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THE MECHANICAL AERATION OF SEWAGE BY SHEFFIELD PADDLES AND BY AN ASPIRATOR

BY

HAROLD E. BABBITT



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HAROLD E. BABBITT
PROFESSOR OF SANITARY ENGINEERING

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THE MECHANICAL AERATION OF SEWAGE BY SHEFFIELD PADDLES AND BY AN ASPIRATOR

I. INTRODUCTION

1. *Object of Tests.*—Aeration of sewage is among the most promising methods of treatment for the production of a clear, colorless effluent, with little suspended solids, no settleable solids, and low biochemical oxygen demand. Methods of aeration of sewage to obtain such results include diffusion of air through porous media placed at the bottom of aeration tanks containing the sewage to be aerated, and various methods of mechanical agitation so that the surface of the sewage in contact with the atmosphere is broken and absorption of oxygen takes place. Many ingenious contrivances for mechanical agitation have been devised and are in use. Among these mechanical devices are the Sheffield Paddle aerator and aspirators.

The principal purpose of these tests was to measure the efficacy of the Sheffield Paddle aerator and to study aspirating devices for the purpose of aerating sewage in the activated sludge process of sewage treatment. An air diffusion aerator was used as a check upon some of the results obtained from the aspirator.

2. *Acknowledgments.*—The tests herein described were made partly as work of the Engineering Experiment Station of the University of Illinois, of which ACTING DEAN A. C. WILLARD is the Acting Director, and partly as work of the Department of Civil Engineering, of which PROF. W. C. HUNTINGTON is the head. Much of the work on the aspirator was done by members of the staff of the Engineering Experiment Station, as a cooperative research project, the greater part of the expenses of which were borne by Vogt Brothers Manufacturing Company of Louisville, Kentucky. The work on the Sheffield Paddles was performed by undergraduate students registered in the Department of Civil Engineering.

G. E. ATKINSON and S. W. WOODS did the experimental work in 1929 on the Sheffield Paddles.* Work on the investigation of an aspirator for the aeration of sewage was commenced on October 10, 1930. W. R. HILDERMAN and G. C. UNGER, JR., Graduate Research Assistants, conducted the tests from October, 1930 to July, 1931. After being discontinued for the summer, tests were resumed in Sep-

*"Aeration by Sheffield Paddles in the Activated Sludge Process of Sewage Treatment," G. E. Atkinson and S. W. Woods; Thesis for Degree of Bachelor of Science, University of Illinois, 1929.

tember, 1931, and continued until July, 1932, by G. C. UNGER and C. L. WATERBURY, a Graduate Research Assistant. Mr. Unger carried the work through the summer of 1932 until September when MAX SUTER, a graduate student, took up the task of performing the chemical and biological tests. Mr. Suter wrote a thesis entitled "Tests of a Sewage Aerator of the Aspirator Type." The thesis was completed in February, 1933. Mr. Unger alone operated the plant and made the laboratory tests from January until the close of the work on June 1, 1933. Much of the material in this bulletin on aeration by aspiration has been taken from Mr. Unger's thesis, entitled "The Mechanical Aeration of Sewage in the Activated Sludge Process."†

The members of the advisory board for the work done under a cooperative agreement with Vogt Brothers Manufacturing Company were SOREN THURSTENSEN, H. A. VAGTBORG, and H. A. ALLEN. Valuable advice and material assistance were given by these men in the conduct of the tests. Thanks are due ERNEST VOGT for his sustained active and financial assistance and his unflinching confidence which made the completion of the tests possible.

3. *History of Investigations.*—Success attained abroad, particularly in England and in Germany, by various methods of mechanical aeration as used in the activated sludge process of sewage treatment pointed to the possible adoption of such methods of sewage treatment in the United States, where practice was almost entirely confined to air-diffusion methods. The Sheffield Paddle system of aeration, devised by John Haworth, General Manager of the Sewage Disposal Works at Sheffield, England, was reported as giving satisfaction even though handling an industrial waste of considerable strength. The possibilities of the installation and testing of such a device at the University of Illinois became evident in the fall of 1927, resulting in the installation of the unit ultimately tested. Tests were started in the fall of 1928, and were completed in the spring of 1929.

On October 10, 1930, a contract was entered into between The Engineering Experiment Station and Vogt Brothers Manufacturing Co., of Louisville, Kentucky, for the conduct of a series of tests on the "Aeromix," an aspirating device for the aeration of water and the mixing of chemicals with water. It was the belief that this device might be found valuable in the activated sludge process of sewage treatment, and the tests were directed towards discovering its suitability therefor. Although the original contract called for only two

†"The Mechanical Aeration of Sewage in the Activated Sludge Process," G. C. Unger, Jr.; Thesis for Degree of Master of Science, University of Illinois, 1932.

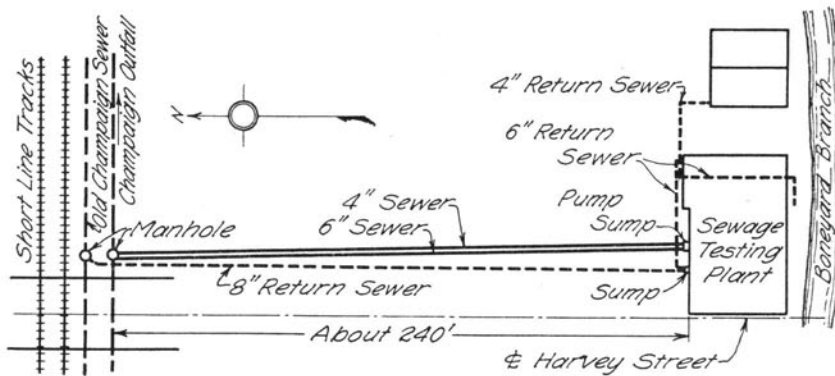


FIG. 1. ARRANGEMENT FOR OBTAINING SEWAGE FROM CHAMPAIGN OUTFALL SEWER

years of investigation, it was extended beyond that time so that the last tests were made in May 1933. The plant was shut down on May 31, 1933.

4. *Source of Sewage.*—The sewage upon which the investigations were made was obtained from the Champaign outfall sewer. This sewer, at the point where sewage is taken to supply the testing plant, parallels the tracks of the Illinois Terminal Railway. The sewage is carried from the outfall sewer to the testing plant, a distance of about 400 feet, through two vitrified clay pipes, from which it enters the main sump of the plant. The general plan of the arrangement for securing sewage for testing is shown in Fig. 1.

5. *Characteristics of Sewage.*—The Champaign city sewage is an ordinary domestic sewage, practically free from industrial wastes, and receiving large quantities of ground water in wet seasons. As a rule the strongest sewage reaches the plant between 10 a.m. and 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. Large amounts of debris, rags, vegetable and animal matter are present in the day sewage. Some typical analyses of Champaign sewage are given in Table 1.

6. *Fluctuations in Rate of Sewage Flow.*—In other tests of methods for the treatment of sewage made at this testing plant it has been customary to vary the rate of flow of sewage through the apparatus

TABLE 1
ANALYSES OF SEWAGE FROM CHAMPAIGN OUTFALL SEWER
Composite of 24 samples, collected hourly, October 23-24, 1929

	p.p.m.		p.p.m.
Free ammonia.....	20	Total Solids.....	736
Organic nitrogen.....	13.6	Suspended.....	91
Nitrites.....	0.2	Settleable.....	6 e.c.
Nitrates.....	0.1	Chlorides.....	70
Oxygen Consumed.....	204 (?)	Alkalinity.....	435
5-day, 20 deg. C. B.O.D.....	222		

Monthly Averages for 1928

Month	pH	Turbidity	Settling Solids ml. per l.	Suspended Matter Gooch	Oxygen Consumed 30 deg. C	Ammonia
March.....	...	200	5.0	193
April.....	7.6	189	3.6	160	84	12.4
May.....	...	150	4.6
June.....	...	189	3.4	176	74	...
July.....	7.6	126	3.7	209	94	...
August.....	...	180	4.5	205	109	6.0

approximately proportionally to the variations of rates of flow in the Champaign outfall sewer in order that field conditions might be simulated. Averages of the hourly variations in the flow of sewage in the Champaign outfall sewer were computed for twelve selected weeks by the State Water Survey and are shown in Table 2. These averages were used in computing the rates of flow used in other tests. In these tests the sewage was pumped through the tanks at a constant rate, the efficiency of the method of treatment being measured by a comparison of the quality of the influent and of the effluent as indicated by the analyses of grab samples.

7. *Distribution of Sewage Through Testing Plant.*—The plan of the Sewage Testing Plant is shown in Fig. 2. A low dam, built in a manhole in the Champaign outfall sewer, causes sewage to flow to the testing plant through 6-in. and 4-in. vitrified clay sewer pipes. The sump into which these two sewers discharge was made as small as possible, by means of partitions, so as to reduce to a minimum the settling of the sewage at this point. A 2-in. centrifugal pump, driven by a 5-h.p. induction motor, lifts the sewage to an influent control box from which raw sewage is fed to the various equipments in the plant. The details of the influent control box are shown in Fig. 3. A float in this box operates an automatic cut-out switch which causes all electric power in the building to be cut off in case the

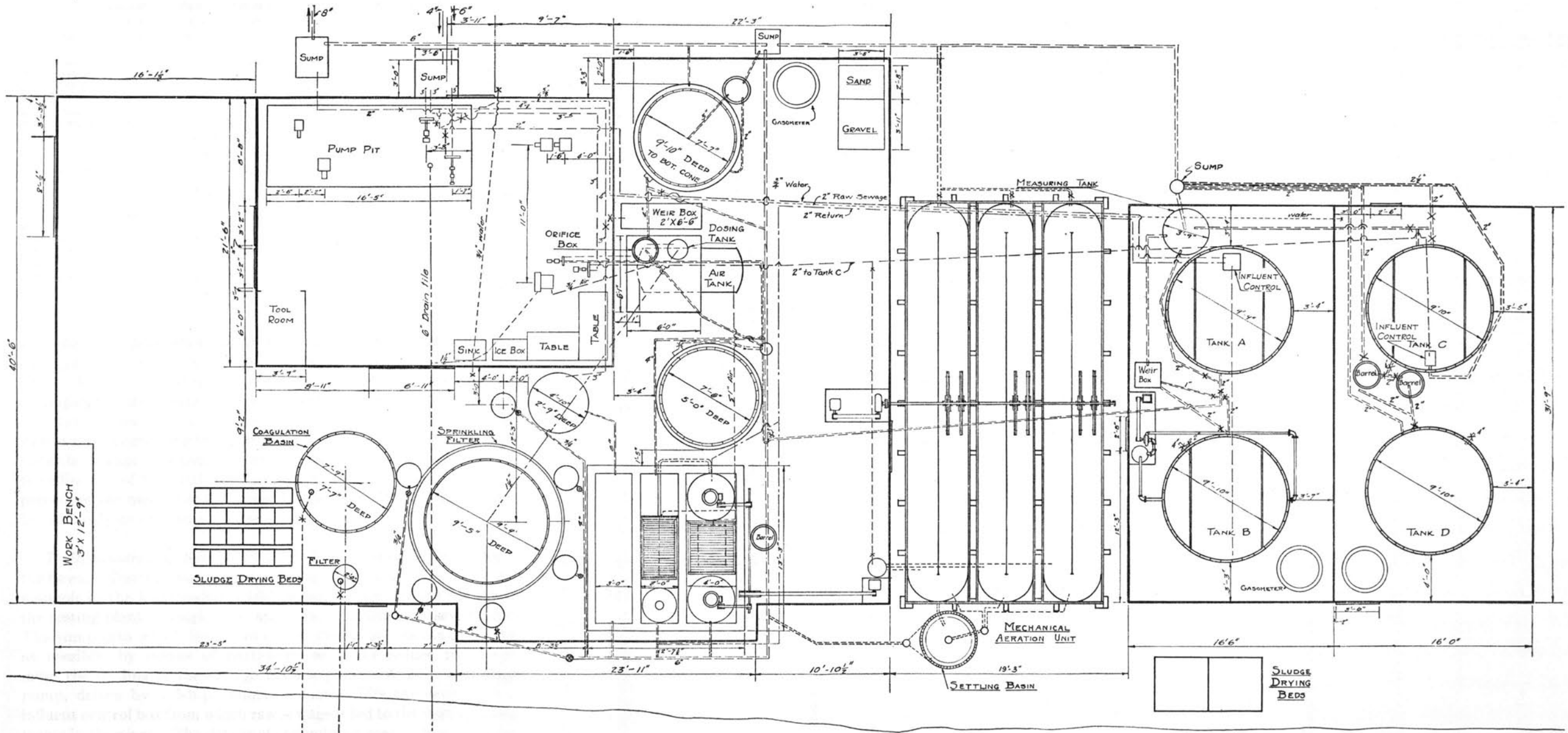


FIG. 2. GENERAL LAYOUT OF SEWAGE TESTING PLANT

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TABLE 2
WEEKLY AVERAGES OF HOURLY FLOW IN CHAMPAIGN OUTFALL SEWER
From Table VII, Bulletin 18, Illinois State Water Survey, 1920-1922
Unit rate given is 1,000 gal. per hour

