THE MECHANISM OF WASTE TREATMENT AT LOW TEMPERATURE

PART B: SANITARY ENGINEERING

by

John C. Ward, John S. Hunter,
Richard P. Johansen

ENVIRONMENTAL RESOURCES
CENTER

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THE MECHANISM OF WASTE TREATMENT AT LOW TEMPERATURE

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Partial Completion Report

OWRR Project No. A-007-COLO

by

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Colorado Water Resources Research Institute
Colorado State University
Fort Collins, Colorado

Norman A. Evans, Director

PREFACE

This report is part B of the overall project entitled, "The Mechanism of Waste Treatment at Low Temperature". Part A of this report was published separately by S. M. Morrison (director of the overall project), G. C. Newton, G. D. Boone, and K. L. Martin, Microbiology Department.

This report itself is composed of 2 parts: Part 1 entitled, "The Effects of Water Temperature and Elevation upon Aeration," by John S. Hunter and John C. Ward; Part 2 entitled, "BOD and COD Removal from Wastewater by Aeration with Air and Oxygen," by John C. Ward and Richard P. Johansen.

This report covers the work performed during the period of this part of the project, namely July 1, 1970, through June 30, 1972 (2 years). The total amount of support received from the Office of Water Resources Research was $4,700 per year.

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SYMBOLS AND ABBREVIATIONS

PART 1 - THE EFFECTS OF WATER TEMPERATURE AND ELEVATION UPON AERATION

a	air-water interfacial surface area per unit volume of water (ℓ^{-1})
atm	atmosphere ($m\ell^{-1}t^{-2}$)
A	altitude (ℓ) or area (ℓ^2)
cal	calorie
cm	centimeter (ℓ)
C	DO concentration (mg/ℓ)
C_1	saturation DO concentration in pure water at a barometric pressure of 1 atm, (mg/ℓ)
C_s	DO concentration in pure water at stated barometric pressure (mg/ℓ)
°C	degrees centigrade (Celsius)
$CoCl_3$	cobalt chloride
D	coefficient of molecular diffusion (ℓ^2t^{-1})
DO	dissolved oxygen concentration (mg/ℓ)
E	efficiency
E_a	activation energy (cal/mole)
Eq.	equation
ft	foot (ℓ)
°F	degrees Fahrenheit
g	gram (m) or acceleration of gravity (981 cm/sec^2)
gal	gallon (ℓ^3)
hp	horsepower ($m\ell^2t^{-3}$)
hr	hour (t)
in.	inch (ℓ)
k	chemical reaction rate (t^{-1})
°K	degrees Kelvin (°C + 273)
K_L	over-all mass transfer coefficient (ℓt^{-1})
K_La	over-all volumetric mass transfer coefficient, liquid-phase base (t^{-1})
ℓ	length
lb	pound ($m\ell t^{-2}$)
ln	natural logarithm
log	common logarithm
m	mass
M	Molecular weight of air (29 g/mole)
min	minute (t)
mg/l	milligram per liter ($m\ell^{-3}$)
ml	milliliter (ℓ^3)
mm Hg	millimeter of mercury
Na_2SO_3	sodium sulfite
Na_2SO_4	sodium sulfate

SYMBOLS AND ABBREVIATIONS (Continued)

No.	number
O_2	molecular oxygen
p	vapor pressure of water at the stated temperature (atm)
psi	pounds per square inch $(m\ell^{-1}t^{-2})$
P	atmospheric pressure $(m\ell^{-1}t^{-2})$
rpm	revolutions per minute
R	universal gas constant [1.99 cal/(mole)(^oK)]
SCFH	standard cubic feet of gas per hour at 70^oF and 1 atm (ℓ^3t^{-1})
t	time
T	temperature (^oC or ^oK as specified)
V	volume (ℓ^3)
ρ	density $(m\ell^{-3})$
θ	temperature correction coefficient for K_La (dimensionless)

PART 2 - BOD AND COD REMOVAL FROM WASTEWATER BY AERATION WITH AIR AND OXYGEN

atm	atmospheres
BOD	biochemical oxygen demand
COD	chemical oxygen demand
^{o}	degree
^oC	degrees centigrade
^oF	degrees Fahrenheit
DO	dissolved oxygen
mg	milligram
mg/ℓ	milligram per liter
OD	oxygen demand
%	percent
t	time in days
$t_{1/2}$	time required for removal of 50% of the initial oxygen demand, days
$t/t_{1/2}$	ratio of aeration time to time required for removal of 50% of the initial oxygen demand

PART 1 - THE EFFECTS OF WATER TEMPERATURE AND ELEVATION UPON AERATION

by

John S. Hunter and John C. Ward

I. Introduction

The central thrust of this project has been the study of wastewater treatment under conditions of high altitude and low water temperature. Aeration is a fundamental operation used in many wastewater treatment facilities designed to function under these conditions. The study of how aeration is affected by such conditions, then, has become an integral part of this project.

Changes in elevation are accompanied by changes in barometric pressure and atmospheric temperature. Changes in barametric pressure affect aeration directly through changes in the dissolved oxygen saturation concentration because this value determines the available driving force for transferring oxygen from the atmosphere into the water. The dissolved oxygen saturation concentration is directly proportional to atmospheric pressure in accordance with Henry's law. Henry's law is valid over a wide temperature range and can be applied whenever the proportionality constant for the particular wastewater being considered is known (Eckenfelder, 1966, page 52). The proportionality constant for domestic sewage is approximately 95 percent that of clean water (Fair, Geyer, and Okun, 1968, page 23-10).

Changes in atmospheric temperature which accompany changes in elevation do not have as direct an effect on aeration as do changes in atmospheric pressure. The degree to which atmospheric temperatures influence wastewater temperatures is a function of each individual wastewater collection and treatment system. In general, however, warmer wastewater temperatures can be expected in warmer climates and colder wastewater temperatures can be expected in colder climates. It is found through the examination of atmospheric tables that atmospheric temperatures fall with increasing elevation. Because this project was oriented about the effects of high altitude it was necessary to critically examine existing methods for predicting the effects of low water temperature upon aeration.

A review of the literature indicates that most studies which have been performed to date (for determining oxygen mass transfer rates into water at various water temperatures) have typically been carried out in systems where the water temperature was varied between 10 and 30°C. Field studies carried out under this project revealed that many wastewater treatment facilities located in the mountainous regions of Colorado aerate wastewaters having temperatures below 10°C during significant portions of the year. A few plants were found to be aerating wastewaters with temperatures below 1°C. Some doubt exists as to the appropriateness of extrapolating existing aeration data down into the 0 to 10^{o}C range, especially for the design of facilities that are to treat wastewaters having a temperature below 1^{o}C. As a result, the main emphasis of the aeration studies portion of this project has been placed on finding a reliable method for predicting the effect of water temperature upon aeration with particular attention being paid to water temperature between 0 and 10^{o}C. Such a method has been found. It is accurate over the temperature range 0 to 40^{o}C. Henry's law has been incorporated into this method to show in graphical form the combined effect of elevation and wastewater temperature upon aeration. A range in elevation of -3,000 to +18,000 feet above mean sea level and a temperature range of 0 to 40^{o}C have been represented.

II. Experiment Design

The laboratory technique used in this research effort to determine overall oxygen transfer coefficients at various water temperatures closely parallels that used in the testing of full-scale aerators. The underlying method employed is commonly referred to as the clean water, nonsteady state, test technique. Large samples of distilled water were deaerated and then each was subjected to the same mixing and submerged air discharge conditions. The temperature of each sample was rigidly controlled and the barametric pressure was measured for each test run. The absolute value of the dissolved oxygen (DO) concentration of every sample was continuously monitored during each test run with a dissolved oxygen probe. This data was logged by a strip chart recorder so that the DO values were obtained as a graphical display of DO versus time for the entire duration of each test.

A. Test Apparatus

The aeration tank and aerator used in these experiments consisted of a large Pyrex glass jar and a small turbine. The jar was cylindrical in shape with a nearly flat bottom. It had an inside diameter of 11 7/16 in. (29.05 cm) and was 17 5/8 in. (44.77 cm) deep. A flat blade impeller with 6 blades was mounted coaxially within the test cylinder at a distance of 1 7/8 in. (4.76 cm) from the bottom. The impeller diameter was 4 in. (10.16 cm) and each blade was 1/2 in. (1.27 cm) wide. An air sparger was mounted directly under the impeller. It consisted of a small, contoured, plastic, reagent dropper bottle which had been placed on one of its flat sides and then glued to a 5/16 by 2 in. (0.79 by 5.08 cm) brass bar which extended across the full width of the aeration tank bottom. The bottle had a 1/4 in. (0.64 cm) hole which was bored at the center of the flat side facing the impeller. There was approximately a 1/4 in. (0.64 cm) clearance between the sparger and the impeller. Air was supplied to the sparger through a flexible plastic tube which was positioned along the aeration tank bottom and then up the tank wall immediately behind a baffle with respect to the liquid flow induced by the impeller. Baffles were installed in the tank to prevent the formation of a vortex thereby providing better mixing conditions. Four baffles, each 1/8 in. (0.32 cm) thick, 1 in. (2.54 cm) wide, and 17 in. (43 cm) long were positioned at equal intervals around the tank. These baffles were mounted perpendicularly with respect to the tank walls and floor. Each baffle was

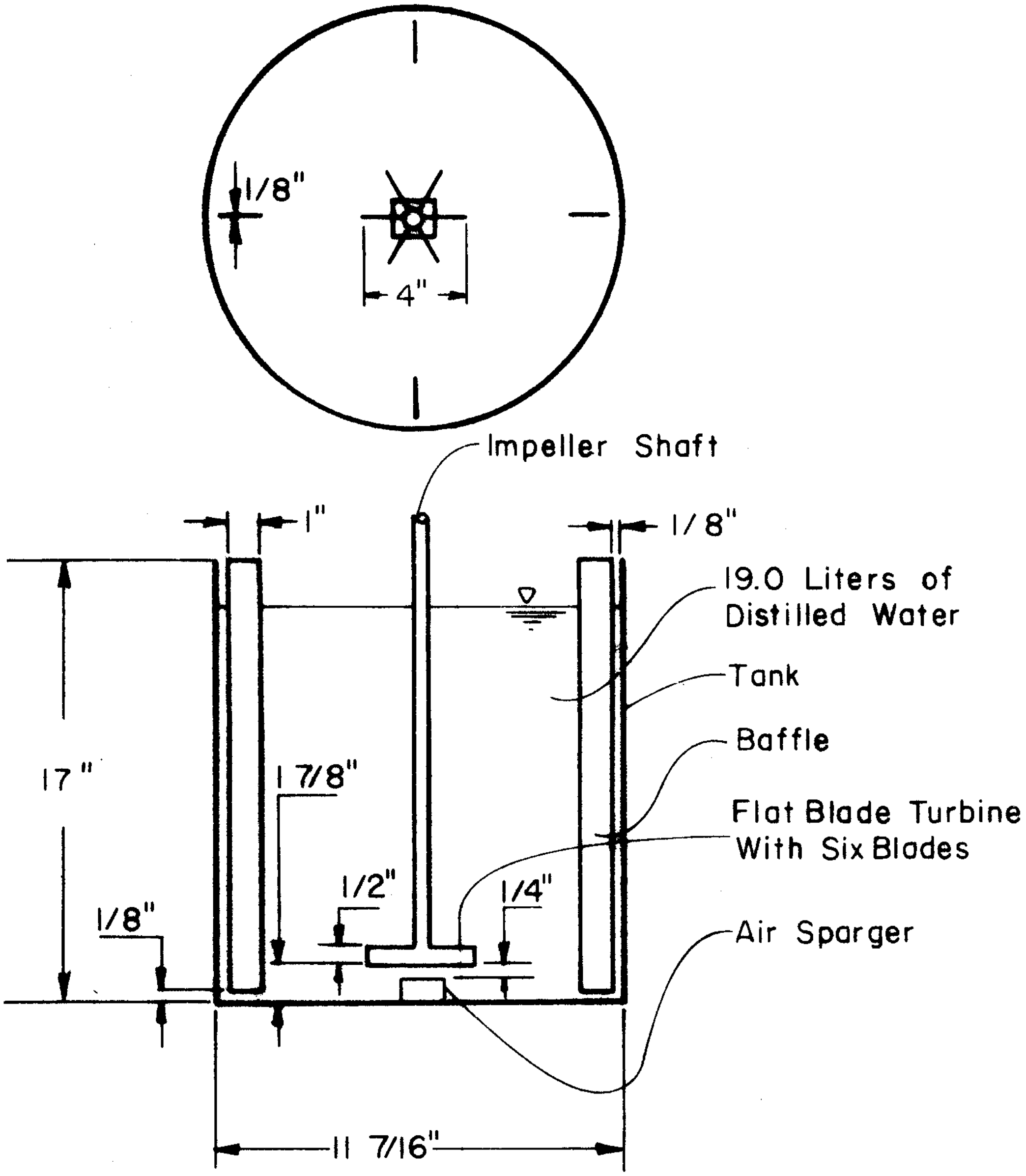

Fig. 1 Experimental Aeration Vessel Configuration

positioned 1/8 in. (0.32 cm) from the tank floor and walls to prevent the formation of any areas of stagnant flow. The above aeration test apparatus geometry was chosen as it meets the pertinent requirements of geometric similarity necessary for comparing results of this study with those of other liquid mixing studies. (Further details on this subject are available from: Bates, Fondy, and Fenic, 1966, pages 111-178; Sterbacek and Tausk, 1965, pages 73-124; and Holland and Chapman, 1966, pages 1-18.)

The compressed air supplied to the sparger was first passed through a laboratory air filter to remove any foreign materials (such as oil) that might affect the oxygen mass transfer process. The air was then passed through bubblers containing distilled water at a temperature approximately that of the water sample in the aeration vessel. This was done to reduce any effects on the data which could arise from heat or water mass exchange between the air bubbles and the water test sample. The air flow rate was controlled by means of a rotometer.

A Model ELB Experimental Agitator power drive and stand manufactured by Chemineer, Inc., of Dayton, Ohio, were used to turn the impeller shaft and hold the shaft in position. This unit could be controlled to provide any constant speed desired for the impeller from 0 to 1100 rpm.

One of the most important tasks involved in carrying out this study was the bringing of water samples to the temperatures of interest and then maintaining them at these temperatures within very small tolerances throughout the duration of the experiment. This was accomplished by supporting the aeration vessel within a slightly larger vessel which had a heat exchange fluid constantly circulating through it from a temperature regulated reservoir. A 7 cubic foot (198 liter) capacity reservoir constructed of stainless steel was used. Cooling was carried out by means of a Model Number PCC-13A Constant Flow Portable Cooling Unit manufactured by the Blue M Electric Company. Heating was accomplished by means of a hot water jacket built into the wall of the reservoir. Hot water was obtained from a laboratory hot water tap. Steam was used instead of hot water in some instances. Uniform temperature of the sample was maintained by adjusting the flow of heat exchange fluid (water containing methyl alcohol as an anti-freeze) between the reservoir and the vessel containing the aeration tank.

Instrumentation included a Cole-Parmer "touchless", portable, solid state, photo-reflective, electronic tachometer which was used for measuring the turbine shaft rotational speed; a dynamometer used to measure power input to the aeration vessel which was supplied by Chemineer, Inc., for use with its impeller drive assembly; and a Yellow Springs Instrument Company Model 54 DO meter which was connected to a Model SR-15 (S72180-15) Sargent strip chart recorder in order to provide continuous time referenced DO data.

B. Test Procedure

1. Place 5.02 gallons (19.00 liters) of distilled water in the aeration tank.

2. Turn on the impeller drive assembly and adjust impeller rotational speed to 600 rpm.
3. Turn on the air supply and adjust flow rate to 1.0 SCFH (see Appendix C for procedure).
4. Add the proper amount of cobalt chloride ($CoCl_3$) solution to the water sample (see Appendix D for dosage calculation).
5. Adjust the water sample temperature to the desired value $\pm$ 0.1°C. It will normally require 1 to 4 hours to attain a stable water sample temperature. When a stable water sample temperature is attained, make any necessary adjustments to the impeller rotational velocity and air flow rate to ensure that they are 600 rpm and 1 SCFH, respectively.
6. Calibrate the dissolved oxygen meter and strip chart recorder with the probe of the DO meter located within the aeration tank and fixed in its monitoring position (it was found that the smoothest, most consistent data output could be obtained by positioning the probe just under the water sample surface on the front side of a baffle with respect to the water flow pattern induced by the impeller. The probe membrane surface should be tilted approximately 10 to 15° from horizontal to permit constant flow of the test sample water across it). Calibrate the monitoring and recording system to the saturation DO concentration in pure water at the water test sample temperature and the existing barometric pressure (see Appendix A for calibration procedure). After the system is calibrated, leave it on line -- do not place on standby or turn if off.
7. Add the proper amount of sodium sulfite (Na_2SO_3) solution (see Appendix D for dosage calculation).
8. Measure torque being applied to the impeller shaft.
9. Continue the test run until the agitated water sample is nearly saturated with dissolved oxygen (this varies between 15 and 30 minutes, depending upon the sample temperature). Constantly monitor and make any necessary adjustments in water sample temperature and air discharge rate during all test runs.
10. Repeat steps 7, 8, and 9 two times in order to obtain 3 test runs at each desired water temperature.
11. Dispose of the water sample.

