THE MECHANICS OF GAS TRANSFER IN OXIDATION LAGOONS

by

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THE MECHANICS OF GAS TRANSFER IN OXIDATION LAGOONS

INTRODUCTION

Increasing population and industrialization in recent years have placed additional emphasis on the need for protection of our water resources. In order to conserve these water resources for the maximum benefit of all the people, new methods of waste treatment have to be developed and applied at a reasonable cost. Furthermore, ways of improving existing methods must be found. In the face of rising costs, many small communities and industries with limited financial capacity, find it most difficult to finance waste treatment facilities.

Waste water oxidation lagoons are an economical method of treatment applicable to small communities and industries where both the capital investment and operating costs are controlling factors. Numerous investigations of lagoons have been made in arid regions, however, until recently, little work has been done in marine climates on determination of the parameters which control oxidation lagoon processes.

The study undertaken at Oregon State College in 1958 by G. A. Whitney and F. J. Burgess is the first investigation on a controlled basis done in the maritime regions of the Pacific Northwest.

Object of this Thesis

The treatment capacity of oxidation lagoons is due to bacterial decomposition wherein the bacteria are supplied oxygen by photosynthetic production of oxygen by algae and by reaeration from the surface source. The object of this thesis is to evaluate the limits of oxygen transfer to the lagoon by surface reaeration.

Studies have been made on reaeration of streams by E. B. Phelps (9, p. 68-86) and the Robert Taft Engineering Center, (5, p. 963. 6, p. 102) however, the mechanics of reaeration of lagoons have only limited published research findings by E. R. Hermann, E. F. Gloyna and H. T. Odum.

History of the Oxidation Lagoons

Lagoons to treat sewage were first used in China, over 200 years ago, but there was no actual recorded date (4, p. 1213-1235). In the United States, the first lagoon was put into operation in 1901 in San Antonio, Texas (11, p. 12). However, it was not until 1927 that the principle of lagoons actually began to gain acceptance. In fact, the first lagoons were operated solely for the purpose of raising fish (2, p. 437).

Many cities in the arid regions of the Midwest and West Coast started using lagoons for the treatment of sewage in 1927. Cities in Texas and South Dakota were among the early leaders in the field of lagooning sewage (11, p.1-5). In 1927, the cities of Santa Rosa and Sonoma, California were the first to use lagoons for waste disposal on the West Coast (2, p. 436). In 1938, Texas A & M College constructed its own lagoon for the purpose of studying the mechanics of the algal-respiration process.

Until 1949, sewage lagoons were designed by using a fixed loading criteria and only recently, have detailed investigations been made relating lagoon operation and efficiency to location and climate and waste water characteristics, (11, p. 13). The most recent and important contributions have been made in Texas by Hermann and Gloyna; in the Dakotas by their respective Public Health Departments, and in Australia by Parker, Jones and Greene, (8, p. 133-139).

In summarizing historical and present data, it can be seen that most of the researchers agree on the physical features of the lagoon and on photosynthetic production of oxygen. However, only limited information is available on oxygen uptake in the oxidation lagoons, from the surface boundary. Most design parameters were based on a fixed loading rate of a given population equivalent per acre, based on previous experience, without regard to climate (10, p. 1390). Recently reported values are found in Sewage Works Journals in the Oregon State Sanitary Codes, (7, p. 692-697).

Discussion of Problem

Surface aeration appears to be of minor consequence in most regions of high solar energy where oxygen produced by photosynthesis is high, but in the climate of western Oregon, it is of major importance since, during the raining season in maritime regions, heavy cloud cover and low temperatures limit the algal production of oxygen and place additional emphasis on oxygen transfer by surface aeration.

Because of the great complexity of controlling factors it is unlikely that a single overall formulation of lagoon operation can be satisfactorily developed. Some of the controlling factors that must be included in such an overall formulation are, temperature, climate, cloud cover, surface area, depth and detention period. Oxygen transfer from surface sources is effected by fewer variables and is therefore more amenable to formulation.

The formulation that is most useful to describe reaeration is $\frac{dD}{dT} = -k_2D$ (see equation 1, p, 11) (9, p. 168). A value of k_2 for quiescent streams has been reported as $k_2 = 0.25$* by Phelps (9, p.179). However, quiescent streams and lagoons present a different problem of lateral and vertical mixing, therefore lagoon k_2 values estimated from known stream values, are of doubtful reliability.

Diffusion promoted by wind, temperature and density currents, resulting in lateral and vertical mixing,

*(reported values are to logarithm to base 10 of k_2)

influences the interface between water and the atmosphere and hence the oxygen transfer rate. Based on the method of analysis used in this study, the reported values of k_2 included the effect of all of the factors effecting mixing. Therefore, the reaeration constant is not a single-meaning value, but encompasses the effect of all variables influencing oxygen transfer.

Method of Study

In order to evaluate the constant of reaeration, a variation of the standard light and dark bottle test was used. To simulate actual conditions, tanks were used as the containers and were placed in the lagoon. These tanks were three feet on each side and extended to the bottom of the lagoon so that there would be no change in the tank content during the test. There were three to five inches of free-board on each container in order to allow for any wave action. Observations indicated that this free-board did not interfere with the algal cycle and biological action by shading sunlight from the container. For the test, values were determined from the three tanks and the lagoon itself. A detailed description of the tanks is as follows:-

The first tank had a clear plastic top, so as to eliminate surface reaeration, but to admit sunlight. The lid was floated on the top of the tank and mineral oil was placed over the exposed water surface to complete the air tight seal.

The second tank was similar to the first except that it had a floating, black polyethylene and plywood top lid to exclude light. A masonite cover was placed over the top of the entire tank to eliminate any snow or rain from entering the water surface. The bottom was left uncovered to obtain the benthal effect on oxygen demand.

The third tank was the same as the second tank except that a masonite cover was placed over the bottom to exclude the benthal effect.

The controlling factors considered in this test were the location of tanks, temperature, weather, and lagoon loading. The tanks were located in the four quadrants of the lagoon to achieve what was felt to be a uniform distribution. It was found that results did not vary appreciably with tank location. However, it should be noted that when the tanks were near the inlet, there was a higher concentration of suspended organic material present.

The weather at the time of sampling was overcast and cold. During tests two and three, ice and snow were on the ground.