Period	Week beginning														Average
	Jan. 1	Feb. 19	Mar. 21	May 16	June 6	June 25	July 20	Aug. 3	Aug. 16	Sept. 2	Nov. 17	Dec. 7			
A.M.															
8.30-9.30.....	49.0	52.5	80.5	62.5	67.5	43.5	36.5	37.0	35.0	62.5	88.0	73.0	57.3		
9.30-10.30.....	58.5	59.5	83.0	70.5	72.5	50.0	44.0	40.0	43.5	62.5	91.5	79.0	63.0		
10.30-11.30.....	58.5	60.0	84.0	70.0	73.5	50.0	46.0	49.0	49.0	62.5	91.5	82.5	64.0		
11.30-12.30.....	59.0	58.5	84.0	68.0	74.0	50.0	43.0	46.5	46.0	60.0	90.5	82.0	63.6		
P.M.															
12.30-1.30.....	57.0	58.0	83.0	67.0	75.5	49.0	44.5	43.5	43.0	57.5	89.0	81.0	62.3		
1.30-2.30.....	56.0	55.0	83.5	64.0	70.5	44.5	42.0	43.0	40.0	57.0	87.5	82.0	60.2		
2.30-3.30.....	58.0	57.5	82.5	64.5	71.0	43.5	45.0	42.0	39.0	56.0	87.0	82.5	60.4		
3.30-4.30.....	56.5	56.0	81.5	64.5	71.0	49.0	45.0	42.0	38.5	54.5	86.0	81.0	60.9		
4.30-5.30.....	56.5	54.0	81.5	62.5	67.0	48.0	44.0	41.5	38.0	53.0	85.5	79.0	59.2		
5.30-6.30.....	55.0	53.0	81.0	62.0	67.0	48.0	41.0	41.5	37.5	51.0	83.5	78.5	57.8		
6.30-7.30.....	53.5	53.0	81.0	62.0	63.0	43.0	36.5	39.0	34.5	48.0	83.5	80.0	56.7		
7.30-8.30.....	53.0	47.5	77.5	58.5	59.5	37.5	36.0	38.0	31.5	48.0	82.0	79.5	53.7		
8.30-9.30.....	53.0	47.5	77.5	58.5	59.5	37.5	34.5	36.0	29.5	46.5	82.0	79.5	53.0		
9.30-10.30.....	51.5	46.5	73.5	53.0	53.5	37.5	33.5	34.0	28.0	43.5	82.5	78.5	51.7		
10.30-11.30.....	46.0	44.0	74.5	46.0	51.6	34.0	30.0	31.0	26.0	42.5	82.5	76.5	48.7		
11.30-12.30.....	44.0	43.0	73.5	43.0	51.0	33.0	27.5	28.5	24.5	40.5	82.5	76.0	47.4		
A.M.															
12.30-1.30.....	42.5	41.0	73.5	36.0	49.5	30.5	24.0	27.0	22.0	38.5	81.0	75.0	45.0		
1.30-2.30.....	36.0	37.0	71.5	33.0	46.5	27.5	23.5	24.0	20.0	37.5	80.5	71.0	42.3		
2.30-3.30.....	32.5	33.0	70.0	33.0	43.5	25.5	21.5	21.5	19.5	36.5	80.0	68.5	40.4		
3.30-4.30.....	30.0	29.0	70.0	33.0	42.5	23.5	20.0	20.0	18.5	38.5	79.0	63.5	38.5		
4.30-5.30.....	29.5	28.5	69.5	33.0	40.5	22.0	19.5	20.5	17.5	44.5	79.0	63.0	39.9		
5.30-6.30.....	29.0	28.5	74.5	37.5	40.0	21.0	18.5	21.5	16.5	46.0	79.0	68.0	39.8		
6.30-7.30.....	31.0	31.0	74.5	36.5	42.0	20.5	18.0	21.0	15.0	48.0	82.0	63.5	41.1		
7.30-8.30.....	32.0	39.0	78.0	41.0	51.0	33.5	24.5	22.0	28.0	56.0	84.5	60.5	43.8		

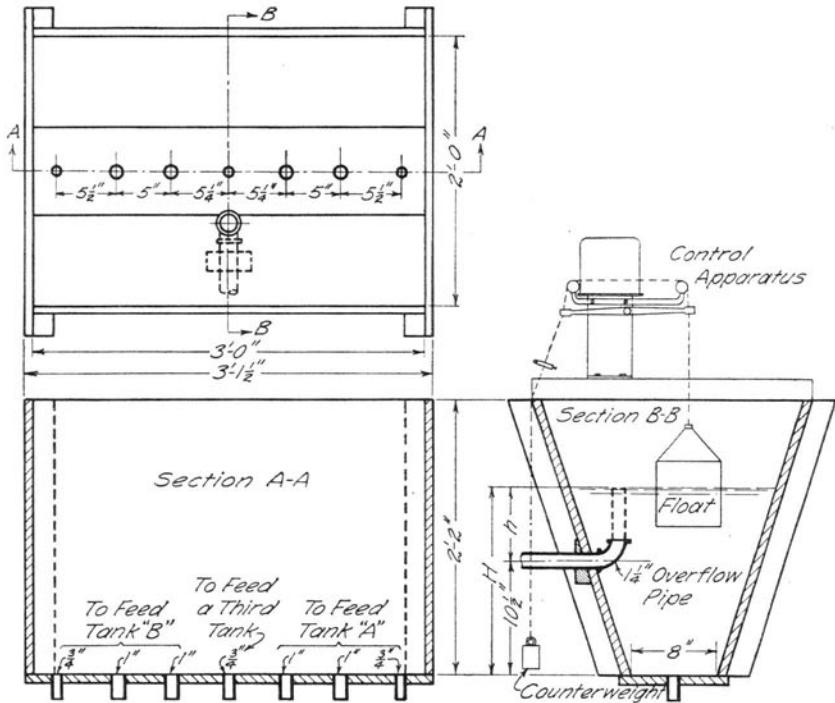


FIG. 3. DETAILS OF INFLUENT CONTROL BOX

flow of sewage stops. This installation prevents wear on the pumps, or freezing of exposed parts of the equipment in cold weather, which would result from continued operation of the pumps without sewage.

The flow of sewage to the influent box occasionally stopped from one cause or another. Numerous devices were used for the purpose of recording the exact time that this occurred during the night when no one was on duty at the plant. The most successful device for this purpose was a Foxboro water level recorder which operated in the influent control box shown in Fig. 3.

The rate of flow of sewage through any one of the Sheffield Paddle tanks could be measured by diverting the outflow from the control box to a large calibrated measuring tank. The rate of flow of sewage to the aspirator tank or to tank B, shown on Fig. 2, which was used as a preliminary settling tank for settling the sewage before treatment in some of the tests, was controlled by means of a box, similar to that shown in Fig. 3, located about two feet higher than the top of both tanks A and B. Sewage was pumped from the outlet of the influent

control box to the control box on top of the tanks at a slightly greater rate than was required for the particular test in hand. A result was that there was a constant flow over the waste weir in the secondary control box. The waste flow over this weir was returned to the Champaign outfall sewer.

Only a general description of the method of taking sewage from the Champaign outfall sewer and distributing it to the testing apparatus is given in this section because of changes and additions made during the tests. Details of these changes and the method of handling the sewage in the testing devices are given in connection with the description of the individual tests. After passing through the testing plant all sewage is returned to the Champaign outfall sewer by means of an 8-in. vitrified clay pipe.

II. AERATION BY SHEFFIELD PADDLES

8. *The Sheffield System.*—

(a) Sewage Treatment Plant at Sheffield, England

The Sheffield System of aerating sewage with paddle wheels was developed by John Haworth, General Manager, Sewage Disposal Department, Sheffield, England. Aeration of sewage with compressed air was tried at Sheffield in early experiments that were started in 1912. Adequate oxidation was secured, but considerable trouble was experienced with clogging of air-distributing devices. This trouble led to an attempt to separate the two functions performed by compressed air, namely, to supply oxygen for the maintenance of biologic life, and to carry out mechanical mixing of the sewage.

It was found that mechanical agitation of sewage in tanks open to the atmosphere produced results similar to those obtained by the use of compressed air.*

After three years of operation on the fill-and-draw system, a plant for operation on the continuous-flow principle was started for test purposes. About 40 tons of sewage sludge and humus were thrown into the tank with the sewage and the contents were circulated for 21 days before sewage was admitted continuously. This plant, which is still in use, consists of an aeration tank, three detention chambers, three settling tanks, and a motor house.

The aeration tank is 201 ft. 6 in. long, 76 ft. wide, and 4 ft. deep below the water surface. Its capacity is 354 000 gallons and it has

*"The Sheffield Activated Sludge Experiments," John Haworth, *Engineering and Contracting*, Nov. 30, 1931, Vol. 56.

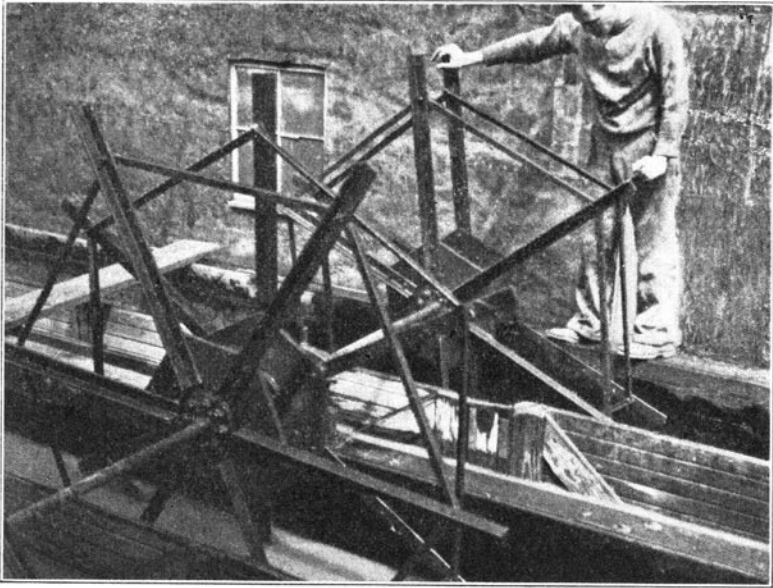


FIG. 4. SHEFFIELD PADDLE WHEELS TESTED AT UNIVERSITY OF ILLINOIS

successfully treated 600 000 gallons of sewage daily. Walls divide the tank into 18 channels, each 4 ft. wide, with a transverse channel 2 ft. 3 in. wide by 6 in. deep along the end facing the retention chambers. The channels are rounded and connected at their ends to form one continuous channel 3,544 ft. long. The transverse channel has been made deeper than the longitudinal channels in order to provide for retention chambers of increased size.

The ends of the division walls forming the return of the channels are enlarged in order to strengthen the division walls, to reduce the eddies in the sewage flowing around the division walls, and correspondingly the losses in velocity due to the eddies, and to aid the action of the paddles in turning over the tank contents to expose constantly-changing surfaces of sewage to the atmosphere. The aeration tank has a flat bottom. Aerated liquor flows from the tank over a weir which extends the full length of the transverse channel and forms one side of the retention chamber.

Typical Sheffield paddle wheels are shown in Fig. 4. Each wheel is constructed of light steel angles suitably braced and connected to cast iron split bosses which are bolted and keyed to the shafts. Each

wheel used at Sheffield weighs about 700 pounds. There are eight arms to each wheel, and each arm presents to the sewage a contact surface of 227 square inches.

With the paddle wheels turning at 15 r.p.m., a minimum channel velocity of 1.7 ft. per sec. is maintained. It was found by experiment that paddle-wheel speeds of less than 13 r.p.m. produced wave effects that resulted in undesirable splashing at the channel ends, regardless of whether the blade area was increased or not.

The retention chambers help to retain sludge in the aeration tank by partial settling out of sludge from the liquid before it passes to the settling tanks. These chambers are 4 ft. 3 in. wide and 4 ft. 3 in. deep, and correspond in length with the width of the aeration tank. The wall adjoining the aeration tank is vertical, and the opposite wall is sloping. The top of the opposite wall serves as a weir over which the liquid discharges into the feed channel to the settling tanks.

Three Dortmund type tanks are employed for settling following aeration. They are pyramidal in shape with the sides sloping one horizontal to one-and-a-half vertical. Each tank is 24 ft. square by 21 ft. 6 in. deep, and the combined capacity of the tanks is 102 000 gallons. The aerated liquor enters each tank through a 12-in. pipe which connects to a bottomless box 4 ft. square inside. This box is submerged in the liquid 7 ft. of its height, acting as a stilling basin. The four walls of each tank form the weir over which the effluent passes to the collecting channels, or direct to the gaging chamber, where the flow is measured by a Lea recorder. From this chamber the effluent empties into a discharge culvert leading to the river.

Sludge from the settling tanks is raised by hydrostatic pressure through 6-in. pipes into small sludge chambers in which the control valves are located. Two small pipes fitted with valves are in each of the sludge chambers. By means of these valves the operator can check at any time the level of the sludge in the tanks. The sludge flows by gravity from the sludge chambers through a stoneware drain to the sludge well below the motor house, whence it is pumped back to the aeration tank by two 4-in. centrifugal pumps, each coupled to a 7.5-h.p. motor. A recorder measures the amount of sludge pumped. There is a by-pass valve on the sludge main near the pump house through which surplus sludge can be drained from the system and permitted to flow upon the land.

The following conclusions were drawn at the end of a series of tests on operation at Sheffield:

- (1) In any satisfactory plant the small orifices used in air diffusion must be eliminated to avoid clogging.
- (2) It is not essential that the air be supplied in small bubbles.
- (3) The greater part of the oxygen introduced into sewage is absorbed at the surface of the liquid.
- (4) It is more economical to produce surface agitation with paddle wheels or screws than with diffused air.

The plant which has just been described was put into regular operation in November, 1921. The sludge in the aeration tank was maintained at between 25 and 30 per cent of the tank liquor. One series of tests on the effluent gave a 5-day biochemical oxygen demand ranging between 8.4 and 27.2 p.p.m., with an average of 14.2 p.p.m.,* the incubation being at 65 deg. F. Haworth estimates the cost of installation at \$125 000 to \$150 000 per million Imperial gallons, and the operating cost at about \$15.00 per million Imperial gallons treated. The total cost of maintenance of the paddle wheels was less than \$10.00 during the six years of service.