III. Data Evaluation

A. Raw Data

The above test procedure was followed in obtaining oxygen mass transfer data in water samples maintained at the following temperatures: 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, and 40°C. A summary of the raw data appears in Table 1. The values recorded in this table are DO concentrations in the samples (C_t) as read from the continuous curves of data produced during each test run. The values were read at one-minute intervals with an arbitrary zero reference time chosen such that $C_{1\ min.}$ occurred within the first portion of what appeared to be a first order reaction rate response for the recovery of DO in the sample. Normally, $C_{1\ min.}$ occurred

TABLE 1--RAW DATA

Data I.D.		C_t																	
Test No.	Run No.	1 min. (mg/ℓ)	2 min. (mg/ℓ)	3 min. (mg/ℓ)	4 min. (mg/ℓ)	5 min. (mg/ℓ)	6 min. (mg/ℓ)	7 min. (mg/ℓ)	8 min. (mg/ℓ)	9 min. (mg/ℓ)	10 min. (mg/ℓ)	11 min. (mg/ℓ)	12 min. (mg/ℓ)	13 min. (mg/ℓ)	14 min. (mg/ℓ)	15 min. (mg/ℓ)	16 min. (mg/ℓ)	17 min. (mg/ℓ)	T (°C)
1	1	1.95	3.25	4.25	5.00	5.60	6.00	6.35	6.65	6.85	7.00	7.10	7.17	7.25	--	--	--	--	20.0
	2	1.95	3.25	4.25	5.00	5.65	6.10	6.50	6.70	6.87	7.02	7.13	7.20	7.25	--	--	--	--	
	3	1.95	3.30	4.35	5.15	5.75	6.15	6.48	6.72	6.88	7.02	7.13	7.20	7.25	--	--	--	--	
2	1	2.35	3.55	4.57	5.40	6.03	6.55	6.93	7.25	7.50	7.69	7.84	7.93	8.02	8.08	8.14	8.17	8.20	15.0
	2	2.12	3.49	4.55	5.43	6.07	6.60	6.99	7.30	7.55	7.73	7.87	7.98	8.06	8.13	8.18	8.20	8.25	
	3	2.27	3.68	4.68	5.55	6.17	6.65	7.05	7.38	7.58	7.75	7.89	8.01	8.10	8.15	8.22	8.25	--	
3	1	2.17	3.85	5.26	6.16	6.87	7.43	7.87	8.23	8.50	8.69	8.85	8.95	9.06	9.13	9.22	--		10.0
	2	2.45	3.81	4.90	5.80	6.53	7.15	7.65	8.04	8.31	8.54	8.73	8.88	8.98	--	--	--	--	
	3	3.20	4.47	5.50	6.26	6.97	7.47	7.90	8.21	8.45	8.67	8.84	8.96	--	--	--	--	--	
4	1	2.10	3.50	4.65	5.65	6.45	7.05	7.60	8.00	8.32	8.56	8.76	8.90	9.05	9.15	9.23	9.30	--	9.0
	2	1.30	3.04	4.30	5.33	6.22	6.86	7.44	7.85	8.21	8.49	8.70	8.87	9.00	9.12	9.20	9.26	--	
	3	1.61	3.08	4.35	5.26	6.10	6.78	7.30	7.73	8.10	8.35	8.57	8.80	8.92	9.05	9.14	9.21	9.30	
	4	0.90	2.17	3.93	4.90	5.80	6.48	7.10	7.58	7.95	8.25	8.50	8.69	8.85	8.97	9.08	9.15	9.20	
5	1	1.23	2.73	4.13	5.17	6.05	6.77	7.36	7.82	8.21	8.54	8.77	8.95	9.13	9.26	9.37	9.46	9.54	8.0
	2	1.58	3.13	4.44	5.47	6.32	7.03	7.57	8.02	8.38	8.64	8.88	9.06	9.20	9.31	9.42	9.50	9.56	
	3	0.95	2.50	3.92	5.07	6.02	6.78	7.37	7.85	8.25	8.55	8.80	8.99	9.18	9.30	9.40	9.51	9.55	
6	1	2.75	4.00	5.05	5.90	6.63	7.21	7.70	8.10	8.43	8.70	8.92	9.11	9.24	9.35	9.42	9.52	9.62	7.0
	2	2.51	3.88	5.02	5.92	6.64	7.30	7.77	8.18	8.52	8.79	8.02	9.17	9.30	9.42	9.50	9.60	9.67	
	3	2.83	4.18	5.25	6.19	6.88	7.47	7.93	8.34	8.61	8.68	9.08	9.24	9.38	9.46	9.57	9.63	9.68	
7	1	2.67	4.02	5.11	6.08	6.82	7.50	8.04	8.47	8.81	9.10	9.32	9.50	9.68	9.80	9.90	9.97	10.00	6.0
	2	2.70	4.02	5.18	6.17	6.93	7.58	8.10	8.49	8.84	9.10	9.31	9.53	9.70	9.84	9.90	9.99	10.06	
	3	2.29	3.74	4.96	5.97	6.79	7.46	8.02	8.44	8.79	9.09	9.30	9.49	9.66	9.76	9.89	9.99	10.02	
8	1	2.74	4.12	5.28	6.22	7.00	7.63	8.19	8.60	8.93	9.23	9.44	9.65	9.80	9.93	10.01	10.11	10.19	5.0
	2	2.48	3.91	5.09	6.08	6.88	7.59	8.13	8.55	8.91	9.20	9.43	9.62	9.82	9.96	10.04	10.15	10.19	
	3	2.53	4.00	5.17	6.17	6.97	7.60	8.17	8.60	8.95	9.23	9.45	9.67	9.81	9.97	10.07	10.13	10.20	
9	1	1.60	3.19	4.48	5.61	6.53	7.30	7.91	8.40	8.84	9.18	9.47	9.71	9.91	10.08	10.70	10.30	10.40	4.0
	2	1.20	2.81	4.17	5.30	6.29	7.08	7.77	8.32	8.74	9.10	9.39	9.66	9.89	10.08	10.20	10.31	10.40	
	3	1.24	2.80	4.19	5.30	6.29	7.13	7.79	8.33	8.77	9.17	9.46	9.71	9.93	10.08	10.22	10.34	10.39	
10	1	1.69	3.15	4.50	5.67	6.60	7.40	8.06	8.58	9.02	9.42	9.73	10.01	10.21	10.39	10.52	10.65	10.77	3.0
	2	1.45	2.96	4.33	5.50	6.47	7.31	7.99	8.55	8.99	9.36	9.70	9.97	10.20	10.38	10.52	10.68	10.75	
	3	1.41	2.93	4.30	5.49	6.47	7.34	8.00	8.60	9.02	9.40	9.77	10.03	10.25	10.42	10.56	10.69	10.80	
11	1	1.30	2.79	4.17	5.38	6.39	7.23	7.93	8.57	9.02	9.43	9.79	10.09	10.30	10.50	10.66	10.79	10.90	2.0
	2	1.75	3.14	4.40	5.55	6.54	7.35	8.04	8.60	9.07	9.47	9.80	10.09	10.30	10.50	10.65	10.80	10.90	
	3	1.70	2.95	4.20	5.30	6.30	7.14	7.88	8.50	8.96	9.37	9.73	10.05	10.26	10.48	10.62	10.78	10.59	
12	1	1.90	3.50	4.87	6.00	6.98	7.75	8.44	9.02	9.50	9.88	10.20	10.48	10.70	10.89	11.03	11.21	11.30	1.0
	2	0.99	2.58	4.10	5.33	6.43	7.34	8.10	8.73	9.22	9.67	10.03	10.34	10.58	10.78	10.96	11.11	11.23	
	3	1.53	3.08	4.47	5.65	6.63	7.48	8.20	8.79	9.27	9.70	10.04	10.34	10.60	10.80	10.97	11.10	11.25	
13	1	1.60	3.10	4.50	5.65	6.73	7.55	8.30	8.91	9.40	9.83	10.23	10.51	10.77	11.00	11.15	11.30	11.45	0.5
	2	1.95	3.40	4.73	5.98	6.90	7.78	8.50	9.06	9.53	9.98	10.35	10.63	10.84	11.07	11.23	11.38	11.50	
	3	1.60	3.02	4.30	5.57	6.61	7.51	8.30	8.90	9.40	9.87	10.23	10.54	10.78	11.02	11.19	11.34	11.48	
14	1	1.70	3.40	4.80	6.05	7.05	7.90	8.63	9.18	9.63	10.07	10.37	10.64	10.83	10.99	11.12	11.30	11.40	1.0
	2	2.69	4.18	5.43	6.53	7.47	8.23	8.80	9.32	9.75	10.08	10.38	10.67	10.84	11.00	11.13	11.23	11.35	
	3	2.59	4.08	5.37	6.47	7.39	8.14	8.78	9.28	9.75	10.11	10.40	10.67	10.87	11.01	11.16	11.30	11.40	
15	1	1.47	2.54	3.77	4.65	5.43	6.03	6.49	6.84	7.14	7.38	7.56	7.69	7.79	7.87	7.94	7.99	8.03	15
	2	1.74	3.12	4.23	5.07	5.75	6.26	6.68	7.01	7.26	7.47	7.63	7.75	7.85	7.91	7.97	8.02	8.05	
	3	1.42	2.85	4.01	4.92	5.62	6.16	6.59	6.93	7.20	7.42	7.57	7.69	7.78	7.86	7.92	7.96	8.00	
16	1	1.73	2.83	3.87	4.68	5.32	5.83	6.19	6.48	6.72	6.88	7.02	7.13	7.20	7.26	7.32	7.37	7.40	20
	2	1.83	3.03	4.06	4.83	5.46	5.92	6.28	6.58	6.77	6.92	7.06	7.15	7.22	7.27	7.32	7.35	7.39	
	3	1.82	3.07	4.15	4.89	5.48	5.91	6.26	6.52	6.75	6.91	7.04	7.12	7.19	7.25	7.30	7.35	7.37	
17	1	1.46	2.54	3.43	4.10	4.51	4.83	5.17	5.52	5.80	6.03	6.21	6.33	6.42	6.48	6.53	6.58	6.62	25
	2	1.15	2.44	3.52	4.33	4.93	5.39	5.72	5.98	6.17	6.31	6.40	6.47	6.53	6.58	6.62	6.63	6.65	
	3	1.31	2.55	3.61	4.42	5.00	5.44	5.75	5.98	6.18	6.32	6.42	6.49	6.55	6.59	6.63	6.65	6.68	
18	1	1.52	2.78	3.68	4.38	4.83	5.18	5.43	5.63	5.76	5.84	5.90	5.96	6.00	6.00	6.02	6.05	6.07	30
	2	1.83	3.01	3.86	4.49	4.94	5.27	5.48	5.65	5.76	5.86	5.92	5.95	6.02	6.05	6.06	6.07	6.08	
	3	1.57	2.88	3.75	4.42	4.88	5.23	5.45	5.63	5.75	5.85	5.92	5.97	6.01	6.03	6.06	6.07	6.09	
19	1	1.45	2.50	3.41	3.99	4.42	4.69	4.92	5.07	5.17	5.24	5.30	5.33	5.35	5.38	5.40	5.42	5.43	35
	2	1.10	2.38	3.27	3.92	4.37	4.67	4.91	5.08	5.17	5.24	5.31	5.35	5.38	5.40	5.42	5.43	5.45	
	3	1.48	2.63	3.48	4.08	4.51	4.78	4.99	5.12	5.23	5.32	5.37	5.40	5.43	5.45	5.45	5.47	5.49	
20	1	1.54	2.52	3.22	3.72	4.08	4.32	4.52	4.62	4.69	4.75	4.80	4.82	4.85	4.87	4.87	4.88	4.89	40
	2	1.12	2.27	3.07	3.63	4.03	4.28	4.48	4.62	4.69	4.75	4.80	4.83	4.85	4.87	4.88	4.88	4.89	
	3	1.40	2.50	3.27	3.78	4.15	4.38	4.54	4.64	4.72	4.78	4.82	4.85	4.87	4.88	4.89	4.90	4.90	
21	1	1.57	2.57	3.50	4.30	4.98	5.52	5.98	6.35	6.69	6.95	7.21	7.43	7.62	7.74	7.88	7.98	8.07	10
	2	1.43	2.27	3.07	3.78	4.45	4.94	5.43	5.83	6.18	6.47	6.73	6.94	7.15	7.32	7.46	7.59	7.68	
	3	1.72	2.43	3.14	3.77	4.34	4.81	5.22	5.57	5.90	6.17	6.43	6.64	6.80	6.95	7.12	7.27	7.37	
22	1	3.57	4.63	5.53	6.33	6.97	7.48	7.92	8.31	8.64	8.91	9.11	9.27	9.37	9.44	9.50	9.60	9.64	7
	2	3.11	4.37	5.39	6.23	6.92	7.48	7.91	8.30	8.65	8.90	9.09	9.23	9.37	9.45	9.50	9.60	9.67	
	3	3.55	4.70	5.65	6.43	7.07	7.60	8.00	8.38	8.62	8.85	9.09	9.25	9.37	9.44	9.52	9.58	9.61	
23	1	1.35	2.78	4.06	5.08	5.97	6.66	7.18	7.62	7.94	8.21	8.42	[illegible]	8.76	8.86	8.94	9.01	9.08	10
	2	1.34	2.79	4.03	5.05	5.87	6.53	7.04	7.50	7.85	8.14	8.32	8.57	8.73	8.85	8.93	9.01	9.05	
	3	1.42	2.82	4.07	5.08	5.87	6.52	7.08	7.52	7.85	8.14	8.37	8.56	8.70	8.82	8.91	8.98	9.05	
24	1	1.42	2.46	3.23	3.75	4.11	4.35	4.53	4.66	4.73	4.78	4.81	4.84	4.86	4.88	4.90	4.90	4.90	40
	2	0.91	2.12	2.98	3.58	3.98	4.26	4.45	4.59	4.68	4.74	4.79	4.83	4.85	4.86	4.89	4.89	4.90	
	3	1.76	2.71	3.37	3.84	4.17	4.40	4.55	4.64	4.73	4.78	4.80	4.83	4.85	4.86	4.88	4.89	4.90	

approximately 1 minute after the sample DO started to rise. The DO values increased from 10 to 80 percent of saturation within 12 to 17 minutes for all test runs. Kalinske (1969, page 2) reports that the most meaningful data for aerator tests is obtained if the DO in the liquid volume increases over this range somewhere within 10 to 30 minutes.

B. Theoretical Considerations

In the technique utilized for these experiments, the sodium sulfite, catalyzed by means of cobalt chloride, reacts with the oxygen present in the sample to form sodium sulfate, removing the dissolved oxygen from the water sample by chemical reaction. Oxygen is constantly being added to the water by the aerator so the finite amount of sodium sulfite added to the sample becomes exhausted with time, and then the DO rises towards its saturation value. An equilibrium DO value of approximately 0.5 mg/l was usually noted during the period when the sodium sulfite was present in significant quantity. A point in time was reached, however, when the quantity of sodium sulfite present was reduced so much as not to be able to maintain this equilibrium DO value and, in accordance with Le Chatelier's principle, the DO level would rise. If the oxygen mass transfer process is a diffusion only process with no chemical reaction involved, the mass transfer of oxygen into the sample should follow first order kinetics as described by Fick's first law of diffusion. It was noted in these experiments that there was a short transition period between the time when the DO value first started to increase from its low equilibrium value and the time when the reaeration of the sample could be described by first order kinetics. As previously noted, this period was approximately 1 minute in duration. This transition period can be interpreted as being the time necessary for the incoming oxygen to eliminate the last fraction of sodium sulfite remaining in the sample.

Assuming that the reaeration process observed was a diffusion only process with no chemical reaction involved and that this process can be adequately described by Fick's first law of diffusion (assumptions made in all aerator tests), the rate of oxygen mass transfer, $\partial m/\partial t$, into the water sample is

$$\frac{\partial m}{\partial t} = - D\left(\frac{\partial C}{\partial x}\right) dy\ dz \qquad (1)$$

where $\partial m/\partial t$ is the rate of mass transfer, mg/hr
D is the coefficient of molecular diffusion, cm^2/hr
$\partial C/\partial x$ is the concentration gradient, mg/cm^4
and $dy\ dz$ is the area through which the oxygen molecules pass.

Fick's law is written in the form of a partial differential equation because the concentration gradient, $\partial C/\partial x$, at any fixed location in the X direction changes with time (Fair, Geyer, and Okun, 1968, page 23-5). For computational convenience the above equation can be reduced to the one-dimensional form

$$\frac{dm}{dt} = - DA\ \frac{dC}{dx} \qquad (2)$$

where A is the surface area (in cm^2) normal to the X axis across which the mass transfer occurs and x is the distance in the X direction. Expressed in terms of the Whitman two-film theory (Lewis and Whitman, 1924, pages 1215-1220) Eq. 2 takes the form

$$\frac{dm}{dt} = DA \frac{(C_s - C)}{x_L} \tag{3}$$

where C_s is the saturation DO concentration, C is the DO concentration in the water, and x_L is the thickness of the water film across which the oxygen mass transfer takes place. Because there is no way to measure the liquid film thickness, x_L, directly, it and the diffusivity term, D, are normally combined into one term designated K_L. By substituting K_L for D/x_L in Eq. 3 and then dividing both sides by the aeration tank volume, V, in cm^3, the following expression is obtained:

$$\frac{dm/dt}{V} = \frac{dC}{dt} = \frac{K_L A}{V} (C_s - C) . \tag{4}$$

The interfacial area, A, encountered in aeration practice is not easily measured. To overcome this difficulty, a term representing the interfacial surface area per unit volume of liquid, a, defined as

$$a \equiv A/V \tag{5}$$

is used to form the product $K_L a$. This product has the dimensions of reciprocal time and is usually expressed in hr^{-1}. $K_L a$ is the overall volumetric mass transfer coefficient, liquid phase base. It is commonly used to calculate oxygen mass transfer rates for aeration systems through use of the following equation which is obtained by combining Eq. 4 and Eq. 5:

$$\frac{dC}{dt} = K_L a\ (C_s - C) \tag{6}$$

where C_s and C are normally expressed in terms of mg/l and $K_L a$ in terms of hr^{-1}.

In addition to the assumptions already mentioned, it is important to note that certain other assumptions have been made in developing the discussion presented up to this point. These include:

1. Perfect mixing is attained and is maintained throughout the entire test procedure,
2. The overall mass transfer coefficient, K_La is constant regardless of time or DO concentration, and
3. The Whitman two-film theory (Lewis and Whitman, 1924, pages 1215-1220) describes the oxygen mass transfer process and the resistance of the gas film to oxygen transfer is negligible compared to the resistance of the liquid film.

Perfect mixing is nearly impossible to attain. Deviations from this condition, however, were considered to be slight for the test apparatus used in these experiments. Also, any deviation from perfect conditions, i.e., the development of DO cencentration gradients within the aeration tank, were compensated for, in part, by placing the DO probe in the same monitoring position for all test runs. The second assumption is apparently correct, but test conditions seem to influence the range of DO concentrations over which K_La can be observed to be constant during a test run. According to Landberg, Graulich, and Kipple (1969, page 447), K_La in full-scale surface aerator tests is constant only when the water sample DO is in the approximate range of 30 to 80% of saturation. Apparently, above 80% of saturation, the errors in the values of C and C_s are compounded by taking their difference. In addition, the value of C is not likely to be precisely the same over the whole aeration volume. Consequently, test results may depend upon such test conditions as size of the aeration tank and aerator characteristics. For example, in this particular study, K_La appeared to be constant between DO concentrations of approximately 5 to 80 percent of saturation. Discussion by Landberg, Groulich, and Kipple (1969, pages 447-448) indicates that the expansion of this range over which a constant K_La applies (which was noted in this study) was due, in part, by the attainment of more perfect mixing conditions than those which occur in full-scale aerator tests. The third assumption that the Whitman two-film theory is applicable, although not necessarily correct in the physical sense, provides a mathematical model which seems to provide very reasonable results (Rich, 1961, page 172).

