.D.
(4) Acidity and pH
(5) Volatile acids
(6) Grease
(7) Sludge characteristics
(8) Odor

2. *Quality of Gas.*—The principal gaseous products of the biolysis of organic matter are methane and carbon dioxide. These two gases normally form more than 95 per cent by volume of the gas evolved.

It was generally assumed that the higher the percentage of methane in the gas the better the quality of the digestion. This is not an invariable index, but it is of value as a rough measure of digestion. Buswell and Boruff[49] state that sour and foaming tanks produce less methane and greater percentages of carbon dioxide than normally operating tanks, and Rudolfs[45] reported low methane, high carbon dioxide, and high nitrogen for the first stage of digestion during which gasification had not attained a high rate. In a few of the routine observations only the quantity of carbon dioxide was determined, it being assumed that the difference between this and 95 per cent of the total volume of the sample indicated the percentage of methane present.

3. *Rate of Gas Production.*—The maximum amount of gas which can be produced by the digestion of sewage and garbage solids is in the neighborhood of 15 to 18 cu. ft. per pound of volatile solids digested.[49] The production of this amount of gas in any test was

assumed to indicate the completion of biologic digestion. The production of smaller amounts of gas was assumed to indicate incomplete or unsatisfactory digestion, dependent upon the percentage of methane produced.

Since gas is produced as a result of biological activity it was assumed in these tests that the rate of gas production was a direct measure of the rate of digestion. Observations of the amount of gas produced were made periodically, and the records were both tabulated and plotted graphically during the tests. They were considered to be the most valuable and precise parameters of the progress of digestion.

4. *Solids.*—The liquefaction and gasification of solids may be the principal objective in the addition of garbage and sewage sludge to a separate digestion tank. It is to be expected, therefore, that the establishment of a constant ratio between the solids in the tank and the solids added to the tank will indicate that constant conditions have been established in the tank for the particular rate of dosing. It has been assumed that only the volatile portion of the solids is gasified or liquefied. Hence, it is to be expected that a constant ratio of volatile and total solids will be reached when the tank is operating at its rated load.

Because of the importance of knowledge of the volatile and total solids contents of the digesting mixtures observations of these indices were made a routine procedure.

5. *Biochemical Oxygen Demand.*—The pollution load placed upon a sewage treatment plant or upon a natural stream may be measured, in part, by the biochemical oxygen demand (B.O.D.) of the material discharged into the plant or into the stream. Because of its wide use as a parameter of the amount of treatment required by sewage, the efficiency of the treatment given, and the volume of diluting water necessary to prevent putrefactive conditions in a stream, the B.O.D. was, in these tests, considered to be a valuable measure of successful performance by a digestion tank.

Routine observations were made of the 5-day, 20-degree B.O.D. and are reported in these terms. In a few cases in which other periods of incubation were found to be convenient, the results were converted to the 5-day basis, by Theriault's method.[32, 51]

6. *Acidity and pH.*—The pH value has generally been considered an important index of digestion; the optimum value being within one or two tenths of neutrality. It is generally to be expected that with

low pH values little digestion will occur, the carbon dioxide content of the gas evolved will be relatively high, and the odors of digestion will be offensive. Bach[24] stated that methane fermentation required a pH between 7.2 and 7.6. Fair and Carlson[43] found that the optimum pH increases during the course of digestion from an initial value of 6.8 to about 7.2. Heukelekian[52] has pointed out that in spite of the relatively low ionization of fatty acids resulting from the hydrolysis of insoluble organic substances such as fats, cellulose, some proteins, etc. they may accumulate in such quantities as to cause the pH to drop to as low as 5.9. The pH values were observed, therefore, in all tests as a routine procedure.

It was found possible, under certain circumstances, to have an alkaline reaction in the digestion containers as indicated by the pH tests, and also to have an appreciable concentration of volatile acids. The total acidity was measured occasionally but it was not used as a routine observation to aid in the control of the digestion.