The reason for selecting the winter season for the test, was that the oxygen production by photosynthesis was at a minimum allowing the surface reaeration to be studied.

Figure 1. Snow Conditions

Figure 2. Clear Conditions

The wind, during the test period, averaged five miles per hour or less, and the air temperature varied over a range of 21°F. with a maximum of 42°F. and a minimum of 21°F.*

To control distribution of organic matter, there was no loading of the lagoon during the period of testing, however, the lagoon was loaded between the tests to maintain biological activity. Based on a preliminary survey, it was found that the circulation in the lagoon could be assumed to be both horizontal and vertical and the dissolved oxygen to be uniformly distributed vertically. The greatest difference between the surface and the bottom was found to be three parts per million.

Tests to determine the upper and lower values of k_2 using a single tank and recirculating the water in the tank rapidly were made (see figures 3 and 4). The results of these tests were not as successful as anticipated. Only limited results could be obtained and many possible sources of error existed since it was difficult to control temperature and surface continuity.

It might be noted, as a side result, that when recirculated at a very high rate, the sewage in the tank would foam due to detergents (see figure 4). When this foaming occurred, the oxygen uptake was extremely fast, because of the large surface area, and the dissolved oxygen content rapidly went to saturation.

*from Corvallis, Oregon, Newspaper, "Gazette Times"

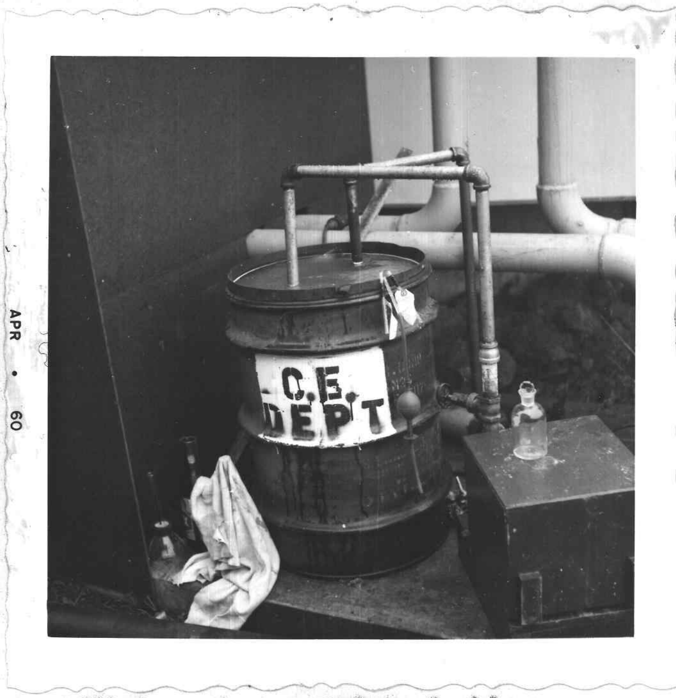


Figure 3. High rate, recirculation

Figure 4. Foaming

Test Procedures

The Winkler method, with the sodium azide modification was used to determine the oxygen content of the lagoon and of the tanks during the test (1, p. 256). Samples were taken at a depth of one foot in the tanks at eight hour intervals or less during test runs. All sampling was done from a boat.

Carefully cleaned bottles were filled with a volumetric pump which was connected to a plastic tube that extended one foot below the water surface. The temperature was taken in the vicinity of the tanks and the lagoon was sampled in the same area. Samples were immediately analyzed and all data recorded. The general weather conditions were noted at the time of each sampling, (see tables 1 through 4).

Tanks were moved from one location to another by means of a specially constructed platform tied between two boats. Special care had to be given to the placement of the tanks since the depth of the lagoon varied slightly and it was desired not to stir the bottom of the lagoon when placing the tanks.

The length of each individual test usually averaged fifty hours, since it was desired to obtain a significant change in dissolved oxygen, in the tank.

The approach used to determine the reaeration constant is based upon the following formulation, first proposed by

E. B. Phelps (9, p. 67-159)

$$\frac{dD}{dt} = -k_2D^* \text{ (3, p. 846)} \qquad (1)$$

Using subscript "0" for conditions at time t, and "1" for conditions at t+dt, values can be defined as follows:-

C_o = Concentration of oxygen at start of period (ppm)

C_1 = Concentration of oxygen at the end of period (ppm)

C_{so} = Saturation of oxygen at the start of period (ppm)

C_{s1} = Saturation of oxygen at the end of period (ppm)

$D_o = C_{so} - C_o$

$D_1 = C_{s1} - C_1$

and

$dD = (C_{so} - C_o) - (C_{s1} - C_1)$

dt = Change in time, hours

k_2 = Reaeration reaction velocity constant

D = Average deficit (ppm)

also

$$D = \frac{(C_{so} - C_o) - (C_{s1} - C_1)}{2} \quad \text{Average deficit}$$

therefore

$$\frac{dD}{dt} = -k_2D \qquad (1)$$

Case I:-

No photosynthetic production of oxygen and the temperature constant.

$$dw = -dD^{**} \text{ (see figure 5.)} \qquad (2)$$

*Parameters of depth and area are taken as constants for a 3 feet lagoon depth and a one acre area

**Good only when C_s is constant

$$\frac{dW}{dt} = -k_2 D$$

$$W_o - W_1 = -(D_o - D_1) \quad \text{(see figure 5)} \qquad (3)$$

<u>Case II:-</u>

No photosynthetic production of oxygen and the temperature varying.

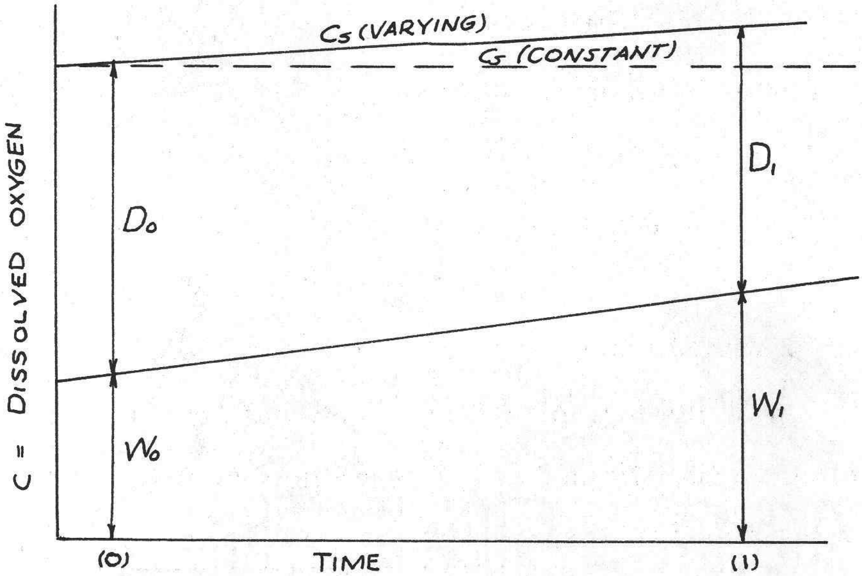


Figure 5.

