THE
AERATION
OF
ACTIVATED SLUDGE
MIXTURES

by

Daniel A. Okun

and

John A. Bonell

In Partial Fulfilment of the Requirements for the Degree of

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The Aeration of Activated Sludge Mixtures

Introduction

The purpose of this investigation is to establish, to the extent possible, the effect of degree aeration on several characteristics of a sewage-sludge mixture: principally, the oxygen utilization by an activated sludge after varying periods of aeration, with varying amounts of air supplied; and secondly, the effect of aeration periods of activated sludges on clarification and dissolved oxygen content.

The work was performed at the Tri-City Sewage Treatment Plant, in Alhambra, California (commonly referred to as the Pasadena Sewage Treatment Plant). Tests were run on samples taken from the new aeration and clarification unit used in conjunction with the original activated sludge plant. These tests were made in the laboratory of the plant.

Tests were begun in January, 1938 and continued until May, 1938, with one interruption, that caused by the floods of early March. The operation of the plant was affected considerably by this flood, and normalcy was not restored until the middle of May. However, the school year necessitated the termination of testing in early May.

Unlike most experimental work, the time the tests are performed is in the case of tests run on actual sewage flows extremely important. Early morning flows are small and weak, rising sharply during later morning hours in both quantity of flow and strength of sewage. But due to the exigencies of scheduled work at the Institute, it was not possible to be at the plant at the requisite hours regularly. There were several occasions where we deemed it necessary to run our tests for twelve consecutive hours, but these were seldom possible. The effect of the change in flow and strength, together with other time factors are treated later in the paper.

Historical Notes

A steadily increasing interest in the oxidation characteristics of activated sludge mixtures, as evidenced by the importance they are assuming in sewage treatment plant design, plant operation, and equipment design, led to this investigation. The following will trace briefly the short history of the development of what is now known as the "oxygen utilization" of activated sludge mixtures.

Although it has been long accepted that the activated sludge method of sewage treatment provides in general the most efficient treatment of domestic sewage, there has been one drawback, excessive operating costs. The largest single item in these operating costs is the power required for aeration. Many investigations and designs have been made for various types of aeration equipment, and many analyses have been made with regard to the respective merits of the diffused air and mechanical types of aeration, with an eye to reducing aeration costs, but until the work by Kessler and Nichols (1), in 1934, little had been done in investigating the actual oxygen requirements of activated sludge mixtures.

Carl H. Nordell, while working on the basis for the design of the proposed activated sludge plant for Milwaukee, in 1916, encountered some difficulty in ascertaining the rate of oxygen utilization. By running a series of controlled tests, he noted that the rate of the utilization of oxygen by fully oxidized activated sludge was independent of the quantity of dissolved oxygen present in the supernatant liquor. He pointed out that "...it would seem that the present practice of maintaining a high oxygen content in the tanks is wasteful" after showing that "...sludge absorbs oxygen from the water just as rapidly when there are only a few parts per million in solution as it does when the water is almost saturated". Further, he points out that his results "...would make it appear that the first tanks in a continuous flow series might well receive a greater proportion of air".

In recognition of Nordell's pioneer work in this field, Kessler, in his research work to check the above discoveries, adopted, for what had been called the "oxygen utilization", the term "Nordell Number", parts per million of oxygen used per hour by the biological activity of the activated sludge mixture. Kessler's research was performed at the Monroe, Wisconsin, sewage treatment plant, which, at that time was not producing a well-activated sludge. The sludge used in the experiments was therefore built up and maintained in a separate tank (7).

The research work at the Monroe plant completed, Kessler conducted tests at numerous activated sludge plants throughout the country to check his results. "Oxygen Utilization by Activated Sludge", published by Kessler and Nichols summarizes the results obtained. They conclude, from these experiments and tests, that (1) their results will indicate a more successful and economical operation of activated sludge plants; (2) activated sludge must be given the required amount of free oxygen, and as the treatment process progresses, the amount of oxygen to be furnished can be decreased in accordance with the observed Nordell Number obtained; and (3) the Nordell Number, together with relation established for it, provides the plant operator with a simple means of determining the sewage strength, the stage of oxidation, and the condition of activity of the sludge within about an hour's time.

Nature of Experiments and Tests

It was believed that the Pasadena Sewage Treatment Plant would offer means for (1) checking the results obtained by Kessler at other activated sludge plants and (2) indicating a simple method by which an operator can affect improvements in operation, if Nordell's and Kessler's effects are found to be present.

Tests by Nordell and Kessler were performed principally in experimental aeration tanks operated by the "draw and fill" scheme. Although this method is to be preferred for research observations, it is not bery practicable for most plant operators, and as above mentioned, it is our purpose to indicate a method for the operator to test the operation of his aeration units. Therefore, our tests were run on sewage-sludge mixtures as they appeared in the aeration tank of the Pasadena Plant. There are many factors which enter into this procedure, and these will be discussed in the following paragraphs.

Essentially, our experiments consist in determining the oxygen requirements (Nordell Number) of a sewage-sludge mixture as it undergoes its normal process of aeration. This would entail taking samples of the mixture as it enters the aeration unit, and taking succeeding samples of the SAME mixture as it proceeds through the aeration tanks. This would mean that a second sample would be taken in the aeration system at a time when the mixture would be computed to appear at the second point under the condidions of flow existant at the time. Similarly with the third sample, and so on, until a sample is taken at the effluent end of the aeration tanks at the termination of the computed detention period. This is precisely what was done in Kessler's survey at Newark, New York; Morristown, New Jersey; Bernardsville, N. J.; and Madison-Chatham, New Jersey.

It is obvious that the validity of the samples taken by this method is questionable, due to mixing of the mixture in the aeration tank, an effect commonly termed "short circuiting", rather than a uniform passage of the liquid through the tanks from influent to effluent end. This would especially be true in aeration tanks where there is violent agitation of the flow, as exista in spiral flow tanks. The effect would also be noted in a tank with transverse baffles along its length, or in aeration units made up of many tanks in series. The longer the detention period in a tank, the greater would be the "short circuiting", as can be observed from an observation of the ordinary open channel with rapid flow. This detention of liquids in continuous flow tanks was treated by Kehr (2) very completely, and is applied to the new Pasadena aeration tanks in another section of this paper in an attempt to establish the effect of this mixing on samples taken at different points along the tanks.

It is also seen that, in order to trace the flow of sewage through the aeration tanks of any plant, samples must be taken over a period of time equalling the detention period for that flow. For normal flow in the new aeration unit at the Pasadena plant, the detention period is six hours. As may be seen by observation of the hourly flow curves (see Figure 1) the design flow which provides for the six-hour detention period is not exceeded, this flow being three million gallons per day. Therefore the minimum amount of time for a complete sampling of any flow is six hours, and for early morning hours, with its extremely low flows, this time must be much greater. As mentioned earlier in the paper, it was impossible to run tests to satisfy this requirement, except on special occasions.

A different procedure was therefore resorted to, a procedure which, while not being adaptable to other plants, is not found to be necessary when samples can be taken throughout the day. As described more fully elsewhere in this paper,

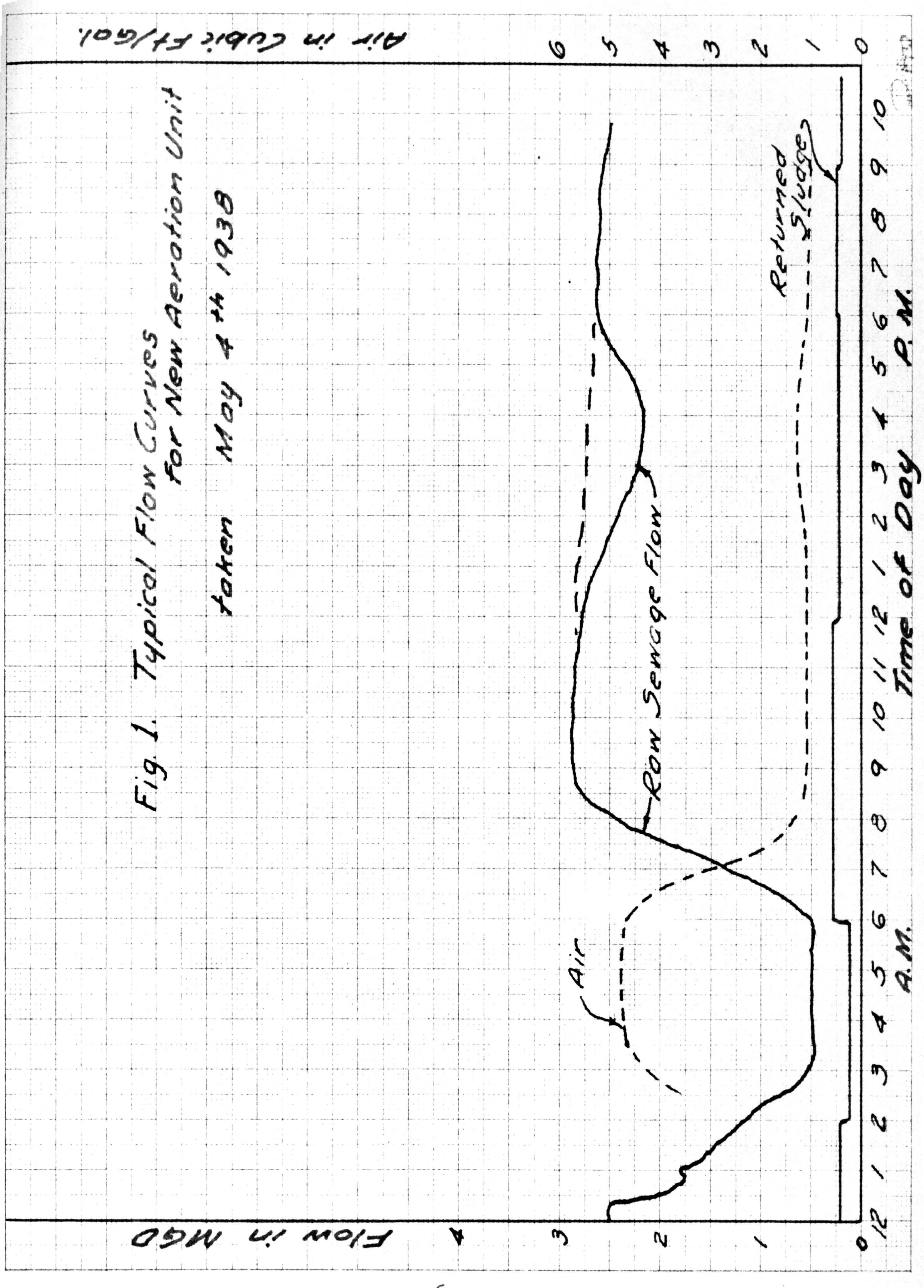


Fig. 1. Typical Flow Curves for New Aeration Unit taken May 4th 1938

the aeration unit from which the samples are taken comprises an auxiliary unit constructed to augment the original units of the Pasadena plant. For this reason, whereas at most plants the hourly variation in raw sewage flow is very great, the flow into the new unit is allowed to reach design flow, but is not allowed to exceed it, and during the hours from about 9:00 AM to late afternoon, the flow in this unit is relatively constant. For this reason it is possible to take samples in the various aeration tanks within a period of three hours, and reasonably compute the period of aeration for each sample. There is one factor, however, which keeps this method of sampling from being as representative as the more ideal scheme of actually following a mixture of sewage-sludge (neglecting, of course, the short-circuiting effect) through the tanks. This factor is the hourly variation of sewage strength (see Figure 2).

If two samples were taken simultaneously, one half-way through the aeration tanks, and the other at the effluent end of the tanks, while the aeration period of the second might be twice that of the first, because of the constancy of flow, the two values for oxygen utilization determined from these samples have questionable relation. The second sample might quite possibly have been of a sewage that was much stronger than the first, distorting the effect of aeration. While under the circumstances, little could be done to remedy this condition of sampling, it is not difficult to adjust the values obtained for this variation in sewage strength. This factor will be taken into account in the analysis of results.

Besides these reasons for errors in sampling, which errors may be estimated, there are others which are less liable of analysis. The presence of an unaerated core in the spiral aeration tank, with an extensively aerated portion near the surface, and the poor homogeneity of sewage samples in general present difficulties which cannot be eliminated with even the use of a sampler designed to provide good displacement

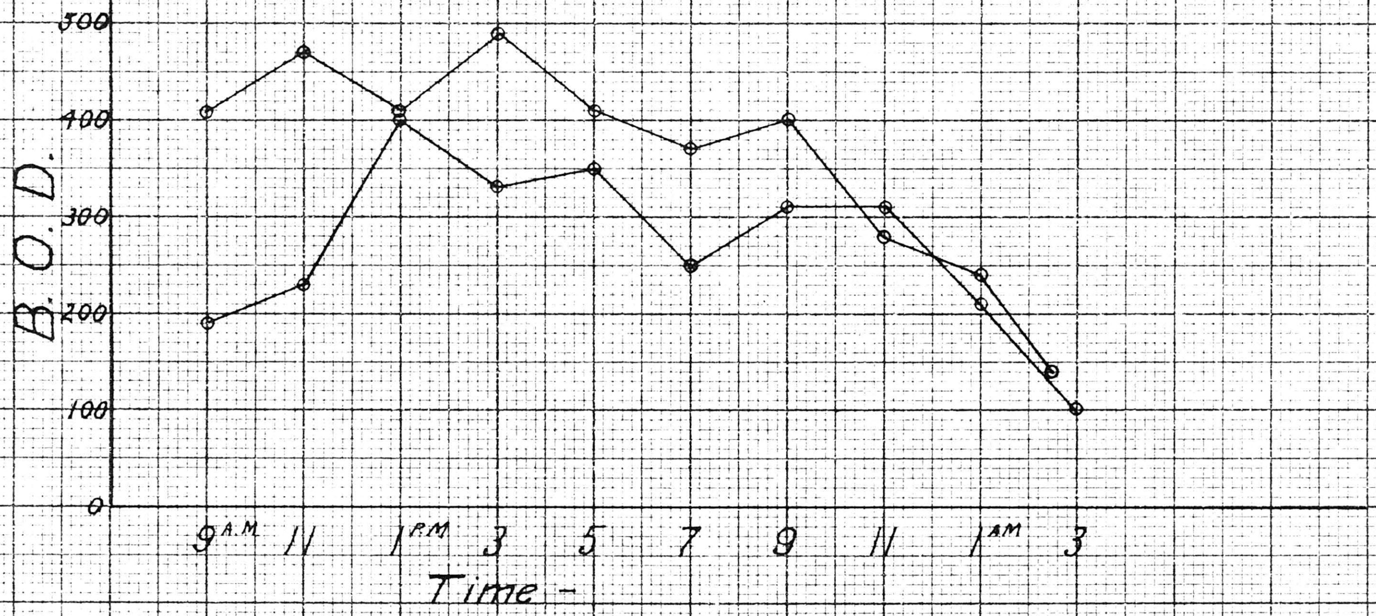


Fig. 2. Hourly Variation in Sewage Strength

in the sampling cylinder of sewage well under the surface of the liquid. These effects can only be reduced, when making tests in an actual plant, by many repetitions of observations.