In 1927 seven mechanical aeration units with 29 to 27 channels, having an average total length of 5 540 feet, were in operation. Nine secondary settling tanks were provided for each aeration unit. The population of Sheffield in 1927 was 540 000 persons, and the normal sewage flow carried between about 16 and 20 million gallons per day, being a combination of domestic sewage and industrial sewage containing a large amount of iron. The activated sludge plant handled 9 300 000 gallons per day, and the rest of the flow was treated on sand filters. The effluent from the activated sludge plant for 1927 had an oxygen consumed figure of from 5 to 18.9 p.p.m., with an average of 9.8 p.p.m. The return sludge varied between 15 and 20 per cent of the sewage flow.†

(b) Sewage Treatment Plant at East Ham, England‡

The sewage treatment plant at East Ham, England, was built in 1923 to handle 550 000 gallons per day. Sheffield paddle wheels are used to secure aeration. The sewage passes through two detritus tanks preliminary to settling.

The aeration tank is 234 ft. 6 in. long, 62 ft. wide, and 5 ft. 3 in. deep, containing fourteen longitudinal channels arranged with alternate open ends to form one continuous channel about two-thirds of a mile in length with a width of 4 ft. 3 in.

*Parts per million.

†Metcalf and Eddy, "Sewerage and Sewage Disposal," McGraw-Hill, 1930.

‡"The East Ham Bio-Aeration Sewage Treatment Plant," The Surveyor, June 1, 1923, and May 30, 1924.

TABLE 3
DEGREE OF PURIFICATION OBTAINED AT EAST HAM, ENGLAND

Date	Time	Crude Sewage			Bio-Aeration Effluent		
		Albuminoid Ammonia p.p.m.	Oxygen Consumed in 4 hrs. at 80 deg. F. p.p.m.	Suspended Solids p.p.m.	Albuminoid Ammonia p.p.m.	Oxygen Consumed in 4 hrs. at 80 deg. F. p.p.m.	Suspended Solids p.p.m.
Sept. 18. . . .	10.00 a.m.	18.8	145	500	3.0	18.8	15
Sept. 25. . . .	11.00 p.m.	11.0	50	250	1.9	17.0	15
Oct. 1.	11.00 p.m.	8.4	137	300	1.5	17.0	15
Oct. 2.	11.00 a.m.	13.0	140	490	2.2	18.0	15

Fourteen paddle wheels agitate the sewage and propel it along the channel. Each paddle wheel is 11 ft. in diameter and revolves at a rate of 12.5 r.p.m. There are two shafts revolving in opposite directions, to each of which seven paddles are attached. Each shaft is driven by a 25-h.p. motor through a gear reducer. It is estimated that 33 horsepower is required per million gallons of sewage treated daily.

Some trouble in aeration has been experienced at the East Ham sewage treatment plant on account of the varying strength of the sewage. When the oxygen-consumed figure is not more than 150 p.p.m., 400 000 gallons can be readily oxidized, but when the oxygen-consumed figure is more than 150 p.p.m. the flow must be correspondingly reduced. Table 3 gives an idea of the degree of purification obtained at this plant. Quantities are given in parts per million.

9. *The Sheffield Apparatus at University of Illinois.*—Three wooden aeration tanks, each 32 ft. long, 4 ft. wide, and 5 ft. 3 in. deep were constructed immediately east of the main building of the University sewage-testing plant. Each tank was divided by a longitudinal baffle into two flowing-through channels, each two feet wide. The tanks could be so connected that the total length of flowing-through channel was 192 ft. The baffles terminated 30 in. from the end of each tank so that the velocity of flow, and hence the loss of head in making the turn, might be minimized. The arrangement of the tanks is illustrated in Figs. 2 and 5.

Sewage was discharged into the tanks, at any desired rate, from an inflow weir box. As the sewage entered the aeration tank it was mixed with a controlled portion of activated sludge taken from the sedimentation tank. The sewage was kept in circulation in the aeration tanks by means of a paddle wheel whose depth of

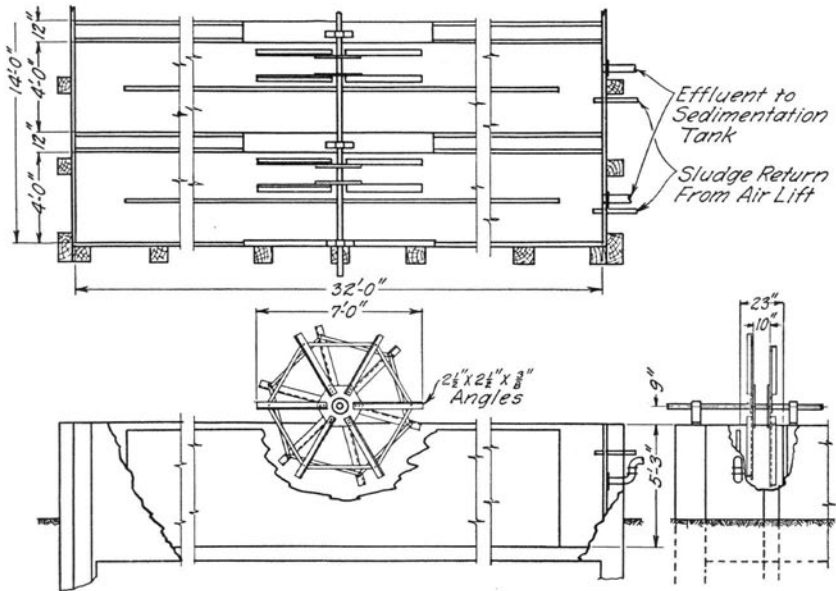


FIG. 5. SHEFFIELD PADDLE WHEELS TESTED AT UNIVERSITY OF ILLINOIS

submergence and rate of revolution were controllable within the mechanical limits of the equipment.

The paddle wheels used were 7 feet in diameter and 15 inches wide overall. They were constructed of $2\frac{1}{2} \times 2\frac{1}{2} \times \frac{1}{2}$ -in. standard steel angles. Some details of the construction of one wheel are illustrated in Fig. 5. Each paddle wheel had two sets of six blades. The ends of the blades on one side of the wheel did not come opposite the ends on the other side of the wheel. The object of the staggering of the ends of the angles was to avoid the creation of surging waves in the aeration tank. Only one channel in each of the aeration tanks was provided with a paddle.

The sedimentation tanks were so arranged that the sewage could be forced to flow through them in series, that is, the effluent from one tank became the influent to the next tank, or they could be operated in parallel, that is, each tank might receive raw sewage as an influent. Sewage passed from the aeration tanks into the sedimentation tank where sludge settled to the bottom. The sludge was returned to the aeration tanks by means of an air lift pump. The effluent from the sedimentation tank is the final treated product from the process which, in routine operation, would be ready for discharge into the

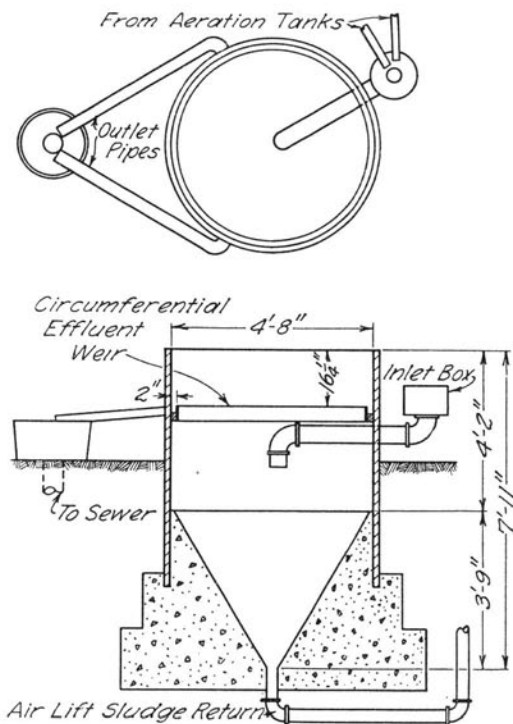


FIG. 6. DETAILS OF SEDIMENTATION TANK USED IN TESTS ON SHEFFIELD PADDLES

stream. Some of the details of the final sedimentation tank are illustrated in Fig. 6.

10. *Factors and Variables.*—The conditions affecting the results of these tests include the following:

- (a) Period of aeration
- (b) Depth of flow in the aeration tank
- (c) Rate of revolution of the paddles
- (d) Depth of submergence of the paddles
- (e) Quantity of return sludge
- (f) Period of secondary sedimentation
- (g) Characteristics of the influent sewage
- (h) Temperature of the atmosphere.

The first six conditions listed are controllable, within the limits of the apparatus, although some of the conditions are interdependent,

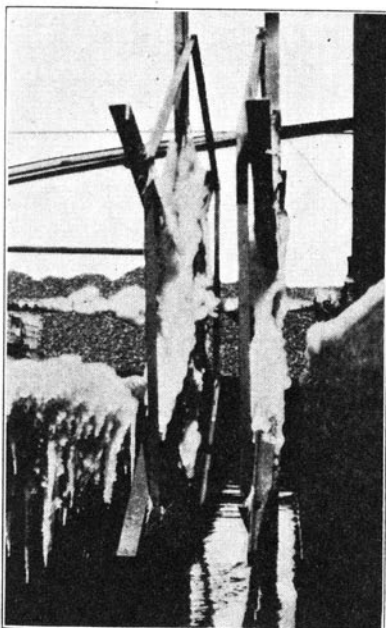


FIG. 7. UNPROTECTED PADDLE WHEEL IN SLIGHTLY FROSTY WEATHER

such as the depth of flow in the aeration tank and the depth of submergence of the paddles. The last two conditions in the list are not within the control of the operator, but tests could be made at favorable times when the sewage was stronger or weaker than normal, or the atmosphere was warmer or cooler than at other times.

Observations were made only on the following which were affected by variations of the preceding conditions:

- (a) Dissolved oxygen in the effluent from the aeration tank and in the effluent from the final sedimentation tank
- (b) Biochemical oxygen demand in the raw sewage and in the effluent from the final sedimentation tank
- (c) Power consumption to drive the paddles.

The conclusions drawn were based upon a study of the results obtained by the variation of the controllable conditions.

11. *Operating Conditions.*—The aeration tanks were filled with sewage and the paddles set in motion for the first time on March 6, 1929. Difficulty was immediately experienced from the formation of

TABLE 4
 CONDITIONS AND RESULTS OF TESTS ON SHEFFIELD PADDLES AT
 UNIVERSITY OF ILLINOIS

Condition Number	Retention Period		Depth of Flow in.	Paddle Wheel Submergence in.	Velocity at Surface ft. per min.	
	hrs.	min.			Computed	Observed
1	6	23	53	23	0.18	36
2	18	30	48	18	0.12	13.8
3	14	27	48	18	0.15	13.8
Condition Number	Return Sludge per cent		Sedimentation Period min.	Power Consumption h.p. per mil. gal.	Number of Wheels In Use	
1	5.1		51	39.6	1	
2	8.2		79	123.4	2	
3	8.6		62	96.5	2	
Condition Number	B.O.D. p.p.m.		Dissolved Oxygen p.p.m.		Paddle Wheels r.p.m.	Capacity of Sedimenta- tion Tank gal.
	Influent	Effluent	Aeration Tank	Sedimenta- tion Tank		
1	183.8*	30.2*	3.1*	3.7*	18	567
2	175.3†	15.8†	3.4	5.0	18	567
3	163.3‡	13.4‡	2.2‡	2.7‡	19	567

*Average of 10 runs.

†Average of 12 runs.

‡Average of 8 runs.

ice on the paddles, even though the temperature of the atmosphere was approximately at freezing point. The condition of the paddles during slightly frosty weather is illustrated in Fig. 7. The difficulty arose from contact between ice on the wheels and ice on the sides of the tank, resulting in the development of sufficient friction to prevent the movement of the paddles.

When satisfactory conditions of air and sewage temperatures had been reached tests under the first of the three different conditions of controlled operation under which the tests were conducted were commenced. The details of these three conditions are given in Table 4. It is to be seen from the information in this table that among the principal conditions which have been controlled there are three different periods of aeration, two different depths of flow in the aeration tank, two different depths of submergence of the paddles, and three slightly different periods of sedimentation in the final sedimentation tank.

12. *Observations.*—A very noticeable amount of light grey flocculent sludge appeared within twelve hours after the commencement of the aeration of sewage without the necessity of seeding the tanks.

TABLE 5
POWER CONSUMED AND VELOCITIES INDUCED BY SHEFFIELD PADDLES

Depth of Submergence of Paddles in.	Depth of Sewage in Tank in.	Horse Power Required to Drive the Paddles	Horse Power Required with Frictionless Paddles	Velocities of Flow ft. per sec.		
				Bottom	Center	Top
23	53	1.61	0.93	0.48	0.51	0.60
18	48	1.57	0.89	0.82	0.83	0.23
15	45	1.41	0.73	0.77	0.63	0.20
12	42	1.21	0.53	0.45	0.59	0.42
9	39	1.025	0.341	0.50	0.45	0.50
6	36	0.785	0.101	0.25	0.22	0.18
0	30	0.684	0.000	0.00	0.00	0.00

Sludge built up rapidly, and its quality improved, as indicated by the observations of its color, its settling properties, and the clarity of the effluent from the sedimentation tank. Quantitative measurements were made only of dissolved oxygen, biochemical oxygen demand, and power consumption. The results of these measurements are recorded in Table 4.

Observations were also made on the amount of power used to drive the paddles and the velocities of flow in the aeration tank at various depths of submergence for the purpose of finding the most desirable depth for the operation of the paddles and the effect of this depth on the power consumption. A watt-hour meter was used to measure the power consumed and submerged floats were used to measure velocities at various depths. Results of these tests are given in Table 5.

Although the field covered by these investigations is restricted by the relatively small number of quantitative measurements made, it is concluded as a result of these studies that domestic sewage, of a quality similar to that in the Champaign outfall sewer, can be treated successfully by the Sheffield System using a period of aeration of $6\frac{1}{2}$ hours followed by a period of one hour in the final sedimentation tank. This can be done by using paddle wheels of a design similar to that shown in Fig. 5, revolving at a rate of 18 r.p.m., with a submergence of 23 inches, in a depth of sewage of 53 inches, and a volume of return sludge equal to 5 per cent of the total volume of the sewage being treated. Such a method of treatment will reduce the biochemical oxygen demand by 85 per cent, with a rate of power consumption of 960 horse-power-hours per million gallons of sewage treated. This is equivalent to a rate of 40 h.p. per million gallons of sewage treated daily.