C. Data Analysis

Solving Eq. 6 by integration yields

$$\ell n\left(\frac{C_s - C_o}{C_s - C}\right) = K_La(t - t_o) \qquad (7)$$

where C_o is the value of C at time t_o. Equation 7 can be rewritten as

$$\ell og\ (C_s - C) = \ell og(C_s - C_o) + \frac{K_La\ t_o}{2.3} - \frac{K_La\ t}{2.3}\ . \qquad (8)$$

From Eq. 8, it can be seen that a graphical plot of $\ell og(C_s - C)$ versus t will be a straight line with

$$\text{slope} = -K_L a/2.3 \tag{9}$$

and ordinate intercept at $t = 0$ of

$$\text{ordinate intercept} = \ell og(C_s - C_0) + \frac{K_L a\ t_o}{2.3} . \tag{10}$$

Values of $(C_s - C)$ were calculated at 1-minute intervals for each test run and then plotted as described above. The $K_L a$ for each test run was then determined by calculating the slope of the straight line of best fit using Eq. 7. The $K_L a$ values found are listed in Table 2 and are displayed graphically in Figure 2. A linear relationship between $K_L a$ and water temperature, T, was apparent from visual inspection. The observation was verified mathematically as the data produced a correlation coefficient for a straight line of 0.989 which shows that the regression explains 97.8 percent of the observed variance. A least squares analysis produced the following equation of the straight line, including 95 percent confidence limits for the slope and intercepts:

$$K_L a = 10.3812\ (\pm\ 0.2000) + 0.2935\ (\pm\ 0.0110)T \tag{11}$$

where $K_L a$ is expressed in terms of hr^{-1} and T in ^oC.

A close examination of the semi-log plots of $(C_s - C_t)$ versus time, t, revealed that several curved away from the straight line of best fit. Some of these plots curved up and some curved down with increasing t. The general shape of these curves was similar to the shape of the curves shown in Figure 3. The curves shown in this figure were generated by calculating $(C_s - C_t)$ values from an idealized, hypothetical set of data using C_s values which were equal to C_s, $C_s \pm 0.1$ mg/l, $C_s \pm 0.2$ mg/l, and $C_s \pm 0.5$ mg/l. If the raw data from any test run is accurate and is representative of first-order kinetics, it should plot as a straight line if the proper value of C_s is used in calculating $(C_s - C)$. This case is represented by the straight line in Figure 3 which lies in the center of the group of curves which have been generated. It can be seen from Figure 3 that if the C_s value used in calculating $(C_s - C)$ is in error, the data will plot as a curve, not as a straight line as theoretically predicted. More significantly, it can be seen that the slope of the straight line of best fit is influenced by the assumed value of C_s. The $K_L a$

TABLE 2--OBSERVED VALUES OF C_S AND K_La

Temp.	Data Identification		C_s		K_La		Note
(°C)	Test Number	Run Number	Calculated (mg/ℓ)	True (mg/ℓ)	Using Calculated C_s (hr^{-1})	Using True C_s (hr^{-1})	
20	1	1	7.52	7.50	15.8	15.7	
		2	--	--	--	--	1
		3	--	--	--	--	1
15	2	1	8.22	8.32	14.9	14.9	
		2	8.22	8.36	15.6	15.2	
		3	8.22	8.38	16.0	15.3	
10	3	1	9.34	9.34	(16.0)	(16.0)	2
		2	9.34	9.52	13.3	13.1	
		3	9.34	9.46	14.6	13.8	
9	4	1	9.57	9.57	13.3	13.3	
		2	9.57	9.57	13.4	13.4	
		3	9.57	9.57	12.6	12.6	
		4	9.58	9.50	12.3	13.0	
8	5	1	9.83	9.83	12.6	12.6	
		2	9.83	9.83	12.9	12.9	
		3	9.83	9.84	13.1	13.0	
7	6	1	10.03	9.91	11.4	11.9	
		2	10.03	9.93	12.1	12.5	
		3	10.03	9.93	12.4	12.7	
6	7	1	10.33	10.38	11.7	12.0	
		2	10.33	10.36	12.1	12.2	
		3	10.33	10.33	12.5	12.5	
5	8	1	10.53	10.53	11.9	11.9	
		2	10.53	10.57	12.1	11.7	
		3	10.53	10.53	12.2	12.2	
4	9	1	10.87	10.85	11.4	11.3	
		2	10.87	10.87	11.6	11.6	
		3	10.87	10.87	11.7	11.7	
3	10	1	11.24	11.24	11.2	11.2	
		2	11.24	11.25	11.4	11.2	
		3	11.24	11.31	11.7	11.2	
2	11	1	11.48	11.48	11.0	11.0	
		2	11.48	11.48	10.8	10.8	
		3	11.48	11.48	10.9	10.9	
1	12	1	11.78	11.88	10.7	10.7	
		2	11.78	11.85	11.0	10.8	
		3	11.72	11.85	10.6	10.8	
0.5	13	1	12.12	12.12	10.4	10.4	
		2	12.12	12.12	10.6	10.6	
		3	12.12	12.12	10.6	10.6	
1	14	1	11.82	11.90	11.5	11.5	
		2	11.82	11.82	11.1	11.1	
		3	11.82	11.90	11.1	11.0	
15	15	1	8.23	8.20	14.2	14.3	
		2	8.23	8.19	14.3	14.5	
		3	8.23	8.13	14.5	14.9	
20	16	1	7.44	7.47	15.3	15.5	
		2	7.44	7.46	15.7	15.9	
		3	7.44	7.43	15.6	16.0	
25	17	1	6.73	--	--	--	3
		2	6.73	6.71	17.4	17.4	
		3	6.73	6.71	18.2	17.7	
30	18	1	6.08	6.08	19.8	19.8	
		2	6.08	6.03	19.7	19.7	
		3	6.08	6.09	19.5	19.7	
35	19	1	5.42	5.41	20.6	21.3	
		2	5.42	5.43	21.2	21.1	
		3	5.42	5.50	22.2	20.1	
40	20	1	4.90	4.89	20.8	21.2	
		2	4.90	4.90	22.1	22.1	
		3	4.90	4.88	22.9	23.2	
10	21	1	9.19	--	--	--	4
		2	9.19	--	--	--	4
		3	9.19	--	--	--	4
7	22	1	10.03	9.93	11.5	12.0	
		2	10.03	9.93	11.9	12.3	
		3	10.03	9.88	11.8	12.3	
10	23	1	9.35	9.30	13.2	13.5	
		2	9.35	9.35	12.7	12.7	
		3	9.35	9.30	12.6	13.1	
40	24	1	4.93	4.91	22.1	22.4	
		2	4.93	4.88	21.6	22.4	
		3	4.93	4.89	21.2	21.9	

NOTES:

1. Control of the sample temperature was lost.
2. This K_La value was discarded as it was 4.7 standard deviations from the estimated K_La based upon all other K_La values calculated through the use of C_s values determined from published tables and application of Henry's law (referred to in this report as "calculated" C_s values) and 7.0 standard deviations from the estimated K_La based upon all other K_La values calculated through the use of C_s values determed by a new graphical procedure described later in this report (referred to as "true" C_s values).
3. It was not possible to calculate a K_La from the data obtained during this test run as the data did not fit a first-order pattern. The raw data tends to indicate that a zone of stagnation developed in the water sample at the DO probe membrane.
4. Some problem developed with the instrumentation which resulted in the loss of calibration. This is apparent from the fact that the recovery in DO towards saturation after an extended aeration time was only about 90 percent while in all other test runs DO recoveries of approximately 97 percent were attained within roughly the same time period. Values of K_La calculated with the data obtained gave results from 8 to as many as 17 standard deviations from the expected value.

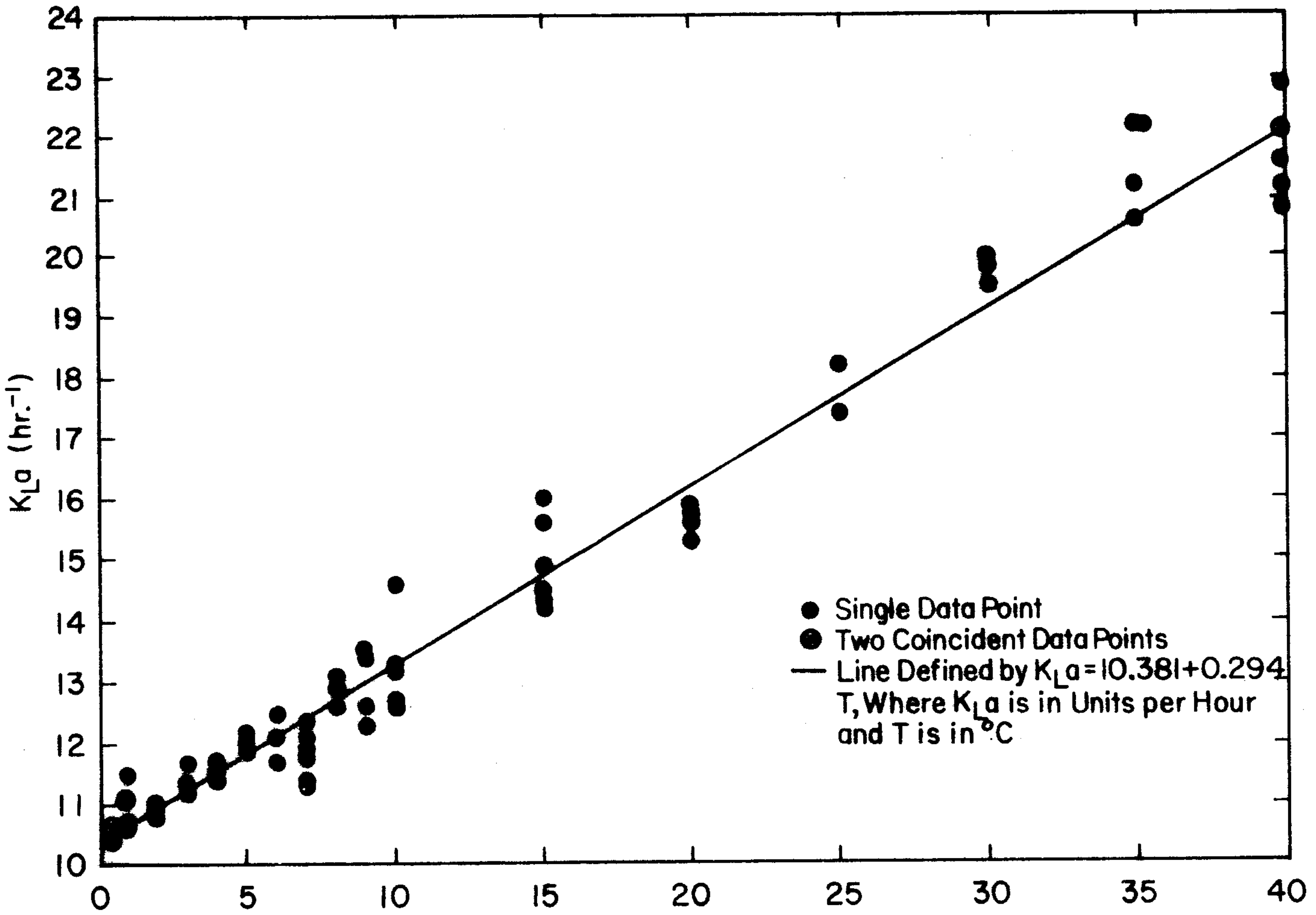

Fig. 2 Values of K_La Based on Calculated C_s

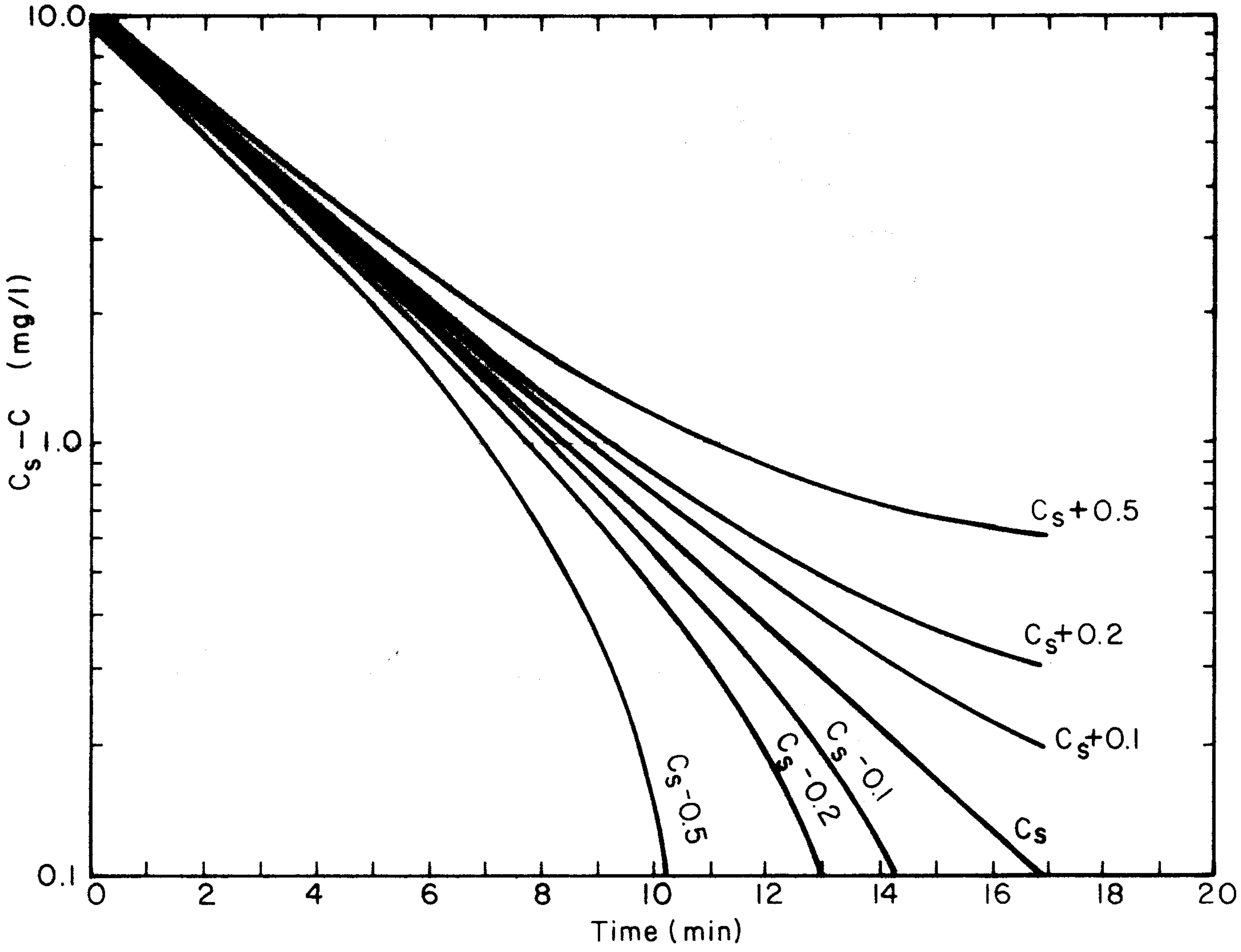

Fig. 3 Deviation From Linearity Due to Assumed Value of C_s

calculated will be too low if the C_s used in the calculations is above the true value for C_s and will be too high if the C_s used in the calculations is below the true C_s value.

After studying Figure 3, it was decided that the semi-log plots used to calculate K_La which were not linear may have been caused by the use of incorrect values of C_s when calculating $(C_s - C_t)$. A trial-and-error procedure was applied to each set of curved data plots to determine if a C_s value could be found which would make the plot of $(C_s - C_t)$ versus t linear. This proved to be a successful approach to the data for, without exception, C_s values were found which could generate linear plots. An example is shown in Figure 4. Data from Test Number 2, Run Number 3 is shown using both the calculated[1] and the true[2] value of C_s . This technique for finding the true value of C_s is analogous to one suggested by Dobbins (1964, page 60) for determining constants in modified versions of the Streeter-Phelps DO sag equation which is used in the analysis of natural stream assimilative capacity.

A tabulation of the true C_s values and respective K_La values calculated by means of the above trial-and-error procedure appears in Table 2. A graph of these K_La values versus water temperature, T , appears in Figure 5. A linear relationship between K_La and temperature was even more apparent than with the same plot using K_La values determined through the use of calculated rather than true C_s values. The data produced a correlation coefficient for a straight line of 0.995 which demonstrated that the regression explains 99.0 percent of the observed variance. A least squares analysis yielded the following equation for this straight line, including 95 percent confidence limits for the slope and intercept:

$$K_La = 10.3878\ (\pm\ 0.1363) + 0.2953\ (\pm\ 0.0075)T \qquad (12)$$

where K_La is expressed in terms of hr^{-1} and T in ^{o}C. A comparison of the results obtained from the two different methods of determining K_La appears in Table 3. It can be seen that the straight-line equation

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[1] C_s values which have been determined from published oxygen saturation concentration tables and the application of Henry's law are referred to herein as "calculated" C_s values.

[2] C_s values which have been determined by means of the trial-and-error procedure described above are referred to herein as "true" C_s values.