$$dW \pm dC_s = -k_2 D \qquad (4)$$

$$dW = (C_{so} - C_o) - (C_{s1} - C_1) \qquad (5)$$

$$= (C_{so} - C_{s1}) - (C_1 - C_o) \qquad (6)$$

$$dW = (C_1 - C_o) \qquad (7)$$

$$dD = dW \pm dC_s \qquad (8)$$

$$dC_s = (C_{so} - C_{s1}) \qquad (9)$$

or $$dW = dD \pm dC_s \qquad (10)$$

Assuming constant temperature, and a lagoon depth of three feet, the final resulting equation for pounds of oxygen transferred through one surface acre, is:-

$W = \Sigma dw$

$W = 196\ k_2D$ (11)

W = pounds of oxygen per day

$k_2 = (\text{days})^{-1}$

D = deficit in parts per million (mg/l)

Equation is the basis of figure 5.

For a condition where photosynthetic production of oxygen by algae is above the requirement for biological oxygen demand satisfaction, the lagoon dissolved oxygen will be below saturation, and the constant k_2 will have a negative value. In other words, oxygen would be given off at the surface instead of being absorbed.

It will be seen from the above equations that the values of k_2 can be determined by using the relationship of change in oxygen content dW as a function of time dt.

Test data is presented in tables in the Appendix (see tables one through four), and are summarized graphically in the curves that follow.

Plate 5 relates oxygen saturation with temperature for the winter range of lake temperatures in the region under study. It should be noted that this curve was plotted for temperatures encountered in the month of January, which was the coldest reported month of the year,

PLATE NO. 1

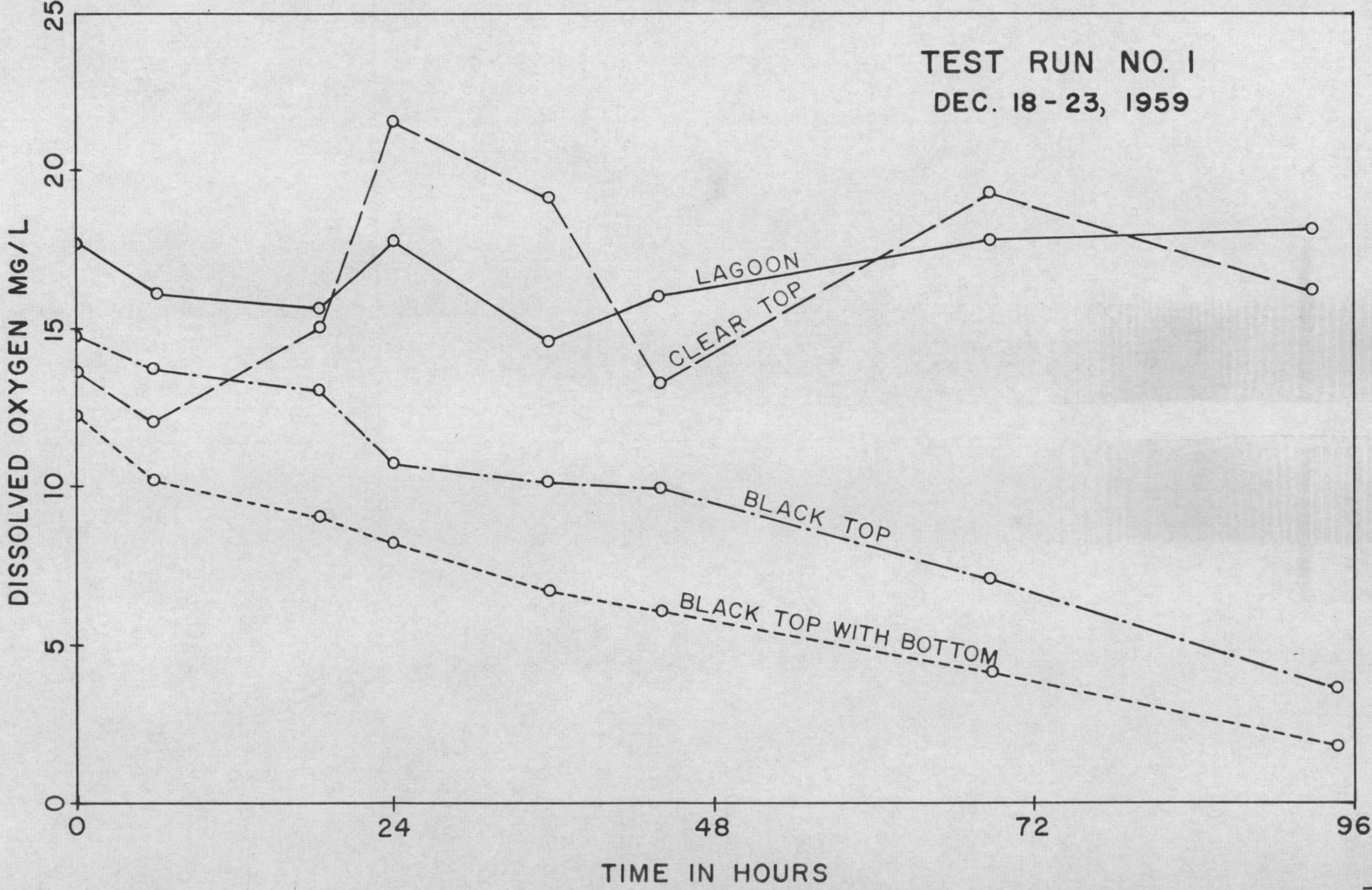
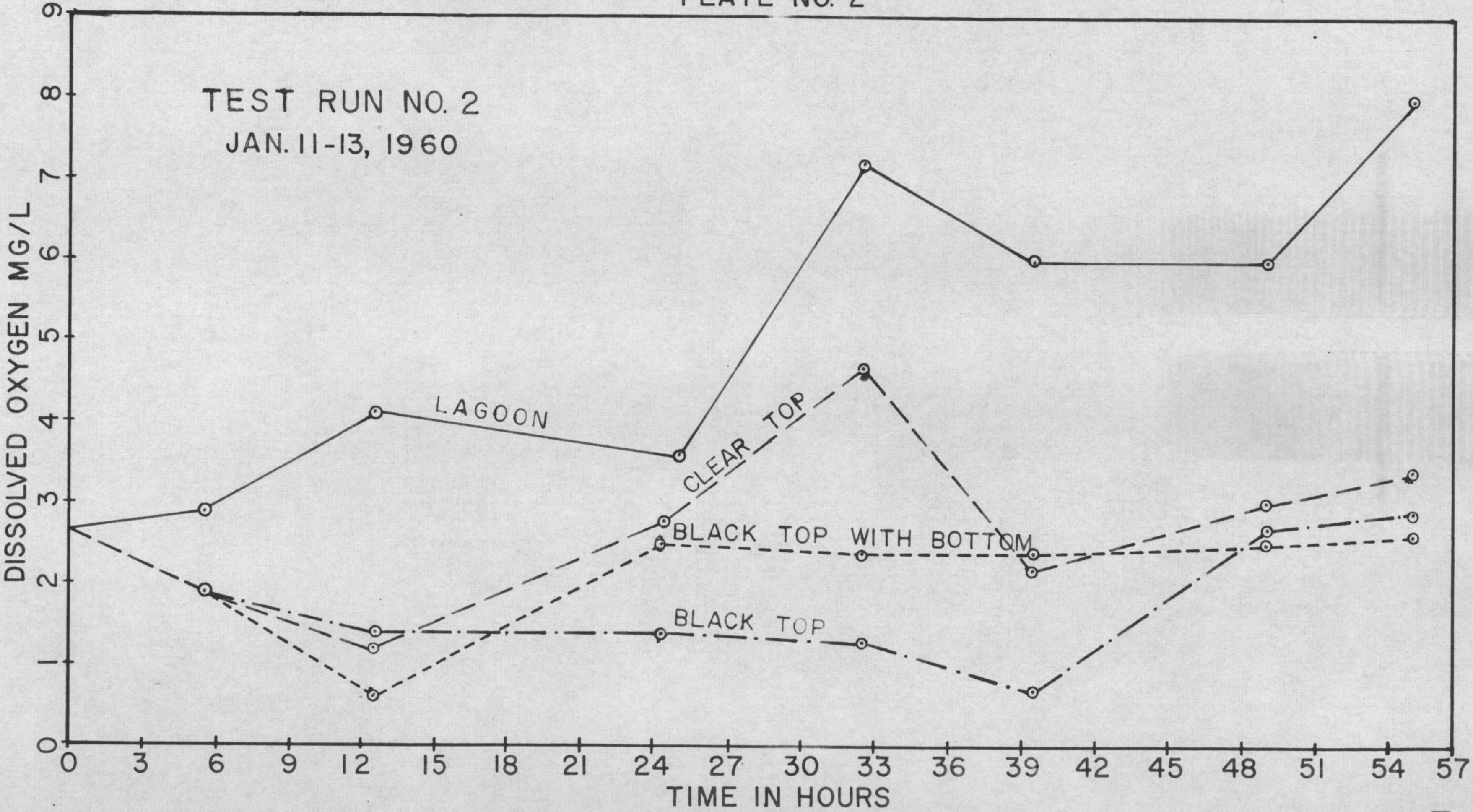