The measurement of the oxygen utilization (Nordell Number) of a sample of sewage-sludge mixture is another point of difficulty. Kessler improved on Nordell's method principally by using copper sulphate, as a coagulant, to settle the solids quickly, so that the supernatant can be used to run the Winkler test for dissolved oxygen. To allow the ordinary time for settling would require too much time, especially with bulking sludges. The copper sulphate was also found to inhibit oxygen utilization immediately after its addition to a sewage-sludge mixture, an important property for accurate determination of the Nordell Number. The liberation of iodine by the cupric ion affects the actual dissolved oxygen determination, but is not a factor when simple differences are taken, as in the Nordell Number determination.

The actual determination of the Nordell Number consists of measuring the depletion of dissolved oxygen content of a sample in a given time interval. However, as the dissolved oxygen present in the aeration tank was very small, not allowing for any depletion, it was found necessary to aerate the sample, and then make the determination. Aeration was accomplished by bubbling air through the sample. A detailed description of the procedure is given in another section of the paper.

Theory of Oxygen Utilization of Activated Sludge

The following is a summary of the theory of the oxygen utilization of activated sludge as formulated by Kessler, Nordell and others in the last few years:

Definition of terms:

N - The rate of oxygen utilization in parts per million per hour. Called the Nordell Number. An index of sludge activity.

M - Maximum sludge activity.

K - An index of sewage strength.

T_m - Time the maximum oxygen utilization persists.

R - Ratio of M/N required to produce a well-activated sludge within the aeration period.

T - Time from the instant the sludge and raw sewage are mixed and begin aeration.

The relationships as established by Kessler and illustrated by the curves shown are:

(1) The length of time for which the maximum sludge activity persists is proportional to the sewage strength. (See Figure 3).

(2) With a fixed condition of returned sludge, the aeration period required to produce a well activated sludge varies directly with the strength of the incoming sewage. (See Figure 3).

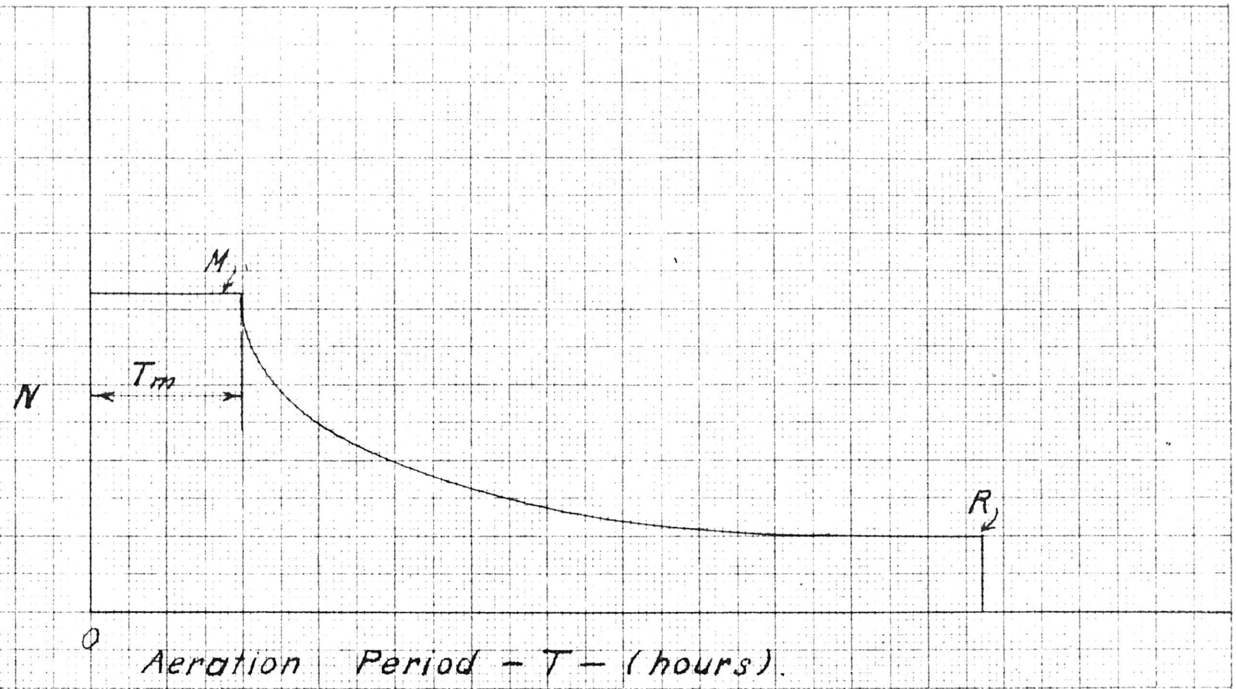
(3) With any given sewage, the aeration period required to produce a well-activated sludge varies inversely with the maximum sludge activity. (See Figure 4).

The value of the Nordell Number:

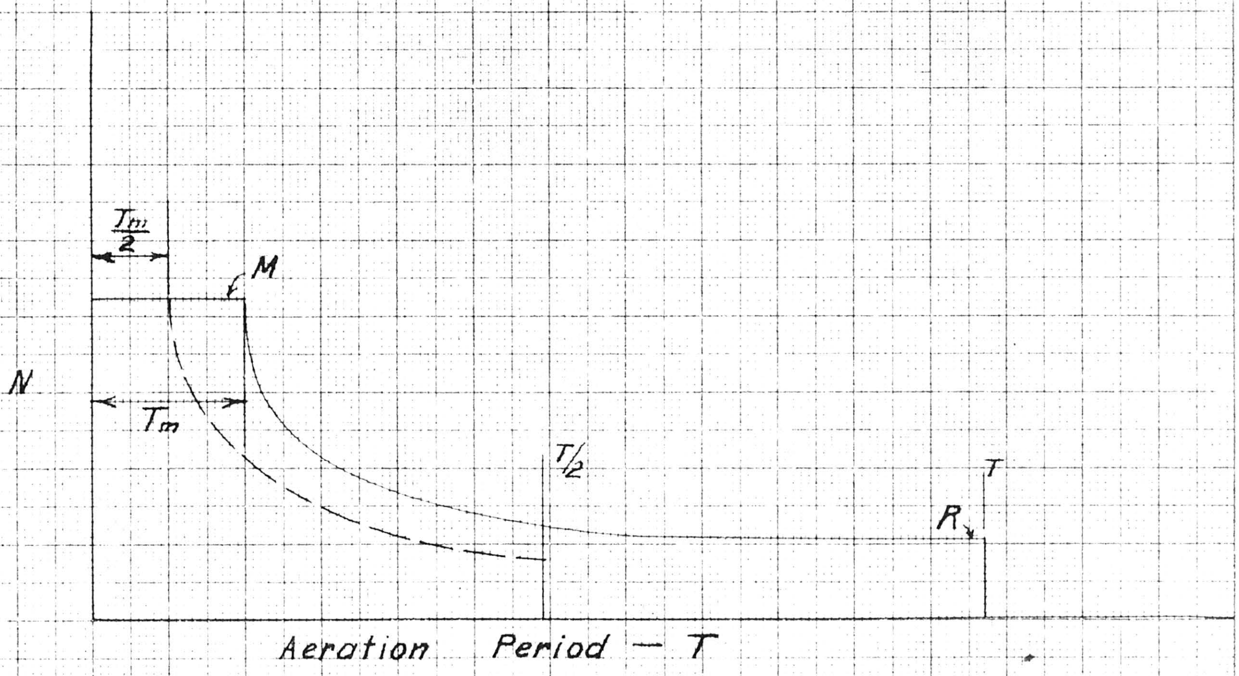
Nordell established, as a result of his investigations, the following value for the Nordell Number:

$$N = \frac{M}{C\sqrt{T - T_m} + 1}$$

where C is a constant, the square of which is apparently inversely proportional to the sewage strength.



Characteristic Curve of the Rate of Oxygen Utilization by Activated Sludge — Sewage Mixtures During the Aeration Period.



The Effect of a Variation in the Sewage Strength Sludge Activity held constant.

Fig. 3.

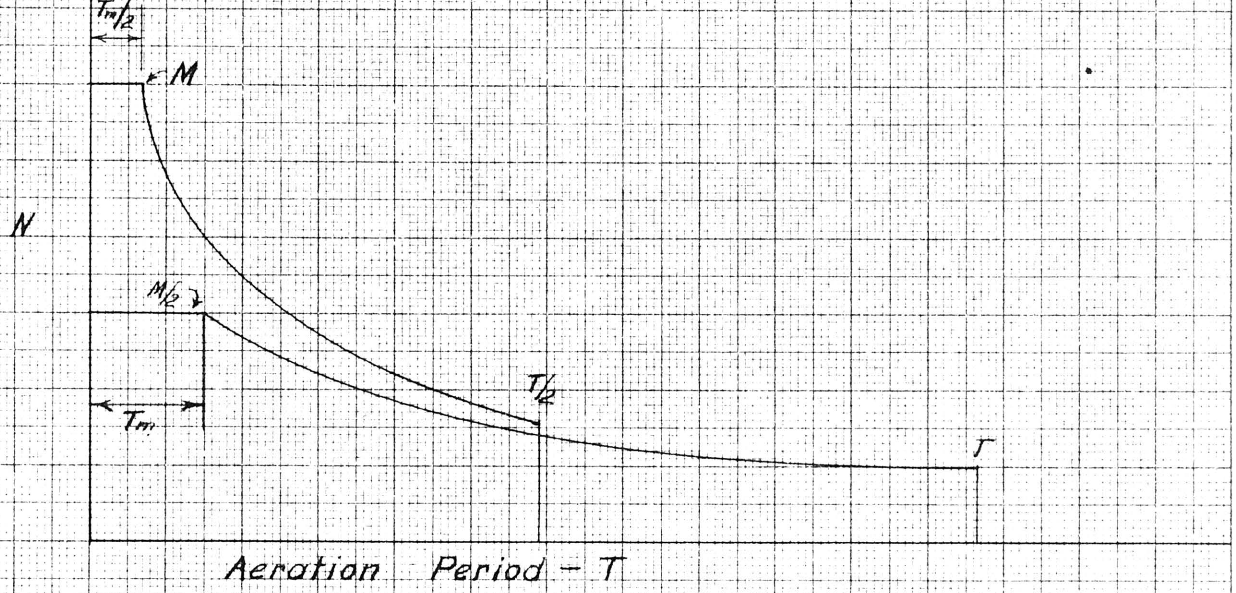


Fig. 4. The Effect of a Variation in the Maximum Sludge Activity. Sewage Strength held constant.

Kessler devised the use of the term "K" to designate sewage strength. As mentioned under (1), T_m in time units is proportional to the sewage strength. Therefore, sewage strength was designated as T_m. It had been found that for the same activated sludge treating sewages of varying strength, T_m, the maximum rate of oxygen utilization, M, for that sludge, multiplied by T_m in time units is a constant varying directly with T_m. This value Kessler designated as "K" because it takes into account the maximum rate of oxygen usage possible, M, with any given sludge, which T_m of course failed to do. Then $MT_m = K$. C^2 was inversely proportional to sewage strength, T_m, and therefore equal to M/K. Then Kessler obtained

$$N = \frac{M}{\sqrt{(MT/K) - 1} + 1}$$

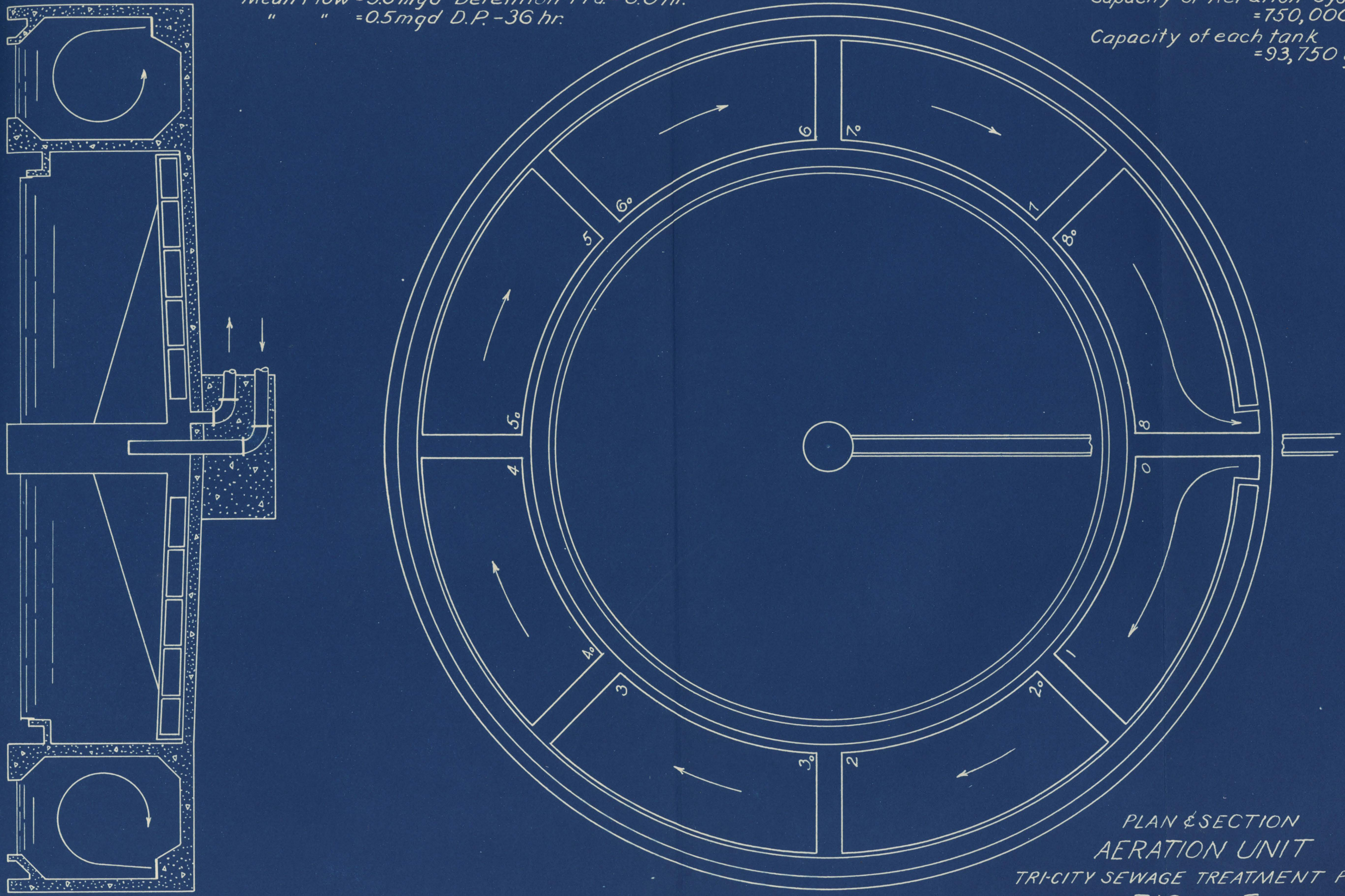
where K is a dimensional quantity in parts per million of oxygen, and solving for K,

$$K = \frac{MT}{\frac{(M - N)^2}{N^2} + 1}$$

From these relations it will be possible to compare the results obtained at the Pasadena plant with the empirical relations established by Kessler. Also, to propose methods for using these principals to adjust aeration tank operation.