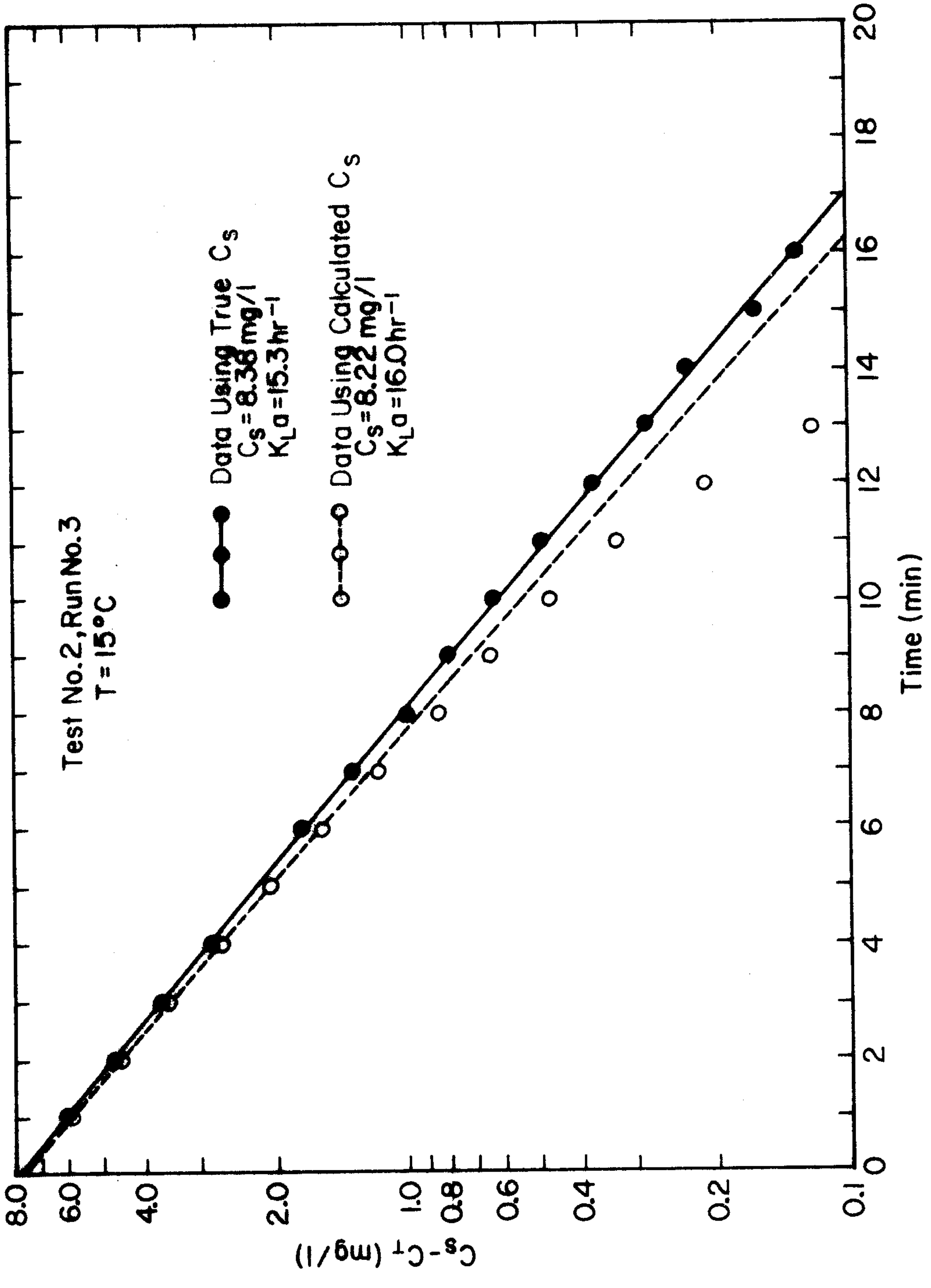

Fig. 4 Plots of $(C_s - C_1)$ Using Calculated and True C_s Values

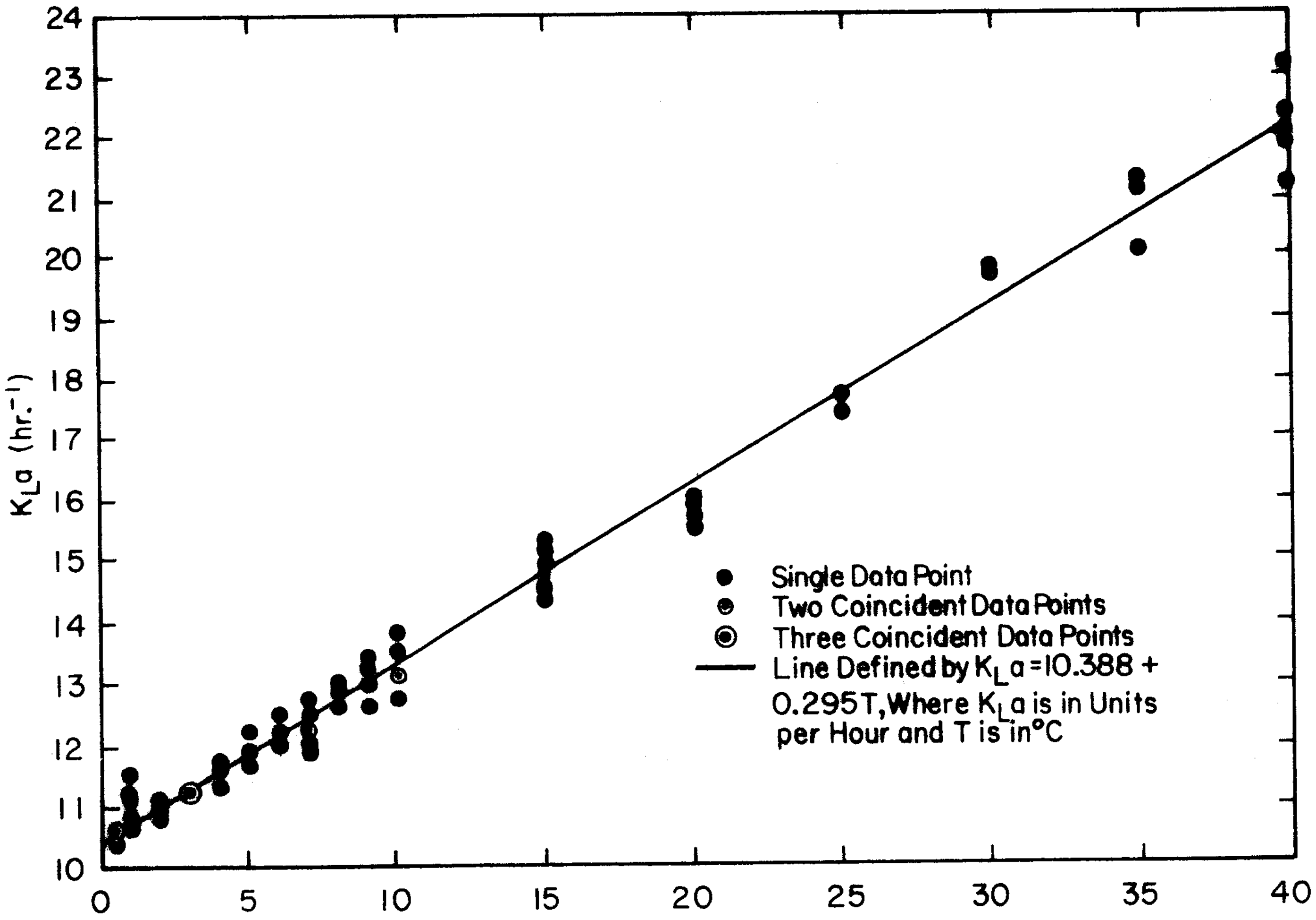

Fig. 5 Values of K_La Based on True C_S

Table 3

Statistical Analysis Summary for Both Methods of Determining K_La

Computational Technique for Determining K_La	Straight Line Correlation Coefficient	Estimate of Standard Error of Estimate (hr^{-1})	Intercept (hr^{-1})	95% Confidence Interval on (hr^{-1})	Slope ($hr^{-1}/^oC$)	95% Confidence Interval on Slope ($hr^{-1}/^oC$)
K_La from Calculated C_s	0.989	0.557	10.3812	±0.2000	0.2935	±0.0110
K_La from True C_s	0.995	0.379	10.3878	±0.1363	0.2953	±0.0075

describing the variation of K_La with water temperature is essentially the same, no matter which method is used for determining K_La but that, statistically speaking, the method which utilizes the true value of C_s provides a more precise analysis. This is also apparent from a visual comparison of Figure 2 with Figure 5 as there is less scatter of the data about the line of best fit in Figure 5.

A partial sensitivity analysis was performed to obtain information about how critical the assumed value of C_s is in determining K_La. Actual data from 0.5, 20, and 40°C test runs were used to plot $(C_s - C_t)$ on semi-log paper for true C_s, true $C_s + 0.10$, and true $C_s - 0.10$ mg/l. K_La was calculated for each plot. The results appear in Table 4. As expected, the K_La determination at higher temperature is more sensitive to the value assumed for C_s. This is due to the greater relative effect equal changes in C_s have on $(C_s - C_t)$ because such small values of C_s are encountered at high water temperatures as compared to low water temperatures. It is interesting to note that an error of $\pm$ 6 percent in the value of K_La can be expected at a water temperature of 40°C if the assumed value of C_s is 0.10 mg/l from the true value. Even at 0.5°C an error of either -4 or +2 percent in K_La can be expected if C_s is either + 0.10 or - 0.10 mg/l, respectively, from the true value.

From Table 2 it can be seen that calculated values of C_s differed from the true C_s by as much as + 0.18 to - 0.15 mg/l. A summary of the differences appears in Table 5. Approximately 32 percent of the calculated C_s values were found to be the same as the true C_s values, 37 percent differed by less than $\pm$ 0.05 mg/l, 9 percent differed from $\pm$ 0.05 up to $\pm$ 0.10 mg/l, and 22 percent differed by $\pm$ 0.10 mg/l or more. The distribution of these differences with respect to temperature appears to be random indicating that the methods used for calculating C_s were correct but that the test conditions influenced the C_s values which actually existed. For example, even though C_s values were calculated for the temperature specified for each test, the water temperature actually maintained during any experiment could vary within the range of $\pm$ 0.1°C according to the tolerances established for these investigations. At a water temperature of 20.0°C, a variation in temperature of $\pm$ 0.10°C changes the C_s value by 0.02 mg/l and at 0.0°C the same change in water temperature affects the value of C_s by 0.04 mg/l. Other assumed "constant" conditions of the experiments could also have varied slightly. In addition, factors

Table 4

Sensitivity Analysis -
Effect of K_La of 0.10 mg/l Change in C_s

	T 0.5°C Test No. 13 Run No. 1	T 20°C Test No. 16 Run No. 2	T 40°C Test No. 24 Run No. 2
K_La from True C_s	10.4	16.0	22.4
K_La from C_s + 0.10	10.0	15.2	21.0
Variation from True K_La	-0.4	-0.8	-1.4
% Variation from True K_La	-4	-5	-6
K_La from C_s - 0.10	10.6	16.6	23.7
Variation from True K_La	+0.2	+0.6	+1.3
% Variation from True K_La	+2	+4	+6

which were not considered or which were assumed to not have any effect on the test results may, in fact, have influenced the data in some unexplained way. The most likely factors involved are the temperature and humidity of the atmosphere in the laboratory which was in contact with the free water surface of the test sample at the top of the aeration tank. Although the effects of these factors cannot be predicted, their influence on the test results can be eliminated in the data analysis step by the procedure outlined for determining the true C_s of the actual test conditions which existed. The number and magnitude of the differences between calculated and true C_s values encountered in this study were great enough to require that the trial-and-error procedure presented for identifying the true value of C_s be used if individual K_La values were to be determined in the most precise manner. It is important to note, however, that the standard approach of calculating C_s from tables and the application of Henry's law gave essentially the same result in terms of the relationship between K_La and temperature. The overall conclusions drawn from this study, then, are not dependent upon the method utilized to compute C_s . (This further substantiates the interrelated conclusions drawn earlier that variations in the true C_s values encountered were random, these variations were due to unbiased differences between assumed and actual test conditions, and the standard approach to calculating C_s is correct.)

Table 5

Differences Between Calculated C_s and True C_s

Difference (mg/ℓ)	Number Greater than True C_s	Number Less than True C_s	Number Equal to True C_s
0.000			21
0.001 - 0.049	8	17	
0.050 - 0.099	6	0	
0.100 - 0.149	6	6	
$\geq$ 0.150	2	1	

IV. Results

A. Effect of Water Temperature Upon Power Requirements

The rotational speed of the experimental aeration vessel impeller was maintained at 600 rpm in order to ensure consistent and idential mixing conditions throughout all test runs. The torque on the impeller shaft was measured during each test run to determine if water temperature had any effect upon power requirements. The applied torque, a measure of the power input to the aeration vessel, was found to be a constant 0.308 foot-pounds for all water temperatures tested $(0 - 40^{\circ}C)$. It was concluded, therefore, that water temperature has no effect upon the power required to achieve the same degree of mixing in aeration operations. The power required (3.08 foot-pounds per second) was applied to a volume of 0.669 cubic feet, so that the power per unit volume was 4.61 pounds/(second)(ft^2). The mean velocity gradient is the square root of the ratio of the power per unit volume divided by the absolute viscosity. For the range of water temperatures involved in this study, the average velocity gradient varied from 351 sec^{-1} at $0^{\circ}C$ to 581 sec^{-1} at $40^{\circ}C$.

B. Effect of Water Temperature Upon Aeration

The nameplate ratings of aerators are usually referenced to an operating water temperature of $20^{\circ}C$. To find the aeration capacity when the expected operating water temperatures are different from $20^{\circ}C$, it has become standard engineering practice to make corrections by adjusting the overall oxygen mass transfer coefficient, K_La . The calculation employed is

$$K_La_{(T)} = K_La_{(20^{\circ}C)} F \tag{13}$$

where F is the $20^{\circ}C$ reference correction factor which is defined by

$$F = \frac{K_La_{(T)}}{K_La_{(20^{\circ}C)}} \tag{14}$$

and T is the water temperature in $^{\circ}C$. When a temperature, T , is specified, it has been assumed in the literature that the $20^{\circ}C$ reference correction factor, F , is a constant for all aeration configurations. If this assumption is correct, F can be expressed in terms of this study's results as

$$F = \frac{10.3878 + 0.2953\ T}{16.2938} \tag{15}$$

or,

$$F = 0.6375 + 0.0181\ T\ . \tag{16}$$

Therefore, the effect of water temperature upon aeration is given by the expression

$$K_La_{(T)} = K_La_{(20^{\circ}C)} (0.6375 + 0.0181\ T)\ . \tag{17}$$

The 1.81 percent per °C variation in the 20°C reference correction factor, F , measured in these experiments agrees reasonably well with values found by other investigators. In four sets of experiments, Downing and Truesdale (1955) observed variations of 2.02, 2.38, 1.73, and 2.06 percent per °C. Truesdale and Vandyke (1958) obtained results of 1.8, 1.5, 0.8, and 1.8 percent per °C. The average of these 8 observations is 1.76 percent per °C, a value which differs little from the results of this study.

It is more meaningful to reference corrections in K_La to a temperature of 0°C because in this way it is possible to show the actual rate of change in K_La with temperature rather than the variation in the 20°C correction factor. The results of this study referenced to 0°C are expressed as (from equation 12)

$$\frac{K_La}{K_La_o} = 1 + 0.0284\ T \qquad (18)$$

where K_La_o is the value of K_La at $T = 0°C$. From Eq. 18 it can be seen that the actual rate of change in K_La is 2.84 percent per °C. Plots of variations in K_La with water temperature, T , for a cross section of correction factors which have been reported in the literature are presented in Figure 6. All have been referenced to 0°C. As will be explained later, the correction factor has been reported in both the exponential and linear form. In Figure 6, those correction factors that are exponential are denoted by θ_e and those that are linear are denoted by θ_ℓ, θ being the coefficient which is either raised to the T power or multiplied by T for the exponential and linear forms, respectively. From Figure 6, it appears that the correction factor identified in this study is approximately the mean of the other correction factors which have been reported in the literature, be they exponential or linear in form.

It can be shown that for the values of θ reported and the water temperatures involved, $\theta_\ell \doteq \theta_e - 1$, so that values of θ_ℓ and θ_e can be compared directly.

C. Combined Effect of Elevation and Water Temperature Upon Aeration

Equation 6 can be used to construct diagrams which show the dependence of aerator capacity upon both elevation and water temperature. A different diagram is required for each operating DO concentration, C , of interest. Only one of these diagrams will be presented herein. The full process of its development will be given as an example of how other such diagrams can be prepared. The operating DO concentration, C , selected for this example was 2.0 mg/l because the use of this

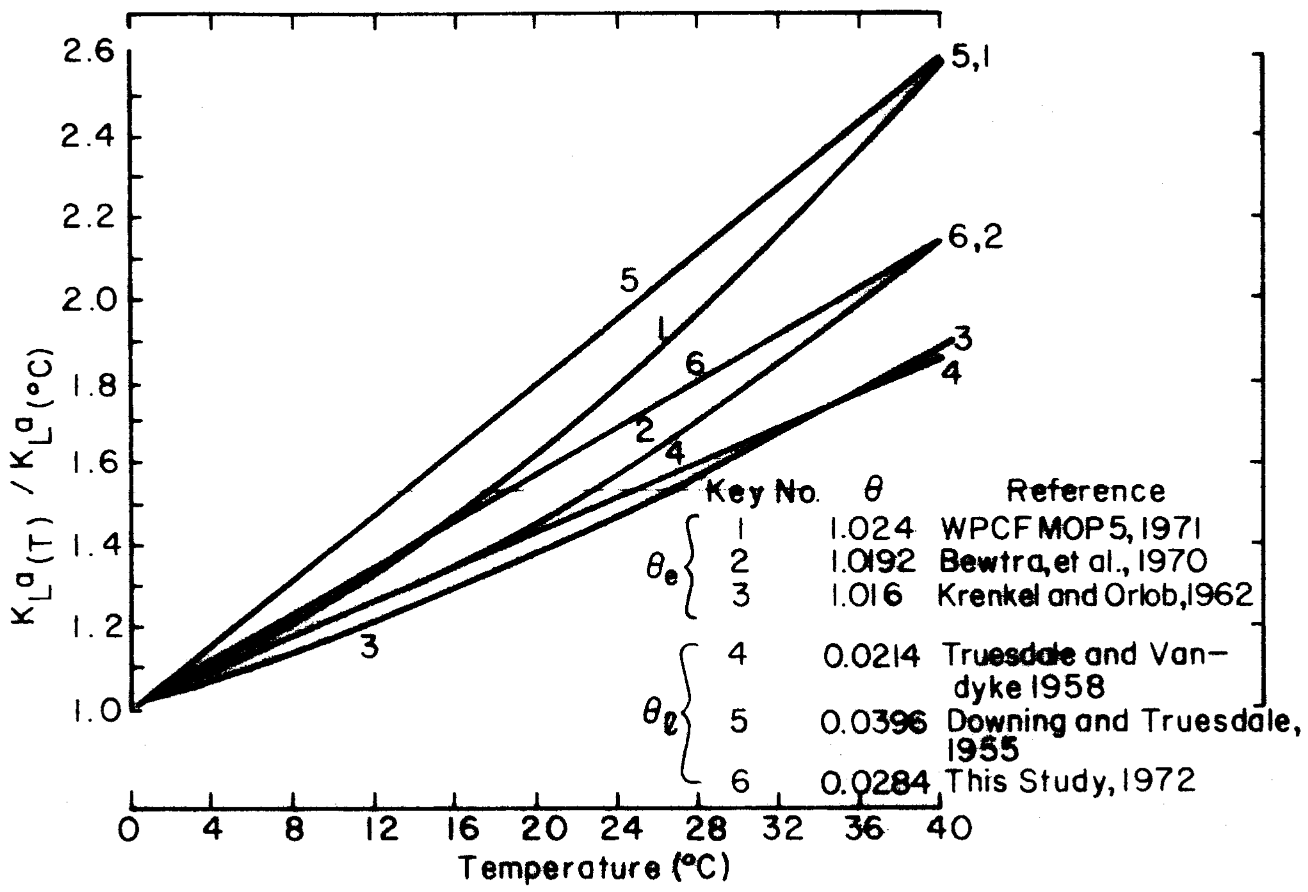

Fig. 6 Variation of K_La with Temperature

value seems to be common practice within the sanitary engineering profession. (It is stated in Water Pollution Control Federation MOP 5 (1971, page 15) that it is usually necessary to maintain this DO concentration in the aeration tank effluent in order to avoid the development of septic conditions in final settling tanks. In addition, Eckenfelder (1970, page 137) states that this DO concentration should be maintained if nitrification of the wastes being treated is to be achieved.)

