# DETERMINATION OF THE OVERALL OXYGEN TRANSFER COEFFICIENT IN AN OPERATING SEWAGE TREATMENT PLANT

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# ABSTRACT

# DETERMINATION OF THE OVERALL OXYGEN TRANSFER COEFFICIENT IN AN OPERATING SEWAGE TREATMENT PLANT

By

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This thesis presents an automated method for the determination of the overall oxygen transfer coefficient ($K_La$) of activated sludge aeration equipment. The experiments were conducted at the East Lansing, Michigan Waste Water Treatment Plant. However, the method and associated apparatus are applicable to the equipment of activated sludge plants in general.

The final output of the apparatus consisted of a continuous dissolved oxygen recording, an hourly ten minute temperature recording, and an hourly recording of the decrease in the dissolved oxygen concentration of a sealed and agitated sample of mixed liquor. These recordings permitted the calculation of the dissolved oxygen concentration (C) and a corresponding mixed liquor oxygen uptake rate ($r_r$) for each hour during an experiment. This data permitted the determination of $K_La$ by calculating the slope of a C versus $r_r$ plot.

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$K_La$ values of 2.610, 1.873, and 2.565/hr. were calculated for the three aeration tanks at the plant, with the aid of a computerized least squares analysis. Corresponding maximum oxygen supply rates of 22.75, 16.4, and 22.7 mg/l/hr were also calculated.

In addition, two experiments were conducted to verify the existence of a dissolved oxygen concentration gradient in the aeration tanks. At the time of the tests, a cross sectional gradient of 3.0 mg/l was present. The maximum concentration obtained during each test was 4.5 mg/l at 1.0 feet below the liquid surface and at the sparger wall. The minimum concentration obtained during each test was 1.5 mg/l which was found 0.5 feet above the tank bottom in each case.

APPROVED R. L.

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By

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| | |
|---|---|
| BOD | 5-day Biochemical Oxygen Demand |
| $r_r$ | Oxygen uptake rate per unit volume, $mgO_2/l/hr.$ or milligrams oxygen consumed per liter per hour |
| $\frac{dC}{dt}$ | Rate of change of the dissolved oxygen concentration with respect to time |
| C | Dissolved oxygen concentration, mg/l |
| $C_s$ | Dissolved oxygen concentration at saturation, mg/l |
| $K_La$ | Overall oxygen transfer coefficient, $hr^{-1}$ |
| D.O. | Dissolved oxygen |
| mg/l | Milligrams per liter |
| mgd | Million gallons per day |
| ppm | Parts per million parts |
| ml | Milliliter |
| lpm | Liters per minute |
| $D_L$ | The gas diffusivity ($cm^2/hr$) |
| $y_L$ | The film thickness (cm) |
| $K_L$ | The gas diffusivity divided by the film thickness (cm/hr) |

# SECTION I

## INTRODUCTION

This study was conducted at the East Lansing, Michigan, Waste Water Treatment Plant, which is located on the Red Cedar River. The plant treats a sewage which is composed almost entirely of municipal waste. It employs the "biosorption" modification of the activated sludge process for its secondary treatment.

The main objective of this research was to determine the overall oxygen transfer coefficient of the aeration tanks and equipment, while they were in normal operation. By means of ½ inch pipe and a submersible pump, a constant flow of mixed liquor from the effluent end of the aeration tanks was supplied to the apparatus. The apparatus was calibrated to continuously record the dissolved oxygen concentration in the flow, and to automatically hourly record the temperature and the oxygen uptake rate of the mixed liquor.

The transfer coefficient was determined for each set of data from the slope of a C versus $r_r$ plot. Sufficient data was obtained from two of the three aeration tanks to permit the calculation of a representative overall oxygen transfer coefficient.

Two experiments were also conducted to determine the amount of dissolved oxygen concentration gradient present at a cross section of an aeration tank.

# SECTION II

## LITERATURE REVIEW

Aeration has been used for many years for the purification of sewage, and at the present time is extensively used in the treatment of sewage and industrial wastes. The activated sludge treatment process was developed near the beginning of the 20th century, with the first plants employing porous plates mounted in the bottom of the aeration tanks. Compressed air was forced through the plates, causing air bubbles to form and rise through the liquid, thereby imparting a dissolved oxygen concentration to it.

The actual transfer process was reported in 1924 by Lewis and Whitman (1) to be a function of a liquid film and a gas film. They also reported that the resistance to transfer through the gas film was negligible as compared to that of the liquid film. Eckenfelder and O'Connor (2) substantiated this, by stating that the diffusivity of a gas in the gaseous phase is $10^4$ times greater than it is in the liquid phase. Bennett and Kempe (3) stated the transfer was triphasic in that it involves the contact of a gas, a liquid, and suspended microorganisms. Bartholomew, Karow, Sfat, and Wilhem (4) reported that a combination of a gas film at the air-liquid interface, a liquid film at the air-liquid interface, a liquid film adjacent to the cell surface, and the diffusion in the media controlled the rate of oxygen transfer. It was also stated that the resistance to transfer through the liquid film at the air-liquid interface was considerably greater than the resistance afforded by the other controlling factors.

Eckenfelder and O'Connor (2) and Eckenfelder (5) stated that oxygen transfer from bubbles occurs in three distinct steps, while the bubbles form at the orifice, as the bubbles rise to the surface of the liquid, and as they burst at the surface, with the greatest amount of transfer taking place as the bubbles are formed. From this it was concluded that $K_L$ decreases with increasing depth, but that the amount of oxygen transfered increases. This was also found by Ippen and Carver (6) when values of $K_L$ were calculated using the mean bubble size, the weight of water, the surface area of the bubbles, and the rate of change of the dissolved oxygen concentration with respect to time. Dobbins (7) measured $K_L$ for hydrogen, oxygen, nitrogen, and propane, and developed an equation for the calculation of $K_L$.

In practice the value of $K_L$ is only occasionally determined, but the value of $K_La$ is frequently determined and used. Bartholomew, Karow, Sfat, and Wilhelm (4) stated that the various film resistances and transfer rates are normally grouped into an overall transfer coefficient. Eckenfelder (5) made a similar statement, in which he commented that $K_La$ is normally the variable used because the measurement of the interfacial area between the gas and liquid phases is impractical. He also stated (8) that $K_La$ is a convenient term when the performance of commercial aeration equipment is being considered. Gaden (9) stated that high $K_La$ values indicate an efficient aeration system, whereas low values indicate an inefficient one. Novak (10), during experiments to determine the optimum type of aeration equipment, concluded that $K_La$ is a measure of the ability of a solution to absorb a gas from a given aeration device. Eckenfelder (11) stressed the usefulness of $K_La$ for treatment plant design. Benjes and McKinney (12) and Conway and Kumke (13) emphasized the value of $K_La$ when the performance of a newly installed or existing aeration system is being evaluated.

Numerous factors influence $K_La$. King (14) and others (13, 15, 16) reported that $K_La$ at 20° C is equal to $K_La$ at temperature, T, in degrees centigrade, times the factor $(1.024)^{20-T}$. Eckenfelder (17) stated that physical properties such as surface tension, viscosity, and density, affect $K_La$. Some investigators (5, 14, 18, 19) have indicated the chemical composition of the waste influences $K_La$. Gaden (9) reported that a small concentration of an antifoam agent considerably reduced $K_La$, but that increasing the concentration caused it to slowly rise again. Mancy and Okun (20) found $K_La$ varies in the same manner with the concentration of surface active agents. Lynch and Sawyer (21) determined that the effect surfactants have on $K_La$ is augmented by the presence of salts, particularly by calcium and magnesium salts. Gaden (9) reported that $K_La$ decreased as the cell tissue concentration increased. Eckenfelder and O'Connor (2) stated that a suspended solids concentration of 10,000 ppm reduced $K_La$ by 1/5 of its value in water. King (14) found that the aeration of mixed liquor after the destruction of the microorganisms with acid or copper sulfate gave very low values of $K_La$ that were obviously in error. Bennett and Kempe (3) concluded that some oxygen is transfered directly from bubbles to microorganisms adhering to the bubble surfaces. Eckenfelder and O'Connor (2) stated that the rate of bubble surface area renewal is increased by increased turbulence. Eckenfelder (17) concluded that more intense agitation increases $K_La$ by increasing the contact time. Kalinske (22) reported that varying turbulence in the aeration tank caused the mixed liquor oxygen uptake rate ($r_r$) to vary from point to point. Weber (19) found a greater surfactant effect on $K_La$ at low turbulences, and a reduced effect at higher turbulences.

A correction factor $\alpha$ is often used as a comprehensive $K_La$ conversion factor between its value in water and mixed liquor. Nogaj and Hurwitz (16) defined $\alpha$ as being the quotient of $K_La$ in mixed liquor, divided by $K_La$ in water. Cleasby and Baumann (18) stated an $\alpha$ value of 0.8 is commonly used. Weston (23) indicated $\alpha$ values as low as 0.5. Conway and Kumke (13) determined $\alpha$ to be 0.75 during tests to determine $K_La$. King (14) reported $\alpha$ varied from 0.27 to 0.46 in aerobic sewage, and from 0.16 to 0.19 in sewage that had been permitted to become anaerobic. Eckenfelder and O'Connor (2) found that in the activated sludge treatment of domestic sewage, four hours of aeration caused $\alpha$ to change from 0.72 to 0.90.

A variety of basic methods have been published for the determination of $K_La$. King (24) and others (9, 13, 14, 25-29) have suggested, outlined, or used, the sulfite ion oxidation method, which normally consists of adding a known amount of sodium sulfite and a catalyst to tap water in an aeration tank, aerating the solution and determining the change in the sulfite concentration with time. Eckenfelder and Ford (29) stated that the method has the advantage of being simple, but that it involves gas absorption plus a chemical reaction, the kinetics of which are not exactly known, that the concentration of the catalyst affects the rate of reaction, and that the oxidation is faster than biological oxidations. King (4) found the rate of oxygen absorption increased 1 percent for each 100 ppm of sodium sulfite added. Gaden (9) stated that it is a measure of transfer into a solution, but that it doesn't give any information on the transfer of oxygen to the sites of microorganisms. Schultz and Gaden (26) concluded that the method was not truly representative of aerobic fermentations, because it involves different processes and fluid properties. Downing (25) reported the sulfite method gave higher results than those obtained with other methods. King (14) found that the oxygen absorption rate in clean water is 93.5 percent of the absorption rate in a sulfite solution. He corrected values obtained using the sulfite method by comparing them with values determined with deoxygenated water. Conway and Kumke (13) found that the results of the sulfite-ion depletion method were 44% higher than the results of the reoxygenation tests.

A group of investigators (9, 10, 14, 18, 25) have given or used the aeration of a low dissolved oxygen or deoxygenated water as a method to determine $K_La$. Cleasby and Baumann (18) stated that $K_La$ can be obtained by determining the slope of a semi-logarithmic plot of the dissolved oxygen deficit against the aeration time. Novak (10) deoxygenated laboratory water samples with nitrogen. Downing (25) suggested filling an aeration tank with a liquid that had a low dissolved oxygen concentration and a negligible oxygen demand. Gaden (9) also stated the limitation that the liquid cannot have an oxygen demand.

A considerable number of investigators (4, 13, 15, 29-35) have used or described the sodium sulfite reoxygenation method for the determination of $K_La$. The method as described and used by Conway and Kumke (13) consists of: cleaning an aeration basin and filling it with tap water, deoxygenating the water with sodium sulfite, using cobaltous chloride as a catalyst, aerating the liquid, measuring the dissolved oxygen concentration at set time intervals, and determining $K_La$ from the slope of a semi-logarithmic oxygen deficit versus time plot. They used this test as a standard for the comparison of results obtained with other methods. Eckenfelder (35) stated this method is the one that has generally been adopted for use; however, he also (29) stated that the method has a limitation in that an $\alpha$ value must be independently determined.

Eckenfelder and Ford (29) and Eckenfelder (17, 35) described a variation of the sulfite-ion reoxygenation method which utilizes the oxygen uptake of activated sludge instead of using sodium sulfite to deoxygenate an aeration basin. The given procedure is the same as that for the sulfite reoxygenation, with the additional requirement that the oxygen uptake rate of the sludge during the reaeration must be determined and held constant. Eckenfelder and Ford (29) stated that this method has the advantage of permitting the determination of $K_La$ under actual field conditions.

Downing (25) suggested that $K_La$ could be determined by enclosing an aeration basin, and measuring the oxygen content of the off-gas. Downing and Boon (36) used the off-gas method. Conway and Kumke (13) used the method in conjunction with an excess of sodium sulfite in the aeration water. The results they obtained with this method were found to be 28% higher than the results obtained with the sulfite-ion reoxygenation method. Novak (10) used this method to determine the oxygen transfer efficiency of an ejector aeration tank under operating conditions.

Eckenfelder (5, 35) described a steady state activated sludge method for the determination of $K_La$. He stated that if steady state conditions existed and $r_r$ and C were measured, $K_La$ could be calculated from the relationship: $K_La = \frac{r_r}{(C_s - C)}$. Eckenfelder and Ford (29) stated the test should be conducted in the absence of an immediate oxygen demand, the dissolved oxygen concentration should be above 1 mg/ml, the BOD and the dissolved oxygen concentration of the feed solution should remain constant during the test period, and that the determined $K_La$ is specific for the tested waste. Gaden (9) successfully applied the method to aerobic fermentations and indicated it was accurate and effective, permitting $K_La$ determinations under process conditions. Benjes and McKinney (12) used the method to check specification compliance of new aeration equipment, but $K_La$ values were not calculated. Hixson and Gaden (37) used the method and simply assumed steady state conditions. Conway and Kumke (13) concluded that the steady state method is convenient for understanding and improving plant operations and that it requires less time and expense than other methods. They also stated that it was difficult to achieve steady state conditions to permit use of the method, and that more investigation is needed for this approach.

Another method which requires the measurement of C and $r_r$ has also been used to determine $K_La$. It consists of determining $K_La$ from a C versus $r_r$ plot. Kooistra (38) measured eleven values of C and $r_r$ which when plotted yielded a $K_La$ value of 2.63 $hr^{-1}$.

Conway and Kumke (13) defined $\beta$ as a correction for $C_s$ which includes the effect of contaminants, temperature, salinity, and the pressure at which the oxygen transfer occurs. Benjes and McKinney (12) during their specification conformance work assumed a $\beta$ value of 0.5. Many investigators (2, 17, 25, 39) have indicated that $C_s$ in sewage is approximately 95% of its corresponding value in water at the same temperature. $\beta = 0.9$ was used by Kooistra (38) to calculate the value of $C_s$ in mixed liquor.

Eckenfelder and O'Connor (2) stated that a $C_s$ corrected for pressure to the tank mid-depth is representative. Ippen and Carver (6) reported that $C_s$ is affected by oxygen absorption from bubbles which lowers the partial pressure of oxygen within the bubble. They also state that this effect is most pronounced at low initial concentrations and that it becomes negligible at concentrations near saturation. King (14) reported that the 0.35 liquid depth should be used to correct $C_s$ for the additional pressure at which the transfer occurs.

Three basic techniques have been used to measure the dissolved oxygen concentrations during $K_La$ tests. The Winkler method was used by Ippen and Carver (6), and Zieminski and Vermillion (31). Conway and Kumke (13) and Morgan and Bewtra (30) also used the Winkler method during reoxygenation of sodium sulfite solutions.

A number of researchers (4, 6, 37, 40) have used the dropping mercury electrode to continuously measure the dissolved oxygen concentration of an aeration column during laboratory studies on surface active agents.

Benjes and McKinney (12) stressed the usefulness of polarographic electrode dissolved oxygen determinations.

Mancy and Okun (20) used a polarographic electrode to continuously measure the dissolved oxygen concentration. Conway and Kumke (13) obtained good correlation between data obtained polarographically and that obtained with a mass spectrometer during off-gas oxygen measurements. They also used a polarographic electrode to measure $r_r$ values during steady state biological uptake tests. Kooistra (38) used a polarographic electrode during work on oxygen uptake rates, and found its use to be rapid, simple, and accurate.

## SECTION III

## OXYGEN TRANSFER THEORY

The method of $K_La$ determination which requires measurement of C and $r_r$ is based on the equation:

$$\frac{dC}{dt} = K_La\ (C_s - C) - r_r \qquad (1)$$

in which as described by Hixson and Gaden (37) and Camp (41):

$C$ = the concentration of the dissolved gas (mg/l) in the body of the liquid at time t.

$C_s$ = the concentration of the dissolved gas (mg/l) in the gas-liquid interface (the saturation concentration).

$a = \frac{A}{V}$ ($cm^{-1}$).

$A$ = the air-liquid interfacial area ($cm^2$).

$V$ = the liquid volume ($cm^3$).

$K_L = \frac{D_L}{Y_L}$ (cm/hr)

$D_L$ = the gas diffusivity ($cm^2$/hr).

$Y_L$ = the hypothetical film thickness (cm).

$\frac{dC}{dt}$ = the rate of change of the dissolved gas concentration (mg/l/hr).

$r_r$ = the oxygen uptake rate of the mixed liquor (mg/l/hr).

During the aeration of mixed liquor, oxygen is the only soluble gas of interest. From the equation, it can be seen that the rate of change of the dissolved oxygen concentration is equal to the rate of supply $[K_La\ (C_s - C)]$ minus the uptake rate $(r_r)$. It can also be seen that the rate of supply is directly proportional to the dissolved oxygen deficit $(C_s - C)$ at any time (t).

During steady state operation, the rate of supply equals the rate of demand i.e., $\frac{dC}{dt} = 0$ and the equation becomes:

$$K_La\ (C_s - C) = r_r \qquad (2)$$

Rearranging:

$$K_LaC = K_LaC_s - r_r$$

$$C = C_s - \frac{r_r}{K_La}$$

$$C = (-\frac{1}{K_La})r_r + C_s \qquad (3)$$

which is of the form:

$$y = mx + b$$

Therefore, equation (3) is an equation of a straight line in which $(- \frac{1}{K_La})$ is the slope, and $C_s$ is the y intercept with $r_r$ and C being plotted on the x and y axes, respectively. It follows, therefore, that $K_La$ is equal to the negative reciprocal of the slope of a C versus $r_r$ plot.

# SECTION IV

## EXPERIMENTAL APPARATUS AND MATERIAL

### A. Material

The material used for the series of tests conducted was mixed liquor taken from the effluent end of the aeration tanks at the East Lansing, Michigan Waste Water Treatment Plant. This plant employs the biosorption modification of the activated sludge process for treatment of settled sewage. The waste flow consists almost entirely of municipal sewage. The plant is designed for a maximum capacity of 12 mgd. At the present time, the flow is approximately 9 mgd during the summer months and 8 mgd during the rest of the year. However, the flow exhibits considerably more fluctuation than that shown above due to the combined sewer system.

### B. Apparatus

Application of equation (3) required the measurement of C and $r_r$ and the determination of whether steady or non-steady state conditions existed. Steady state determinations were made by continuously recording the dissolved oxygen concentration. This also provided the C value. The uptake rate $r_r$ was measured every hour on the hour by means of a specially constructed $r_r$ chamber, an oxygen meter, an amplifier, recorder and timer.

An overall view of the apparatus used for the measurements is shown in Figure 1. A flow of mixed liquor was continuously pumped from the end of an aeration tank into the D.O. chamber. During the initial setting up and testing of the equipment the flow of mixed liquor was permitted to syphon into the chamber; however, this proved to be unreliable and a Barnes model SF31 submersible pump was installed in the aeration tank. The discharge line of the pump was 1¼" in diameter; whereas, the flow line used was ½" diameter black pipe. This required recycling of part of the pumped flow, which was accomplished by connecting the pump to the ½" line with a 1¼" x ½" x ½" tee. Connected in this manner, the pump supplied a reliable and reasonably constant flow of mixed liquor for a period of approximately 48 hours. At the end of this period the pump required dismantling and cleaning to maintain a constant flow. It was also necessary to occasionally back flush the ½" black pipe feed line. The D.O. chamber, as shown in upper right portion of Figure 1, and in Figure 2, was constructed of lucite. The three pieces of lucite tubing bonded into the side of the container were, from base to top, for influent, effluent and excess mixed liquor. This container gave approximately 0.3 min.