7. *Volatile Acids.*—In the production of gas during the decomposition of organic solids there is first a combination with water to form the simpler organic acids such as acetic, propionic, etc. and these acids then decompose to give methane and carbon dioxide. Buswell states: "The limit of acidity for smooth continuous fermentation has been found for most materials to be about 2000 p.p.m. calculated as acetic."[23, 53] Routine observations have been made, therefore, to determine the volatile acids concentration in the digestion containers and to maintain concentrations below this limit.

8. *Grease.*—All material soluble in petroleum ether has been reported, in this investigation, as fats or grease. The grease content of garbage is an indicator of its possible value in garbage reduction processes, and is also an indicator of the probable scum-forming characteristics of the ground material when discharged into an Imhoff tank or separate sludge digestion tank. Many investigators have reported that grease digests readily.[54] Neave and Buswell[55] state: "1. In the acid type of sludge digestion, a rapid destruction of grease and calcium soaps occurs with the production of lower fatty acids. 2. Some of the lower fatty acid ferments further to give methane. . . . . 4. The rate of fermentation, as measured by gas production, is roughly proportional to the grease content of the solids, a scum high in grease content being the most vigorous gas producer." They reported also[56] "grease (soaps and fats) has been shown to be an important sludge component in that it digests to lower fatty acids,

methane, and carbon dioxide. The lower acids also have been shown to yield methane and carbon dioxide. Other studies . . . . show that 58 per cent of the total gas can be attributed to grease digestion."

Since, therefore, there is a rapid decomposition of grease in the normal process of sludge digestion the determination of the grease content of digesting solids should be a valuable measure of the rate of digestion. Observations of the grease content of garbages and sludges used and produced in these tests were made periodically, and are used in the interpretation of the results.

9. *Sludge Characteristics.*—The physical characteristics of well-digested sludges[57] which are comparatively easy to dry and to dispose of without nuisance include a relatively high solids content and a relatively high percentage of ash as compared with these constituents in poorly-digested sludge, a black color, a typical, inoffensive, garden-soil odor, and quick drainability. Desirable chemical characteristics include a pH value between 7.0 and 8.0, a high nitrogen content, and a low grease content. Observations were made of some or all of these characteristics where considered necessary for the interpretation of the results of a series of tests.

10. *Odor.*—Methane, carbon dioxide, nitrogen, and hydrogen are the principal gases given off by the biologic digestion of organic matter and all of these are odorless. Unsatisfactory conditions of digestion are indicated by the production of hydrogen sulphide, skatol, indol, mercaptans, and other substances, mere traces of which will impart intense, characteristic, highly offensive odors. The presence of these odors in the sludges or gases produced by digestion is probably the quickest and most easily found index of unsatisfactory digestion. Observations of odor were made as routine procedure in the progress of the tests.

APPENDIX E

Investigations of Biologic Digestion of Industrial Organic Wastes

Studies of the biological decomposition of industrial wastes have resulted in the publication of numerous reports during the past ten years. Morgan and Beck,[58] in 1928, reported their studies of the effect of the addition of brewers mash and other carbohydrate wastes on the operation of an activated sludge plant, and reference is made to studies by Scott[59] at Bury, Eng. on the effect of milk wastes, starch, brewer's yeast, and glucose added to activated sludge. Hatfield,[60] in 1930, as a result of a study of the disposal of beer slop, made the significant statement: "The digestion of sewage solids in 2-story Imhoff tanks, in separate sludge digestion compartments, by aeration, or by sprinkling filter, is easily disturbed by a change in the acidity of the medium or the introduction of organic matter which may change the character of the fermentations and oxidations taking place in the process." It is evident from this statement that an appreciation of some of the factors involved was beginning.