Mean Flow = 3.0 mgd Detention Prd. - 6.0 hr.
" " = 0.5 mgd D.P. - 36 hr.

Capacity of Aeration System
= 750,000 gal.
Capacity of each tank
= 93,750 gal.



PLAN & SECTION
AERATION UNIT
TRI-CITY SEWAGE TREATMENT PLANT
FIG NO. 5

Description of the New Aeration Unit at the Pasadena Sewage Treatment Plant

The new unit at the Pasadena Sewage Treatment Plant, completed in the fall of 1937, was designed to augment the activated sludge plant previously operating, by taking three million gallons per day from the peak load which had been overloading the plant. The unit provides only for aeration and clarification, and must therefore get its reaerated returned sludge from the older units, and its operation is tied up, therefore, with the operating conditions existant in these units.

The raw sewage reaches the plant by gravity flow, passes through a mechanically cleaned bar screen, and then through a comminutor. At this point the sewage is divided, a maximum of about 3 mgd going into the new unit, and the remainder proceeding on to the older part of the plant. Although there is provision for grease and grit collection with the original plant, this is not available to the sewage entering the new unit.

The sewage then passes into a measuring flume, where a recording meter constantly registers the sewage flow into the new unit. There are also recording devices for the returned sludge flow and for the total quantity of air being blown into the new unit. There is, however, no accurate method for determining the actual quantity of air being blown into each of the aeration tanks, other than by observation of the agitated surface.

After being measured, the raw sewage and the returned sludge, which had been previously reaerated, are mixed and the mixture enters the aeration tank, at the surface.

The new aeration unit (see Figure 5) is placed around the periphery of the circular clarifier. It is designed for a six-hour detention period with a three million gallon per day flow of sewage sludge mixture in the tanks.

The unit is divided into eight tanks by transverse concrete walls, through which the mixture flows by an off-center opening. Looking at the unit in plan, the mixture flows in a clockwise direction, leaving the tanks at the southermost point, where it entered, after completing a 360° circuit of the unit.

Air is blown into the tanks through diffuser plates placed in the bottom, along the length of flow, but near the outside wall of the tanks, providing what is commonly termed "spiral aeration". The amount of air blown into any section may be controlled roughly by valves on the outside of the tanks.

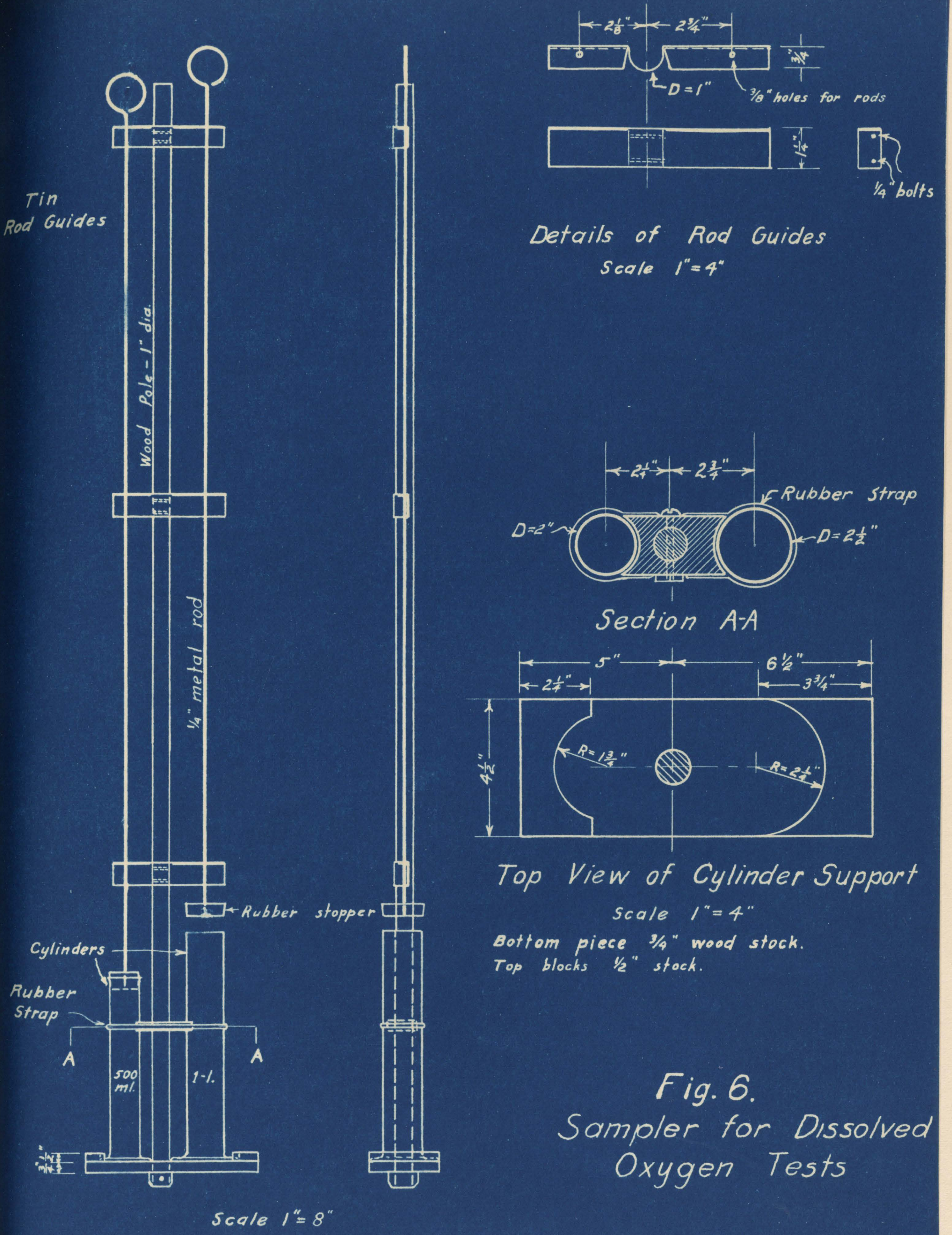
The aerated mixture is carried to the clarifier located at the center of the aeration tanks. The clarifier is, of course, circular in plan, and is equipped with rotating sludge scrapers. The supernatant flows over the peripheral weir. The sludge which is drawn off returns to the original plant for aeration, the excess being used in the manufacture of fertilizer carried on at the plant.

Description of Methods of Collecting Samples

In order to prevent additional aeration of samples as they were collected it was found necessary to devise a means of securing samples below the surface of the sewage. Accordingly the sampler shown in Figure 6 was designed to serve this purpose. This consisted of a wooden pole about six feet long on the end of which was fastened a light wooden board on which to rest the sample cylinders. The cylinders were held in place by wood stops and by rubber straps as shown. In order to secure the sample from below the surface os the sewage rubber stoppers were fastened on the ends of steel rods which acted along the pole in the nature of plungers. With this equipment samples were secured by fastening cylinders on the bottom of the sampler, inserting the stoppers, and lowering into the liquid. The stoppers were removed until the cylinders were filled and until about a three-fold displacement of the liquid in the cylinders was secured; then the cylinders were re-stoppered while still under the surface. It was believed that this method secured as nearly representative samples as possible. Due to the velocity of the sewage some difficulty was experienced in actually collecting the samples and extra care had to be exercised. The apparatus used is so simple to make and use that it should be easily adaptable to any situation.

Two sizes of cylinders were used for collecting the samples: 1000 ml. and 500 ml. The original purpose of this was to take samples for determining settling characteristics in the larger cylinder and to take samples for dissolved oxygen tests in the smaller cylinder. Later when tests for oxygen utilization were started it was necessary to secure larger samples so the 1000 ml. cylinders were used and the smaller cylinders were used only to collect samples for determination of actual DO.

After the samples were removed from the sewage the cylinders



Scale 1" = 8"

Details of Rod Guides
Scale 1" = 4"

Section A-A

Top View of Cylinder Support
Scale 1" = 4"
Bottom piece 3/4" wood stock.
Top blocks 1/2" stock.

Fig. 6.
Sampler for Dissolved Oxygen Tests

were immediately removed from the sampler and stoppers placed in them. When taking samples for determination of DO care was exercised to prevent the entrainment of any air in the cylinder.

Settling Tests

In determining the settling characteristics of the sewage sludge mixture from the aeration tanks, two factors were considered, namely, the rate at which the sludge subsided, and the clarification resulting in the supernatant liquor.

The sewage-sludge mixture, after being collected in the 1000 ml. cylinder, was kept agitated until it reached the laboratory, after which, with a final stirring, it was allowed to settle. The amount of time elapsing between sampling and laboratory settling was kept to a maximum of 10 minutes.

In order to eliminate as many variables as possible, identical graduates were used, and four settling tests were run simultaneously. The various effects due to shape of container, temperature, stirring etc. are discussed very fully by Rudolfs and Lacy (4).

Observations were made on the percentage of sludge by volume formed after varying periods of settlement.

After a suitable period of clarification, usually one and one-half or two hours, a 50 ml. or 100 ml. sample was taken from the supernatant for a determination of the quantity of suspended solids present. Although a tedious procedure, the Gooch crucible method was the only method available for measuring the extent of clarification of the supernatant. It is believed that the quickest method for the determination would be with the use of the Jackson Candle Turbidimeter.

It was found that by using a minimum amount of asbestos cream as many as four and five determinations could be made per crucible matting, cutting the number of weighings necessary in half. Care muct be taken, however, that with the matting so thin, no spaces are left through which the solids may percolate.

Dissolved Oxygen Tests

Due to the possible presence of ferrous salts or nitrites in the samples the Rideal-Stewart or permanganate modification of the Winkler method was used for all tests. As a matter of fact during the period that the tests were carried out there was practically no nitrification going on in the aeration unit. Usually titration was made immediately after completion of the test so that high results from the presence of ferric salts owing to the liberation of iodine from iodides in the final step of the test were not a factor. The procedures used were taken from "Standard Methods" of the American Public Health Association (9).

The bottles used for the tests ranged in size from 265 to 300 ml. capacity but were considered to be near enough to the same size so that the same quantities of reagents were added to all of them.

The first step in the permanganate modification was the addition of exactly 0.7 ml. of sulphuric acid. This was added with a 1 ml. pipette and was allowed to trickle down the side of the bottle. Permanganate solution was then added until a permanent violet coloration was obtained. For most of the tests an initial amount of 1.5 ml. was added and an additional 0.5 ml. was then added if necessary after allowing solution to stand for five minutes. However, for the samples taken during the early morning, when the sewage was very weak, it was found that only 0.6 or 0.7 ml. of permanganate solution was necessary to obtain a permanent violet color. This reduction in the amount of permanganate necessary was probably due to reduced organic matter present in the weaker sewage. When it was apparent that additional permanganate would be necessary it was added while a faint violet tinge still persisted and before the appearance of brownish colorations. Thorough mixing followed each addition of permanganate solution. As with all other solutions, except sulphuric acid, the permanganate solution was added just below the surface of the liquid.

After letting the sample stand for five minutes the excess permanganate was removed by the addition of a small amount of potassium oxalate. Usually an initial amount of 0.5 ml. was added; if permanent decolorization was not then secured an additional 0.5 ml. portion was added in order to be sure that complete decolorization was secured. Some times this second portion was only 0.2 or 0.3 ml. if it appeared that only that amount was necessary, since it is not advisable to have too great an excess of oxalate. After each addition of oxalate the sample was shaken and allowed to stand for at least five minutes.

After the sample had stood for five minutes and the permanganate was fully decolorized, 1 ml. of manganous sulfate solution and 3 ml. of alkaline-iodide reagent were added below the surface. The bottles were then well shaken and the precipitate was allowed to settle part way and the bottle was then shaken again. If a clear supernatant was not obtained the shaking was repeated to be sure that all dissolved oxygen was absorbed.

The sample was then acidified by the addition of 1 ml. of sulphuric acid by allowing the acid to run down the sides of the bottles. Immediately after the addition of the acid the samples were shaken to avoid the reduction of manganic salts by organic materials. After the samples had been acidified they were usually clear and had a yellow color. In case there was still some precipitate left in the sample a slight amount of acid was added in addition to the above. The samples were allowed to stand for a few minutes before proceeding with the titration.

A correction for the loss of dissolved oxygen by displacement with the reagents was made to the amount measured out for titration. Assuming an average size of bottle of 280 ml. and desiring to titrate 200 ml. of the sample the following correction was made:

(200 x 280)/(280 - 5.7) = 204 ml. should be measured out. Although the bottles used varied in size from 265 to 300 ml. it was found that this variation had practically no effect on the amount to be measured out for titration. Approximately 204 ml. of the sample was titrated with N/40 sodium thiosulfate until the yellow color was almost gone or was equivalent to a pale straw color. This should be equivalent to about 0.5 ml. of thiosulfate solution. Then 1 or 2 mls. of starch solution was added and the titration was continued until the first disappearance of the blue color. Subsequent recolorations of blue occurred seldom and very faintly; they were disregarded.

Usually about four samples were run at one time. Titrations were usually performed within a few minutes after the addition of the sulphuric acid and the bottles were kept stoppered until the titration was begun.

As two hundred mls. of the sample were titrated the mls. of thiosulfate was exactly equal to the dissolved oxygen in parts per million.

Oxygen Utilization Tests

The purpose of the oxygen utilization tests was to determine the oxygen demand of the sewage at various points in the aeration unit. For the test, two one liter graduates were filled by use of the sampler from the same point on the unit, stoppered, and brought to the laboratory. In the lab air was blown through about 700 ml. in each graduate at the same rate and for varying lengths of time depending on the position in the aeration unit from which the sample was taken. The times used ranged from 2 1/2 to 10 minutes.

After the aeration the samples were poured into two 500 ml. cylinders, half of each cylinder being filled from each graduate. Agitation in pouring was kept to a minimum. One ml. of copper sulphate was then added to one of the cylinders to prevent loss of dissolved oxygen and both cylinders were tightly stoppered without the entrainment of air bubbles. The cylinder to which copper sulphate was added was agitated to secure thorough mixing; the other cylinder was shaken intermittently during a period of time sufficient to cause a depletion of about 2 ppm. of dissolved oxygen. At the end of this period, which ranged from about 2 1/2 minutes to 10 minutes (first tank to eighth, respectively), one ml. of copper sulphate was added to the second cylinder and thoroughly mixed to accelerate settling as well as to prevent further loss of dissolved oxygen.

Finally, after the samples had settled sufficiently, the supernatant liquid was siphoned off into bottles of approximately 270 ml. capacity and the permanganate modification of the Winkler method used to determine the dissolved oxygen present. In no case was the DO content used if found to be below 1.5 ppm. so that the initial DO content was above 3.5 usually around 5.0.

The difference between the DO content of the two supernatants was the reduction in ppm. for the period of shaking of the second bottle. This reduction was converted to a Nordell Number by computation to ppm. per hour.

Detention Period in Aeration Tanks in Series

As mentioned earlier in this paper, there is little appreciation of the fact that all of a liquid entering any tank does very rarely enjoy its full detention period. Calvert, in his operation experiments at Indianapolis (8), found that "...when sludge was added at the halfway point (in an aeration tank), 238 feet from the influent end, it soon worked back in reduced concentration nearly to the influent end".