It is evident, from observations made of the behavior of the apparatus during the tests, that the power consumption can be reduced, without diminishing the effectiveness of the treatment, by decreasing the submergence of the paddles, and increasing the efficiency of the mechanical drive. The measurements recorded in Table 5 indicate the possibility of decreasing the paddle submergence to 9 inches, ample agitation being still maintained, using 648 horse-power-hours per million gallons of sewage treated. This is equivalent to 27 h.p. per million gallons of sewage treated daily.

Difficulties with ice forming on the paddle wheels and on the sides of the aeration tanks demonstrate conclusively the need for covering the paddles, while in operation, to protect them from the effect of frost which causes light spray to congeal on the paddles and on the sides of the aeration tank. Successful operation of similar devices in rigorous climates has demonstrated the feasibility of this method of overcoming the difficulty.

It is interesting to note, from the data in Table 5, that the power consumption varies about as the $\frac{2}{3}$ power or the $\frac{3}{4}$ power of the depth of submergence of the paddles above a depth of about nine inches, and that the velocities of flow of the mixed liquor at various depths in the tank are apparently unaffected by the depth of submergence of the paddles, provided the depth is greater than about nine inches. Since the data presented in Table 4 are based on a submergence of 23 inches, the power consumption for a 9-inch submergence and a 6-hour retention period would be at the rate of about 20 h.p. per million gallons of sewage treated per day, with a resulting percentage reduction of biochemical oxygen demand of eighty or more.

III. AERATION BY ASPIRATION

13. *Principles of Aspiration.*—When water flows rapidly through a conduit in which there is a constriction the pressure at the constriction is less than that in the portion of the conduit above the constriction. If the pressure in the conduit above the constriction is atmospheric or only slightly above atmospheric, then the pressure in the constricted portion will be less than atmospheric. This condition can be formulated, by an application of Bernoulli's theorem, into the familiar expression for the rate of flow through a Venturi tube. It is

$$Q = C \frac{\pi D_c^2 D_t^2}{4(D_c^4 - D_t^4)^{\frac{1}{2}}} (2gh)^{\frac{1}{2}}$$

in which Q = the rate of flow through the conduit

C = the coefficient of discharge through the conduit

D_o = the diameter of the conduit

D_t = the diameter of the throat

g = the acceleration due to gravity

h = the difference in pressure in the conduit and in the throat.

If the pressure in the conduit above the throat or constriction is approximately atmospheric, and an open tube is connected with the throat of the Venturi tube, since the pressure in the throat is less than atmospheric, air will be drawn into the throat through the inserted tube. If water is allowed to fall vertically through a pipe and to discharge freely from the lower end of the pipe a suction will be created in the upper portion of the vertical pipe.* The conditions in an aspirator aerator, such as the Taylor air compressor, placed at the upper end of a vertical pipe and designed with a constricted throat, combine the effects of flow through a Venturi tube and that through a vertical tube. The amount of air induced to flow into such an aspirator aerator will depend upon a combination of some or all of the following factors:

- (a) Rate of flow through the device
- (b) Velocity of flow past the constricted section
- (c) Distance of fall in the downdraft tube
- (d) Area of the constricted section
- (e) Area of the conduit above the constricted section
- (f) Area of the conduit below the constricted section

The action in a Venturi tube and in the flow of water down a vertical pipe combine to produce the results of an aspirator aerator as used in this investigation.

If the height of water above the constricted portion of an aspirator is increased the velocity of flow through the aspirator will be increased. The intensity of vacuum may not be increased, however, since the decrease in pressure at the constriction, due to increased velocity, may be less than the increase in pressure at the constriction due to increased height of water pushing the water through the constriction. In all aspirating devices, there is, therefore, an optimum flow for which they have been designed, above and below which the amount of air drawn in will decrease.

Aspirator devices, depending on these principles, have been known for many centuries, one of the earliest types being known as a

*"Tests on the Hydraulics and Pneumatics of House Plumbing," Univ. of Ill. Eng. Expt. Sta. Bul. 143, 1924.

"trompe." "One of the oldest forms of compressing air is by means of a trompe, a device of historic interest, in which water was led from a higher to a lower level through a pipe or bamboo pole with openings in the side through which air entered and mingled with the descending water and was later trapped from it."* The well-known Taylor compressor, depending on these principles, was among the first to introduce the plan of dividing the air inlets into a great number of small openings evenly distributed over the area of the water inlet. Air compressors of this type, known as hydraulic compressors, have been used for power developments,*† for the aeration of water,‡ for mixing chemicals with water in water purification plants‡ and for the aeration of sewage.¶

The type of bubble, and the intimacy of the mixture of the air and the flowing water are dependent upon the size and shape of the orifice which admits the air to the water. It is possible, by proper design of the orifices, to produce a small bubble and an intimate mixture which approaches the characteristics of an emulsion.

14. *Aspirating Devices for Sewage Aeration.*—Devices for the aeration of sewage by aspiration have been installed in recent years in a few small sewage-treatment plants and aeration of sewage by means of an aspirator is being investigated by the American Well Works in Aurora, Illinois. No data on the results of the tests at Aurora have been published. Watsco aerators have been installed in various places in California.§

15. *The Watsco Aerator at Montezuma School, California.*—The information in this section was taken from a report of tests by J. L. Mason, published in "Western Construction News."§

The Watsco Sewage Aerator, which operates submerged, is composed of a vertical Venturi tube with a piezometer ring attached at the throat; air pipes extend from this ring above the surface of the sewage in the tank. A semi-displacement screw pump mounted above the Venturi tube, forces the sewage downwards through the tube, causing

*Thorkelson, H. J. "Air Compression and Transmission," p. 129, 1913.
 J. P. Frizell. "Compressed Air in the Direct Application of Water," Jour. Frank Inst., Vol. 110, p. 45, 1880.
 †Harris, E. G. "Compressed Air," p. 43, 1910.
 Hiscox, G. D. "Compressed Air and Its Applications," 1901.
 "The Hydraulic Compressed Air Power Plant at the Victoria Mine," Eng. and Min. Jour., Vol. 83, p. 125, Jan. 19, 1907.
 "Choosing Air Compressors for Activated Sludge Tanks," C. H. Nordell, Eng. News, Vol. 74, p. 904, Nov. 4, 1915.
 ‡"Aeromix Results at Western Springs, Illinois," Water Works and Sewerage, p. 107, March, 1933.
 "Water Purification Aeration at Waukegan, Illinois," American City, p. 111, October, 1930.
 ¶"Watsco Sewage Aerator at Montezuma School, California," J. L. Mason, West. Const. News, p. 523, October 10, 1929.
 "The Treatment and Disposal of Sewage from a Small Installation," Water Works and Sewerage, September, 1931.
 §Ibid.

a high velocity at the throat with pressure that is below atmospheric. Air is then drawn into the sewage at the throat through holes in the piezometer ring. The mixture of sewage and air passes downward, through what Mason calls a velocity recovery and mixing tube, and is discharged from the diffuser bell at the end of the tube.

The aerator unit tested at the Montezuma School is the standard Watsco unit, with a flow of 1500 gal. per min., drawing in 42 cu. ft. per min. of air, that is, one cubic foot of air is drawn in for each five cubic feet of sewage recirculated. The proportion of air drawn in to sewage circulated can be varied by changing the ratio of the area of the throat section to the area at the straight section above the throat.

The mixture of sewage and air leaving the Venturi tube contains $16\frac{2}{3}$ per cent of air; it is discharged from the diffuser bell at a velocity of three feet per second. The introduction of a conical baffle assists in mixing the contents of the tank by producing an effect similar to the spiral-flow, air-diffusion method of aeration. The rising bubbles of air are deflected outwards to the circumference of the tank, where they create the greatest disturbance.

An electric motor, revolving at 900 r.p.m. is directly connected to the screw pump. The power demand of an aerator unit is constant, and is unaffected by variations of sewage flow through the tank. The pumping head consists of the losses at the entrance fitting of the pump, pump losses, frictional head used to draw air in at the throat ring, hydraulic friction in the downdraft tube, static head due to the difference in density between the mixture in the downdraft tube and the aeration tank liquor, and velocity head at the downdraft tube exit.

Results of tests run April 4, 1929, were reported as follows:

- (1) B.O.D.* of preliminary settling tank influent, 440 p.p.m.
- (2) B.O.D. of aeration tank influent, 220 p.p.m.
- (3) B.O.D. of aeration tank effluent after 30 minutes settling, 21 p.p.m.
- (4) B.O.D. reduction in aeration tank, 90.5 per cent.
- (5) Appearance of effluent, clear.
- (6) Appearance of sludge, light brown.

The following data are given on the performance of the aerator:

- (1) Rate of circulating sewage liquor, 1600 gal. per min.
- (2) Quantity of air entrained in liquor, 320 gal. per min. or 42 cu. ft. per min.
- (3) Pounds of oxygen furnished at 80 degrees F. and 760 mm. pressure, 0.7 per min.

*Biochemical oxygen demand.

- (4) Pounds of oxygen furnished in six hours, 250.
- (5) Quantity of 100 p.p.m. B.O.D. sewage which aerator will treat in six hours, 60 000 gallons.
- (6) Daily capacity of standard aerator unit, 100 p.p.m. B.O.D. sewage, six hours retention, 240 000 gal.
- (7) Horsepower requirement, per unit, 2.68.
- (8) Capacity of unit for any given sewage =
24 000 000

B.O.D. of sewage under consideration

16. *The Watsco Aerator at Santa Barbara County Hospital, California.*—The information given in this section was taken from a report by M. L. Grist.*

A small activated sludge plant was designed and installed at the Santa Barbara County Hospital, California, to treat sewage from a population of 350 at the hospital and on an adjacent farm, and also to handle dairy wastes, especially floor washings. In 1931 the average sewage flow from the hospital was 16 000 gallons per day. The maximum flow was at the rate of 120 000 gallons per day, and the minimum rate was about 720 gallons per day. The total daily discharge from the dairy was 7 000 gallons. This was treated for a while, but as it contained considerable debris it was soon by-passed, and has not since been subjected to activation. A stable effluent is required because no diluting water is available. The plant was designed to treat a flow of 50 000 gallons per day.

Sewage entering the plant is given preliminary settling in a small Imhoff tank with a retention period of 40 minutes at average design flow. The sludge compartment has a volume of 130 cubic feet. A four-inch centrifugal pump, controlled by an adjustable time switch, is operated for pumping periods ranging from zero to 72 minutes every two hours. Sludge from the Imhoff tank is pumped to an old septic tank serving as a digestion tank. The period of pumping is adjusted to keep the Imhoff tank free from sludge, without pumping water into the digestion tank. Twenty per cent return sludge is added to the settled effluent from the Imhoff tank, and the mixed liquor flows to a circular aeration tank with a cone-shaped bottom. At average design flow the aeration period is six hours.

The aerator screw pump has a capacity of 1700 gal. per min. and is driven by a 5-h.p. electric motor. The maximum quantity of air taken in is 40 cu. ft. per min., which equals 1.15 cu. ft. per gallon treated at the design flow of 50 000 gallons per day.

*Ibid.

TABLE 6
RESULTS OBTAINED BY WATSCO AERATOR AT SANTA BARBARA
COUNTY HOSPITAL, CALIFORNIA

	Raw Sewage p.p.m.	Settled Sewage p.p.m.	Final Effluent p.p.m.
Free Ammonia.....	17	11.5	2.5
Organic Nitrogen.....	8.5	8	1.5
Nitrites.....	0.015	0.001	1.4
Nitrates.....	0.1	0.1	3.4
Oxygen Consumed.....	190	144	40
B.O.D.....	367	267	4.5
D.O.*.....	188	92	1.7
Suspended Solids.....	188	92	50
Volatile.....	165	86	34
Fixed.....	23	6	16

*Dissolved oxygen.

A Dortmund type tank is used for final settling following aeration. The aerated liquor is introduced at the center, seven feet below the surface, and is withdrawn over a peripheral skimming weir. The average designed detention period is two hours. Settled activated sludge is withdrawn by a 1½-in. centrifugal pump. The effluent from the settling tank flows into a dry ditch several hundred feet long, finally percolating into the soil.

The aerator has been operated 18 months without maintenance expense. Air is supplied at a rate of 4 cu. ft. of free air per gallon of sewage treated as the plant is operating considerably below the designed capacity. The rising air bubbles effectively stir the greater portion of the tank contents, giving them a dissolved oxygen content varying from ½ to 4 p.p.m. The present retention period is slightly over 10 hours. A heavy, typical activated sludge has not yet been built up. The cause is thought to be the character of the sewage and complete over-aeration because a standard Watsco unit at Folsom Prison in California is producing a typical activated sludge with a high quality of effluent. Grist admits that the screw pump may be breaking up the floc in the liquor being recirculated, but he does not consider that this is what is causing the peculiar conditions at the Santa Barbara County Hospital treatment plant.

At intervals the sludge becomes almost white in color, occurs in large spongy flakes, scarcely heavier than water, and does not settle well, as 10 p.p.m. remain in the supernatant liquor from a total of 800 to 1 000 p.p.m. in a sample of aeration tank mixed liquor after 30 minutes settling. A floating sludge mat occasionally forms, but it does not become offensive and does not seem to affect the quality of the effluent. It has been found that the mat will not form if 50 per cent of the sludge settling in the secondary tank is wasted.