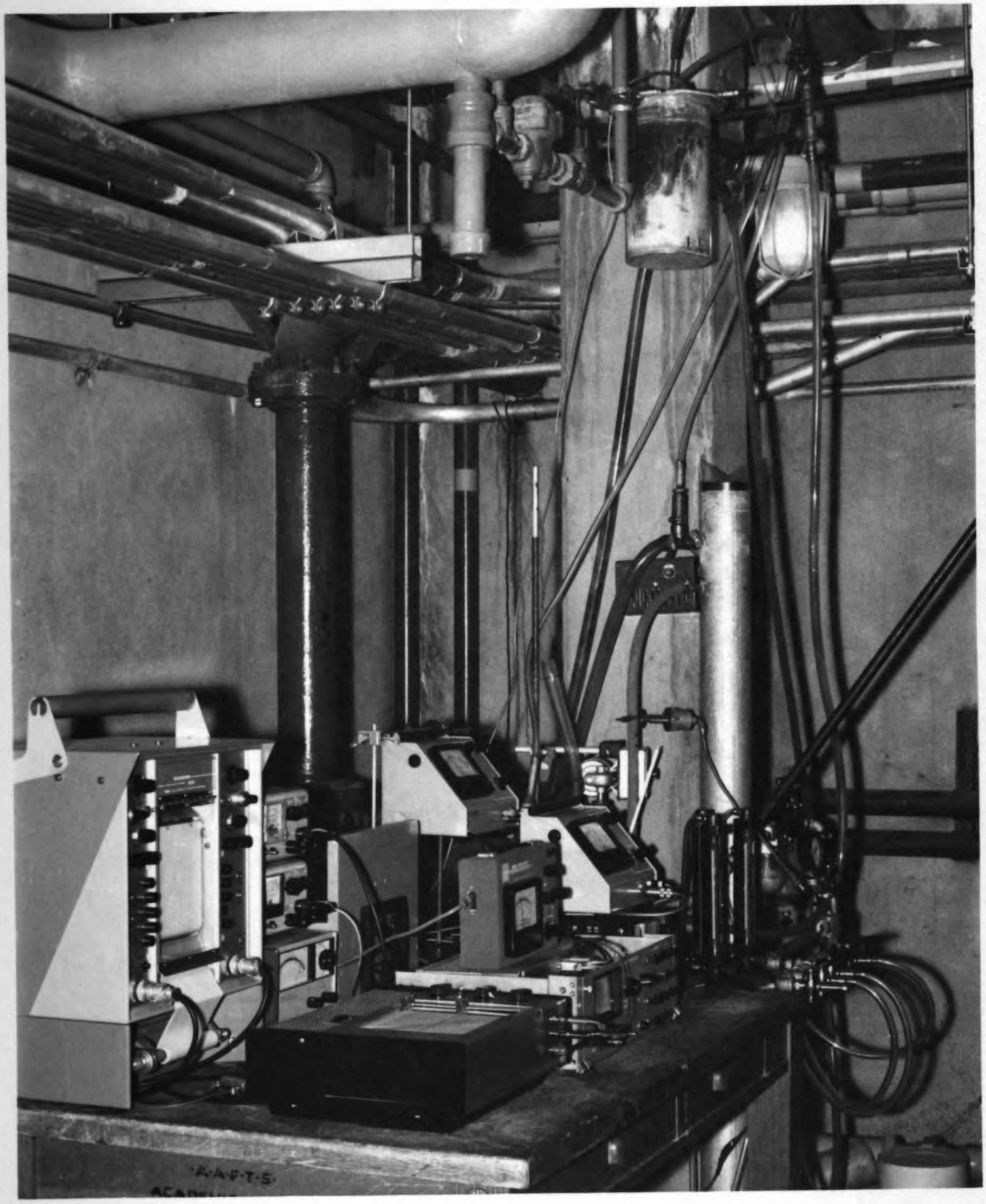
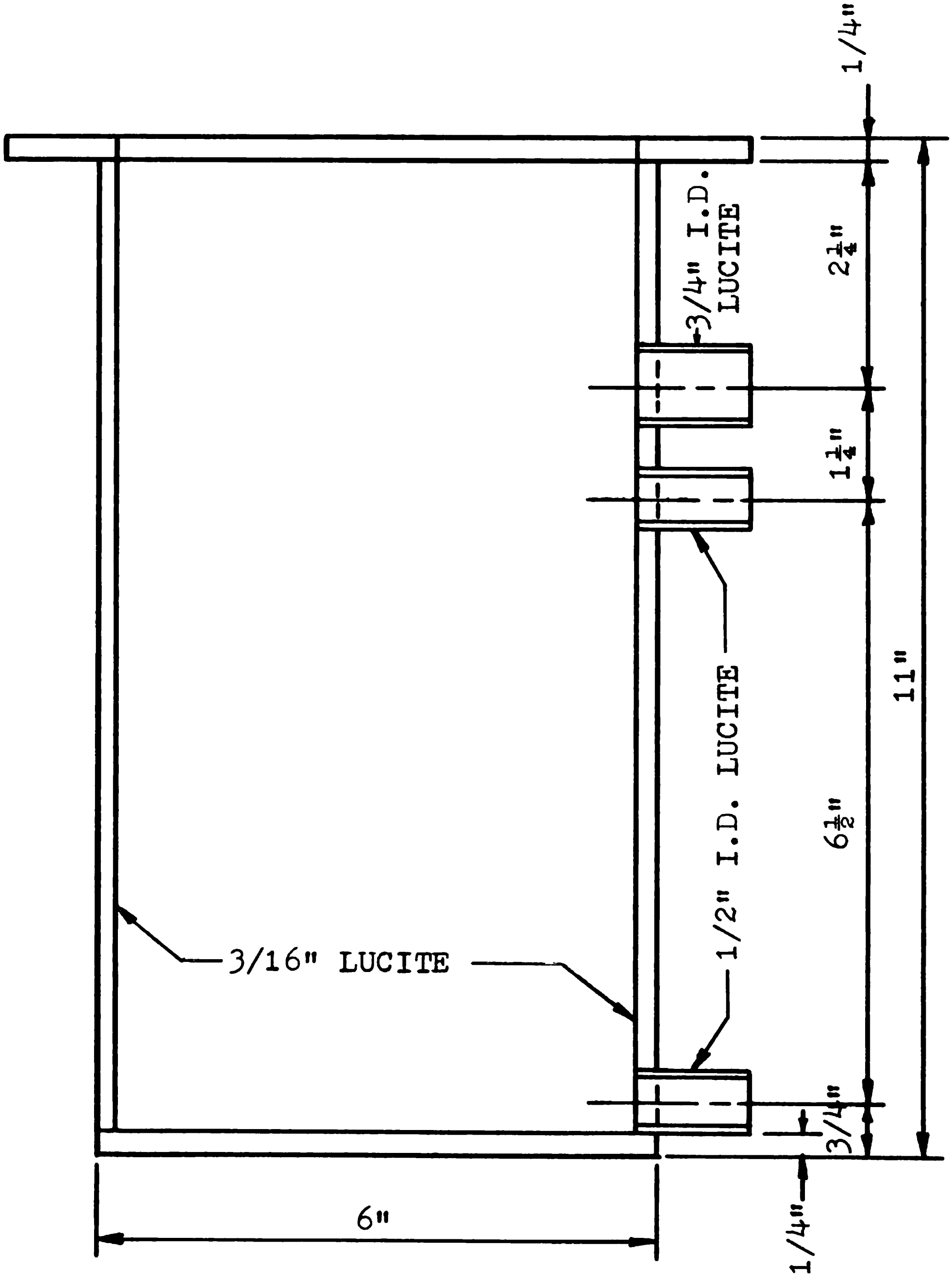


Figure 1. Overall View of Apparatus



½ SCALE

Figure 2. D.O. Chamber

retention time to permit the continuous measurement of the dissolved oxygen concentration. The momentum of the incoming flow provided sufficient agitation for the measurements.

After passing through the D.O. chamber, the flow entered the bottom of the aeration chamber. The aeration chamber, as shown in Figures 1 and 3, was constructed of 26 G.A. galvanized sheet metal with soldered seams. The tubing connections were short (1½") pieces of copper tubing. Three 5/8 inch holes were drilled 120° apart near the bottom of the container to permit the insertion of three No. 3 rubber stoppers each containing a ½ inch diameter by 1 inch long fritted glass diffuser. This provided approximately 0.9 min. retention time and raised the dissolved oxygen concentration of the incoming flow to permit $r_r$ determinations when the initial dissolved oxygen concentration was low.

The compressed air used for the aeration and the operation of the air valve was taken from plant high pressure air supply. Due to considerable water and rust in the plant air, it was passed through a Foxboro and a Norgren model 22B2 air filter. Following filtration, the air passed through a Kendall model 30 pressure regulator which was set to reduce the pressure from 120 to 30 psi. It them passed through a flow valve and a F&T model 01-150/S-51801 Flowrator (foreground Figure 4)

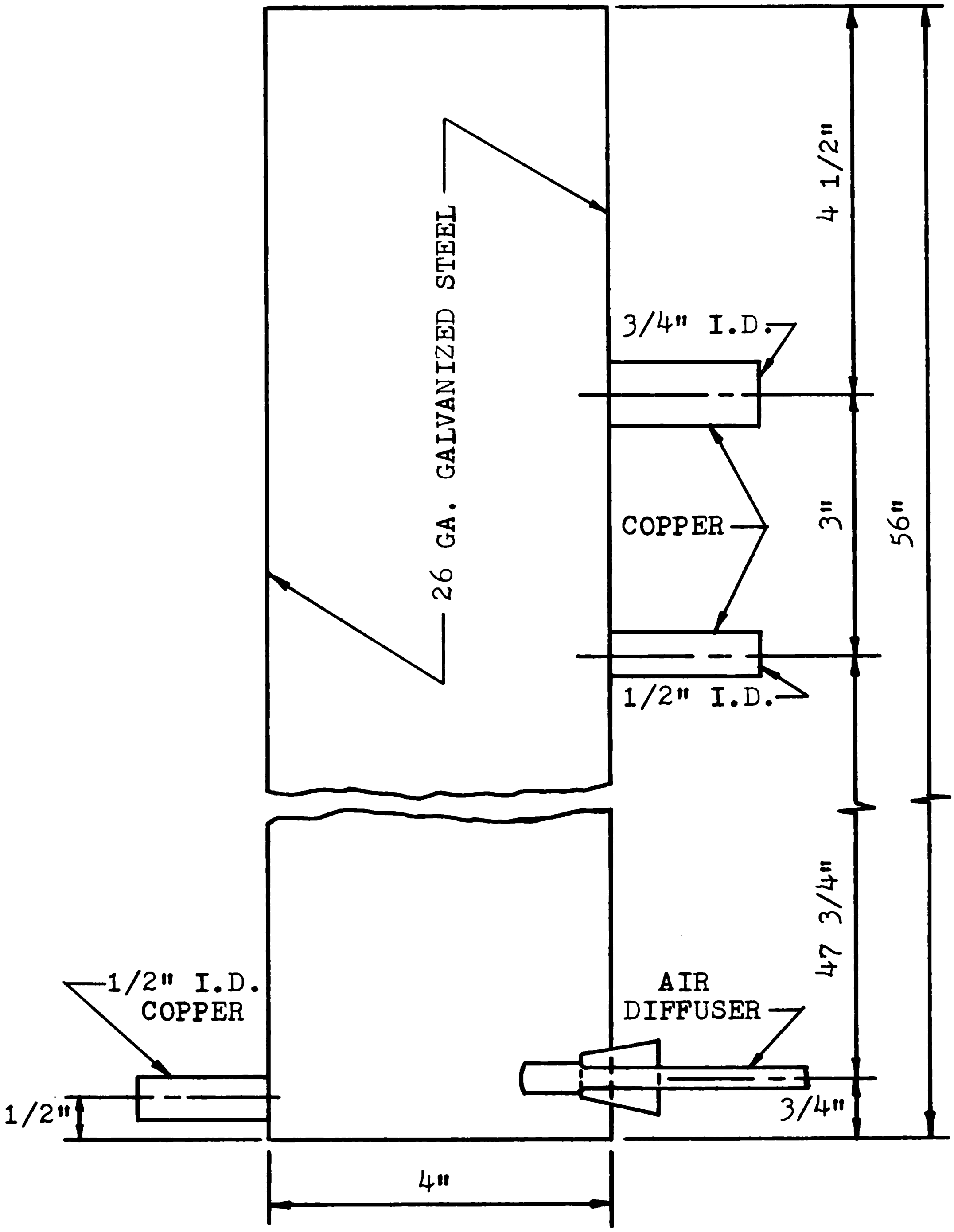


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Figure 3. Aeration Chamber

Figure 4. $r_r$ Chamber in Operation

before it was diffused into the aeration chamber contents. The air flow was held at 2 lpm per diffuser during the experiments. The flow was regulated by the air valves, and constantly measured by the Flowrators to permit adjustments when necessary. As shown in Figures 1 and 4, black pipe was used to carry the air flow to the flow valves after which it was carried by 5/16 inch tygon tubing. This provided metered aeration for the flow of mixed liquor.

Following aeration, the mixed liquor passed through the $r_r$ chamber for 51 minutes of each hour and was discharged. The $r_r$ chamber is shown in Figure 5 with its stirring motor and thermometer. It is also shown in operation in Figure 4, and a cross sectional drawing of it is shown in Figure 6. The body of the container was also constructed of 26 G.A. galvanized sheet metal, but the slanted top was made of ¼ inch lucite attached to the base with eight screws to permit removal for cleaning. As shown in Figure 6, the inlet piece of ½" I.D. lucite tubing extended to within 3/4 of an inch of the bottom of the container. This provided sufficient agitation to keep suspended particles from accumulating on the bottom. The outlet of the interior chamber was constructed of 3/4" I.D. lucite tubing to prevent possible clogging. The lucite top also contained a tapered 1¼ inch hole for the insertion of a No. 7 rubber stopper. The hole was

Figure 5. $r_r$ Chamber

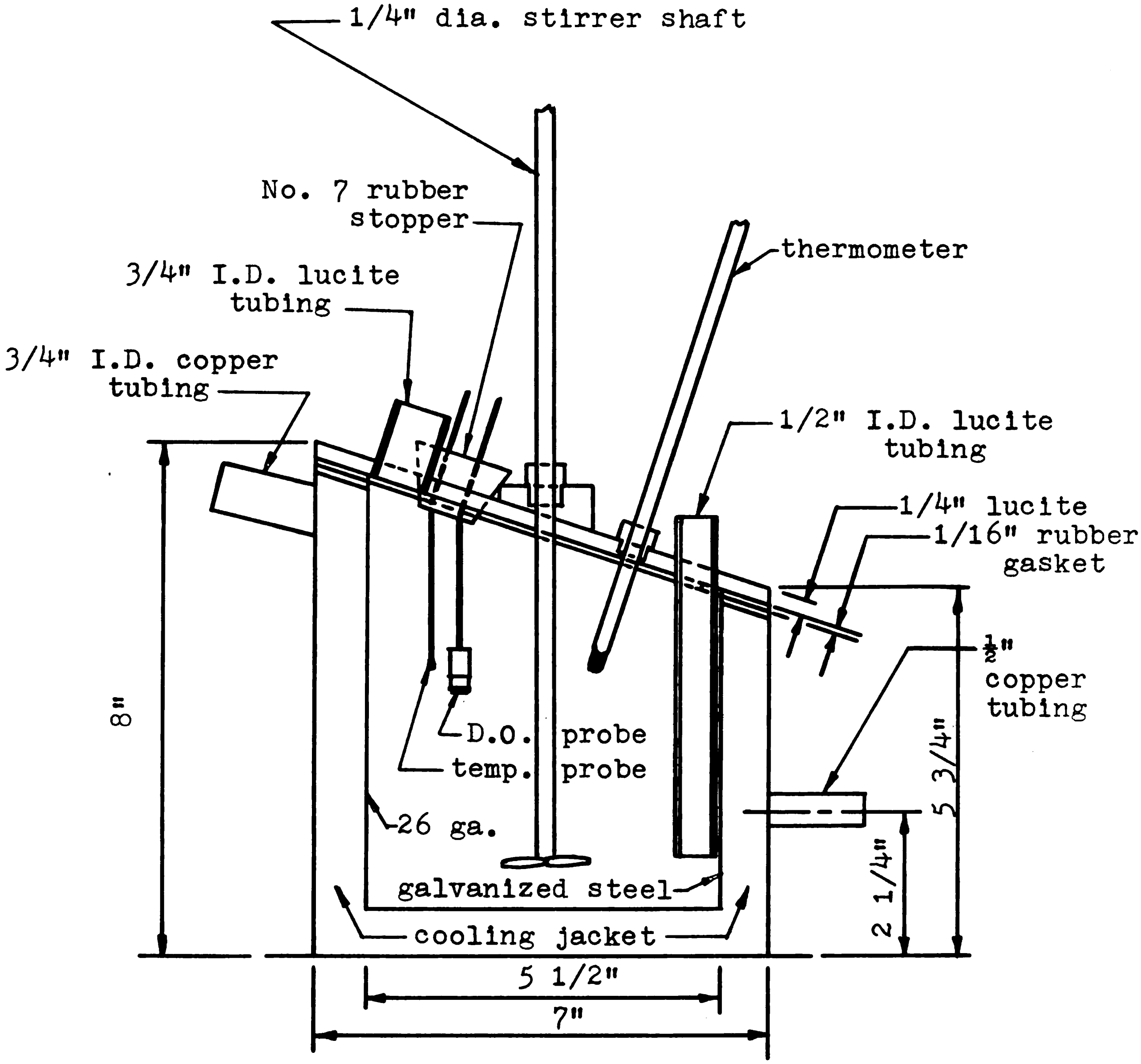

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Figure 6. Cross Section of $r_r$ Chamber

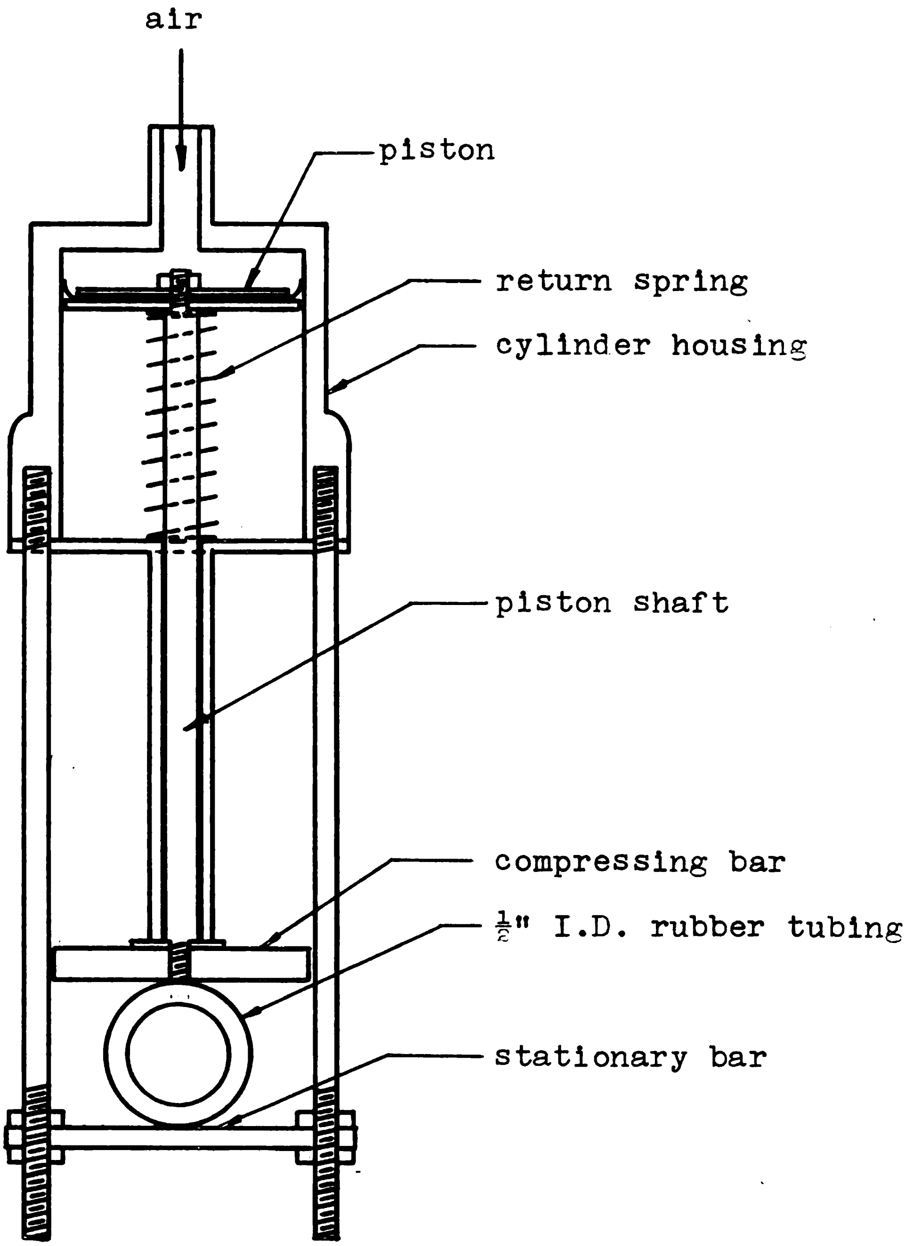
tapered to match the taper of the stopper to avoid the collection of solids and air bubbles. Two threaded holes with fittings and "O" rings were also made in the top. These were to provide water and air tight seals around the thermometer and stirrer shaft. The model K43 Tri-R Stir-R shown in Figure 5 was equipped with a ¼" chuck into which the stirrer shaft was tightened. The stirrer was operated at approximately 250 rpm, which was sufficient to keep solids in suspension during $r_r$ tests. The mixing motor was clamped to a ring stand, and the $r_r$ chamber was simply held in position with two studs in the base of the ring stand. This retained the $r_r$ chamber in position, but provided tolerance for any misalignment between the stirrer shaft and "O" ring fitting.

The $r_r$ chamber was also constructed with a surrounding temperature jacket to maintain a constant temperature during $r_r$ determination. This jacket was around the sides of the container and under the bottom, which, together with the $r_r$ chamber, made an integral unit, as shown in Figures 5 and 6. The inlet and outlet of the temperature jacket were short pieces of ½ inch and 3/4 inch copper tubing, respectively. The construction of the jacket with the larger outlet was once again to eliminate clogging.

To stop the influent into the $r_r$ chamber every hour, an air operated pinch valve was constructed. It is shown in the upper right of Figure 4, and in Figure 7. The air cylinder was operated by a model V437A1006 Honeywell Magnetic Valve. When the magnetic valve was energized it permitted air to flow into a Kendall model 30 pressure regulator which was set to reduce the pressure from 30 to 12 psi. This pressure then caused the plunger of the air cylinder to pinch the $r_r$ chamber $\frac{1}{2}$ inch rubber tubing influent line, stopping the mixed liquor flow and holding a sample of it.

Figure 8 shows an overall schematic flow diagram with the three chambers, piping and tubing. The flow was split just before it entered the D.O. chamber. The majority of it passed through the D.O. chamber and on through the system. The diverted portion became the cooling liquid used in the temperature jacket of the $r_r$ container to maintain a constant temperature during $r_r$ determinations.

The effluent flow rates from the D.O. chamber and the aeration chamber were regulated by varying their respective elevations. This was facilitated by attaching the D.O. chamber to a vertical pipe in the plant by means of a 2" muffler clamp. The aeration chamber's elevation was varied by placing objects of different thicknesses under it. Assuming the bottom of the aeration chamber was elevation 100.00, the final operating elevation of the base of the $r_r$ chamber was 101.83 and the bottom of the D.O. chamber was 106.00



Full Scale

Figure 7. Cross Section of Air Valve

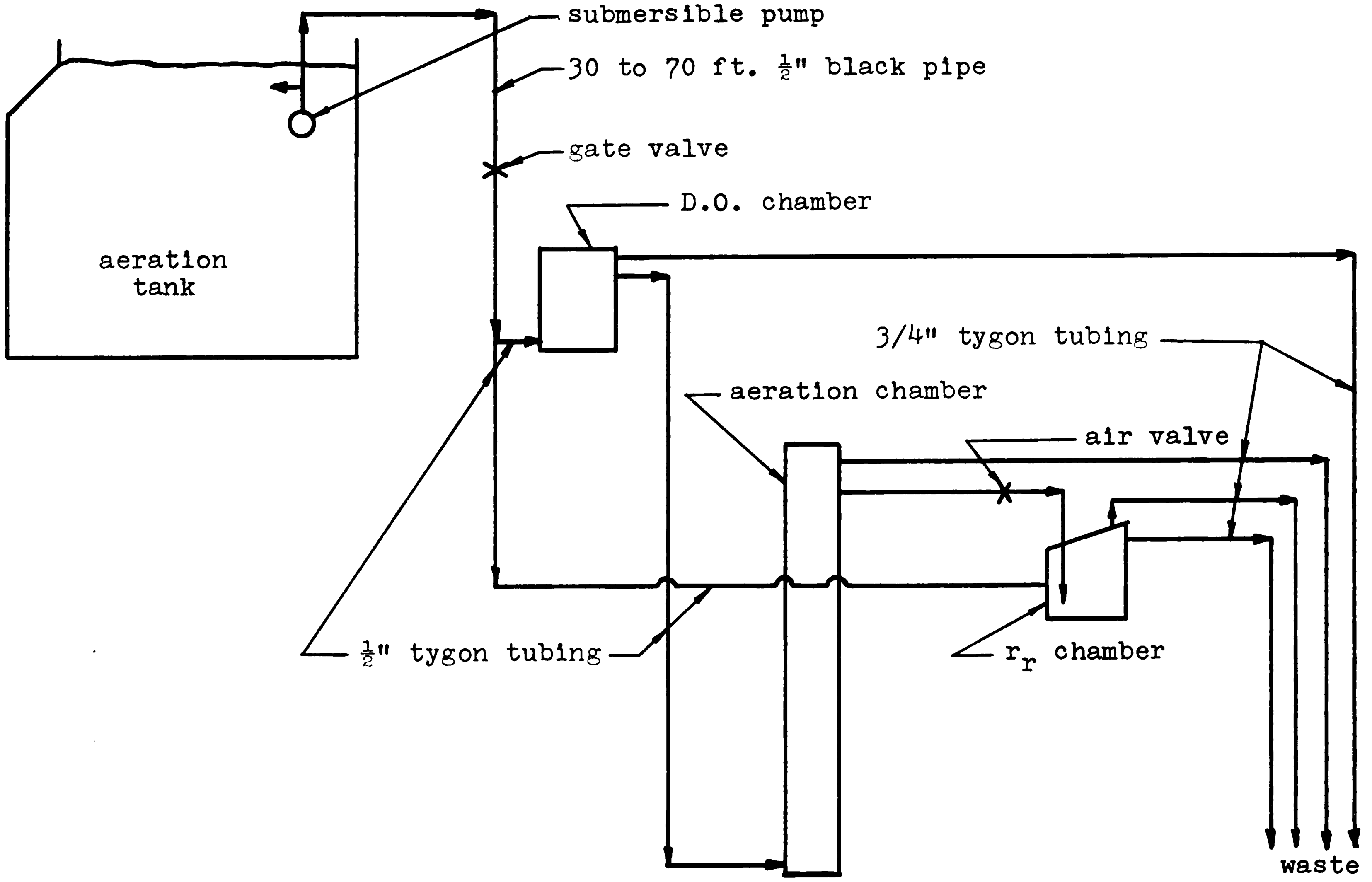


Figure 8. Schematic Flow Diagram

The dissolved oxygen concentration of the influent mixed liquor was continually measured with a YSI temperature corrected model 5418 polarographic oxygen probe and a model 54 oxygen meter manufactured by the Yellow Springs Instrument Company. The output of the YSI meter was recorded by a Bausch and Lomb model V.O.M. 5 Recorder. The chart speed of this recorder was set at 2.5 inches/hour during all the $K_La$ experiments.