Kehr, in 1936, analyzed the effect of mixing (2), and established definite relationships of detention period to flow, which he checked with the use of chlorine concentrations added to the influent of series of tanks. The basis for Kehr's theory is the assumption that in each of the tanks in series there is complete mixing. This assumption is seen to be very reasonable for aeration tanks, where there is great agitation, which would provide this mixing, and there is also usually a large transverse cross-sectional area plus a large detention period, all factors which tend to allow for thorough mixing in each tank. It is our purpose to adapt Kehr's work to our own problem, that of eight aeration tanks in series, in an attempt to establish the effect of this mixing on samples taken at various points along the aeration tanks.

Before using the relationships Kehr obtained for chlorine, it is thought wise for us to derive these expressions with an end in view of applying them for our own purposes.

Let X = total fresh sewage-sludge mixture in a tank.
t = time from the addition of this fresh mixture.
w = volume of influent per unit of time.
W = volume of tank.
$R = w/W$, reciprocal of displacement time.

For our purposes it can be assumed that the fresh mixture is unique, and before the addition of this mixture, there was none present in the tank. Then, assuming a unit amount of fresh mixture added per unit of time, the rate of increase of this mixture in a tank will be the amount added less the amount leaving:

$$\frac{dX}{dt} = 1 - RX$$

solving this differential equation

$$dt = \frac{dX}{1 - RX}$$

taking limits for t, from 0 to t, and for X from 0 to X:

$$(t)_0^t = \left(-\frac{1}{R}\log_e(1 - RX)\right)_0^X$$

$$t = -\frac{1}{R}\log_e(1 - RX)$$

$$e^{-Rt} = 1 - RX$$

$$RX = 1 - e^{-Rt}$$

where RX would be the ratio of effluent to influent, or the decimal part of the fresh mixture influent which will appear as effluent from a tank in time t.

For tanks in series, we assume that there is complete mixing in each tank, as discussed above. With two tanks in series, the volume of each tank will be W/2. The rate of increase of the mixture entering the second tank is $\frac{dX_2}{dt}$, which equals the effluent leaving the first tank (influent to the second tank) minus effluent from the second tank:

$$dX_2 = 2RX_1dt - 2RX_2dt$$

where $\frac{w}{W/2} = 2R$ and $X_1 = \frac{1 - e^{-2Rt}}{2R}$ from above.

Then

$$dX_2 = (1 - e^{-2Rt})dt - 2RX_2dt$$

and

$$\frac{dX_2}{dt} + 2RX_2 = 1 - e^{-2Rt}$$

if $f = e^{2Rdt}$

then

$$e^{2Rt}dX_2 + 2Re^{2Rt}X_2dt = (e^{2Rt} - 1)dt$$

and

$$X_2e^{2Rt} = \frac{e^{2Rt}}{2R} - t + C$$

$$2RX_2 = 1 - 2Rte^{-2Rt} + 2Re^{-2Rt}C$$

$$2RX_2 = 1 - 2Re^{-2Rt}(t + C)$$

when $t = 0$, and $X_2 = 0$, then $C = 1/2R$
and the final expression is

$$\underline{2RX_2 = 1 - e^{-2Rt}(1 + 2Rt)}$$

for two tanks in series.

In general, for N number of tanks in series, it may further be shown, extending the above procedure, that

$$NRX_n = 1 - e^{-NRt}(1 + NRt + \frac{(NRt)^2}{2\,!} + \frac{(NRt)^3}{3\,!} + \cdots\cdots + \frac{(NRt)^{N-1}}{(N - 1)\,!})$$

where NRX_n is the decimal part of the influent mixture to the series of tanks, that appears as effluent from the Nth tank by time t. If we call $Rt = D$, some part of the theoretical detention period, then if we establish NRX_n for any detention period, or fractional part of the detention period, it becomes a simple matter to adjust our computations for any flow. Since $D=Rt$, and $N=8$;

$$8RX_8 = 1 - e^{-8D}(1 + 8D + \frac{(8D)^2}{2\,!} + \frac{(8D)^3}{3\,!} + \cdots\cdots + \frac{(8D)^7}{7\,!})$$

This expression will give the decimal part of the influent to the series of tanks which will have appeared at the effluent end of the last tank after any part of the detention period D. An expression will also be set up to determine that part of the influent which will appear at the effluent of any one of the other intermediate tanks, after any part of its detention period.

Taking the expressions shown, the percentage of influent reaching the effluent of the first, second, fourth, sixth, and eighth tanks was computed for 0.1, 0.25, 0.5, 0.75, 0.9, 1.0, 1.25, 1.50, and 2.0 times the detention period. In using the above expressions for these various combinations of tanks and detention periods, the number of tanks from which the effluent is desired is substituted for "N" and this number of terms is used on the right hand side of the equation. The decimal part of the detention period for which the effluent is desired is substituted wherever "D" appears in the equation.

The results obtained are summarized as follows:

	Decimal Part of Theoritical Detention Period								
Tank No.	0.1	0.25	0.50	0.75	0.90	1.00	1.25	1.50	2.00
1	9.5%	22.1%	39.4%	52.8%	59.3%	63.2%	71.4%	77.7%	86.5%
2	1.7	9.0	26.4	44.3	53.8	59.5	71.3	80.0	91.0
4	0.0	1.8	14.6	35.2	48.5	56.6	73.6	84.9	95.8
6	0.0	0.5	8.4	29.7	45.5	55.4	75.8	88.4	98.0
8	0.0	0.4	5.2	25.8	43.3	54.8	78.3	91.1	99.0

The percentages indicate that part of the influent which appears as effluent from the indicated tank at the end of the indicated portion of the theoretical detention period for that number of tanks.

These figures are plotted and curves are shown in Figure 7. In this set of curves it is possible to observe the variation of the actual flow through the tanks with that flow that is assumed to have its theoretical detention period. For theoretical detention, none of the influent should reach the effluent until the detention period is reached, and when this time is reached, all the influent should pass out with none remaining to appear as effluent afterwards. Obviously, from these curves in Figure 7, when complete mixing is assumed in each tank of a series, there is considerable distortion from theoretical assumption of detention. For example, more than 5% of a fresh mixture reaches the end of eight tanks in series in half the detention period. At the end of the theoretical detention period, only 55% of the total fresh mixture has succeeded in passing through all the tanks. At the end of one and one-half the detention period, there is still about 9% of the influent that is still in the tanks.

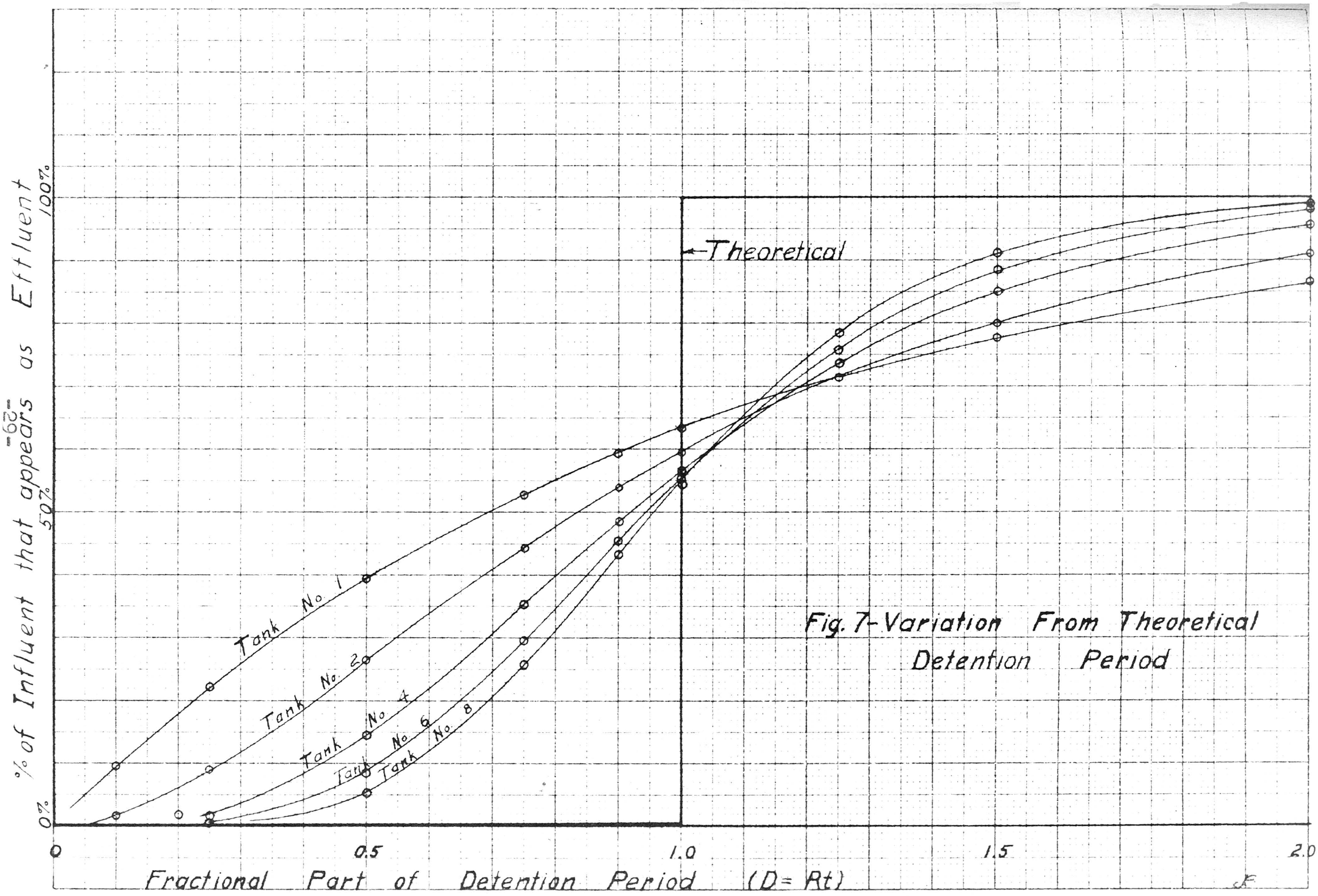


Fig. 7-Variation From Theoretical Detention Period

These effects are more striking at the end of the intermediate tanks. To indicate the effect at the ends of different numbers of tanks in series, additional curves were drawn, see Figure 8.

From this set of curves, together with those discussed above from Figure 7, it is easily seen that the effect of short circuiting is much more apparent the fewer the number of tanks in series. This would mean, roughly speaking, that samples taken at the end of the first few tanks would be less accurate representations of the influent than those taken towards the end of the series. This was to be expected, because the effect of baffling continuous flow tanks is a diminishing of short circuiting.

It must be realized, before extending this treatment any further, that all the figures established, are based on one important assumption; that in each tank there is complete mixing of the influent to that tank with the liquid already in the tank, so that the instant after the addition of influent to a tank, it appears to some extent in the effluent. That this assumption is reasonable has been borne out in many instances, although for complete assurance in the use of these relations, tests should be made on the actual tanks. At the Los Angeles County Pogi Ranch plant, with long (169 feet) aeration tanks, it was found that a comparatively short time was required to make the contents of the tank uniform throughout its length. The effect of the agitation at the Pasadena Plant would be increased by the short length of the tanks, and the long detention period. Therefore it may be said, that if the extreme variation from the theoretical detention is not actually existant, there will be only a slight diminishing in these effects.

Constitution of a Sample: Using the curves in Figure 7 it is possible to draw charts (see Figure 10) which will indicate the constituents of any sample taken at the end of any

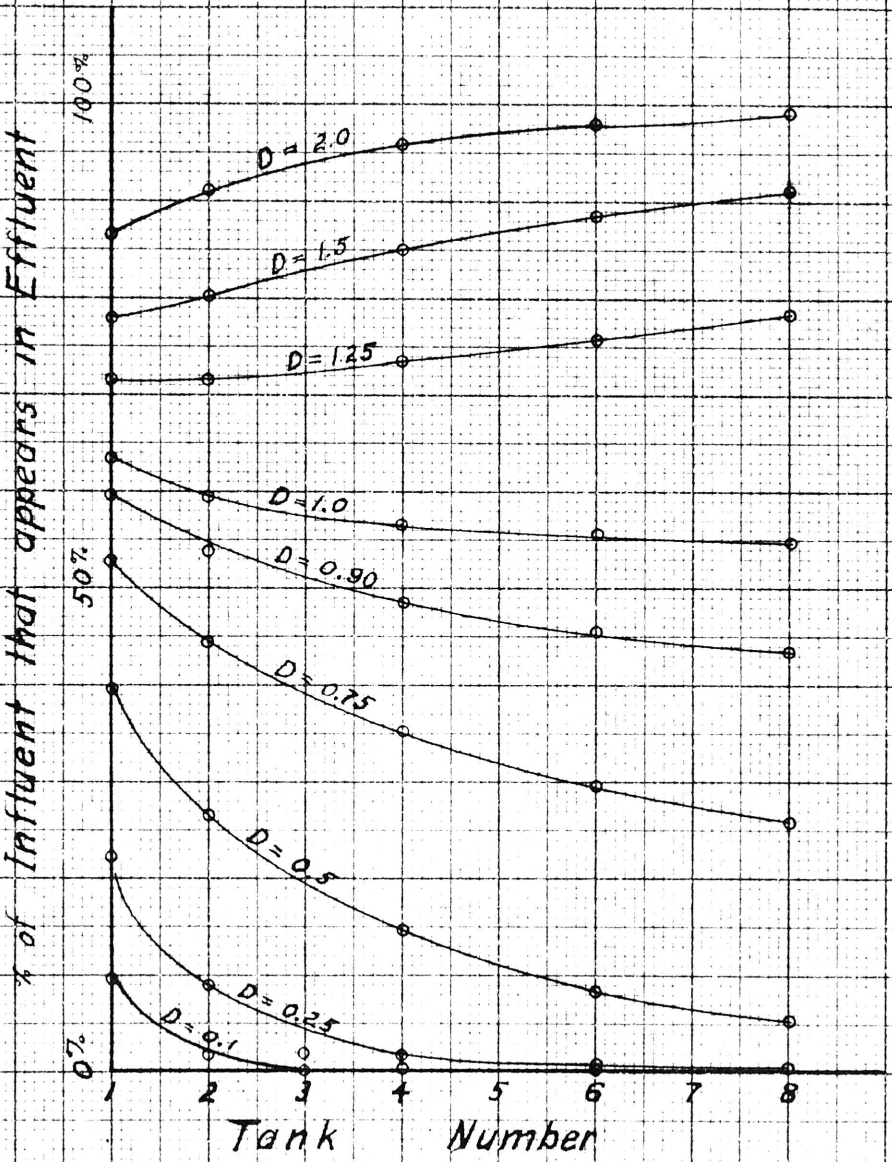


Fig. 8. Effect of Tanks in series on Natural Detention Period.