TEST RUN NO. 1
DEC. 18 - 23, 1959
DISSOLVED OXYGEN MG/L
TIME IN HOURS
LAGOON
CLEAR TOP
BLACK TOP
BLACK TOP WITH BOTTOM
0
5
10
15
20
25
0
24
48
72
96

PLATE NO. 2


TEST RUN NO. 2
JAN. 11-13, 1960
LAGOON
CLEAR TOP
BLACK TOP WITH BOTTOM
BLACK TOP
DISSOLVED OXYGEN MG/L
0 1 2 3 4 5 6 7 8 9
0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57
TIME IN HOURS

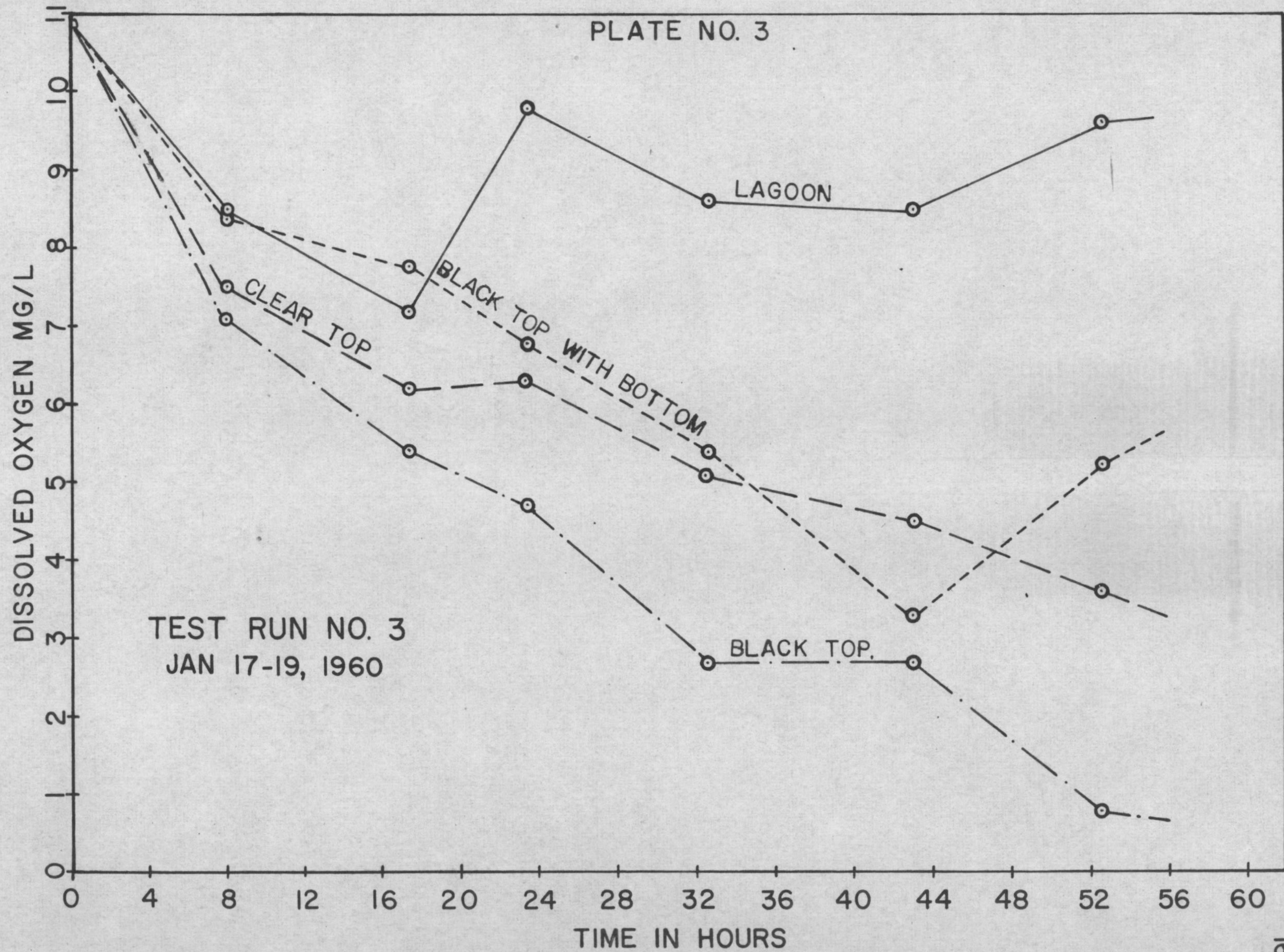
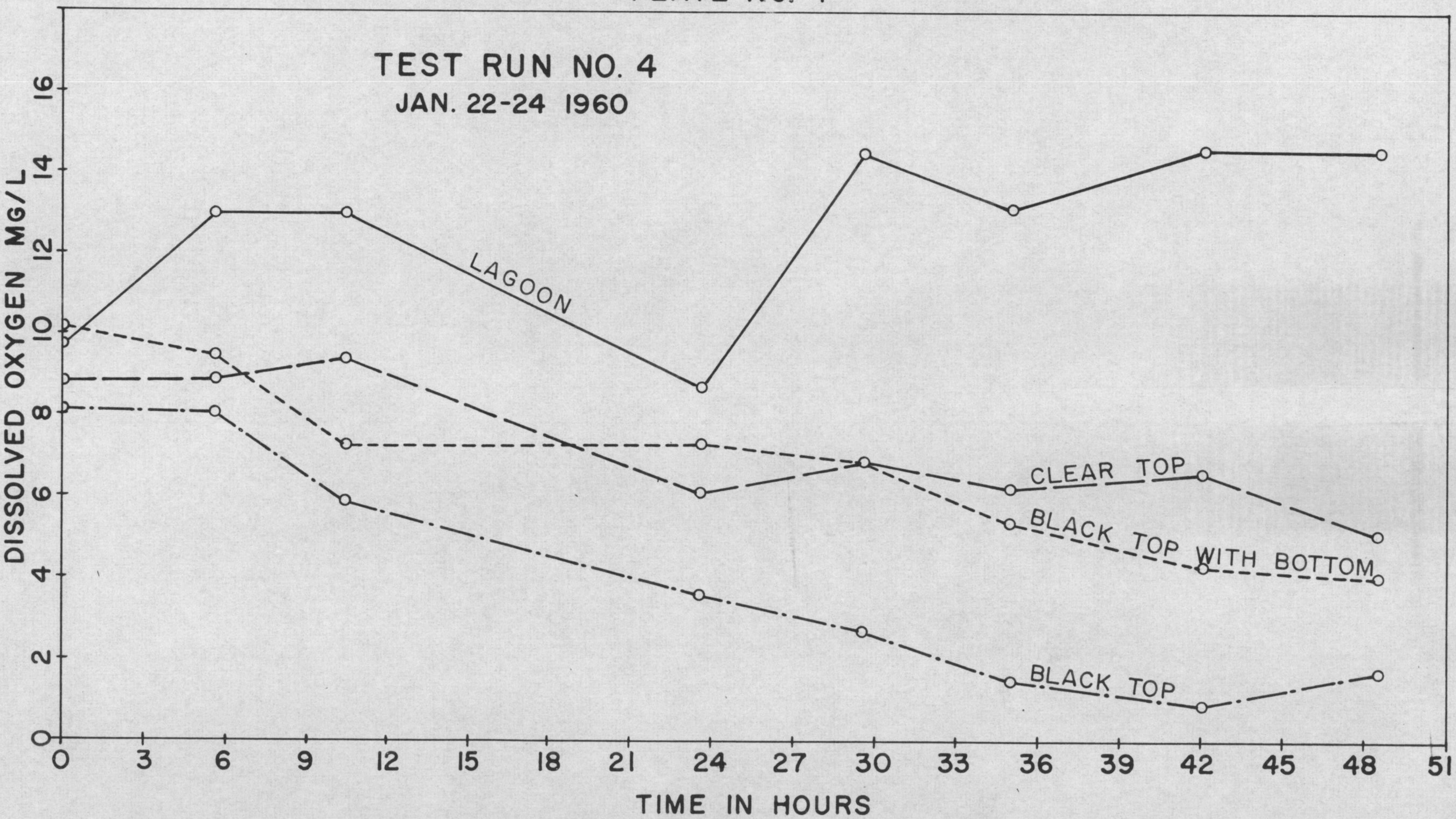