The $r_r$ determinations and the temperature measurements were also automatically recorded by a model 322 Sanborn Dual Channel D.C. Amplifier-Recorder. A General Electric Process Timer model 3TSA1SBAC160 was used to turn on the Sanborn recorder, a Hewlett Packard model 721A Power Supply, the mixing motor, and to energize the magnetic valve. The timer was equipped with two circuits, which have been denoted as A and B in Figure 9 a schematic wiring diagram. Circuit A was set to start at 49 min. and circuit B at 50 min. Circuit B was set to end at 59 min. and Circuit A at 60 min. Therefore, by starting the timer 10 min. after the hour circuit B would start on the next hour. The timer was also equipped with an automatic reset which immediately started a new cycle at 10 min. after each hour when the previous cycle had finished.

The Sanborn recorder and the Hewlett Packard power supply were connected to circuit A; whereas, the mixing motor and magnetic valve were connected to circuit B.

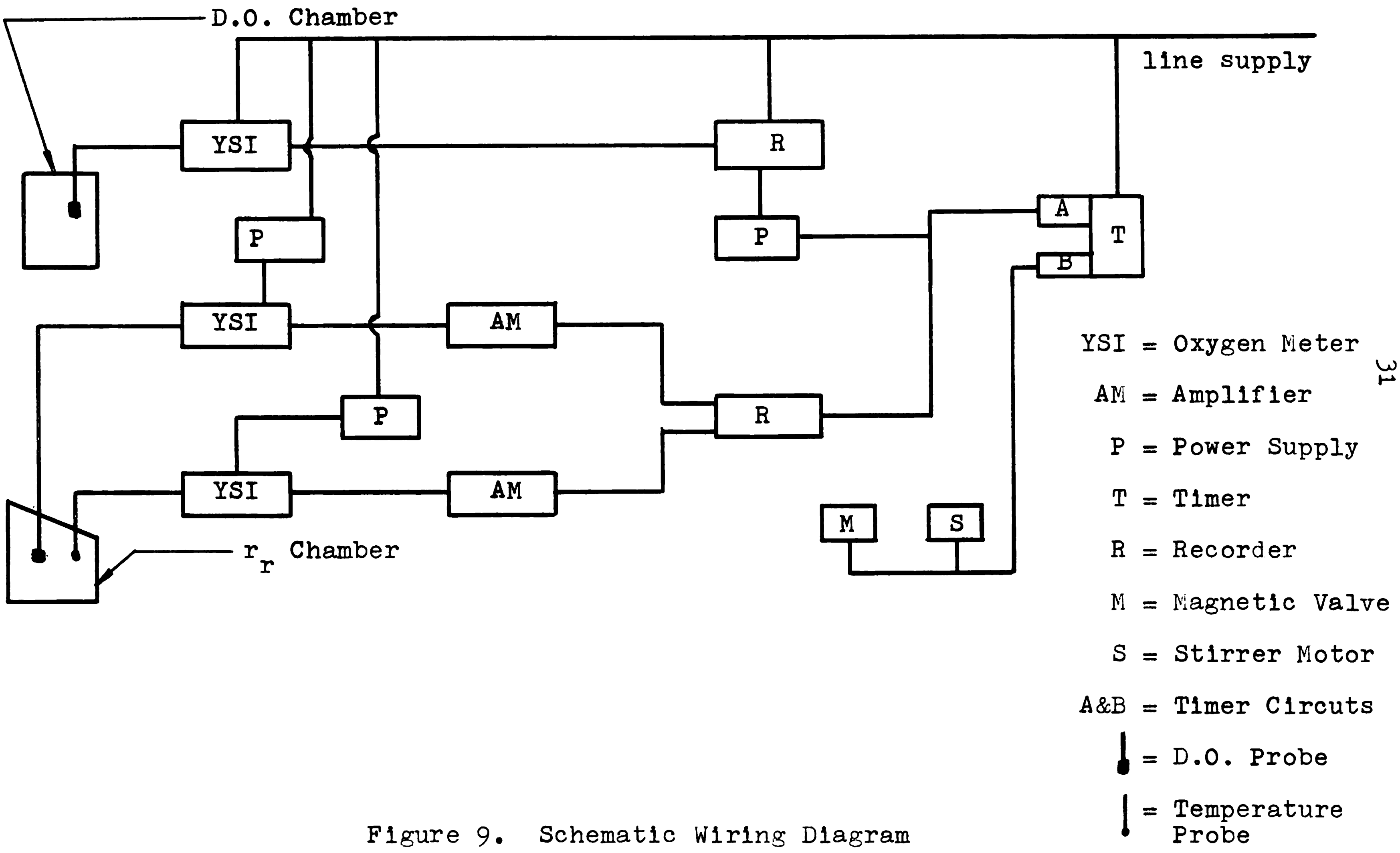


Figure 9. Schematic Wiring Diagram

This provided a short warm up time for the recorder, and a definite end point on each $r_r$ recording when the air valve opened. The power supply was set for an output of 6 volts, which was required to operate the event marker of the Bausch and Lomb recorder. This recorder was equipped with two pens. One pen recorded the output of the model 54 YSI meter, and the other traced a line at the upper edge of the paper. The 6 volt output of the power supply caused a solenoid to deflect the tracer pen approximately 1/16 inch; therefore, this provided direct correlation between the two recorders as shown by the deflection of the tracer line on the Bausch and Lomb chart paper in Figure 10.

The actual measurement of the decrease of the dissolved oxygen concentration in the sample of mixed liquor held in the $r_r$ chamber was made with a YSI non-temperature corrected model 5101 polarographic oxygen probe with a model 51 oxygen meter manufactured by the Yellow Springs Instrument Company. The output of this YSI meter was amplified by a Hewlett Packard model 419A Null Voltmeter. The output of the null voltmeter was recorded by one channel of the Sanborn recorder. The chart speed of both channels of the recorder was set at 1.0 mm./sec. during the $K_La$ experiments.

The temperature of the mixed liquor sample was measured by a YSI model 401 temperature electrode with a YSI model 51 oxygen meter. The output of this meter

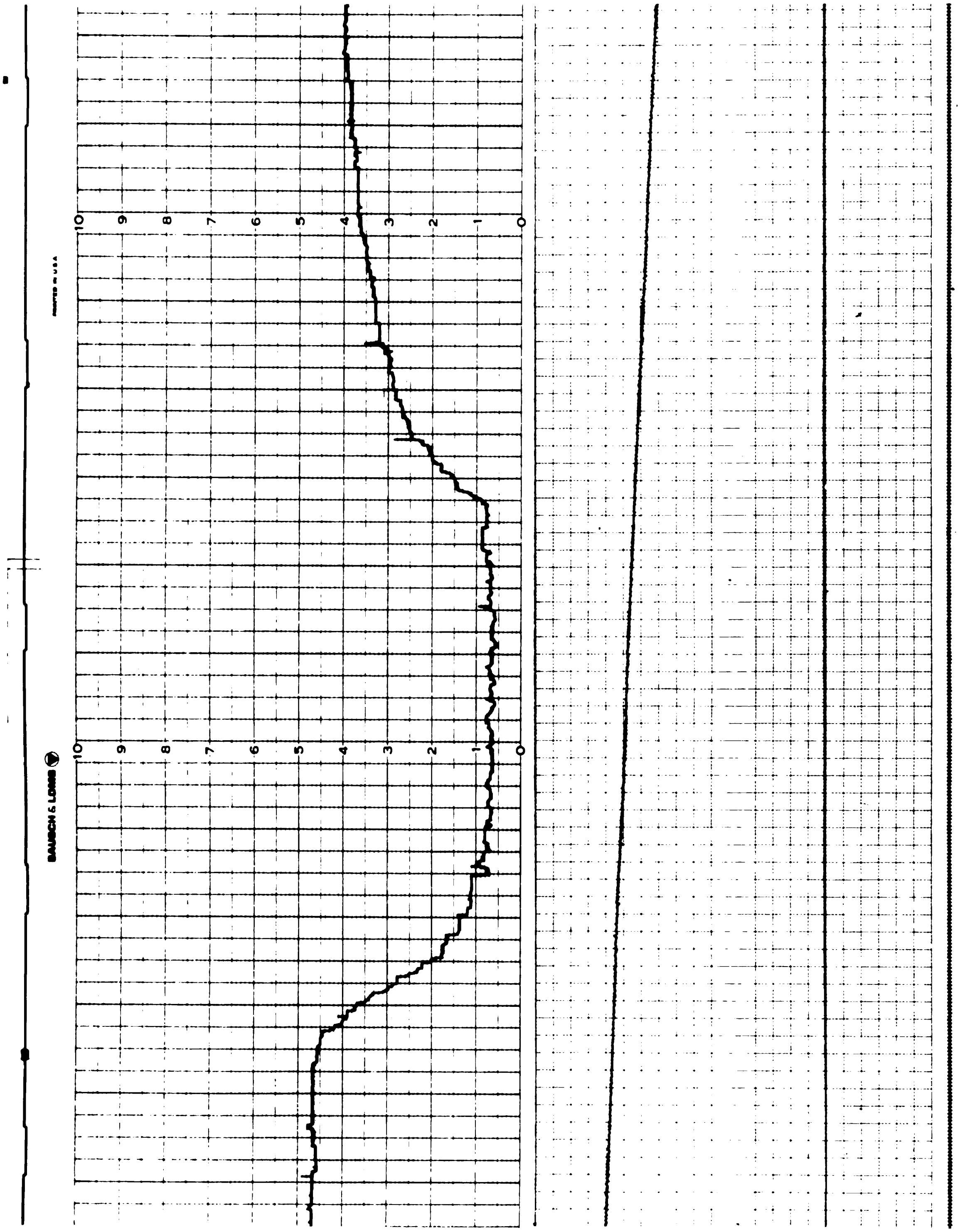


Figure 10. Recorder Chart Papers

was amplified by an Electronics Associates Inc. model TR5 analog computer. The output of the analog computer was recorded by the second channel of the Sanborn recorder. Two tach filters were required between the analog computer and the recorder to eliminate a considerable amount of noise.

The oxygen probe and temperature electrode were suspended in the $r_r$ chamber by running their cords through a No. 7 rubber stopper, as shown in Figure 6. Each electrode cord was slipped in a slit made to a previously bored hole in the stopper. This facilitated the suspending of the electrodes in the $r_r$ chamber and it gave a water tight seal.

The two model 51 YSI meters used for the recording of the temperature and $r_r$ recordings were designed to be powered by one 3.5 volt and two 7 volt dry cells. To permit 24 hr. recordings, the dry cells were replaced by a Hewlett Packard model 721A Power Supply and a Trygon model HR40-750 Power Supply. The Hewlett Packard Power Supply was used to replace the two 7 volt dry cells, and the Trygon Power Supply replaced the 3.5 volt dry cells. This eliminated the periodic replacement of the dry cells, and permitted continuous operation.

The complexity and the number of pieces of electronic apparatus used could have been reduced if equipment other than that readily available had been used. By using a dual channel recorder with a sensitivity equivalent to that of the Bausch and Lomb, the null voltmeter and analog computer which were used as amplifiers could have been eliminated. The Trygon and one Hewlett Packard power supply could have been eliminated by using a model 54 YSI meter, which is equipped with a line cord, instead of the dry cell powered model 51 YSI meter used for the $r_r$ recordings. Using a model 54 YSI meter would have also eliminated the necessity of recording the temperature during each $r_r$ test, because its output is temperature corrected. The temperature variation could have been obtained by periodic readings of the thermometer in the $r_r$ chamber, or a thermistor could have been used instead of one of the model 51 YSI meters. By altering the equipment in the above described manner, the electrical wiring could have been substantially simplified.

# SECTION V

# EXPERIMENTAL PROCEDURE

## A. $K_La$ Determination

The actual D.O. measurements and $r_r$ determinations were performed automatically by the equipment. The three YSI meters, the two amplifiers, the two power supplies and the Bausch and Lomb recorder operated continuously. One minute before each hour, circuit A of the timer started, which started the Sanborn recorder and turned on the power supply connected to the tracer pen of the Bausch and Lomb recorder. On each hour, circuit B of the timer started, which started the mixing motor, and energized the magnetic valve, causing the air valve to stop the flow into the $r_r$ chamber. At nine minutes after each hour, circuit B had completed its cycle, discontinuing the operation of the mixing motor and air valve and permitting the mixed liquor to once again flow through the $r_r$ chamber. At ten minutes after each hour, circuit A completed its cycle, which stopped the Sanborn recorder, turned off the tracer pen power supply, and reset the timer to begin another hourly cycle. Therefore, the complete hourly cycle of the timer made the Sanborn recorder record the temperature and dissolved oxygen concentration of a sample of agitated mixed liquor, and made a deflection of the plot of the Bausch and Lomb tracer pen that continued until the recorder was turned off. The recordings on the Sanborn chart paper represented the amplified output of a model 5101 YSI oxygen probe and a model 401 YSI temperature electrode.

During preliminary studies, it was found that the sensitivity of the YSI model 5101 electrodes varied, as reported by Kooistra (38). However, the electrodes used during this testing received fresh potassium chloride and a new teflon membrane approximately three months prior to the beginning of the tests. This provided stable electrodes, the calibration of which changed very slowly with time.

The YSI electrodes were calibrated at the beginning of each series of tests. Before each calibration, tap water was aerated for approximately 24 hours to obtain a dissolved oxygen concentration near saturation. The Azide modification of the Winkler Method as described in Standard Methods (42) was used to determine the actual dissolved oxygen concentration of the aerated tap water. Prior to each of these determinations, the sodium thiosulfate was restandardized against a potassium iodide solution. The titrations were normally conducted in duplicate with the results normally agreeing to the nearest tenth of a ppm of dissolved oxygen. When a tenth variance was obtained, a third test was run to determine the concentration value to use. This provided a tap water sample of known dissolved oxygen for the calibration of the YSI electrodes.

The YSI model 5101 electrode, the model 51 oxygen meter, the null voltmeter, and the Sanborn recorder were calibrated as a unit at the beginning of each test series. The unit was first adjusted to read approximately 8 ppm in a sample of the aerated tap water. It was then calibrated to read zero in a grab sample of return sludge taken near the beginning of the plant sludge reaeration tanks. Such a sample could almost always be assumed to have zero dissolved oxygen. However, if some dissolved oxygen was present it was quickly depleted by the microorganisms in the sludge which normally had a suspended solid concentration of approximately 7,000 mg/l. Tap water with its dissolved oxygen reduced to zero with sodium sulfite was first used as a zero calibration liquid, but it was found that this gave a false zero recorder reading, therefore the return sludge was used.

After setting the zero reading, the recorder reading was calibrated for various temperatures. The electrode, along with a magnetic stirring bar and thermometer, was placed in a 250 ml wide mouth Erlenmeyer flash. The flash was then placed in a 1500 ml beaker on a magnetic stirrer. Sufficient water was added to the beaker to submerse approximately three-fourths of the Erlenmeyer flask, and the temperature of the known dissolved oxygen water and the surrounding water bath was equilibrated at approximately 22°C. This temperature was normally sufficient to give a full scale deflection of the Sanborn recorder. At this point, crushed ice was added to the surrounding water bath with the magnetic stirrer in operation. Sufficient ice was added during the calibration to keep the temperature of the known dissolved oxygen water slowly decreasing. The recorder reading was read at every degree centigrade in the temperature range of approximately 10 to 22°C.

The data from the May 18 calibration is listed in Table 1. The sensitivity of the electrode at the various temperatures was calculated by dividing the recorder reading by the actual dissolved oxygen concentration. To facilitate use of the calibration data during calculations, a semi-logarithmic plot of the sensitivity versus temperature was constructed after each electrode calibration. Such a plot of the data listed in Table 1 is shown in Figure 11. By using this plot, recorder readings could be converted to mg/l of dissolved oxygen if the temperature of the reading was known.

## TABLE 1

## OXYGEN PROBE CALIBRATION DATA FOR JUNE 18, 1968

Dissolved Oxygen Concentration = 8.55 mg/l

| Temp. ($^{o}$C) | Recorder Reading | Sensitivity (divisions/mg$O_2$/l) |
|---|---|---|
| 21.1 | 10.00 | 1.17 |
| 20.0 | 9.30 | 1.088 |
| 19.0 | 9.00 | 1.052 |
| 18.0 | 8.55 | 1.00 |
| 17.0 | 8.15 | 0.953 |
| 16.0 | 7.80 | 0.912 |
| 15.0 | 7.40 | 0.866 |
| 14.0 | 7.00 | 0.819 |
| 13.0 | 6.40 | 0.749 |
| 12.0 | 6.20 | 0.725 |
| 11.8 | 6.10 | 0.714 |

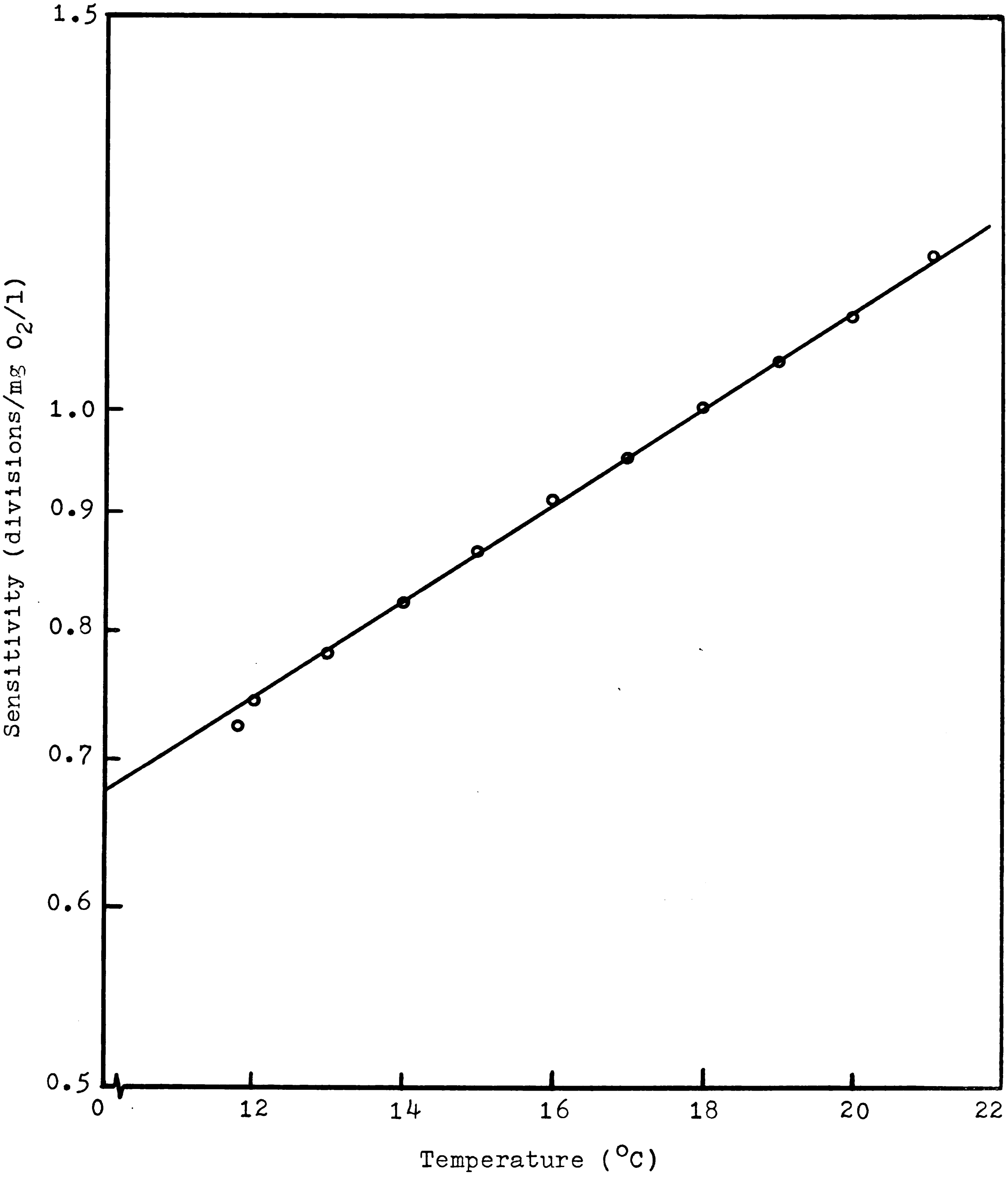


Figure 11. Sensitivity Plot

The calibration of the model 5418 YSI oxygen probe, which was temperature corrected, was considerably simplified as compared to the calibration of the model 5101 probe. During preliminary studies, the temperature correction of the model 5418 oxygen probe with the model 54 oxygen meter was checked. It was found that its effectiveness increased from 0 to approximately 10 or 12°C and remained constant in the temperature range of 12°C to approximately 25°C. Therefore, a temperature calibration of this electrode was not necessary. The electrode was, however, calibrated at zero dissolved xoygen and at another value with a water of known concentration. The model 5418 electrode was calibrated as a unit with the model 54 YSI oxygen meter and the Bausch and Lomb recorder. The zero calibration was conducted as before, with the recorder reading being set at zero when the electrode was in a return activated sludge sample. The calibration in the water of known dissolved oxygen concentration was conducted with the electrode in a stoppered 250 ml Erlenmeyer flask with a magnetic stirring bar and a magnetic stirrer. The stirrer was adjusted to give approximately the same agitation as that given by the mixed liquor flow in the D.O. chamber. During the calibration, the recorder was adjusted to read in mg/l of dissolved oxygen. Therefore, the numbers on the Bausch and Lomb chart paper represented mg/l of dissolved oxygen. This simplified calculations by permitting the value of C to be read directly from the chart paper. It also made it possible to very quickly check the accuracy of the dissolved oxygen recording during operation.