B

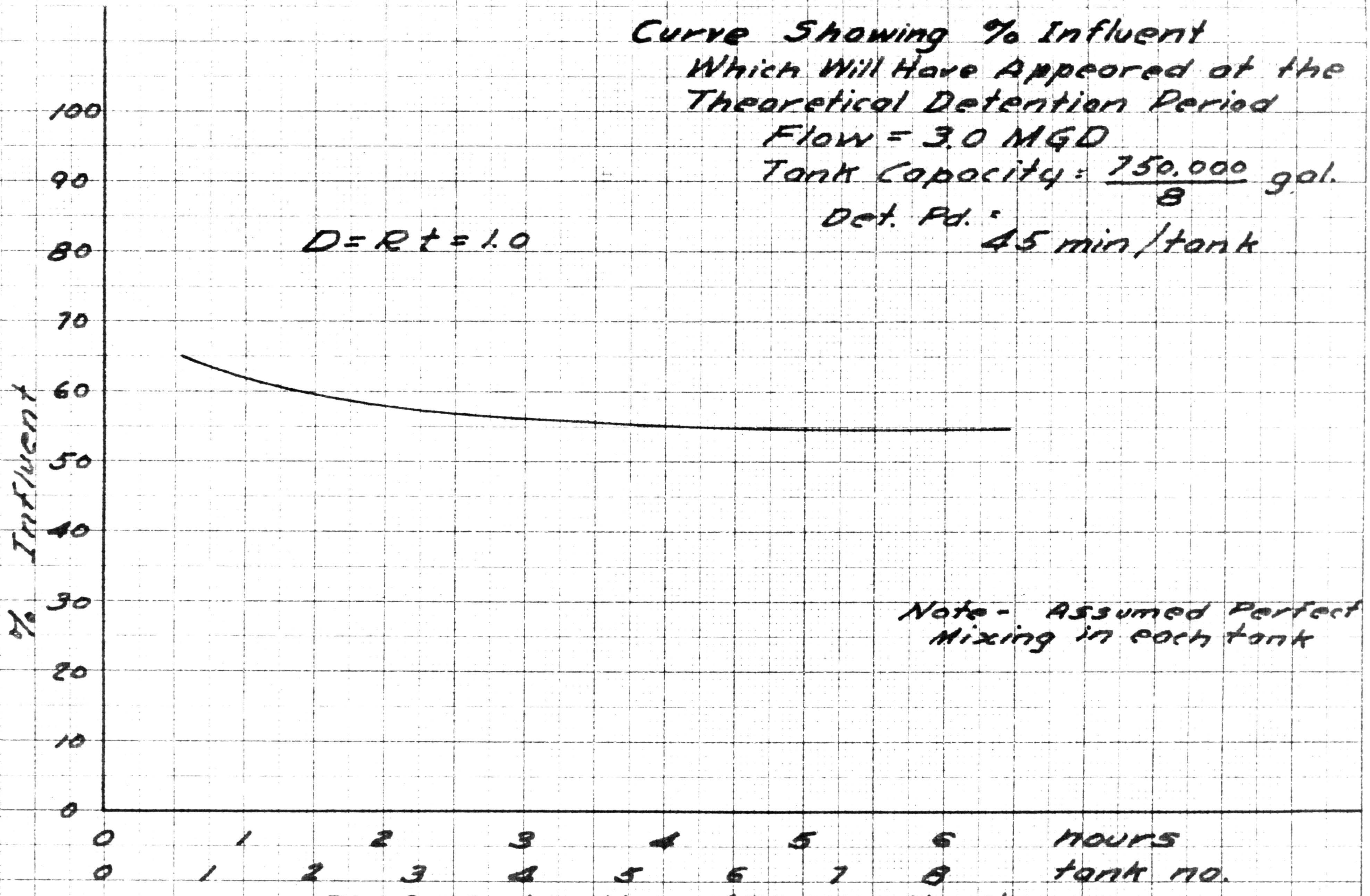


Fig. 9. Detention (theoretical)

of the series of aeration tanks. This is done by assuming some convenient increment of detention period, say one-tenth of the theoretical detention period, and from the above mentioned curves establishing the percentage of the influent which reaches the effluent for each of the one-tenth detention period increments. This will give, for a sample taken at any time, the composition of the sample, in percent, which entered the aeration system during different times previous to the sampling. This is done for samples taken at the end of the intermediate tanks, as well as those taken at the end of the full series of tanks.

For example, referring to the chart in Figure 10, in a sample taken at the end of the eighth tank, about 7% of the sample had been aerated for from 0.5 to 0.6 of the detention period of the flow, while about 12% of the sample had been aerated for from 0.9 to 1.0 times the detention period. Or stating it differently, assuming a six-hour detention period for the eight tanks, 7% of the sample taken at any time had entered the aeration tanks from 3 hours to 3 hours 36 minutes previous, while only 12% had entered from 5 hours 24 minutes to the theoretical 6 hours previous. In the case of a sample taken at the end of the first tank, with a detention period of one-eighth the six hours, or 45 minutes, 9 1/2 % of the sample entered the tank from 4 1/2 minutes previous to the actual time the sample was taken.

The chart indicates cogently the effect of mixing in the tanks on samples and on the operation of aeration tanks. It also illustrates graphically the effect of the number of tanks in series on the operation of the aeration tanks. Although the effect of the short-circuiting is least at the end of the eighth tank it is seen that goodly portions of the sample are made up from mixture which entered the aeration system much before and much after the theoretical detention period previous. This effect is seen to increase with samples taken from the other tanks, in that the maximum on the chart

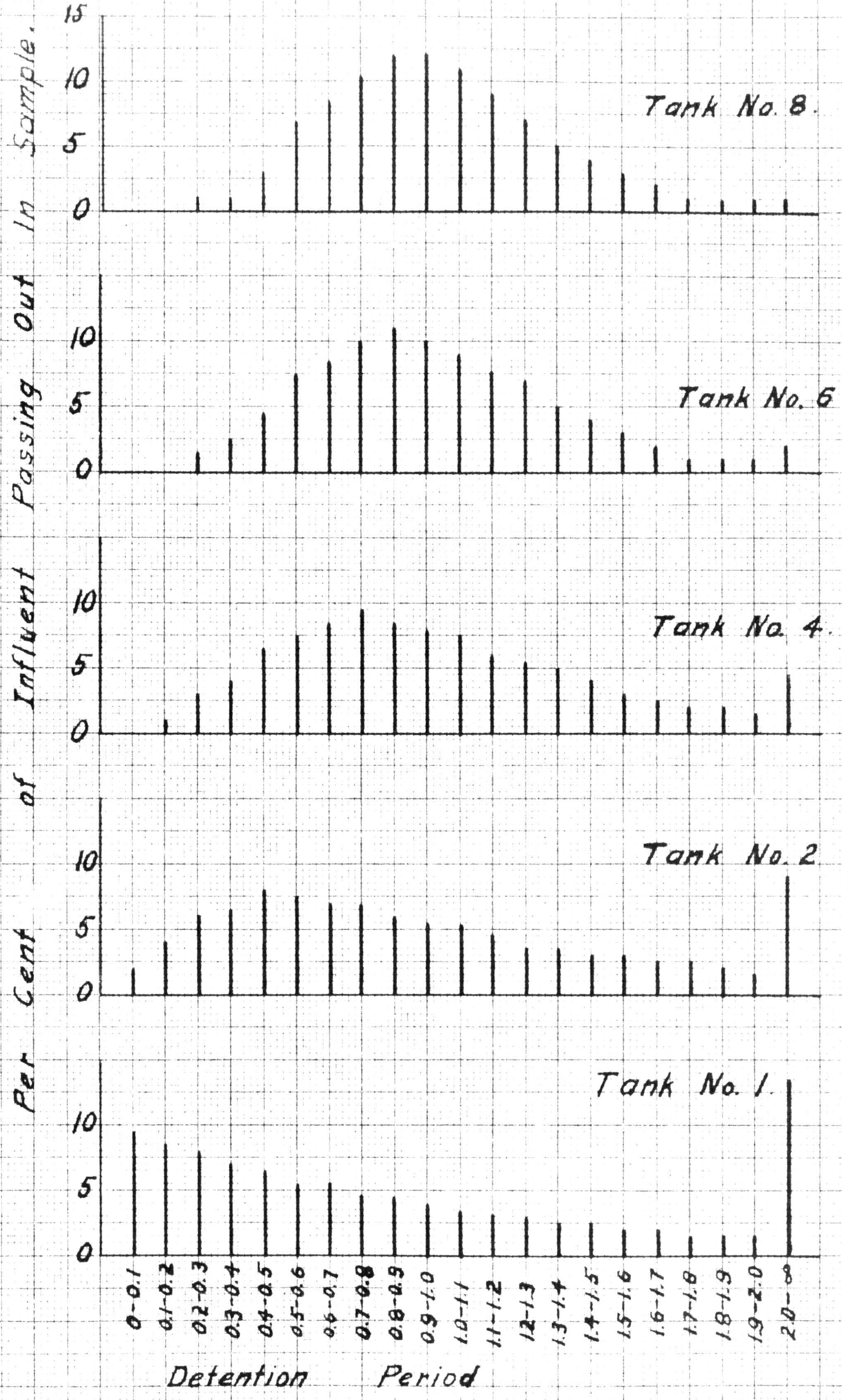


Fig. 10. Chart Showing Actual Composition of any Sample.

shifts to the left as the number of tanks becomes fewer.

For research work, the chart can be used to indicate how corrections should be made with any sample, or at any rate, it illustrates the incorrectness in the procedure often followed (as mentioned concerning Kessler's work). To our knowledge, when investigating in continuous flow tanks there has been no recognition of this very important factor by any of the men in the field. The chart can also be used in researches to make correction for the changes in sewage strength. If there is a sudden increase in sewage strength, when tests were being run on a weak sewage, the entrance of certain percentages of this new stronger sewage into samples of supposed weak sewage could easily be traced, and its effect accurately computed.

Mixing and Aeration Tank Deaign. The curves and the discussion have adequately illustrated the effect of the number of tanks in series in an aeration system on short circuiting. For any detention period, the greater the number of individual tanks in series, the smaller will be the evident effect of short circuiting. This is very important in the design of aeration tanks. It has long been thought, that so long as the proper aeration period is provided, it will not matter whether aeration tanks are in series or in parallel. But the chart shows that with one tank, or even many more, a large part of the effluent is aerated much less than its nominal designed aeration period, causing poor clarification. The fact that some of the effluent is aerated more than its nominal aeration period is no advantage, because it has been shown that clarification is not particularly enhanced by an increase in aeration period over the normal period.

This would then indicate that in aeration tank design, unless the plant is exceptionally large, parallel flow should be avoided, and as many tanks in series be used as is economically possible. Where it is not thought wise to use many tanks, or where the tanks are already built, transverse baffles are recommended to prevent short circuiting of aeration tanks, with its resultant poorer operation.

Mixing on Operation Samples: While it may be necessary to take into account the effect of mixing on samples taken for research purposes, in taking samples for operation tests this should not be done. In making oxygen utilization tests in an attempt to fix the quantity of air to be sent into any aeration unit, continually during actual plant operation short circuiting will exist, and operations shoulw be conducted, not on theoretical detention periods and oxygen demands, but on those which are found to exist. For example, if the Nordell Number of a mixture in the last tank of an aeration system is found to be 25, whereas with its full theoretical detention period it was decided that the Nordell Number is actually 15, air should still be supplied to satisfy a Nordell Number of 25.

Therefore, an operator in making these oxygen utilization tests is not required to determine the effect of short circuiting, but rather to use the actual Nordell Numbers as found. Our tests are much like those that would be made by a plant operator desiring to improve his aeration operation.

Results of Clarification Tests

As described earlier in this paper, clarification tests were run on samples of the sewage-sludge mixture taken from different points along the aeration tanks. These tests consisted of a determination of the rate of subsidence of the solids and the clarification of the supernatant resulting therefrom. The attempt was made to find the effect of different periods of aeration upon these characteristics, and therefore only like samples are related, those from two different flows being entirely different. The explanations for the "bulking" of a sludge on settling, that is, the refusal of a sludge to settle, have been many and varied, but they are not within the scope of this paper. Regardless of how the sludge is settling under any particular conditions, the effect of aeration period, although not an entirely separate entity, is distinct from other effects.

The rate of settling of the sludge was plotted in the form of a curve, illustrated in Figure 11. Rudolfs and Lacy, in their very extensive paper on "Settling and Compacting of Activated Sludge" (4) have analyzed many of the factors that affect settling of sludge, including temperature, pressure, concentration, shape of container, etc., and the effect of prolonged aeration. The last is the only data of particular interest, although it might be well to note that the shape of the subsidence curve in Figure 11 is found to be the same as those determined by Rudolfs and Lacy. These authors have for some unknown reason neglected to determine the effect on settling of normal periods of aeration in hours. Their data illustrated the effect of days of aeration on settling.

They found that, up to about nine days aeration, there was a gradual decrease in the volume of sludge produced. They failed, however, to make the important determination for the quantity of suspended solids in the supernatant. For thirty minute settling samples, they found that the percentage

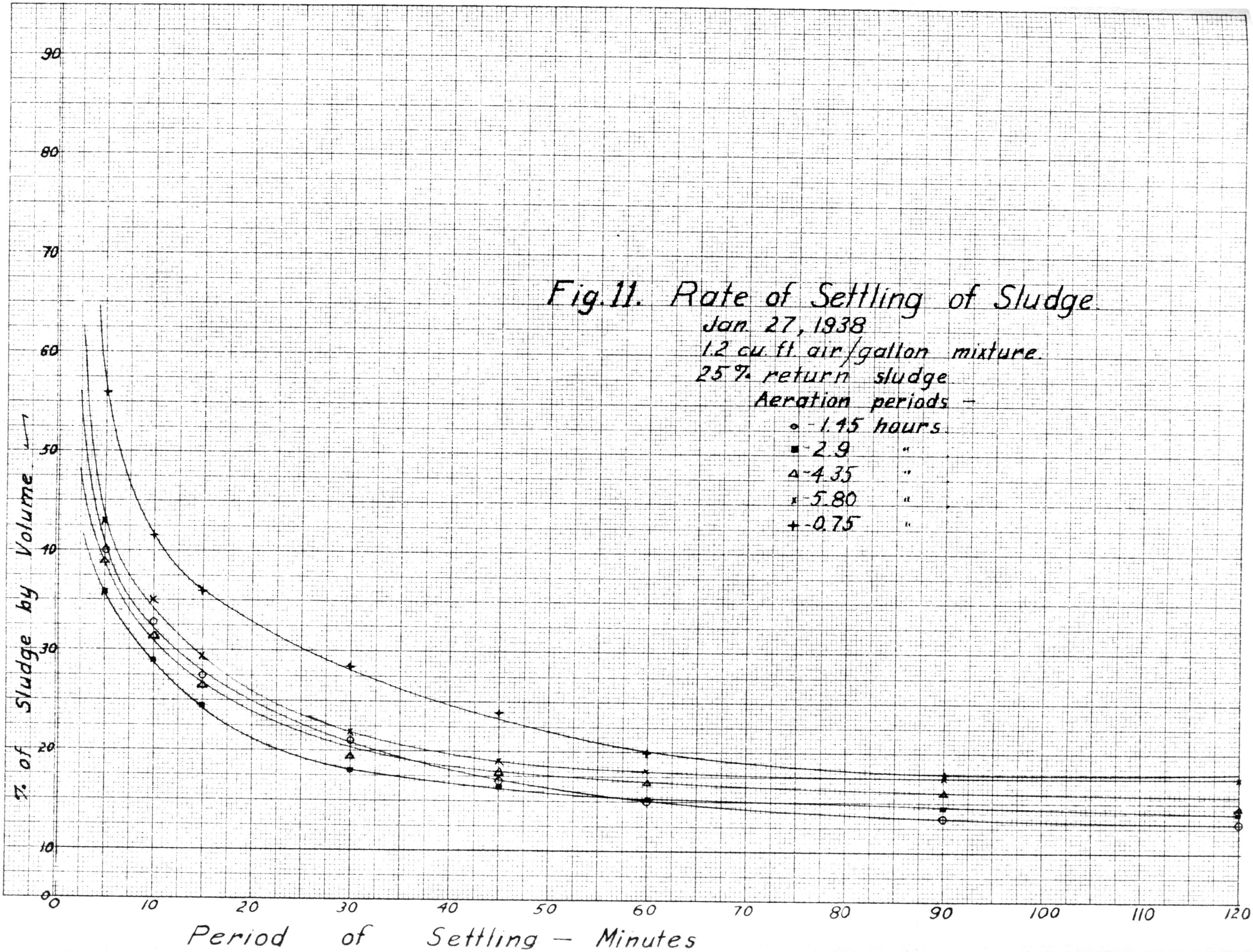


Fig. 11. Rate of Settling of Sludge.

sludge went from about 36% to 27%. Their samples were run daily, rather than hourly, so any closer correlation is impossible. From the ninth to fourteenth day, the percentage sludge formed in 30 minutes remained constant, slowly dropping to 25% on the nineteenth day.