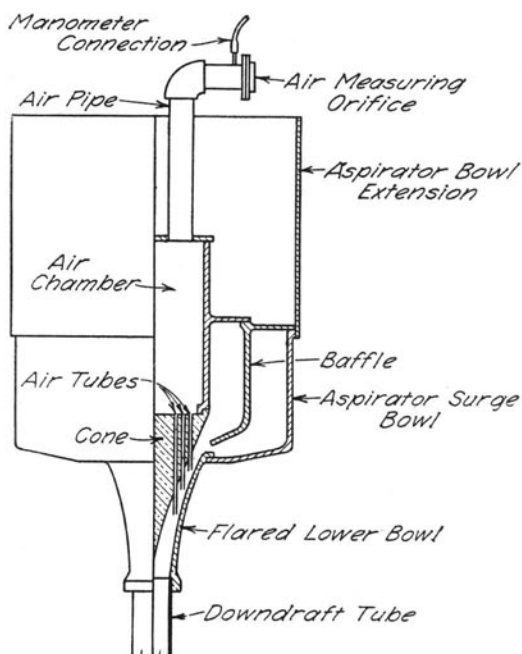


FIG. 8. AEROMIX USED IN TANK A, UNIVERSITY OF ILLINOIS TESTS

Analyses of the raw sewage, the settled sewage, and the final effluent from the plant, were made by the California State Board of Health, in March 1931. The averages of two composite samples are shown in Table 6. The power consumption is 5 horse power continuously, costing \$25.00 per month. The construction cost of the plant was \$9970.00.

17. *The Aeromix at University of Illinois.*—The aspirator used in the tests at the University of Illinois is a proprietary article, designed, and patented on Aug. 14, 1917 and Feb. 19, 1918 under United States patent numbers 1236645 and 1256862, by Henry A. Allen, and manufactured by Vogt Brothers Manufacturing Company of Louisville, Kentucky.

The aspirator consists of rows of small tubes placed vertically in a constricted passage formed by a cone and a flared bowl, as illustrated in Figs. 8 and 9. The aspirator head shown in Fig. 8 was installed in tank A, Fig. 14 and the aspirator head shown in Fig. 9 was installed in tank C. In the operation of the device sewage flows down-

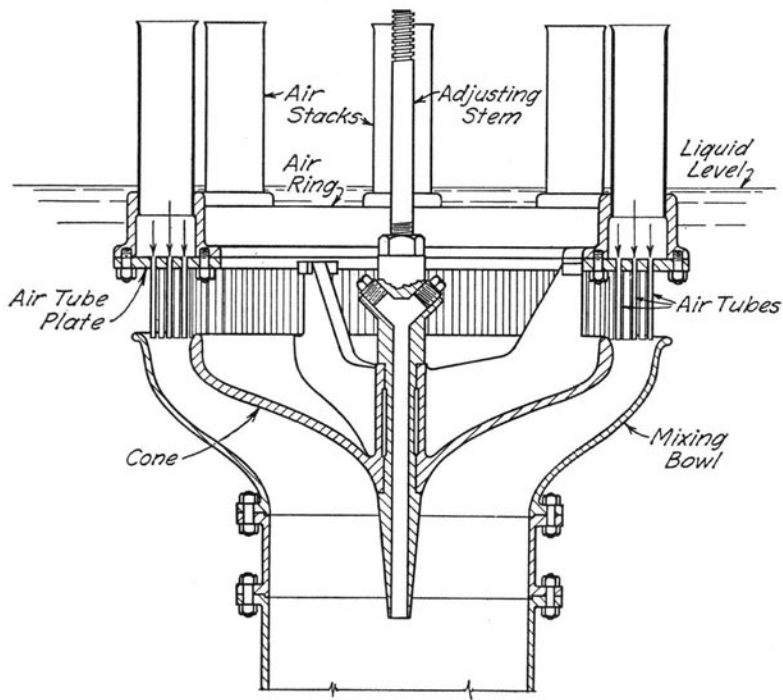


FIG. 9. AEROMIX USED IN TANK C, UNIVERSITY OF ILLINOIS TESTS

ward through the constricted passage at a velocity which reduces the pressure below that of the atmosphere at the end of each row of tubes. The upper ends of the tubes protrude into an air chamber which has an inlet from the atmosphere so that air flows into the descending stream of water. Smoothness of the parts forming the constricted section and of the inside of the downdraft tube is essential if the hydraulic losses are to be small.

The procedure by which the mixture of air and sewage is led away from the aerator was found to be essential to proper action of the aerator in the aeration of sewage. Diagrams of various arrangements of the downdraft tube are shown in Fig. 10. None of the arrangements shown in this figure was found to be satisfactory. In forcing mixed liquor to flow through these arrangements of aerator and piping it was pumped into the top of the aerator bowl and allowed to flow through the apparatus by gravity. In the arrangement illustrated in Fig. 10b, the back pressure at the lower end of the downdraft tube restricted the capacity of the aerator to act as an aspirator. Although the aspi-

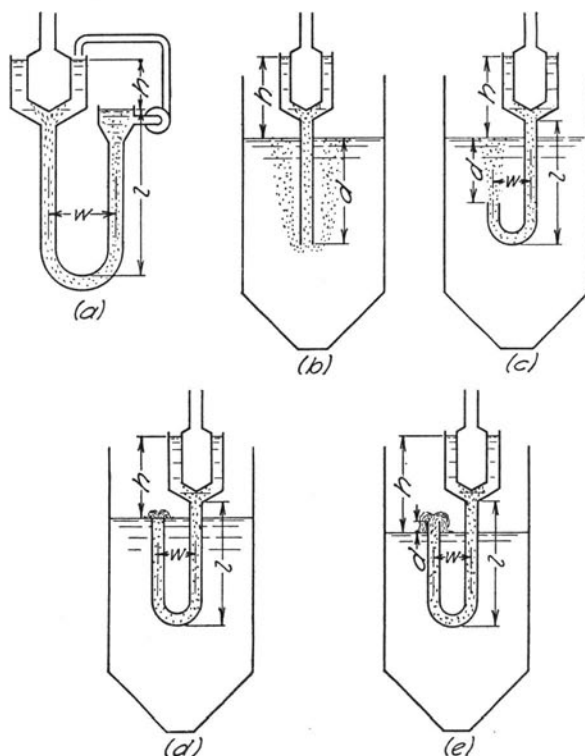


FIG. 10. VARIOUS ARRANGEMENTS OF DOWNDRAFT TUBES

rating action was satisfactory in the other arrangements illustrated in Fig. 10, the discharge of the air near the surface of the mixed liquor in the aeration tank was found to give insufficient aeration for satisfactory action in the activated sludge process. An arrangement of the aspirator and circulating pump which was found to give satisfactory results is illustrated in Fig. 11. Various other methods for circulating the mixed liquor through the aspirator were tried, as illustrated in Fig. 12, but none was found to give results as satisfactory as the arrangement in Fig. 11.

There was a slight clogging of the aspirator tubes when the mixed liquor contained fifteen per cent, by volume, of activated sludge, when measured in a graduated cylinder after 30 minutes settling. The slight clogging seemed to have no unfavorable effect on the operation of the aerator. In many of the tests it was found necessary to use settled sewage as an influent, as no screens fine enough to remove

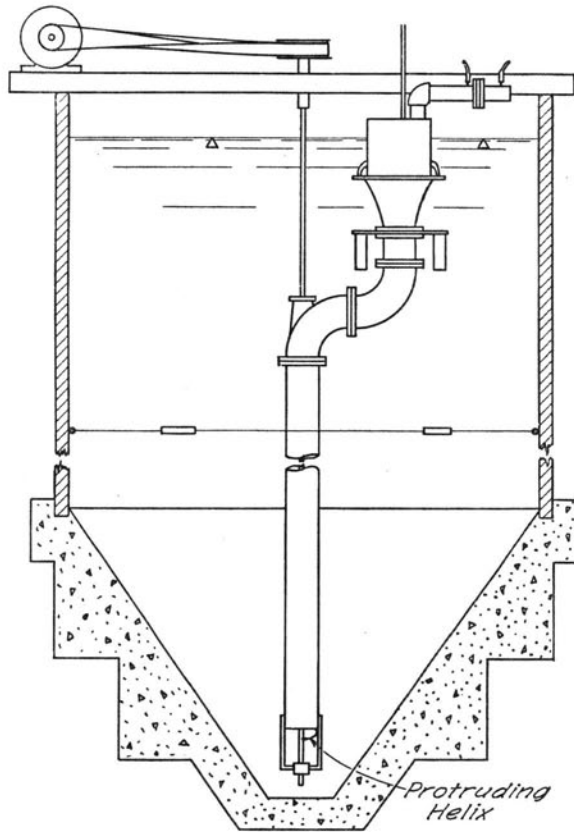


FIG. 11. SATISFACTORY ARRANGEMENT OF ASPIRATOR AERATION APPARATUS

clogging particles from the raw sewage were available. No serious difficulty from clogging of the aerator was experienced when settled sewage was used as the influent.

18. *Apparatus Tested.*—A diagram of the general arrangement of the apparatus tested is shown in Fig. 14; the arrangement of the apparatus when tank *A* alone was used is shown in Fig. 15, and a view, looking down into tank *A*, is shown in Fig. 16. Raw or settled sewage was pumped into the aspirator in tank *A*, where it was mixed with return sludge and mixed liquor from the sedimentation tank and from tank *A*, respectively. The mixture was passed through the aspirator in which air was mixed with the mixed liquor. The air was measured through a calibrated standard orifice as it entered the air

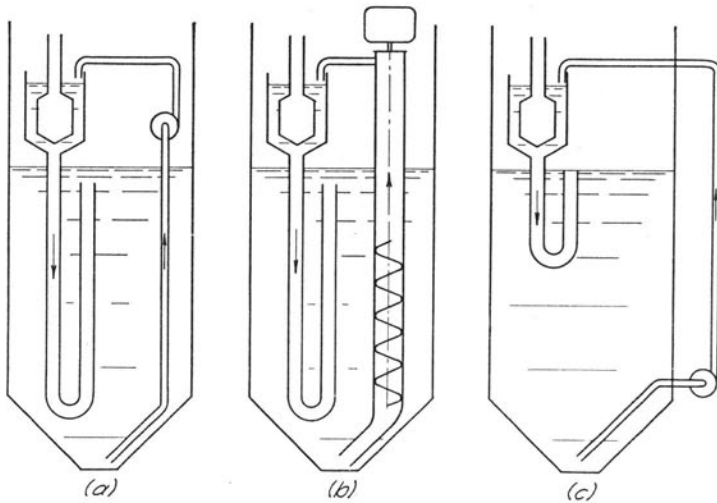


FIG. 12. UNSATISFACTORY METHODS OF RECIRCULATING MIXED LIQUOR

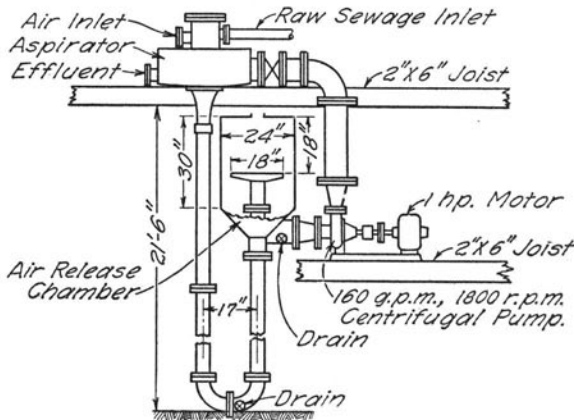


FIG. 13. ARRANGEMENT OF ASPIRATOR AERATOR WITHOUT AERATION TANK

intake pipe. The emulsion of air and mixed liquor was discharged from the downdraft tube into tank A. The mixed liquor in tank A was drawn from the bottom of the tank and pumped back into the aspirator head at the top of the tank by means of the mixed liquor recirculating pump. The loss of head through the apparatus illustrated in Fig. 15 was 5 ft. 6 in., for a flow of 210 gal. per min. The total loss, including pump suction and discharge line, was about eight feet.