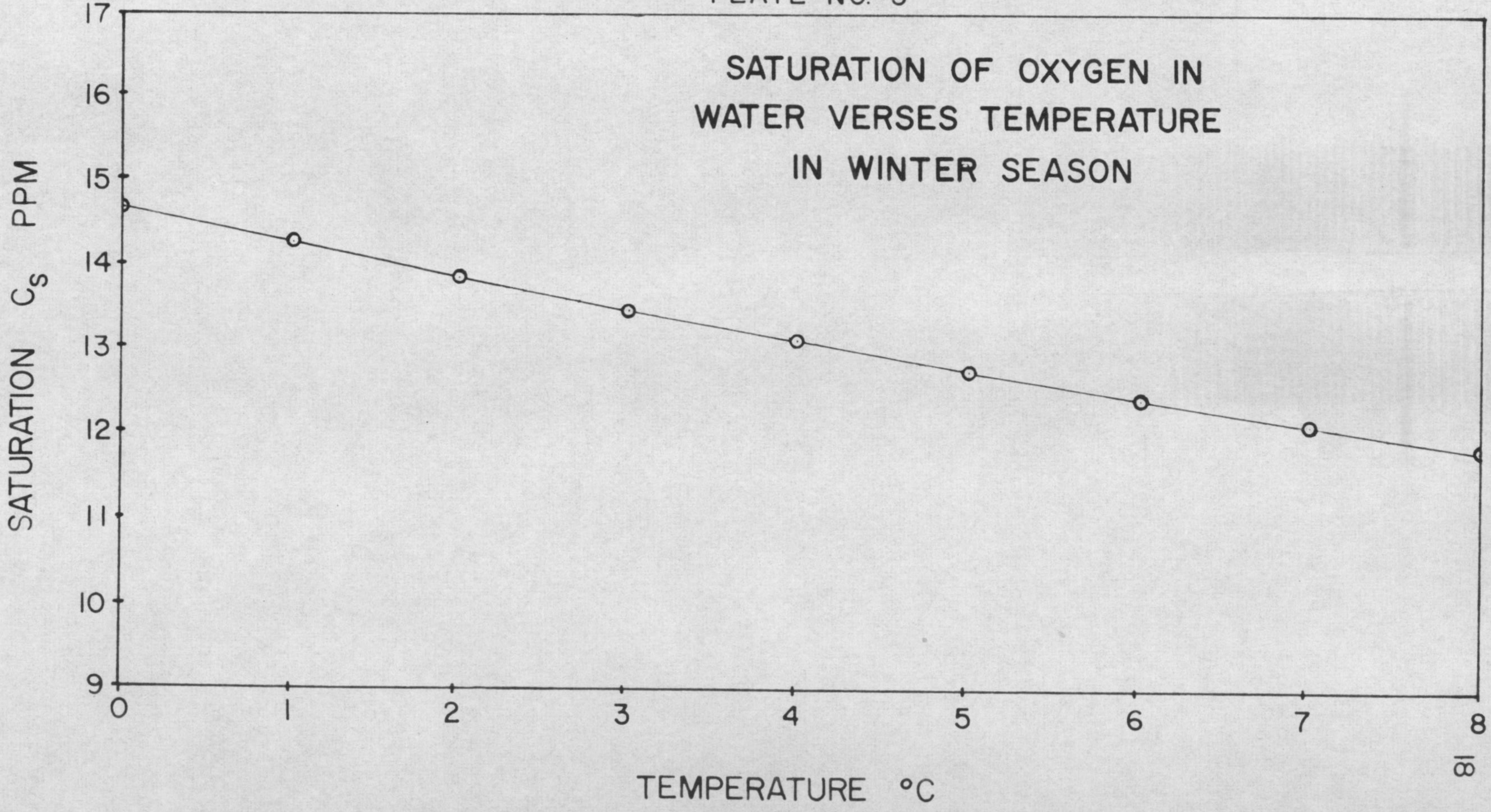
PLATE NO. 3
LAGOON
BLACK TOP WITH BOTTOM
CLEAR TOP
BLACK TOP.
TEST RUN NO. 3
JAN 17-19, 1960
DISSOLVED OXYGEN MG/L
TIME IN HOURS
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
1
2
3
4
5
6
7
8
9
10
11

PLATE NO. 4



TEST RUN NO. 4
JAN. 22-24 1960
DISSOLVED OXYGEN MG/L
0
2
4
6
8
10
12
14
16
LAGOON
CLEAR TOP
BLACK TOP WITH BOTTOM
BLACK TOP
0
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
48
51
TIME IN HOURS

PLATE NO. 5


SATURATION OF OXYGEN IN
WATER VERSES TEMPERATURE
IN WINTER SEASON
SATURATION C_S PPM
TEMPERATURE °C
9
10
11
12
13
14
15
16
17
0
1
2
3
4
5
6
7
8

1959-1960.*

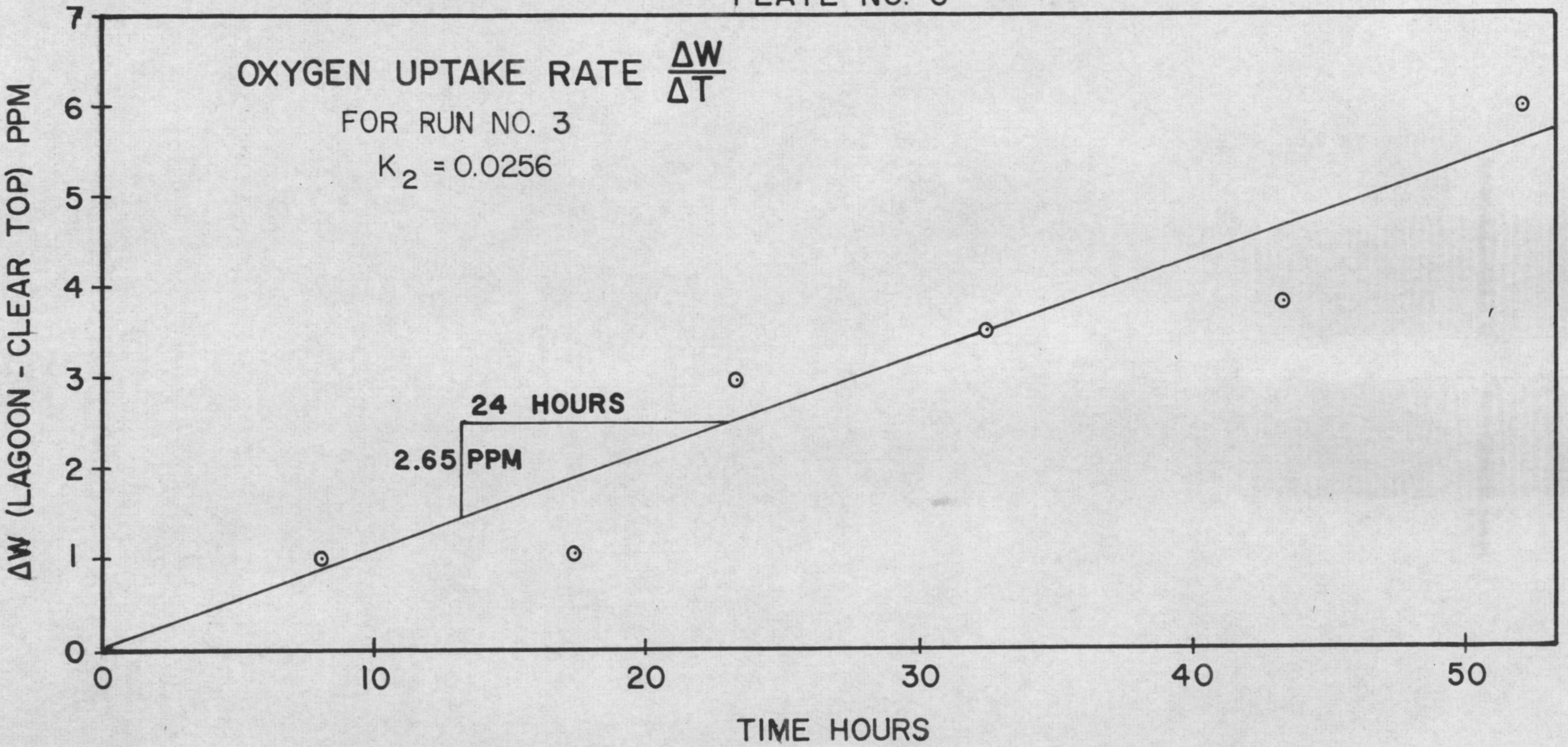
On two of the test runs, the production of oxygen by algae was so great that oxygen was being given off, instead of being absorbed at the surface. For this period, the values of k_2 were negative and of no use in this study. Two of the test runs gave satisfactory results for the period of sampling.