Our 30 minute settling for different periods of aeration is shown in Figure 12 for two different sewage-sludge mixtures, one bulking considerably. From these curves, and the others showing rate of subsidence for mixtures having different aeration period, it is seen that there is no visible effect from period of aeration on the volume of sludge produced. Regardless of the condition of the mixture, the volume of sludge does not seem to be affected by period of aeration. The important effect of period of aeration is found in the state of the supernatant liquor after long settling.

Suspended solids, in parts per million, in the supernatant were determined after one and one-half hour's settling, for mixtures with different periods of aeration. The results of this determination are shown in the curve in Figure 13. A decided diminishing of suspended solid content is observed as the period of aeration is increased, from about 100 ppm. for a mixture undergoing less than one hour aeration, down to about 20 ppm. for a mixture undergoing about six hours aeration. It should be noted that the mixture in the aeration tanks maintained a good residual dissolved oxygen content at the time these tests were made (prior to floods). The returned sludge was about 25% during this period.

From this curve, it is possible to assume a definite conclusion, that the clarification of an activated sludge effluent is improved with increased periods of aeration, at least up to six hours. Aeration beyond that was not practicable, as the plant detention period was six hours. However, an effluent of 20 ppm. suspended solids is as clear as could be desired.

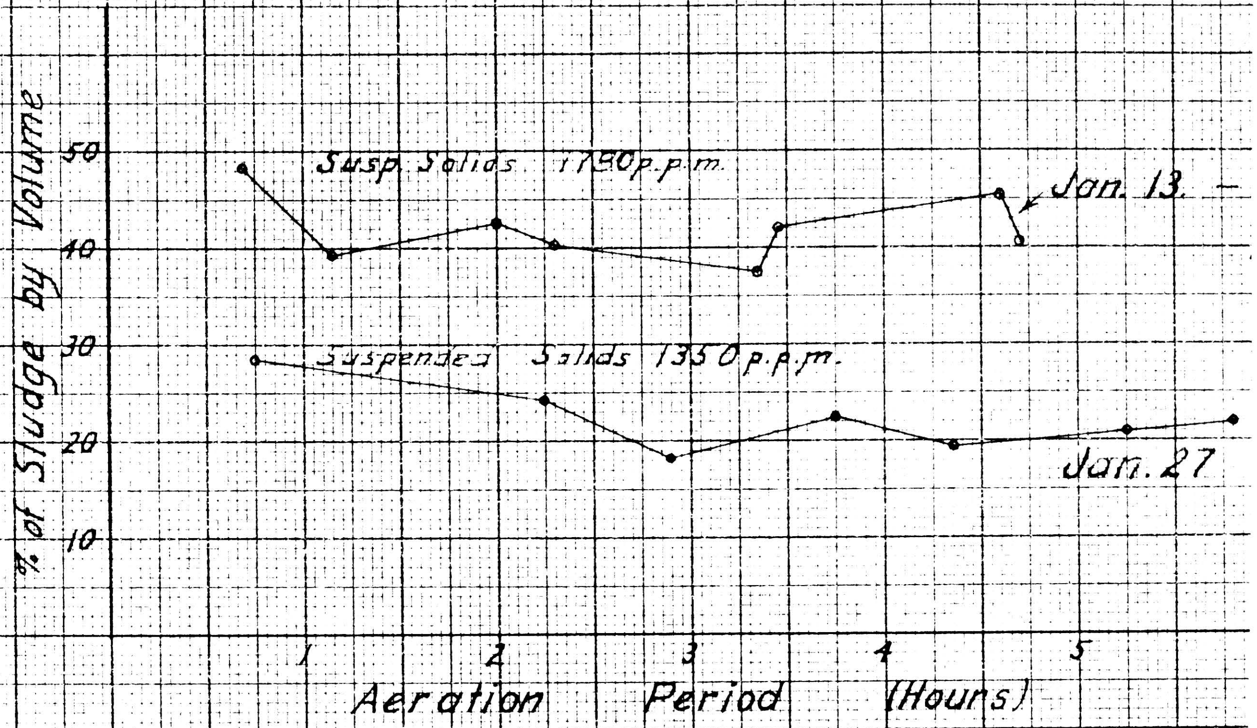
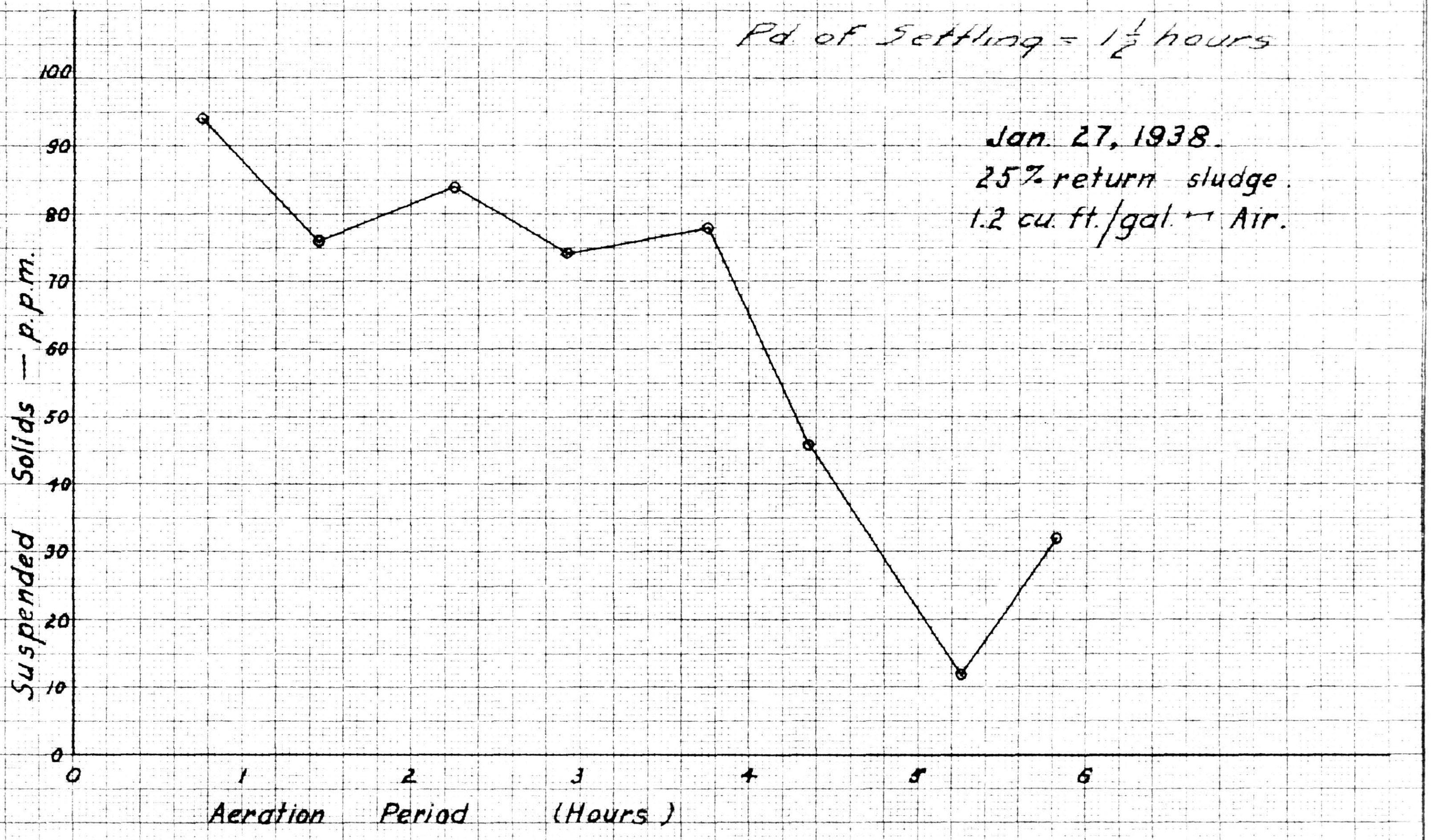


Fig. 12. Effect of Aeration on Settling

30 Minute Settling Samples.

Fig. 13 Effect of Clarification of Varying Periods of Aeration



Pd of Settling = $1\frac{1}{2}$ hours

Jan. 27, 1938.
25% return sludge.
1.2 cu. ft./gal. [illegible] Air.

Results of Dissolved Oxygen Content Determinations

These tests were made prior to the flood of early March, when it was possible to actually measure dissolved oxygen in samples taken from the aeration tanks. After these floods, there was very little dissolved oxygen present, so that a Winkler test would be apt to give results as much as 100% different from actual values. At best the Winkler test is not very satisfactory for an outright dissolved oxygen determination, especially when the content runs below 1 ppm. When simple differences are to be taken, as in Nordell Number determinations, the Winkler test is sufficiently accurate.

Difficulties encountered in dissolved oxygen determinations are fully discussed by Theriault and McNamee (3), pioneers in work with dissolved oxygen of sewage-sludge mixtures. A governing consideration, they state, as we have discussed, is the oxygen demand of the sample, which makes the time element important in a dissolved oxygen determination. As will be seen in our oxygen utilization determinations, the dissolved oxygen content of a sample may be decreased by about 2 ppm. in several minutes. The use of copper sulphate to inhibit this biological action is disadvantageous in that results are slightly distorted by liberation of iodine due to the use of this reagent. Where dissolved oxygen contents are large enough, the use of copper sulphate is to be recommended and a correction applied. Another interfering factor in the dissolved oxygen determination is the practice of allowing the sludge to settle so that the supernatant might be used for the test. This is especially poor when the sludge is bulking, necessitating a considerable period for settling.

For these reasons, we believe that much too much faith is placed in dissolved oxygen determinations in many plant and research laboratories, where these tests are made by the Winkler method. For these reasons, little importance is attached to our dissolved oxygen tests. An attempt will be made to indicate that a Nordell Number determination is much more satisfactory than the above dissolved oxygen test for plant operation purposes. If it is desired, however, to make a dissolved oxygen test, apparatus such as devised by Theriault and McNamee (3), for gas extraction is recommended. It is not felt desireable to go into a description of this apparatus in this paper.

Despite the above criticisms, a brief comment on the results of the dissolved oxygen tests is not out of place. All precautions were taken in running these tests to avoid the above difficulties. Results of our observations are plotted in Figure 14. These observations were made during the same period as the clarification tests previously discussed. From this graph it is seen that the dissolved oxygen increases from zero prior to aeration to slightly greater than 1 ppm. after six hours aeration. This, in general would indicate enough aeration, but not necessarily efficient aeration.

In the discussion of the application of Nordell Number to plant operation, the effect on dissolved oxygen content will be more extensively treated.

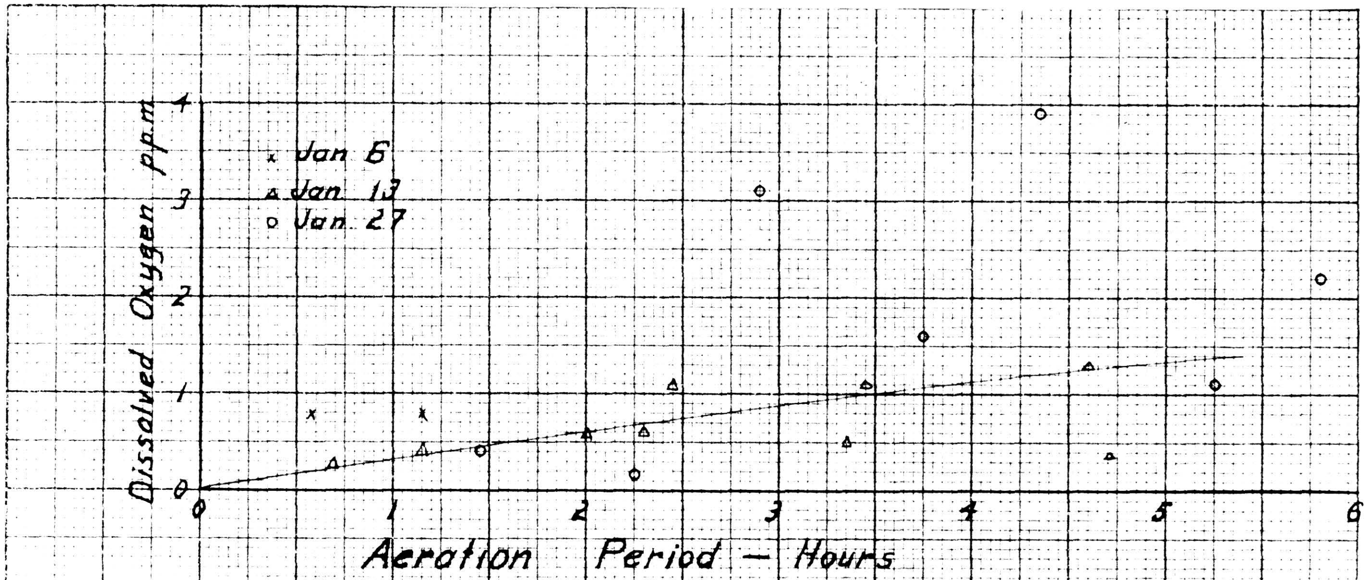


Fig.14 Effect of Aeration Period on D.O. Content

Results of Oxygen Utilization Tests

The observations from the oxygen utilization tests are shown in Figures 16 and 17. Figure 16 indicated the oxygen utilization for afternoon flow, all the observations being made almost simultaneously, with no attempt to trace the detention period in the aeration tanks. Figure 17 shows the results of tests on samples taken in an attempt to follow the detention period of the sewage-sludge mixture through the tanks, with early morning flow and late morning flow.