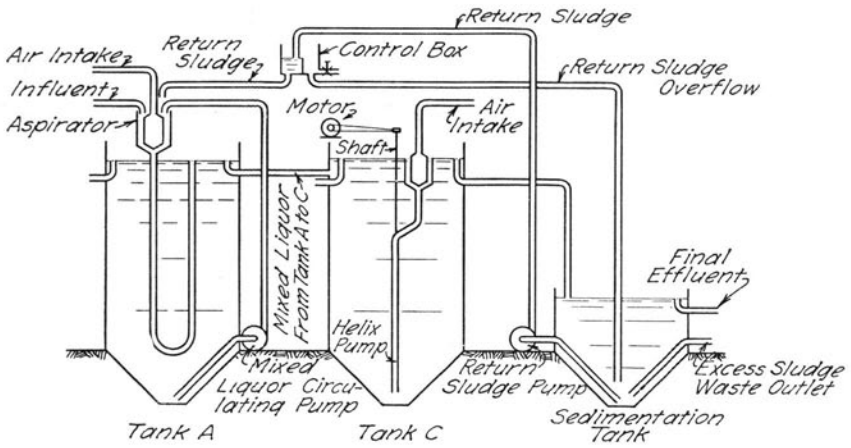


FIG. 14. ARRANGEMENT OF ASPIRATOR AERATION APPARATUS USED IN SERIES XI TESTS

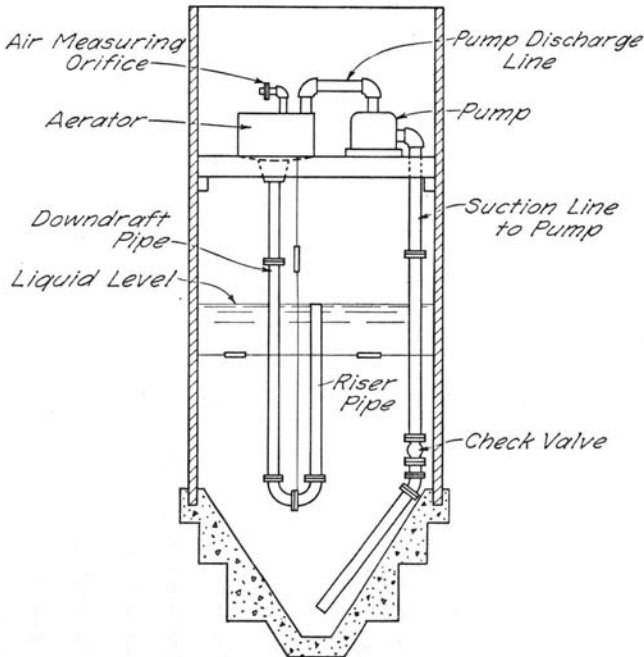


FIG. 15. ARRANGEMENT OF AERATION TANK A WHEN USED ALONE

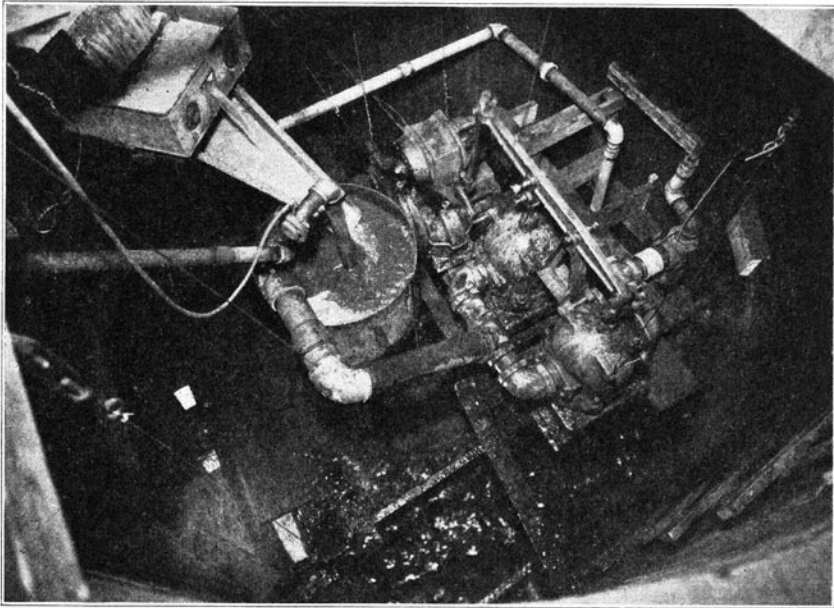


FIG. 16. VIEW LOOKING DOWN INTO TANK A WHEN DIAPHRAGM PUMP WAS INSTALLED FOR CIRCULATION OF MIXED LIQUOR

Excess mixed liquor from tank *A* passed through the mixed liquor pipe to the surface of the mixed liquor in tank *C*. The mixture then flowed into the bowl of the partly-submerged aspirator in tank *C*. This aspirator was of the type illustrated in Fig. 9. The passage of the emulsion of air and mixed liquor through the aspirator and down-draft tube in tank *C* was forced by the revolving helix which protruded from the lower end of the down-draft tube. The air bubbles, emerging from the end of the down-draft tube, were dispersed through the contents of tank *C*, partly by the centrifugal action of the revolving helix, and partly by the rising currents as they ascended to the surface of the tank. The rising bubbles and the revolving helix served to stir thoroughly the contents of the tank.

The overflow of excess liquor passed from tank *C* into the sedimentation tank, at the bottom of which activated sludge was collected. The arrangement of the sedimentation tank is shown in greater detail in Fig. 17. Sludge needed in the formation of mixed liquor was pumped from the bottom of the sedimentation tank to the sludge control box near the top of tank *A*. The location of this box is shown in Fig. 14. The amount of sludge required was discharged into the aspi-

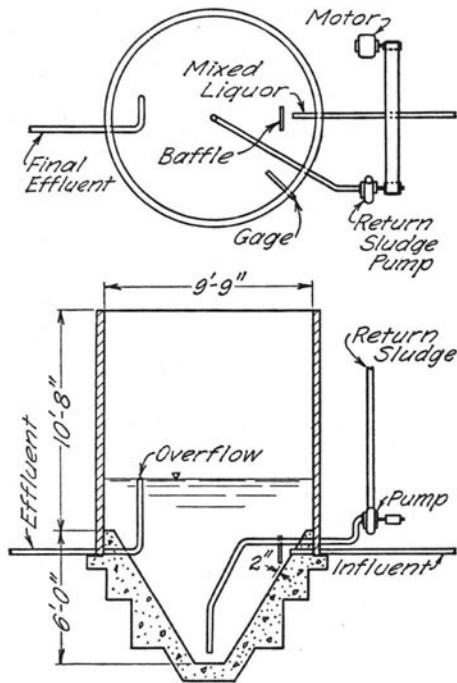


FIG. 17. ARRANGEMENT OF SEDIMENTATION TANK USED IN TESTS OF AERATION BY ASPIRATION

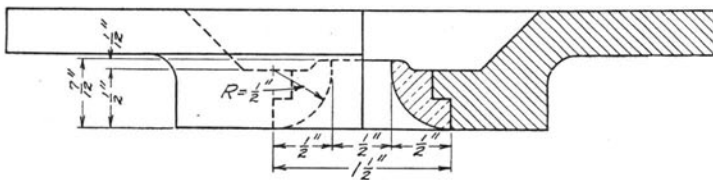


FIG. 18. AIR ORIFICE

rator bowl in tank A, and the excess was returned to the sedimentation tank.

Extensive tests were made of various parts and combinations of parts of the apparatus during the investigation. Both tanks A and C were operated alone, and in series, and many other arrangements of the aspirator in tank A alone were investigated.

19. *Measurement of Flow of Air.*—The orifice used for measurement of the flow of air into the aerator heads is illustrated in

Fig. 18. The orifice, with an opening of one-half inch, with a rounded approach, was made in accordance with the instructions given in University of Illinois Engineering Experiment Station Bulletin No. 207.* It was calibrated by measuring the weight of air passing through the orifice in accordance with the standard calibration requirements stated in Bulletin 207. The calibration was carried out under pressure conditions different from those that existed in the tests made, because the calibration in the laboratory was made for flows of air through the orifice from a plenum into the atmosphere, whereas the conditions of flow in the aspirator are from atmospheric pressure into a partial vacuum. It is believed, however, that the error, considering the low pressure and the small flow of air, is not appreciable. No measurements were made to determine the reduction in the volume of air drawn into the aspirator as a result of the constriction offered by the orifice. It is possible that the reduction in the volume of the aspirated air was appreciable, so that the results of aeration by the aspirator, without the use of the measuring orifice might be more effective than the results shown here would indicate.

Under normal conditions the flow of air through the orifice was found to be relatively steady, and intensities of vacuum of as much as two feet or more of water were observed. Under the conditions of one arrangement of the apparatus in tank A it was found that a flow of 210 gal. per min. of mixed liquor induced a flow of 9 cu. ft. per min. of air through the orifice. The mixture of air and liquid flowing in the downdraft tube contained, therefore, 32 per cent of air by volume. On the basis of a volume of 5400 gallons in the aeration tank, of which one-third was activated sludge, and a flow of incoming sewage of 5 gal. per min., giving a period of aeration of 12 hours, the quantity of air furnished by the aerator was equivalent to 1.8 cu. ft. per gallon of sewage treated.

20. *Helix Used for Pumping.*—Recirculation pumps which lifted the mixed liquor from the bottom of the aeration tank to the top of the bowl of the aerator head having proven unsatisfactory, two different types of propellers, inserted in the downdraft tube, were designed and tested. Neither proved satisfactory because of air binding, resulting either in complete cessation of flow, or of intermittent surges through the apparatus, regardless of the speed of operation of the propellers. The air apparently accumulated immediately below the propeller, which lost its suction, but held the binding air bubble in place in the downdraft tube.

*"The Flow of Air Through Circular Orifices With Rounded Approach," Univ. of Ill. Eng. Expt. Sta. Bul. 207, 1930.

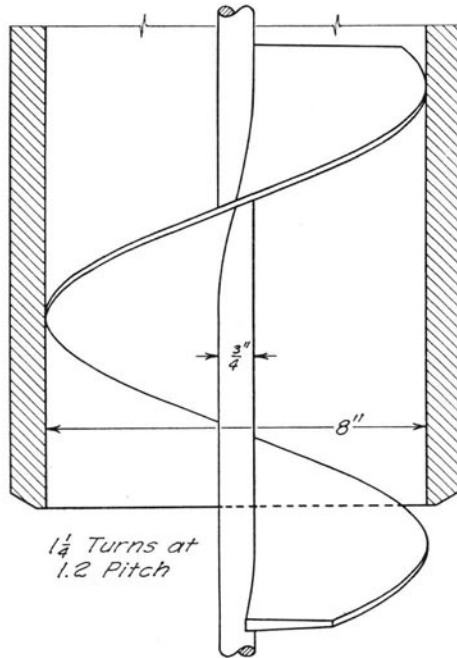


FIG. 19. HELIX

A helix was then designed and tested with satisfactory results. The helix, made of brass, was designed with a pitch ratio of 1.2 and with $1\frac{1}{4}$ turns, or 450 degrees, of the blade. It was installed with $\frac{1}{4}$ turn, or 90 degrees, protruding from the bottom of the downdraft tube, the purpose of the projection being to break up the air bubble which tended to form at this point. The arrangement is illustrated in Fig. 19.

The helix was attached to a vertical shaft which extended upwards through an ell that was bored out for the shaft and fitted with a thrust ball-bearing held in place with a packing gland. A brass sleeve restrained the shaft at the lower end. Above the water line the shaft of the helix was joined to a vertical pulley shaft which was set in a frame provided with babbitted bearings and a thrust ball-bearing. The arrangement is shown in Fig. 11.

The double-flanged vertical pulley was driven by an electric motor with a horizontal shaft by means of a leather belt, twisted 90 degrees. The belt was spliced with a rawhide strip, and gave no trouble in

operation. The pulley ratio of motor and pump was such that the helix was revolved at 1200 r.p.m.

This method of pumping a mixture of air and liquid down a pipe so that it will discharge at the bottom of a body of liquid was conceived and developed at the Engineering Experiment Station of the University of Illinois.

21. *Power Consumption.*—Power consumption was measured only during the runs of Series X, XI, and XII, the conditions of which are described in Section 29. It was possible in the earlier series of tests to approximate the power consumption by the following expression:

$$H.P. = 0.175 \frac{L M}{S E}$$

in which *H.P.* = the horse power per million gallons of sewage treated daily.

E = the assumed mechanical efficiency of the pump and power equipment.

L = the loss of head, or the distance in feet, from the surface of the mixed liquor in the aeration tank to the surface of the liquor in the aerator bowl.

M = the rate of flow of the mixed liquor, in gallons per minute.

S = the rate of inflow of sewage, in gallons per minute.

As the installations of the equipment for the earlier series of tests were inefficient, power observations would have been of little significance. The installations in Series X and XII approach the efficiency attainable in practice, although possibilities of improvement are obvious. Readings of power consumption were made by means of a watt-hour meter placed on the electric power line leading to the motor. These readings were direct in kilowatt hours consumed. The only computations necessary were, therefore, to convert the meter readings to horse power per million gallons of sewage treated daily. Results of these readings are recorded in Section 29.

22. *Control of Conditions.*—Recognition and classification of the conditions to be encountered are essential to the efficient progress of a research problem. The controllable conditions affecting the aeration of activated sludge by aspiration include:

- (A) Completely controllable conditions:
 - (1) Rate of flow of raw sewage
 - (2) Rate of flow of return sludge
 - (3) Retention period in aeration tanks
 - (4) Retention period in final settling tank
 - (5) Rate of recirculation of mixed liquor
 - (6) Frequency of recirculation of mixed liquor
 - (7) Changes in types of plant
- (B) Partly controllable conditions:
 - (1) Composition of influent to the aeration tank
 - (2) Amount of sludge to be wasted
 - (3) Composition of mixed liquor
 - (4) Rate of aeration.
- (C) Uncontrollable conditions:
 - (1) Temperatures of operation
 - (2) Composition of raw sewage
- (D) Characteristics affected by controllable conditions:
 - (1) Composition of return sludge
 - (2) Composition of final effluent
 - (3) Laboratory observations, which include:
 - (a) Dissolved oxygen
 - (b) Biochemical oxygen demand
 - (c) Stability
 - (d) Total solids
 - (e) Fixed solids
 - (f) Suspended solids
 - (g) Rate of settling of sludge
 - (h) Sludge density
 - (i) pH
 - (j) Microscopic observations

The usefulness of this classification lies in the fact that it allows systematic planning of the tests.

Under completely controllable conditions are included those conditions that can be influenced by mechanical means, such as regulation by valves, change of speed of motor or pumps, height of overflow of tanks, or partial bypassing. Any desired rate of flow of raw sewage could be obtained up to 70 gallons per minute. The rate of flow of return sludge could be adjusted up to 15 gallons per minute, the limiting capacity of the sludge return pump. The rate of recirculation of the mixed liquor through the aerator head could be adjusted between 125 and 280 gal. per min. for the first series of tests. The frequency of

recirculation was changed by variations of the volume of liquid in the aeration tank, the rate of flow of sewage plus return sludge, and the rate of recirculation of mixed liquor. The frequency of recirculation is the quotient of the volume of liquid recirculated during the retention period and the volume of mixed liquor in the aeration tank or tanks.

Composition of the influent to the aeration tank is listed as a partially controllable condition as it could be changed, to some degree, by changing the period of retention in the preliminary sedimentation tank, by diluting with water, or by mixing raw sewage with it. Within the limits of the amount of sludge produced and that required for the process, the amount of sludge to be wasted was under the control of the operator. The composition of the mixed liquor was partially controllable through the relative amounts of raw sewage and return sludge combined to form the mixed liquor. As neither the quality of the raw sewage nor the amount or quality of return sludge were completely under the operator's control the quality of the mixed liquor was only partially controllable. The amount of aeration was only partially controllable because of the limitations of the operation of the aerator heads. It was necessary to maintain an adequate velocity through the downdraft tube in order to produce a vacuum in the air tubes. The amount of air drawn in was a function of the velocity of flow through the downdraft tube.