Experimental results did not justify a refined mathematical method of curve fitting. Results were analyzed graphically and determinations were made by a line of the best fit. The values of the constant k_2 were computed for each time interval. Results of the graphical and analyzed methods varied slightly, since the graphical method gave an overall average, while the computed values were for a specific time interval and therefore included wider variations. (see Appendix, tables 1 through 4 and plate 6).

The curve illustrated in plate 7 was computed by plotting the dissolved oxygen (mg/l)** against the oxygen deficit for various temperatures. The oxygen uptake was then plotted against the deficit with oxygen uptake expressed in pounds of oxygen per 24 hours per acre of area. A single co-axial chart of these plots was made for a convenience of interpretation.

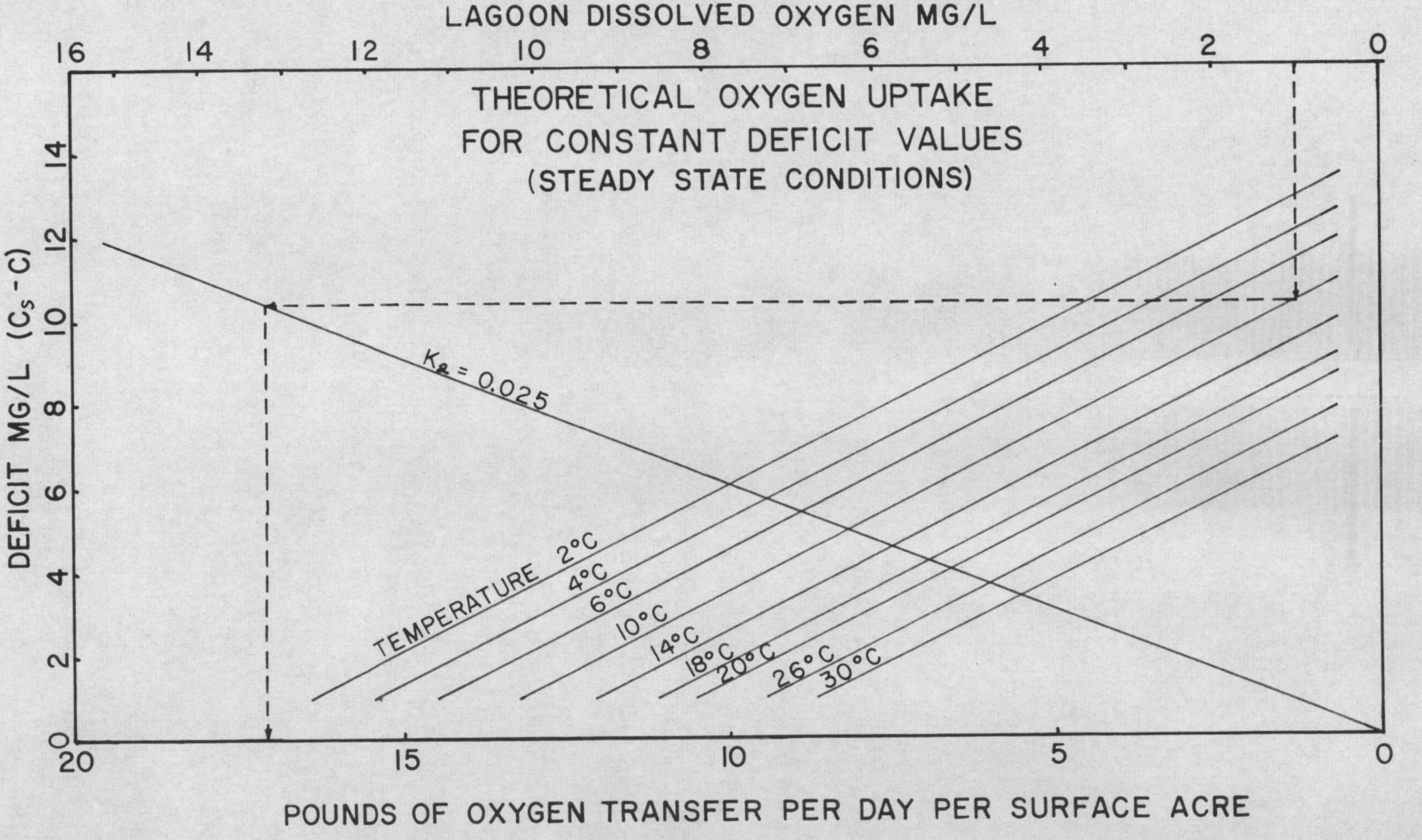
*from Corvallis, Oregon, newspaper, "Gazette Times"
**milligrams of oxygen per liter