It is seen that with afternoon flow, giving a comparatively strong sewage with 10% returned sludge, which sludge was very poorly activated, there is a small but definite decrease in the Nordell Number with an increase in aeration period. The oxygen utilization is about 38 parts per million of oxygen per hour, with samples taken in the first aeration tank at the influent to the tank, and then gradually decreasing in value to about 20 parts per million per hour after about 6 hours aeration.

As mentioned earlier in the paper there are several factors which influence the character of these curves and we will try to estimate these effects before attempting to analyze the results themselves. These factors are: (1) The impossibility of determining the period of maximum sludge activity when making tests on continuous-flow tanks. Kessler, in his tests on continuous-flow tanks, was never able to measure this period either. The reason for this difficulty is of course obvious. With any mixing whatsoever, the result is that aerated sewage-sludge mixture contaminates the early samples, yielding diminished Nordell Numbers. (2) The hourly variation in the strength of the raw sewage. In general, the strength of the sewage entering the unit tends to decrease slightly from a maximum before noon to late afternoon. As all the afternoon tests were made practically simultaneously, this would affect the samples. A sample

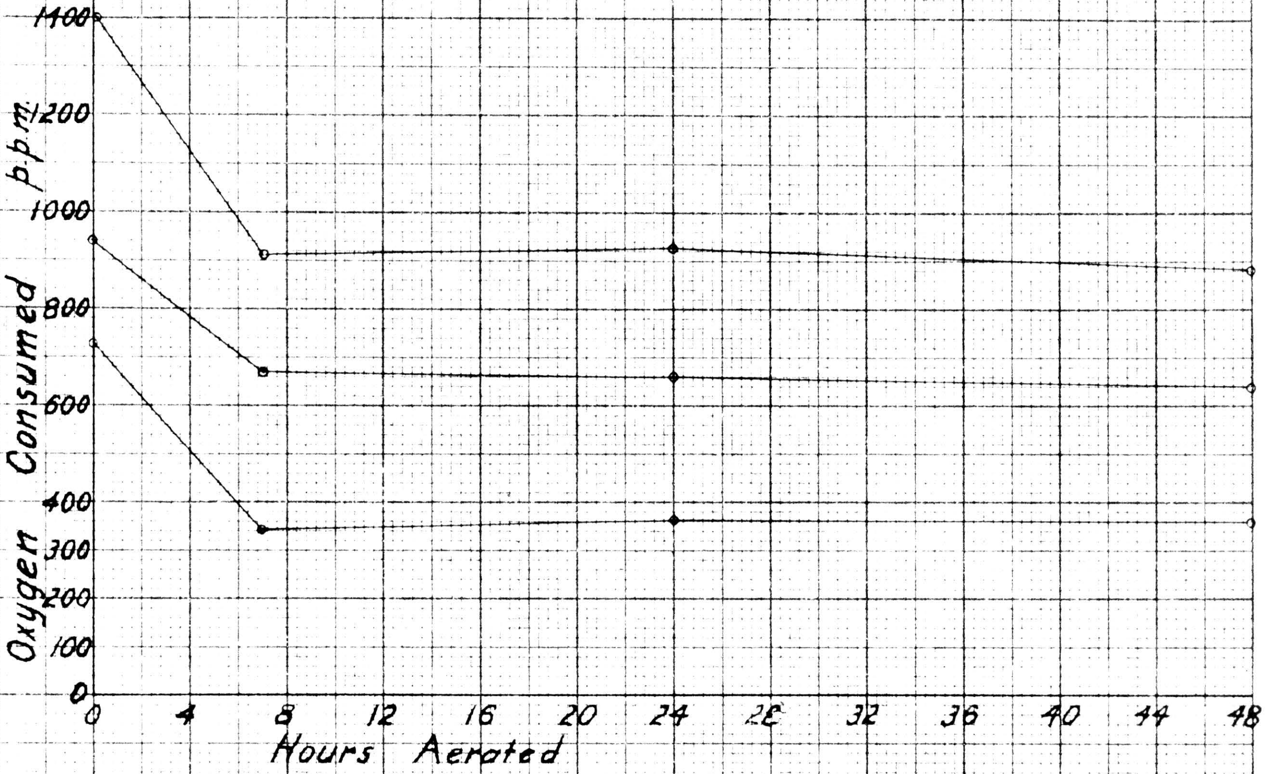


Fig. 15. Heukelekian's Observations - Permangate Oxygen Consumed -1934.

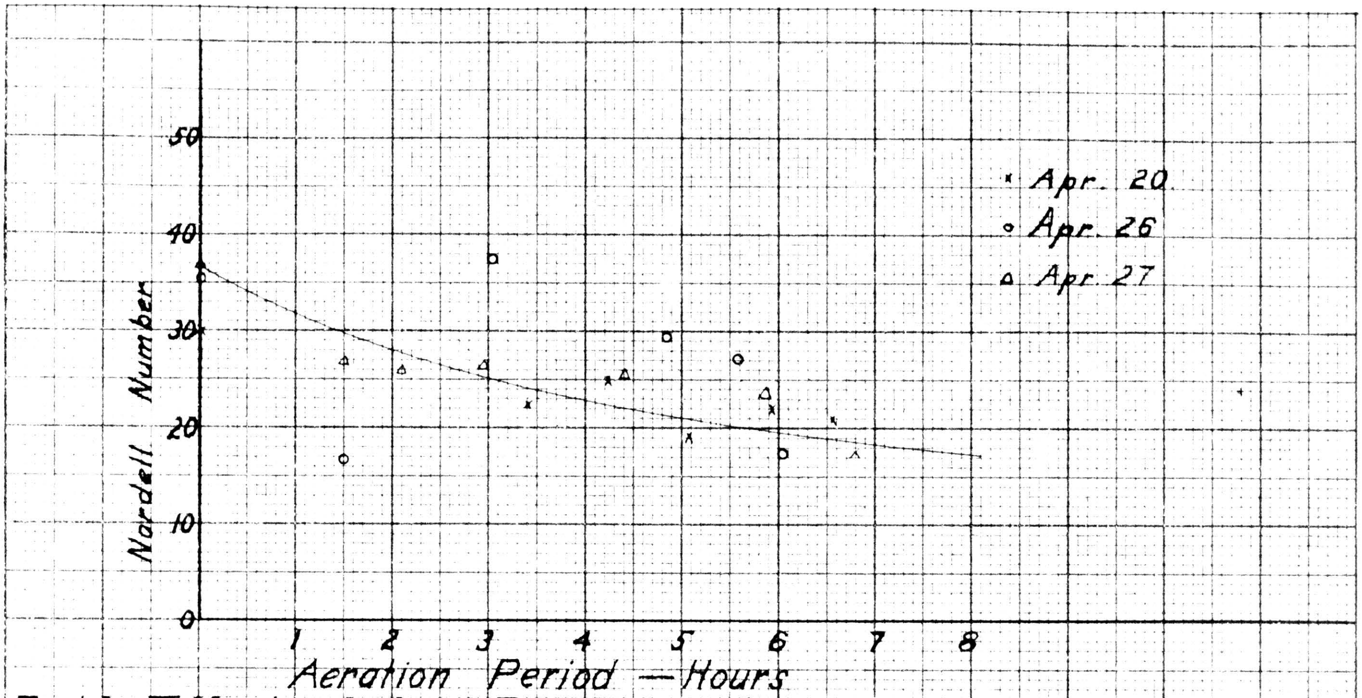


Fig.16. Effect of Aer. Period on Oxygen Utilization.

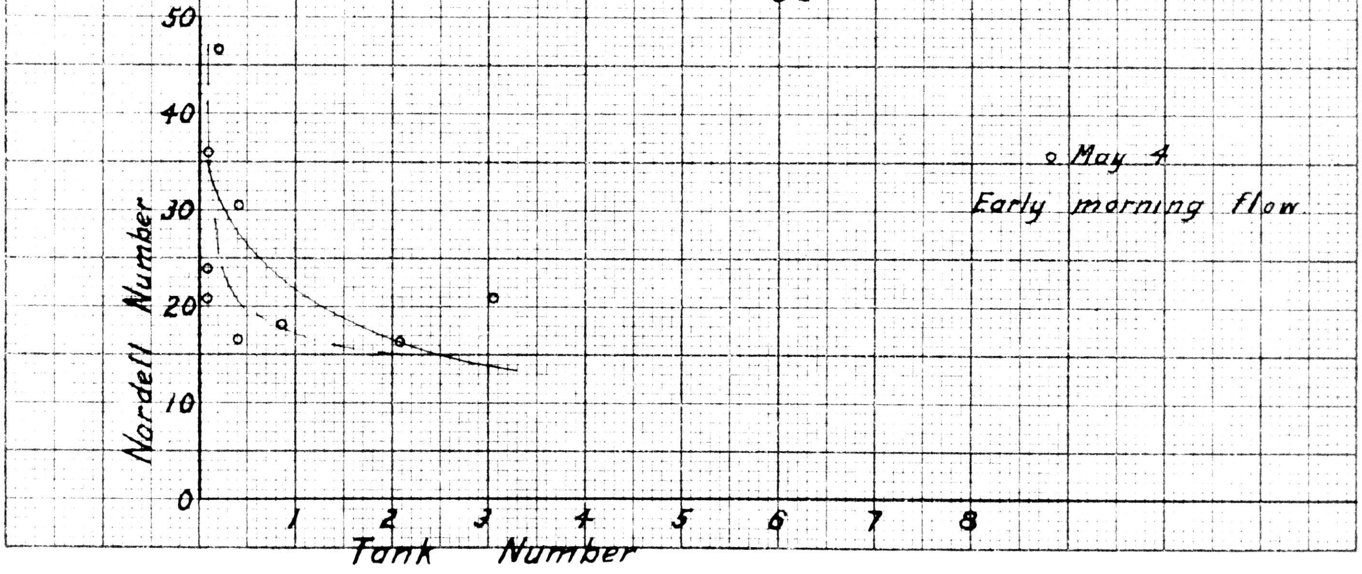


Fig.17 Oxygen Utilization of Weak Flow

taken at the end of the aeration system would tend (neglecting short-circuiting momentarily) to have originally been stronger sewage than samples taken nearer the beginning of aeration. The amount of air being blown into the unit remaining constant, by observing the theoretical curves in Figure 3, it is seen that with two sewages of different strengths, after any reasonable aeration period, the stronger will have a greater Nordell Number. If conditions permit, B.O.D.'s of the raw sewage should be run simultaneously with the oxygen utilization tests, so that this effect may be more accurately estimated. This does, however, bring out the fact that if the tests were run on the same sewage after increasing periods of aeration, the Nordell Numbers in Fig-16 would tend to fall more quickly with an increase in the aeration period, or else commence higher, or in other words, magnify the depletion in oxygen utilization with aeration (this does not affect tests run for plant operation). (3) The effect of mixing on the samples. This has been discussed fully earlier in the section on actual detention period of activated sludge in continuous flow aeration tanks, with respect to both research investigation and plant operation. All that need be said here, is that the effect of mixing is to flatten out the curves in Figure 16, very much as would the decrease in sewage strength as treated in (2). The reason for this may be explained with the assistance of the chart in Figure 10. The composition of the effluent from eight tanks, and therefore a sample taken of the sewage at that point, tends to be made up of mixture that has been under-aerated and over-aerated to the same degree and in about the same quantity. But the effect on the Nordell Number of the under-aerated portion is much more pronounced than that of the over-aerated portion, due to the fact that the oxygen utilization curve tends to flatten out as the theoretical detention period is reached. This means that a given percentage of mixture, over-aerated one hour, "contaminating" a sample would decrease the Nordell Number much less than a same percentage of mixture under-aerated would increase it. Again glancing at the chart, samples taken at the effluent of intermediate tanks would contain a greater percentage of under-aerated sewage-sludge mixture than over-aerated mixture, tending to increase the Nordell Number. Reducing this distortion would make the oxygen utilization curves in Figure 16 much sharper in slope. (4) The poor condition of the returned sludge. From Figure 4 it is possible to observe the effect of the activity of the returned sludge on the curve of oxygen utilization. This poor sludge tends to render a smaller degree of purification than would be obtained from the use of a better sludge, with the same period of aeration. A better sludge would tend to give a sharper curve of oxygen utilization, an effect similar to those indicated under (2) and (3) above.

Taking these several factors into consideration, it is seen that the results obtained are in accordance with the general theory as outlined by Kessler, that is, as indicated in Figures 3 and 4, there is marked decrease in the oxygen utilization of an activated sludge with an increase in aeration. As detailed in the theoretical discussion, Kessler established, from his fill and draw observations, the equation for this curve, given the maximum sludge activity and sewage strength.

Although it is seen that our curves follow the general shape of those obtained by Kessler, it is impossible to intelligently go any further in this direction, but it may be of some interest to compare our actual observations (without including the above mentioned effects) with computed values using Kessler's relations, and then compare this with similar work performed by Kessler.

The first value to be ascertained is the strength of the sewage, in terms of parts per million of oxygen per unit of time, the value "K". This is computed from the observed maximum sludge activity and the observed final oxygen utilization after some period of aeration. Taking means of observed values, we have:

Maximum sludge activity = M = 38
Nordell Number after 6 hours aeration = N = 17
Time of aeration = T = 6 hours

$$K = \frac{MT}{\frac{(M - N)^2}{N^2} + 1}$$

$$K = \frac{38x6.0}{\frac{(38 - 17)^2}{17^2} + 1} = \underline{90}$$

Using this value for K, it becomes possible to compute what the Nordell Number would be after different periods of aeration from

$$N = \frac{M}{\sqrt{(MT/K) - 1} + 1}$$

Then, after making the computations we have:

Period of Aeration	Computed Nordell Number	Mean Observed Nordell Number
0 hours	38 ppm / hour	38 ppm / hour
2	38	27
3	25	25
4	21	24
5	19	21
6	17	17

Although the variation between observed and computed values of the Nordell Number is within experimental error, it is no proof of the validity of Kessler's equation, but it does verify the general shape of the curve given by the equation. It must be remembered that the first and last values in the table are made to be identical by the method of computing the Nordell Numbers. It should also be remembered at this point that the factors influencing the observed values tend to make the curve flatter than it should be. The result of these effects can be seen in the table, in that the observed values make a flatter curve than the computed values. (See Figure 18)

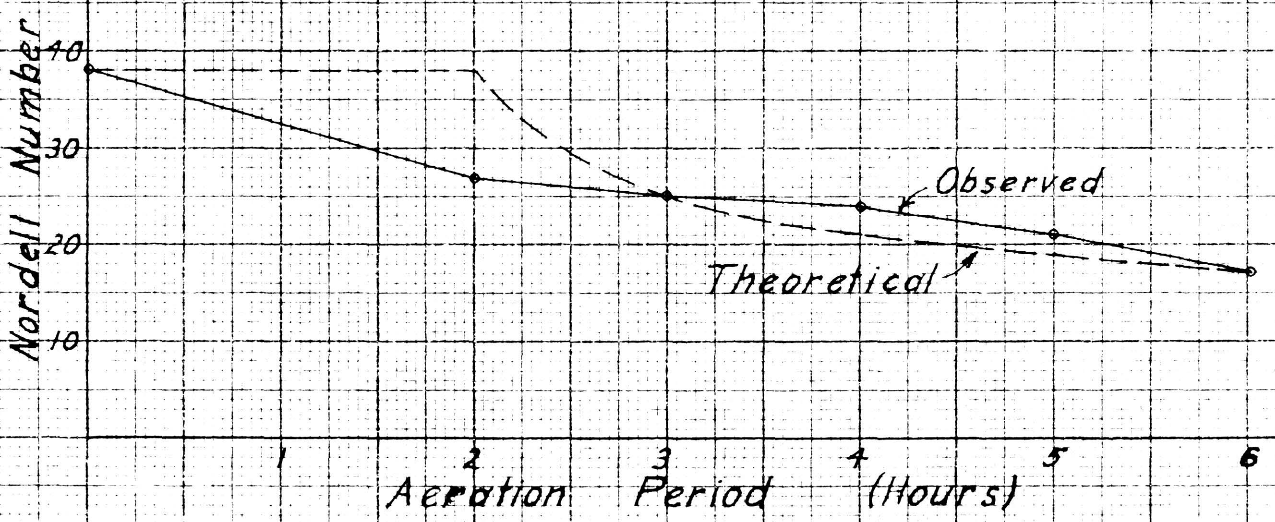


Fig. 18. Comparison of Theoretical and Observed Curves of Oxygen Utilization.