The YSI model 401 temperature electrode that was used for the temperature recordings also required calibration. During the first part of experiment 1, this electrode was not used, but it was later incorporated into the equipment. The temperature electrode, as the other electrodes, was calibrated as a unit with the model 51 YSI oxygen meter, the Electronics Associates Inc. analog computer, and the Sanborn recorder. An attempt was made to calibrate the electrode and recorder so that one division on the chart paper would be equivalent to one degree centigrade; however, this was not successful. The range used on the recorder gave a slightly smaller deflection than one division for each degree. Therefore, the electrode required calibrated similar to that of the model 5101 oxygen probe. The electrode was once again placed in a 250 ml Erlenmeyer flask with a magnetic stirring bar and thermometer. After the flask had been filled with tap water and stoppered, it was placed in a 1500 ml beaker containing sufficient water to submerse approximately three-fourths of the flask. The magnetic stirrer was started, and the apparatus was permitted to equilibrate at approximately 25°C. At this time, the recorder was adjusted to full scale deflection. Crushed ice was then added to the beaker which served as a water bath. As the temperature decreased, the recorder reading was read at every degree centigrate until the recorder indicated a zero reading. The data taken during the May 18 calibration is shown in Table 2. To facilitate its use, the data from each calibration was plotted as shown in Figure 12. These plots permitted the conversion from chart paper readings to degrees centigrade.

Due to the manner in which the Bausch and Lomb recorder was calibrated, the values of C could be read directly from the chart paper in mg/l, which eliminated the need for calculating these values. The particular C value to use was indicated by the beginning of the deflection of the tracer pen. Before the tracer pen was incorporated into the equipment, the time was periodically written on the chart paper when an $r_r$ test started, and the proper place to read a C value was determined by linearly proportioning the distance between these periodic recordings. The proportioning was necessary, because the chart speed of the Bausch and Lomb recorder varied slightly as the amount of used paper increased. These methods provided the C values used for the $K_La$ determinations.

The determinations of whether a specific $r_r$ was

## TABLE 2

## TEMPERATURE PROBE CALIBRATION DATA FOR JUNE 18, 1968

| Temp. (°C) | Recorder Reading |
|---|---|
| 24.5 | 9.3 |
| 24.0 | 9.1 |
| 23.0 | 8.1 |
| 22.0 | 7.1 |
| 21.1 | 6.7 |
| 20.0 | 5.55 |
| 19.0 | 4.7 |
| 18.0 | 3.9 |
| 17.0 | 3.0 |
| 16.0 | 2.1 |
| 15.0 | 1.3 |
| 14.0 | 0.3 |

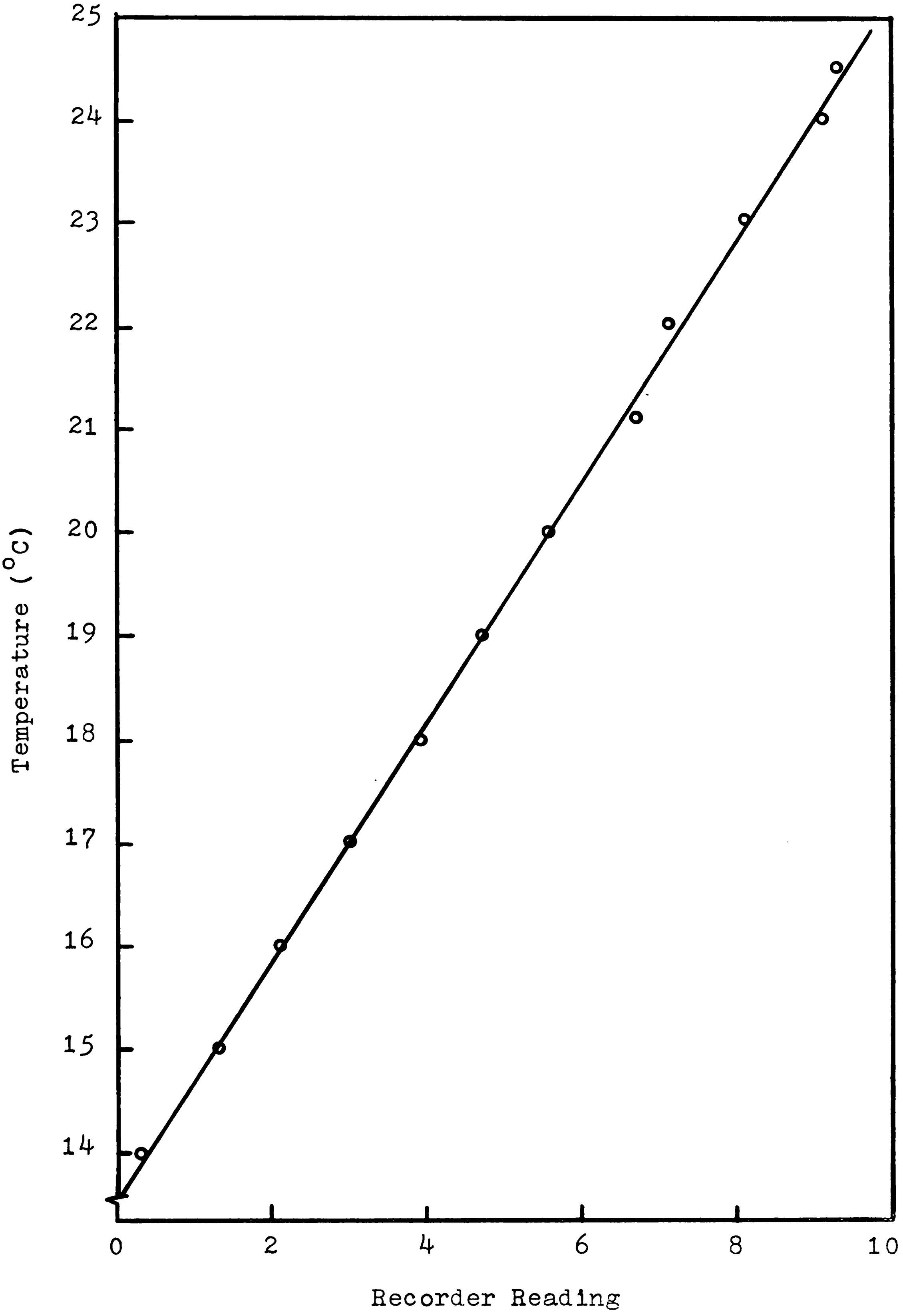


Figure 12. Temperature Calibration Plot

representative of steady state conditions were made using the Bausch and Lomb recording. An arbitrary standard of 0.5 mg/l/hr. variance of the dissolved oxygen concentration was used for classifying a specific $r_r$ as representative of steady state or non-steady state conditions. The $r_r$ values obtained during an hour in which the dissolved oxygen concentration varied more than 0.5 mg/l were classified as non-steady state and were not plotted or used for the determination of $K_La$. Most of the values obtained were recorded during periods in which the variation was less than 0.5 mg/l/hr.; however, this does not indicate that most of the values were obtained during periods that exhibited $\frac{dC}{dt}$ values near 0.5 mg/l/hr. A large percentage of the values represent periods during which the dissolved oxygen concentration varied less than 0.5 mg/l for three to four hours. Therefore, the Bausch and Lomb chart paper, as shown in Figure 10, provided the C values and the information for the determination of steady state or non-steady state conditions.

The Sanborn chart paper, as shown in Figure 10, provided the information to permit the determination of the temperature and the calculation of $r_r$ values. Temperature determinations were made by simply reading the recorded value on the chart paper and finding the corresponding temperature on a plot such as that shown in Figure 12. Once the temperature had been determined for each $r_r$ test, $r_r$ could be evaluated. The Sanborn recorder was equipped with a timer, which every second made a small dash mark along one edge of the chart paper. By counting a certain number of dash marks and measuring the distance between them, the chart speed could accurately be determined. This was periodically checked and found to remain constant. When the chart speed had been accurately determined, the duration of the various $r_r$ tests could be measured. This was done by first determining a point near the end of each $r_r$ recording and measuring a distance with a meter stick along the chart paper that corresponded to a non fractional number of minutes. Normally, the slope of the dissolved oxygen plot remained constant for slightly more than nine minutes; therefore, the average $r_r$ listed represents a nine minute test. However, occasionally the plot exhibited fluctuations at the beginning of the test and shorter test durations were used. The initial and final dissolved oxygen readings were then read from the chart paper. At this point, the change in the dissolved oxygen concentration during the test period was calculated in mg/l. This was done by subtracting the final reading from the initial and dividing the value by the electrode sensitivity for the specific test temperature. The sensitivity in each case was obtained from a plot such as that shown in Figure 11. By multiplying the change in the dissolved oxygen concentration by the quotient of 60 divided by the test duration in minutes, the dissolved oxygen change was converted into an $r_r$ value with the units of mg/l/hr. These calculations were greatly simplified by constructing a table such as that shown in Table 3 which is the data for June 20.

When the C and corresponding $r_r$ values had been determined for each hour, they were plotted to permit the determination of $K_La$ from the slope of a C versus $r_r$ plot. The line of best fit through the data was obtained by a least squares analysis of the various points. To reduce the time required for this analysis, the University computer was used to perform the calculations.

After a series of tests, all the equipment and containers were checked and cleaned. It was decided that the $r_r$ chamber required cleaning before the beginning of each experiment. This decision was based on the fact that before the chamber was cleaned a noticeable biological growth had accumulated on its walls; however, a considerable growth was not found after the first cleaning.

The flow rates, primary effluent BOD's and suspended solids concentrations given with each set of data

# TABLE 3

## TYPICAL DATA AND CALCULATION SHEET

June 20, 1968, Tank No. 1

| Time | Temp. (°C) | Sensitivity (microamps/ $mgO_2/l$) | Recorder Reading Initial | Recorder Reading Final | Δ D.O. | $r_r$ (mg/l/hr) | D.O. (mg/l) |
|---|---|---|---|---|---|---|---|
| 12:00 | 19.7 | 1.097 | 6.50 | 5.00 | 1.368 | 16.40 | 3.5 |
| 1:00 **A**.M. | 19.7 | 1.097 | 7.40 | 4.70 | 2.460 | 16.40 | 4.9 |
| 2:00 | 19.7 | 1.097 | 5.60 | 2.80 | 2.550 | 19.12 | 4.9 |
| 3:00 | 19.6 | 1.090 | 7.30 | 4.80 | 2.290 | 15.28 | 5.0 |
| 4:00 | 19.6 | 1.090 | 7.85 | 5.30 | 2.340 | 15.60 | 5.1 |
| 5:00 | 19.4 | 1.075 | 7.50 | 4.90 | 2.420 | 16.13 | 5.3 |
| 6:00 | 19.4 | 1.075 | 7.55 | 5.10 | 2.260 | 15.08 | 5.6 |
| 7:00 | 19.4 | 1.075 | 7.10 | 5.20 | 1.767 | 13.24 | 6.0 |
| 8:00 | 19.4 | 1.075 | 7.50 | 5.30 | 2.045 | 13.63 | 6.1 |
| 9:00 | 19.4 | 1.075 | 7.50 | 5.30 | 2.045 | 13.63 | 6.4 |
| 10:00 | 19.4 | 1.075 | 7.50 | 5.70 | 1.674 | 11.17 | 6.5 |
| 11:00 | 19.4 | 1.097 | 6.80 | 5.10 | 1.550 | 10.33 | 6.2 |
| 12:00 | 19.8 | 1.105 | 6.50 | 4.55 | 1.748 | 11.65 | 5.7 |
| 1:00 **P**.M. | 19.9 | 1.112 | 6.40 | 4.35 | 1.844 | 12.30 | 5.5 |
| 2:00 | 20.0 | 1.120 | 6.30 | 4.10 | 1.963 | 13.09 | 5.6 |
| 3:00 | 20.0 | 1.120 | 5.95 | 3.50 | 2.190 | 14.60 | 5.3 |
| 4:00 | 20.0 | 1.120 | 5.75 | 3.45 | 2.050 | 15.38 | 5.2 |
| 5:00 | 20.0 | 1.120 | 4.00 | 1.70 | 2.050 | 15.38 | 2.8 |
| 6:00 | 20.0 | 1.120 | 3.95 | 1.95 | 1.786 | 13.39 | 2.0 |
| 7:00 | 19.9 | 1.112 | 4.50 | 1.70 | 2.520 | 18.90 | 3.2 |
| 8:00 | 19.8 | 1.105 | 4.70 | 2.30 | 2.150 | 16.12 | 4.4 |
| 9:00 | 19.8 | 1.105 | 5.00 | 2.30 | 2.420 | 16.12 | 4.1 |
| 10:00 | 19.8 | 1.105 | 5.00 | 2.00 | 2.690 | 17.92 | 4.0 |
| 11:00 | 19.8 | 1.105 | 5.00 | 2.00 | 2.690 | 17.92 | 4.3 |
| 12:00 | 19.8 | 1.105 | 4.30 | 2.05 | 2.020 | 15.51 | 4.5 |

were taken from the records of the East Lansing Waste Water Treatment Plant. The various listed flows represent the maximum and minimum flow rates for each day of a test series. Primary effluent BOD values are given, due to the fact that the sewage receives sedimentation prior to its treatment with activated sludge. The suspended solids concentrations given represent the average of values obtained in duplicate with a 0.45 micron Millipore filter.

## B. Dissolved Oxygen Gradient

The dissolved oxygen concentration variance tests employed the D.O. chamber, the model 5418 YSI oxygen probe, the model 54 YSI oxygen meter, and the Bausch and Lomb recorder. A sample of mixed liquor was continuously supplied to the D.O. chamber by a syphoning action. A 25 ft. section of 3/4 inch hose was attached to a 20 ft. section of 1/2 inch black pipe and the 1/2 inch black pipe used as the feed line during the regular C and $r_r$ measurements was once again used to deliver the flow to the D.O. chamber. A particular point in the aeration chamber was continuously sampled from 5 to 10 minutes by holding the influent end of the 20 ft. section of black pipe at a certain elevation and position. This gave a representative sample from that particular point. Prior to the start of these tests, the chart speed of the Bausch and Lomb recorder had been changed to 0.2 inches per minute. This provided one to two inches of chart for each position sampled.

# SECTION VI

## EXPERIMENTAL RESULTS

The East Lansing Sewage Treatment Plant was designed to have two mixed liquor aeration tanks and five return sludge aeration tanks. At the time of these experiments, one of the return sludge aeration tanks was being used as a mixed liquor aeration tank; therefore, the plant was actually using three mixed liquor aeration tanks. The cross section of the three tanks was the same; however, due to the difference in length, the sludge aeration tank had a volume of 284,000 gallons which is 56,000 gallons larger than the 228,000 gallon volume of the mixed liquor tanks. The tanks had cross sectional dimensions of 18.5 feet wide and 14.5 feet from the bottom to the liquid surface. Each tank was also equipped with a 45° deflector baffle with vertical and horizontal dimensions of approximately 2.5 feet. Dimensions given in the following experiment descriptions are either given to the wall opposite the sparges, or to the vertical face above the deflector baffle, which, although referred to as the sparger wall, is actually 2.5 feet from it.

The mixed liquor flowed through the three tanks in parallel; therefore, each tank acted as an individual unit. Consequently, the data are divided into three groups, depending upon the tank from which they were obtained. The data is also divided into individual experiments on each tank. The separate experiments represent periods of continuous testing of the particular tank involved. They also represent the results of a specific sampling point in each tank. This is due to the fact that the submersible pump was mounted at a particular point for the duration of each individual experiment, but was not necessarily mounted in the same position for subsequent experiments on the same tank.

Each table of data for the individual experiments includes the date and time of sampling, the temperature during the $r_r$ test, the dissolved oxygen concentration at the beginning of the $r_r$ test, and the $r_r$ value obtained from the test. The corresponding C and $r_r$ values are also shown on a plot for each experiment, along with the computed line of best fit obtained in the previously described manner.

When the experimental apparatus had been set up and started as previously described, the procedure during an experiment was simply the automatic operation of the equipment which was controlled by the timer. The only attention required was that of visits to the plant. Normally, three visits were made each day while an individual experiment was in process. This was to insure the continuance of a mixed liquor flow and to check the performance of the various pieces of equipment. During one of the visits each day, the model 54 oxygen meter and the Bausch and Lomb recorder were checked at zero dissolved oxygen in return sludge and at a value near saturation in a sample of tap water with a known dissolved oxygen concentration. This was done during the first few experiments, but found to be unnecessary; therefore, it was done only occasionally during subsequent experiments. The time and temperature were also recorded manually during each visit to provide the information for the proration of the Bausch and Lomb chart paper and to provide a check on the temperature recorded by the Sanborn recorder. The manual time recordings were eliminated, when the Bausch and Lomb event marker was put into use, but the temperature recordings were continued for the duration of the experiments.

The length of an individual $K_La$ experiment varied from 4 to 6 days, with all of these experiments being conducted between April 29, 1968, and June 25, 1968. June 8, 1968, was the end of the Spring term at Michigan State University and June 17, 1968, was the beginning of the Summer term; therefore, the data applied to flows which represented the maximum, minimum, and an intermediate organic loading. This is due to the fact that during terms, the students represent a major portion of the population of East Lansing. The change in the population affected the BOD load placed on the plant and the flow treated. Due to the combined sewer system, a period of thunder storms also varied the flow, but to a considerably greater extent. These variations effected the magnitude of the individual values, but did not greatly effect the method of determining $K_La$.

## A. $K_La$ Determinations

Experiment No. 1: Tuesday, April 29, 1968, and
Sunday, May 5, 1968, through
Friday, May 10, 1968
Table 4, Figure 13

This experiment was begun at 2:45 P.M. on April 29, and continued until 10:45 P.M. on the same day at which time it was stopped to permit changes in the elevation of the D.O. chamber and aeration chamber which also require modification of the length and position of the influent line. At 1:00 A.M. on Sunday, May 5, the experiment was restarted and continued until 8:00 P.M. on Friday, May 10, 1968. The lack of data for certain times during this experiment represents periods during which modifications were made. The submersible pump and temperature recording apparatus were added during this experiment.

This experiment was conducted on the converted

## TABLE 4

## ANALYTICAL DATA FOR EXPERIMENT 1

Tuesday, April 29, and Sunday, May 5, through Friday, May 10, 1968

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| 4/29 | 2:45 P.M. | - | 5.90 | 19.50* |
| | 3:45 | - | 5.25 | 20.00 |
| | 4:45 | - | 4.60 | 21.50 |
| | 5:45 | - | 4.70 | 22.00 |
| | 6:45 | - | 4.95 | 20.30 |
| | 7:45 | - | 4.70 | 18.90 |
| | 8:45 | - | 3.80 | 21.50 |
| | 9:45 | - | 3.80 | 23.00 |
| | 10:45 | - | 4.40 | 22.85* |
| 5/5 | 1:00 A.M. | 17.9 | 5.70 | 17.74 |
| | 2:00 | 17.5 | 5.80 | 17.00 |
| | 3:00 | 17.4 | 6.00 | 16.54 |
| | 4:00 | 17.4 | 6.30 | 15.88 |
| | 5:00 | 17.3 | 6.60 | 15.40 |
| | 6:00 | 17.3 | 6.80 | 15.40 |
| | 7:00 | 17.2 | 6.90 | 15.48 |
| | 8:00 | 17.2 | 7.20 | 14.60 |
| | 9:00 | 17.1 | 7.30 | 13.73 |
| | 10:00 | 17.1 | 7.40 | 13.13 |
| | 11:00 | 17.1 | 7.50 | 11.93 |
| | 12:00 | 17.0 | 7.30 | 11.87 |
| | 1:00 P.M. | 17.1 | 6.75 | 13.40 |
| | 2:00 | 17.3 | 6.30 | 14.27 |
| | 3:00 | 17.5 | 5.80 | 15.81 |
| | 4:00 | 17.7 | 5.10 | 17.28 |
| | 5:00 | 17.9 | 3.90 | 14.00* |
| | 6:00 | 18.0 | 3.60 | 22.15 |
| | 7:00 | 18.0 | 4.10 | 22.65 |
| | 8:00 | 17.9 | 4.50 | 20.70 |
| | 9:00 | 17.8 | 4.75 | 18.80 |
| | 10:00 | 17.7 | 5.10 | 18.20 |
| | 11:00 | 17.6 | 5.20 | 17.14 |
| | 12:00 | 17.6 | 5.40 | 16.20 |
| 5/6 | 1:00 A.M. | 17.6 | 5.40 | 16.20 |
| | 2:00 | 17.6 | 5.50 | 16.90 |
| | 3:00 | 17.6 | 5.60 | 17.20 |
| | 4:00 | 17.5 | 5.70 | 17.60 |

## TABLE 4 CONTINUED

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| | 5:00 | 17.5 | 5.90 | 17.00 |
| | 6:00 | 17.5 | 5.80 | 17.30 |
| | 7:00 | 17.5 | 5.90 | 18.20 |
| | 8:00 | 17.4 | 6.20 | 17.20 |
| | 9:00 | 17.4 | 6.50 | 16.90 |
| | 10:00 | 17.4 | 6.40 | 15.30 |
| | 11:00 | 17.4 | 6.10 | 15.30 |
| | 12:00 | 17.4 | 5.60 | 16.20 |
| | 1:00 **P.M.** | 17.4 | 5.10 | 18.30 |
| | 2:00 | 17.4 | 4.50 | 20.20 |
| | 3:00 | 17.4 | 4.00 | 21.70 |
| 5/8 | 12:00 | 19.0 | 2.80 | 26.20 |
| | 1:00 **A.M.** | 18.9 | 3.10 | 22.90 |
| | 2:00 | 18.9 | 3.00 | 23.50 |
| | 3:00 | 18.8 | 3.30 | 23.90 |
| | 4:00 | 18.8 | 3.50 | 23.60 |
| | 5:00 | 18.7 | 3.60 | 23.10 |
| | 6:00 | 18.7 | 4.40 | 22.30 |
| | 7:00 | 18.6 | 5.20 | 25.40* |
| | 8:00 | 18.6 | 5.40 | 25.40* |
| | 9:00 | 18.5 | 5.60 | 17.10 |
| | 10:00 | 18.5 | 5.60 | 16.60 |
| | 11:00 | 18.4 | 5.20 | 16.10 |
| | 12:00 | 18.4 | 4.70 | 16.80 |
| | 1:00 **P.M.** | 18.5 | 4.30 | 19.40 |
| | 2:00 | 18.6 | 4.90 | 18.70 |
| | 3:00 | 18.7 | 3.40 | 20.10 |
| | 4:00 | 18.8 | 3.30 | 19.90* |
| | 5:00 | 18.9 | 3.30 | 20.40 |
| 5/9 | 3:00 **P.M.** | 19.0 | 3.25 | 21.21 |
| | 4:00 | 19.2 | 2.75 | 22.10 |
| | 5:00 | 19.2 | 2.40 | 23.90 |
| | 6:00 | 18.9 | 2.60 | 22.70 |
| | 7:00 | 18.7 | 3.10 | 21.80 |
| | 8:00 | 18.6 | 2.75 | 21.70 |
| | 9:00 | 18.6 | 2.45 | 22.20 |
| | 10:00 | 18.7 | 1.60 | 24.50 |
| | 11:00 | 18.7 | 1.40 | 26.50 |
| | 12:00 | 18.7 | 2.20 | 24.70 |
| 5/10 | 1:00 **A.M.** | 18.5 | 3.60 | 21.80 |
| | 2:00 | 18.4 | 4.10 | 21.10 |
| | 3:00 | 18.3 | 4.00 | 20.20 |
| | 4:00 | 18.2 | 4.40 | 20.30 |
| | 5:00 | 18.2 | 4.90 | 20.20 |

TABLE 4 CONTINUED

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| | 6:00 | 18.1 | 5.20 | 19.60 |
| 5/10 | 12:00 | 18.1 | 5.60 | 15.10 |
| | 1:00 P.M. | 18.4 | 4.80 | 18.40 |
| | 2:00 | 18.7 | 3.40 | 22.10 |
| | 3:00 | 18.9 | 2.20 | 30.60* |
| | 4:00 | 19.0 | 2.00 | 26.50 |
| | 5:00 | 19.2 | 2.65 | 24.00 |
| | 6:00 | 18.9 | 3.40 | 16.70* |
| | 7:00 | 18.8 | 3.90 | 19.10 |
| | 8:00 | 18.6 | 3.30 | 20.70 |

Points marked thus * were not plotted due to the existence of non-steady state conditions.