The development of a diagram which can be used to determine the dependence of aerator capacity upon both elevation and water temperature follows these seven basic steps:

1. Calculate C_s for a wide range of water temperatures and elevation (see Table 6).
2. Calculate $(C_s - C)$ for all the above values of C_s (see Table 7).
3. Calculate values of K_La for all the water temperatures using Eq. 12 (see Table 8).
4. Multiply the corresponding values of $(C_s - C)$ and K_La (see Table 9).
5. Calculate the value $K_La(C_s - C)$ for water at 20°C located at sea level.
6. Calculate values of operating efficiencies relative to the nameplate rating conditions specified in Step 5 for all water temperatures and elevations by means of the following relationship which has been developed from Eq. 6 (see Table 10):

$$\text{relative operating eff.} = \frac{K_La_{(T)}\ (C_s - C)}{K_La_{(20^\circ C)}\ (C_{s_{\text{sea level}}} - C)} \quad (19)$$

7. Enter all the values of Eq. 19 on a piece of rectilinear graph paper with elevation as ordinate and water temperature as abscissa. Draw isoaeration lines connecting all points of equal relative aeration efficiencies at desired intervals (see Figure 7).

It can be seen from Figure 7 that an aerator maintaining a constant aeration tank DO of 2.0 mg/l which is located at any combination of elevation and water temperature represented by the 1.00 isoaeration line will be transferring the same amount of oxygen into the water as the same aerator could if it was maintaining the same operating DO in the same aeration tank located at mean sea level and containing water having a temperature of 20°C. Likewise, the same aerator operating in water with a DO concentration of 2.0 mg/l and located at any combination of elevation and water temperature represented by the 0.50 isoaeration line can only produce 50 percent of its 20°C, constant 2.0 mg/l DO concentration, mean sea level output.

Charts for other operating DO concentrations would have the same general configuration as represented in Figure 7 although the isoaeration lines would not be located in idential positions.

Table 6

DO at Saturation for Various Elevations and Water Temperatures

Elevation (ft)	Atmospheric Pressure (atm.)	C_s(mg/ℓ) for								
		0^oC	5^oC	10^oC	15^oC	20^oC	25^oC	30^oC	35^oC	40^oC
+ 18,000	0.499	7.28	6.35	5.60	4.98	4.48	4.06	3.70	3.35	3.01
+ 15,000	0.565	8.24	7.19	6.33	5.64	5.07	4.60	4.18	3.79	3.40
+ 12,000	0.637	9.30	8.12	7.15	6.37	5.72	5.19	4.72	4.28	3.84
+ 9,000	0.715	10.43	9.12	8.03	7.15	6.43	5.83	5.30	4.81	4.32
+ 6,000	0.802	11.74	10.25	9.04	8.05	7.24	6.56	5.97	5.42	4.85
+ 3,000	0.897	13.11	11.44	10.08	8.98	8.08	7.32	6.66	6.05	5.42
sea level	1.000	14.65	12.79	11.27	10.03	9.02	8.18	7.44	6.75	6.05
- 3,000	1.114	16.33	14.27	12.57	11.19	10.06	9.12	8.30	7.53	6.75

Table 7

$C_s - C$ ($C = 2.0$ mg/ℓ)

Elevation (ft)	$C_s - C$ (mg/ℓ) for								
	0°C	5°C	10°C	15°C	20°C	25°C	30°C	35°C	40°C
+ 18,000	5.28	4.35	3.60	2.98	2.48	2.06	1.70	1.35	1.01
+ 15,000	6.24	5.19	4.33	3.64	3.07	2.60	2.18	1.79	1.40
+ 12,000	7.30	6.12	5.15	4.37	3.72	3.19	2.72	2.28	1.84
+ 9,000	8.43	7.12	6.03	5.15	4.43	3.83	3.30	2.81	2.32
+ 6,000	9.74	8.25	7.04	6.05	5.24	4.56	3.97	3.42	2.85
+ 3,000	11.11	9.44	8.08	6.98	6.08	5.32	4.66	4.05	3.42
sea level	12.65	10.79	9.27	8.03	7.02	6.18	5.44	4.75	4.05
- 3,000	14.33	12.27	10.57	9.19	8.06	7.12	6.30	5.53	4.75

Table 8

K_La (hr^{-1})

0°C	5°C	10°C	15°C	20°C	25°C	30°C	35°C	40°C
10.39	11.86	13.34	14.81	16.29	17.76	19.24	20.70	22.18

Table 9

$K_La\ (C_s - 2.)$

Elevation (ft)	$K_La(C_s - 2.)$ mg/(ℓ)(hr) for								
	0^oC	5^oC	10^oC	15^oC	20^oC	25^oC	30^oC	35^oC	40^oC
+ 18,000	54.8	51.5	48.0	44.2	40.4	36.6	32.7	28.0	22.4
+ 15,000	64.8	61.5	57.8	53.9	50.0	46.2	41.9	37.0	31.1
+ 12,000	75.8	72.5	68.7	64.7	60.6	56.6	52.3	47.2	40.8
+ 9,000	87.6	84.4	80.5	76.2	72.2	68.0	63.5	58.2	51.5
+ 6,000	101.1	97.7	93.9	89.5	85.3	81.0	76.4	70.8	63.2
+ 3,000	115.5	111.8	107.9	103.3	99.0	94.4	89.6	83.8	75.8
sea level	131.4	127.8	123.8	118.9	114.3	109.7	104.7	98.8	89.8
- 3,000	149.0	145.3	141.0	136.0	131.2	126.3	121.2	114.4	105.2

Table 10

$$\frac{K_La_{(T)}(C_s - 2.0)}{K_La_{(20^oC)}\,(C_{s_{\text{sea level}}} - 2.0)}$$

Elevation (ft)	$K_La_{(T)}(C_s - 2.0)/K_La_{(20^oC)}\,(C_{s_{\text{sea level}}} - 2.0)$								
	0^oC	5^oC	10^oC	15^oC	20^oC	25^oC	30^oC	35^oC	40^oC
+ 18,000	0.47	0.45	0.41	0.38	0.35	0.32	0.28	0.24	0.19
+ 15,000	0.56	0.53	0.50	0.47	0.43	0.40	0.36	0.32	0.27
+ 12,000	0.66	0.63	0.60	0.56	0.53	0.49	0.45	0.41	0.35
+ 9,000	0.76	0.73	0.70	0.66	0.63	0.59	0.55	0.50	0.45
+ 6,000	0.88	0.85	0.82	0.78	0.74	0.70	0.66	0.61	0.55
+ 3,000	1.01	0.97	0.94	0.90	0.86	0.82	0.78	0.73	0.66
sea level	1.14	1.11	1.08	1.04	1.00	0.95	0.91	0.86	0.78
- 3,000	1.30	1.27	1.23	1.18	1.14	1.10	1.06	1.00	0.92

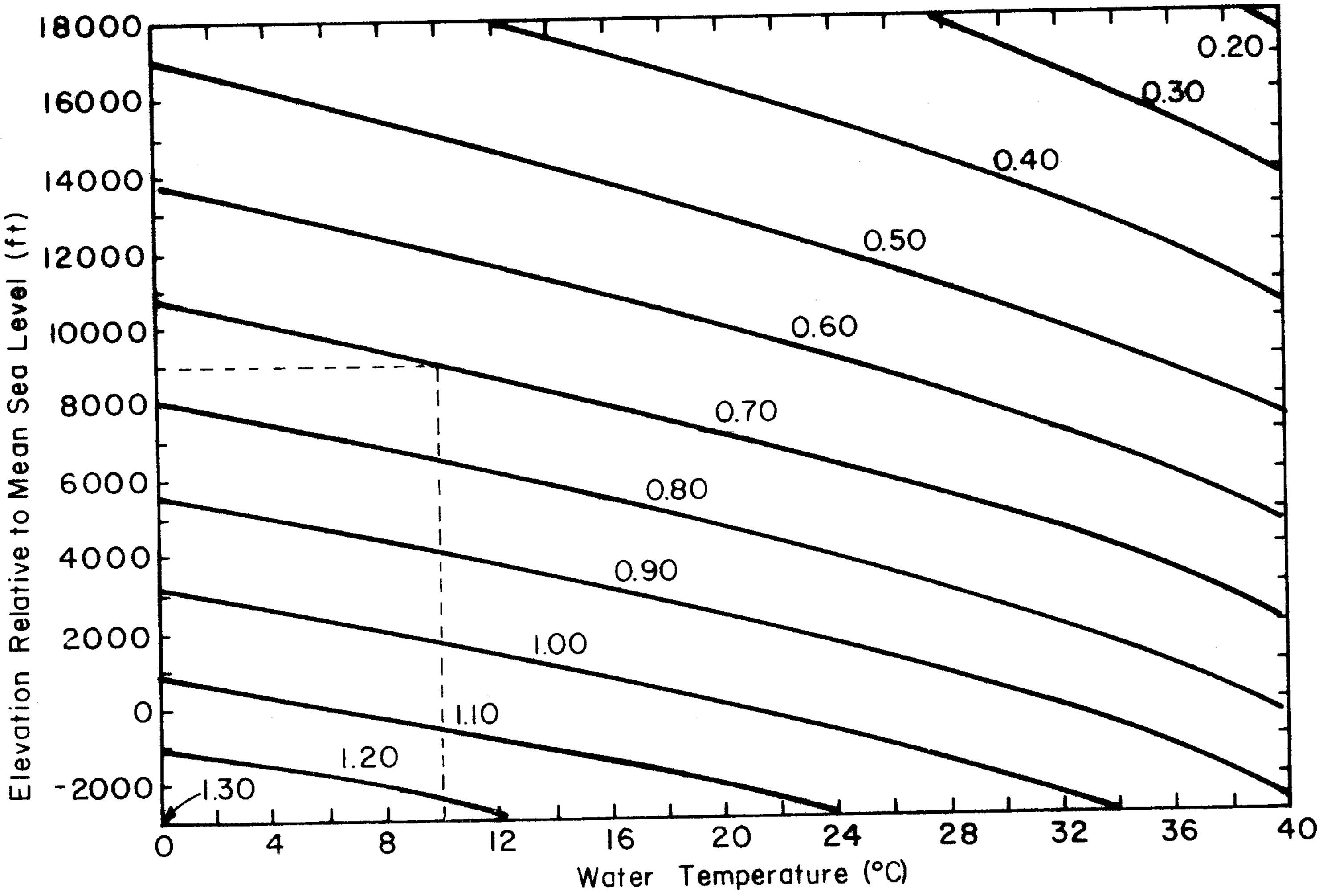

Fig. 7 The Combined Effect of Elevation and Water Temperature Upon Aeration (Operating DO= 2.0mg/l)

In order to use Figure 7 in aeration design it is only necessary to calculate aerator capacity at mean sea level in water having a temperature of 20°C and a DO concentration of 2.0 mg/l by means of Eq. 6. This value is then multiplied by the relative operating efficiency factor found in Figure 7 at the point represented by the operating elevation and water temperature. This procedure is illustrated in the following example:

> A 50-hp aerator is rated at 2.5 lb O_2/(hp)(hr) in a 10^6 gal aeration tank. What will its output be in a 10^6 gal aeration tank located at an elevation of 9,000 ft. The water temperature of concern is 10°C and the DO level to be maintained is 2.0 mg/l.

1. Calculate aerator capacity in a 10^6 gal aeration tank located at an elevation of mean sea level and containing water at a temperature of 20°C and a DO level of 0.0 mg/l.

$$(50 \text{ hp})(2.5 \text{ lb } O_2/(\text{hp})(\text{hr}) = 125 \text{ lb } O_2/\text{hr} \ .$$

2. Apply Eq. 6 to find K_La of the aerator

$$K_La = \frac{125 \text{ lb/hr}}{(10^6 \text{ gal})(9.02 \text{ mg/l})} \times \frac{\text{mg/l}}{(8.34 \text{ lb}/10^6 \text{ gal})} = 1.66 \text{ hr}^{-1} .$$

3. Apply Eq. 6 to find aerator capacity at mean sea level, a water temperature of 20°C, and an operating DO concentration of 2.0 mg/l .

$$\frac{\Delta C}{\Delta t} = (1.66)(9.02 - 2) = 11.63 \frac{\text{mg}/\ell}{\text{hr}} \ .$$

4. Apply the correction factor obtained from Figure 7:

$$(0.7)(11.63)(8.34) = 67.8 \text{ lb } O_2/\text{hr}.$$

The above answer can be adjusted to any other design DO concentration, C , through Eq. 6. For design purposes, however, a chart based on a 0.0 mg/l DO design concentration instead of 2.0 mg/l would be more convenient as it would eliminate one calculation step if the design DO was different than 2.0 mg/l. The 2.0 mg/l DO example chart was produced in this report in order to more adequately show actual relative operating efficiencies commonly encountered in standard design practice.

Although the procedure outlined for developing the chart in Figure 7 appears to be dependent upon the K_La values characteristic of the aerator used in these experiments, it, in fact, was not. This can be seen by rewriting Eq. 19 of Step 6, the basis for constructing this chart, in the following form:

$$\text{rel. op. eff.} = \left[\frac{K_La_{(T)}}{K_La_{(20^\circ C)}}\right]\left[\frac{(C_s - C)}{(C_{s_{\text{sea level}}} - C)}\right] . \qquad (20)$$

The ratio $K_La_{(T)}/K_La_{(20^oC)}$, as mentioned earlier, is independent of the aerator being considered. So are the terms $(C_s - C)$ and $(C_{s_{\text{sea level}}} - C)$. Figure 7 and any other charts like it which are produced for other operating DO concentrations, therefore, are general in nature and are applicable for the design or evaluation of any aeration device.

One basic question has been of special interest in this investigation. That question is whether or not the tendency toward decreased aerator output due to the decreasing C_s and K_La values resulting from decreasing atmospheric pressure and water temperature, respectively, which are associated with increasing elevation can be overcome by the tendency toward increased aerator output due to increasing C_s values resulting from expected decreases in water temperature with increasing elevation. This question can be answered from the relationships shown in Figure 7. Most of the isoaeration lines are very nearly linear within the temperature range of 0 to 15°C, a range which includes water temperatures commonly encountered in domestic wastewater treatment facilities located in the mountainous regions of Colorado and, presumably, in many other similar regions of the United States. The slopes of those portions of the isoaeration lines located in this water temperature range vary from approximately 140 ft/°C for the 1.10 isoaeration line to 200 ft/°C for the 0.50 isoaeration line. By visually matching these values with their respective isoaeration lines in Figure 7 it is seen that a 1°C increase in water temperature is equivalent to an increase in elevation of between 140 and 200 ft as far as aerator performance is concerned, the actual value depending upon the particular altitude of reference. In order to determine whether the change in altitude or whether the change in water temperature predominates in influencing aerator performance it is necessary to find out if the change in elevation associated with a 1°C change in water temperature in actual wastewater treatment plants falls above or below the 140 to 200 ft range. Water temperatures encountered in wastewater aeration units are not solely a function of elevation. Many other factors are involved, the most important being detention time and ambient air temperature. Two extreme cases are encountered: (1) a completely housed activated sludge facility and (2) shallow aerated ponds. Intuitively, there are only moderate changes in water temperature with changes in elevation for an enclosed activated sludge plant. There should be little doubt that it would require a change in elevation greater than 200 ft to realize a 1°C change in water temperature. The remaining critical consideration is whether or not the case on the other extreme, the shallow aerated pond, would also require a change in elevation greater than 200 ft to realize a 1°C change in water temperature. In this case, the water temperature will be strongly influenced by ambient air temperature due to the long detention times involved. According to standard atmospheric tables, for ground elevations existing in the United States (or in the world for that matter), there is a 1°C decrease in atmospheric temperature for approximately every

500 foot increase in elevation. Even if the change in aeration pond temperature with elevation was twice that experienced in the atmosphere, it would still mean that a change in elevation greater than 200 ft would be required to experience a 1°C change in the water temperature within the aeration pond. Because this is unlikely, it indicates that for all types of treatment facilities, ranging from enclosed activated sludge plants to shallow aeration ponds, those factors associated with increasing altitude which tend to reduce aerator output predominate over those factors which tend to enhance aerator output. This same conclusion can be drawn by examining Figure 7 by itself. There is absolutely no way to obtain a relative operating efficiency of 1.00 at elevations greater than 3,200 ft, no matter what the operating water temperature. If the effects of increasing elevation could be overcome by reduced water temperatures, it would be possible to find water temperatures at any elevation where a relative operating efficiency of 1.00 or greater could be attained.

