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DETERMINATION OF OXYGEN UPTAKE RATES
IN ACTIVATED SLUDGE MIXED LIQUOR

by

Ronald D. Kooistra

AN ABSTRACT

Submitted to
Michigan State University
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DETERMINATION OF OXYGEN UPTAKE RATES
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Continuous measurement of dissolved oxygen in an aqueous solution can be made by a polarographic electrode. In this thesis a gold-silver polarograph cell has been used to measure dissolved oxygen depletion in mixed liquor samples from the East Lansing Sewage Treatment Plant over short periods of time.

A schedule of sampling at 2 hour intervals throughout the day revealed a basic pattern in the variation of the activated sludge activity, k_r = milligrams oxygen consumed per gram mixed liquor suspended solids per hour. The activity increased from a minimum between 7 and 10 AM to a peak value between 2 and 5 PM after which the rate slowly decreased during the evening until at about midnight the rate decreased more rapidly to the minimum value at the following morning. Over the weekend, k_r, was much lower than for a weekday, with Saturday being the period of lowest k_r values while Wednesday was the period of highest k_r values.

BOD determinations upon the primary effluent taken at the time of the mixed liquor sampling revealed that k_r was directly related to both the total and dissolved BOD of the primary effluent.

The aeration system of the sewage treatment plant was analyzed for its capacity by observing the D.O. in the mixed liquor and simultaneously determing r_r, the oxygen uptake rate per unit mixed liquor volume. The capacity of the East Lansing aeration system was found to be 20.3 mg/l/hr. while maintaining a D.O. of 1 ppm in the aeration tank at 15°C.

The slope of a semilogarithmic plot of the specific oxygen utilization rate, k_r, against temperature, °C, was found to be 0.0323/°C.

The activity, as measured by r_r, of a starved activated sludge was found to double within one half hour after being fed 500 mg/l glucose.

APPROVED ____________________________

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I would like to express my sincere gratitude to my wife for her aid and understanding during the years of my education.

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LIST OF SYMBOLS

BOD	Biochemical Oxygen Demand
BOD_5	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
k_r	Oxygen uptake rate per unit weight of suspended solids, mgO_2/gSS/hr. or milligrams oxygen consumed per gram suspended solids per hour
M.L.S.S.	Mixed liquor suspended solids
M.L.V.S.S.	Mixed liquor volatile suspended solids
P.E.	Primary effluent
O_2	Oxygen
μ	Micro
g	Grams
mg	Milligrams
ppm	Parts per million
D.O.	Dissolved Oxygen

SECTION I

INTRODUCTION

This study has been carried out at the East Lansing Sewage Treatment Plant. This waste treatment plant employs the "biosorption" modification of the activated sludge process for its secondary treatment. The plant treats nearly 100% domestic wastes.

The main objective of this study has been to measure the oxygen uptake rates occurring in the aeration tanks. Several 24 hour surveys using two hour sample intervals have been made in order to outline the rate variation according to the day of the week. The four month study has also revealed the effects on the mixed liquor oxygen uptake rates due to changes in the student population at Michigan State University, which contributes a large portion of the total sewage flow treated by the plant.

Other variables measured during the four month survey were:

1. Primary Effluent BOD (Total and Dissolved)
2. Primary Effluent COD
3. Primary Effluent Suspended Solids
4. Mixed Liquor pH
5. Mixed Liquor Suspended Solids and Volatile Suspended Solids.

SECTION II

LITERATURE REVIEW

A. Oxygen Electrode

The dropping-mercury polarographic electrode was the first polarographic electrode to be used for the determination of dissolved oxygen. There are several advantages of the polarographic technique of D.O. determination over the standard Winkler (1) test. Among the advantages are the rapidity of measurement, the possibility of determining the D.O. "in situ" thereby offering a means of plant control, the feasibility of continuous recorded observations and automatic operating control, the possible use of the sample for other determinations after its D.O. has been determined, and the rapid measurement of D.O. in sludges or suspensions which makes the measurement of mixed liquor oxygen utilization rates feasible.

Many workers in the field of waste treatment investigated the use of the polarographic technique for D.O. measurement. Ingols (2) and Moore, Morris and Okun (3) concluded from their investigations that the dropping mercury electrode was a rapid and accurate instrument for the measurement of D.O. in waste waters. Rand and Heukelekian (4) in their studies of D.O. determination in industrial wastes reported that the dropping mercury electrode method permitted reasonably accurate determination of D.O. even under conditions which render the standard Winkler method inapplicable. Lynn and Okun (5) reported that the dropping-mercury electrode suffered the disadvantage of interference with the mercury drop by the turbulence necessary to keep the activated sludge in suspension. Furthermore the toxicity of the mercury introduced a serious problem into the measurement of the biological activity of the sludge floc.

Lynn and Okun (5) concluded from their investigation that the platinum electrode was not applicable to the determination of D.O. in waste waters due to deleterious effects of impurities in the sample medium. Recent developments in the field of solid electrodes have overcome the poisoning effects of impurities in the sample medium. Carritt and Kanwish (6) made a very important contribution by developing a temperature-compensated electrode composed of a plastic membrane covered platinum electrode. The plastic membrane is not permeable to the ionic contaminants of the sample solution, but it is permeable to gases. Mancy and Westgarth (7) also made an important contribution by the development of the plastic membrane covered silver-lead galvanic cell oxygen sensitive electrode.

Today electrodes based on both the polarographic and galvanic cell principles are commercially produced. The electrodes in general have the desired characteristics of: (a) ability for continuous monitoring of oxygen, (b) ease of operation and maintenance, (c) long-term stability, and (d) suitability for field use.

B. Activated Sludge Activity

The concept of dissolved oxygen monitoring for the conservation of power by the proper proportioning of aeration to oxygen demand and for the early discovery of sludge activity disturbances is recognized by many sewage treatment plant operators. Considerable savings may be obtained by the proper control of aeration equipment. Greely (8) reports that from 50 to 60 percent of the total power consumption in a sewage treatment plant is used by aeration equipment. A report by the APHA (9) indicated that many plant operators monitor the aeration tanks by periodically checking the D.O. in the aeration tanks with the minimum permissible D.O. ranging from 0.2 to 2 ppm. However, the activity of the sludge organisms is best evaluated by measuring the rate at which oxygen is utilized by the organisms. Thus there exists a need for a suitable oxygen uptake rate test which can be conducted rapidly and which can serve as an immediate guide in the control of plant operation.

Several methods have been used for the measurement of mixed liquor oxygen utilization rates. Bloodgood (10) used the Odeeometer and reported that the control of the sludge activity could be accomplished by changing the sewage flow, quantity of air used, or the quantity of mixed liquor solids. Kessler and Nichols (11) used the standard Winkler D.O. test with cupric-sulfamic acid to determine oxygen utilization rates by observing the D.O. depletion over short periods of time. They reported that the oxygen utilization rate, designated Nordell Number, could be used to ascertain the progress of oxidation of sewage, the sewage strength, and the condition of "activity" of a sludge. Later Kessler (12) using an Odeeometer further studied the Nordell Number and its mathematical relationships with other variables in the activated sludge treatment process. Dawson and Jenkins (13) used both the Barcroft and Warburg manometers for oxygen utilization studies upon mixed liquors. Hoover, Jasewicz and Porges (14) showed that the Magnetic Oxygen Analyzer could be used for the measurement of oxygen utilization rates. Lamb, Westgarth, Rogers and Vernimmen (15) in their studies of industrial waste have reported that the galvanic cell electrode provides a simplified experimental approach for the measurement of oxygen utilization rates. It is the purpose of this thesis to demonstrate the application of a polarographic oxygen electrode to the analysis of the mixed liquor oxygen consumption rates at an operating sewage treatment plant.

1. Effect of Dissolved Oxygen Concentration

Smith (16) has reported that no effect on mixed liquor oxygen utilization rates was observed within a dissolved oxygen range of 0.2 to 6 ppm. The APHA committee (9) reported that a survey of many operators revealed that the minimum permissible D.O. varied from 0.2 to 2 ppm. The WPCF Manual of Operation (17) recommends that a D.O. of 2 to 4 ppm be maintained in the mixed liquor.

2. Effect of Temperature

Activated sludge consists mostly out of microorganisms and its metabolic rate will therefore be markedly effected by temperature. Bloodgood (10) reported that between $10^{o}C$ and $30^{o}C$ each one degree rise increased the oxygen utilization rate by 3 $mgO_2/l/hr$. Sawyer and Nichols (18) have reported the oxygen utilization rate at 10^{o}, 15^{o}, and $20^{o}C$ to be 26, 43.5, and 70.5 percent respectively of the rate at $25^{o}C$. Sawyer and Rohlich (19) have confirmed Sawyer and Nichols results and further observed that winter sludges are adapted to the low temperatures since they have higher oxygen uptake rates at a given low temperature than summer sludges.

3. Effect of Solids Concentration

The amount of activated sludge to carry in the aeration tanks is a question upon which few plant operators will agree. The APHA committee (9) reported that the maintenance of an optimum solids concentration in a mixed liquor is important but that the optimum amount at any plant must be determined by the operators experience. Sawyer and Nichols (18) have reported that the oxygen utilization rate is directly proportional to the amount of activated sludge solids. Lamb, Westgarth, Rogers and Vernimmen (15) have reported that the oxygen uptake rate is directly proportional to the volatile solids concentration and have presented the specific oxygen uptake rate ($mgO_2/gVSS/hr$) as being helpful in defining the viability of a sludge in relation to a specific substrate.

4. Effect of pH

Microbiologists have long recognized that pH has a very pronounced effect on microbial growth. In the activated sludge treatment process Keefer and Meisel (20) reported that an effective process range is from pH 6.0 to 9.0 with an optimum range from pH 7.0 to 7.5. Smith (16) and Eckenfelder and O'Connor (21) maintain the same position.

5. Effect of BOD Concentration

Smith (16) has reported that the oxygen uptake rate per unit weight of sludge solids is linearly related to the BOD of the sewage being treated. Eckenfelder and O'Connor (21) maintain the same position but express the relationship a little differently. They reported that the oxygen utilization rate per unit weight of sludge is directly proportional to the 5-day BOD removal per unit weight of sludge. In this thesis a new relationship will be introduced namely, that between the oxygen utilization rate and the dissolved 5-day BOD of the sewage being treated.

SECTION III

EXPERIMENTAL APPARATUS AND MATERIAL

A. Material

Mixed liquor from the East Lansing, Michigan, Sewage Treatment Plant was used for all the oxygen uptake rate measurements. The sewage treated by this plant is strictly of a residential nature. During the summer months, the plant operates on a decreased volume because the number of students attending the university is reduced by about two-thirds. The collection system is a combined one, thus during the periods of rain the strength of the waste is reduced considerably. Naturally all of the factors mentioned above have a marked effect on the strength of the primary effluent with respect to BOD.

During the term of this study the highest primary effluent BOD found was 243 mg/l and the lowest was 36 mg/l based on grab samples taken simultaneously with the mixed liquor samples.

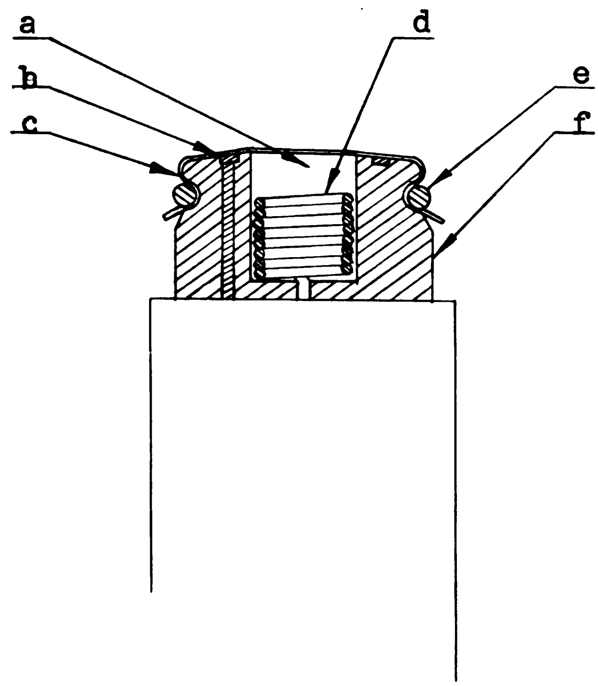
B. Apparatus

1. Polarograph Oxygen Electrode

The oxygen sensor used to make all of the oxygen uptake rate measurements was the YSI model 5101 polarographic oxygen probe with model 51 oxygen meter manufactured by the Yellow Springs Instrument Company. Figure 1 shows the details of the polarograph electrode. Figures 2 and 3 show the sample flask and oxygen meter assembly.

The basic components of the respirometer consisted of a 250 ml widemouth Erlenmeyer flask, a 1-1/4 inch long by 5/16 inch diameter teflon coated magnetic stirring bar, a number 8 rubber stopper in which a thermometer, a 1/8 inch diameter glass tube and the electrode were held. The glass tube served as a vent for escaping air and excess liquid when stoppering the flask. A five inch length of lucite tubing was glued with epoxy to the two inch long electrode in order to facilitate the placing of the electrode about 1-1/4 inches above the magnetic stirring bar when the respirometer was closed.

The polarograph cell consists of a gold ring cathode imbedded in a lucite block, and a silver coil recessed in a central well. The well is filled with 1 N potassium chloride solution. A thin teflon membrane stretched across the end of the cell isolates the cell from its environment with the exception of gases. The membrane is permeable to gases and allows them to make contact with the polarograph cell by diffusion. The correct polarizing voltage across the



a. Potassium Chloride, KCl, Solution
b. Gold Ring Anode
c. Teflon Membrane
d. Silver Coil Cathode
e. Neoprene "O" Ring
f. Lucite Block

Figure 1. Cutaway View of the Electrode.

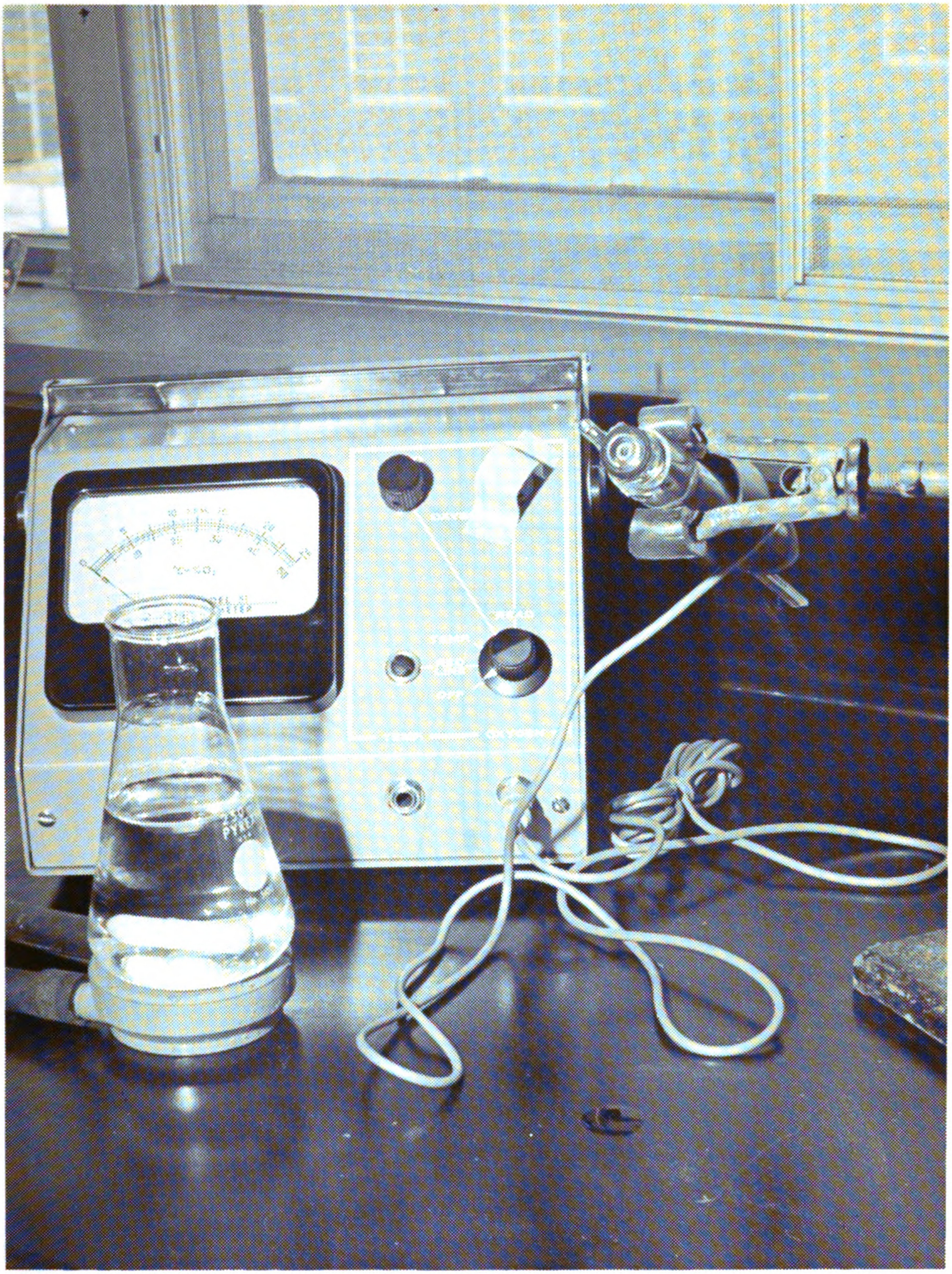
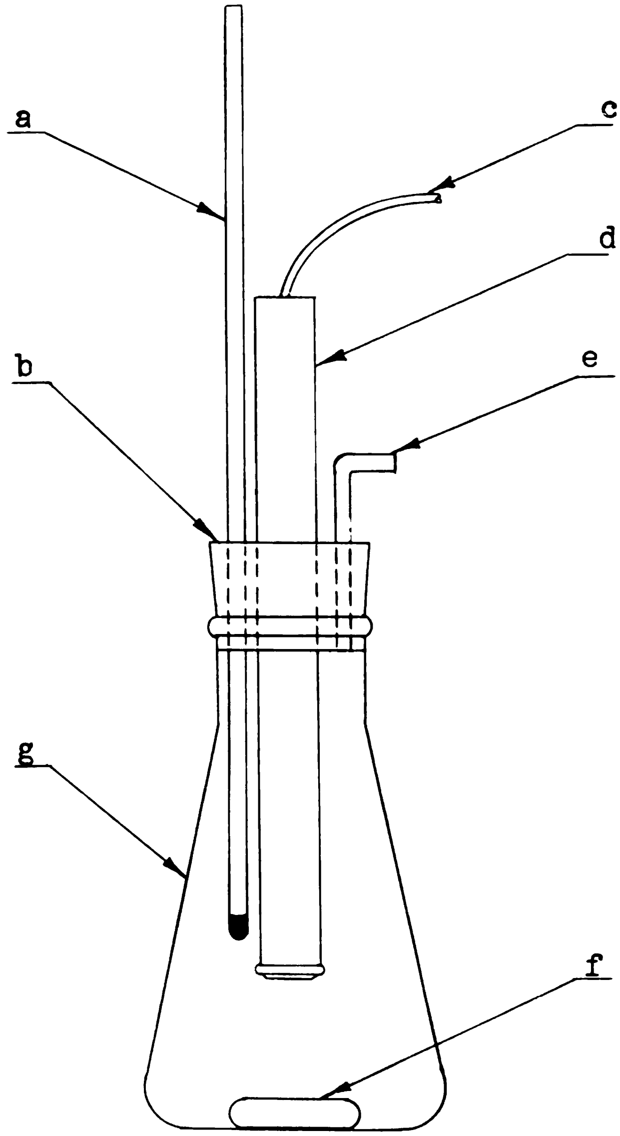


Figure 2. Sample Flask and Oxygen Meter Assembly.



a. Thermometer
b. Number 8 rubber stopper
c. Lead wire to oxygen meter
d. Electrode
e. Glass tube vent, 1/8 inch inner diameter
f. Teflon coated magnetic stirring bar, 1-in. x 5/16-in. diameter
g. 250 ml Erlenmeyer widemouth flask

Figure 3. Respirometer Assembly.

cell allows the reduction of molecular oxygen at the gold cathode surface. The oxidation of the silver anode surface supplies the current for the reduction of the oxygen at the cathode.

The amount of diffused oxygen reaching the cell is proportional to the driving force which is the partial pressure of the oxygen in the sample medium, an aqueous solution in this study. The partial pressure of the oxygen is directly proportional to the concentration of the dissolved oxygen. A linear relationship exists between the external oxygen pressure and cell current.

2. Air Supply

A small portable air compressor was used to supply compressed air for the aeration of the mixed liquor samples. A quart jar approximately 3/4 full of mixed liquor was aerated at a high rate by forcing compressed air through a 1/2 inch diameter by 1 inch long fritted glass diffuser. Approximately a 200 ml aliquot of this aerated mixed liquor was used for the oxygen uptake rate determination by observing the oxygen depletion after the air supply had been shut off.

3. Magnetic Stirrer

In order not to add any heat to the samples an air driven magnetic stirrer was used, Bronwill Mag-

Jet, with a 5/16 inch by 1-1/4 inch long teflon covered magnetic stirring bar. The basic factor considered in stirring the sample was to obtain adequate liquid velocity past the electrode membrane in order to prevent the formation of a stagnant diffusion zone at the membrane surface.

The necessary rate of stirring can be easily established by noting the effect of various stirring speeds upon the current output when the electrode is in a sample of water having a constant D.O.; distilled water is good. The rotation speed of the stirrer at which no more significant current increase is produced is the speed to be used for all measurements with the electrode. A pressure regulator was used to obtain the same stirring speed for each test. This was accomplished by noting the pressure reading, 3 psi, and keeping the needle valve at a constant setting. The air flow was shut off by decreasing the pressure to zero and the correct air flow re-established by increasing the pressure to the control pressure reading.

SECTION IV

EXPERIMENTAL PROCEDURE

1. Electrode Calibration

The current output of the electrode is markedly effected by temperature. This is caused by the fact that the permeability of the plastic membrane is temperature dependent, in the order of 4 per cent per ^{o}C as stated in the instruction pamphlet for the oxygen meter. Mancy and Westgarth (7) have shown that the temperature effect is linear.