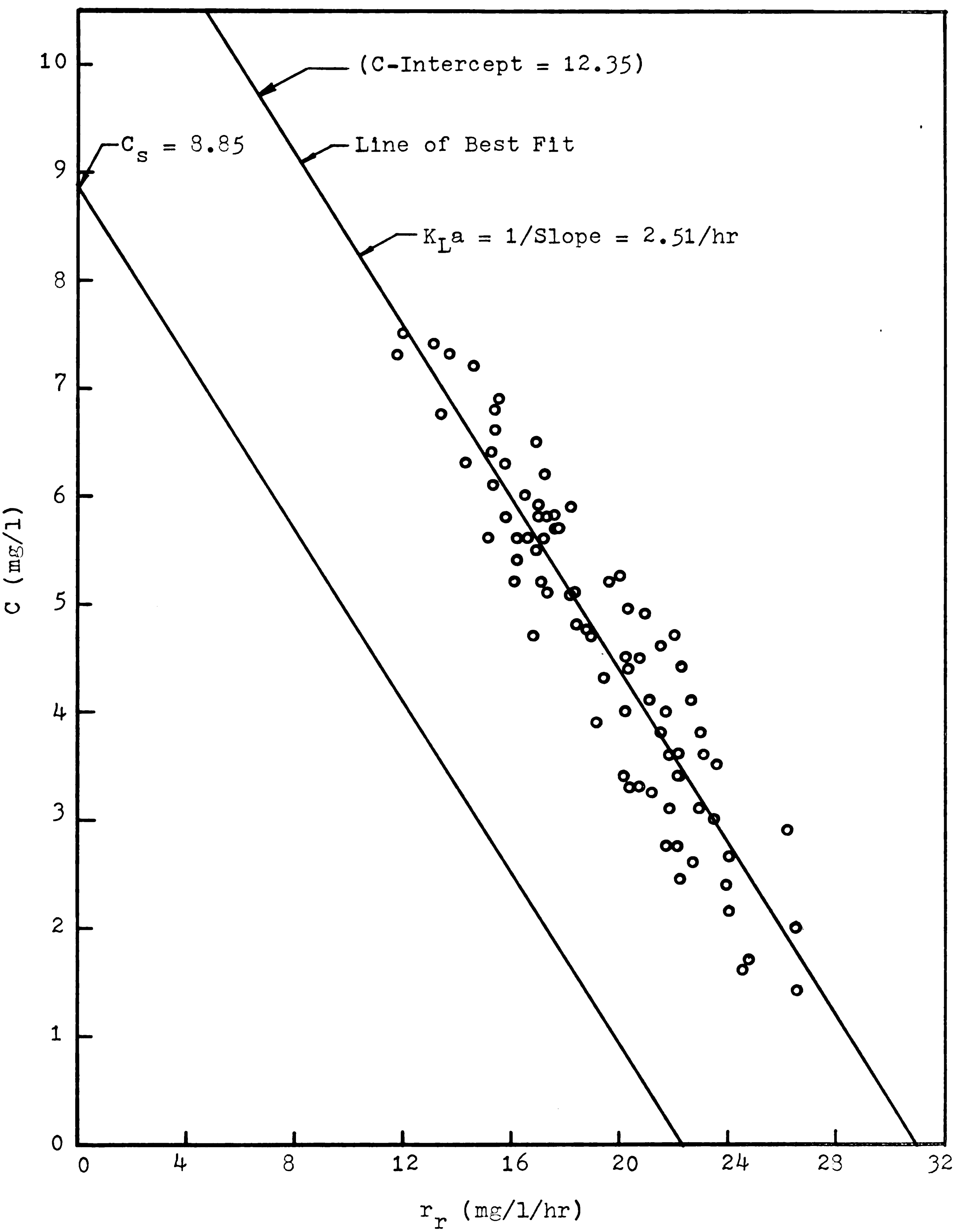


Figure 13. Plot of Data From Experiment 1

sludge aeration tank, which received the lightest load of the three tanks. The submersible pump was located approximately 1.5 feet below the liquid surface and 9.0 feet from the tank wall opposite the spargers. The sewage flow treated by the plant varied from 4.5 to 10.5 mgd during the course of this experiment, with a normal daily variance of from 5 to 10 mgd. The mixed liquor suspended solids concentration varied from 1050 to 1420 mg/l, with an average of approximately 1250 mg/l. The BOD ranged from 73 to 200 mg/l, with an average of approximately 140 mg/l. The C values obtained during the experiment varied from 1.4 to 7.5 mg/l, and the $r_r$ values varied from 11.93 to 26.50 mg/l/hr. as shown in Table 4. The temperature of the mixed liquor during $r_r$ tests, as also shown in Table 4, varied from 17.0 to 19.2°C with an average of 17.9°C. As shown in Figure 13, a $K_La$ value of 2.51/hr. was calculated for tank No. 1 from the tabulated C and $r_r$ values, which corresponds to maximum supply rate of 22.3 mg/l/hr. when a calculated $C_s$ value of 8.85 mg/l is used.

Experiment No. 2: Thursday, June 13, 1968 through
Monday, June 17, 1968
Table 5, Figure 14

This experiment was also conducted on tank No. 1. It started at 6:00 P.M. on Thursday, June 13, and continued until 8:00 A.M. on Monday, June 17. It was

## TABLE 5

## ANALYTICAL DATA FOR EXPERIMENT 2

Thursday, June 13 through Monday, June 17, 1968

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| 6/13 | 6:00 P.M. | 19.8 | 4.90 | 15.98 |
| | 7:00 | 19.5 | 4.90 | 15.00 |
| | 8:00 | 19.5 | 4.70 | 15.00 |
| | 9:00 | 19.5 | 4.90 | 14.40 |
| | 10:00 | 19.5 | 5.00 | 13.80 |
| | 11:00 | 19.5 | 5.00 | 13.80 |
| | 12:00 | 19.4 | 5.10 | 14.20 |
| 6/14 | 1:00 A.M. | 19.4 | 5.20 | 14.80 |
| | 2:00 | 19.4 | 5.20 | 16.04 |
| | 3:00 | 19.4 | 5.20 | 13.50 |
| | 4:00 | 19.3 | 5.20 | 14.00 |
| | 5:00 | 19.3 | 5.40 | 12.80 |
| | 6:00 | 19.3 | 5.40 | 12.20 |
| | 7:00 | 19.3 | 5.50 | 12.80 |
| | 8:00 | 19.3 | 5.70 | 12.20 |
| | 9:00 | 19.3 | 5.90 | 11.60 |
| | 10:00 | 19.3 | 6.10 | 11.00 |
| | 11:00 | 19.4 | 6.20 | 11.00 |
| | 12:00 | 19.4 | 6.30 | 11.00 |
| | 1:00 P.M. | 19.6 | 6.40 | 9.00 |
| | 2:00 | 19.8 | 6.50 | 10.70 |
| | 3:00 | 19.8 | 6.50 | 11.20 |
| | 4:00 | 19.9 | 6.40 | 10.00 |
| | 5:00 | 19.9 | 6.20 | 10.30 |
| | 6:00 | 20.1 | 6.20 | 10.70 |
| | 7:00 | 20.2 | 6.10 | 11.60 |
| | 8:00 | 20.1 | 6.10 | 10.50 |
| | 9:00 | 20.1 | 610 | 11.30 |
| | 10:00 | 20.2 | 6.30 | 10.10 |
| | 11:00 | 20.2 | 6.60 | 11.60 |
| | 12:00 | 20.2 | 6.80 | 11.00 |
| 6/15 | 1:00 A.M. | 20.1 | 6.90 | 11.10 |
| | 2:00 | 20.0 | 6.90 | 10.80 |
| | 3:00 | 20.0 | 6.80 | 9.90 |
| | 4:00 | 20.0 | 6.80 | 10.50 |
| | 5:00 | 19.9 | 6.90 | 10.00 |
| | 6:00 | 19.9 | 6.90 | 10.00 |

## TABLE 5 CONTINUED

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| | 7:00 | 19.9 | 6.90 | 10.30 |
| | 8:00 | 19.9 | 7.00 | 9.40 |
| | 9:00 | 19.9 | 7.00 | 10.00 |
| | 10:00 | 19.8 | 7.10 | 10.00 |
| | 11:00 | 19.8 | 7.20 | 9.50 |
| | 12:00 | 19.8 | 7.30 | 9.50 |
| | 1:00 P.M. | 19.8 | 7.30 | 8.60 |
| | 2:00 | 19.9 | 7.20 | 9.10 |
| | 3:00 | 19.9 | 7.00 | 9.70 |
| | 4:00 | 20.0 | 6.90 | 9.90 |
| | 5:00 | 20.0 | 6.90 | 10.80 |
| | 6:00 | 20.1 | 6.90 | 9.60 |
| | 7:00 | 20.1 | 6.80 | 9.90 |
| | 8:00 | 20.2 | 6.70 | 10.80 |
| | 9:00 | 20.1 | 6.60 | 10.70 |
| | 10:00 | 20.1 | 6.50 | 12.20 |
| | 11:00 | 20.1 | 6.40 | 11.00 |
| | 12:00 | 20.1 | 6.40 | 11.00 |
| 6/16 | 1:00 A.M. | 20.1 | 5.20 | 14.80 |
| | 2:00 | 20.0 | 4.60 | 21.30* |
| | 3:00 | 19.9 | 4.40 | 20.90* |
| | 4:00 | 19.8 | 4.50 | 22.80* |
| | 5:00 | 19.7 | 4.60 | 22.00* |
| | 6:00 | 19.6 | 4.10 | 20.40* |
| | 7:00 | 19.5 | 4.20 | 21.00* |
| | 8:00 | 19.5 | 4.20 | 19.90* |
| | 9:00 | 19.4 | 4.20 | 20.90* |
| | 10:00 | 19.3 | 3.80 | 20.10* |
| | 11:00 | 19.2 | 4.10 | 19.60* |
| | 12:00 | 19.1 | 4.40 | 20.30* |
| | 1:00 P.M. | 19.1 | 4.80 | 20.70* |
| | 2:00 | 19.1 | 5.10 | 11.10 |
| | 3:00 | 19.1 | 5.10 | 11.10 |
| | 4:00 | 19.1 | 5.20 | 12.00 |
| | 5:00 | 19.1 | 5.10 | 12.30 |
| | 6:00 | 19.2 | 5.00 | 12.90 |
| | 7:00 | 19.2 | 4.70 | 13.50 |
| | 8:00 | 19.2 | 4.50 | 12.90 |
| | 9:00 | 19.2 | 4.00 | 15.30 |
| | 10:00 | 19.2 | 3.90 | 14.70 |
| | 11:00 | 19.3 | 4.00 | 15.20 |
| | 12:00 | 19.2 | 4.00 | 14.70 |

TABLE 5 CONTINUED

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| 6/17 | 1:00 A.M. | 19.0 | 4.10 | 13.00 |
| | 2:00 | 19.0 | 4.10 | 13.30 |
| | 3:00 | 19.0 | 4.20 | 13.00 |
| | 4:00 | 19.1 | 4.30 | 12.90 |
| | 5:00 | 19.3 | 4.40 | 12.80 |
| | 6:00 | 19.4 | 4.60 | 12.10 |
| | 7:00 | 19.4 | 5.00 | 11.50 |
| | 8:00 | 19.4 | 5.20 | 10.40* |

Points marked thus * were not plotted due to the existence of non-steady state conditions.

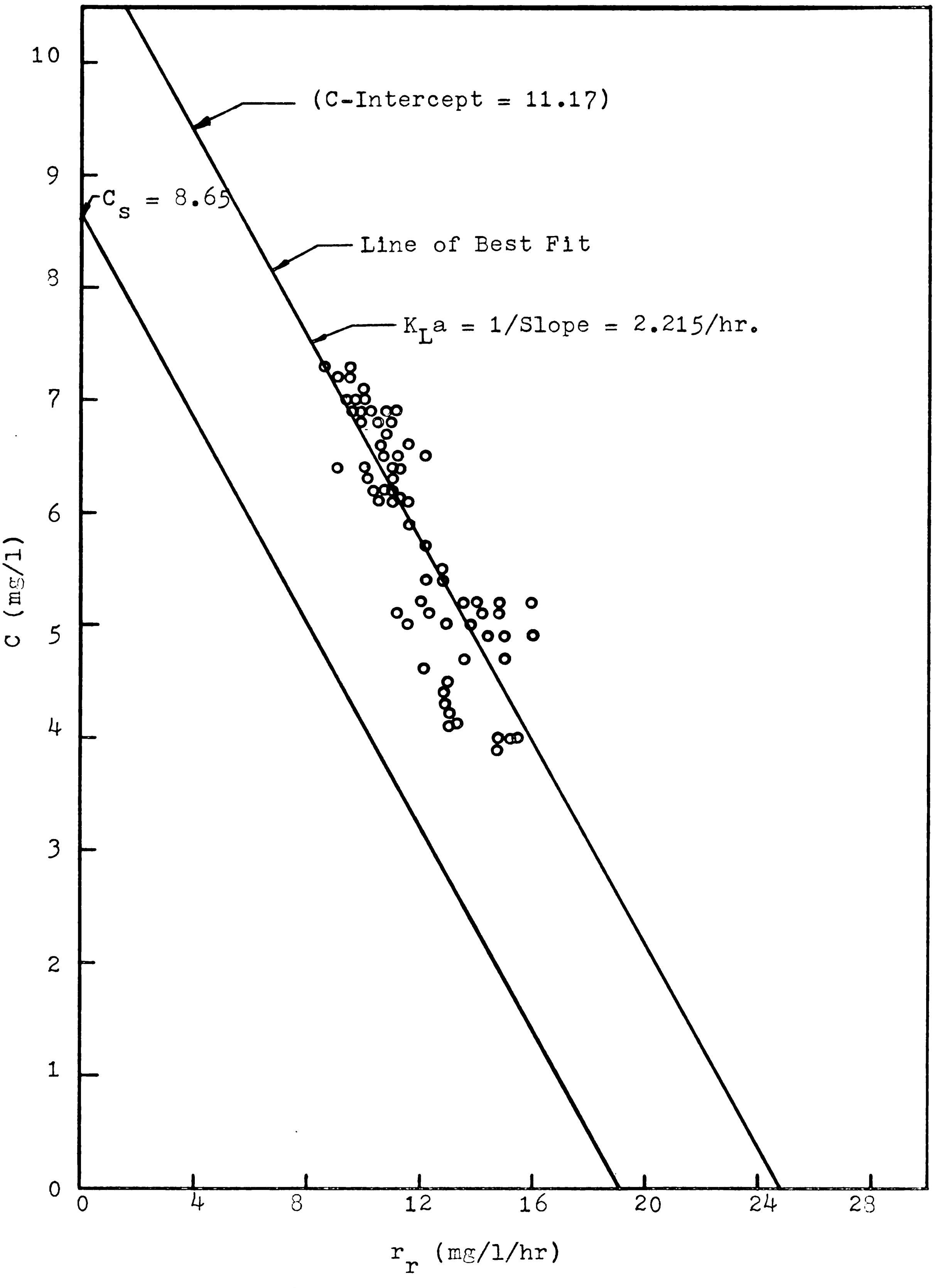


Figure 14. Plot of Data From Experiment 2

conducted between the Spring and Summer terms, and over a weekend. The combination of these factors caused the higher C values and lower $r_r$ values. The reduced plant loading is reflected by the sewage flow which varied from 5 to 10.5 mgd during the experiment, but the normal daily fluctuation was between 6 and 9 mgd. The submersible pump was once again approximately 1.5 feet below the surface of the liquid, but it was 7.0 feet from the wall opposite the spargers. The mixed liquor suspended solids concentration varied from 1480 to 1680 mg/l with an approximate average of 1570 mg/l. The BOD of the settled sewage ranged from 73 to 93 mg/l, with an average of approximately 80 mg/l. The temperature of the mixed liquor during $r_r$ tests varied from 19.0 to 20.2°C, with an average of 19.6°C. The various C and $r_r$ values obtained during the experiment ranged from 3.8 to 7.3 mg/l and from 8.6 to 22.8 mg/l/hr., respectively, as shown in Table 5. As shown in Figure 14, a $K_La$ value of 2.215 was calculated for tank No. 1 from the data of this experiment, which corresponds to a maximum supply rate of 19.1 mg/l/hr when a calculated $C_s$ value of 8.65 mg/l is used.

Experiment No. 3: Tuesday, June 18, 1968 through
Friday, June 24, 1968
Table 6, Figure 15

This was the third and final experiment conducted

## TABLE 6

## ANALYTICAL DATA FOR EXPERIMENT 3

Tuesday, June 18, through Friday, June 21, 1968

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| 6/18 | 4:00 P.M. | 19.2 | 4.90 | 15.10 |
| | 5:00 | 19.3 | 5.10 | 14.04 |
| | 6:00 | 19.2 | 4.90 | 13.83 |
| | 7:00 | 19.1 | 4.70 | 14.27 |
| | 8:00 | 19.1 | 4.80 | 14.57 |
| | 9:00 | 19.0 | 4.70 | 14.33 |
| | 10:00 | 19.0 | 4.50 | 13.73 |
| | 11:00 | 19.0 | 4.60 | 14.67 |
| | 12:00 | 19.1 | 4.70 | 14.57 |
| 6/19 | 1:00 A.M. | 19.1 | 5.20 | 15.20 |
| | 2:00 | 19.0 | 5.00 | 15.07 |
| | 3:00 | 19.0 | 5.20 | 13.40 |
| | 4:00 | 18.9 | 5.40 | 13.17 |
| | 5:00 | 18.9 | 5.50 | 12.86 |
| | 6:00 | 19.0 | 5.70 | 12.43 |
| | 7:00 | 19.0 | 5.80 | 13.07 |
| | 8:00 | 19.0 | 6.30 | 12.43 |
| | 9:00 | 19.0 | 6.00 | 11.12 |
| | 10:00 | 19.1 | 6.40 | 10.77 |
| | 11:00 | 19.2 | 6.30 | 11.31 |
| | 12:00 | 19.5 | 5.90 | 11.39 |
| | 1:00 P.M. | 19.7 | 5.50 | 22.90* |
| | 2:00 | 19.8 | 4.80 | 12.67 |
| | 3:00 | 19.9 | 4.50 | 25.20* |
| | 4:00 | 19.9 | 4.20 | 23.40 |
| | 5:00 | 19.8 | 4.10 | 21.70 |
| | 6:00 | 19.8 | - | 17.20 |
| | 7:00 | 19.7 | - | 23.25 |
| | 8:00 | 19.7 | - | - |
| | 9:00 | 19.6 | - | - |
| | 10:00 | 19.5 | - | 19.08 |
| | 11:00 | - | - | - |
| | 12:00 | 19.7 | 3.50 | 16.40 |
| 6/20 | 1:00 A.M. | 19.7 | 4.90 | 16.40 |
| | 2:00 | 19.7 | 4.90 | 19.12* |
| | 3:00 | 19.6 | 5.00 | 15.28 |
| | 4:00 | 19.6 | 5.10 | 15.60 |
| | 5:00 | 19.4 | 5.30 | 16.13 |

## TABLE 6 CONTINUED

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| | 6:00 | 19.4 | 5.60 | 15.08 |
| | 7:00 | 19.4 | 6.00 | 13.24 |
| | 8:00 | 19.4 | 6.10 | 13.63 |
| | 9:00 | 19.4 | 6.40 | 13.63* |
| | 10:00 | 19.4 | 6.50 | 11.17 |
| | 11:00 | 19.7 | 6.20 | 10.33 |
| | 12:00 | 19.8 | 5.70 | 11.65 |
| | 1:00 P.M. | 19.9 | 5.50 | 12.30 |
| | 2:00 | 20.0 | 5.60 | 13.09 |
| | 3:00 | 20.0 | 5.30 | 14.60 |
| | 4:00 | 20.0 | 5.20 | 15.38 |
| | 5:00 | 20.0 | 2.80 | 15.38* |
| | 6:00 | 20.0 | 2.00 | 13.39* |
| | 7:00 | 19.9 | 3.20 | 18.90 |
| | 8:00 | 19.8 | 4.40 | 16.12 |
| | 9:00 | 19.8 | 4.10 | 16.12 |
| | 10:00 | 19.8 | 4.00 | 17.92 |
| | 11:00 | 19.8 | 4.30 | 17.92 |
| | 12:00 | 19.8 | 4.50 | 15.51 |
| 6/21 | 1:00 A.M. | 19.7 | 4.80 | 15.03 |
| | 2:00 | 19.7 | 4.30 | 16.42 |
| | 3:00 | 19.7 | 4.40 | 17.10 |
| | 4:00 | 19.6 | 4.50 | 14.43 |
| | 5:00 | 19.6 | 4.30 | 13.08 |
| | 6:00 | 19.6 | 4.60 | 13.77 |
| | 7:00 | 19.5 | 4.70 | 13.17 |
| | 8:00 | 19.4 | 5.20 | 12.54 |
| | 9:00 | 19.4 | 5.30 | 11.70 |
| | 10:00 | 19.5 | 5.30 | 11.43 |
| | 11:00 | 19.5 | 5.00 | 11.10* |
| | 12:00 | 19.7 | 4.20 | 12.30* |
| | 1:00 | 19.8 | 3.80 | 12.67* |
| | 2:00 | 19.8 | 3.50 | 11.31* |
| | 3:00 | 19.8 | 2.90 | 10.87* |
| | 4:00 | 19.8 | 2.70 | - |
| | 5:00 | 19.8 | 0.50 | 16.30* |
| | 6:00 | 19.8 | 1.20 | 10.87* |
| | 7:00 | 19.7 | 2.10 | 10.39* |
| | 8:00 | 19.7 | 1.80 | 11.72* |
| | 9:00 | 20.1 | 2.20 | 11.41* |
| | 10:00 | 20.4 | 3.10 | 10.42* |
| | 11:00 | 20.5 | 3.30 | 11.98* |

Points marked thus * were not plotted due to the existence of non-steady state conditions.