Kessler's tests at Morristown, N. J. and at Madison-Chatham, N. J. show results and variations almost identical with those found at the Pasadena plant. He does not make any use of these tests to validate the theory, except that the inclusion of these reports, following the theoretical treatment, with the tables of observed data and computed values, seems to indicate a desire to show agreement between the results and the theory as found in his Monroe tests. In fact he does state these tests were made "to see what correspondence could be obtained between observed and calculated data". For his observations on tanks operated by fill and draw this may well be satisfactory, but for those continuous-flow systems listed previously (see page 4) no correlation can be drawn with any particular significance. With maximum and minimum values fixed, the others could show close correlation without following any law whatsoever.

The other important factor, fully discussed previously, but of which Kessler makes no mention, is the effect of mixing. Mixing, from the analysis made of it herein, would vitiate the results obtained, so far as comparisan with theory is concerned.

With respect to the early morning flow, the very long detention period made conclusive tests impossible. The detention period for the eight tanks, with this flow, is 36 hours, or 4 1/2 hours per tank. This means that a sample taken in the first tank, regardless of the point at which it was taken, is representative of the mixture throughout the tank. This made it difficult to obtain points for a curve for periods of aeration of less than 4 1/2 hours. At the end of the detention period for the first tank, samples were taken from the second, and then the third. At this point, the length of time required being considerable, the interference of the stronger sewage made further samples useless.

The results of these tests are shown in Figure 17. A curve through the points could be drawn in two ways. The accepted method would be to begin the curve with the points of great Nordell Numbers at the beginning of the first tank, and draw the curve with a steep slope until it reaches the end of the first tank, then flatten it out. This curve is shown dashed in the figure. Despite the fact that this curve appears satisfactory, every value in the first tank indicates the character of the mixture throughout the tank, so that the first point on the curve should be a mean of all the observations taken in the tank. The proper curve is shown solid. This curve does not show very much, except that after about 4 hours aeration there is a decrease in the Nordell Number.

Application of Oxygen Utilization Curves to Activated Sludge Plant Operation

The Biochemical Oxygen Demand reduction is not a function of the final Nordell Number attained after a certain period of aeration, but is rather a function of the ratio of the Nordell Number indicating maximum sludge activity to the final Nordell Number. That is, if the maximum sludge activity for some mixtures is 25, and the final Nordell Number attained after aeration is 10, the B.O.D. reduction will be less than if the maximum sludge activity were 60, and the final Nordell Number 15. The former ratio, "R", is less than that of the latter.

It was found that for high B.O.D. reduction, the value of AR" should be about 4:1. For the Pasadena unit, at the time tests were performed, the ratio was a good deal less than 4:1. From the curve in Figure 18, it is seen to be about 2.2:1. With the poor purification existing at the time at Pasadena this is a verification, although not a proof, of the principle that a small ratio indicated insufficient B.O.D. reduction. The use of a better returned sludge, that is, a sludge with greater activity, would increase the ratio, and provide better purification. The basis for good activated sludge treatment has always been the seeding of the raw sewage with a "good" sludge, but the reason has never, prior to Kessler's work, been expressed in this manner. However, the sludge problem is beyond the scope of this paper, the real intent here being to determine the air requirements.

In determining the amount of air required to satisfy the oxygen demand of an activated sludge, there is one important consideration that, as yet, has not been satisfactorily determined. This is the percent absorption of oxygen by the mixture of the air blown through it. In a spiral diffused air tank, oxygen is absorbed from both the air blown through the liquid, and the atmosphere. The former is a function of several things, the depth of the diffuser plates, the permeability of the plates, the amount of air being blown through, and the mixture itself. The latter is a function of the turbulence created by the air, the area open to the atmosphere, and the rate of blowing the air. Tests have been made in an attempt to estimate the quantity of oxygen absorbed with a variation of these controlling factors, but until recently most of the tests were made on water. It has since been found that water shows a better absorption of oxygen than sewage. With the lack of information concerning the absorption ofoxygen, it is very difficult to make more than an intelligent assumption regarding the percentage take-up of oxygen.

The actual value is only of importance in providing a point for departure in computing the total quantity of air necessary for purification, and on operation, can be checked by making dissolved oxygen tests in the tanks. The presence of several parts per million of dissolved oxygen will prove that sufficient oxygen has been applied. The importance of the oxygen utilization tests is in determining the distribution of the air to the various tanks. The actual quantity of air required will be haphazard until more work is done in an attempt to ascertain the actual percentage of the oxygen in the air supplied, plus that in the atmosphere, which is absorbed into the activated sludge.

The estimated percentages have varied from about one per cent to more than six per cent. Assuming proper design, the aeration tanks being newly designed, as a basis a percentage absorbtion of the oxygen supplied may be estimated as about 5%, keeping in mind the uncertainty of this figure.

The amount of air required in each of the eight tanks to supply an oxygen utilization of 1 ppm/hour will be computed for the design flow in the aeration tanks of 3 million gallons per day of raw sewage and returned sludge:

$$1 \text{ ppm/hr.} = 1 \times 8.34 = 8.34 \text{ lb. } O_2\text{/mil. gal./hr.}$$

$$\frac{8.34 \times 3 \text{ mgd}}{24 \times 60} = 0.0174 \text{ lb. } O_2\text{/minute/hour.}$$

Detention period per tank = 0.75 hours.

$$0.0174 \times 0.75 = 0.0131 \text{ lb. } O_2\text{/min. per tank}$$

Assuming the 5% oxygen absorption, the oxygen required is

$$\frac{0.0131}{0.05} = 0.262 \text{ lb. } O_2\text{/min.}$$

Weight of oxygen at atmospheric pressure and temperature = 0.0892 lb./cu. ft.

$$\frac{1.0 \times 5}{0.0892} = 56 \text{ co. ft. air/ lb. } O_2$$

Therefore $0.262 \times 56 = 14.7$ cu. ft. air/minute/tank per unit Nordell Number.

Using the theoretical oxygen utilization curve as indicated in Figure 19 (obtained from previous computations), it is possible to determine the mean Nordell Number per tank, and the oxygen supply can be fixed according to the requirements indicated. This is illustrated in the following table:

Tank Number	Nordell Number ppm O_2/hr.	Constant (See above)	Air Requirement cu. ft./min.
1	38	14.7	560
2	38		560
3	38		560
4	30		440
5	23		340
6	20		290
7	19		280
8	18		260
		Total	3290 cfm.

This is more than was being supplied to the unit, and may account partly for the poor purification. But due to the uncertainty of the actual absorption of oxygen supplied, too much weight should not be given to this air requirement. However, from the above, it is possible to apportion the

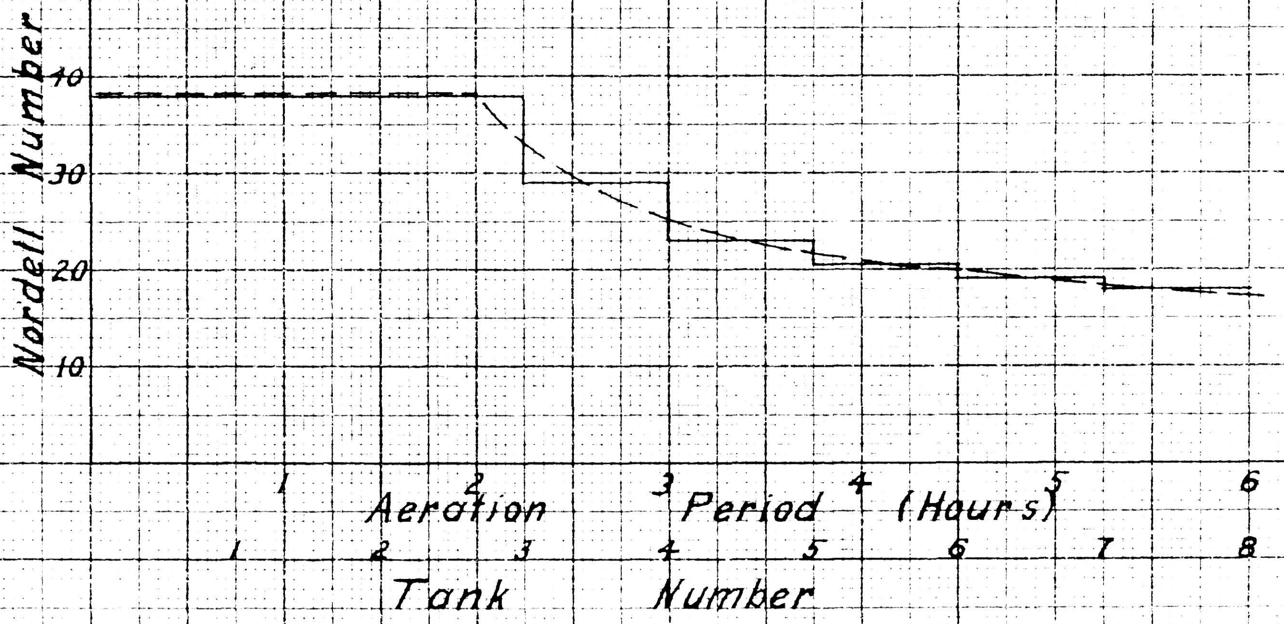


Fig. 19. Application of Theoretical Oxygen Utilization Curve to Control of Air Supply.

existing air supply through the tanks with proper regard for the oxygen utilization values. The air being supplied to the unit at this time is 2500 cfm., equally to each of the tanks. The following table will indicate a better distribution of this air supply, according to the oxygen utilization curve. All that needs be done is to multiply each of the air quantities in air requirement column of the above table by a factor of $\frac{2500}{3290}$. This will indicate an application of air as follows:

Tank No.	Air Requirement cfm., see above	Factor	Air Supply recommended	% of total	cfm. actual
1	560	$\frac{2500}{3290}$	425	17%	312.5
2	560		425	17	312.5
3	560		425	17	312.5
4	440		335	13.4	312.5
5	340		260	10.4	312.5
6	290		220	8.8	312.5
7	280		210	8.4	312.5
8	260		200	8.0	312.5
		Totals	2500	100.00	2500

From this it is seen that more than twice as much air is applied to the first tanks in series than to the last tanks. With better returned sludge, the ratio could well be greater. The advantages of this are several. With any given quantity of air, it becomes possible to obtain better purification, by application of this air where it is most needed to satisfy the demand. In a plant achieving good purification, the amount of oxygen applied to the first tanks need not be maintained throughout the system, with a resultant saving in cost for the same purification.

In this connection, it might be appropriate to mention the "Odeeometer", a device for the measurement of oxygen demand. It simply measures the shrinkage (10) of the air in a closed chamber, due to the oxygen utilized therefrom by a sewage-sludge mixture contained within this chamber. This piece of apparatus offers a plant operator a convenient, simple, and rapid means for determination of the Nordell Number at many points in his aeration system, enabling him to make adjustments in the air supply to fit the demand.

It is, of course, important that where it is desired to apply this scheme there be means to determine the quantity of air going into each of the units. There are many plants where this is impossible. At the Pasadena Plant, the amount of air being applied to each unit is controlled by observation of the surface agitation. During the tests, the quantity of air blown into each tank was the same.

As a result of the dissolved oxygen tests, it was seen that in the duration of the oxygen utilization tests, there was scarcely any residual dissolved oxygen. This is an indication of an insufficiency of air application, among other things. Although dissolved oxygen tests do not offer good means for regulating plant operation, due to the many variables in its determination, as detailed earlier in the paper, it can indicate whether there is or is not sufficient air being blown into the unit. Samples indicating less than 1 ppm. of dissolved oxygen cannot be used as any criterion of aeration however.

As a result of these investigations, it is believed that besides restoration of a good activated return sludge, operation may be improved by the application of greater quantities of air into the first tanks of the aeration system, with a diminishing of this quantity in succeeding tanks.

Summary

As a result of dissolved oxygen, oxygen utilization, clarification, and settling tests run at the Pasadena Sewage Treatment Plant, and after analysis of these results, together with other pertinent factors, the following conclusions were established:

(1) The actual detention period in continuous flow aeration tanks differs considerably with the theoretical computed detention period as a result of mixing in the tanks. This effect diminishes as the number of separate units in series is increased. This "short-circuiting" seriously affects the composition of samples taken for research purposes, although this is of no consequence in samples taken for plant operation analysis.

The design of aeration systems should provide for as many separate tanks in series as is economical, or should provide for transverse baffles to prevent short-circuiting. It was shown that the effluent of a system of aeration tanks consists of a great portion of under-aerated mixture, providing poor treatment, this effect being very marked when there were but few units in series, although it is also very noticeable with as many as eight tanks in series.

(2) There was found to be no effect on rate of subsidence of sludge due to various aeration periods up to six hours.

(3) Clarification of the supernatant liquor after settling the sludge was found to be improved considerably with increases in period of aeration up to six hours.

(4) Dissolved oxygen determinations are beset with many interfering considerations, and although offering an indication as to whether a mixture is sufficiently aerated or not, is not considered a satisfactory test for research investigations or activated sludge plant operation.

At the Pasadena plant, increasing dissolved oxygen residuals were found as the mixture proceeded through the aeration tanks, in tests made prior to the flood. Tests made afterward, at the time of the oxygen utilization tests, showed only traces of dissolved oxygen, which are not thought to be an indication of sufficiency of oxygen.

(5) It was found that the oxygen utilization of the activated sludge, the Nordell Number, decreased with increased aeration. Although several factors tended to keep the curve of oxygen utilization flat, there was still definite indication of its diminishing.

This decrease in oxygen utilization was shown to be of value in more efficient and economical activated sludge plant operation.

(6) As a result of the tests on oxygen utilization, the recommendation is made that the application of air in the new unit at the Pasadena Plant be such that about 17% of the total air applied to the unit be applied in each of the first three tanks, with a gradual diminishing until about 8% is applied in the last tank. It is believed that further tests will be of value in adjusting the aeration as purification improves.

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