The linear relationship to the electrode sensitivity to temperature provides a convenient means for calibration of the electrode. The electrode is placed into a sample for which the dissolved oxygen concentration has been previously determined by the standard Winkler test. A minute or two is allowed for stabilization of the current output. Then the sample is immersed in an ice bath and the current output recorded at $2^{o}C$ intervals. The usual temperature range is from $10^{o}C$ to room temperature ($24^{o}C$). The sensitivity, is equal to the microamp output divided by the Winkler D.O. expressed as mg per liter. A semi-logarithmic plot of sensitivity versus temperature, as shown in Figure 4, produces a straight line and is called the "calibration curve". Thus a current reading taken at

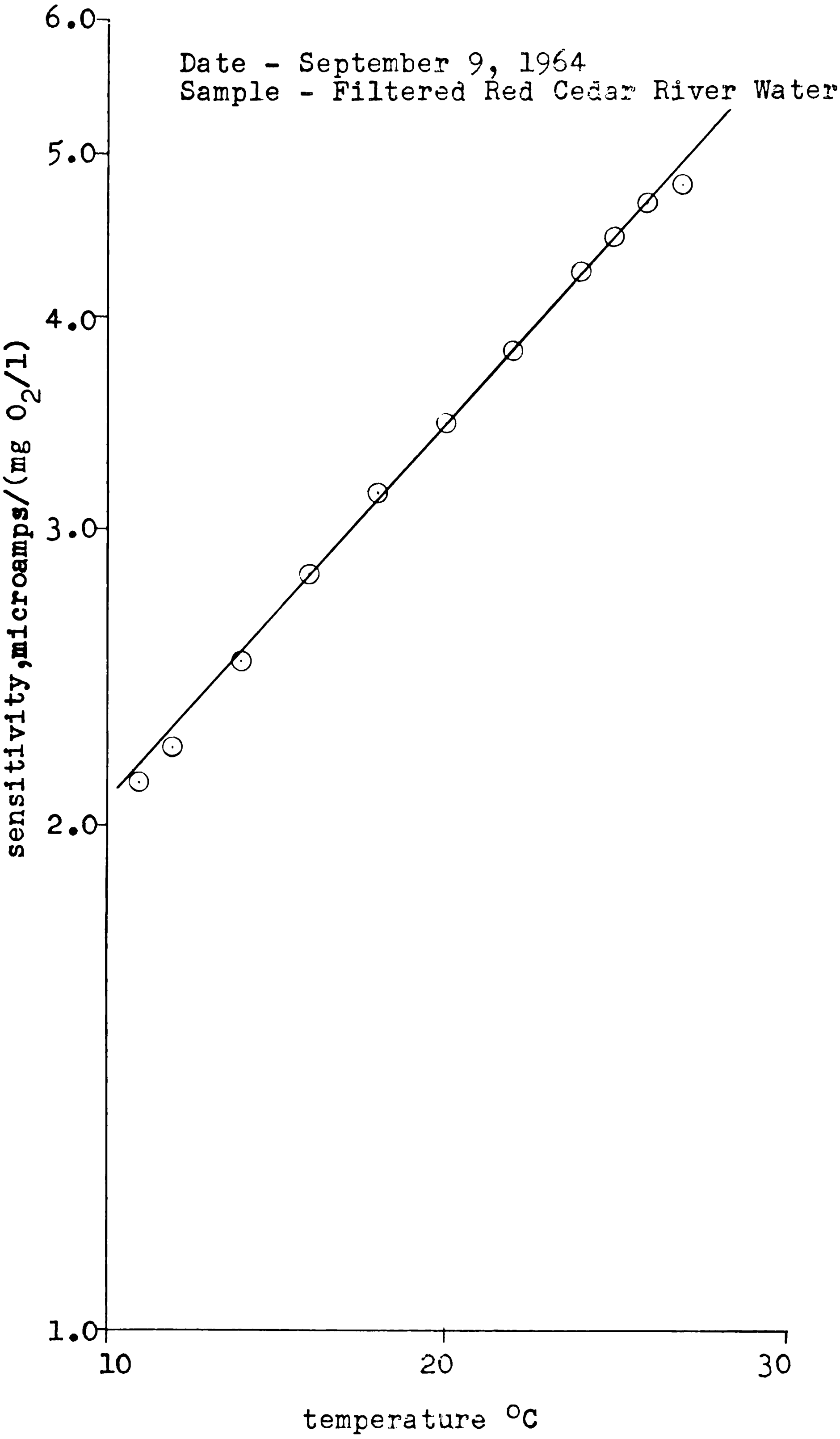


Figure 4. Calibration Curve for the Electrode.

a known temperature can easily be converted to mg/l D.O. by dividing the current by the sensitivity obtained from the calibration curve.

The current output of the electrode was observed to be dependent upon the stirring speed of the magnetic stirring bar at slow speeds. Mancy and Westgarth (7) have shown that the current output of the galvanic cell oxygen sensor is greatly effected by the stirring of the liquid at slow speeds. The formation of a stagnant diffusion layer at the membrane surface is prevented at higher speeds.

The current output of the electrode was also observed to be effected by constituents in the aqueous solution other than oxygen. Red Cedar River water filtered through Whatman no. 2 filter paper was used as the calibration reference medium. The calibration curves obtained by this procedure were assumed to be similar to that of sewage.

The accuracy of the electrode was checked by making several comparisons between the dissolved oxygen concentration as measured by the electrode and by the standard Winkler test. It was found that the accuracy was in the order of ± 0.5 mg/l.

2. Measurement of the Mixed Liquor Oxygen Uptake Rate

The sampling point was the center of the first bay of aeration tank number 2. This point is located approximately 10 feet from both the primary effluent entrance and the return activated sludge entrance. Thus the contact time between the activated sludge and the primary effluent is about one minute. Samples were taken at 2 hour intervals for each survey. The samples were immediately taken to the Michigan State University Sanitary Engineering Experiment Station located at the plant where they were aerated for 15 minutes. After shutting off the air supply, an aliquot was immediately poured into the respirometer flask for observation of the oxygen uptake rate by measuring the rate of depletion of the dissolved oxygen over time. Depending upon the magnitude of the oxygen demand rate either 2 or 5 minute current readings were recorded.

It was found advantageous to place the electrode in a solution of low D.O. a minute or two prior to the use of the electrode. The supernatant from a settled mixed liquor sample is well suited for this purpose. The advantage of this procedure is that the current ouput will rise when the electrode is placed in the aerated sample. The point of no more rise defines the beginning of equilibrium between the dissolved oxygen concentration and the current output. The initial current reading was taken after the current had fallen from the peak value at least 1 microamp reading. It was endeavored to maintain a constant temperature by placing the respirometer into a 600 ml beaker full of fresh primary effluent as shown in Figure 5. A typical data sheet is shown in Table 1. The usual temperature rise was about 1°C. The average temperature of the mixed liquor during the time of this survey was approximately 22°C. The maximum temperature was 25°C and the minimum 14°C.

3. Biochemical Oxygen Demand

Primary effluent grab samples were obtained simultaneously with the mixed liquor samples. The standard five day BOD test as described in Standard Methods was used throughout the investigation. In determining the amount of dissolved BOD the primary effluent was filtered through a 0.45 micron Millipore membrane filter. Seeded dilution water as described in Standard Methods (1) was used in determining the BOD of the filtrate. The incubation temperature of 20°C was controlled by means of a water bath in which the bottles were completely submerged.

4. Chemical Oxygen Demand

The standard COD test as described in Standard Methods was used for all COD determinations. The digestion process was not catalyzed.

5. Suspended Solids

Mixed liquor suspended solids were determined by

TABLE I

TYPICAL DATA SHEET FOR THE MEASUREMENT OF OXYGEN UPTAKE RATE BY THE OXYGEN ELECTRODE

Sampling Time	Test Time (min)	Temp. °C	μ amps	D.O. mgO_2/l	Δ(D.O.)	Average O_2 Uptake Rate r_r $mgO_2/l/hr.$
Example - Thursday, July 23, 1965						
6 AM	0	23.0	22.4	5.42	-	15.85
	5	23.4	17.3	4.12	1.30	
	10	23.8	12.0	2.79	1.33	
8 AM	0	22.8	22.0	5.37	-	15.50
	5	22.8	17.5	4.26	1.11	
	10	23.0	12.3	2.97	1.29	
	15	23.4	7.0	1.67	1.30	

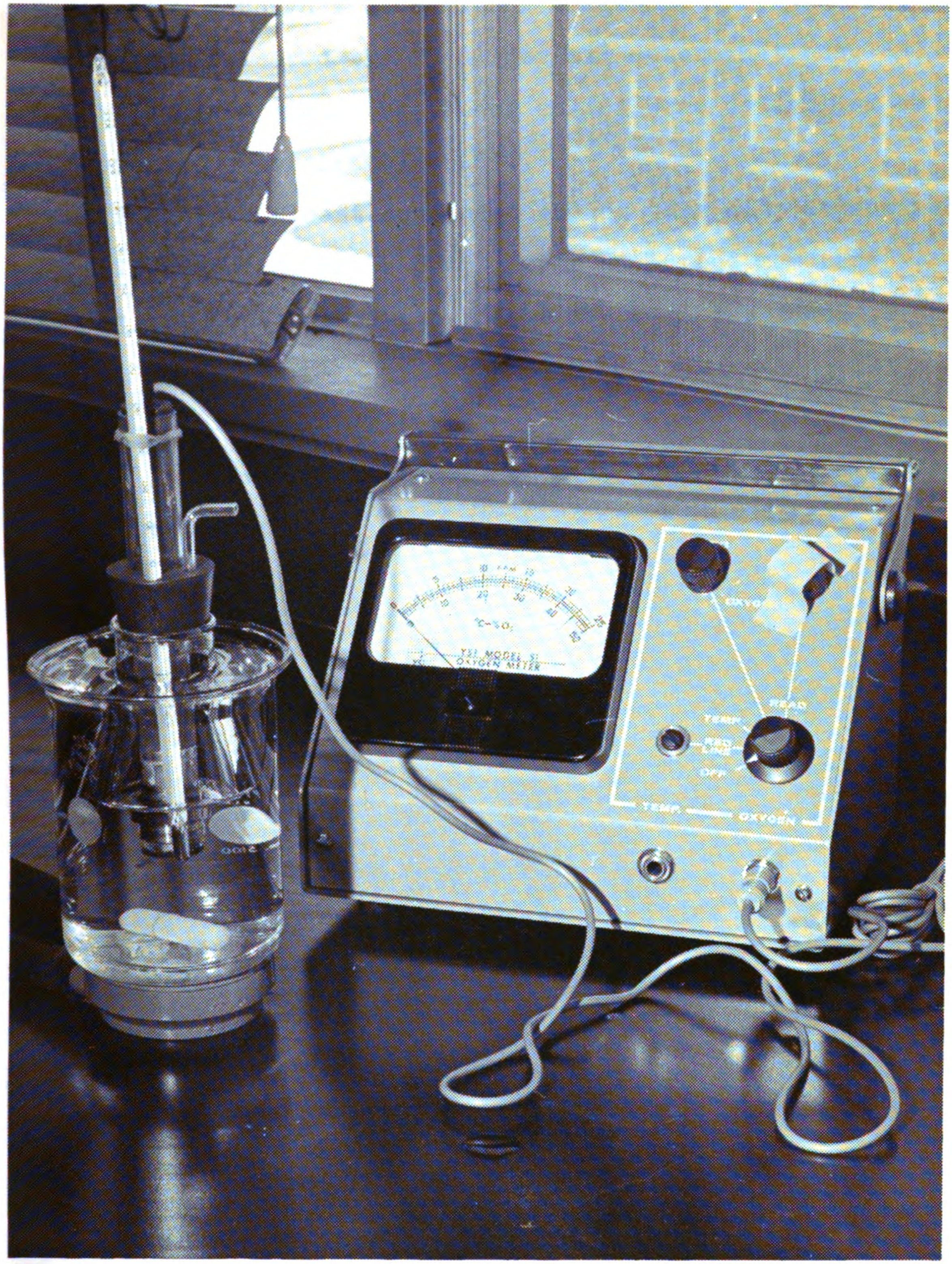


Figure 5. Temperature Control of the Respirometer.

filtration through a 0.45 micron Millipore membrane filter. The volume filtered was 25 ml for all determinations. Volatile mixed liquor suspended solids were determined by ignition at approximately 600°C.

Primary effluent suspended solids were also determined by filtration through a 0.45 micron Millipore membrane filter. A constant sample volume of 50 ml was used.

6. pH

A Beckman model H2, pH meter was used to measure pH of each sample.

SECTION V

EXPERIMENTAL RESULTS

A. Mixed Liquor Oxygen Uptake Rate Measurement at the Sewage Treatment Plant

The data have been divided into six groups according to whether they were obtained between terms or during terms. During terms not only the volume but also the strength of the sewage increases significantly. This increased BOD load has marked effects upon the respiration rate per unit dry weight of the mixed liquor suspended solids (k_r) as will be shown later.

The test procedure consists of taking simultaneously grab samples of mixed liquor and primary effluent at 2 hour intervals. The majority of the test series comprise less than 24 hours. However, test series of 24 hours duration and over weekends are included.

The oxygen uptake rate per unit liquid volume is denoted as r_r and the oxygen uptake rate per unit weight of suspended solids is denoted as k_r. The units are defined as:

r_r = milligram oxygen consumed per liter mixed liquor per hour, $mgO_2/l/hr$.

k_r = milligram oxygen consumed per gram dry weight mixed liquor suspended solids per hour, $mgO_2/gSS/hr$.

1. Between Spring and Summer Terms

Experiment No. 1: Friday, June 18, 1964

Table 2, Figure 6

This test series was begun at 8:00 AM and ended at 4:00 PM. The oxygen uptake rate was a minimum, r_r = 15.6 and k_r = 9.9, at 10:00 AM after which the rate steadily increased until a peak, r_r = 31.0 and k_r = 19.5, was reached at 2:00 PM. The average temperature of the mixed liquor was 22.5°C. The activity of the sludge was relatively low because the majority of the Michigan State University students had left the campus for a vacation break. The BOD concentration of the primary effluent was not determined.

Experiment No. 2: Friday, June 26, 1964

Table 3, Figure 7

This test series was begun at 8:00 AM and ended at 8:00 PM. The M.L.S.S. were relatively low because the treatment plant operators were pumping all of the return activated sludge to another aeration tank which was being restarted after a period of repairs. With the exception of a slight dip at 2:00 PM, the oxygen uptake rate increased steadily from 8:00 AM (r_r = 12.2 and k_r = 8.6) to 4:00 PM (r_r = 24.1 and k_r = 68.5). Sometime between 3 and 4:00 PM the plant operators diverted nearly all of the return activated sludge to the newly repaired aeration tank. As

TABLE 2

ANALYTICAL DATA FOR EXPERIMENT 1

Sampling Time	Mixed Liquor Temp. °C	Mixed Liquor O_2 Uptake Rate r_r	Mixed Liquor O_2 Uptake Rate k_r	S.S. mg/l	pH
8:00 a.m.	22.5	15.9	11.2	1430	7.7
10:00 a.m.	23.0	15.6	9.9	1580	7.7
12:00 p.m.	22.6	26.6	15.2	1750	7.6
2:00 p.m.	23.0	31.0	19.5	1590	7.7
4:00 p.m.	22.6	24.3	14.6	1660	7.8

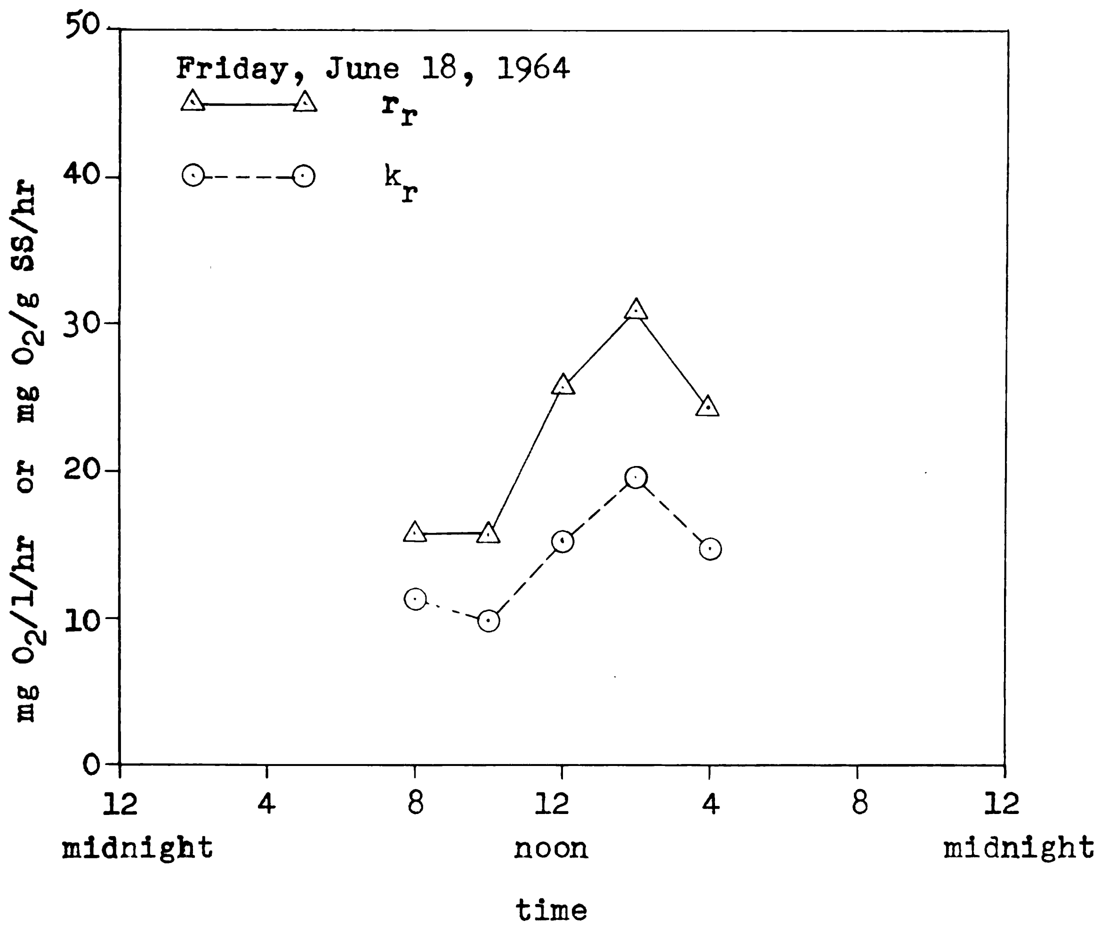


Figure 6. Experiment Number 1.

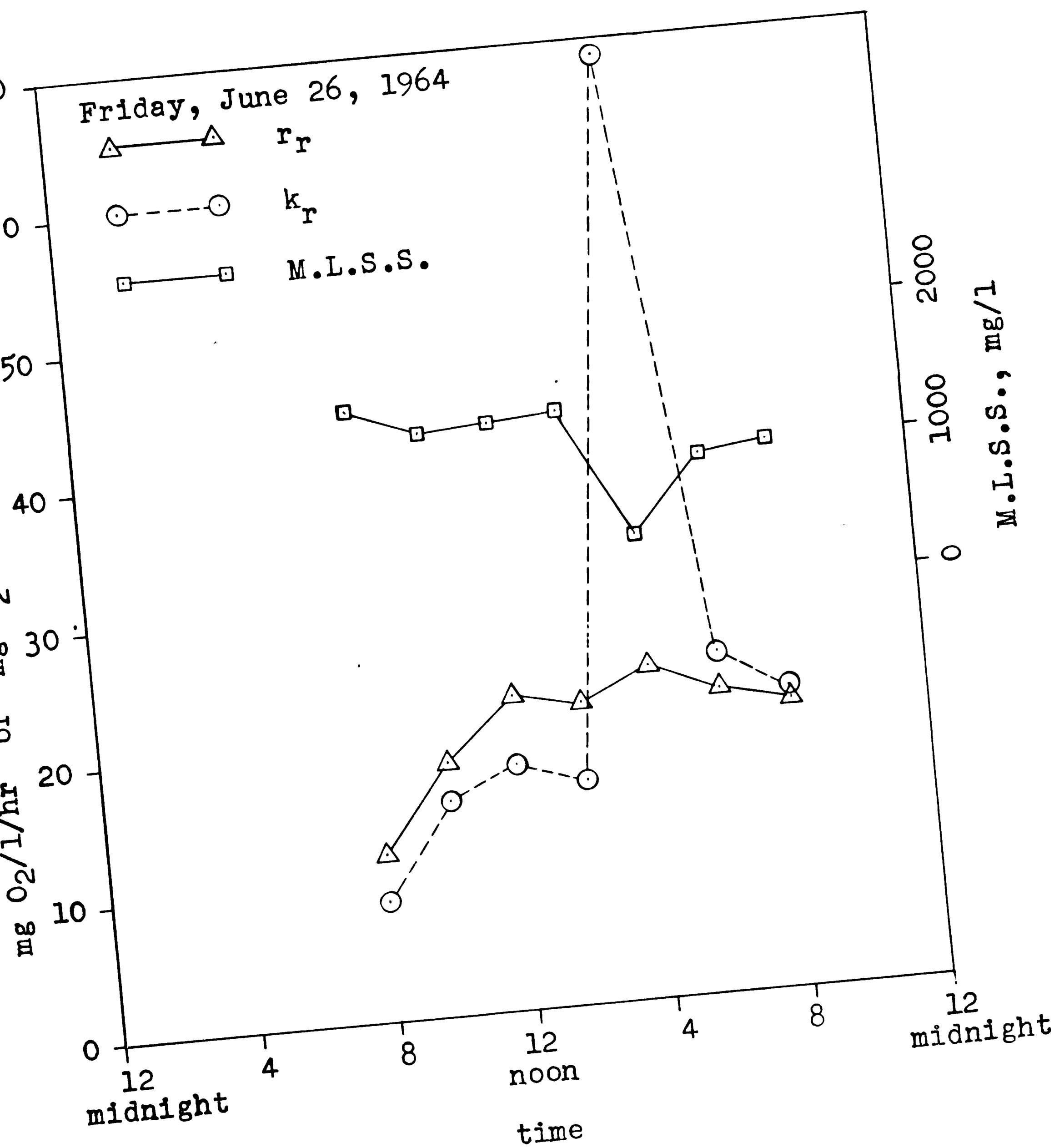


Figure 7. Experiment Number 2.

shown in Figure 7 this caused a sudden decrease in M.L.S.S. and surprisingly a massive increase of the k_r value from 16.4 to 68.5 mgO_2 per gram M.L.S.S. per hour. Accordingly the activity of the mixed liquor at 4:00 PM remained rather high, r_r = 24.1, in spite of the loss of cell material. The BOD at this time was at the maximum for the day which apparently offset the expected decrease in r_r.

TABLE 3

ANALYTICAL DATA FOR EXPERIMENT 2

Sampling Time	Mixed Liquor					Primary Effl.	
	Temp. ^oC	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l	COD mg/l
8:00 a.m.	21.0	12.2	8.6	1410	7.5	96	222
10:00 a.m.	21.8	18.5	15.3	1240	7.4	128	270
12:00 p.m.	22.2	22.8	17.8	1280	7.4	108	298
2:00 p.m.	23.0	21.8	16.4	1320	7.3	-	205
4:00 p.m.	23.0	24.1	68.5	352	7.4	140	-
7:00 p.m.	22.8	22.3	24.7	905	7.5	120	269
8:00 p.m.	22.8	21.2	21.9	969	7.5	126	217

2. Summer Term

Experiment No. 3: Thursday, July 9, 1964

Table 4, Figure 8

This test series was begun at 6:00 PM and ended at 3:00 PM on the following day. The oxygen uptake rate decreased from a maximum, r_r = 22.1 and k_r = 12.6, at 12 midnight. The 2:00 AM and 6:00 AM data indicate that the oxygen utilization rate of the cells, k_r, remained relatively stable from midnight to 6:00 AM. The oxygen uptake rate then continued to rise throughout the morning and afternoon.

The treatment plant was receiving its full summer load as the summer school term had begun several days earlier. The primary treatment facilities were greatly overloaded due to the fact that one of the four primary tanks was closed down for repairs.