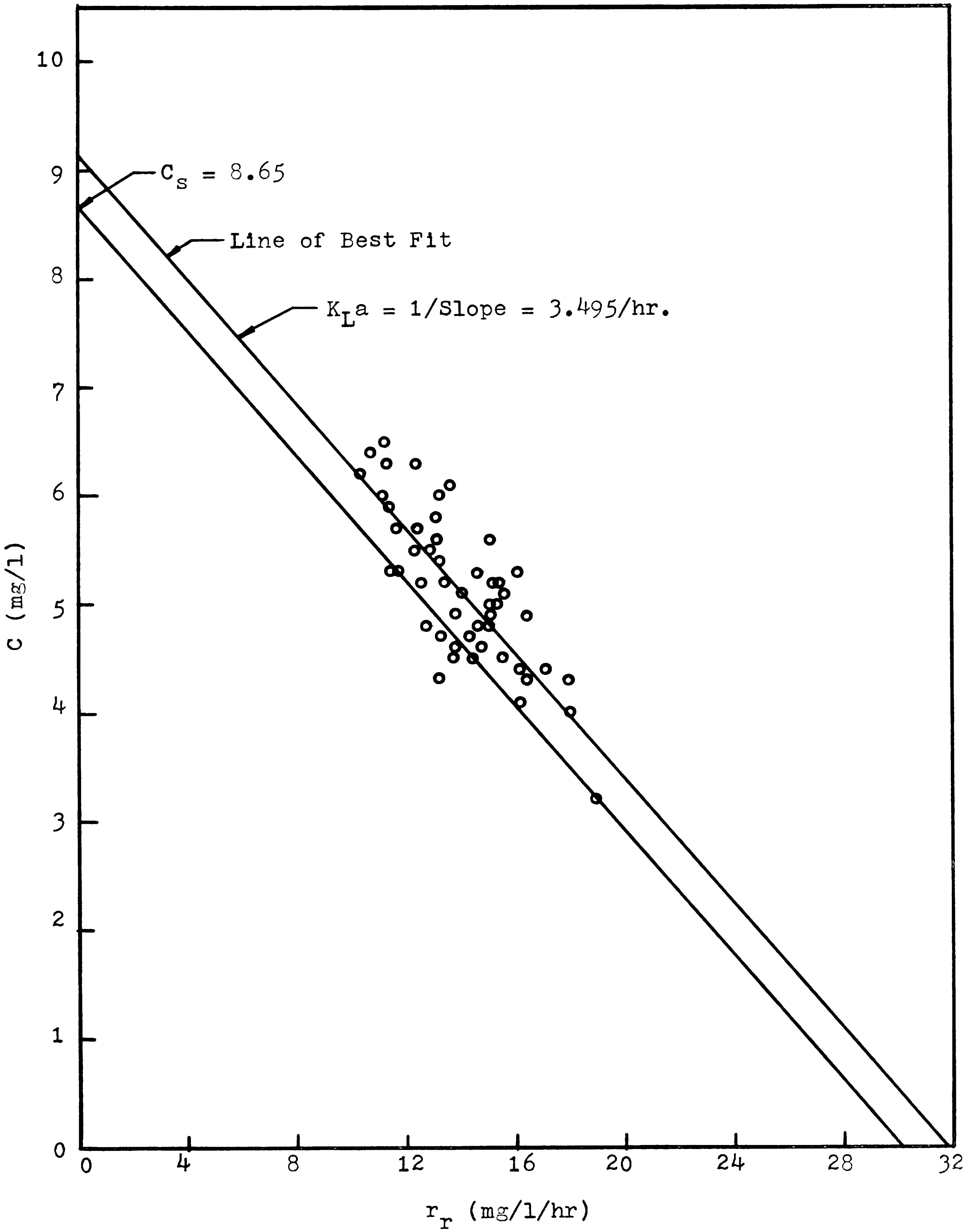


Figure 15. Plot of Data From Experiment 3

on tank No. 1. It was started at 4:00 P.M. on Tuesday, June 18, and continued until 11:00 P.M. on Friday, June 21. It was conducted during the Summer term, and during the week. The additional load was shown by the flow which varied from 5 to 15 mgd during the experiment. The mixed liquor suspended solids concentration varied from 1520 to 1720 mg/l, with an average of approximately 1640 mg/l. The BOD of the settled sewage varied from 64 to 88 mg/l, with an approximate average of 80 mg/l. The temperature of the mixed liquor varied from 18.9 to 20.5°C, with an average value of 19.3°C. The C and $r_r$ values recorded fluctuated from 0.5 to 6.5 mg/l and from 10.33 to 25.20 mg/l/hr., respectively, as shown in Table 6. As shown in Figure 15, a $K_La$ value of 3.495 was determined from the data recorded during this experiment, which corresponds to a maximum oxygen supply rate of 30.2 mg/l/hr when a calculated $C_s$ value of 8.65 mg/l is used. The submersible pump was located 1.5 feet below the surface and 7.0 feet from the tank wall opposite the spargers.

Experiment No. 4: Saturday, May 11, 1968 through
Wednesday, May 15, 1968
Table 7, Figure 16

This experiment was conducted on tank No. 2 which was designed to be a mixed liquor aeration tank. It received a lighter load than the other normal mixed

## TABLE 7

## ANALYTICAL DATA FOR EXPERIMENT 4

Saturday, May 11, through Wednesday, May 15, 1968

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| 5/11 | 2:30 A.M. | 17.7 | 4.60 | 22.70 |
| | 3:30 | 17.7 | 5.00 | 20.90 |
| | 4:30 | 17.6 | 5.80 | 21.00 |
| | 5:30 | 17.6 | 6.30 | 20.30 |
| | 6:30 | 17.6 | 6.80 | 19.10 |
| | 7:30 | 17.6 | 7.20 | 17.90 |
| | 8:30 | 17.6 | 7.15 | 17.30 |
| | 9:30 | 17.5 | 7.20 | 15.50 |
| | 10:30 | 17.6 | 7.20 | 14.10 |
| | 11:30 | 17.7 | 6.70 | 14.70 |
| | 12:30 P.M. | 17.7 | 4.80 | 16.60* |
| | 1:30 | 18.1 | 4.30 | 18.10 |
| | 2:30 | 18.5 | 3.30 | 20.70 |
| | 3:30 | 18.5 | 3.50 | 23.00 |
| | 11:00 | 18.3 | 1.50 | 26.20 |
| | 12:00 | 18.4 | 2.10 | 25.70 |
| 5/12 | 1:00 A.M. | 18.3 | 2.60 | 24.30 |
| | 2:00 | 18.1 | 3.20 | 22.90 |
| | 3:00 | 18.0 | 3.70 | 21.80 |
| | 4:00 | 18.0 | 5.00 | 21.50 |
| | 5:00 | 17.9 | 5.80 | 21.90 |
| | 6:00 | 17.9 | 6.50 | 21.30* |
| | 7:00 | 17.8 | 6.90 | 19.50 |
| | 8:00 | 17.8 | 7.30 | 19.30 |
| | 9:00 | 17.8 | 7.50 | 17.70 |
| | 10:00 | 17.7 | 7.30 | 17.40 |
| | 11:00 | 17.5 | 6.90 | 16.30 |
| | 12:00 | 17.5 | 5.80 | 16.30 |
| | 1:00 P.M. | 17.7 | 4.70 | 17.70 |
| | 2:00 | 18.1 | 3.30 | 19.20 |
| | 3:00 | 18.2 | 2.00 | 18.90* |
| | 4:00 | 18.4 | 1.50 | 22.40* |
| | 5:00 | 18.6 | 1.00 | 23.80 |
| | 6:00 | 18.6 | 0.90 | 26.30 |
| | 7:00 | 18.5 | 1.00 | 27.20 |
| | 8:00 | 18.4 | 2.00 | 26.00 |
| | 9:00 | 18.3 | 2.20 | 23.90 |

TABLE 7 CONTINUED

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| | 10:00 | 18.1 | 2.40 | 22.90 |
| | 11:00 | 18.1 | 2.40 | 22.00 |
| | 12:00 | 18.0 | 2.40 | 21.20 |
| 5/13 | 1:00 A.M. | 18.0 | 2.50 | 21.70 |
| | 2:00 | 18.0 | 3.40 | 23.40 |
| | 3:00 | 18.0 | 3.60 | 22.40 |
| | 4:00 | 18.0 | 3.10 | 21.20 |
| | 5:00 | 18.0 | 3.90 | 21.80 |
| | 6:00 | 17.9 | 5.30 | 21.90 |
| | 7:00 | 17.9 | 5.70 | 22.20* |
| | 8:00 | 17.9 | 5.70 | 21.90 |
| | 9:00 | 17.8 | 5.50 | 21.50 |
| | 10:00 | 17.8 | 5.10 | 18.30 |
| | 11:00 | 18.0 | 2.90 | 18.00* |
| | 12:00 | 18.6 | 2.50 | 19.60* |
| | 1:00 P.M. | 18.8 | 1.90 | 20.60* |
| | 2:00 | 19.2 | 0.80 | 22.20* |
| | 3:00 | 19.4 | 0.10 | 27.20 |
| | 4:00 | 19.4 | 0.10 | 30.80* |
| | 5:00 | 19.4 | 0.10 | 30.90* |
| | 6:00 | 19.4 | 0.00 | 30.00 |
| | 7:00 | 19.4 | 0.00 | 35.00* |
| | 8:00 | 19.2 | 0.00 | 30.60* |
| | 9:00 | 19.2 | 0.00 | 34.80* |
| | 10:00 | 19.2 | 0.00 | 42.00* |
| | 11:00 | 19.2 | 0.00 | 35.30* |
| | 12:00 | 19.1 | 0.00 | 30.70* |
| 5/14 | 1:00 A.M. | 18.8 | 0.80 | 27.80 |
| | 2:00 | 18.7 | 0.80 | 27.70 |
| | 3:00 | 18.7 | 1.30 | 36.40* |
| | 4:00 | 18.5 | 3.00 | 27.90* |
| | 5:00 | 18.4 | 5.00 | 26.00* |
| | 6:00 | 18.4 | 5.10 | 25.90* |
| | 7:00 | 17.8 | 5.70 | 22.70* |
| | 8:00 | 17.7 | 6.20 | 22.30* |
| | 9:00 | 17.5 | 6.10 | 18.50 |
| | 10:00 | 17.4 | 2.60 | 17.50 |
| | 11:00 | 17.6 | 3.10 | 17.20* |
| | 12:00 | 18.0 | 2.90 | 17.10* |
| | 1:00 P.M. | 18.1 | 2.80 | 19.20* |
| | 2:00 | 18.1 | 2.20 | 15.10* |
| | 3:00 | 18.2 | 0.80 | 24.70 |
| | 4:00 | 18.3 | 0.30 | 25.60 |

TABLE 7 CONTINUED

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| | 5:00 | 18.4 | 0.00 | 20.10* |
| | 6:00 | 18.5 | 0.00 | 23.10* |
| | 7:00 | 18.6 | 0.10 | 22.60* |
| | 8:00 | 18.6 | 0.00 | 23.50* |
| | 9:00 | 18.8 | 0.00 | 28.70 |
| | 10:00 | 18.8 | 0.00 | 37.60* |
| | 11:00 | 18.6 | 0.00 | 36.40* |
| 5/15 | 9:27 A.M. | 18.4 | 4.50 | 22.00 |
| | 10:00 | 18.6 | 2.70 | 22.60 |
| | 11:00 | 18.7 | 1.60 | 24.70 |
| | 12:00 | 18.8 | 0.80 | 26.80 |
| | 1:00 P.M. | 18.9 | 0.50 | 27.10 |
| | 2:00 | 19.0 | 0.20 | 26.60 |
| | 3:00 | 19.1 | 0.20 | 25.40 |
| | 4:00 | 19.2 | 0.00 | 26.30 |

Points marked thus * were not plotted due to the existence of non-steady state conditions.

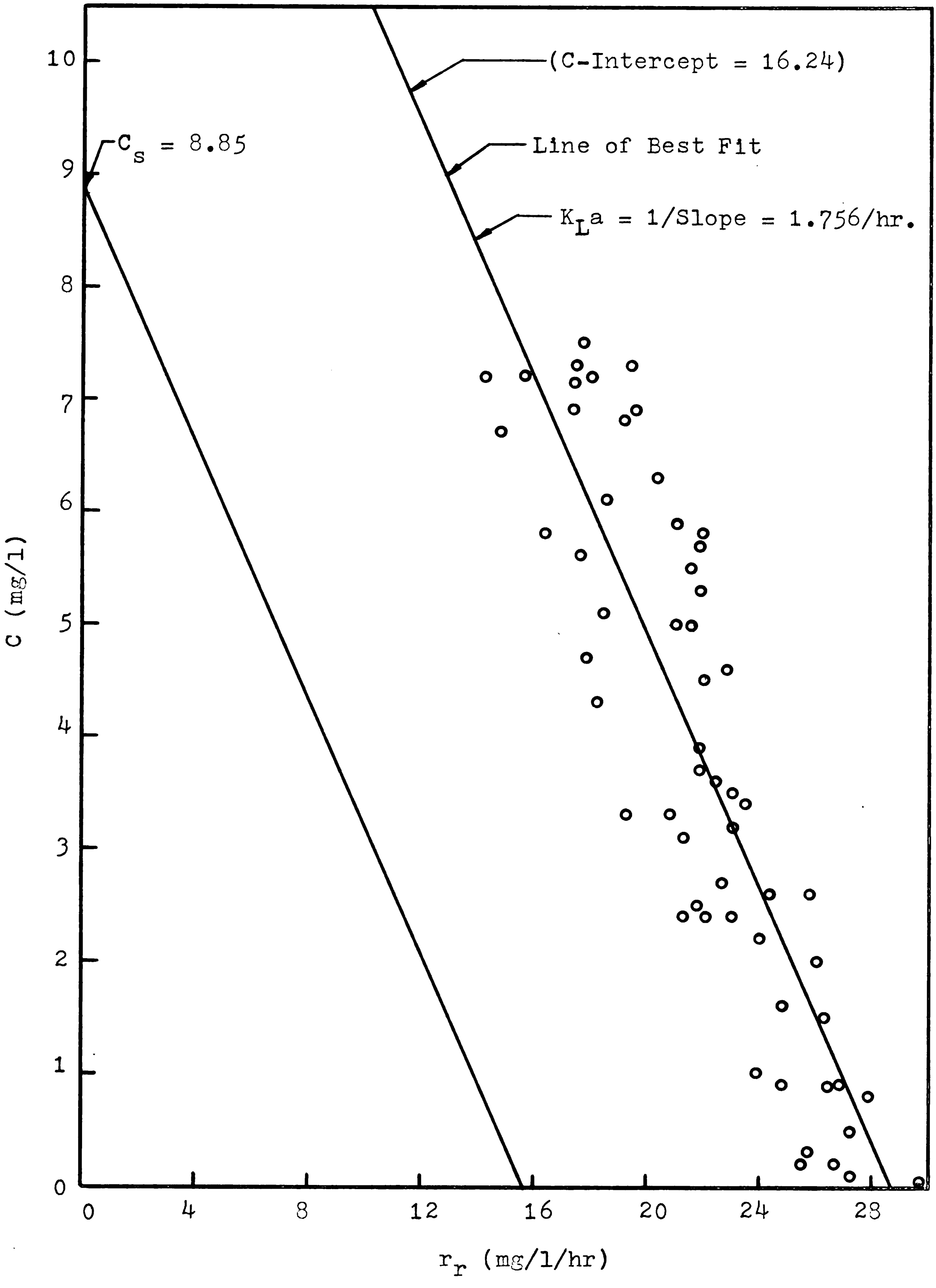


Figure 16. Plot of Data From Experiment 4

liquor tank, but its loading was heavier than that of the converted tank. During this experiment, the submersible pump was located 1.5 feet below the mixed liquor surface and 2.0 feet from the sparger wall of the aeration tank. The equipment was started at 2:30 A.M. on Saturday, May 11, and continued until 4:00 P.M. on Wednesday, May 15. This period represented a time during which the main student body was present. The span also included a weekend and part of the following week. The sewage flow during this experiment varied from 4.5 to 12.0 mgd, with the weekend flow varying between 4.5 and 9 mgd and the week day flow varying between 5 and 12 mgd. The mixed liquor suspended solids concentration fluctuated between 1040 and 1560 mg/l, with an average of approximately 1410 mg/l. The BOD of the settled sewage varied between 120 and 140 mg/l, with an approximate average of 130 mg/l. The temperature of the mixed liquor, as shown in Table 7, ranged from 17.4 to 19.4°C, with an average of 18.1°C. Also, as shown by Table 7, the C and $r_r$ values obtained during the experiment varied from 0.0 to 7.5 mg/l and from 14.1 to 37.6 mg/l/hr., respectively. As shown in Figure 16, a $K_La$ value of 1.756 was calculated for tank No. 2 from the data of this experiment, which corresponds to a maximum supply rate of 15.54 mg/l/hr when a calculated $C_s$ value of 8.85 mg/l is used. The air flow to each fritted glass diffuser was increased from 2.0 to 2.5 lpm during this experiment due to the lower initial dissolved oxygen concentrations.

Experiment No. 5: Saturday, June 22, 1968 through
Tuesday, June 25, 1968
Table 8, Figure 18

This experiment was also conducted on tank No. 2, but the sampling point was changed from 2.0 feet from the sparger wall of the tank to within a foot of the wall opposite the spargers. The experiment was started at 12:00 A.M. on Saturday, June 22, and continued uninterrupted until 8:00 P.M. on Tuesday, June 25, thus it was conducted during the Summer term and is representative of a weekend and part of the following week. Due to severe thunder storms during the experiment, the flow fluctuated from 7 to 25 mgd. Also, due to the storms, the mixed liquor suspended solids concentration varied from 880 to 1240 mg/l, with an approximate average of 1050 mg/l. The diluting effect of the storm water was reflected by the BOD concentrations which varied from 26 to 46 mg/l with an average of approximately 35 mg/l. The mixed liquor temperature varied between 19.2 and 20.5$^{\circ}$C, as shown in Table 8, with an average of 19.6$^{\circ}$C. Also, as shown in this table, the C and $r_r$ values varied from 0.2 to 7.0 mg/l and from 1.21 to 18.0 mg/l/hr., respectively. A $K_La$ value of 2.10 was calculated from the data obtained during this period, as shown in Figure

## TABLE 8

## ANALYTICAL DATA FOR EXPERIMENT 5

Saturday, June 22, through Tuesday, June 25, 1968

| | Time | Temp. ($^oC$) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| 6/22 | 12:00 | 20.4 | 4.80 | 10.43 |
| | 1:00 A.M. | 20.2 | 5.10 | 7.93* |
| | 2:00 | 19.8 | 4.40 | 12.21 |
| | 3:00 | 19.7 | 4.90 | 12.77 |
| | 4:00 | 19.6 | 5.00 | 11.79 |
| | 5:00 | 19.6 | 5.50 | 12.58 |
| | 6:00 | 19.6 | 5.80 | 13.38 |
| | 7:00 | 19.6 | 6.15 | 13.08* |
| | 8:00 | 19.5 | 6.60 | 11.88 |
| | 9:00 | 19.4 | 6.70 | 9.17 |
| | 10:00 | 19.4 | 6.60 | 8.77 |
| | 11:00 | 19.5 | 6.50 | 10.30 |
| | 12:00 | 19.6 | 6.20 | 7.86 |
| | 1:00 P.M. | 19.7 | 5.90 | 10.93 |
| | 2:00 | 19.8 | 5.20 | 9.05 |
| | 3:00 | - | - | - |
| | 4:00 | 19.8 | 4.80 | 13.27 |
| | 5:00 | 19.8 | 4.10 | 14.83 |
| | 6:00 | 20.0 | 1.40 | 17.88 |
| | 7:00 | 20.0 | 1.90 | 17.40 |
| | 8:00 | 19.9 | 1.80 | 18.00 |
| | 9:00 | 19.7 | 2.50 | 15.80 |
| | 10:00 | 19.6 | 3.10 | 15.93 |
| | 11:00 | 19.6 | 3.20 | 14.07 |
| | 12:00 | 19.7 | 3.40 | 15.38 |
| 6/23 | 1:00 A.M. | 19.7 | 3.40 | 15.20 |
| | 2:00 | 19.6 | 3.50 | 14.10 |
| | 3:00 | 19.5 | 3.40 | 13.48 |
| | 4:00 | 19.4 | 2.90 | 14.73 |
| | 5:00 | 19.3 | 2.90 | 12.86 |
| | 6:00 | 19.4 | 3.00 | 12.56 |
| | 7:00 | 19.4 | 3.20 | 13.68 |
| | 8:00 | 19.4 | 3.30 | 12.40 |
| | 9:00 | 19.4 | 3.30 | 8.06* |
| | 10:00 | 19.6 | 3.70 | 3.67* |
| | 11:00 | 19.8 | 3.30 | 12.07* |
| | 12:00 | 19.8 | 3.10 | 9.50* |

## TABLE 8 CONTINUED

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| | 1:00 P.M. | 20.1 | 2.60 | 11.52* |
| | 2:00 | 20.2 | 2.30 | 6.46* |
| | 3:00 | 20.4 | 2.30 | 10.43* |
| | 4:00 | 20.2 | 2.10 | 5.29* |
| | 5:00 | 20.2 | 2.00 | 9.98* |
| | 6:00 | 20.0 | 1.80 | 14.73 |
| | 7:00 | 20.0 | 4.60 | 14.53* |
| | 8:00 | 20.0 | 0.20 | 16.08 |
| | 9:00 | 20.2 | 4.20 | 6.46* |
| | 10:00 | 20.3 | 2.50 | 7.00* |
| | 11:00 | 20.5 | 5.90 | 2.60* |
| | 12:00 | 20.4 | 5.90 | 2.86* |
| 6/24 | 1:00 A.M. | 20.4 | 5.90 | 3.48* |
| | 2:00 | 20.2 | 5.90 | 1.76* |
| | 3:00 | 20.1 | 5.80 | 2.66* |
| | 4:00 | 19.9 | 5.90 | - |
| | 5:00 | 19.9 | 6.00 | 2.39* |
| | 6:00 | 19.8 | 6.40 | 1.81* |
| | 7:00 | 19.8 | 6.80 | 1.21* |
| | 8:00 | 19.5 | 6.90 | 1.54* |
| | 9:00 | 19.5 | 7.00 | - |
| | 10:00 | 19.5 | 6.50 | - |
| | 11:00 | 19.6 | 6.50 | 7.23* |
| | 12:00 | 19.8 | 5.80 | 7.46* |
| | 1:00 P.M. | 20.0 | 5.50 | 10.70 |
| | 2:00 | 20.2 | 5.20 | 9.92 |
| | 3:00 | 20.2 | 4.70 | 9.92 |
| | 4:00 | 20.2 | 4.70 | 10.23 |
| | 5:00 | 20.2 | 1.30 | 14.52 |
| | 6:00 | 20.2 | 0.70 | 23.75* |
| | 7:00 | 20.2 | 2.90 | 13.53* |
| | 8:00 | 20.1 | 3.80 | 11.83 |
| | 9:00 | 20.1 | 4.10 | 12.72 |
| | 10:00 | 20.0 | 4.40 | 12.40 |
| | 11:00 | 20.0 | 4.70 | 13.09 |
| | 12:00 | 20.0 | 5.00 | 14.06 |
| 6/25 | 1:00 A.M. | 20.0 | 5.20 | 11.90 |
| | 2:00 | 20.1 | 5.20 | 11.31 |
| | 3:00 | 20.1 | 5.00 | 11.64 |
| | 4:00 | 20.1 | 5.10 | 8.65* |
| | 5:00 | 20.1 | 5.30 | 11.64 |
| | 6:00 | 20.1 | 5.70 | 9.31 |

TABLE 8 CONTINUED

| Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|
| 7:00 | 20.1 | 6.00 | 8.65 |
| 8:00 | 20.0 | 6.30 | 7.36 |
| 9:00 | 19.9 | 6.60 | 8.08 |
| 10:00 | 19.9 | 6.50 | 7.79 |
| 11:00 | 19.8 | 6.30 | 8.14 |
| 12:00 | 19.7 | 5.90 | 7.18 |
| 1:00 P.M. | 19.7 | 5.50 | 8.21 |
| 2:00 | 19.7 | 5.70 | 10.63 |
| 3:00 | 19.6 | 5.70 | 11.00 |
| 4:00 | 19.6 | 5.60 | 10.70 |
| 5:00 | 19.6 | 6.10 | 8.56 |
| 6:00 | 19.6 | 6.20 | 12.22 |
| 7:00 | 19.3 | 2.70 | 13.12* |

Points marked thus * were not plotted due to the existence of non-steady state conditions.