23. *Laboratory Aeration Tests.*—Aeration tests were made in the laboratory to determine if under-aeration was the cause of unsatisfactory sludge in the earlier series of tests. In the conduct of these tests return sludge was mixed with different amounts of raw sewage, and the mixture was aerated by introducing compressed air through a glass tube ending near the bottom of a $4\frac{1}{2}$ -litre bottle of the mixture to be aerated. A portion of the contents of the bottles was withdrawn from time to time for examination of settling properties, total and fixed solids, and to make microscopical observations. Some of the results of these aeration tests are given in Table 7.

The aeration tests indicated under-aeration in the large scale experimental equipment for the earlier series of tests, because the density of the sludge was increased by the laboratory aeration. In most cases the solids content of the original sludge could be more than doubled in the laboratory.

24. *Sludge Settling Rates.*—Settling rates of the sludges, observed in the laboratory, gave a quick estimate of the quality of the sludge

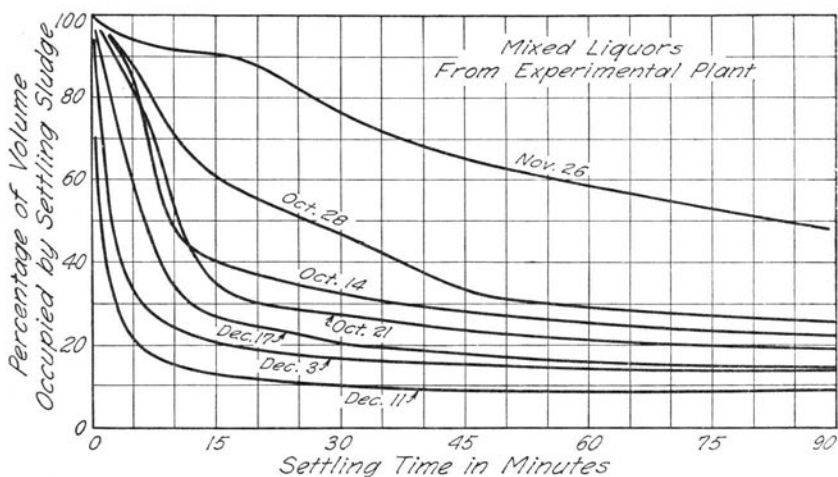
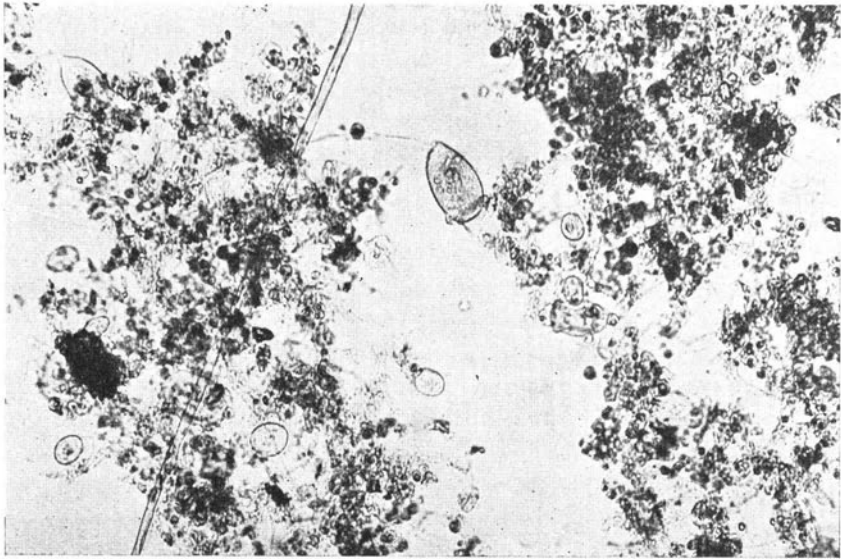


FIG. 20. SLUDGE SETTLING CURVES

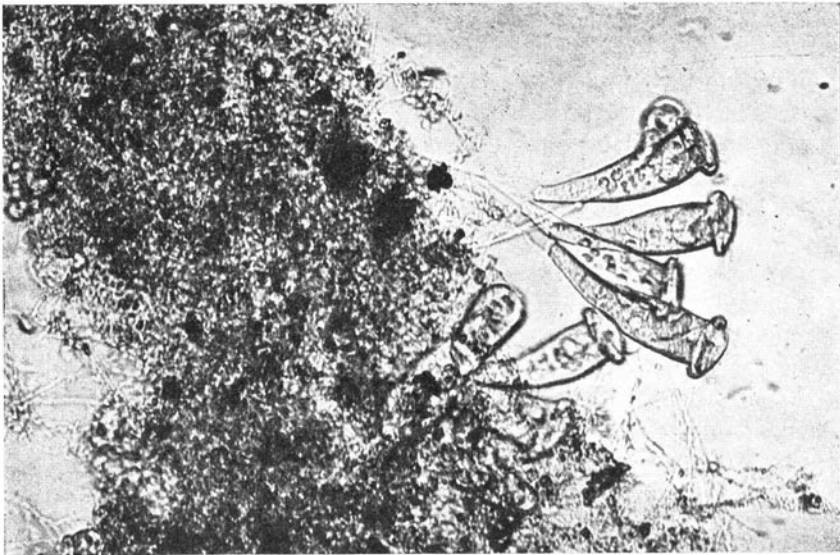
because of the nature of the settling curve. Some typical settling curves are shown in Fig. 20. The different types of sludge were recognizable from the curves and through their behavior in the sedimentation flasks. Bulking sludge did not settle; good sludge collected quickly in the bottom of the flask, leaving a clear supernatant liquor; and over-aerated sludge collected more slowly in the bottom of the flask, leaving a turbid supernatant liquor.

25. *Microscopical Observations.*—Microscopical observations were made on raw sewage and on sludges at various stages of development and aeration. An interesting photograph of a well-aerated sludge is reproduced in Fig. 21. An extensive series of observations was made on the sludges in the large scale experimental equipment as well as on the sludges aerated in the laboratory.

Sphaerotilus was always present in large quantities in light, bulking sludge, whereas protozoa were seldom found. A balance seemed to exist between the sphaerotilus and the protozoa. As the latter increased the former decreased, the change being controllable, between limits, by the degree and period of aeration. A long period of intense aeration produced a high quality, dense, activated sludge, free from sphaerotilus and teeming with protozoa. It was noted that it required more and longer aeration to produce satisfactory sludge from a sample in which sphaerotilus had been permitted to develop than from a fresh, intensely aerated sludge in which sphaerotilus had never appeared.



(a) Return sludge December 6, 1932, after two weeks of use of filter plate; total solids of sludge 3034 p.p.m. Magnification 200 x.



(b) Laboratory-aerated sludge of November 12 on November 14; prominent organism is carchesium. Magnification 200 x.

FIG. 21. PHOTOMICROGRAPHS OF A WELL-AERATED SLUDGE

26. *Laboratory Procedure.*—All tests were made on grab samples usually taken between eight a.m. and six p.m. The majority of the more significant samples were taken during the late afternoon when the load on the plant was the greatest. Turbidity determinations were made with the Jackson turbidimeter. All tests were run according to the Standard Methods of Water Analysis, Sixth Edition, except as follows:

Dissolved Oxygen

The procedure recommended by the Federation of Sewage Works Associations Committee Report, published in Sewage Works Journal, May, 1932, p. 413, was followed. The permanganate modification of the Winkler Methods was used on all dissolved oxygen determinations in raw sewage, mixed liquor, return sludge, and effluent. In the diluted samples of the biochemical oxygen demand determination, and with the blank, the straight Winkler Method was used.

In determining the dissolved oxygen of the mixed liquor and the return sludge, identical results on identical samples were not secured. The sample which stood the longer before chemicals were added showed a smaller content of dissolved oxygen. The amount of potassium permanganate necessary to give a permanent violet color was irregular. The iodine liberated after the addition of manganous sulphate and alkaline potassium iodide solutions seemed to be partly absorbed by the sludge particles. When the sulphuric acid was added to dissolve the manganous hydroxide formed in the previous reaction, the activated sludge coagulated and settled to the bottom. Only the clear supernatant liquor could be used for the titration with sodium thiosulphate to determine the iodine content. It is doubtful if this clear liquor had the average content of iodine of the full sample. In many titrations the presence of iron or other substances in the sample caused the blue color due to starch iodide to return immediately after a slight weakening of the color caused by the inflow of sodium thiosulphate. The presence of iron also gave a color-free end point only after the oxygen content of the liquid corresponding to the titration far exceeded the saturation possible. These difficulties were never fully overcome. By working fast, stirring with glass rods instead of shaking the bottles, and by titrating as soon as the sludge had settled, more consistent results could be obtained.

Biochemical Oxygen Demand

The biochemical oxygen demand determinations were made by the dilution method. The calculations for the B.O.D. were made from the expression

$$d = c(1 - f) + fa$$

in which a = the dissolved oxygen of the sewage, in p.p.m.

c = the dissolved oxygen in the blank before incubation,
in p.p.m.

d = the dissolved oxygen in the mixture before incubation,
corrected for loss in blank during the incubation,
in p.p.m.

f = the proportion of sewage in the mixture.

The biochemical oxygen demand is then calculated from the expression

$$\text{B.O.D.} = \frac{d - e}{f}$$

in which e = the dissolved oxygen in the mixture after incubation,
in p.p.m.

Total Solids

Total solids were determined mostly on samples of 50 ml. Several samples were weighed and found from 0.1 to 0.3 gram less than the 50-gram weight they should have had as water. No good reason is suggested for the apparently low specific gravity of these impure samples containing settling solids.

Fixed Solids

These were determined by heating the dishes and Gooch crucibles with the dried solids in a muffle furnace at a temperature of 800 to 900 degrees C. The fixed solids determination is inaccurate as the particles may be blown away in burning or material in the furnace may be burned into the dish. The inaccuracy of the test is increased if calcium is present in the sample. Calcium is reduced to calcium oxide in the furnace. On cooling the calcium oxide combines with carbon dioxide in the air to form calcium carbonate. At the time of weighing of the cooled sample it is not known how far this combination has proceeded or what is being weighed. To overcome this difficulty the crucibles were cooled in a desiccator which had both calcium chloride to produce dry air and sodium hydroxide to remove the carbon dioxide from the air.

Rate of Settling of Sludge

This was determined by placing one litre of mixed liquor in a one-litre graduate and making periodic readings of the sludge level. In many cases the rate of settling could not be determined as some of the sludge started floating.

TABLE 7
RESULTS OF LABORATORY AERATION TESTS

Test No.	Total Solids in Sludge Before Laboratory Aeration p.p.m.	Amounts of Constituents in Aerated Mixture ml.			Time of Aeration days	Total Solids in Aerated Sludge After One Hour Settling p.p.m.
		Sludge	Sewage	Water		
1	2060	100	100	800	2	2008
2	2090	250	0	250	14	6455
3	1157	1000	500	0	4	1090
4	1157	1000	500	0	11	2978
5	1808	1000	500	0	7	6928
6	2960	500	1500	0	14	6800
7	2960	200	1800	0	14	5780
8	2146	400	1600	0	14	6250
9	3146	400	1600	0	21	4535
10	2146	400	1600	0	38	7300
11	3650	600	3400	0	7	9910
12	3650	600	3400	0	14	10040
13	2006	1000	2500	0	17	11910

Sludge Density

"The quotient of the suspended solids in the mixed liquor, expressed in p.p.m., by weight, divided by the per cent sludge, by volume, in the mixed liquor as determined after standing one hour in a litre graduate" is the sludge density.*

pH

Determinations of pH were made with a Sanitary District of Chicago colormetric set, allowing readings between 4.0 and 7.8. The set allowed compensation for readings with turbid waters.

Microscopical Observations

These were made on freshly prepared, unstained slides without any attempt to count carefully the different organisms. Magnifications up to 215 times were observed, restricting the observations to the larger microscopic organisms. Notice was taken only of the presence or absence of certain groups. Characteristic organisms were photographed.

27. *Sampling Procedure.*—The strength and rate of flow of domestic sewage is known to vary with the hours of the day and with the days of the week. The influence of these variations was expected to be largely eliminated by taking samples regularly at the same time of the same day of the week. The differences shown by the laboratory tests indicate that uniformity of conditions was not maintained. Another factor in sampling may affect the results. With a retention

*Sewage Works Journal, May 1932, p. 465.

period of eight hours, sewage presumably leaves the tank eight hours after entering it. In order to get the effect of the treatment on certain inflowing sewage the effluent sample should, therefore, be taken eight hours after the influent sample has been taken. Such a procedure was impractical and is not, theoretically, necessary.

Inasmuch as the untreated sewage entering the tank is quickly and thoroughly mixed with the tank contents, the tank acts not only as a treatment unit but as a quality stabilizer or integrator. Without treatment or other biological change the quality of the effluent would, necessarily, represent an eight-hour average of the varying qualities of the influent. Effluent samples were, therefore, taken at the same time as the influent samples. As this procedure was regularly followed any error of method might be partially compensated by the comparative values of the results. A variation in the times of sampling was felt to be impractical as such refinement of procedure would require another time of sampling the mixed liquor and the return sludge. The determination of such times would be indefinite because of the unavoidable short circuiting through the plant.

28. *Biochemical Oxygen Demand Modulus*.*—In order to overcome the difficulties inherent in an attempt to compare plant performance either by percentages of reduction of B.O.D. or by the B.O.D. of the effluent a "B.O.D. Modulus" was devised which is based on a combination of B.O.D. reduction and the B.O.D. of the effluent. It can be expressed as

$$M = 100 \frac{d}{c} \log \left(\frac{a - b}{2} \right)$$

in which a = B.O.D. of the influent, in p.p.m.

b = B.O.D. of the effluent, in p.p.m.

c = B.O.D. of the mixture of the effluent and the stream into which the effluent is discharged, in p.p.m.

d = an arbitrarily selected standard for the B.O.D. of polluted water, in p.p.m.