Experiment No. 4: Thursday, July 16, 1964

Table 5, Figure 9

This test series began at 6:00 AM and ended at 8:00 PM. The oxygen uptake rate rose steadily throughout the day from a minimum, r_r = 18.5 and k_r = 8.6, at 8:00 AM to a maximum, r_r = 34.3 and k_r = 21.0, at 4:00 PM after which the rates declined. The temperature of the mixed liquor was quite high in the afternoon, average being 24°C. The afternoon oxygen utilization rates in

TABLE 4

ANALYTICAL DATA FOR EXPERIMENT 3

Sampling Time	Mixed Liquor					Primary Effl.	
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l	COD mg/l
6:00 p.m.	22.0	37.7	20.5	1840	7.4	153	272
7:00 p.m.	22.0	43.9	26.0	1685	7.5	135	230
8:00 p.m.	21.5	31.6	19.1	1655	7.4	132	215
10:00 p.m.	21.5	29.4	15.6	1885	7.4	156	310
12:00 a.m.	21.0	22.1	12.6	1765	7.3	132	253
2:00 a.m.	20.6	23.3	13.6	1720	7.4	117	178
6:00 a.m.	20.5	29.0	12.4	2340	7.4	76	132
8:00 a.m.	21.1	31.8	14.8	2145	7.5	96	200
11:00 a.m.	22.0	31.9	19.3	1650	7.5	162	219
1:00 p.m.	23.5	33.7	20.9	1610	7.5	144	334
3:00 p.m.	23.0	36.1	20.6	1745	7.5	159	245

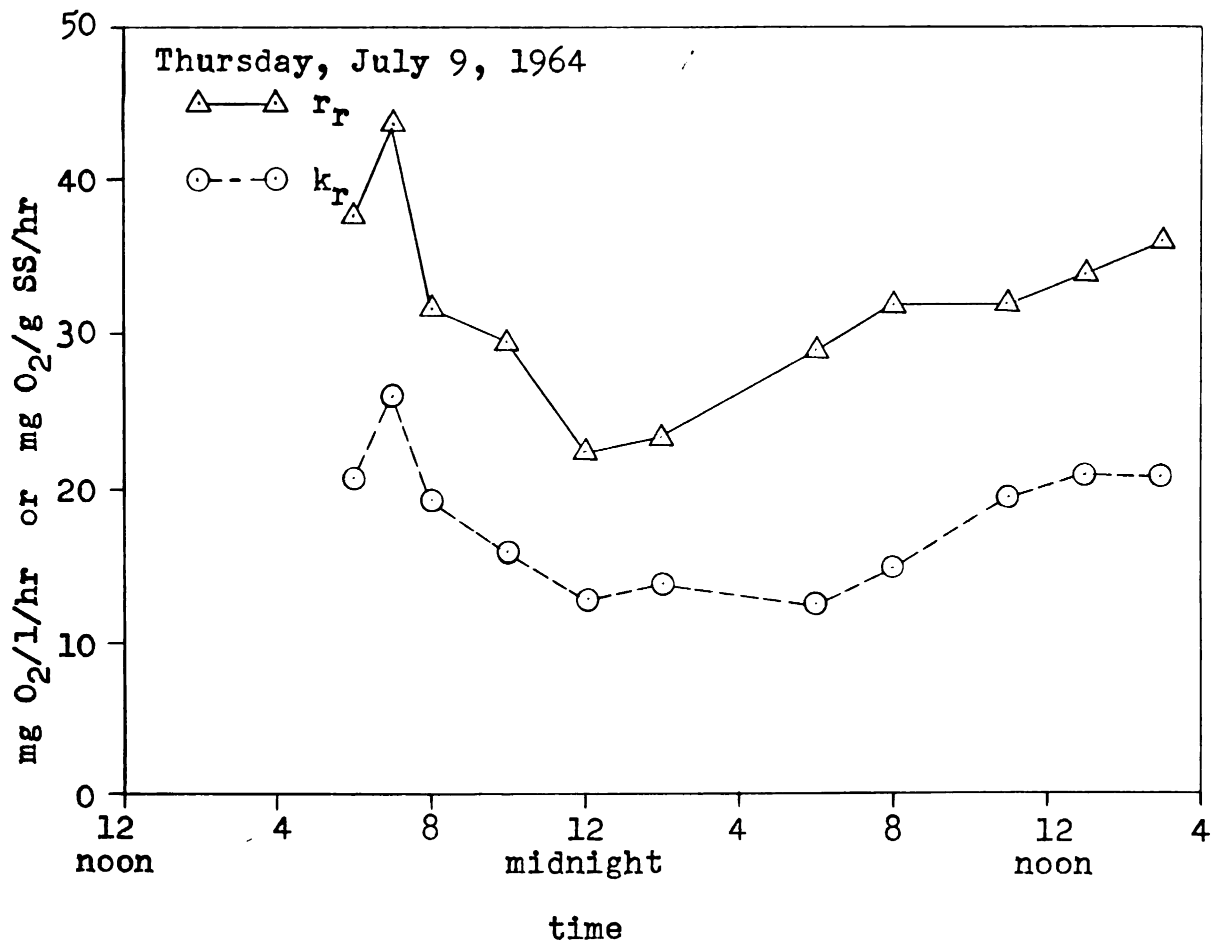


Figure 8. Experiment Number 3.

TABLE 5

ANALYTICAL DATA FOR EXPERIMENT 4

Sampling Time	Mixed Liquor					Primary Effl.	
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l	COD mg/l
6:00 a.m.	20.9	23.4	11.3	2065	7.4	80	136
8:00 a.m.	21.5	18.5	8.6	2160	7.5	68	155
10:00 a.m.	22.5	25.4	13.9	1830	7.5	72	173
12:00 p.m.	23.3	29.3	19.2	1525	7.5	132	198
2:00 p.m.	23.8	31.7	19.9	1590	7.5	122	204
4:00 p.m.	24.3	34.3	21.0	1630	7.3	120	196
6:00 p.m.	24.0	29.9	18.8	1595	7.5	102	186
8:00 p.m.	23.5	28.8	18.1	1585	7.5	120	194

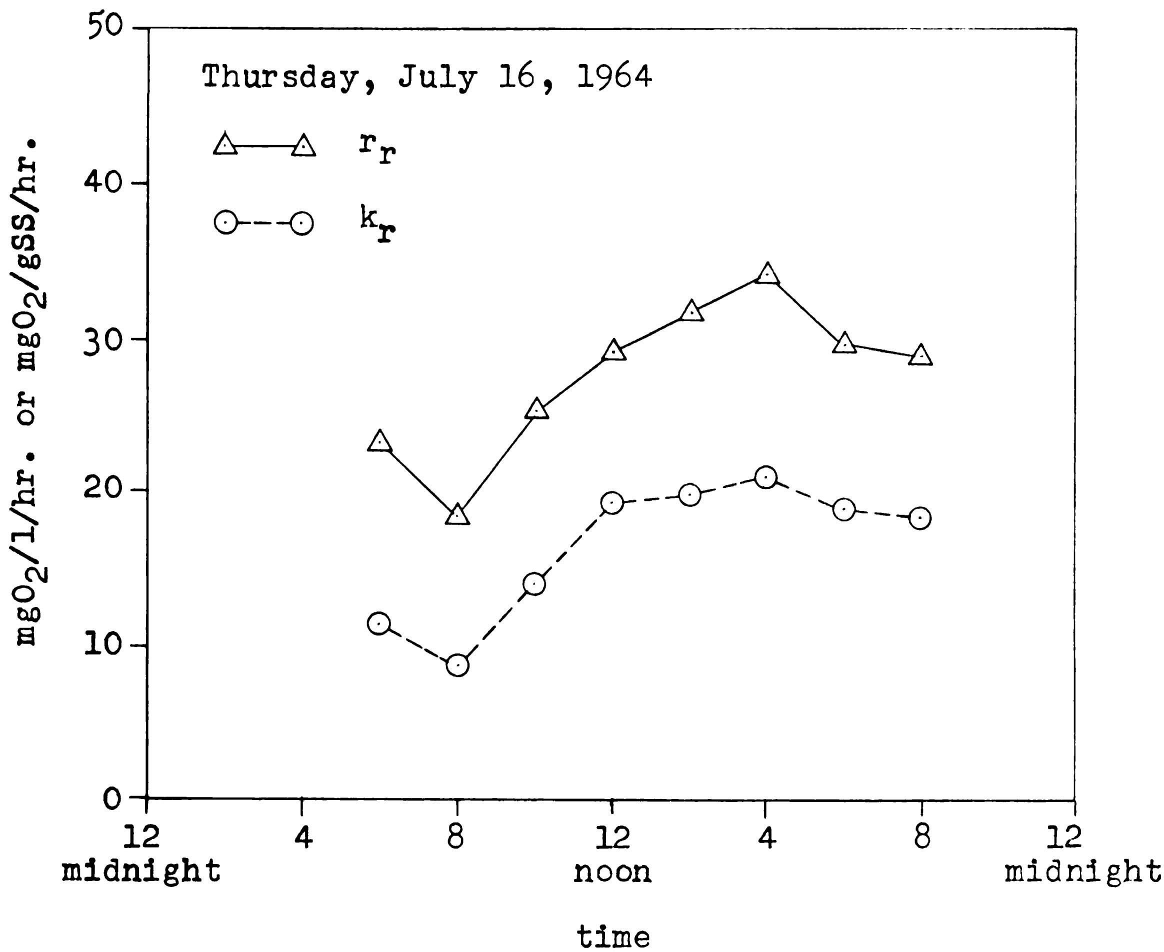


Figure 9. Experiment Number 4.

experiment no. 3 are similar in magnitude to those of experiment 4 but the BOD concentration being applied in experiment no. 3 was higher than in no. 4, an average of 150 as compared to 120 mg/l.

<u>Experiment No. 5</u>: Thursday, July 23, 1964

Table 6, Figure 10

This test series began at 6:00 AM and ended at 8:00 PM. The treatment plant was operating at a reduced sewage flow due to the diversion of the flow of a large sewer main into the Red Cedar River in order to facilitate repair of the sewer main. This diversion took place at a point above the Michigan State University campus and therefore the treatment plant was still receiving all of the Michigan State University flow plus a large portion of the city's flow. The oxygen uptake rate remained stable between 6 and 8:00 AM, $r_r = 15.5$ and $k_r = 13.4$, after which the rate steadily rose until a peak, $r_r = 33.2$ and $k_r = 28.4$, was reached at 2:00 PM; the rate then began to decline.

The COD data of experiments 2 and 3 show little correlation to the primary effluent BOD. This may have been caused by the fact that the COD test samples of experiments 2 and 3 were stored overnight in a small portable electric cooler. The data of experiments 4 and 5 where the samples were not stored overnight do

TABLE 6

ANALYTICAL DATA FOR EXPERIMENT 5

Sampling Time	Mixed Liquor					Primary Effl.	
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l	COD mg/l
6:00 a.m.	23.0	15.9	13.4	1180	7.5	63	118
8:00 a.m.	22.8	15.5	13.4	1155	7.5	78	98
10:00 a.m.	23.2	20.4	15.9	1265	7.6	102	98
12:00 p.m.	23.5	21.0	18.6	1130	7.4	96	110
2:00 p.m.	23.8	33.2	28.4	1170	7.5	156	172
4:00 p.m.	24.0	28.8	22.0	1305	7.4	159	133
6:00 p.m.	24.0	27.7	19.2	1495	7.5	201	180
8:00 p.m.	23.5	30.7	20.8	1470	7.4	144	139

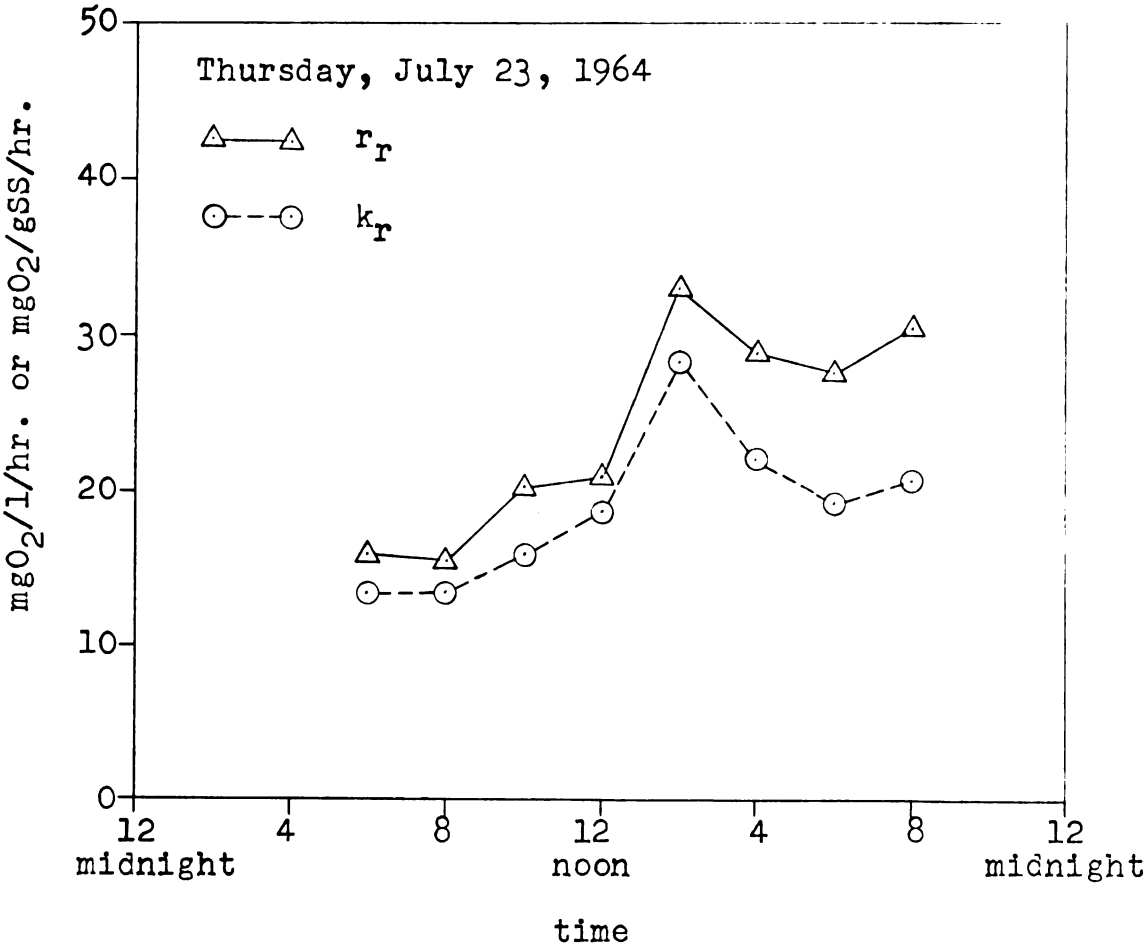


Figure 10. Experiment Number 5.

show some relationship to the BOD for each particular day. Due to these inconsistent results it was decided to discontinue the COD test.

Experiment No. 6: Wednesday, July 29, 1964
Table 7, Figure 11

This test series began at 6:00 AM and ended at 12:00 AM. The activity of the sludge, k_r, remained unusually stable throughout the day and evening. The average temperature during the day was 23°C and 22°C in the evening. The respiration rate, r_r, ranged from 26.9 to 34.2 while k_r ranged only from 14.6 to 16.3, which are quite small ranges. The BOD at 6, 7 and 8:00 AM averaged about 80 mg/l while the BOD from 10:00 AM to 8:00 PM averaged about 140 mg/l excluding the high 2:30 PM BOD of 192 mg/l. Since the activity of the sludge, k_r, remained relatively stable throughout the day, while the BOD ranged from 80 mg/l in the early morning to 140 mg/l in the afternoon, it is assumed that the amount of dissolved BOD probably remained relatively stable throughout the day even though the total BOD varied by 60 mg/l. Since only dissolved BOD is immediately available to the oxidative processes of the cells, this would explain the relative stability of k_r. The respiration rate r_r in turn remained stable because the M.L.S.S. and k_r maintained

$mgO_2/l/hr.$ or $mgO_2/gSS/hr.$

TABLE 7

ANALYTICAL DATA FOR EXPERIMENT 6

Sampling Time	Mixed Liquor					Primary Effl.
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l
6:00 a.m.	23.0	33.8	15.7	2160	7.5	87
7:00 a.m.	22.8	34.2	15.9	2150	7.5	87
8:00 a.m.	22.0	31.4	14.3	2190	7.5	75
10:00 a.m.	23.0	20.8	14.2	2170	7.6	138
12:00 p.m.	23.0	31.2	16.3	1915	7.6	144
2:30 p.m.	23.0	30.1	15.9	1890	7.6	192
4:00 p.m.	23.0	30.9	15.1	2050	7.5	144
6:00 p.m.	23.3	31.2	15.9	1965	7.4	135
8:00 p.m.	22.2	26.9	13.2	2044	7.5	138
10:00 p.m.	22.1	30.0	15.9	1890	7.5	129
12:00 a.m.	22.0	27.4	14.6	1870	7.5	123

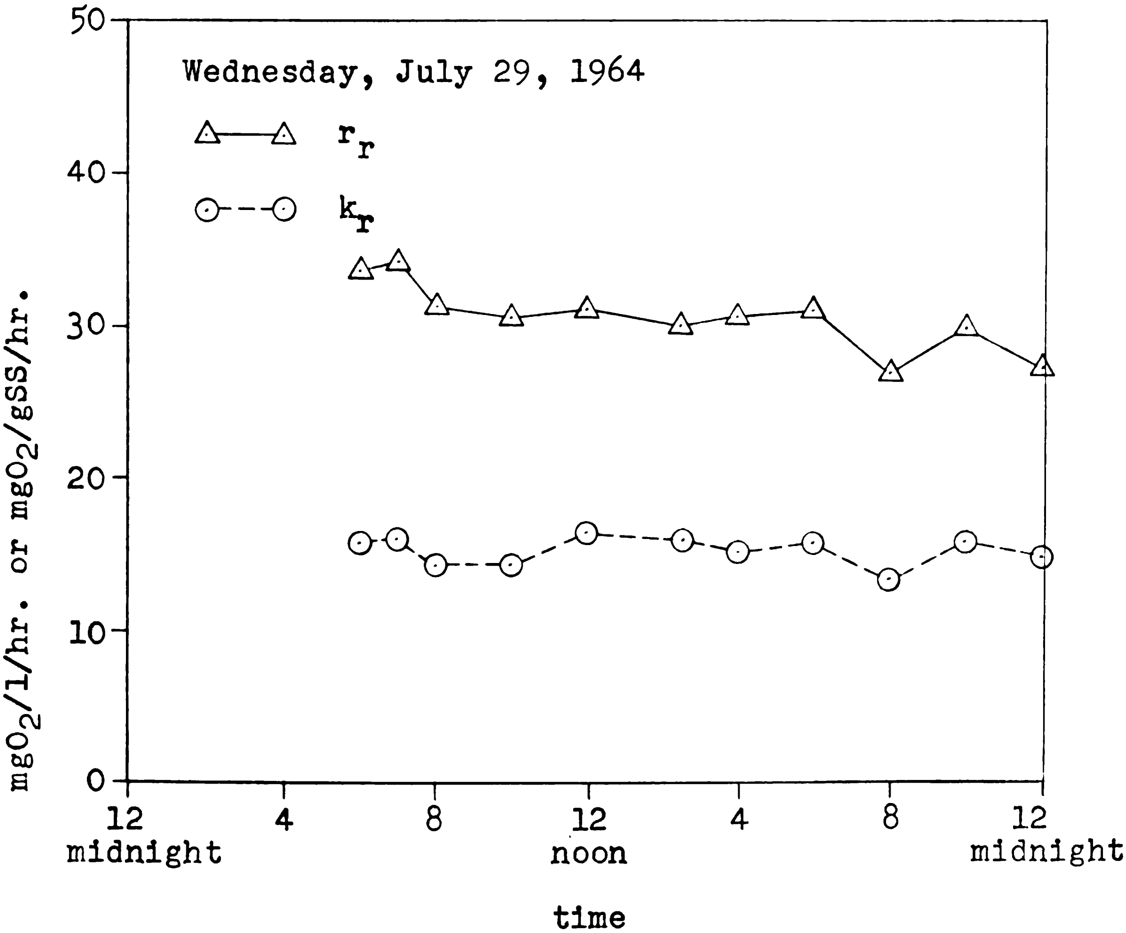


Figure 11. Experiment Number 6.

a steady level.

Experiments No. 7, 8 and 9:

No. 7 - Saturday, August 1, 1964

No. 8 - Sunday, August 2, 1964

No. 9 - Monday, August 3, 1964

Table 8, 9, 10, Figure 12

This weekend survey began at 6:00 AM Saturday and ended at 11:00 PM Monday. On Saturday a definite minimum oxygen uptake rate, r_r = 7.4 and k_r = 4.9, occurred at 8:00 AM after which the activity of the sludge increased steadily until at 4:00 PM a peak, r_r = 16.4 and k_r = 10.4, was reached after which a steady decline in the activity took place during the evening.

On Sunday the minimum oxygen uptake rate occurred from 8 to 10:00 AM, the average r_r and k_r being 11.4 and 6.9 respectively, after which the activity increased steadily until a plateau was reached beginning at 4:00 PM, r_r and k_r ranged from 21.6 to 22.8 and 12.7 to 14.2 respectively over the plateau which was still maintained at 11:00 PM, the last sample for the day.

On Monday the minimum activity occurred from 7:00 to 9:00 AM, average r_r and k_r being 12.4 and 8.2 respectively, after which the activity suddenly jumped up to r_r = 23.8 and k_r = 14.9 and then slowly rose until

TABLE 8

ANALYTICAL DATA FOR EXPERIMENT 7

Sampling Time	Mixed Liquor Temp °C	Mixed Liquor O_2 Uptake Rate r_r	Mixed Liquor O_2 Uptake Rate k_r	Mixed Liquor S.S. mg/l	Mixed Liquor pH	Primary Effl. BOD mg/l
6:00 a.m.	21.0	12.3	7.3	1685	7.4	84
7:00 a.m.	20.8	9.5	5.7	1675	7.4	54
8:00 a.m.	20.8	7.4	4.9	1530	7.4	75
10:00 a.m.	21.2	8.5	5.5	1555	7.5	111
12:00 p.m.	21.8	10.6	7.0	1520	7.3	93
2:00 p.m.	22.5	12.5	7.9	1575	7.4	99
4:00 p.m.	22.8	16.4	10.4	1525	7.5	126
6:00 p.m.	23.4	14.6	9.5	1555	7.5	93
8:00 p.m.	23.2	14.4	9.0	1595	7.5	96

TABLE 9

ANALYTICAL DATA FOR EXPERIMENT 8

Sampling Time	Mixed Liquor Temp °C	Mixed Liquor O_2 Uptake Rate r_r	Mixed Liquor O_2 Uptake Rate k_r	Mixed Liquor S.S. mg/l	Mixed Liquor pH	Primary Effl. BOD mg/l
6:00 a.m.	22.3	13.0	7.3	1776	7.4	45
8:00 a.m.	22.5	11.5	7.0	1640	7.4	51
10:00 a.m.	23.2	11.3	6.8	1660	7.4	45
12:00 p.m.	23.5	12.6	7.8	1620	7.5	60
1:30 p.m.	24.2	15.6	9.1	1710	7.5	75
4:00 p.m.	24.5	22.3	13.4	1670	7.5	111
5:00 p.m.	24.0	21.7	13.8	1570	7.6	-
7:00 p.m.	24.5	22.1	13.4	1648	7.4	93
9:00 p.m.	24.0	22.8	12.7	1795	7.4	87
11:00 p.m.	23.8	21.6	14.2	1520	7.5	-

TABLE 10

ANALYTICAL DATA FOR EXPERIMENT 9

Sampling Time	Mixed Liquor					Primary Effl.
	Temp ^oC	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l
7:00 a.m.	23.8	12.6	8.3	1495	7.3	69
9:00 a.m.	23.8	12.2	8.2	1490	7.4	60
11:00 a.m.	24.0	23.8	14.9	1600	7.4	126
1:00 p.m.	24.2	23.2	14.6	1592	7.3	117
3:00 p.m.	24.8	23.4	14.4	1625	7.5	120
5:00 p.m.	25.0	24.5	15.1	1620	7.5	123
7:00 p.m.	24.8	24.5	15.0	1632	7.5	117
9:00 p.m.	24.8	26.7	16.2	1645	7.5	129
11:00 p.m.	24.0	24.5	15.6	1565	7.4	117

an apparent peak was reached at 9:00 p.m., $r_r = 26.7$ and $k_r = 16.2$

The oxygen uptake rate data indicate that the load on the aeration system was very light on Saturday, a little heavier on Sunday, and still heavier on Monday. A comparison of the BOD data on Saturday and Sunday with respect to the respective oxygen consumption rates reveals that the organic load on Sunday was more easily oxidized than on Saturday because higher oxygen uptake rates were experienced Sunday, even though the primary effluent BOD values were very similar to those observed on Saturday. The BOD data for Monday show a definite plateau corresponding

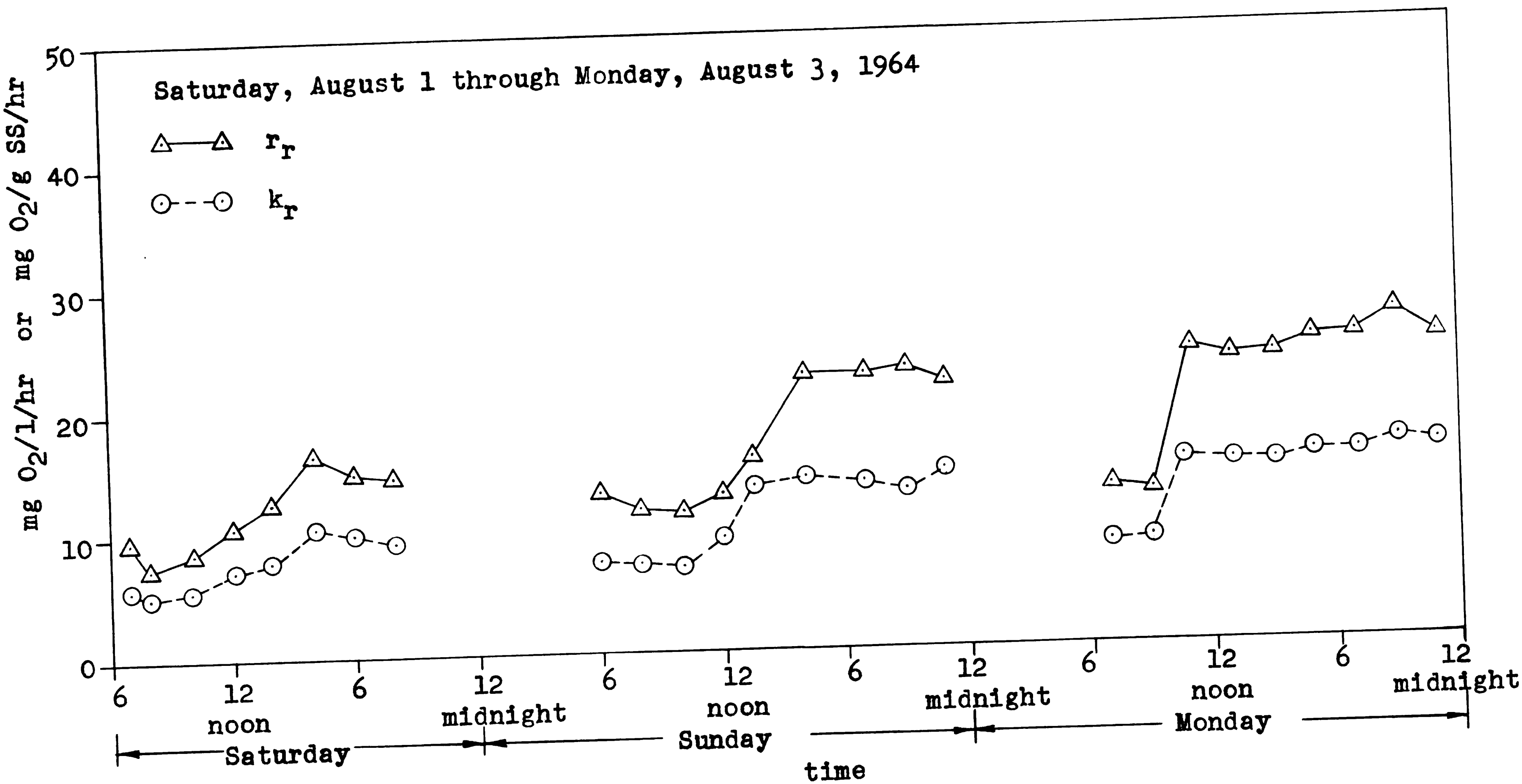


Figure 12. Experiments Number 7, 8, and 9.

to the oxygen uptake rate plateau; therefore the characteristics of the organic load must have remained relatively constant.