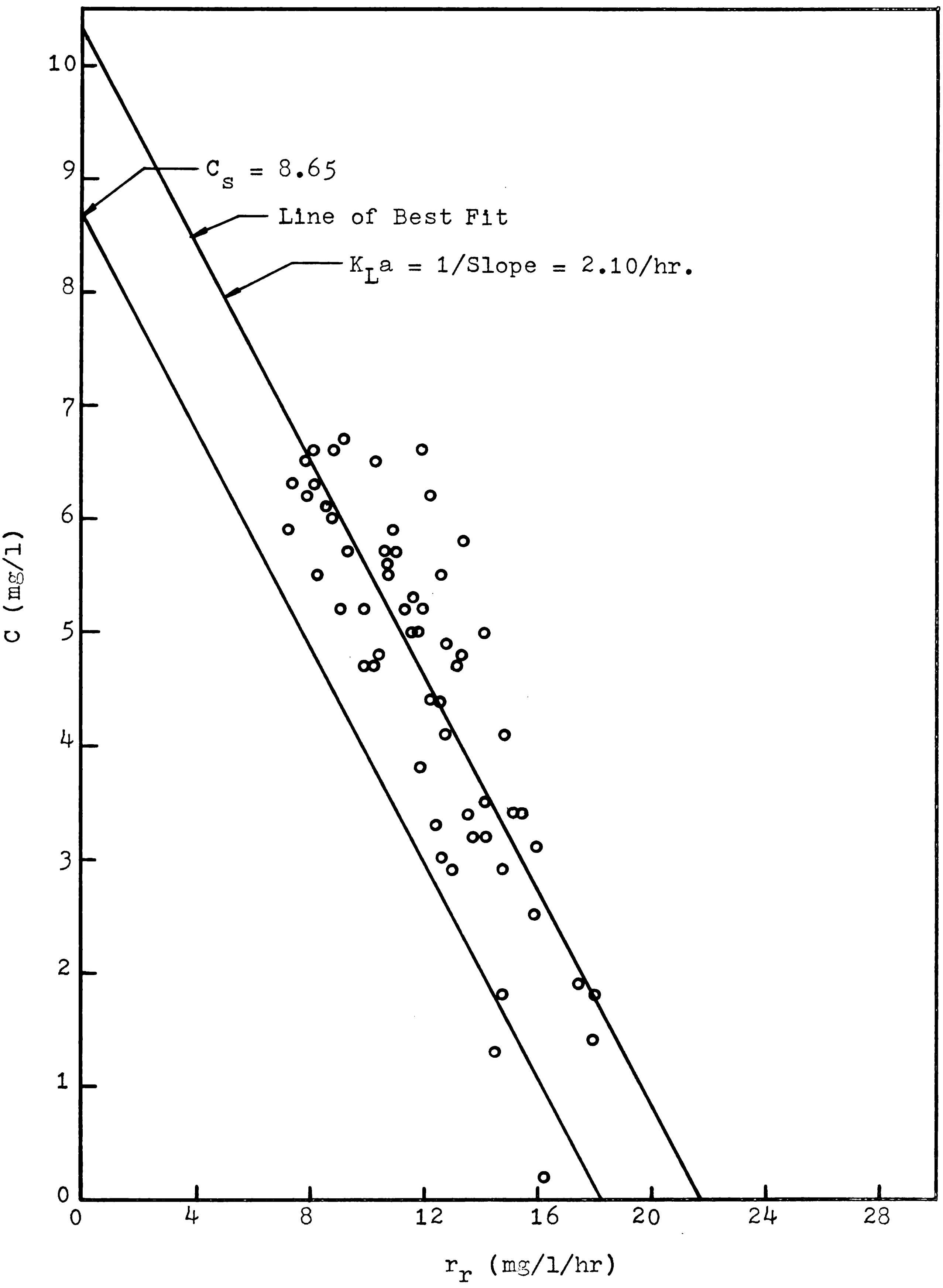


Figure 17. Plot of Data From Experiment 5

17, which corresponds to a maximum oxygen supply rate of 18.2 mg/l/hr when a calculated $C_s$ value of 8.65 mg/l is used. The air flow to each fritted glass diffuser was also raised to 2.5 lpm during this experiment.

Experiment No. 6: Thursday, May 16, 1968 through
Monday, May 20, 1968
Table 9, Figure 18

This experiment was conducted on tank No. 3, which received the greatest load of the three mixed liquor aeration tanks. The experiment was begun at 1:00 A.M. on Thursday, May 16, and continued periodically until 11:00 A.M. on Monday, May 20. The interruptions in the data were caused by daily stopping and starting the equipment. This was done to permit the equipment to operate only at times during which the mixed liquor contained a dissolved oxygen concentration. The daily absence of a dissolved oxygen concentration was a reflection of the greater load placed on tank No. 3. The C and $r_r$ values recorded during this experiment at times of normally maximum dissolved oxygen concentrations ranged from 0.0 to 3.4 mg/l and from 16.5 to 37.2 mg/l/hr., respectively, as shown in Table 9. The mixed liquor temperature, which varied from 17.2 to 19.2°C, showed a normal variance and averaged 18.1°C. The influent raw sewage flow varied from 4 to 10 mgd. The mixed liquor suspended solids concentration varied from 920 to 1120 mg/l, with an approximate average

## TABLE 9

## ANALYTICAL DATA FOR EXPERIMENT 6

Thursday, May 16, through Monday, May 20, 1968

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| 5/16 | 1:00 A.M. | 19.2 | 0.00 | 35.30* |
| | 2:00 | 18.9 | 0.00 | 35.20* |
| | 3:00 | 18.8 | 0.00 | 34.80* |
| | 4:00 | 18.7 | 0.00 | 33.20* |
| | 5:00 | 18.4 | 0.00 | 29.10* |
| | 6:00 | 18.4 | 0.00 | 27.50* |
| | 7:00 | 18.2 | 0.10 | 24.70* |
| | 8:00 | 18.0 | 0.30 | 22.70 |
| | 9:00 | 17.9 | 0.50 | 23.10 |
| | 10:00 | 17.8 | 0.50 | 21.40 |
| | 11:00 | 18.0 | 0.10 | 22.70 |
| 5/18 | 2:00 A.M. | 17.9 | 0.30 | 35.65* |
| | 3:00 | 17.8 | 0.20 | 37.20* |
| | 4:00 | 17.8 | 0.40 | - |
| | 5:00 | 17.7 | 1.00 | 31.30* |
| | 6:00 | 17.6 | 1.90 | 24.80* |
| | 7:00 | 17.8 | 2.50 | 23.90* |
| | 8:00 | 18.1 | 2.00 | 28.20* |
| | 9:00 | 18.3 | 2.10 | 25.20* |
| | 10:00 | 18.5 | 2.20 | 22.90* |
| | 11:00 | 18.8 | 1.90 | 23.80* |
| | 12:00 | 18.9 | 0.00 | 33.70* |
| 5/19 | 2:00 A.M. | 18.5 | 0.10 | 28.50* |
| | 3:00 | 18.5 | 0.10 | 29.30* |
| | 4:00 | 18.4 | 0.00 | 26.80* |
| | 5:00 | 18.1 | 0.20 | 25.50* |
| | 6:00 | 17.6 | 1.30 | 20.80 |
| | 7:00 | 17.4 | 2.20 | - |
| | 8:00 | 17.4 | 2.60 | 18.93 |
| | 9:00 | 17.2 | 3.20 | 17.70 |
| | 10:00 | 17.5 | 3.00 | 17.40 |
| | 11:00 | 17.3 | 3.40 | 16.05 |
| | 12:00 | 17.7 | 2.80 | - |
| | 1:00 P.M. | 17.9 | 1.80 | 17.82 |
| | 2:00 | 18.2 | 0.60 | 20.80 |
| | 3:00 | 18.2 | 0.00 | 33.20* |
| | 9:00 | 17.7 | 0.00 | 36.00* |

TABLE 9 CONTINUED

| | Time | Temp. (°C) | C (mg/l) | $r_r$ (mg/l/hr) |
|---|---|---|---|---|
| | 10:00 | 17.8 | 0.00 | 24.20* |
| | 11:00 | 17.9 | 0.10 | 25.10* |
| | 12:00 | 18.0 | 0.10 | 25.60* |
| 5/20 | 1:00 A.M. | 18.1 | 0.00 | 29.70* |
| | 2:00 | 18.1 | 0.00 | 31.40* |
| | 3:00 | 18.1 | 0.00 | 28.80* |
| | 4:00 | 18.1 | 0.20 | 24.80* |
| | 5:00 | 18.1 | 0.50 | 24.10 |
| | 6:00 | 18.1 | 0.90 | 20.90 |
| | 7:00 | 18.3 | 1.40 | 21.70 |
| | 8:00 | 18.3 | 1.75 | 18.14 |
| | 9:00 | 18.5 | 1.80 | 17.13 |
| | 10:00 | 18.8 | 1.40 | 19.80 |
| | 11:00 | 19.2 | 0.30 | 22.20 |

Points marked thus * were not plotted due to the existence of non-steady state conditions.

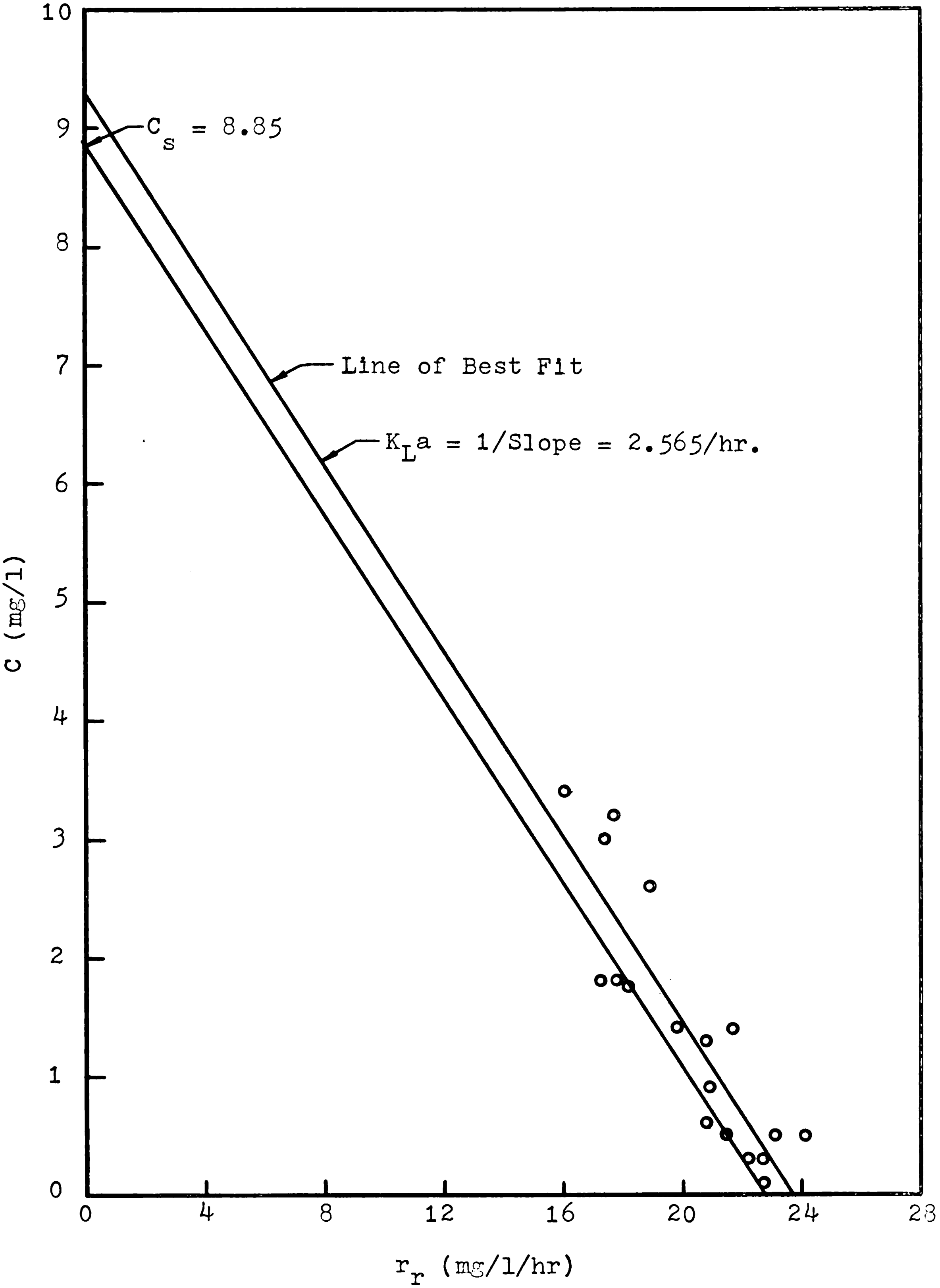


Figure 18. Plot of Data From Experiment 6

of 1020 mg/l. The BOD of the primary effluent ranged from 87 to 120 mg/l, with an average of approximately 110 mg/l. As shown in Figure 18, a $K_La$ value of 2.565/hr, which corresponds to a maximum supply rate of 22.7 mg/l/hr when a calculated $C_s$ value of 8.85 mg/l is used, was calculated for tank No. 3 from the limited data obtained during this experiment. The air flow to each fritted glass diffuser was also increased from 2.0 to 2.5 lpm during this test period due to the lower initial dissolved oxygen concentrations and higher $r_r$ values. The feed pump was located at the normal depth of 1.5 feet and 8.0 feet from the tank wall opposite the diffusers.

## B. Dissolved Oxygen Gradients in a Spiral Flow Aeration Tank

Experiment No. 7: Sunday, July 27, 1968
Table 10, Figure 19

This experiment was conducted on tank No. 2 and was started at 3:15 P.M. on Sunday, July 28. It took approximately one hour to complete. A mixed liquor flow was syphoned from different points in the tank into the D.O. chamber and wasted. The results from several sampling points are shown in Table 10 and plotted on Figure 19 at their respective locations. The dissolved oxygen concentration had a maximum variance at this time of from 1.5 to 4.5 mg/l. The settled sewage flow during

## TABLE 10

## ANALYTICAL DATA FOR EXPERIMENT 7

July 28, 1968          Tank No. 2

| D.O. (mg/l) | Sampling Point |
|---|---|
| 4.5 | 1.0 ft. deep at 0.5 ft. from vertical surface of deflector baffle |
| 3.2 | 1.0 ft. deep at tank center line |
| 1.8 | mid. depth at tank center line |
| 2.0 | 0.5 ft. above bottom 1.0 ft. from tank wall opposite the spargers |
| 2.0 | 0.5 ft. above bottom at center line |
| 1.5 | 0.5 ft. above bottom at spargers |

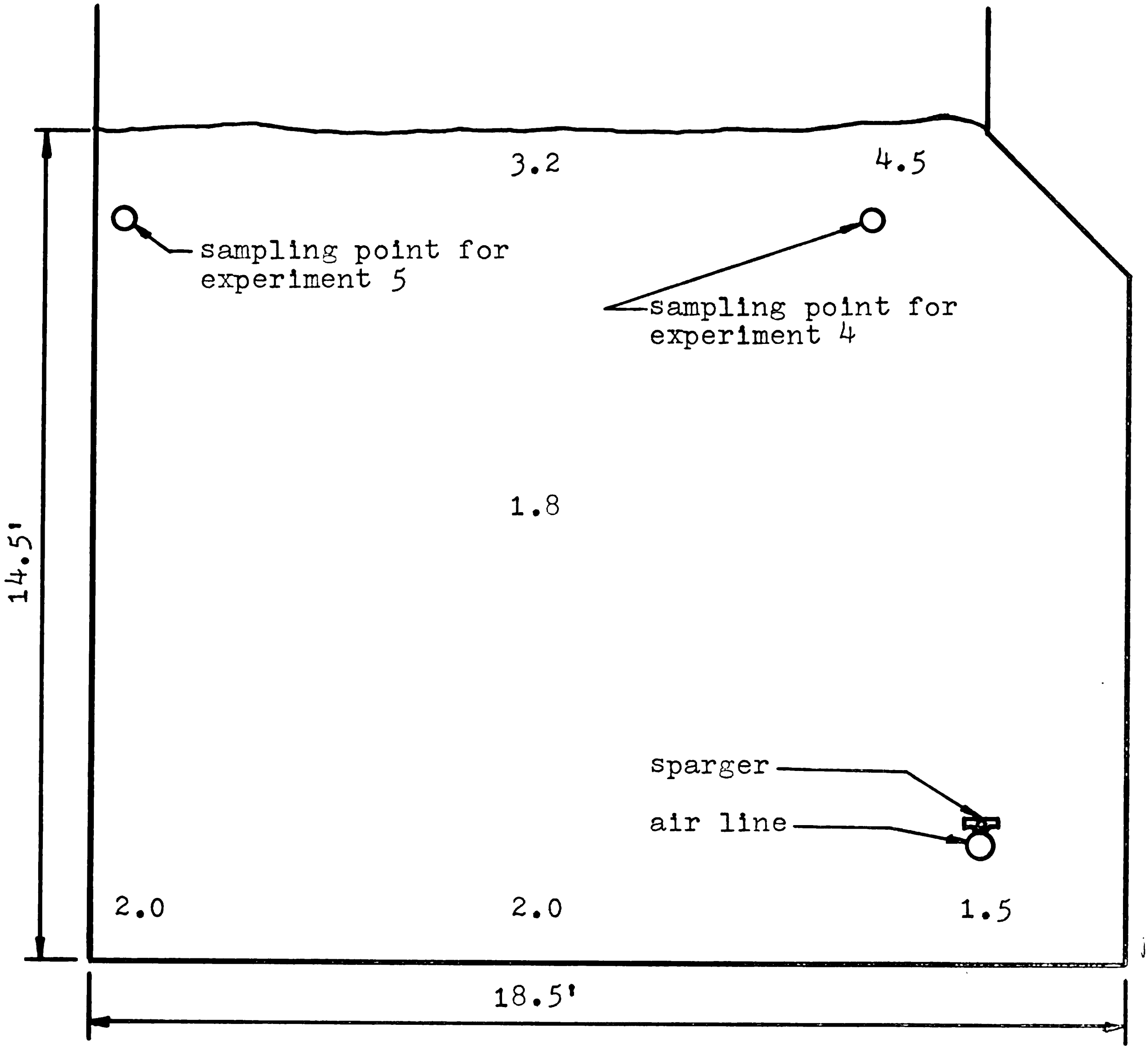


Figure 19. Plot of Data From Experiment 7

the experiment was 8.0 mgd, and the mixed liquor suspended solids concentration and BOD were approximately 2,200 mg/l and 145 mg/l, respectively.

Experiment No. 8: Monday, July 29, 1968
Table 11, Figure 20

This experiment was also conducted on tank No. 2. It started at 10:00 A.M. on Monday, July 29, and required approximately an hour for completion. As shown in Table 11 and on Figure 20, the dissolved oxygen concentration varied from 1.5 to 4.5 mg/l. The plant influent settled sewage flow was 7.0 mgd, and the mixed liquor suspended solids concentration and BOD were approximately 2,400 mg/l and 136 mg/l, respectively.

## TABLE 11

## ANALYTICAL DATA FOR EXPERIMENT 8

July 29, 1968 Tank No. 2

| D.O. (mg/l) | Sampling Point |
|---|---|
| 4.5 | 1.0 ft. deep at 0.5 ft. from vertical surface of deflector baffle |
| 3.0 | 1.0 ft. deep at tank center line |
| 2.5 | 1.0 ft. deep at wall opposite spargers |
| 1.5 | mid. depth at tank center line |
| 1.5 | 0.5 ft. above bottom at tank center line |
| 1.8 | 0.5 ft. above bottom at spargers |

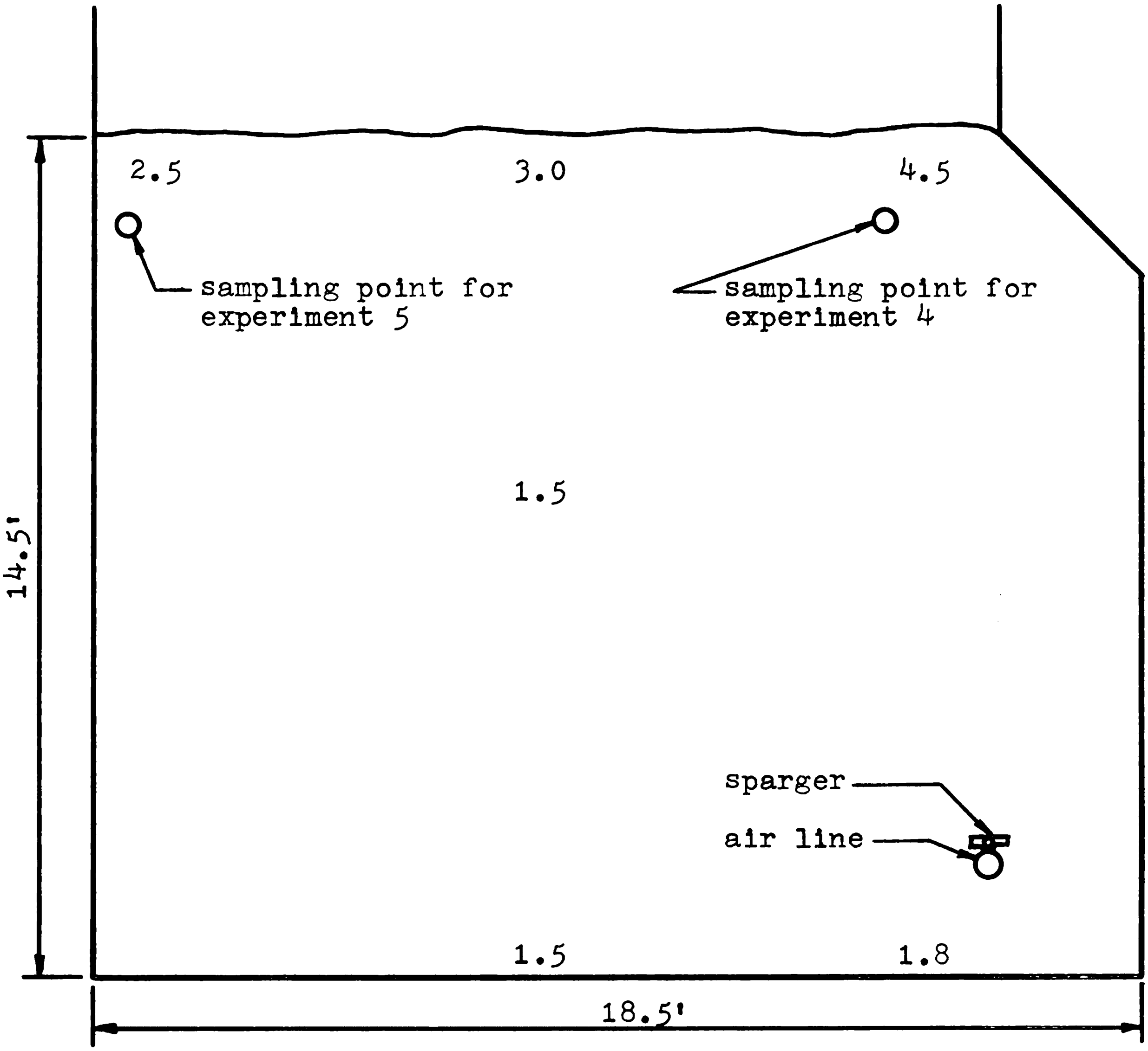


Figure 20. Plot of Data From Experiment 8

# SECTION VII

# DISCUSSION

The $K_La$ values calculated from the data obtained during experiments 1, 2, and 3, as shown in Figures 13, 14 and 15, respectively, vary from a minimum of 2.210/hr. to a maximum of 3.495/hr. At first, this seems to be an extremely large variation, with the maximum 158% of the minimum; however, it can be explained when the range of C values obtained during the three experiments is considered. The steady state C values of Experiment 1 ranged from 1.4 to 7.5 mg/l which is a 6.1 mg/l variance; whereas, the steady state C values in Experiments 2 and 3 ranged from 3.9 to 7.3 mg/l and from 3.2 to 6.5 mg/l, respectively, which is a 3.4 and a 3.3 mg/l range. By observing Figure 15, it can be seen that although the C values have a total range of from 3.2 to 6.5 mg/l, the majority of the points are between 4.2 and 6.3 mg/l, which is a range of only 2.1 mg/l. This actually represents only a grouping of points, and when such a grouping is subjected to a least squares analysis, a line may be obtained that is not representative of the actual conditions.