It is interesting to derive and examine the mathematical relationship between elevation, water temperature, and efficiency, a specific case being represented in Figure 7. The saturation DO concentrations used in this study were calculated from the following empirical equation (ASCE Committee on Sanitary Engineering Research, 1960, page 48)

$$C_s = 14.652 - 0.41022\ T + 7.991 \times 10^{-3}\ T^2 - 7.7774 \times 10^{-5}\ T^3 \tag{21}$$

where C_s is in mg/ℓ and T is °C. Equation 21 becomes quite inaccurate at water temperatures above 40°C.

From Eq. 6, the value of dC/dt at 0°C, zero elevation, and for $C = 0$ mg/ℓ is

$$\left(\frac{dC}{dt}\right)_0 = 14.652\ K_L a_0 \quad . \tag{22}$$

For an atmospheric pressure P (in atm), Eq. 6 can be written

$$\frac{dC}{dt} = K_L a(PC_s - C) \ . \tag{23}$$

If one divides Eq. 23 by Eq. 22, one obtains

$$\frac{dC/dt}{(dC/dt)_0} = \left(\frac{K_L a}{K_L a_0}\right) \frac{(PC_s - C)}{14.652} \equiv E \tag{24}$$

where E is the relative aeration efficiency. Setting $C = 0$ mg/ℓ in Eq. 24, gives

$$E_0 = \left(\frac{K_L a}{K_L a_0}\right) \frac{PC_s}{14.652} \quad . \tag{25}$$

For water temperatures between 0 and 100°C, the following empirical equation is reasonably accurate:

$$\ell n \left(\frac{-dC_s}{dT}\right) = \alpha + \beta\ T \qquad (26)$$

where the numerical values of α and β are -0.92 and -0.0398 respectively. Integration of Eq. 26 gives

$$C_s = C_{s0} - \frac{e^{\alpha}}{\beta} (e^{\beta T} - 1) \qquad (27)$$

where C_{s0} is the value of C_s at $T = 0^{\circ}$C. Substitution of the appropriate values of α and β into Eq. 27 gives

$$C_s = C_{s0} - 10 + 10 \exp(-0.04\ T)\ . \qquad (28)$$

Clearly a plot of $\log[(C_s + 10 - C_{s0})/10]$ versus T should be a straight line. Defining $\beta \equiv -\gamma$, for $\gamma T < 1$,

$$e^{-\gamma T} - 1 \doteq - \gamma T + \frac{\gamma^2 T^2}{2} - \frac{\gamma^3 T^3}{6} + \ldots \qquad (29)$$

so that Eq. 27 can be approximated by (for $T < 25^{\circ}$C)

$$C_s = C_{s0} - 0.4\ T + 8 \times 10^{-3} T^2 - 1.07 \times 10^{-4}\ T^3 + \ldots \qquad (30)$$

It is worth noting that the coefficients in Eq. 30 are practically identical to those of Eq. 21.

Equations 18, 25, and 28 can be combined to obtain

$$\frac{E_o}{P} = 0.317 + 0.009\ T + \frac{(0.683 + 0.0194\ T)}{e^{0.04\ T}}\ . \qquad (31)$$

Values of E_0/P calculated by Eq. 31 are listed in Table 11.

Table 11

Maximum Possible Efficiencies as a Function of Water Temperature

Water Temperature, $^{\circ}$C	Maximum Possible Relative Efficiency, E_0/P, atm^{-1}
0	1.000
10	0.994
20	0.979
30	0.968

Table 11 (continued)

Maximum Possible Efficiencies as a Function of Water Temperature

Water Temperature ^{o}C	Maximum Possible Relative Efficiency, E_o/P, atm^{-1}
40	0.972
50	0.991
60	1.025
70	1.072
80	1.128
90	1.194
100	1.266

From Table 11, it is clear that $E_o/P \doteq 1$ for the water temperature range of 0 to 60°C with a maximum error of only 3.2% (at 30°C), which is less than the error in reported dissolved oxygen saturation concentrations (5% at 30°C).

Equations 24 and 25 can be combined to obtain

$$E = E_o - \left(\frac{K_L a}{K_L a_0}\right) \frac{C}{14.65} \quad . \tag{32}$$

In addition, it is true that

$$E_o = (E_o/P)P \quad . \tag{33}$$

Making use of the fact that $E_o \doteq P$ for $0 \le T \le 60^oC$, Eq. 32 can be written

$$E = P - \left(\frac{K_L a}{K_L a_0}\right) \left(\frac{C}{14.65}\right) \quad . \tag{34}$$

The variation of P with elevation is given by the following equation which is derived in Appendix E

$$P = (1 - 6.87 \times 10^{-6} A)^{5.29} \tag{35}$$

where A is the altitude in feet and P is in atm. Equations 18, 34, and 35 can be combined to obtain

$$E = (1 - 6.87 \times 10^{-6} A)^{5.29} - (1 + 0.0284 T)(C/14.65) \quad . \tag{36}$$

Equation 36 is plotted in Figures 8 and 9.

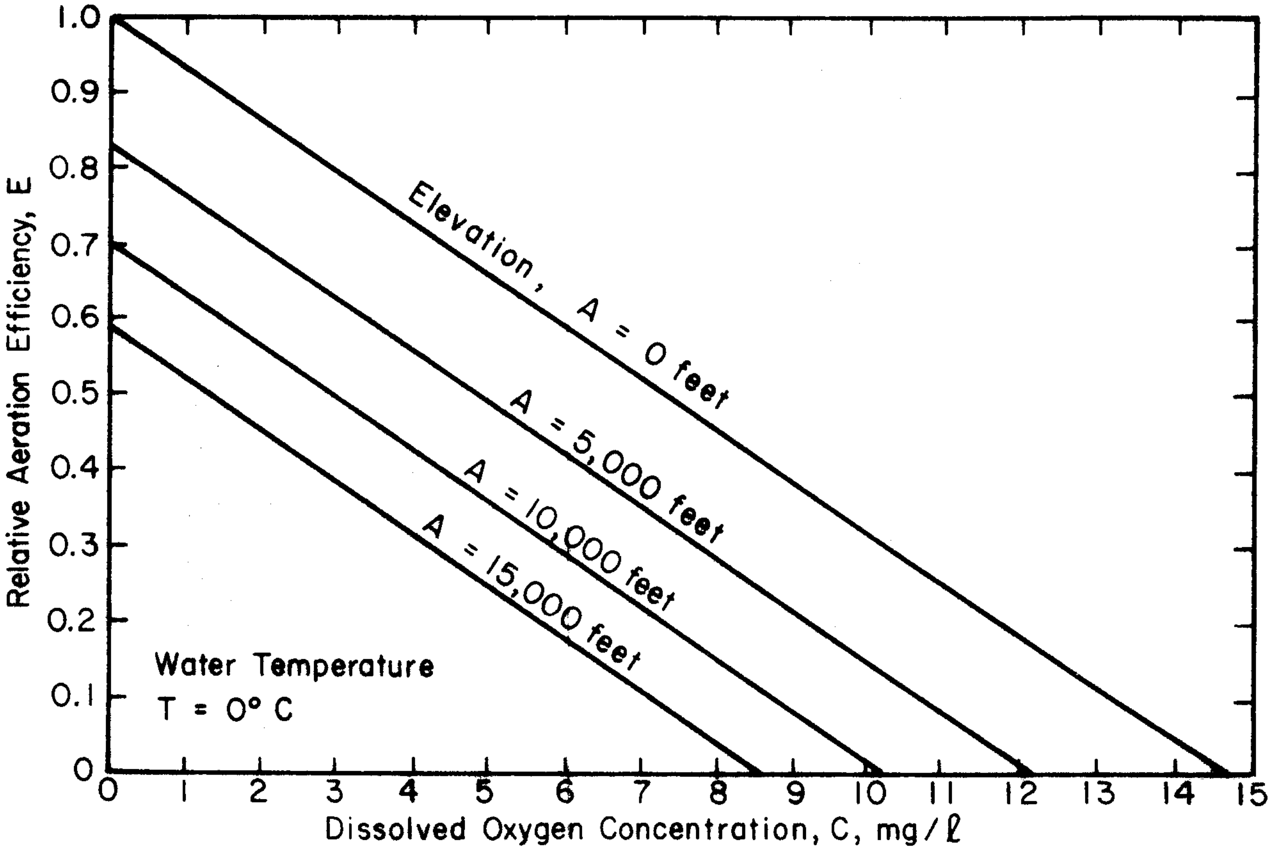

Fig. 8 - Effect of Elevation on Relative Aeration Efficiency.

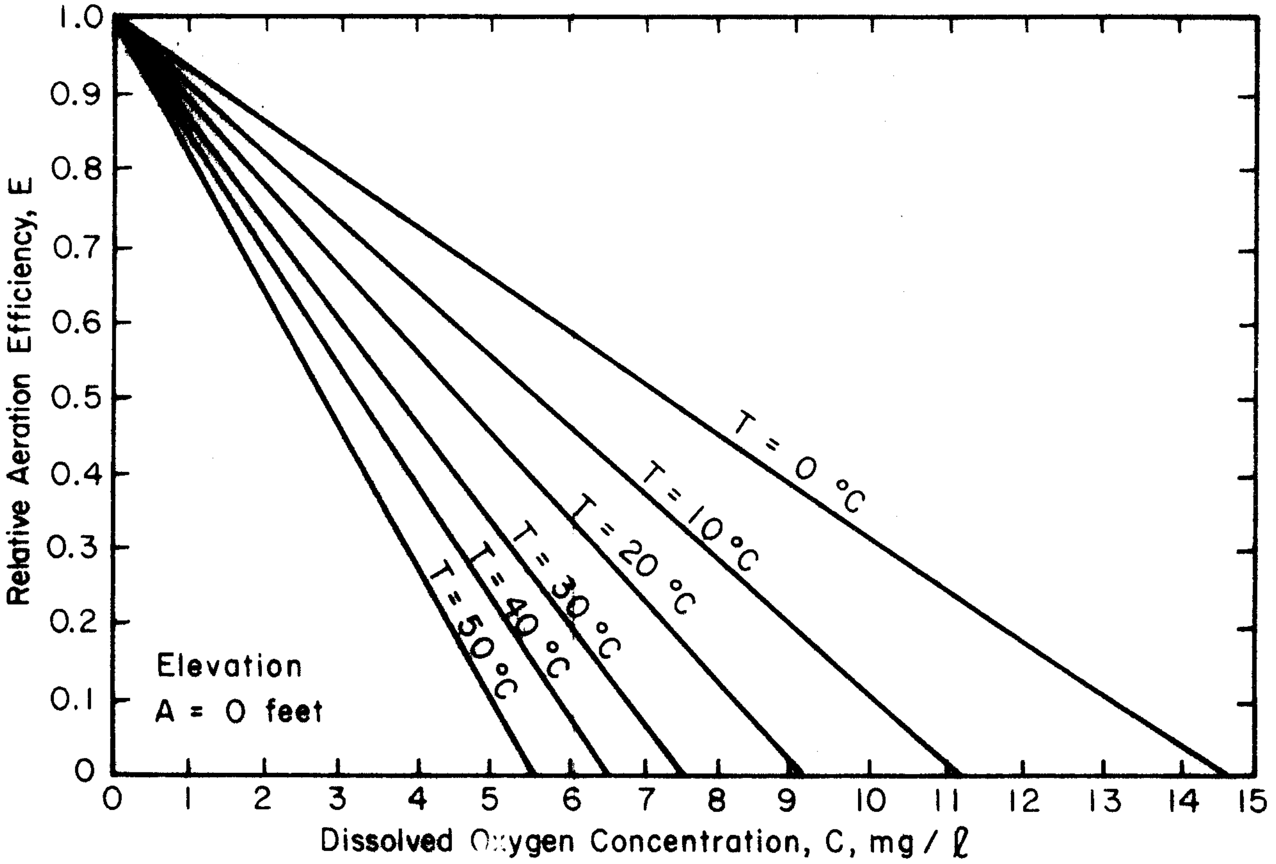

Fig. 9 - Effect of Water Temperature on Relative Aeration Efficiency.

V. Discussion

A. Arrhenius Equation

The rates of all chemical reactions are influenced by temperature. The fundamental relationship involved was first set down by Arrhenius. Working from the van't Hoff equation describing the dependence of the chemical equilibrium constant upon temperature he formulated the following equation which is commonly referred to as the van't Hoff-Arrhenius equation:

$$\frac{d(\ell n\ k)}{dT} = \frac{E_a}{RT^2} \tag{37}$$

where k is the reaction rate, T is temperature in degrees Kelvin ($^oC + 273$), E_a is the activation energy in cal/mole, and R is the universal gas constant, 1.99 cal/(mole)(^oK). Arrhenius assumed that the activation energy, E_a, was independent of temperature. Using this assumption and solving Eq. 37 by integration yields

$$\ell n\ \frac{k_2}{k_1} = \frac{E_a}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \ . \tag{38}$$

If one defines

$$\ell n\ B \equiv \frac{E_a}{RT_1} + \ell n\ k_1 \tag{39}$$

then, Eq. 38 can be expressed in the commonly encountered exponential form of the van't Hoff-Arrhenius equation, i.e., (Andrews, 1970, pages 320-322)

$$k = B\ \exp(-\ E_a/RT) \ . \tag{40}$$

From Eq. 40 it can be seen that when experimental measurements are made of the variation in rate constant, k, with temperature, the ideal rate theory predicts that a plot of $R(\ell n\ k)$ versus $1/T$ should produce a straight line having a slope equal to $-E_a$. Likewise, a semi-log plot with k on the log ordinate scale and $1/T$ on the abscissa should produce a straight line with slope $-E_a/2.3R$.

It has been suggested by Krenkel and Orlob (1962, pages 58-59) that it is reasonable to consider the aeration process as an energy controlled kinetic rate process and, as such, its rate dependence upon temperature should be described by the van't Hoff-Arrhenius equation. They suggest that the activation energy, E_a, should be approximately 5 kcal/mole. A semi-log plot of K_La versus $1/T$ for the values of K_La predicted from Eq. 12 is shown in Figure 10. These data plot as

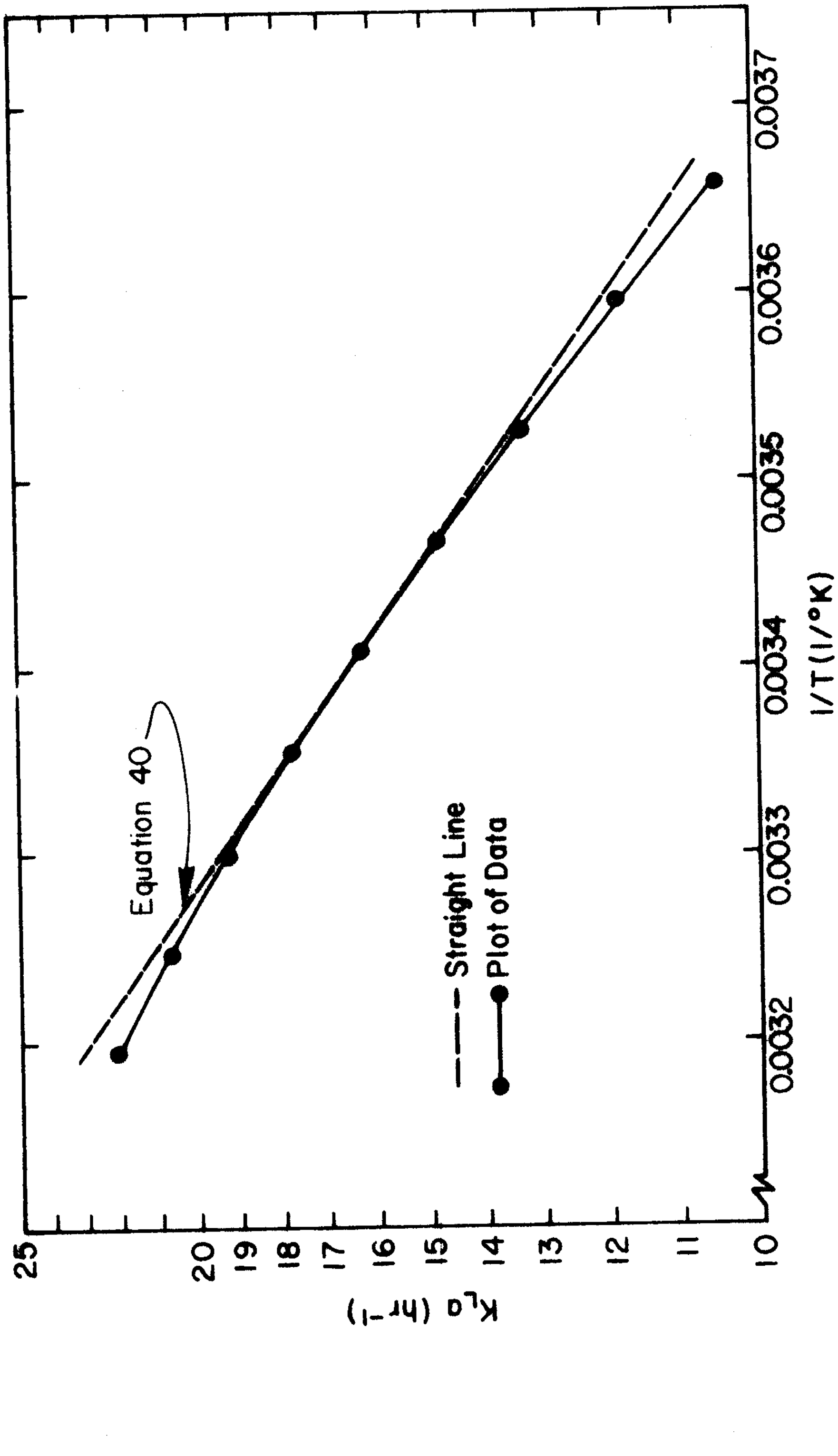

Fig.10 Applicability Test for van't Hoff-Arrhenius Equation

a curve indicating that the activation energy, E_a, is not a constant as predicted by the ideal rate theory.