The temperature ranged from 23.8°C to 25.0°C which is quite high for this treatment plant.

<u>Experiment No. 10</u>: Wednesday, August 5, 1964
Table 11, Figure 13

This test series began at 7:00 AM and ended at 11:00 PM. The activity of the sludge increased from a minimum, r_r = 17.6 and k_r = 9.9, at 9:00 AM throughout the morning and afternoon until reaching a peak at 3:00 PM, r_r = 31.5 and k_r = 18.9. Between 5:00 PM and 11:00 PM both r_r and k_r remained at plateaus fluctuating about r_r = 26.0 and k_r = 15.0 respectively. The average mixed liquor temperature was 23.0°C.

<u>Experiment No. 11</u>: Wednesday, August 12, 1964
Table 12, Figure 14

This test series began at 7:00 AM and ended at 11:00 PM. The activity of the sludge increased throughout the morning and afternoon from a minimum at 9:00 AM of r_r = 12.5 and k_r = 6.2, to a peak at 3:00 PM of r_r = 25.0 and k_r = 11.9. After 3:00 PM the respiration rate per gram cell material remained at a plateau fluctuating about k_r = 11.0. This plateau remained even at 11:00 PM,

TABLE 11

ANALYTICAL DATA FOR EXPERIMENT 10

Sampling Time	Mixed Liquor					Primary Effl.
	Temp. ^{o}C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l
7:00 a.m.	23.5	20.5	11.3	1815	7.4	84
9:00 a.m.	22.2	17.6	9.9	1776	7.5	111
11:00 a.m.	23.0	21.6	13.8	1560	7.6	117
1:00 p.m.	23.2	23.5	14.3	1645	7.6	105
3:00 p.m.	23.0	31.5	18.9	1667	7.6	129
5:00 p.m.	23.2	25.5	15.4	1660	7.5	126
7:00 p.m.	23.0	27.5	16.4	1680	7.6	111
9:00 p.m.	23.0	24.2	13.5	1790	7.6	108
11:00 p.m.	22.0	26.6	15.0	1776	7.5	117

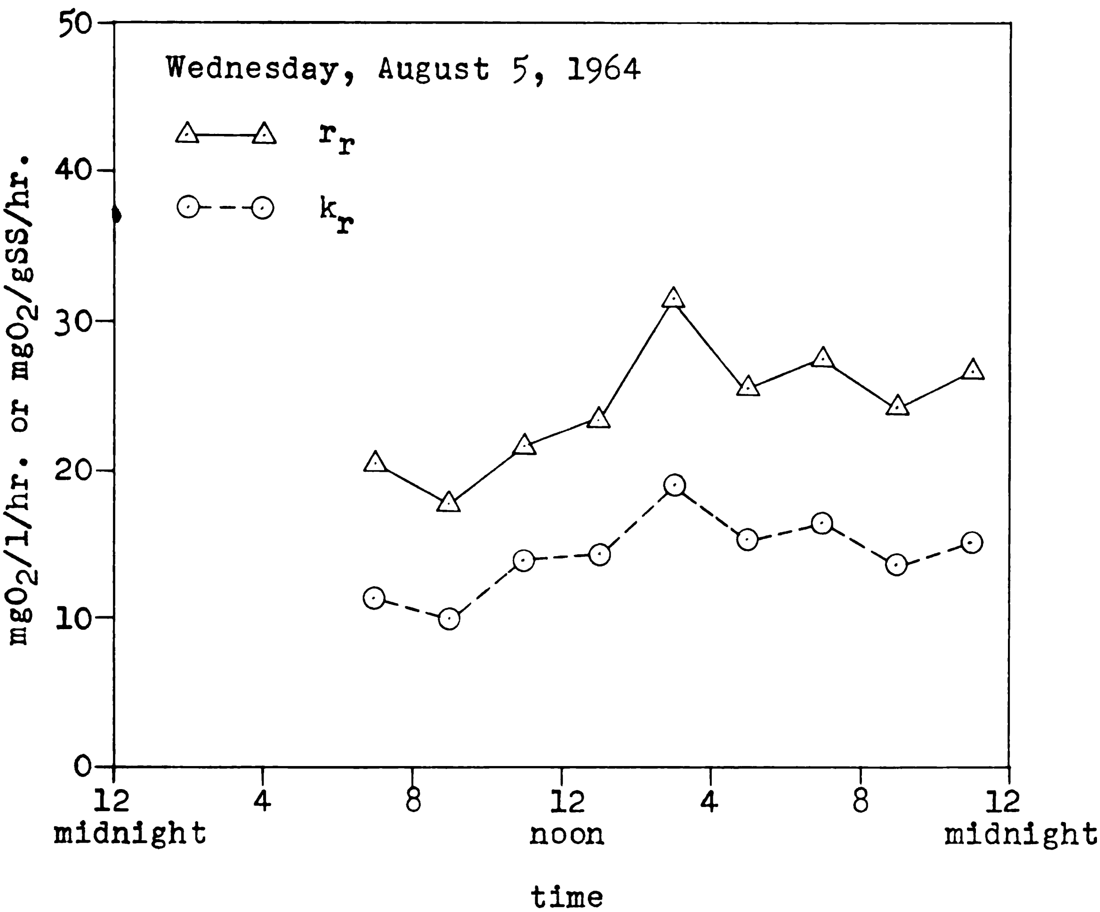


Figure 13. Experiment Number 10.

the time of the last sample. The magnitude of the plateau value of k_r (11.0) is rather low for the BOD loading being applied, from 138 to 150 mg/l. For example, in experiment no. 10 a plateau was observed for which the average k_r was 15.0 mgO_2/gSS/hr. at a BOD of 120 mg/l. Also the average temperature of 20.5°C was lower than the usual 22 to 24°C and this could be partially responsible for the lower activity.

Experiment No. 12 and 13:

No. 12 - Sunday, August 16, 1964

No. 13 - Monday, August 17, 1964

Table 13, 14, Figure 15

This weekend survey began at 7:00 AM Sunday and ended at 1:00 AM Tuesday. On Sunday the minimum activity of the sludge occurred at 11:00 AM, r_r = 8.7 and k_r = 5.1, after which the activity steadily rose until reaching a peak at 5:00 PM, r_r = 17.8 and k_r = 8.9. The activity of the sludge, k_r, remained steady between 7:00 PM and 1:00 AM within a range of 7.9 to 8.0, and the BOD of the primary effluent ranged only from 96 to 108 mgO_2/l. The steady cellular respiration rate and primary effluent BOD indicate that the plant was receiving a relatively constant type of waste for this period. At 2:00 AM the BOD load and the activity were beginning to decrease.

TABLE 13

ANALYTICAL DATA FOR EXPERIMENT 12

Sampling Time	Mixed Liquor					Primary Effl.
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l
7:00 a.m.	19.8	11.1	6.4	1750	7.4	96
9:00 a.m.	19.2	10.2	5.7	1776	7.5	54
11:00 a.m.	19.8	8.7	5.1	1708	7.5	66
1:00 p.m.	20.8	10.2	6.2	1744	7.5	-
3:00 p.m.	21.2	13.3	7.0	1892	7.5	102
5:00 p.m.	21.0	17.8	8.9	2004	7.4	96
7:00 p.m.	21.0	16.6	8.0	2072	7.5	99
9:00 p.m.	20.8	15.6	7.9	1974	7.5	105
11:00 p.m.	20.8	15.2	7.8	1948	7.4	108
1:00 a.m.	20.5	15.0	7.9	1900	7.4	87
2:00 a.m.	20.0	14.0	6.8	1896	7.4	-

TABLE 14

ANALYTICAL DATA FOR EXPERIMENT 13

Sampling Time	Mixed Liquor					Primary Effl.
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l
7:00 a.m.	20.2	8.8	5.1	1720	7.6	54
9:00 a.m.	20.2	9.1	5.4	1690	7.5	66
11:00 a.m.	21.2	13.5	7.2	1875	7.6	66
1:00 p.m.	21.8	19.9	10.7	1865	7.6	-
3:00 p.m.	21.5	23.8	12.1	1965	7.4	126
5:00 p.m.	21.8	27.6	13.7	2020	7.5	141
7:00 p.m.	21.5	23.1	12.1	1915	7.5	132
9:00 p.m.	21.0	27.2	13.1	2072	7.5	141
11:00 p.m.	21.0	26.2	12.7	2060	7.2	120
1:00 p.m.	20.8	26.5	13.4	1980	7.4	117

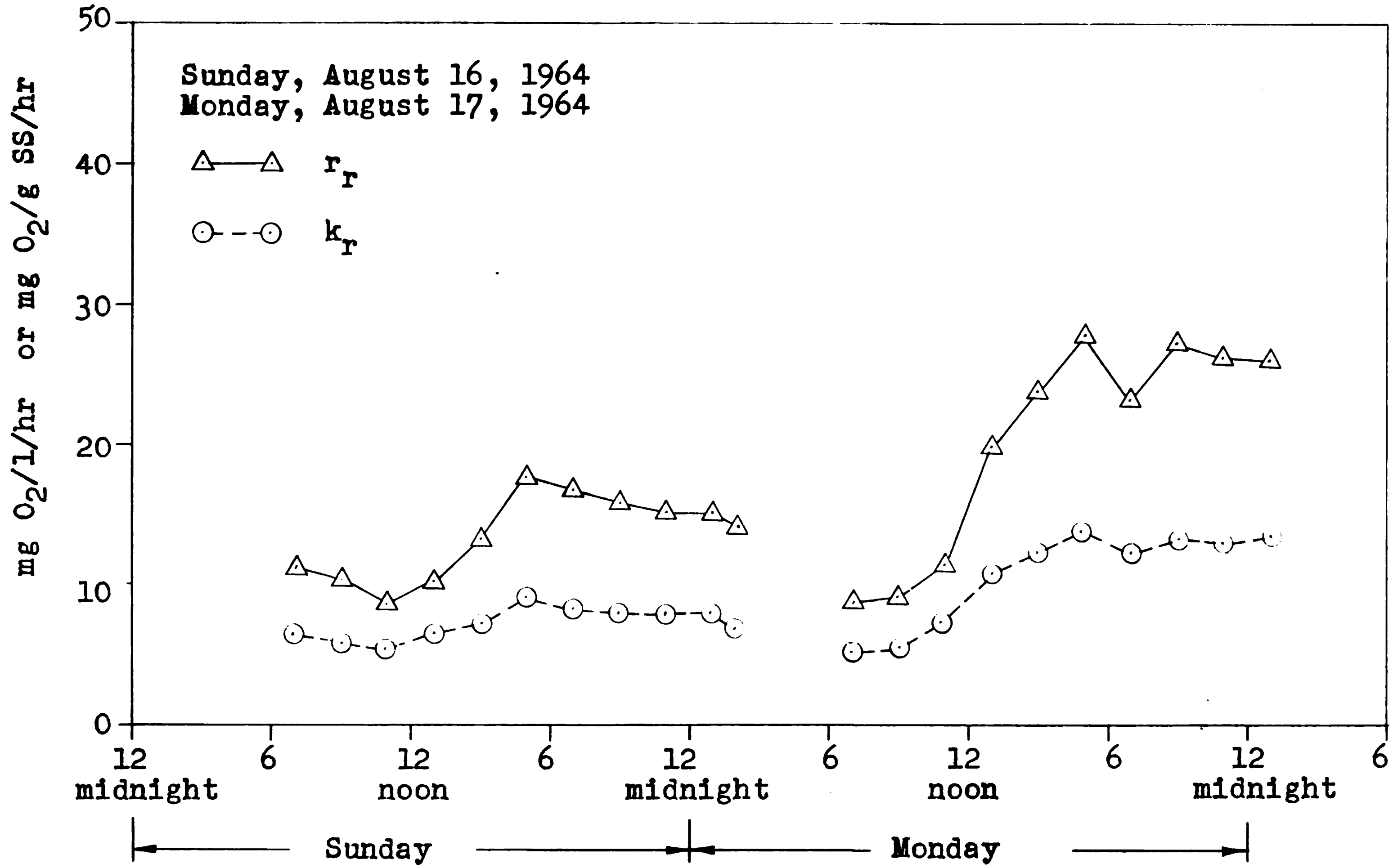


Figure 15. Experiments Number 12 and 13.

On Monday the situation was changed. The minimum activity, r_r = 9.1 and k_r = 5.4, occurred at 9:00 AM, 2 hours sooner. The maximum activity occurred again at 5:00 PM but was much larger, r_r = 27.6 and k_r = 13.1. The activity of the sludge, k_r, also remained steady between 7:00 PM and 11:00 AM but at a higher range. The k_r range was from 12.1 to 13.4. During this period, the primary effluent BOD ranged from 117 to 141 mgO_2/l. In general the shape of the plots of the sludge activity, k_r, (see Figure 15) for this weekend survey are very similar to the corresponding plots for the previous weekend survey (see Figure 12). Essentially the minimum and maximum oxygen uptake rates occurred at the same time, and the same leveling off at a high plateau during the evening was observed, although the numerical values differed for reasons attributable to differences in the temperature and the BOD load characteristics.

<u>Experiment No. 14 and 15</u>:

No. 14 - Friday, August 21, 1964

No. 15 - Saturday, August 22, 1964

Table 15, 16, Figure 16

This weekend test survey began at 7:00 AM Friday and ended at 7:00 PM Saturday. The activity of the sludge, k_r, for these two consecutive days showed only small fluctuations over each respective day. On Friday k_r

TABLE 15

ANALYTICAL DATA FOR EXPERIMENT 14

Sampling Time	Mixed Liquor					Primary Effl.
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l
7:00 a.m.	19.0	20.1	9.3	2144	7.3	60
9:00 a.m.	18.8	14.1	7.3	1925	7.2	36
11:00 a.m.	19.0	15.0	7.2	2090	7.2	51
1:00 p.m.	19.8	18.1	8.3	2175	7.4	66
3:00 p.m.	20.5	20.9	9.3	2250	7.4	99
5:00 p.m.	21.0	16.4	7.4	2210	7.4	93
7:00 p.m.	21.0	19.0	9.2	2064	7.4	93
9:00 p.m.	21.5	20.9	10.0	2092	7.3	108
11:00 p.m.	21.5	21.9	10.1	2188	7.4	87
1:00 a.m.	21.2	20.9	9.9	2108	7.2	87
2:30 a.m.	21.0	20.6	9.3	2200	7.3	72

TABLE 16

ANALYTICAL DATA FOR EXPERIMENT 15

Sampling Time	Mixed Liquor					Primary Effl.
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l
7:00 a.m.	20.8	14.3	7.5	1895	7.4	72
9:00 a.m.	20.8	15.0	8.0	1885	7.4	54
11:00 a.m.	21.0	14.1	7.5	1865	7.5	57
1:00 p.m.	21.2	14.9	8.0	1868	7.4	75
3:00 p.m.	21.0	17.2	8.7	1964	7.4	84
5:00 p.m.	21.0	13.8	6.6	2076	7.4	42
7:00 p.m.	20.8	13.2	6.4	2092	7.4	45

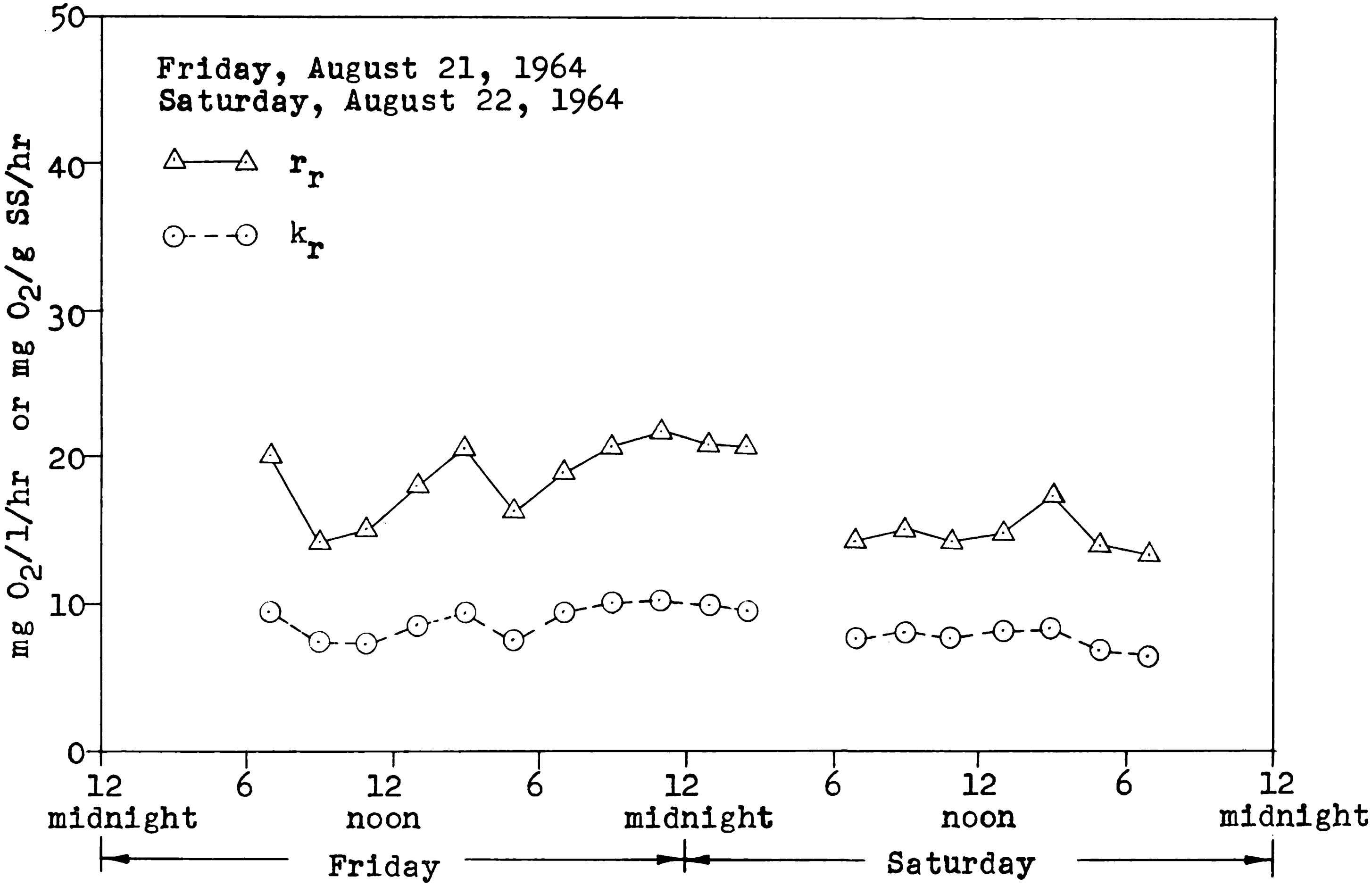


Figure 16. Experiments Number 14 and 15.

ranged from 7.2 to 10.1 while on Saturday k_r ranged from 6.4 to 8.7. For each day r_r fluctuated widely at times due mainly to fluctuations in the M.L.S.S. concentration. On Friday the minimum activity occurred from 9:00 to 11:00 AM, the average r_r and k_r being 14.5 and 7.3 respectively, after which the activity reached a plateau beginning at 3:00 PM and lasting through 1:00 AM, for which k_r varied only slightly about the 10.0 mg/gSS/hr. level.

On Saturday the activity of the sludge, k_r, remained at a level of about 8.0 from 7:00 AM until 3:00 PM after which k_r began to decrease.

3. Between Summer and Fall Terms

The week of Monday, August 31 to Friday, September 4, 1964 was final examination week at Michigan State University. During the week some students began leaving the campus and on Friday the campus began closing down. Nearly all of the students had left by the following Monday.

With the decrease in student population the mixed liquor at the treatment plant responded to the lower BOD load by turning from the dark grey-black color which predominated during the summer term to a light brown color. The mixed liquor was now being sufficiently aerated. The treatment plant data for the time between terms, September 7 to September 28, indicate that the average primary effluent BOD concentration was 100 mg/l which is considerably less than the average summer BOD concentration of about 130 mg/l.

No oxygen uptake rate measurements were made during the time of low load, but measurements were taken during the final exam week as shown in Tables 17, 18 and 19 and in Figures 17, 18 and 19.

Experiments No. 16, 17 and 18:

No. 16 - Monday, August 31, 1964

No. 17 - Wednesday, September 2, 1964

No. 18 - Friday, September 4, 1964

Tables 17, 18, 19, Figures 17, 18, 19

These three surveys have been grouped together because the conditions at the treatment plant over the week were essentially stable. The average temperature of the mixed liquor for each of the surveys was about 22.0°C and the primary effluent BOD loading was similar for each day although the corresponding oxygen consumption rates differ.

On Monday the oxygen uptake rate increased continusouly all day. The range of r_r and k_r being 8.4 to 24.6 and 5.1 to 14.4 respectively. The rate of increase was much slower in the afternoon and evening than in the morning. The primary effluent BOD did not show any steady rise but fluctuated between 120 and 140 mgO_2/l. Since the activity of the sludge k_r, is assumed to be proportional to the amount of dissolved BOD (see Figure 31), the increased activity indicates that the percentage of dissolved BOD increased.

The Wednesday survey began at 7:00 AM and ended at 11:00 PM. On Wednesday the oxygen uptake rate increased, from r_r = 18.0 and k_r =11.5, until reaching a peak at 3:30 PM, r_r = 42.1 and k_r = 23.4. The rates then declined to a steady level, r_r and k_r being 35.0 and 19.0 respectively, from 5 to 11:00 PM.