In 1931 Warrick[61] and Lanphear[62] of Wisconsin reported on the effect of certain industrial wastes, particularly pea-canning wastes, on municipal sewage treatment plants, and attempts at the biological treatment of creamery wastes have been reported by various investigators.[63, 64] In the same year Eldreidge and Mallman[65] reported upon the biological decomposition of strawboard wastes, and in 1935 Knechtges, Dawson, and Nichols[66] reported the results of experience on the digestion of packinghouse waste with sewage sludge.

Tests on the decomposition of organic substances were reported by Van Suchtelen[67] in 1931. Among his published reports are to be found the following statements:

". . . . anaerobically generated substances, such as wax, paraffin, oil, fat, peat, and wood are broken down predominantly in an aerobic way. Such substances possess a reduced oxygen content due to their mode of formation. Their relatively low density causes such substances to float at the surface of the water, where oxygen is available and an aerobic decomposition results. Substances which owe their existence more definitely to aerobic conditions such as oxygenated cellulose, starch, and glucose are susceptible primarily to anaerobic decomposition. After the oxygen in such compounds is reduced by biological action so that further transformations must cease, these materials and fermentation products may also rise to the surface of the liquid, where they are aerobically attacked and further broken down . . . . it may be possible to control the environment so that the biochemical decomposition will take place in the proper phase, either aerobic or anaerobic."

Buswell and associates have published extensively the results of investigations and studies on the biological stabilization of organic matter, with particular reference to the treatment of industrial wastes.[18, 34, 49, 53, 68, 69, 70, 71] In their work they have made tests on materials similar to domestic garbage under conditions similar to those in a sewage treatment plant receiving such wastes. They have reported on the extent of bacterial degradation, the quantity and quality of gases evolved, and the character of the resulting sludge. They have shown that sewage grease and soap are decomposed during the normal alkaline digestion of sewage sludge as well as during the acid phase.

Pearson and Buswell[72] state that acid sludge digestion is an undesirable condition where the purpose is the anaerobic stabilization of the organic solids, and that the sole aim of studies of such digestion should be directed towards its prevention and remedy.

Neave and Buswell[55] in drawing conclusions with respect to acid digestion, state: "1. In the acid type of sludge digestion a rapid destruction of grease and calcium soaps occurs with the production of lower fatty acids. 2. Some of the lower fatty acid ferments further to give methane. 3. Proteolysis is hindered by the low pH and, as a result, the sludge is not well digested. 4. The rate of fermentation, as measured by gas production, is roughly proportional to the grease content of the solids, a scum high in grease being the most vigorous gas producer. 5. Cellulose is believed to undergo little, if any, digestion during the ordinary sludge-digestion period."

Boruff and Buswell,[70] in a general discussion of the digestion of organic wastes, state: "Danok[73] suggests a pure culture method of decomposing such wastes. He states that the success of his method depends on the use of a sterile waste and a pure culture of specific bacteria. A British patent (284 267 Jan. 26, 1927) outlines a process for the aerobic or anaerobic decomposition of such wastes by the addition of butane-destroying organisms . . . . Hatfield[60] after studying the rate of settling and gasification of Commercial Solvent beer slop waste, reported that when diluted with 6 to 13 parts of sewage the solids were easily settled out . . . . that the sludge was readily settled with sewage solids and that it produced the same quantity and quality of gas as the organic matter in the sewage." In a discussion of the quantity and quality of gas which can be produced by the anaerobic decomposition of organic matter Boruff and Buswell[49] conclude that the quantity of gas and its methane content depend on the ratio of Carbon: Oxygen: Hydrogen: Nitrogen in the organic material being decomposed.

Sewage screenings are similar in character to garbage in that they consist of relatively fresh organic solids other than those found in human excrement. Some research has been pursued in the biologic digestion of such material and has been reported upon within the past five years.[53, 54, 74, 75, 76, 77, 78] Nishihara[79] reported, in 1935, on the digestion of human fecal matter with garbage with control of some of the conditions of digestion.

APPENDIX F

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