For chemical reactions and some biological processes, it has been found that the activation energy varies linearly with temperature[3] (Moore, 1962, page 568, and Ward and Jex, 1969). Activation energies were calculated over a wide range of temperatures using values of K_La predicted from Eq. 12 in order to find out if this relationship could be used to define the variation in activation energy, E_a, observed in these studies. This was done by starting with Eq. 37 and proceeding to the finite difference form assuming that E_a is constant over the temperature range being considered

$$\frac{d(\ln K_La)}{dT} = \frac{E_a}{RT^2} = \frac{\Delta \ln(K_La)}{\Delta T} \quad (43)$$

For R equal to 1.99 cal/(mole)(^{o}K), Eq. 43 can be expressed in the form

$$E_a = (1.99)(T^2)(\Delta 2.3 \log K_La)/(\Delta T) \quad (44)$$

where E_a is expressed in cal/mole and T in ^{o}K. Results obtained from Eq. 44 are shown in Table 12. No linear or exponential relationship between temperature and either E_a or changes in E_a could be identified from plots on either rectangular, semi-log, or log-log graph paper. This indicates that the van't Hoff-Arrhenius equation may be valid for any particular temperature, but it cannot be readily used for predicting the dependence of K_La values upon water temperature.

B. Linear Versus Exponential Variation in K_La

The effect of water temperature upon K_La is commonly expressed in the following form:

$$K_La_{(T)} = K_La_{(20^oC)}\ \theta_e^{(T-20)} \quad (45)$$

where T is expressed in ^{o}C and θ_e is the dimensionless temperature coefficient. Equation 45 states that K_La changes in a constantly

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[3] For ordinary chemical reactions in liquid and solid systems near atmospheric pressure (Moore, 1962, page 568),

$$E_a = E_{ao} + RT = (E_{ao} + 544) + (1.99)\ (^oC) \quad (41)$$

where E_{ao} is the value of E_a at 0^{o}K. The rate of change in E_a is

$$d(E_a)/dT = R\ . \quad (42)$$

Table 12

Activation Energies

T (^oC)	E_a (cal/mole)	ΔE_a (cal/mole)	$\Delta E_a/^oC$ [cal/(mole)(^oC)]
0.0	4221		
2.5		393	78.6
5.0	3828		
7.5		298	59.6
10.0	3530		
12.5		240	48.0
15.0	3290		
17.5		192	38.4
20.0	3098		
22.5		157	31.4
25.0	2941		
27.5		133	26.6
30.0	2808		
32.5		120	24.0
35	2688		
37.5		91	18.2
40.0	2597		
45.0		156	15.6
50.0	2441		
55.0		123	12.3
60.0	2318		
65.0		97	9.7
70.0	2221		
75.0		69	6.9
80.0	2152		
85.0		56	5.6
90.0	2096		
95.0		49	4.9
100.0	2047		

proportional (geometric) manner with respect to water temperature. Some investigators, however, have reported that K_La varies linearly (arithmetically) with temperature (ASCE Committee on Sanitary Engineering Research, 1961, pages 62-63). The linear expression takes the form of Eq. 17, i.e.,

$$K_La_{(T)} = K_La_{(20^oC)}\ [C + \theta_1(T)] \qquad (46)$$

where C is a dimensionless constant which is the 0^oC intercept of the $K_La_{(T)}/K_La_{(20^oC)}$ versus T line, θ_1 is the temperature coefficient having units of $^oC^{-1}$, and T is water temperature in ^oC.

As pointed out by Fair, Geyer, and Okun (1968, page 28-45), the exponential form of the temperature correction relationship (Eq. 45) is limited in its applicability because θ_e is not a constant but varies with temperature. Use of either the exponential or linear relationship, however, gives results which are not significantly different over a moderate temperature range (Hull and Carbaugh, 1959). Calculations made from values of θ_e and θ_l reported in the literature indicate that this temperature range is approximately 10 to 25°C (see Figure 11). It is significant that a review of the literature revealed that most studies which have been designed to date for studying the dependence of aeration upon water temperature have typically been carried out in systems where the water temperature was varied over the same range, $\pm$ 5°C in either direction. Therefore, there seems to be no real basis available for identifying the variation in K_La if large temperature corrections are to be made, i.e., if the expected temperature is more than about $\pm$ 10°C from 20°C, the standard reference temperature used in aeration calculations.

Field studies carried out under this project revealed that many wastewater treatment facilities located in the mountainous regions of Colorado aerate wastewaters having temperatures which are below 10°C during several months of the year. A few plants were found to be aerating wastewaters with temperatures below 1°C over the same period. Design of aerators for use in these extreme water temperatures has had to be based upon extrapolations of the moderate-temperature aeration data mentioned above. Standard practice has been to use the exponential relationship given in Eq. 45 for making these extrapolations (WPCF MOP 5, 1971, page 19, and Eckenfelder, 1970, page 136). However, Hull and Carbaugh (1959) state: "For large temperature changes, it appears that the available evidence favors the use of the linear relationship." The results of the study reported herein support Hull and Carbaugh's conclusion. It has been shown that a linear relationship exists between K_La and water temperature over the entire range of 0 to 40°C, a range almost twice as great as any tested to date. Besides testing the more general case by including a much greater temperature range, this study included a large number of data points, 68 to be exact, which produced a correlation coefficient for a straight line relationship of 0.995. From Table 3, it can be seen that the deviation of the data from the line of best fit was small [1 standard deviation equalled 2.3 percent of the best estimate of $K_La_{(20^oC)}$]. In short, there seems to be little reason to question the conclusion that the relationship between K_La and water temperature is linear.

VI. Summary

A laboratory-scale mechanical aeration system which simulated near perfect mixing conditions was used to study the variation in oxygen mass transfer rates into water with respect to changes in water temperature. A water temperature range of 0 to 40°C was tested. It was found that the variation of K_La for aeration systems varies linearly with temperature and that this variation can be predicted from the expression

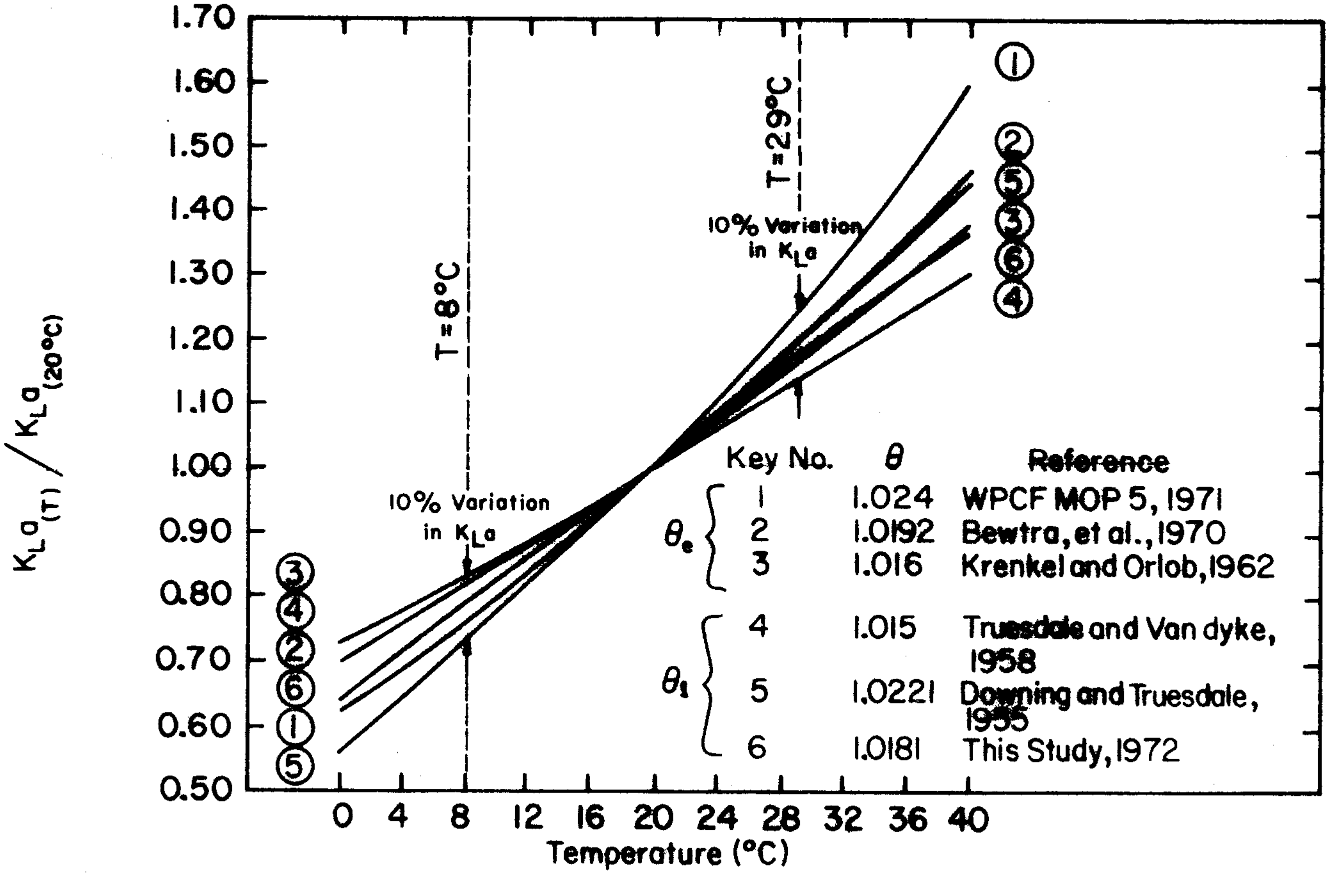

Fig. 11 Correction Factors for K_La from the Literature, 20°C Reference

$$K_La_{(T)} = K_La_{(20^oC)} \ (0.6375 + 0.0181\ T) \qquad (47)$$

where T is the water temperature in ^oC.

The above equation can be used in conjunction with Eqs. 35 and 28 to construct diagrams which show the combined effects that elevation and water temperature have upon aeration. Such diagrams show that those factors associated with increasing elevation which tend to reduce aerator output predominate over those factors which tend to enhance aerator output.

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Appendix A

CALIBRATION OF DISSOLVED OXYGEN METER AND STRIP CHART RECORDER

1. Set the dissolved oxygen meter control to "Red Line" and adjust the meter reading to the red mark.
2. Set the dissolved oxygen meter control to "Zero" and adjust the meter reading to 0.0 ppm.
3. Adjust the dissolved oxygen meter reading to the calculated saturated dissolved oxygen value for pure water at the sample temperature and measured barometric pressure (see Appendix B for calculating the saturated dissolved oxygen value).
4. Repeat Steps 1 through 3 until no further adjustment is necessary.
5. Set the dissolved oxygen meter control to "Zero" and adjust the zero setting on the strip chart recorder.
6. Set the dissolved oxygen meter control to an appropriate reading scale and adjust the strip chart recorder to record the calculated dissolved oxygen saturation value.
7. Repeat Steps 5 and 6 until no further adjustments need to be made on the strip chart recorder.

Appendix B

SATURATION DISSOLVED OXYGEN CONCENTRATIONS IN WATER

Standard Methods (Standard Methods for the Examination of Water and Wastewater. 1971. American Public Health Association, New York, page 480) recommends that the saturated dissolved oxygen concentration for water at a given barometric pressure be calculated according to the following formula:

$$C_s = C_1(P - p)/(1 - p) \tag{48}$$

where C_s is the saturation DO concentration (mg/ℓ) in water at the stated barometric pressure, P, which is expressed in atmospheres. C_1 is the saturation DO concentration (mg/ℓ) in water at a barometric pressure of 1 atmosphere (mean sea level) and p is the vapor pressure of water in atmospheres at the temperature of the water being considered. Values of C_1 can be obtained from the following table (ASCE Committee on Sanitary Engineering Research. 1960. "Solubility of Atmospheric Oxygen in Water." Jour. Sanitary Engineering Division, Proceedings of ASCE SA4: 41-53, page 48) which is based on Eq. 21:

Table 13

Saturation Dissolved Oxygen Concentrations Used

Water Temperature, T, (°C)	C_1 (mg/l)	Water Temperature, T, (°C)	C_1 (mg/l)
0.0	14.65	8.0	11.84
0.5	14.45	9.0	11.55
1.0	14.25	10.0	11.27
2.0	13.86	15.0	10.03
3.0	13.49	20.0	9.02
4.0	13.13	25.0	8.18
5.0	12.79	30.0	7.44
6.0	12.46	35.0	6.75
7.0	12.14	40.0	6.05

Values of p can be obtained from Table 14 (Weast, Robert C. 1970. Handbook of Chemistry and Physics. The Chemical Rubber Co., Cleveland, Ohio, page D-143):

Table 14

Water Vapor Pressures Used

Water Temperature, T,(°C)	(mm of Hg)	Water Temperature, T, (°C)	(mm of Hg)
0.0	4.58	8.0	8.04
0.5	4.75	9.0	8.61
1.0	4.93	10.0	9.20
2.0	5.29	15.0	12.79
3.0	5.69	20.0	17.54
4.0	6.10	25.0	23.76
5.0	6.54	30.0	31.82
6.0	7.01	35.0	42.18
7.0	7.51	40.0	55.32

If one is willing to accept an error of 100(1-x)%, then

$$\frac{P-p}{1-p} = xP \quad \text{or} \quad p = \frac{P(1-x)}{1-xP} \tag{49}$$

For example, for an acceptable error of 1%,

$$p = \frac{0.01P}{1-0.99P} \quad . \tag{50}$$

Using Eq. 50, one can determine water temperatures (as a function of elevation) below which Eq. 48 may be ignored with an error of only 1%. These values are listed in Table 15.

Table 15

Maximum Water Temperatures for an Error of 1%

Elevation, feet	Maximum Water Temperature for which Eq. 48 can be Ignored with an Error of 1%, °F
0	212
1,000	150
2,000	125
3,000	111
4,000	99
5,000	90
6,000	84
7,000	78
8,000	74
9,000	70
10,000	66
11,000	63
12,000	60
13,00	57
14,000	55
15,000	53

Appendix C

ADJUSTMENT OF AIR FLOW

1. With the air flow set at approximately 1 SCFH, determine air pressure above existing atmospheric pressure at the discharge port of the flowmeter, P_A , by means of the water manometer connected to the air line at that point. Convert to pounds per square inch (psi) by means of the following formula:

$$P_A = \frac{0.036 \text{ psi}}{\text{in. of water}} \text{ X (inches of water)} . \qquad (51)$$

2. Determine the existing barometric pressure, P_B , by means of a mercury barometer. Convert to psi by means of the following formula

$$P_B = \frac{0.0195 \text{ psi}}{\text{mm of Hg}} \text{ X (mm of Hg)} . \qquad (52)$$

3. Determine the absolute pressure of the air at the discharge port of the flowmeter, P_D , by means of the following formula:

$$P_D = P_A + P_B . \qquad (53)$$

4. Determine the difference between the absolute pressure of the air at the discharge port of the flowmeter, P_D , and standard atmospheric pressure by means of the following formula:

$$\Delta P = P_D - 14.70 \text{ psi} . \qquad (54)$$

5. Correct the flowmeter reading for the air pressure at the flowmeter discharge port using ΔP from Step 4 and the following equation (valid only for ΔP between 0 and -4 psi):

$$\text{Actual Flow} = (1.00 - 0.0375\ \Delta P)(\text{Observed Flowmeter Reading}) \qquad (55)$$

6. Determine the flowmeter reading under standard conditions for 1 SCFH from the flowmeter calibration curve.

7. Adjust the air flow until the flow calculated in Step 5 equals the flowmeter reading determined in Step 6.

Appendix D

DETERMINATION OF SODIUM SULFITE AND COBALT CHLORIDE DOSAGE

Experiments with actual test runs have shown that the use of 20 mg/l sodium sulfite (Na_2SO_3) per mg/l of DO contained in the agitated sample provides good dissolved oxygen annihilation and a short time lag before reaeration begins. Colbalt chloride ($CoCl_3$) was added as a catalyst at a ratio of 1 part $CoCl_3$ to 50 parts of Na_2SO_3 by weight.

Prepare a Na_2SO_3 solution with a concentration of 100g Na_2SO_3 per liter in distilled water. Also prepare a $CoCl_3$ solution of 20g $CoCl_3$ per liter in distilled water. The amounts of these solutions to be added to a sample under test can be calculated by means of the following formulas:

$$\text{ml } Na_2SO_3 \text{ solution} = 0.2\,(\text{sample DO})(\text{sample volume}) \qquad (56)$$

$$\text{ml } CoCl_3 \text{ solution} = 0.1\,(\text{ml } Na_2SO_3 \text{ solution used}) \qquad (57)$$

where sample DO is in mg/l and sample volume is in liters.

Appendix E

DERIVATION OF AN EQUATION FOR PREDICTING ATMOSPHERIC PRESSURE AS A FUNCTION OF ELEVATION AND AIR TEMPERATURE

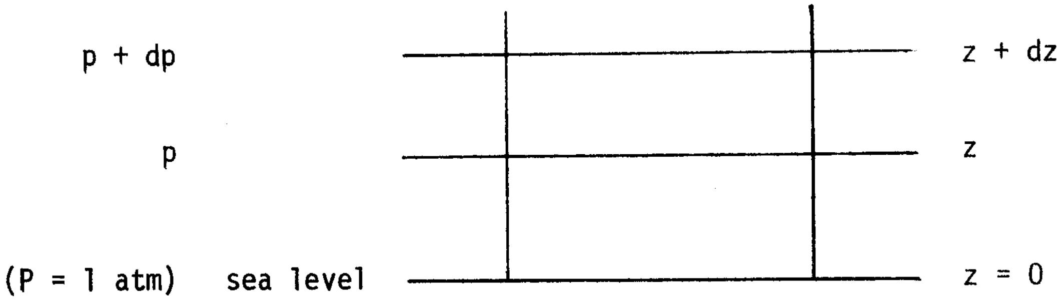


Figure 12 - Definition Sketch of Model Atmosphere

Let

p = atmospheric pressure, dynes/cm^2
z = elevation, cm
g = acceleration due to gravity, 981 cm/sec^2
ρ = density of air at elevation z , g/cm^3 .