The Friday survey began at 7:00 AM and ended at 11:00 PM. The oxygen uptake rates increased from a minimum at 9:00 AM, r_r = 21.4 and k_r = 15.3, to an average r_r and k_r of 35.0 and 20.0 respectively. These values were maintained from 1:00 PM through to the last sample at 11:00 PM.

TABLE 17

ANALYTICAL DATA FOR EXPERIMENT 16

Sampling Time	Mixed Liquor					Primary Effl.
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l
7:00 a.m.	21.0	9.1	5.6	1644	7.3	72
9:00 a.m.	20.8	8.4	5.1	1656	7.4	80
11:00 a.m.	21.5	9.7	6.2	1560	7.5	124
1:00 p.m.	21.5	13.2	8.5	1560	7.5	122
3:00 p.m.	22.0	20.7	12.6	1636	7.5	140
5:00 p.m.	21.8	19.9	11.3	1760	7.5	140
7:00 p.m.	22.0	22.7	13.6	1664	7.5	130
9:00 p.m.	21.8	23.5	13.4	1752	7.4	124
11:00 p.m.	21.5	25.1	14.1	1776	7.4	114
1:00 a.m.	21.2	24.6	14.4	1704	7.5	124

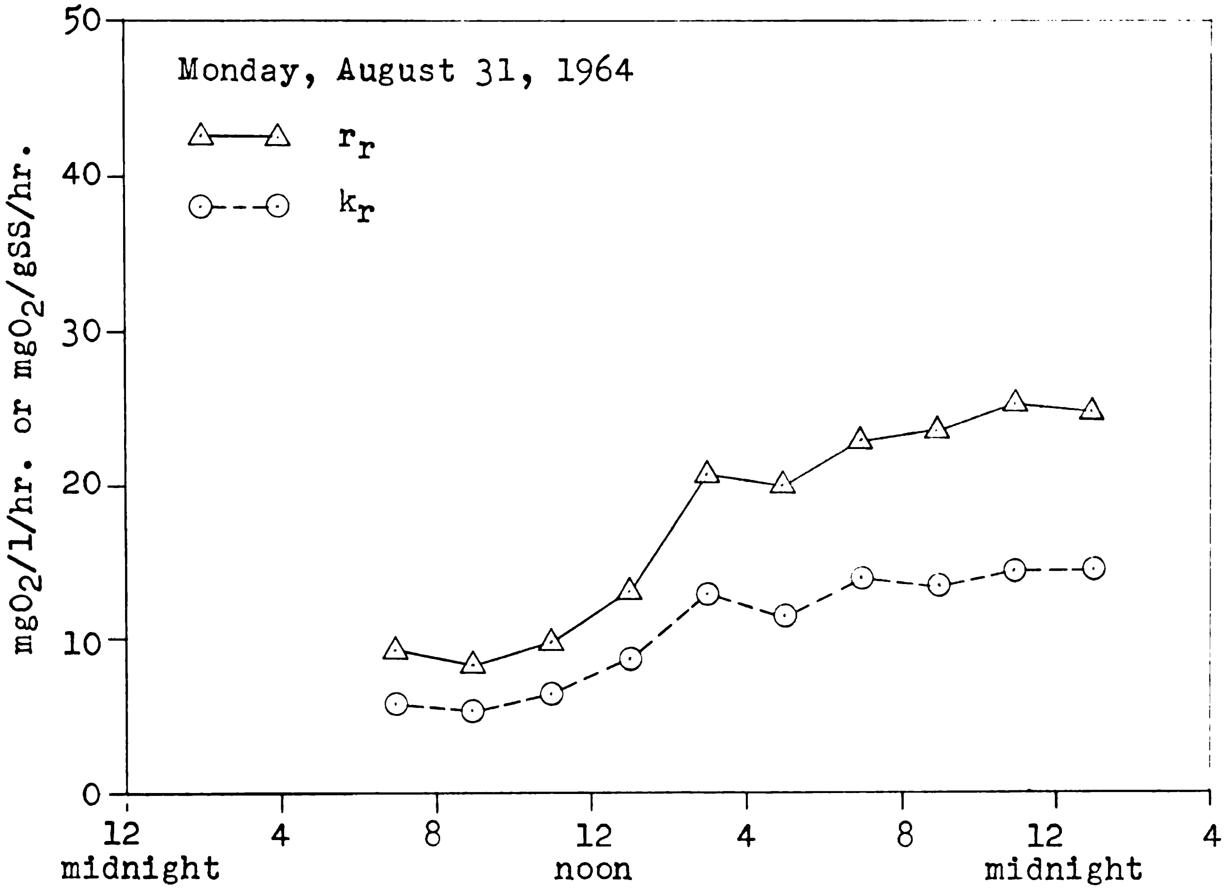


Figure 17. Experiment Number 16.

TABLE 18

ANALYTICAL DATA FOR EXPERIMENT 17

Sampling Time	Mixed Liquor					Primary Effl.
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	pH	BOD mg/l
7:00 a.m.	20.2	18.0	11.5	1564	7.4	82
9:00 a.m.	20.5	20.4	13.4	1516	7.5	114
11:00 a.m.	21.0	28.3	16.7	1692	7.4	134
1:00 p.m.	21.2	30.8	17.7	1740	7.5	142
3:30 p.m.	21.8	42.1	23.4	1796	7.5	136
5:00 p.m.	21.8	34.1	18.9	1804	7.6	-
7:00 p.m.	21.8	35.5	18.5	1920	7.5	-
9:00 p.m.	22.0	35.5	19.7	1804	7.3	-
11:00 p.m.	21.5	34.0	18.7	1816	7.4	-

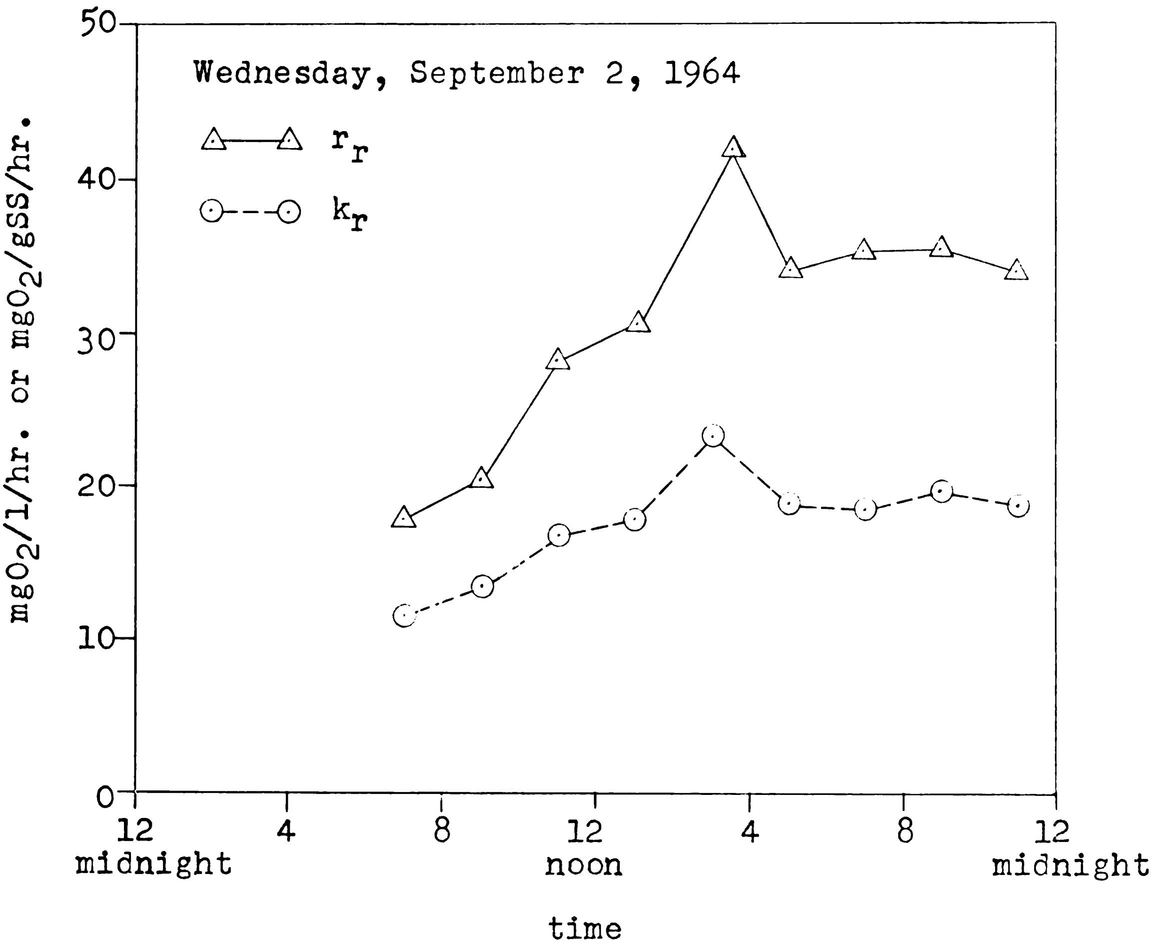


Figure 18. Experiment Number 17.

TABLE 19

ANALYTICAL DATA FOR EXPERIMENT 18

Sampling Time	Mixed Liquor Temp. °C	Mixed Liquor O_2 Uptake Rate r_r	Mixed Liquor O_2 Uptake Rate k_r	Mixed Liquor S.S. mg/l	Mixed Liquor VSS %	Mixed Liquor pH	Primary Effl. BOD mg/l
7:00 a.m.	21.8	22.9	15.7	1464	71.5	7.4	94
9:00 a.m.	21.8	21.4	15.3	1392	74.1	7.4	82
11:00 a.m.	22.2	24.6	18.2	1356	73.9	7.4	114
1:00 p.m.	22.5	34.7	20.7	1676	70.1	7.4	-
3:30 p.m.	23.0	35.2	19.2	1832	71.1	7.5	-
5:00 p.m.	22.0	31.6	18.7	1692	72.9	7.5	138
7:00 p.m.	22.5	35.3	20.6	1712	75.0	7.5	122
9:00 p.m.	22.0	34.9	20.8	1676	74.2	7.5	-
11:00 p.m.	21.8	33.1	19.8	1668	-	-	-

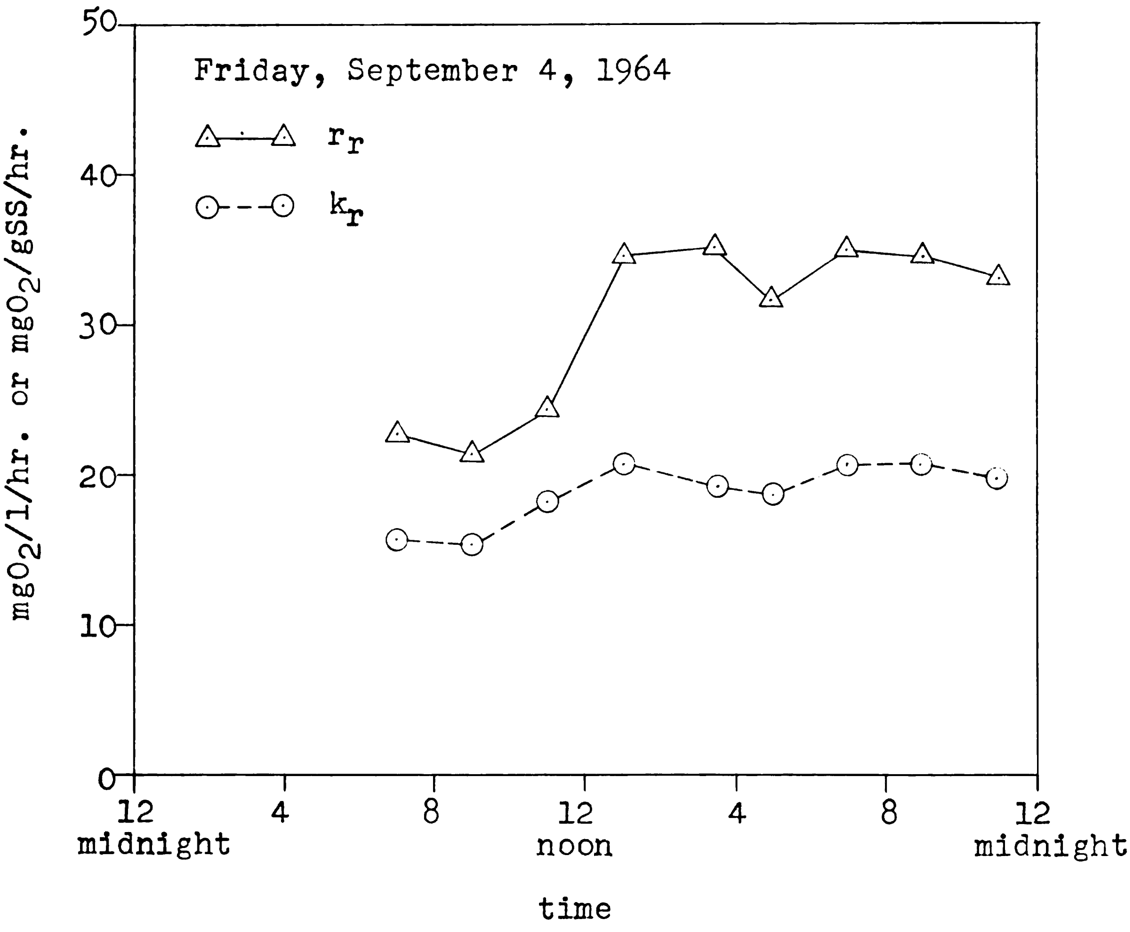


Figure 19. Experiment Number 18.

4. <u>Fall Term</u>

On September 28, 1964 registration began for the fall term at Michigan State University. The sudden influx of students to the MSU campus resulted in heavy overloading of the aeration system and a rapid deterioration of the mixed liquor. Since no dissolved oxygen could be maintained in the aeration tanks, the mixed liquor turned from the brown color which it had obtained during the time between terms to a dark grey-black color. The average primary effluent BOD concentration increased from 130 mg/l to about 200 mg/l as shown in Table 28. As a result of this greatly increased BOD concentration the specific oxygen consumption rates, k_r, increased to about double the summer term rates as shown in Tables 27 and 28.

<u>Experiment No. 19</u>: Tuesday, September 29, 1964
Table 20, Figure 20

This test series began at 7:00 AM Tuesday and ended at 8:00 AM Wednesday. The oxygen uptake rates were minimum at 9:00 AM, r_r = 21.1 and k_r = 12.2. The values then increased less rapidly until at 3:00 PM, r_r and k_r were 45.9 and 23.2 respectively, at which time the primary effluent BOD measured 182 mg/l. The 7:00 and 11:00 PM data show marked increases in both the BOD and oxygen uptake rates. At 7:00 PM r_r and k_r were 72.0, and 37.9 respectively while the BOD amounted to 216 mg/l. At 11:00 PM r_r and k_r were 87.5 and 17.8 respectively at a

TABLE 20

ANALYTICAL DATA FOR EXPERIMENT 19

Sampling Time	Mixed Liquor					Primary Effl.			
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	VSS %	S.S. mg/l	BOD mg/l	Dis. mg/l	BOD %
7:00 a.m.	16.5	22.5	12.3	1835	65.6	72	81	50	61.8
9:00 a.m.	16.5	21.1	12.2	1735	69.5	104	147	72	49.0
11:00 a.m.	19.0	38.9	21.4	1820	67.3	110	192	74	38.3
12:30 p.m.	19.8	38.7	20.9	1845	71.4	-	-	-	-
3:00 p.m.	20.0	47.1	22.7	2080	87.0	88	183	84	46.0
5:00 p.m.	20.5	45.9	23.2	1975	78.6	182	174	86	49.5
7:00 p.m.	20.5	72.0	37.9	1900	76.8	216	210	106	50.5
9:00 p.m.	19.8	-	-	1920	70.1	180	228	110	48.3
11:00 p.m.	20.0	85.5	24.2	1932	66.1	192	243	114	46.5
8:00 a.m.	19.0	27.0	17.8	1522	67.4	-	-	-	-

TABLE 21

ANALYTICAL DATA FOR EXPERIMENT 20

Sampling Time	Mixed Liquor					Primary Effl.			
	Temp. °C	O_2 Uptake Rate r_r	k_r	S.S. mg/l	VSS %	S.S. mg/l	BOD mg/l	Dis. mg/l	BOD %
7:00 a.m.	18.0	31.5	184.	1716	72.8	88	105	-	-
11:00 a.m.	19.0	71.0	40.0	1776	72.5	104	222	157	70.6
1:00 p.m.	20.0	75.2	37.8	1966	73.1	90	186	105	57.0
3:00 p.m.	20.0	84.6	41.2	2056	70.4	98	174	130	74.8
5:00 p.m.	21.0	90.0	48.8	1848	77.1	204	234	154	65.9
7:00 p.m.	20.5	82.0	42.5	1922	76.8	186	174	115	66.2
9:00 p.m.	20.5	77.6	40.3	1926	75.8	192	180	142	78.8
12:00 a.m.	20.2	78.0	40.5	1922	-	250	216	109	50.4
2:00 a.m.	19.5	73.2	39.7	1840	-	-	-	-	-
7:00 a.m.	19.2	52.7	38.8	1380	-	-	-	-	-

mg O_2/l/hr or mg O_2/g SS/hr

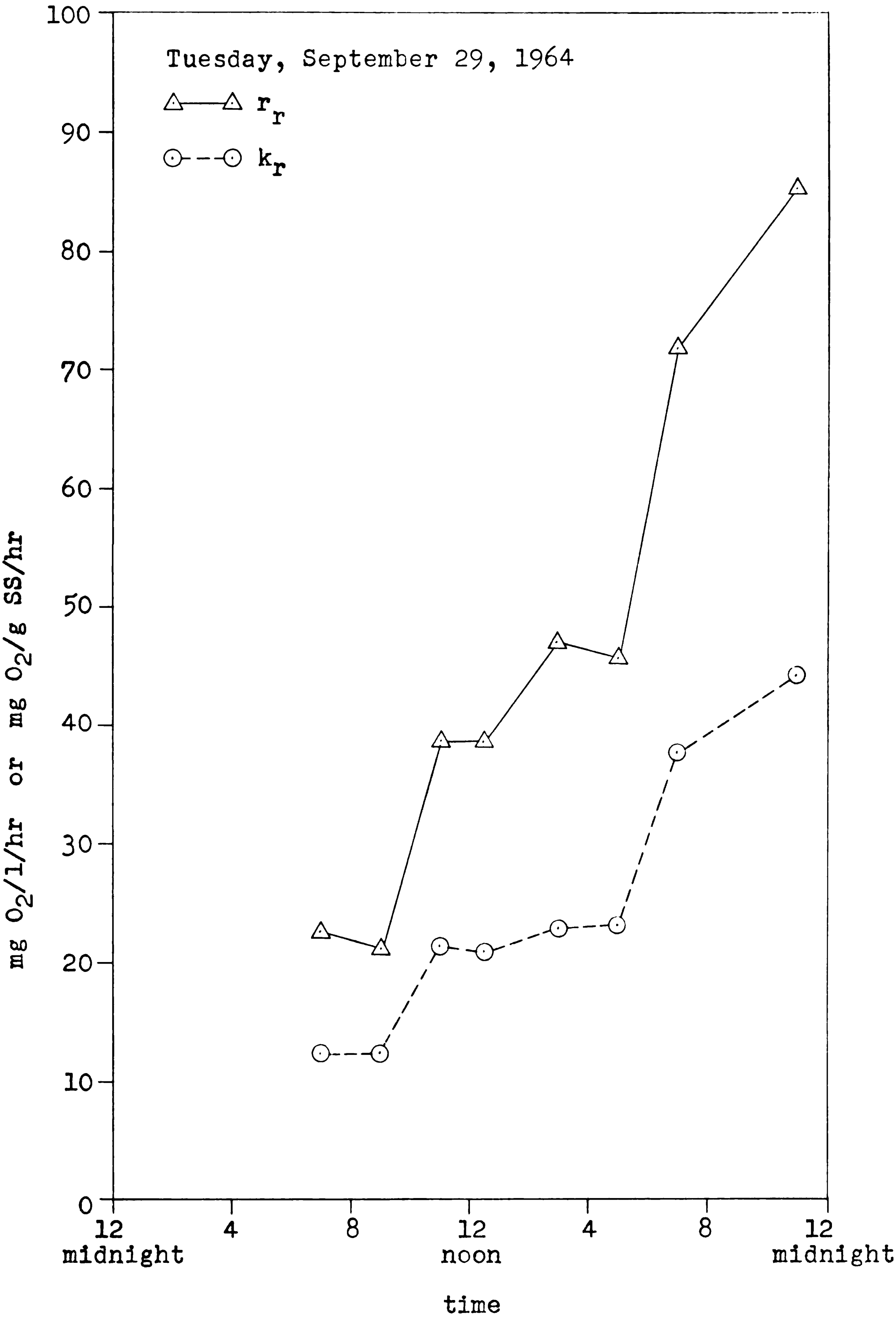


Figure 20. Experiment Number 19.

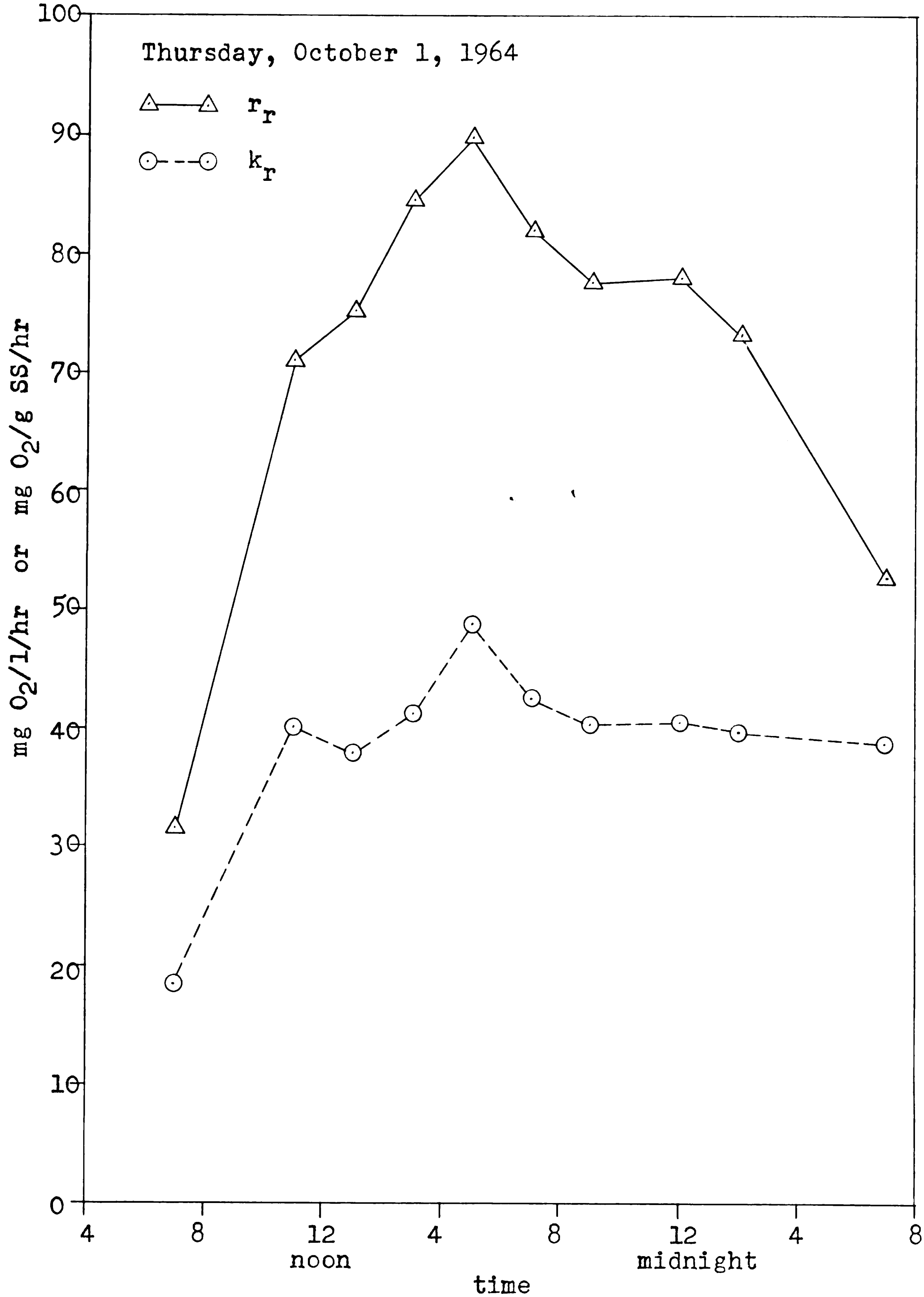


Figure 21. Experiment Number 20.