The greater the modulus the more satisfactory the results of the plant. The modulus can be used for purposes of comparing the performances of plants operating under identical conditions of quality and quantity of diluting water. In a study of these tests it was assumed that 2 p.p.m. of B.O.D. in the polluted river water would be satisfactory, and that a volume of diluting water equal to the amount

*"Tests of a Sewage Aerator of the Aspirator Type," Max Suter; Thesis for Degree of Master of Science, University of Illinois, 1933.

TABLE 8
VALUES OF BIOCHEMICAL OXYGEN DEMAND MODULUS

Run No.	Series	B.O.D. in p.p.m.		Modulus	Run No.	Series	B.O.D. in p.p.m.		Modulus
		Influent	Effluent				Influent	Effluent	
1	N*	600	5	196	16	8	403	27	34
2	N	600	10	98	17	8	438	37	25
3	N	600	30	18	18	8	376	32	28
4	N	200	5	159	19	8	525	28	34
5	N	200	10	79	20	8	227	29	28
6	N	200	30	14	21	8	369	43	21
7	7	351	35	25	22	8	567	40	24
8	7	415	24	38	23	Av.†	427	34	31
9	7	336	15	59	24	9a	319	25	35
10	7	270	34	24	25	9a	272	27	31
11	7	407	27	34	26	9a	193	28	27
12	7	547	50	17	27	Av.†	261	27	35
13	7	402	33	32	28	9b	196	8	98
14	Av.†	390	31	33	29	9b	132	24	30
15	8	509	36	26	30	9b	125	11.5	66
					31	Av.†	151	14.5	59

*Hypothetical values assumed to indicate effect of different assumptions on the value of the modulus.

†Average for the preceding series. The modulus is computed from the arithmetical averages of the B.O.D. of the influent and the effluent.

In series 9a the aeration was caused by the aspirator, and in series 9b the aeration was created by means of a filtros plate.

of sewage from the plant would be available. If the diluting water has zero B.O.D., then $c = b/2$, and

$$M = \frac{400}{b} \log \left(\frac{a - b}{2} \right)$$

The values of the modulus for various values of a and b are given in Table 8. The figures in the table show that for a strong, raw sewage the value of the modulus varies approximately inversely as the B.O.D. of the effluent, and that the modulus is affected more by the B.O.D. of the effluent than by the amount of reduction of B.O.D. effected. Values of the modulus for various runs and series are entered in Table 8. They are indicative, in an approximately quantitative form, of the relative performance of the equipment.

29. *Conditions and Results of Tests.*—A record of the experience in the preliminary tests with the aspirator is one of mechanical difficulties with recirculation. The arrangement of the apparatus was varied for twelve different series of tests in each of which different conditions of operation were tried.

Different methods of recirculation of the mixed liquor were tested in each of the nine preliminary series of tests. This was done to aid in indicating the most desirable arrangement of the apparatus. The various methods of recirculation used in the preliminary tests are

illustrated in Fig. 12. The general procedure in all of the tests was to discharge the influent into the bowl at the top of the aspirator or aerator head into which the return sludge and the recirculated mixed liquor were also being discharged. The mixed liquor flowed down through the aerator head, details of which are illustrated in Figs. 8 and 9, where air was drawn into the liquor. The emulsion of air and mixed liquor passed through the downdraft tube and discharged either into the air-release chamber or the aeration tank, where the air escaped before the mixed liquor entered the recirculation pump. A portion of the aerated mixed liquor was withdrawn from either the aspirator bowl, at the point marked "effluent" in Fig. 13, or from the surface of the liquid in the aeration tank through the overflow in Fig. 15. Mixed liquor was withdrawn at the same rate as the influent entered the apparatus. The mixed liquor withdrawn was sent to the sedimentation tank illustrated in Fig. 17, from which the return sludge was pumped by means of an open-impeller, volute pump.

Experience with the aspirator tested showed that a submergence of the end of the downdraft tube of one foot or more, when a recirculation pump was used for recirculating the mixed liquor, reduced the air drawn by the aspirator to a negligible amount as compared with that taken in when the discharge was free, even though the full rate of circulation was maintained. A submergence of as little as two inches reduced the quantity of air appreciably.

The height of liquid in the aerator bowl above the upper end of the air tubes has a marked effect on the quantity of air drawn in, as it affects the intensity of the vacuum in the constricted portion of the aspirator. The best height found with the aspirator used in these tests was in the neighborhood of 27 to 30 inches. The best height for any particular aerator head will depend upon the design of the device.

Recirculation was attempted with five different types of pumps: a high-speed turbine centrifugal pump; a low-speed, open-impeller, volute centrifugal pump; a diaphragm pump; a chain-and-bucket pump; and a long, revolving helix, or screw of Archimedes. It was found impossible to produce activated sludge with the high-speed turbine pump used for recirculation as it broke up the particles of sludge and sewage into a clear, highly colored liquor with a high biochemical oxygen demand. The results obtained with the volute pump were only slightly less objectionable in this regard. All other types of pumps were found to be unsatisfactory for recirculation because of mechanical difficulties which resulted either in brief shut-downs of the plant or complete inability of the pump to operate.

The conclusion reached from the preliminary tests, insofar as the recirculation pumps were concerned, was that none of the types of pumps used in the preliminary tests was satisfactory for the recirculation of mixed liquor. It was also concluded that an aeration tank is necessary with this type of aeration, to minimize the number of passages of the mixed liquor through the aerator head, and at the same time obtain the desired period of aeration.

In the final test series, numbered X, XI, and XII, the results were satisfactory both mechanically and in the quality of sludge and effluent produced.

Series X

The arrangement of the equipment in this series of tests is illustrated in Fig. 11. Recirculation was provided by means of a revolving helix which was placed in the down-draft tube, as shown in the figure. After many difficulties with the helix a satisfactory design and speed of operation were secured so that the aeration and the distribution of fine bubbles throughout the liquid in the aeration tank were satisfactory. When all mechanical conditions had been satisfactorily adjusted a series of observations was made under the following conditions of operation:

Period of aeration, 8 hours.

Rate of application of air, 5 cubic feet of free air per minute.

Rate of recirculation of mixed liquor, not measured, but the capacity of the aerator head for best efficiency of aspiration was designed for a flow of 350 gallons per minute. It was assumed that approximately this rate of flow was obtained.

Number of passages of mixed liquor through the aerator head in one period of retention, computed on the basis of a rate of recirculation of 350 gallons per minute, 30.

Return sludge, one third of the volume of the inflow of settled sewage.

Rate of flow of settled sewage through the apparatus, $9\frac{1}{3}$ gallons per minute.

Volume of liquid in the aeration tank, 6000 gallons.

Total depth of liquid in the tank, 15 feet.

Some of the results of the principal laboratory tests of the performance of this equipment are listed in Table 9. Although the results of the tests were considered to be satisfactory it was realized that with a single aeration tank considerable short circuiting of the sewage might occur, resulting in a reduction of the efficiency of the treatment. A new series was, therefore, attempted with a slightly different arrangement of equipment.

TABLE 9
RESULTS OBTAINED IN SERIES X TESTS

B.O.D. of influent.....	106 p.p.m. (settled sewage)
B.O.D. of effluent from sedimentation tank.....	20 p.p.m.
B.O.D. reduction.....	80 per cent
Relative stability of the effluent from the sedimentation tank.....	100
Return sludge.....	98.2 per cent moisture after one hour of settling in a beaker
Increase of dissolved oxygen in the mixed liquor over that in the influent.....	3.1 p.p.m.
Appearance of the activated sludge.....	light brown
Appearance of the final effluent.....	clear

Series XI

The apparatus was arranged in this series, as shown in Fig. 14. The conditions of operation were:

- Rate of inflow of settled sewage, 9 gallons per minute.
- Period of retention in primary aeration tank, 8 hours.
- Period of retention in secondary aeration tank, 8 hours.
- Rate of aspiration of air in primary aeration tank, 10 cubic feet of free air per minute.
- Rate of aspiration of air in secondary aeration tank, 2.5 cubic feet of free air per minute.
- Rate of recirculation in primary aeration tank, 250 gallons per minute.
- Rate of recirculation in secondary aeration tank, 350 gallons per minute.
- Number of turnovers of contents of the primary aeration tank in one aeration period, 22.
- Number of turnovers of the contents of the secondary aeration tank in one aeration period, 30.
- Percentage of return sludge in the mixed liquor, 25.
- Volume of liquid in each of the aeration tanks, 5500 gallons.
- Time of sedimentation in the final settling tank, 2 hours.

It was discovered that the reason for the aspiration of so small a quantity of air in the secondary aeration tank was the clogged condition of the aspirator tubes. This difficulty was overcome in subsequent tests, but it existed throughout the observations of this series. It is evident that the greater amount of aeration was probably secured in the primary aeration tank, where the volume of air circulated was four times that in the secondary aeration tank. In spite of the relatively poor aeration in the secondary aeration tank the laboratory observations indicate satisfactory results, as is shown in Table 10.

During the early part of the tests in this series it rained almost continuously so that the settled raw sewage delivered into the appar-

TABLE 10
RESULTS OBTAINED IN SERIES XI TESTS

B.O.D. of influent.....	274 p.p.m. (raw sewage)
B.O.D. of effluent from sedimentation tank.....	26 p.p.m.
B.O.D. reduction.....	91 per cent
Relative stability of the effluent from the sedimentation tank weighted average of all samples.....	97
Return sludge.....	98.9 per cent moisture after one hour of settling in a beaker
Increase of dissolved oxygen in the mixed liquor in the final aeration tank over that in the influent to the primary aeration tank.....	2.3 p.p.m.
Turbidity of influent.....	455 p.p.m.
Turbidity of effluent.....	60 p.p.m.
Turbidity reduction.....	82 per cent

TABLE 11
RESULTS OBTAINED IN SERIES XII TESTS

B.O.D. of influent.....	266 p.p.m. (settled sewage)
B.O.D. of effluent.....	7 p.p.m.
B.O.D. reduction.....	97 per cent
Relative stability of the effluent from the sedimentation tank.....	100
Increase of dissolved oxygen in the mixed liquor in the aeration tank over that in the influent.....	2.5 p.p.m.
Turbidity of influent.....	270 p.p.m.
Turbidity of effluent.....	38 p.p.m.
Turbidity reduction.....	87 per cent
Appearance of activated sludge.....	light brown, rapidly settling

atus became extremely weak; one relative stability sample of the raw sewage retained the methylene blue color for over 14 hours. Sludge was lost from the final sedimentation tank faster than it could be built up. In order to aid in overcoming this difficulty screened raw sewage, seeded with activated sludge from another activated sludge plant, was used as an influent in place of the settled sewage. A heavy, brown activated sludge was soon built up in large quantities and was maintained. It settled well, and left a clear, supernatant liquor.

Series XII

The arrangement of the equipment for this series was the same as in Series X. The only change made was to reduce the period of retention to six hours by increasing the flow of sewage to the tank. The volume of sludge added to the incoming settled sewage was 25 per cent of the incoming sewage. Shortly after the start of the tests the pump began to show signs of failure, due to wearing of the bearings, so that it was possible to secure only 2 cubic feet per minute of air for aeration. In spite of this relatively low quantity of air the sludge remained heavy and brown. Some of the results of laboratory tests in this series of observations are listed in Table 11.

IV. CONCLUSIONS

30. *General Conclusions.*—Satisfactory activated sludge can be formed and an effluent of desired quality can be obtained by thorough agitation of sewage in shallow tanks by means of Sheffield Paddles. Under proper conditions the method of aeration is highly satisfactory. With efficient mechanical equipment and a sewage with a biochemical oxygen demand of less than 300 to 500 p.p.m. a power consumption in the neighborhood of 20 to 40 horsepower per million gallons of sewage treated daily can be attained. In cold climates the difficulties from ice forming on the paddles can be avoided by housing the upper or exposed portions of the paddles. Satisfactory aeration is obtained, with the lowest expenditure of power, by submerging the paddles from 6 to 9 inches in the mixed liquor. Greater submergence increases the power consumption, without materially improving the aeration. A lower submergence diminishes the effects of aeration. Conditions most suitable to the installation of this process include low cost of land, and difficult excavation or foundation conditions necessitating the use of shallow tanks.

Under-aerated and bulking sludge, a low biochemical oxygen demand modulus, mechanical difficulties, and inefficient pumping equipment all point to the conclusion that the circulation of sewage through an aspirator by means of a pump which must lift the sewage into the aspirator head is not a successful method of sewage treatment.

Aeration of sewage through an aspirator is mechanically efficient and biologically and chemically satisfactory when the equipment is arranged with two or more aeration tanks and aspirators in series, with each tank equipped as shown in Fig. 11. Greater mechanical efficiency could probably be obtained by the use of a vertical shaft passing symmetrically through the center of the aspirator and down-draft tube with the motor and helix on this shaft. Such a device has been put into operation subsequent to the completion of the tests herein reported.

Satisfactory results were obtained, as indicated in Tables 9 and 10, in the tests on the aspirator when treating sewage from the Champaign outfall sewer, with an eight-hour period of aeration, with the use of approximately 0.5 cu. ft. of free air per gallon of sewage treated, and with a power consumption of between 30 and 40 horse power per million gallons of sewage treated daily. The tests indicate that improvements in the arrangement of the apparatus and the mechanical equipment might effect successful results with a shorter aeration

period, and lower air and power consumption. Short-circuiting in the aeration tanks should be overcome by using two or more aeration tanks in series.

Effective aeration by the use of an aspirator is secured because of the thorough circulation in the aeration tank which is maintained by the pump, in addition to the stirring due to the rising air, and because the air bubbles discharged at the lower end of the downdraft tube are extremely fine, giving excellent diffusion through the mixed liquor. The small bubbles formed in the aspirator are probably further broken up, or prevented from coalescing, by the revolving helix in the downdraft tube. The agitation caused by this helix is not harmful to the quality of the sludge formed.

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