With this in mind, it can be seen that the results of the three experiments should be weighted differently. This can be done by weighting the results proportional to the range of C values obtained during the individual experiments, which are 6.1, 3.4, and 2.1 mg/l. Using this as the criteria, the weight ratio becomes 2.9:1.6: 1.0 for the results of Experiments 1, 2, and 3, respectively. When this ratio is applied to the results of the three experiments, a weighted average $K_La$ value of 2.61/hr. is obtained for tank No. 1; whereas, if a simple average is taken, the $K_La$ value becomes 2.74/hr. The weighted value indicates experimental errors of 3.6, 15.1, and 33.9% for Experiments 1, 2, and 3, respectively, which are rational errors, when the ranges of the corresponding C values are considered. The $K_La$ value of 2.61/ hr. is considered by the writer to be representative of tank No. 1.

The $K_La$ values calculated from the data of Experiments 4 and 5, which were conducted on tank No. 2, are 1.756 and 2.10/hr., respectively. The respective C ranges of the two experiments are 7.5 and 6.5 mg/l; however, once again it can be seen that the majority of the values plotted on Figure 17 are between 2.9 and 6.7 mg/l, which is a range of only 3.8 mg/l. Using the previously described criteria for weighting results, the weight ratio becomes 1.97:1.0. When this ratio is employed, a weighted average $K_La$ value of 1.873/hr. is obtained. The writer considers this value to be representative of the conditions in tank No. 2.

The data obtained during Experiment 6 on tank No. 3 is extremely spotty, as shown in Figure 18. A $K_La$ value of 2.565/hr. was calculated from this data, but it is not considered representative due to the fact that only 19 points were used and that only four of the C values were above 1.8 mg/l.

Figure 13 through 18 each have a point on the C axis designated as $C_s$. The $C_s$ value shown in each of these figures was calculated by taking 95% of the saturation dissolved oxygen concentration listed in "standard Methods" (42) for distilled water at the corresponding temperature. The 95% was used as being in accordance with the majority of other investigators cited in the literature review. The given values have also been corrected for the pressure differential between the pressure at the mid-depth of the aeration tanks and 760 mm of mercury, the pressure at which the concentrations are listed in the published table.

According to equation (3) as presented in the theory, the lines of best fit should all pass through $C_s$ on the C axis. By looking at Figures 16 and 17, it can be seen that the difference between the two $K_La$ values calculated from the data of the experiments was only 0.34/hr., but that the two lines of best fit shown pass through 16.24 and 10.32 mg/l on the C axis instead of 8.85 and 8.65 mg/l, which are the $C_s$ values for the respective average temperatures. The experiments corresponding to these figures were both performed on tank No. 2. The only difference between them is that different sampling points were used. For Experiment 4, which corresponds to Figure 16, the pump was located approximately 1.5 feet below the liquid surface and 2.0 feet from the sparger side of the aeration tank; whereas, for Experiment 5, which corresponds to Figure 17, the pump was located at the same depth, but it was approximately 1.0 feet from the wall opposite the spargers. Due to the fact that these experiments gave different but very nearly parallel lines and that all the lines of best fit failed to pass through the calculated $C_s$ values, it was hypothesized that a cross sectional dissolved oxygen concentration gradient existed in the aeration tanks.

Experiments 7 and 8 were performed expressly to substantiate or disprove this hypothesis. As shown in Figures 19 and 20, a pronounced gradient was present. This finding is contradictory to that of Eckenfelder (5), who reported that although the liquid velocity varied considerably over a cross section of a sprial flow aeration tank, the dissolved oxygen concentration remained substantially constant when a traverse sampling was made. However, the finding is in agreement with

Kalinske (22), who reported that plots of ($C_s$ - C) against time gave parallel lines depending upon the position of the sampling point with respect to the aeration equipment, Benjes and McKinney (12), who found a dissolved oxygen profile in a "completely mixed" aeration tank, and Novak (10), who presented a plot of the dissolved oxygen concentration versus tank depth on which it was shown that the concentration varied from above 2.5 ppm near the surface to approximately 0.7 ppm at a depth of from 2.0 to 3.5 feet below the surface.

The methods of determining $K_La$ for which C and $r_r$ are measured are all based on equation (1). Kalinske (22) stated that application of this equation to steady state aeration requires uniform bubble distribution, mixing, and turbulence. In agreement with this, Eckenfelder (29) also indicated the requirements of complete mixing and uniform composition; however, he (5) found that the liquid velocity in a spiral flow aeration tank varies considerably from point to point. These authors state the requirement of complete mixing for the application of equation (1), but also state that it is not present in a spiral flow aeration tank. This is verified by the finding of a dissolved oxygen concentration gradient during Experiments 7 and 8, and by the lines of best fit shown in Figures 13 through 18 not passing through the calculated $C_s$ value.

The gradient is what caused the shifting of the $(C_s - C)$ versus time plots, and it was a major factor that affected the position of the lines of best fit shown in Figures 13 through 18. This can best be seen by the use of an example. As previously stated and shown in Figure 19, the sampling point for Experiment 4 was approximately 1.5 feet below the liquid surface and 2.0 feet from the sparger side of the aeration tank. This as also shown in Figure 19 was a point which provided samplings that were not representative of the cross section of the tank. It can be seen that when the equipment recorded a C value of 4.0 mg/l during Experiment 4, the actual existing average cross sectional C value was probably approximately 2.0 mg/l. In other words, the C values recorded were all approximately 2.0 mg/l too high. The effect of this was that the resulting line of best fit was shifted 2.0 mg/l upward on the C scale, but the slope was unchanged.

Although the gradient or sampling point effect caused a considerable amount of the shifting of the lines of best fit, it was probably not the only factor involved. The previously described biological film in the $r_r$ chamber and the effect of turbulence on $r_r$ may have also contributed to the shifting of the lines. When present, both of these factors would shift the resulting line of a C versus $r_r$ plot to the right; however, this would not influence the value of $K_La$ calculated from the slope of such a line.

When present and increasing, the biological film on the chamber walls could have a considerable influence. If the growth increased at a considerable rate, it would cause the points to be arranged in a wider band on either side of the line of best fit, and it would shift the line of best fit slightly to the right on Figures 13 through 18. This is due to the fact that the same dissolved oxygen concentration was measured several times during each experiment. The band widening and shift actually produced by this growth is, however, probably insignificant. The film was first observed after Experiment 6, which chronologically was the third experiment conducted. At this time it was of noticeable proportion, but 22 days were required for this growth to form. The chamber was cleaned at this time, and when observed one week later, only a very slight coating had formed. This indicated a slow rate of formation and practically eliminated the probability of the biological film causing a wider band or slightly shifting the lines of best fit by growing at a considerable rate.

Also, at this time, two $r_r$ tests were conducted concurrently on equivalent samples. One test was conducted in the $r_r$ chamber with the one week growth employing the normal apparatus, and the other was performed in a clean 250 ml Erlenmeyer flask with the model 54 YSI meter and Bausch and Lomb recorder. A magnetic stirrer was used to provide approximately the same agitation as that of the $r_r$ chamber. The flask and chamber $r_r$ values obtained were 15.30 and 14.80 mg/l/hr., respectively. The results were considered equal, with the 0.5 mg/l/hr. difference attributed to warming of the flask sample by the electric magnetic stirrer. Due to the fact that the two $r_r$ values for practical purposes were equal and because the $r_r$ chamber was cleaned prior to the start of subsequent experiments, the effect of this growth after May 20th was neglected. Prior to this date, the growth probably slightly augmented the shifting effect of the dissolved oxygen gradient and the possible effect of turbulence.

Varying turbulence has been reported by Kalinske (22) to cause $r_r$ to vary from point to point in an aeration tank. Eckenfelder (17) stated that high degrees of turbulence tend to break up clumps of activated sludge cells, thereby increasing the number of cells to which dissolved oxygen is available. Hartmann and Laubenberger (43) were in agreement with the preceeding statement, and verified it with experimental data presented in an oxygen uptake rate versus Reynold's number plot. The plot indicated a two stage direct relationship between the uptake rate and turbulence. They concluded that turbulence affects the uptake rate by breaking up of the agglomerated biological flocs, and by exchanging the contact area between the bacteria and their environment. These statements and experimental results indicate that $r_r$ is directly affected by turbulence; i.e., that as the turbulence increases $r_r$ increases and vice versa.

As previously stated, the position of the C versus $r_r$ plots could be shifted to the right by increasing all the recorded $r_r$ values by a constant amount. This is what was probably caused by the turbulence imparted to the mixed liquor flow by the submersible pump and by the three diffusers in the aeration chamber, which were used to raise the initial dissolved oxygen concentration of the mixed liquor flow. Although no attempts were made to verify this effect with experimental data, it, along with the dissolved oxygen gradient, is probably the explanation for the fact that the lines of best fit in Figures 13 through 18 do not pass through the calculated $C_s$ values as predicted by equation (3). The position of the sampling point also varied the amount of agitation received by the flow before it entered the submersible pump.

Other investigators have also raised the initial dissolved oxygen concentration of samples to permit the determination of $r_r$ values. Benjes and McKinney (12) vigorously shook samples in a closed container to increase the dissolved oxygen. Conway and Kumke (13) used an oxygen sparger to increase the dissolved oxygen of most of their samples. When this is done in connection with the method of determining $K_La$ used in this study, the turbulence connected with the aeration step produces a shift to the right of the C versus $r_r$ plot, but the same $K_La$ value is obtained. However, the results of other methods of $K_La$ determination could be influenced by the turbulence associated with increasing the dissolved oxygen concentration in any of the afore mentioned ways. If the steady state relationship $K_La = r_r/(C_s - C)$ is being used to calculate $K_La$ from a few tests, the value obtained would probably be considerably higher than the true one, due to the fact that the $r_r$ values would be higher than they would have been if no extra agitation had been given the $r_r$ samples.

The line of best fit through the data points obtained for this method of $K_La$ determination gives the correct value of $K_La$ for the equipment being tested, even though it doesn't pass through the calculated $C_s$ value. This has been shown by the lines in Figures 16 and 17 which, for practical purposes, have the same slope. This not only makes the calculated $K_La$ values valid, but it also permits the drawing of a line through $C_s$ parallel to the line of best fit for the determination of the maximum rate at which the equipment can supply dissolved oxygen. This maximum supply rate is, of course, also the maximum $r_r$ that can be met by the equipment; therefore, the value can also be calculated with equation (2). This would be done by setting C equal to zero, and the plotting of a parallel line would not be required.

The parallel lines through $C_s$ have been constructed in Figures 13 through 18. A definite relationship can be seen between the sampling point location with respect to the sparger wall of the aeration tank and the perpendicular distance between the parallel lines in Figures 13, 14, 16, and 17. The perpendicular distance between the lines of Figures 16, 13, 14, and 17 decreases in the listed order, but the distance from the sparger wall of the respective sampling points increases in the same order. This indicates the relationship is: that as the distance of the sampling point from the sparger wall increases, the perpendicular distance between the lines decreases. This relationship is exactly what could be predicted from the dissolved oxygen concentration gradient data, and is exemplified by the example given to demonstrate the effect of the dissolved oxygen concentration gradient on the various C values recorded during Experiment 4.

The relationship can be used to somewhat verify the probability that the line of best fit in Figure 15 is not completely representative of the conditions in the aeration tank. Due to the fact that the sampling points of Experiments 2 and 3, which correspond to Figures 14 and 15 respectively, were both located 9.0 feet from the sparger wall of the aeration tank, the lines of best fit in the figures should be the same distance apart; however, the distance between the lines in Figure 14 is considerably greater than the distance between the lines in Figure 15. If the lines of Figure 15 were constructed the same distance apart as those of Figure 14, and if the line of best fit still passed through the center of gravity of the data points with the other line passing through the calculated $C_s$, a plot very similar to that of Figure 14 would be obtained. Therefore, the slope of the line of best fit in Figure 15 should probably be greater, which would decrease the calculated $K_La$ value, causing it to agree considerably better with the other values calculated for tank 1. This same relationship and reasoning can also be used for Figure 18, in that although the sampling point was located 8.0 feet from the sparger wall the distance between the two lines is considerably less than the distance between the lines of either Figures 13 or 14 which had sampling points located 7.0 and 9.0 feet from the sparger wall respectively.

Even though it is not necessary to construct the parallel line through $C_s$, it should be constructed due to the fact it represents the actual manner in which the aeration equipment tested operated. This actual operating line should be of interest to plant operators. A series of such lines could be used to determine the amount by which the air flow could be reduced during periods of low organic loading to provide more economical plant operation. An extension of the maximum supply line could be used to calculate the amount by which the mixed liquor suspended solids concentration could be reduced during periods of high organic loading to provide the maximum treatment with a trace of dissolved oxygen in the effluent of the aeration tanks.

A series of C versus $r_r$ plots could be obtained by conducting experiments at different air flow rates. Once such plots had been constructed, the air flow rate could be maintained at a level that provided the desired dissolved oxygen concentration in the aeration tank effluent, by simply periodically measuring the dissolved oxygen concentration. The procedure would be as illustrated in Figure 21. The C versus $r_r$ plot would be entered at the present dissolved oxygen concentration. By proceeding horizontally along this concentration until the $K_La$ line corresponding to the existing air flow was encountered and by then proceeding downward from this line, the existing $r_r$ could be obtained. The desired air flow could then be determined by retracing the vertical line until the desired dissolved oxygen concentration was

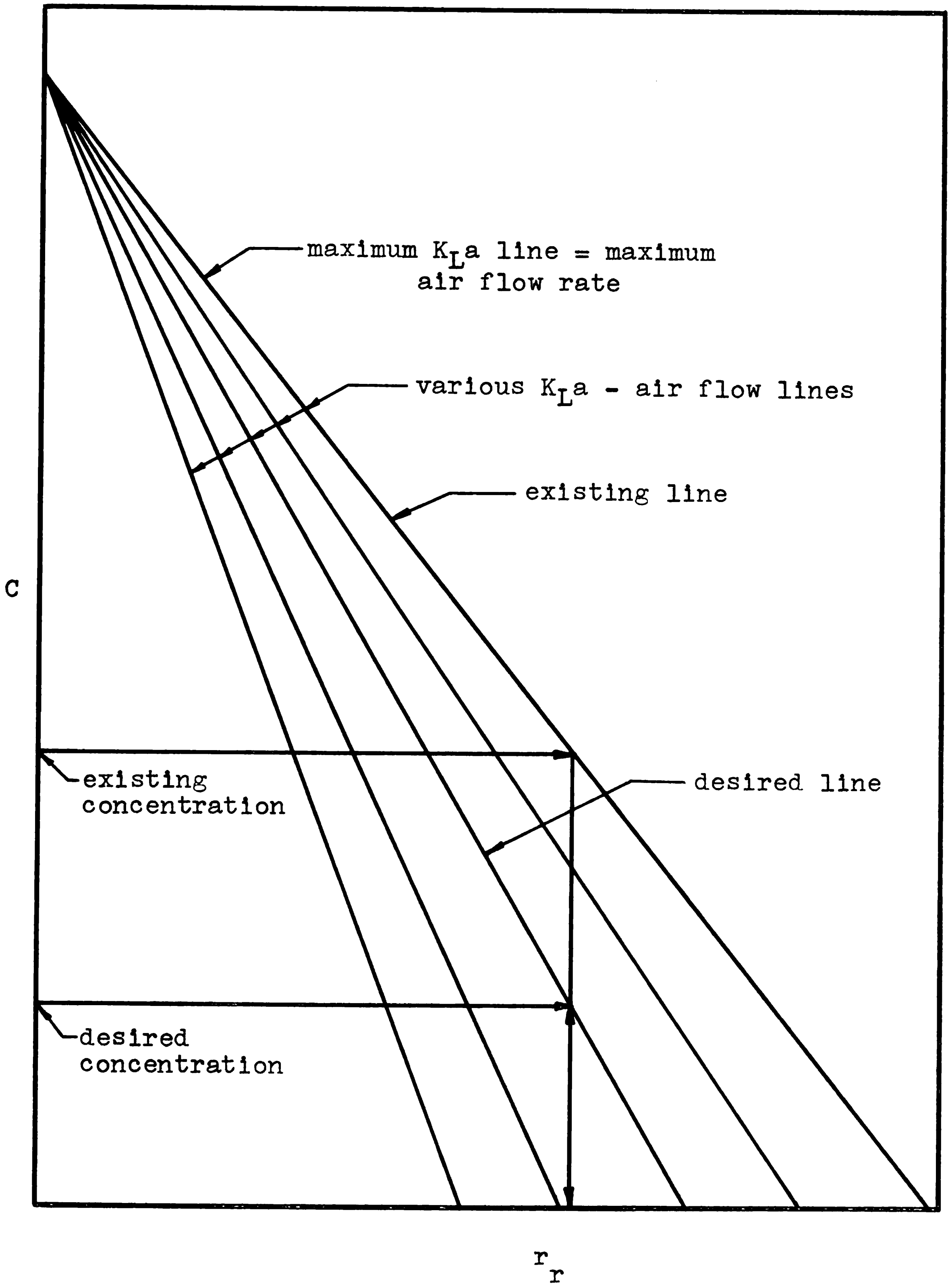


Figure 21. Effect of Air Flow on $K_La$

reached. If this point fell on a particular $K_La$ line, the corresponding air flow would give the desired concentration. If not, the flow rate would be determined by extrapolating between the straddling $K_La$ lines, unless the maximum air flow line had been exceeded. For example, if the present dissolved oxygen concentration was 6.0 mg/l and the maximum air flow was being used, the C versus $r_r$ plot would be entered at 6.0 mg/l. The present $r_r$ would be read at the intersection of the 6.0 mg/l concentration line and the maximum air flow line. If the desired dissolved oxygen concentration was 2.0 mg/l, the desired air flow would correspond to the $K_La$ line passing through the point that corresponds to 2.0 mg/l of dissolved oxygen and the present $r_r$. If no line passed through this point, the above described extrapolation would have to be performed.

When a value that exceeded the maximum $K_La$ line was reached, the mixed liquor suspended solids concentration could be reduced to provide maximum treatment while maintaining aerobic conditions at the end of the aeration tanks. The maximum $K_La$ line would always be exceeded when the existing $r_r$ was greater than, or equal to, the maximum supply rate. By measuring the existing $r_r$ and suspended solids concentration and assuming zero oxygen uptake when no suspended solids are present, the reduction of the existing solids concentration required to provide some dissolved oxygen in the aeration tank effluents can be calculated. A simple ratio would be involved; i.e., the desired concentration would be equal to the quotient of the product of the existing solids concentration multiplied by the desired $r_r$ and divided by the existing $r_r$. The desired $r_r$ chosen would be equal to or slightly less than the maximum rate at which the equipment can supply dissolved oxygen. For example, assume the existing $r_r$ ($r_{rE}$) is 40 mg/l/hr., the mixed liquor suspended solids concentration ($SS_E$) is 4000 mg/l, and the desired $r_r$ ($r_{rD}$) is 30 mg/l/hr. The desired mixed liquor suspended solids concentration would be equal to $(SS_E)(r_{rD})/r_{rE} = (4000)(30)/40 = 3000$ mg/l.

Due to the almost negligible attention required by this method of $K_La$ determination and associated apparatus, it would be very feasible for a plant operator, or design engineer, to determine $K_La$ values while changing other variables. The method is unaffected by many of the common treatment plant variables. Normal fluctuations of the suspended solids concentrations may cause some scattering of the points, but it does not provide a significant factor. Normal variances of the influent BOD did not provide a substantial alteration. The presence of a dissolved oxygen gradient and different sampling positions altered the position of the $K_La$ line, but did not change its slope. However, the air flow during a particular experiment must be held constant.

Not only is the air flow an important variable, but also the degree of steady state, the temperature, the composition of the sewage, and the influent raw sewage flow. The air flow, as previously discussed, will change $K_La$, but the other variables will simply increase the scattering of the points on a C versus $r_r$ plot. Equation (1) describes the manner in which a small $\frac{dC}{dt}$ value affects the results. As previously documented in the literature review, the temperature has an effect on $K_La$; however, as shown in the data tables, the temperature did not greatly fluctuate. The variations in the incoming flow rate somewhat affected the liquid volume in the aeration tanks. This changed the values of A and V which are included in the a of a $K_La$ value. The flow variations also varied the head against which the plant air compressors were operating.

# SECTION VIII

# CONCLUSIONS

1. The method of plotting C versus $r_r$ values measured during periods of steady state conditions combined with the apparatus employed, can be used to determine $K_La$ and the maximum oxygen supply rate in a relatively simple, accurate, and reproducible manner. The method with the associated apparatus had four basic requirements: sufficient space and shelter for operation of the equipment, an electrical outlet, a supply of compressed air, and a steady supply of mixed liquor to be tested.

2. Continuous recording of the dissolved oxygen concentration can be used to actually determine whether steady or non-steady state conditions exist at the time of C and $r_r$ measurements. This can be used to eliminate the doubt and inherent error associated with assuming steady state conditions.

3. Apparatus similar to that employed can be used to hourly measure C and $r_r$ values, without the need of constant attendance and attention. It also provides a means by which 24 hour measurements can be made without the presence of technical personnel.

4. The East Lansing Waste Water Treatment Plant has a low $K_La$ value of approximately 2.0/hr. in the three aeration tanks, and the maximum supply rate of approximately 17.5 mg/l/hr. is also low, which indicates an inability to maintain aerobic conditions during periods of high organic loading.

5. The spiral flow aeration tanks contain a pronounced dissolved oxygen gradient, with the surface layers exhibiting the highest dissolved oxygen concentrations which are substantially greater than those in the remaining parts of the tanks.

6. The line of best fit on a C versus $r_r$ plot can be shifted by using different sampling points in the aeration tanks. This, however, does not affect the $K_La$ determined from the slope of such a plot.

7. The method along with periodic dissolved oxygen measurements could be used for economic plant control. It could also be used by design engineers and equipment manufacturers to specify, design and evaluate aeration equipment.

8. When the method is being used, considerably more reliable results are obtained if $r_r$ values are recorded that correspond to a wide range of dissolved oxygen concentrations.

9. The air flow must be held constant during a particular $K_La$ determination, but by conducting experi-

ments at different air flow rates a corresponding $K_La$ can be determined from the data.

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