BOD of 243 mg/l. The 8:00 AM data on Wednesday indicate that sometime after 11:00 PM Tuesday the consumption rates decreased to the much lower level of $r_r = 27.0$ and $k_r = 17.8$.

Experiment No. 20: Friday, October 1, 1964
Table 21, Figure 21

This test series began at 7:00 AM Friday and ended at 7:00 AM Saturday. The data of this series again show the marked effect of the BOD concentration upon the oxygen consumption rate. The oxygen uptake rate rose steeply throughout the morning and afternoon, from $r_r = 31.5$ and $k_r = 18.5$ at 7:00 AM, to a peak of $r_r = 90.0$ and $k_r = 48.8$ at 5:00 PM. Then from 9:00 PM until 2:00 AM the activity of the sludge remained steady at about $k_r = 40.0$. The value of k_r at 7:00 AM Saturday was 38.8 which is rather high.

5. Peak Oxygen Uptake Rate

The purpose of these two test series was to observe the variation of the 3-4 PM sample's oxygen uptake rate over a week. It had been observed in many of the daily surveys that the peak oxygen demand occurred between 2:00 and 5:00 PM.

Test Series No. 1

From Monday, August 31 to Sunday, September 6 the mixed liquor oxygen uptake rate and suspended solids were determined at 3:30 PM each day. These data are still representative of the summer term since few of the students had left before Friday night. However, nearly all of the students left on either Saturday or Sunday. See Table 22 and Figures 22 and 23 for the data of the survey.

Test Series No. 2

From Monday, September 29 to Sunday, October 3 the mixed liquor oxygen uptake rate and suspended solids were determined at 3:30 PM each day. The data reflect very markedly the arrival of the main Michigan State University student body for fall term registration which began on Monday. The oxygen uptake rates are very much higher than for series number 1 which was run when only about one third of the main student body was present on campus attending summer school. See Table 23 and Figures 22 and 23 for the data of the survey.

Both test series show that the activity of the sludge, measured by k_r, increases steadily from Monday to a maximum on Wednesday after which the activity decreases. On the basis of these two test series it can be said that the heaviest demand on the aeration system of the treatment plant occurs at mid-week, Wednesday.

TABLE 22

PEAK OXYGEN UPTAKE RATE SERIES NO. 1

Monday, August 31, to Sunday, September 6, 1964

Day	Sampling Time	Mixed Liquor O_2 Uptake Rate r_r mg/l/hr.	k_r mg/gSS/hr.
Monday	3:30 p.m.	20.7	12.6
Tuesday	3:30 p.m.	32.5	18.3
Wednesday	3:30 p.m.	42.1	23.4
Thursday	3:30 p.m.	37.2	21.7
Friday	3:30 p.m.	35.2	19.2
Saturday	3:30 p.m.	21.5	15.1
Sunday	3:30 p.m.	13.3	11.1

TABLE 23

PEAK OXYGEN UPTAKE RATE SERIES NO. 1

Monday, September 28, to Sunday, October 3, 1964

Day	Sampling Time	Mixed Liquor O_2 Uptake Rate r_r mg/l/hr.	k_r mg/gSS/hr.
Monday	3:00 p.m.	36.3	20.2
Tuesday	3:00 p.m.	47.1	22.7
Wednesday	3:00 p.m.	88.5	50.6
Thursday	3:00 p.m.	84.6	41.2
Friday	3:00 p.m.	85.2	47.4
Saturday	-	-	-
Sunday	3:00 p.m.	47.0	28.5

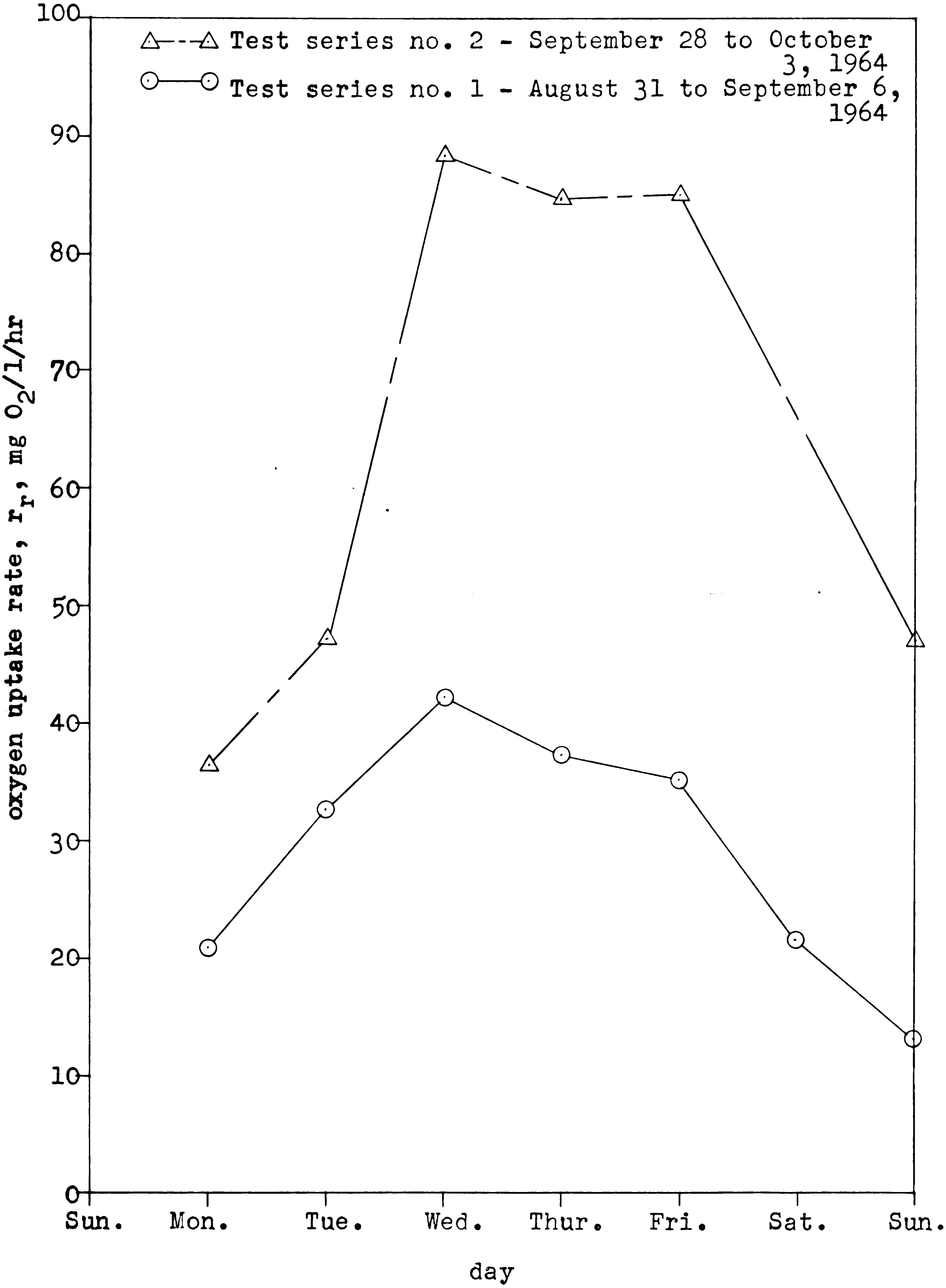


Figure 22. **Peak Oxygen Demand,** r_r, **Over a Week.**

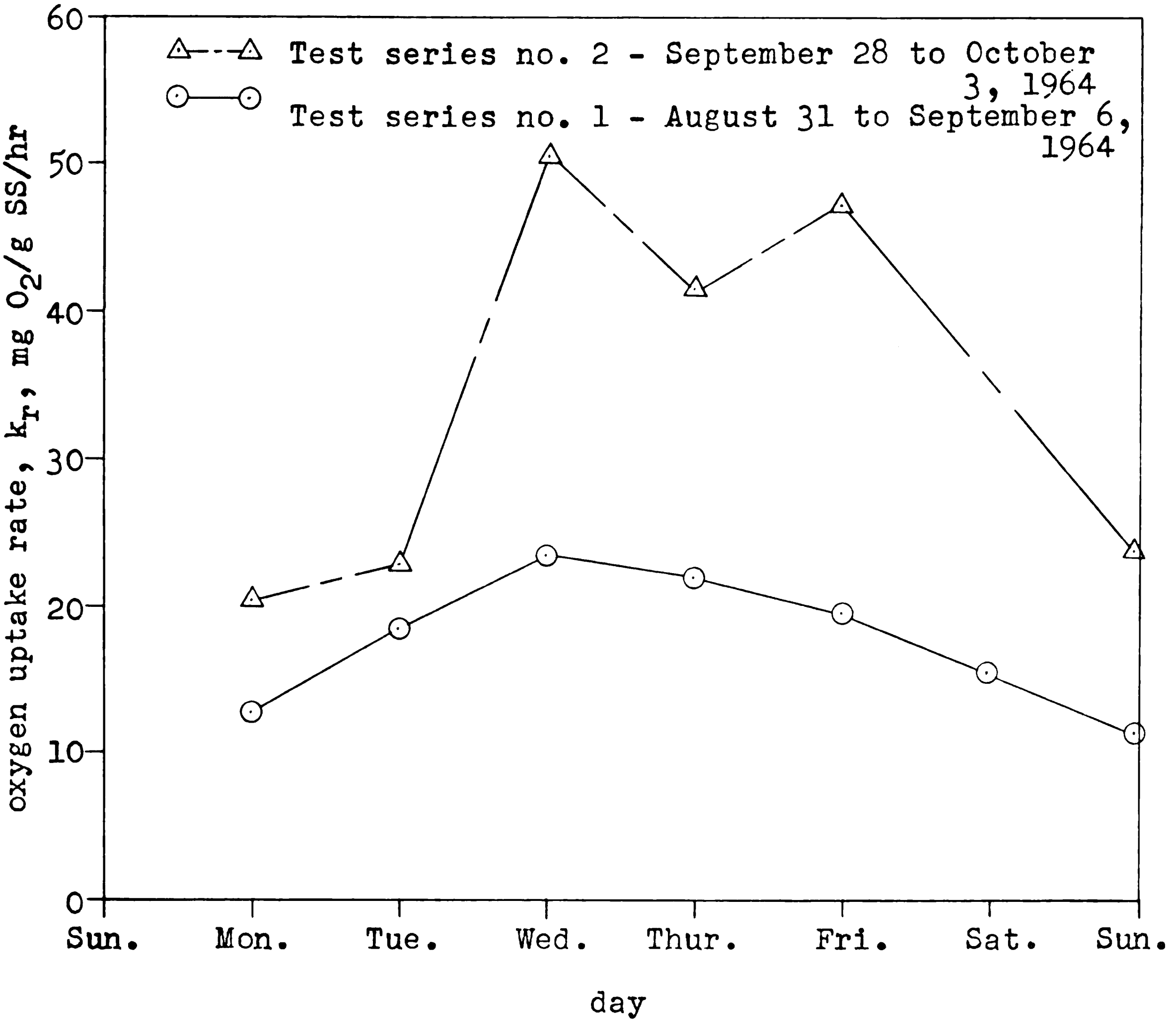


Figure 23. Peak Oxygen Demand, k_r, Over a Week.

6. Determination of the Oxygen Transfer Coefficient, K_La, for the Treatment Plant's Aeration Equipment

The theory of oxygen transfer to a liquid body has been discussed quite thoroughly by Eckenfelder and O'Connor (21). The rate of molecular diffusion of a dissolving gas into a liquid is a function of the characteristics of the gas and the liquid, the temperature, the concentration gradient, and the cross-sectional area through which diffusion occurs. The rate of oxygen transfer is given by: $dc/dt = K_La\ (C_s - C)$ where K_La is the "oxygen transfer coefficient" which is a function of the interfacial area, volume of the liquid, and other physical and chemical variables characteristic of the system, and $C_s - C$ is the dissolved oxygen gradient.

Eckenfelder and O'Connor (21) modified the above equation for application in the steady-state aeration of an activated sludge system by introducing the term r_r:

$$dc/dt = K_La\ (C_s - C) - r_r \qquad (1)$$

in which r_r = oxygen uptake rate in milligram oxygen consumed per liter per hour. Under steady-state dc/dt = 0 and the equation becomes

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

This relation is very useful for analyzing and operating an aeration system. By measuring the D.O. in the mixed liquor tank, C, and determining the oxygen uptake rate r_r at the same time, the oxygen transfer coefficient for the aeration system can be evaluated from the slope of a plot of D.O. versus r_r. The relationship is linear as is shown by rearranging the equation:

$$r_r = K_L a \ (C_s - C) \qquad (3)$$

$$= K_L a \ C_s - K_L a \ C$$

$$\text{then } C = C_s - \frac{1}{K_L a} \ r_r \qquad (4)$$

Equation 4 can be compared to the straightline y = a - bx where:

$y = C$

$a = C_S$, the ordinate intercept

$b = 1/K_L a$, the slope

$x = r_r$

Therefore, assuming steady-state, and by determining C and r_r, the transfer coefficient $K_L a$ can be evaluated from the slope.

The measurements of C and r_r shown in Table 23 and in Figure 24 were taken over a two day period during the Christmas holidays. The students had left the MSU campus thereby reducing the load on the treatment plant. Under the reduced loading, the aeration system was adequate to maintain several parts per million D.O. in the mixed liquor, otherwise this survey would not have been feasible. The temperature of the mixed liquor varied from 14^{o} to $15^{o}C$ which is allowable since a $1^{o}C$ difference will not effect K_La significantly. In agreement with data given by Eckenfelder and O'Connor (21) the D.O. saturation limit, $C_s = 8.7$ mg/l, was taken as 90 per cent of the saturation value given in Standard Methods at $15^{o}C$. This value was used as a fixed point on the ordinate when locating the line through the data. The value of the oxygen transfer coefficient determined from the graph is $K_La = 2.63$ per hour. Thus, for every unit (1 mgO_2/l) of concentration gradient, $C_s - C = 8.7 - C$, 2.63 milligrams oxygen per liter per hour are transferred to the mixed liquor. Thus, the capacity of the aeration system is very low since the maximum oxygen uptake rate, r_r, which can be satisfied while still maintaining a D.O. of 1 mg/l is only $7.7\ (2.63) = 20.3$ $mgO_2/l/hr$. A value of $r_r = 20.3$ is very low indeed. The daily test series during the summer and fall have all shown that r_r greatly exceeds 20.3 most of the day, with the exception of weekends where r_r is not greater than 20.3 for the majority of the day.

TABLE 24

ANALYTICAL DATA FOR THE DETERMINATION OF THE OXYGEN TRANSFER COEFFICIENT

Temp (^{o}C)	Mixed Liquor D.O. mgO_2/l	Oxygen Uptake Rate r_r $mgO_2/l/hr.$
15	0.89	20.7
14.5	1.3	19.5
14	1.8	15.1
15	2.2	15.9
15	2.2	14.9
15	2.9	14.4
15	3.3	15.0
15	3.6	13.5
14.5	4.3	12.0
14.5	4.6	11.2
14	5.2	11.4

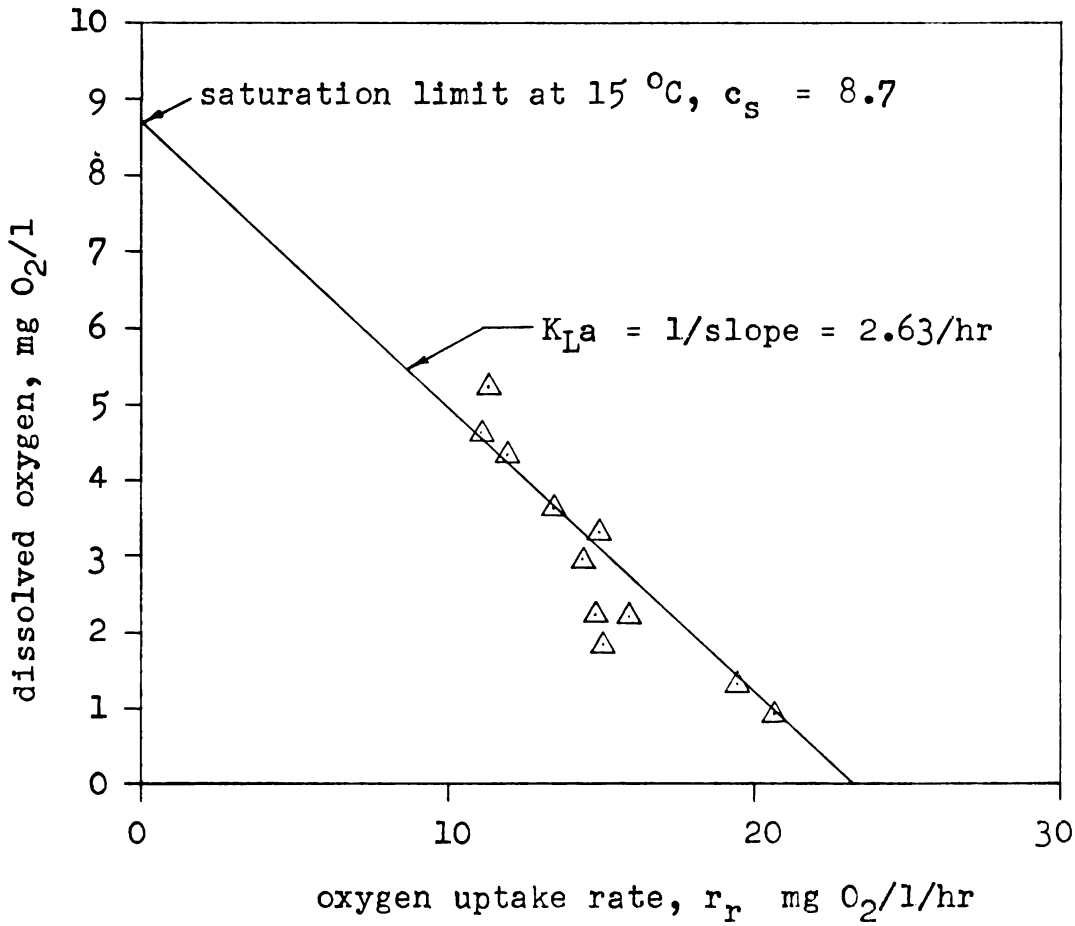


Figure 24. Determination of the Oxygen Transfer Coefficient, K_La.

B. Other Investigations

1. Temperature Effect

Identical mixed liquor batches were prepared by mixing aerated return sludge with a primary effluent sample using the proportions of 1 to 1.5 respectively. This procedure allowed each sample to be treated individually without any error due to aging of one sample while the oxygen uptake rate of another was being observed. Three temperature controlled water baths were available. The baths were first set at 15^{o}, 20^{o} and $30^{o}C$. Then the 15^{o} and $30^{o}C$ baths were cooled to 10^{o} and $25^{o}C$ respectively. Each sample was placed in its respective water bath and aerated at a high rate in order to obtain an adequately high D.O., preferably 6 to 7 mg/l, for the observation of the oxygen depletion rate over time. During the aeration the sample was stirred by means of a submersible Bronwill Mag-Jet magnetic stirrer with a teflon coated stirring bar. After 15 minutes of aeration the sample was assumed to be in equilibrium with the temperature of the water bath. The D.O. depletion was followed by means of the polarographic oxygen electrode.

As demonstrated in Table 24 and in Figure 25 the data show a straightline relationship, when a semilogarithmic plot is made of k_r versus temperature. The slope of the line is $0.0323/^{o}C$. The equation of the slope is:

$$\log k_2 - \log k_1 = 0.0323\ (t_2 - t_1) \qquad (1)$$

then

$$k_2 = k_1\ 10^{0.0323\ (t_2 - t_1)} \qquad (2)$$

This is in agreement with data published by Eckenfelder (21), Wuhrman (22) and Phelp's (23). The slopes reported by these authors as given by Eckenfelder and O'Connor (21) were 0.0368, 0.0315 and 0.0273/°C respectively.

TABLE 25

EFFECT OF TEMPERATURE ON RESPIRATION RATE

Temp. °C	Sludge to Primary Effluent Ratio	Contact time minutes	Mixed Liquor O_2 Uptake Rate r_r mg/l/hr.	k_r mg/gSS/hr
10	1:1.5	15	11.8	5.4
15	1:1.5	15	17.8	8.1
20	1:1.5	15	28.6	13.0
25	1:1.5	25	30.3	13.8
30	1:1.5	15	50.0	22.7

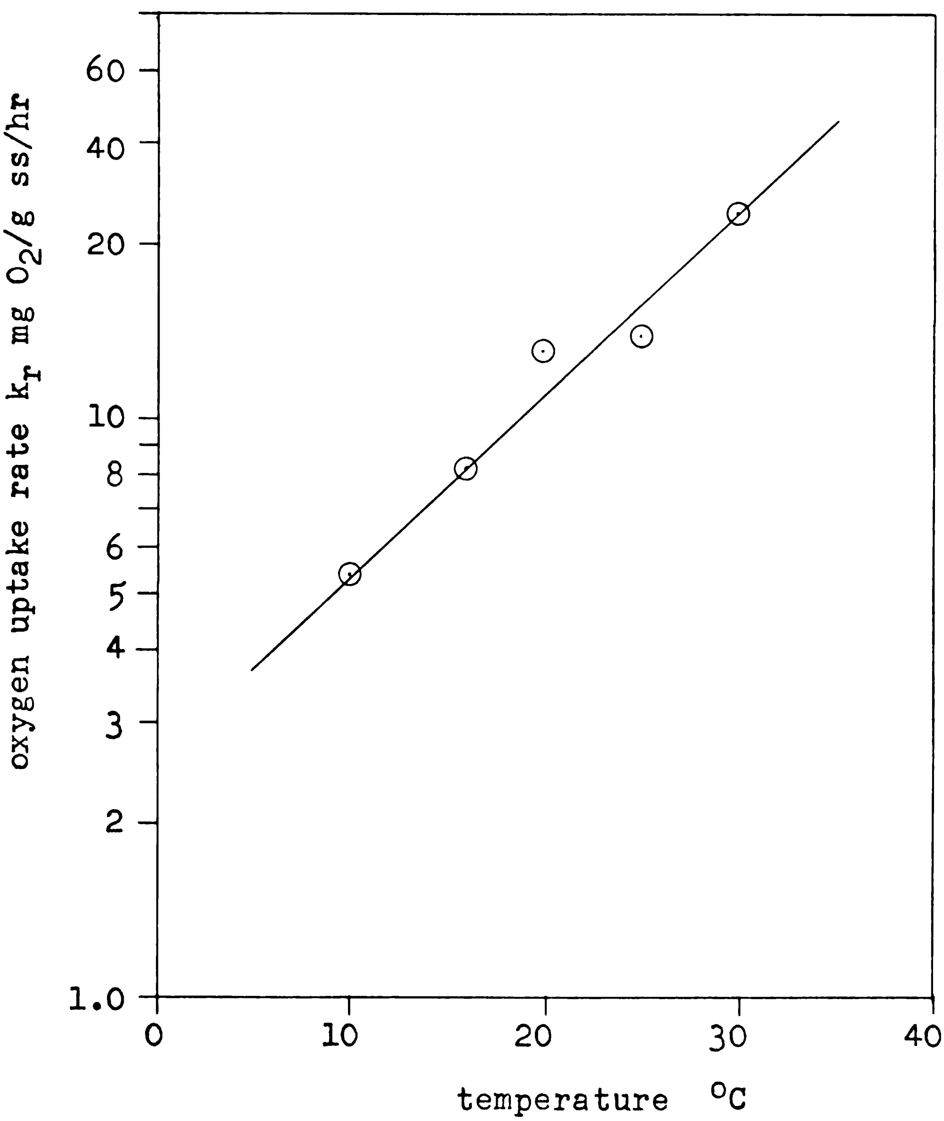


Figure 25. Effect of Temperature upon the Oxygen Uptake Rate of a Mixed Liquor.