PLATE NO. 6



OXYGEN UPTAKE RATE $\frac{\Delta W}{\Delta T}$
FOR RUN NO. 3
K_2 = 0.0256
24 HOURS
2.65 PPM
ΔW (LAGOON - CLEAR TOP) PPM
0
1
2
3
4
5
6
7
0
10
20
30
40
50
TIME HOURS

PLATE NO. 7


LAGOON DISSOLVED OXYGEN MG/L
16
14
12
10
8
6
4
2
0
THEORETICAL OXYGEN UPTAKE
FOR CONSTANT DEFICIT VALUES
(STEADY STATE CONDITIONS)
DEFICIT MG/L $(C_s - C)$
$K_2 = 0.025$
TEMPERATURE 2°C
4°C
6°C
10°C
14°C
18°C
20°C
26°C
30°C
20
15
10
5
0
POUNDS OF OXYGEN TRANSFER PER DAY PER SURFACE ACRE

CONCLUSIONS

1. Surface reaeration is an important source of oxygen in the winter season in western Oregon.

2. The maximum value of the reaeration parameter k_2 found by this study, was 0.0256 per hour ($\frac{ppm\text{-}O_2}{hours}$ per ppm deficit).

3. At a minimum dissolved oxygen content of 1 ppm* (temperature four-degree centigrade), 20.0 pounds of oxygen would be transferred through each surface acre per day, at a minimum rate of transfer.

4. The mechanics of measuring the reaeration constant are sensitive, requiring oxygen values in the lagoon to be considerably less than 50 percent saturation, and requiring periods of low algal activity. This can only be achieved on days of heavy overcast, where the diurnal fluctuation of oxygen, due to algal activity, is at a minimum. These conditions can be met on only a few days each year.

5. The subject of surface reaeration warrants further study to evaluate the controlling factors in a marine climate and as found in western Oregon.

*Parts per million equal milligrams per liter

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APPENDIX

RUN 1

Sample Time Hrs	Lagoon Oxygen ppm	Cleartop Tank ppm	Dissolved Oxygen Uptake	Temperature, C	Saturation Oxygen ppm	Deficit ppm	dW/dT	k_2
0	17.8	13.7	4.1	8	11.87	5.93		
							0.0236	0.0047
4.25	16.3	12.1	4.2	7	12.17	4.13		
							---	---*
8.25	15.7	15.1	0.6	8	11.87	3.83		
							---	---
24.0	17.9	21.7	3.8	9	11.59	6.31		
							---	---
32.0	14.8	19.3	4.5	8	11.87	2.97		
							---	---
45.0	16.0	13.4	2.6	8	11.87	4.13		
							----	---
69.0	17.9	19.4	1.5	8	11.87	6.03		
							---	---
93.0	18.0	16.3	1.8	7	12.17	5.83		

Weather: High overcast and partial sun.

Date: 18 December to 23 December, 1959

ppm = mg/l which is milligrams per liter

*Oxygen given off at surface.

RUN 2

Sample Time hrs	Lagoon Oxygen ppm	Cleartop Tank ppm	Dissolved Oxygen Uptake	Tempera-ture. C	Saturation Oxygen ppm	Deficit ppm	dW/dT	k_2
0	2.65	2.65	0	3	13.48	10.8		
							0.184	0.0179
6	3.05	1.95	1.1	5	12.80	9.75		
							0.240	0.0256
12	3.80	1.25	2.55	5	12.80	9.0		
							---	---
18	3.90	1.75	2.15	5	12.80	8.9		
							---	---
24	3.90	2.80	1.10	5	12.80	8.9		
							0.117	0.0147
30	5.8	4.0	1.80	5	12.80	7.0		
							0.209	0.0317
36	6.6	3.55	3.05	5	12.80	6.2		
							---	---
42	6.0	3.30	2.70	4	13.13	7.13		
							0.050	0.0069
48	6.0	3.0	3.00	3	13.48	7.48		

Weather: Clear, cold with a slight overcast

Date: 11 January to 13 January, 1960

RUN 3

Sample Time Hrs	Lagoon Oxygen ppm	Cleartop Tank ppm	Dissolved Oxygen Uptake	Tempera-ture, C	Saturation Oxygen ppm	Deficit ppm	dW/dT	k_2
0	11.2	10.9	0.00	6	12.48	1.28		
							0.125	0.0412
8	8.5	7.5	1.00	6	12.48	4.00		
							0.00	0.00
17.5	7.2	6.2	1.00	4	13.13	5.93		
							0.334	0.0676
23.5	9.8	6.8	3.00	2	13.84	4.04		
							0.056	0.0121
32.5	8.6	5.1	3.50	2	13.84	5.24		
							0.030	0.00587
43.0	8.5	4.7	3.80	3	13.48	5.01		
							0.232	0.050
52.5	9.6	3.6	6.00	2	13.84	4.24		

Weather: Overcast, snow and partial freezing of pond

Date: 17 January to 19 January, 1960

ppm = mg/l - milligram per liter

Dissolved Oxygen Uptake averaged from plot of curve

RUN 4

Sample Time Hrs	Lagoon Oxygen ppm	Cleartop Tank ppm	Dissolved Oxygen Uptake	Tempera- ture. C	Saturation Oxygen ppm	Deficit ppm	dW/dT	k_2
0	9.7	8.8	0.9	3	13.48	3.80		
							0.580	0.290
5.5	13.0	8.9	4.1	5	12.80	0.21		
							---	---*
10.5	13.0	9.4	3.6	6	12.48	0.52		
							---	---
23.5	8.7	6.1	2.6	4	13.13	4.43		
							0.833	---
29.5	14.5	6.9	7.6	5	12.80	1.71		
							---	---
35.0	13.1	6.2	6.9	5	12.80	0.32		
							0.157	---
42.0	14.6	6.6	8.0	6	12.48	2.12		
							0.231	---
48.5	14.6	5.1	9.5	5	12.80	1.80		

Weather: Changed from sunny clear to overcast sky, finally resulting in a precipitation.

Date: 22 January to 24 January, 1960

ppm = mg/l - milligram per liter

*Oxygen given off at surface