2. Effect of Substrate Addition

The purpose of this experiment was to observe the effect of a sudden BOD loading upon a mixed liquor which had not been fed for several hours. On November 19, 1964 a mixed liquor grab sample was taken from the East Lansing Sewage Treatment Plant. The mixed liquor was black indicating that it was in a very poor condition. The sample was aerated for four hours after which time a 2 liter sample was fed 1000 mg glucose. The temperature was held constant by means of a controlled water bath at 20^{o}C. The effect of the glucose addition was observed by determining the oxygen uptake rate at frequent intervals. The data are listed in Table 26 and shown graphically in Figure 25.

In Figure 26 there are four distinct portions of the curve. In portion I the mixed liquor had reached the endogenous phase after four hours of aeration and no feed, average $r_r = 14.5$. Then a sudden doubling of the respiration rate, $r_r = 28.8$, was observed in section II which was obtained within one half-hour after feeding. In section III there was a slow increase in the respiration rate for approximately 3 hours, after which $r_r = 32.4$, then a more rapid rise in the respiration rate occurred for the next two hours until a maximum of $r_r = 38.7$ was reached. In section III an adaptive process to the glucose substrate seems to have been occurring. Finally in section IV the substrate has either been completely used up or has reached such a low concentration that the organisms could no longer maintain the relatively high oxygen uptake rate and within two hours r_r decreased to the endogeneous level, $r_r = 11.9$.

Since the East Lansing Sewage Treatment Plant where this thesis work was done is a "biosorption" plant with approximately 7 hours aeration of the return activated sludge, the activated sludge entering the mixed liquor aeration tanks is in the endogeneous phase, similar to section I. Then, when this starved sludge is contacted with the primary effluent an immediate response similar to section II occurs. Thus by measuring the oxygen uptake rate within 10 to 20 minutes after initial contact of the return activated sludge and primary effluent, the maximum oxygen demand rate placed upon the aeration system is determined. This has been done in this thesis. In the above statement section III of the curve in Figure 26 has not been disregarded, but it is felt that it is relatively unimportant for most domestic sewage treatment plants. In such treatment plants, it is expected that the sludge is adapted to the sewage.

It was observed during the course of this work that the oxygen uptake rate rapidly decreased after 20 to 30 minutes as shown in Figure 27. This would be expected since the BOD concentrations are quite low compared to the activated sludge solids concentration. Eckenfelder and O'Connor (21) and Bargman, Betz and Garber (24) have reported that the oxygen utilization rate of activated sludges decreased rapidly within one half hour of aeration.

TABLE 26

EFFECT OF SUBSTRATE ADDITION USING GLUCOSE

Run No.	Time hours	Mixed Liquor O_2 Uptake Rate, r_r $mgO_2/l/hr.$
1	4.0	14.6
2	4.5	14.4
	Addition of 500 mg/l glucose	
3	5.0	28.8
4	5.25	28.8
5	5.5	27.9
6	6.0	30.3
7	6.5	31.5
8	7.0	31.5
9	8.0	32.4
10	10.0	38.7
11	11.0	27.0
12	11.5	23.4
13	12.66	11.9

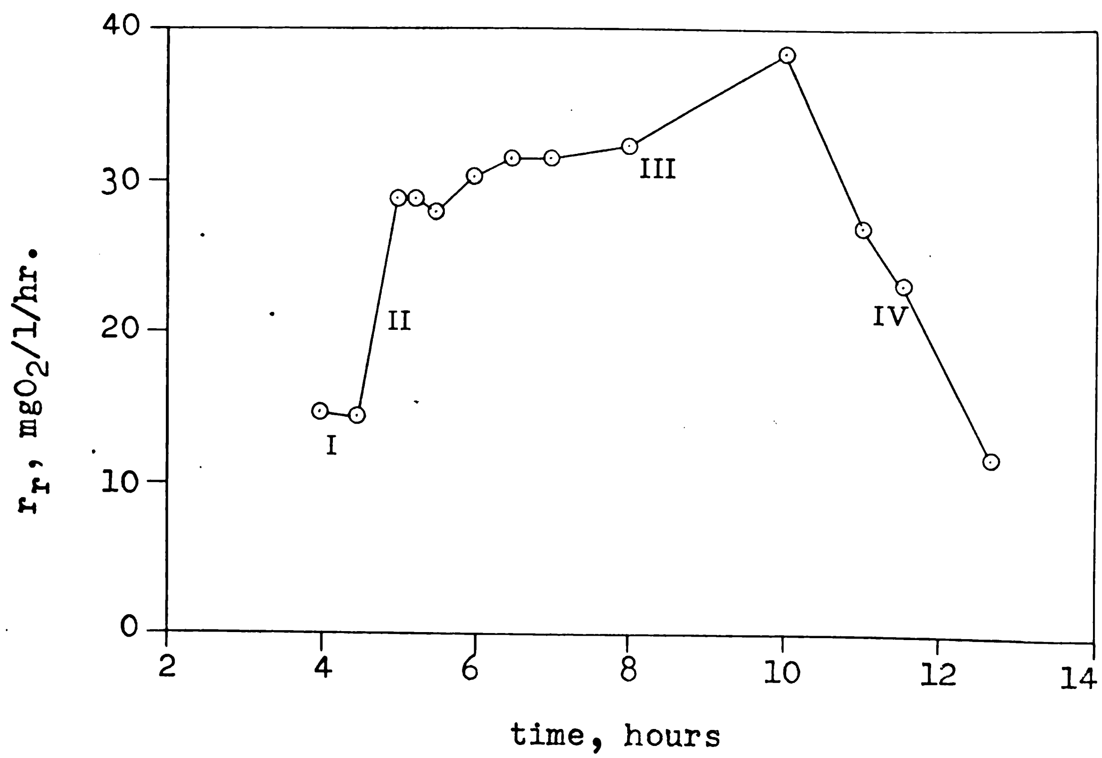


Figure 26. Effect of Substrate Addition Using Glucose.

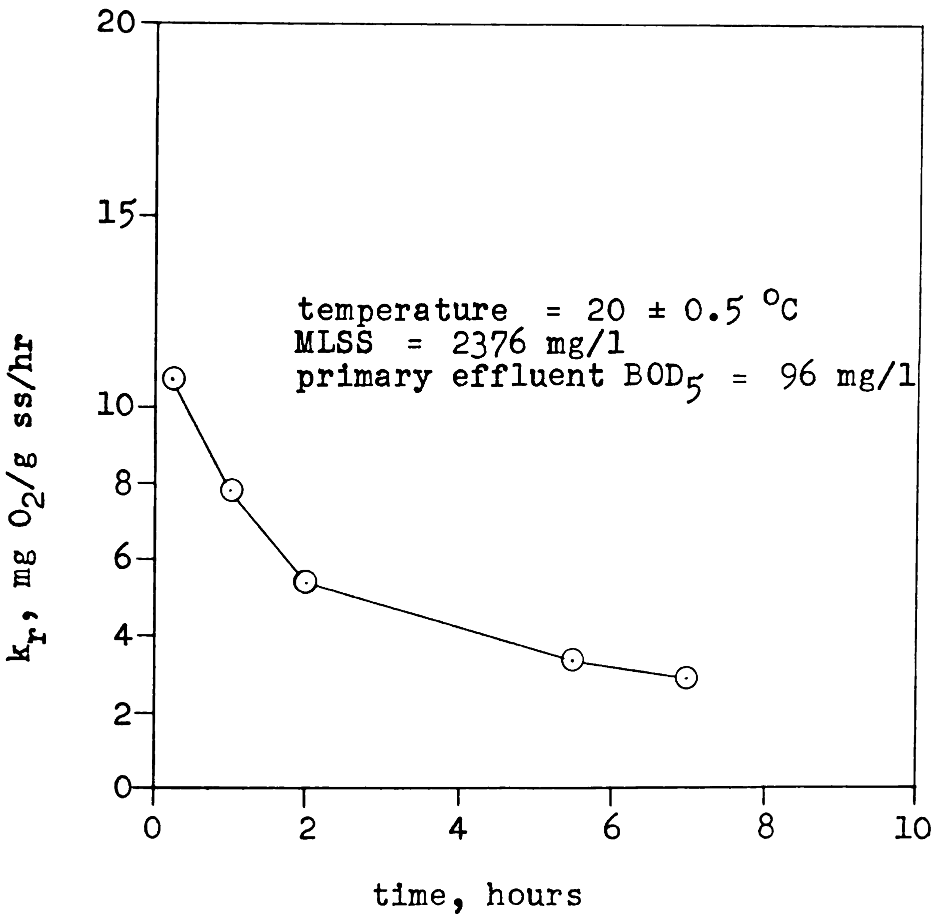


Figure 27. Variation in Specific Oxygen Uptake Rate with Time.

SECTION IV

DISCUSSION OF RESULTS

A. Oxygen Uptake Rates by the Polarographic Oxygen Electrode Technique

The measurement of mixed liquor oxygen uptake rates by observation of the dissolved oxygen concentration depletion over short periods of time with the oxygen sensitive polarographic electrode has been found to be a rapid, simple, and accurate technique. The oxygen meter and respiration flask assembly were easily used at the sewage treatment plant due to the portability of the instrument and the simplicity of the technique in determining respiration rates.

The electrode functioned well and it was only due to membrane damage incurred by accidentally bumping the membrane against a rough surface that the electrode had to be recharged after three months of service. Although the electrode functions well over long periods of time, it is necessary to check the calibration of the instrument from time to time. The electrode shows a definite aging effect which makes itself felt by decreasing sensitivity with time. The rate of aging is quite slow as shown in Figures 28 and 29. The greatest rate of aging occurs immediately following the charging of the cell with the

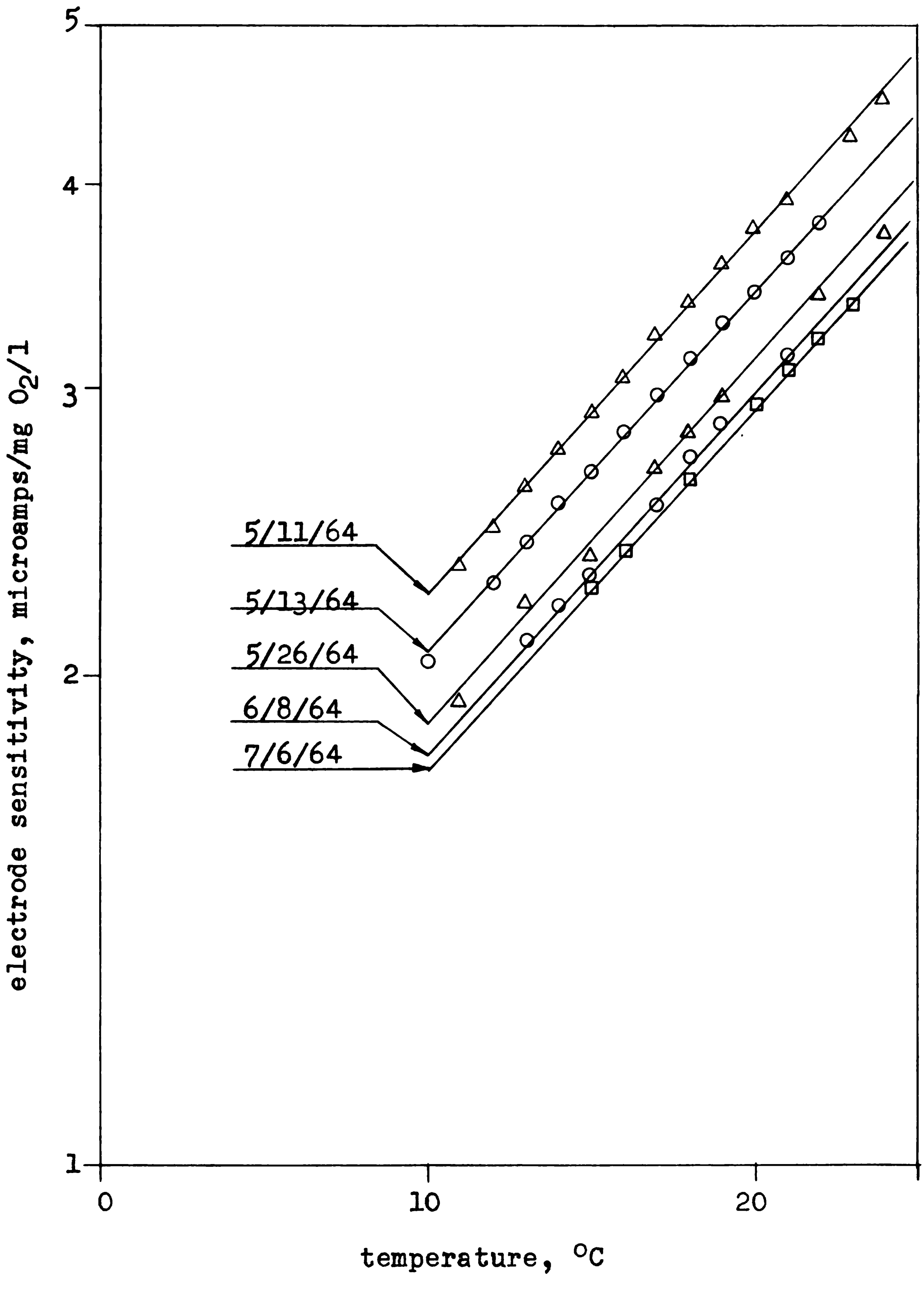


Figure 28. Aging Effect Upon the Electrode Sensitivity.

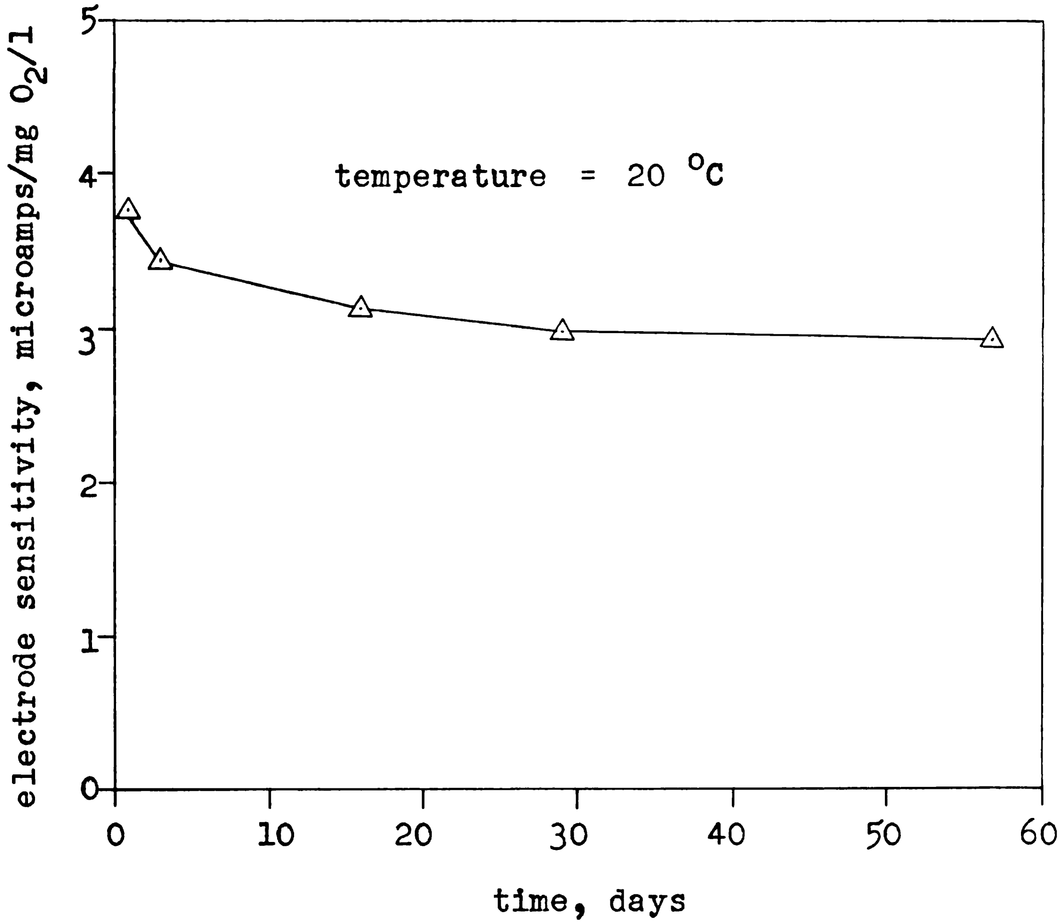


Figure 29. **Aging Effect Upon the Electrode Sensitivity at 20 °C.**

potassium chloride electrolyte and installing a new membrane. The writer feels that the aging process involves a decreasing permeability of the protective teflon membrane, although a small reduction in the sensitivity undoubtedly occurs due to the deterioration of the batteries and the silver coil cathode.

The electrode allows to measure the oxygen depletion rate over time with a rather high precision. The observed dissolved oxygen concentrations when plotted against time show a very good correlation to a straight-line as shown in Figure 30. The slope of this type of plot is the oxygen uptake rate for the sample. The oxygen uptake rates reported in this thesis were obtained by computing the average oxygen uptake rate per 5 or 2 minute interval used in observing the D.O. depletion and multiplying by the corresponding conversion factor, either 12 or 30 respectively, in order to convert the rate to an hourly rate.

B. Mixed Liquor Oxygen Uptake Rates at the Sewage Treatment Plant

1. The Oxygen Uptake Rate Curve Over a Day

The series of experiments 1 through 20 indicate that a characteristic loading curve exists at the East Lansing Sewage Treatment Plant. The form of this characteristic loading curve, given by the specific

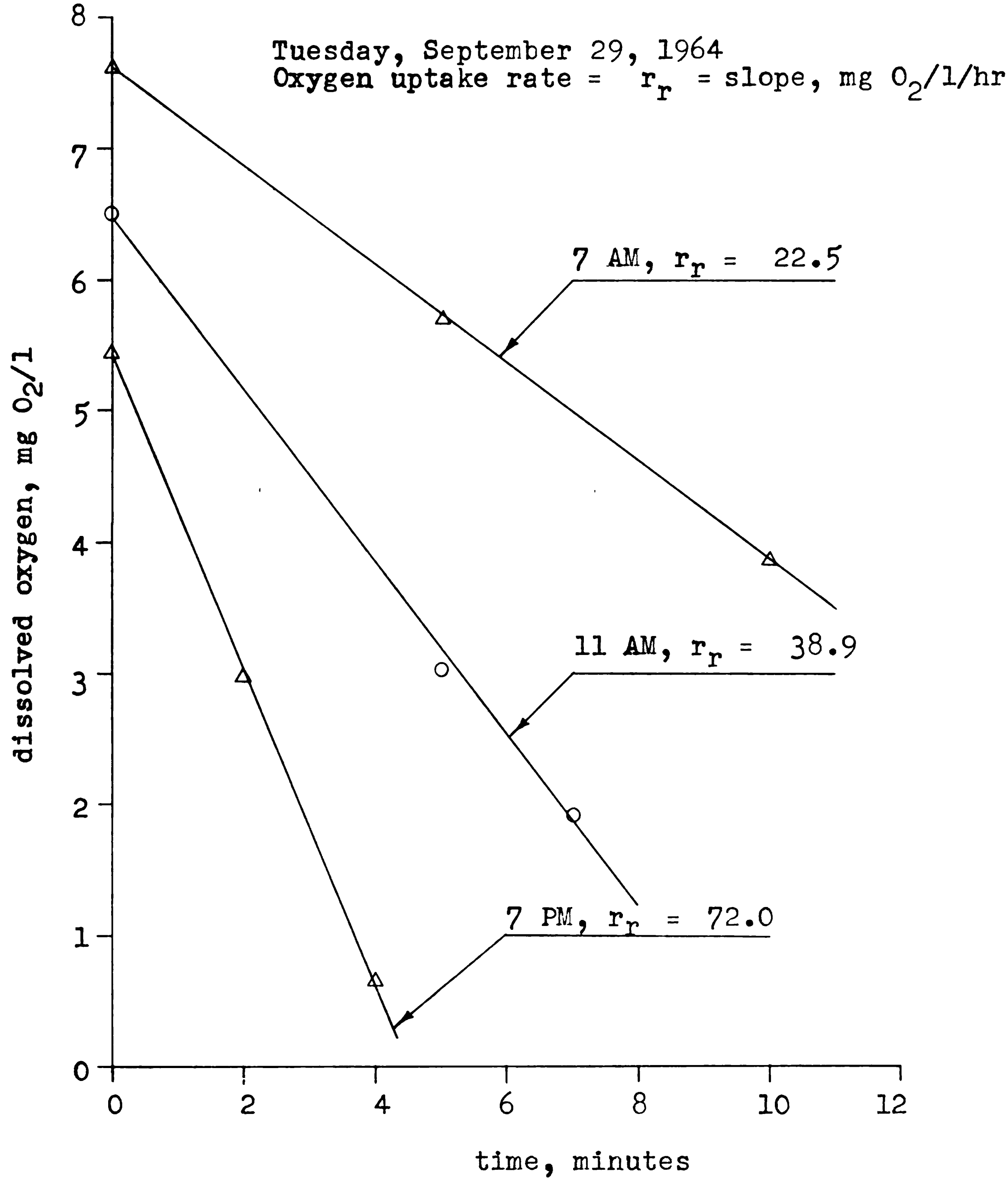


Figure 30. Mixed Liquor Dissolved Oxygen Depletion Over Time.

oxygen uptake rate, k_r, is the following: (1) the minimum respiration rate occurs from 7 to 10 AM after which the activity steadily increases to the afternoon maximum, (2) the maximum respiration rate occurs from 2 to 5 PM after which the activity decreases to an evening plateau, and (3) in the evening the respiration rate remains quite steady from about 7 PM to about midnight, after which the activity decreases to the minimum rate for the following day. The numerical value of the oxygen uptake rates is dependent on the BOD concentration of the primary effluent. The peak oxygen uptake rate survey shows that these rates vary daily with Wednesday having the highest oxygen consumption rate. The weekend survey has shown that k_r is considerably lower for the weekend than for weekdays. The comparison of data obtained during terms and in between terms shows that the whole curve is raised considerably by the increase in population during terms.

2. The Oxygen Uptake Rate Curve Over a Weekend

In general the k_r measurements show that the demand placed upon the aeration equipment of the sewage treatment plant during the summer months over a weekend, was about 1/3 less than that experienced during a weekday. The lower aeration demand exists during Saturday and through Sunday until Monday morning. The first weekend survey, see Figure 12, clearly shows that the aeration demand on

Saturday and Sunday is lower than on Monday although Sunday was not quite as low as Saturday. The second survey, see Figure 15, again showed that the Sunday oxygen demand is lower than on Monday and that the specific respiration activity k_r shows a rapid rise on Monday morning. The third survey, see Figure 16, shows that the Saturday demand is less than on Friday.

On the basis of the above three weekend surveys, the oxygen demand on Saturday is the minimum for the entire week, with the Sunday demand being the next lowest. The BOD data for the respective days agree with this concept. Saturday is the period of lowest BOD concentrations, although the differencebetween Saturday and Sunday is not very great. Dissolved BOD determinations may have illustrated this point better but no such determinations were made for the weekend surveys.

The above surveys also reveal that the r_r value did not exceed 20 mg/l/hr. on Saturday and that on Sunday the portion of the r_r curve above 20 mg/l/hr. was much less than the portion below this level. It is therefore evident that the mixed liquor was being adequate aerated only over the weekend. Throughout the week the aeration equipment was not capable of supplying the oxygen needed to maintain even a trace of D.O. in the mixed liquor.

3. Relationship of the Specific Respiration Rate, k_r, to the Primary Effluent - Total and Dissolved BOD

In experiments 2 through 20, BOD determinations were made upon primary effluent grab samples simultaneously with the r_r and k_r measurements. The majority of the BOD determinations were made on unfiltered primary effluent; these were recorded as total BOD and tabulated in Table 27 and plotted against the solids respiration rate, k_r, as shown in Figure 31. The graph shows that the activity of the activated sludge increases directly with the concentration of the primary effluent BOD. The data show a wide band of variation which is probably due to differences in the dissolved BOD, which is the only part of the total BOD immediately available to the bacterial cell. Secondly, the cellular respiration rate, k_r, is based upon the total mixed liquor suspended solids concentration. As has been shown by several authors, (21), (25) and (20) the mixed liquor suspended solids consist only partially out of viable microorganisms.

The mixed liquor volatile suspended solids determinations obtained in experiments 18 through 20 indicate that the ash content of the mixed liquor suspended solids is about 30%, as shown in Tables 19, 20 and 21. This indicates that the East Lansing activated sludge contains a significant fraction of inert material since pure bacterial substance has ash contents of only about 8 - 12% as reported by Schulze (26). Even the volatile content probably still does not represent pure active cells but it is certainly closer to a more realistic value of the amount of viable cells than the total suspended solids. The mixed liquor volatile suspended solids (M.L.V.S.S.) of experiences 18 through 20 have been used in the computation of k_r for these experiments as tabulated in Table 28. This table also lists dissolved BOD data, as obtained by filtering the sample through a 0.45 micron pore size Millipore membrane filter. Figure 32 shows the plot of k_r based upon the M.L.V.S.S. versus both the dissolved and total BOD of the primary effluent. The lines drawn through both sets of data are tentative. The data show that k_r increases directly with the dissolved and total BOD_5. More data over a larger range of BOD values would be required for a more definite evaluation of the shape of the curves.

The graph shows that the dissolved BOD has a pronounced effect on k_r which is as expected since the dissolved BOD represents that portion of the BOD which is immediately available to the bacterial cells.

TABLE 27

TABULATION OF THE PRIMARY EFFLUENT BOD DATA OF EXPERIMENTS 2 THROUGH 20

BOD	k_r	BOD	k_r	BOD	k_r
36	7.3	86	11.3	114	14.1
42	6.6	87	6.8	114	18.2
45	7.3	87	9.9	115	15.0
45	6.8	87	10.1	117	13.6
45	6.4	87	12.7	117	13.8
51	7.0	87	15.7	117	14.6
51	7.2	87	15.9	117	15.0
54	5.7	92	9.2	117	15.6
54	5.7	93	7.0	120	14.4
54	8.0	93	7.4	120	18.1
57	7.0	93	9.5	120	21.0
57	7.5	93	13.4	122	8.5
60	7.8	94	15.7	122	19.9
60	8.2	96	6.4	122	20.6
60	9.3	96	8.6	123	14.6
63	13.4	96	8.9	123	15.1
66	10.5	96	9.0	124	6.2
66	5.1	96	14.8	124	13.4
66	8.3	96	18.6	124	14.4
68	8.6	99	7.9	126	10.4
68	6.2	99	8.0	126	14.9
69	8.3	99	9.3	126	15.4
72	13.9	102	7.0	126	21.9
72	9.3	102	15.9	128	15.3
72	7.5	102	18.8	129	15.9
72	5.6	105	7.9	129	16.2
75	4.9	105	14.3	129	19.9
75	9.1	105	18.4	130	11.3
75	8.0	107	7.8	130	24.7
75	14.3	107	10.0	132	12.6
76	12.4	107	13.5	132	19.1
78	13.4	107	17.8	134	16.7
80	11.3	111	5.5	134	19.2
80	5.1	111	9.9	135	15.9
82	11.5	111	13.4	135	26.0
82	15.3	111	16.4	136	23.4
84	7.3	114	8.3	138	8.7
84	8.7	114	13.4	138	11.3

BOD Total Primary Effluent BOD, mgO_2/l

k_r Mixed Liquor Cellular Respiration Rate, $mgO_2/gSS/hr$.

TABLE 27 CONTINUED

BOD	k_r	BOD	k_r	BOD	k_r
138	13.2	147	10.8	164	42.5
138	14.2	147	12.2	183	22.7
138	18.7	150	11.9	186	37.8
140	12.6	153	20.5	190	15.9
142	17.7	156	15.6	190	21.4
142	20.7	156	28.5	201	19.2
142	19.2	159	20.6	210	37.9
144	15.1	159	22.0	216	40.5
144	16.3	162	19.3	222	40.0
144	20.8	164	23.3	234	48.8
144	20.9	164	41.2	243	44.2

TABLE 28

TABULATION OF THE PRIMARY EFFLUENT BOD DATA OF EXPERIMENTS 18, 19, and 20

Total BOD mgO_2/l	Dissolved BOD mgO_2/l	Mixed Liquor O_2 Uptake Rate k_r $mgO_2/gSS/hr.$	Mixed Liquor O_2 Uptake Rate k_r $mgO_2/gVSS/hr.$
81	50	12.3	18.6
147	72	12.2	17.4
192	74	21.4	31.1
183	84	22.7	26.0
174	86	23.2	29.5
186	105	37.8	52.2
210	106	37.9	49.8
216	109	40.5	54.0
243	114	44.2	66.9
174	115	42.5	56.5
174	130	41.2	58.9
180	142	40.3	53.2
234	154	48.8	63.2
222	157	40.0	57.6
94		15.7	21.9
82		15.3	20.7
114		18.2	24.6
142		20.7	29.5
142		19.2	27.0
138		18.7	25.5
122		20.6	27.5

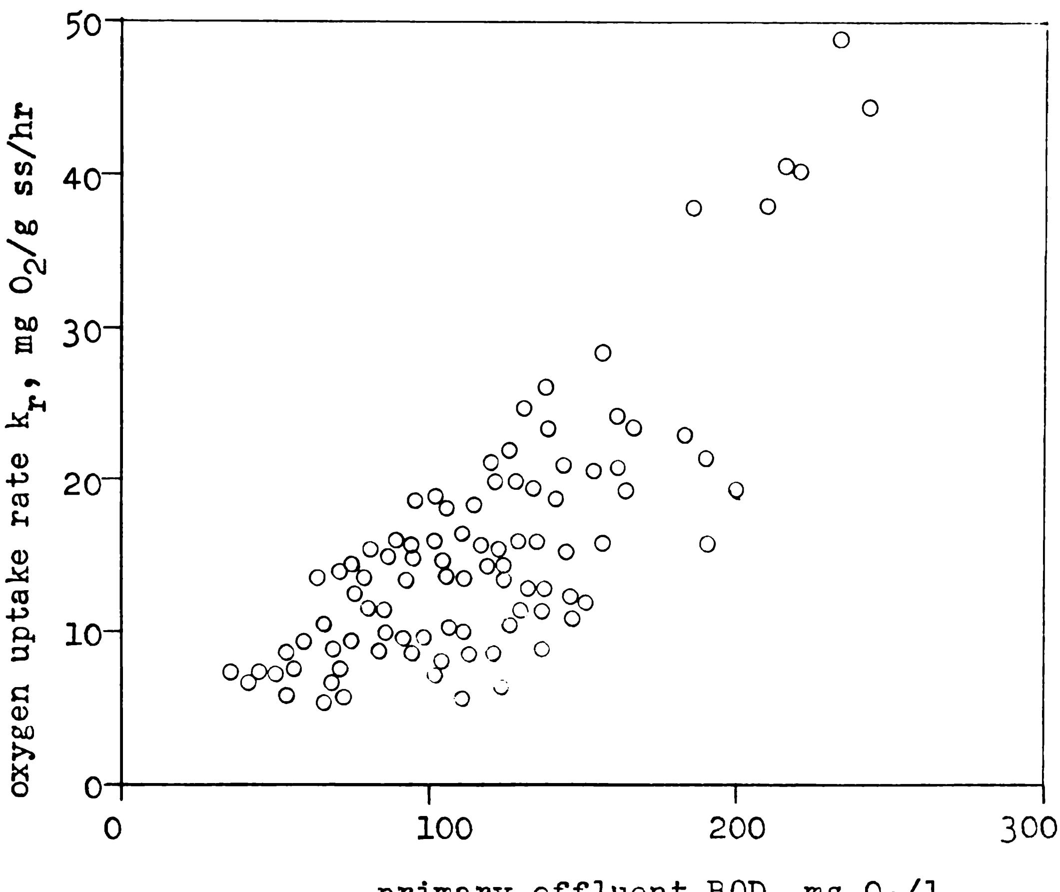


Figure 31. Relationship Between Primary Effluent Total BOD to the Cellular Respiration Rate, k_r, Based on M.L.S.S.

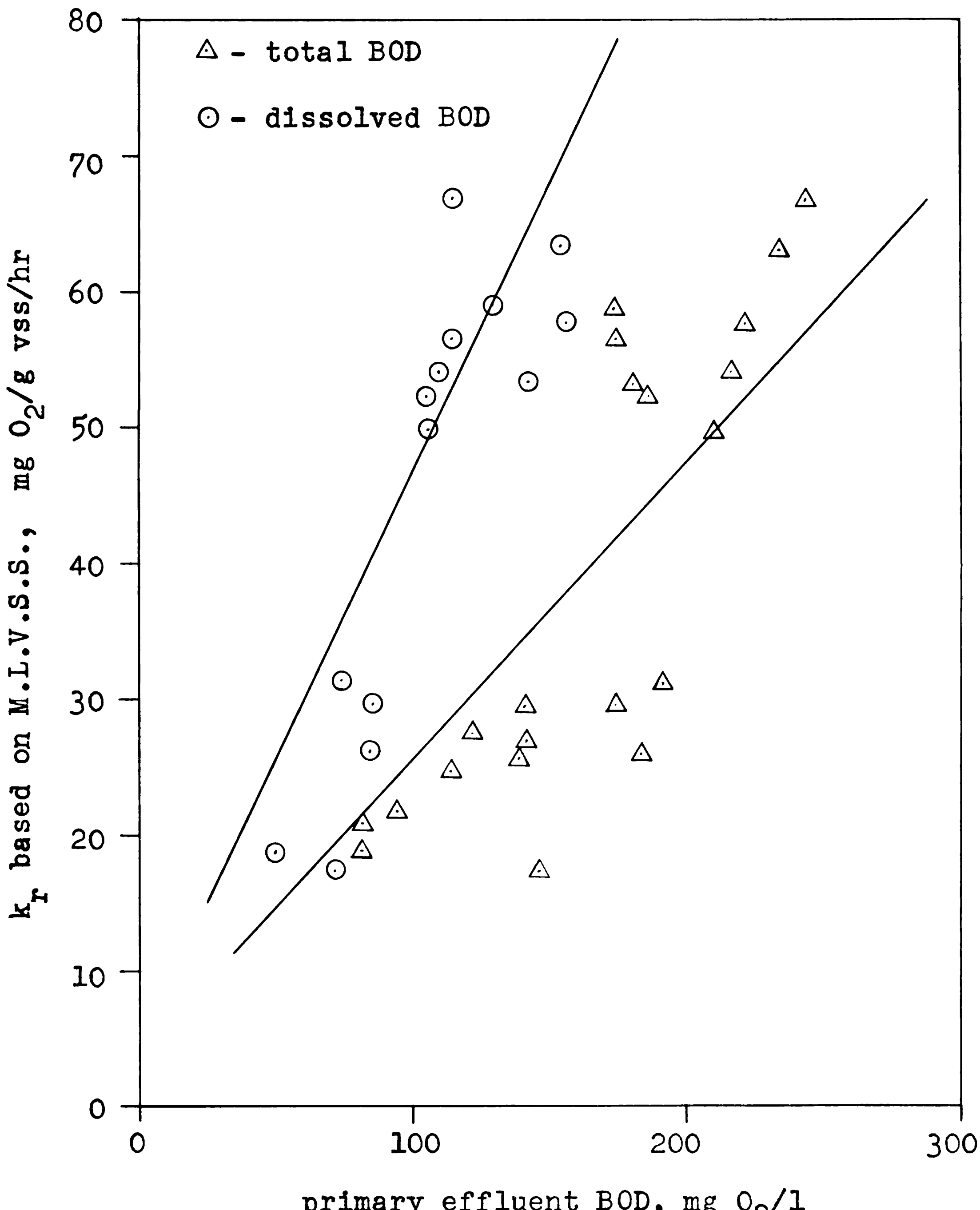


Figure 32. Relationship Between Primary Effluent Total and Dissolved BOD to the Respiration Rate, k_r, Based on M.L.V.S.S.

4. Measurement of the Capacity of Aeration Equipment Under Operating Conditions

The use of the polarographic oxygen electrode for the rapid and simple measurement of oxygen uptake rates of heavy suspensions such as sewage-activated sludge mixtures has opened up a new concept of treatment plant control. As shown in Figure 23 in the experimental results, Section V-6, the oxygen transfer coefficient of the East Lansing Sewage Treatment Plant aeration equipment was determined as the inverse of the slope of the plot of the D.O. in the mixed liquor tank versus the oxygen uptake rate existing at the time of the measurement of the D.O.

A great practical asset of this type of graph is that it tells the plant operator what his aeration system is capable of doing. By varying the rate of air supply, the operator can obtain a set of curves showing K_La at each aeration rate. Then, with these graphs as a guide he can regulate the aeration rate in a adequate manner to meet changes in r_r. If the operator desires to maintain 1.5 mg/l D.O. in the mixed liquor but finds that he is actually obtaining 4.7 mg/l due to a low sludge activity, such as observed on the weekend, he can determine what aeration rate to use merely by extrapolating the activity, r_r, at D.O. = 4.7 from the high aeration rate curve. Then by referring to the lower aeration rate curves find that curve at which the D.O. is closest to 1.5 at the extrapolated r_r value as illustrated in Figure 33.

Eckenfelder and O'Connor (21) have reported that the logarithm of K_La V, the product of tank volume V times K_La, increases directly with the logarithm of the aeration rate within limits. Since V, the aeration tank volume is constant, K_La increases directly with the air flow rate. A graph illustrating the above relationship was given for the sparger and discfuser, hydraulic shear box, saran tubes, plastic tubes, and aloxite tube diffused aeration device.

The increase in K_La results in an increase in the capacity of the aeration equipment which is equal to K_La (C_s - C). Therefore at a given D.O. higher oxygen utilization rates can be supplied by increasing the aeration rate. The effect which the aeration rate is illustrated in Figure 33. The graph shows that the lower aeration rate can supply the oxygen demand rate of 12.5 mg/l/hr. and maintain an adequate D.O. concentration of 1.5 mg/l while the high aeration rate is maintaining an unnecessary high D.O. of 4.7 mg/l.

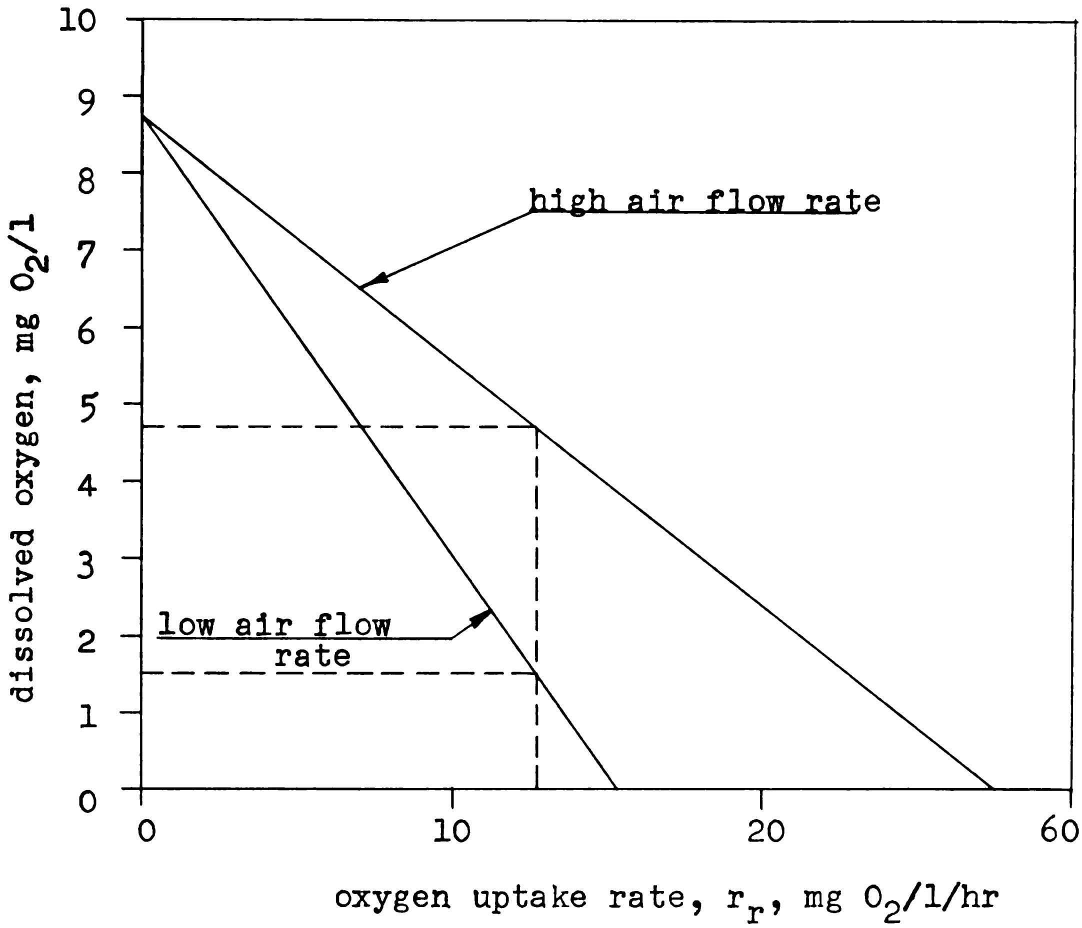


Figure 33. Effect of Aeration Rate Upon Aeration Capacity.

SECTION VII

CONCLUSIONS

1. The oxygen uptake rate of a heavy floc suspension such as a sewage-activated sludge mixture can be measured rapidly and accurately by the polarographic oxygen electrode technique.

2. The portable oxygen meter and electrode assembly can be used to measure the dissolved oxygen concentration in "situ" at a mixed liquor aeration tank.

3. The rapidity and simplicity of the polarographic oxygen electrode technique for the measurement of oxygen uptake rates by the continuous observation of the oxygen depletion over short periods of time makes it feasible to study actual plant operating conditions.

4. Experimental data indicate that the solids oxygen uptake rate, k_r, for any given day increases from a minimum between 7 and 10 AM to a peak value between 2 and 5 PM after which the rate slowly decreases during the evening until at about midnight the rate decreases more rapidly to the minimum value at the following morning. Over the weekend, k_r, is much lower than for a weekday, with Saturday being the period of lowest k_r values while Wednesday is the period of highest k_r value.

5. The oxygen uptake rate, k_r, of activated sludge treating a domestic sewage has been found to vary directly

with the total and dissolved BOD of the primary effluent.

6. Temperature markedly effects k_r. The slope of a semilogarithmic plot of k_r against temperature, ^{o}C, was found to be $0.0323/^{o}C$.

7. The activity of a starved activated sludge doubled within one half hour after being fed 500 mg/l glucose. This immediate acceleration of the sludge activity is assumed to be analogous to the response of an aerated return activated sludge such as found in the biosorption modification of the activated sludge treatment process.

8. The aeration system of an activated sludge plant can be analyzed for its efficiency and capacity by observing the D.O. in the mixed liquor and simultaneously determining the oxygen uptake rate, r_r. The plot of D.O. against r_r is linear; the inverse of the slope is the oxygen transfer coefficient, K_La, and the abscissa intercept is the maximum capacity of the aeration system for the given conditions of temperature, aeration rate, and other characteristics of the aeration system.

BIBLIOGRAPHY

1. Standard Methods for the Examination of Water and Wastewater, 11th Ed. American Public Health Assoc., Inc., New York, N.Y. (1960).

2. Ingols, R. S. "Determination of Dissolved Oxygen by the Dropping Mercury Electrode," Sewage Works Journal, 13, 6, 1097 (November 1941).

3. Moore, E. W., Morris, J. C., and Okun, D. A., "The Polarographic Determination of Dissolved Oxygen in Water and Sewage," Sewage Works Journal, 20, 6, 1041 (November 1948).

4. Rand, M. C., and Heukelekian, H., "Determination of Dissolved Oxygen in Industrial Wastes by the Winkler and Polarographic Methods," Sewage and Industrial Wastes, 23, 9, 1141 (September 1951).

5. Lynn, W. R., and Okun, D. A., "Experiences with Solid Platinum Electrodes in the Determination of Dissolved Oxygen," Sewage and Industrial Wastes, 27, 1, 4 (January 1955).

6. Carritt, D. E., and Kanwish, J. W., "An Electrode System for Measuring Dissolved Oxygen," Anal. Chem., 31, 5, (1959).

7. Mancy, K. H., and Wetgarth, W. C., "A Galvanic Cell Oxygen Analyzer," Journal of Water Pollution Control Federation, 34, 10, 1037 (October 1962).

8. Greely, S. A., "The Development of the Activated Sludge Method of Sewage Treatment," Sewage Works Journal, 17, 6, 1135 (November 1945).

9. APHA Committee on Sewage Disposal, "The Operation and Control of Activated Sludge Sewage Treatment Works," Sewage Works Journal, 14, 1, 3 (January 1942).

10. Bloodgood, D. E., "Studies of Activated Sludge Oxidation at Indianapolis," Sewage Works Journal, 10, 1, 26 (January 1938).

11. Kessler, L. H., and Nichols, M. S., "Oxygen Utilization by Activated Sludge," Sewage Works Journal, 1, 810, (September 1935).

12. Kessler, L. H., "The Odeeometer-Its Place in the Control of Activated Sludge Plants," Water Works and Sewage, 83, 13 (January 1936).

13. Dawson, P. S. S., and Jenkins, S. H., "The Oxygen Requirements of Activated Sludge Determined by Manometric Methods," Sewage Works Journal, 21, 4, 643 (July 1949).

14. Hoover, S. R., Jasewicz, L., Porges, M., "The Magnetic Oxygen Analyzer in Studies of Oxygen Uptake," Water and Sewage Works, 101 (February 1954).

15. Lamb III, J. C., Westgarth, W. C., Rogers, S. L., and Vernimmen, A. P., "A Technique for Evaluating the Biological Treatability of Industrial Wastes," Journal of Water Pollution Control Federation, 36, 10, 1263 (October 1946).

16. Smith, D. B., "Measurements of Respiratory Activity of Activated Sludge," Sewage Works Journal, 25, 767, (July 1953).

17. Water Pollution Control Federation, "Activated Sludge," WPCF Manual No. 11: Operation of Wastewater Treatment Plants, (1961).

18. Sawyer, C. N., and Nichols, M. S., "Activated Sludge Oxidations. I. Effect of Sludge Concentration and Temperature upon Oxygen Utilization," Sewage Works Journal, 11, 1, 51 (January 1939).

19. Sawyer, C. N., and Rohlich, G. A., "Activated Sludge Oxidations. IV. The Influence of Temperature upon the Oxygen Utilization by Activated Sludges," Sewage Works Journal, 11, 6, 964 (November 1939).

20. Keefer, C. E., and Meisel, J., "Activated Sludge Studies III. Effect of pH of Sewage on the Activated Sludge Process," Sewage and Industrial Wastes, 23, 8, 982 (August 1951).

21. Eckenfelder, W. W., and O'Connor, D. J., Biological Waste Treatment, Pergamon Press, New York, (1961).

22. Wuhrman, K., "High-Rate Activated Sludge Treatment and Its Relation to Stream Sanitation I Pilot Plant Studies," Sewage and Industrial Wastes, 26, 1, 1 (1954).

23. Phelps, E. B., Stream Sanitation, John Wiley and Sons, New York, (1944).

24. Bargman, R. D., Betz, J. M., and Garber, W. F., "Aeration Requirements of a High Oxygen Demand Sewage," Sewage and Industrial Wastes, 29, 7, 768 (July 1957).

25. Schulze, K. L., "The Activated Sludge Process as a Continuous Flow Culture, Part 2. Application," Water Works and Sewage, 112, 1, 11 (January 1965).

26. McKinney, R. E., Microbiology for Sanitary Engineers, McGraw-Hill Book Co., New York, (1962).