Then, for a horizontal slice of atmosphere which is dz thick,

$$dp + \rho g \, dz = 0 \tag{58}$$

and

$$p(z + dz) = p(z) + dp \, . \tag{59}$$

From the ideal gas law,

$$pV = NRT \tag{60}$$

where V is volume in cm^3, N is moles of gas, R is the universal gas constant, 8.31×10^7 (dyne)(cm)/(mole)(^oK), and T is the absolute air temperature in $^oK(^oC + 273.1)$. By definition

$$\rho = \frac{MN}{V} \tag{61}$$

where M is the molecular weight of air (29 g/mole). Substituting Eq. 61 into Eq. 60 gives

$$p = \frac{\rho}{M} RT \, . \tag{62}$$

From Eq. 58,

$$dp = -\rho g \, dz \, . \tag{63}$$

Dividing Eq. 58 by Eq. 62 gives

$$\frac{dp}{p} = - \frac{gM\,dz}{RT} \quad . \tag{64}$$

Ordinarily,

$$T_z = T_o - (\frac{\Delta T}{\Delta z})\,z \tag{65}$$

where $\Delta T/\Delta z$ is 6.48 X 10^{-5} °K/cm, T_z is the air temperature at elevation z in °K, and T_o is the corresponding air temperature at mean sea level in °K (for the U.S. standard atmosphere $T_o = 15 + 273 = 288$ °K). Substituting Eq. 65 into Eq. 64 and integrating between the appropriate limits gives

$$\int_{p_o}^{p} \frac{dp}{p} = - \frac{gM}{R} \int_{o}^{z} \frac{dz}{T_o - (\Delta T/\Delta z)z} \tag{66}$$

which yields

$$p = p_o[1 - (\Delta T/\Delta z)(z/T_o)]^{\,gM/R(\Delta T/\Delta z)} \tag{67}$$

or,

$$p = p_o[1 + (\Delta T/\Delta z)\frac{z}{T_z}]^{-gM/R(\Delta T/\Delta z)} . \tag{68}$$

Substituting the numerical values of the constants into the exponent of Eqs. 67 and 68 gives

$$\frac{gM}{R(\Delta T/\Delta z)} = \frac{(981)(29)}{(8.31 \text{ X } 10^{7})(6.48 \text{ X } 10^{-5})} = 5.29 \ .$$

For the altitude A in feet,

$$A = z/30.5 \quad \text{or} \quad z = 30.5\,A \quad . \tag{69}$$

Substituting Eq. 69 into Eq. 67 along with the values previously given for the remaining constants and changing the units of p and p_o to atm, one obtains Eq. 35 which gives the correct value of P (in atm) for the U.S. standard atmosphere.

A more precise estimate of barometric pressure can be made with Eq. 68 because it takes into account the actual absolute air temperature T_z . Again, substituting Eq. 69 into Eq. 68 along with the values of the constants already given, and converting p and p_o to atm, one obtains

$$P = [1 + \frac{1.98 \text{ X } 10^{-3}\,A}{T_A}]^{-5.29} \tag{70}$$

where T_A is the air temperature in ^{o}K at altitude A, where A is in feet.

PART 2 - BOD AND COD REMOVAL FROM WASTEWATER BY AERATION WITH AIR AND OXYGEN

by

John C. Ward and R. P. Johansen

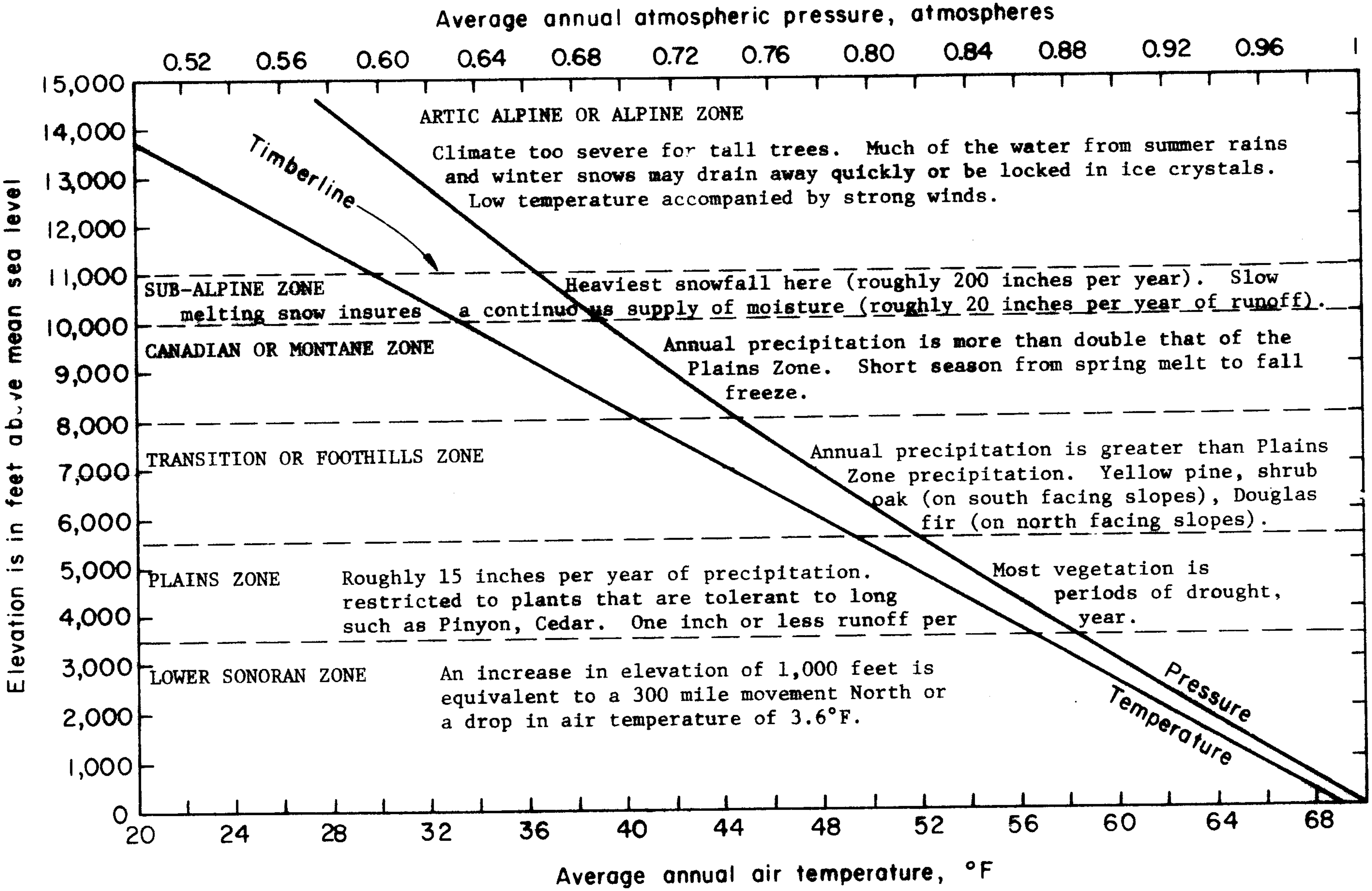
The primary purpose of this study was to determine if the higher DO (dissolved oxygen) concentrations obtainable by using pure oxygen (O_2) for aeration would increase the removal rate of BOD (biochemical oxygen demand) and COD (chemical oxygen demand) in settled, municipal wastewater. All experimentation was carried out at an elevation of 5,226 feet above sea level where the annual average atmospheric pressure is 0.833 atm (atmospheres). All experimental work was done at room temperature, and the wastewater temperature was approximately 20°C (degrees centigrade). At this temperature and elevation, the saturation DO concentration is about (9 X 0.833 =) 7.5 mg/ℓ (milligrams per liter) when air is used for aeration, and about (7.5 X 100/20.9 =) 35.8 mg/ℓ when oxygen is used for aeration.

REASON FOR THE AERATION STUDY

From Figure 1, it is clear that the annual average air temperature decreases at a rate of about 3.6°F (degrees Fahrenheit) per 1,000 feet increase in elevation or per 300 miles toward true north. For example, the following are the approximate latitude equivalents of the corresponding elevations:

Elevation, feet	Latitude equivalent
5,000	Fort Collins, Colorado
6,000	Northern Wyoming Border
7,000	Canadian Border
8,000	Edmonton, Alberta, Canada
9,000	Northern Saskatchewan, Canada
10,000	Anchorage, Alaska
11,000	Artic Circle
12,000	Point Barrow, Alaska
13,000	75° North Latitude

When BOD is removed from wastewater by aeration, the rate of removal is considerably less at lower wastewater temperatures. In addition, while the saturation DO concentration is higher at low temperatures, it decreases with elevation in a manner directly proportional to atmospheric pressure. For example, for a wastewater at a temperature that is the same as the air temperature for a given elevation, the saturation DO concentrations would tend to be as follows:



ARTIC ALPINE OR ALPINE ZONE

Climate too severe for tall trees. Much of the water from summer rains and winter snows may drain away quickly or be locked in ice crystals. Low temperature accompanied by strong winds.

SUB-ALPINE ZONE

Heaviest snowfall here (roughly 200 inches per year). Slow melting snow insures a continuous supply of moisture (roughly 20 inches per year of runoff).

CANADIAN OR MONTANE ZONE

Annual precipitation is more than double that of the Plains Zone. Short season from spring melt to fall freeze.

TRANSITION OR FOOTHILLS ZONE

Annual precipitation is greater than Plains Zone precipitation. Yellow pine, shrub oak (on south facing slopes), Douglas fir (on north facing slopes).

PLAINS ZONE

Roughly 15 inches per year of precipitation. Most vegetation is restricted to plants that are tolerant to long periods of drought, such as Pinyon, Cedar. One inch or less runoff per year.

LOWER SONORAN ZONE

An increase in elevation of 1,000 feet is equivalent to a 300 mile movement North or a drop in air temperature of 3.6°F.

Figure 1. ELEVATION CLASSIFICATION FOR COLORADO

Elevation, feet	Saturation DO concentration corresponding to wastewater temperature equal to mean annual air temperature, mg/ℓ*
0	10.0
1,000	10.1
2,000	10.2
3,000	10.4
4,000	10.4
5,000	10.7
6,000	10.8
7,000	11.0

*Air temperatures used were those of the U.S. standard atmosphere which are 10°F less than those shown in Figure 1.

EXPERIMENTAL PROCEDURE

The wastewater used was the effluent from the primary settling basin of the Fort Collins, Colorado, wastewater treatment plant. Each sample was divided in half volumetrically and each half was placed into a battery jar. One jar was aerated with air and the other was aerated with industrial grade pure oxygen gas.

EXPERIMENTAL CONDITIONS

The experimental conditions for each of 6 separate tests are given in Table 1. Detailed conditions for each test follow.

Table 1

Experimental Conditions

Test Number	Initial volume in each battery jar, liters	Evaporation rate, liters per day		Gas flow rate, liters per hour		DO concentration mg/ℓ		Total volume loss due to sampling, liters	
		Air	Oxygen	Air	Oxygen	Air	Oxygen	COD	BOD
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	6.325	0.290	0.290	80	80	6.6	29	0.05	
2	8.045	0.445	0.310	80	80	7.0	30	0.03	
3	7.630	0.170	0.170	80	50	6.9	32	0.05	
4	9.050	0.360	0.430	15	15	7.0	29		0.785
5	8.800	0.240	0.240	4	4	5.2	22	0.11	
6	9.230	0.300	0.290	4	4	3.4	19	0.03	

In tests 1 and 2, aeration was by means of one inch diameter spherical stone diffusers placed at the bottom center of each battery jar. The samples from run 2 were all filtered before the COD determinations. This filtering removed up to 80% of the sample COD, so the data for this test is considered unrepresentative.

In test 3, a circumferential diffusor of plastic tubing perforated with small holes was used. This prevented a floc buildup on the jar walls observed in tests 1 and 2. In tests 1, 2, and 3, the COD was determined colorimetrically using a Hach colorimeter.

The same circumferential diffusor was used again for test 4. The BOD values are the ultimate BOD at 20°C. Sample volumes for this test were 0.157 liters each, and the BOD concentration was determined manometrically.

For tests 5 and 6, the stone diffusors used in tests 1 and 2 were placed at the bottom edge of the circular jars and stirring was accomplished by mechanical means. The COD determinations for tests 5 and 6 were done potentiometrically using an oxidation-reduction probe and a recording automatic titrator. In test 6, the wastewater in the jars was permitted to settle about 30 minutes before the samples were taken from the supernatant.

EXPERIMENTAL RESULTS

The experimental results are given in Table 2. Sample volumes for the COD determination were 0.01 liters each. The evaporation rates given in Table 1 include the volume loss due to sampling except for test 4. The total volume loss due to sampling was less than 1% of the original volume for every test with the exception of tests 4 and 5 where it was 9 and 1% respectively.

In test 5 (observation numbers 36 and 37), distilled water was added to bring the volume back to the original volume before sampling. In test 6, distilled water was added to bring the volume back to the original volume after taking the sample.

ANALYSIS OF EXPERIMENTAL RESULTS

Table 3 shows the mass (in mg) of oxygen demand remaining as a function of time. These values were obtained by multiplying the mg/ℓ of oxygen demand by the corresponding volume in liters. The oxygen demand remaining is expressed as a fraction of the original mass of oxygen demand in columns 8 and 9 of Table 3.

Using the data in columns 2, 8, and 9 of Table 3, the time required for removal of 1/2 of the initial oxygen demand ($t_{1/2}$) in days was determined for each of the 6 tests, and these values are listed in Table 4.

Table 2 - EXPERIMENTAL RESULTS

Test	Time, Days	Oxygen Demand, mg/ℓ		Volume Before Taking Sample, liters		Observation Number
		Air	Oxygen	Air	Oxygen	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	0	250	250	6.325	6.325	1
1	0.94	220	100	6.052	6.052	2
1	1.87	100	75	5.783	5.783	3
1	2.94	175	120	5.473	5.473	4
1	3.87	60	90	5.203	5.203	5
1	4.00	75	75	5.165	5.165	6
1	5.00	50	25	4.875	4.875	7
2	0	100	80	8.045	8.045	8
2	0.17	35	25	7.969	7.992	9
2	1.17	30	30	7.524	7.682	10
2	2.17	30	25	7.080	7.371	11
2	4.0	30	30	6.265	6.805	12
3	0	180	170	7.630	7.630	13
3	0.82	120	100	7.491	7.491	14
3	2.0	55	25	7.290	7.290	15
3	3.86	25	35	6.974	6.974	16
3	4.93	30	25	6.794	6.794	17
3	5.94	20	20	6.621	6.621	18
3	12.2	20	20	5.550	5.550	19
4	0	215	170	9.050	9.050	20
4	0.98	84	94	8.540	8.472	21
4	1.95	42	52	8.033	7.897	22
4	2.99	0	10	7.502	7.292	23
4	4.03	0	6	6.972	6.690	24
5	0	283	259	8.800	8.800	25
5	0.35	358	362	8.716	8.716	26
5	1.04	269	260	8.550	8.550	27
5	2.06	232	220	8.305	8.305	28
5	3.33	246	237	8.000	8.000	29
5	3.92	230	222	7.858	7.858	30
5	4.02	201	176	7.835	7.835	31
5	4.83	282	249	7.640	7.640	32
5	5.81	193	202	7.406	7.406	33
5	6.85	169	200	7.158	7.158	34
5	17.85	307	295	4.510	4.510	35
5	38	127	133	8.800	8.800	36
5	44	26	29	8.800	8.800	37
6	0	322	329	9.190	9.230	38
6	0.95	275	282	8.905	8.955	39
6	1.88	183	182	8.911	8.960	40
6	7.08	222	233	7.630	7.720	41
6	9.08	187	191	8.590	8.650	42

Table 3 - ANALYSIS OF EXPERIMENTAL RESULTS

Test	Time, Days	Oxygen Demand Remaining, mg		Oxygen Demand Remaining, Fraction of Original		$\frac{t}{t_{1/2}}$
		Air (3x5)	Oxygen (4x6)	Air (8)	Oxygen (9)	
(1)	(2)					(10)
1	0	1582	1582	1.000	1.000	0
1	0.94	1330	605	0.840	0.382	0.467
1	1.87	578	434	0.365	0.274	0.931
1	2.94	957	657	0.605	0.415	1.462
1	3.87	312	468	0.197	0.295	1.923
1	4.00	388	388	0.245	0.245	1.990
1	5.00	244	122	0.154	0.077	2.49
2	0	805	644	1.000	1.000	0
2	0.17	279	200	0.347	0.311	0.159
2	1.17	225	231	0.280	0.359	1.093
2	2.17	213	184	0.265	0.286	2.03
2	4.0	188	204	0.233	0.317	3.74
3	0	1373	1296	1.000	1.000	0
3	0.82	900	749	0.656	0.577	0.377
3	2.0	401	182	0.292	0.140	0.921
3	3.86	174	244	0.127	0.180	1.778
3	4.93	204	170	0.148	0.131	2.27
3	5.94	132	132	0.096	0.102	2.74
3	12.2	111	111	0.088	0.086	5.62
4	0	1950	1540	1.000	1.000	0
4	0.98	717	795	0.368	0.516	0.98
4	1.95	338	411	0.173	0.267	1.95
4	2.99	0	73	0.000	0.047	2.99
4	4.03	0	40	0.000	0.026	4.03
5	0	2490	2280	1.000	1.000	0
5	0.35	3120	3160	1.252	1.386	0.016
5	1.04	2300	2220	0.924	0.974	0.049
5	2.06	1928	1828	0.774	0.802	0.097
5	3.33	1970	1898	0.792	0.832	0.156
5	3.92	1810	1745	0.727	0.765	0.184
5	4.02	1573	1378	0.632	0.604	0.189
5	4.83	2150	1903	0.864	0.835	0.226
5	5.81	1430	1497	0.575	0.606	0.272
5	6.85	1210	1430	0.486	0.627	0.321
5	17.85	1383	1330	0.556	0.583	0.839
5	38	1118	1170	0.449	0.513	1.783
5	44	229	255	0.092	0.112	2.06
6	0	2960	3040	1.000	1.000	0
6	0.95	2450	2520	0.828	0.829	0.134
6	1.88	1630	1630	0.551	0.537	0.265
6	7.08	1695	1800	0.573	0.592	0.995
6	9.08	1608	1650	0.544	0.543	1.280

Table 4

Time Required for Removal of 50% of the Oxygen Demand

Test	$t_{1/2}$, days		$\frac{t_{1/2}\text{ (oxygen)}}{t_{1/2}\text{ (air)}}$	Average $t_{1/2}$, days
	Air	Oxygen		
(1)	(2)	(3)	(4)	(5)
1	2.36	1.67	0.708	2.01
2	1.01	1.14	1.128	1.07
3	2.28	2.06	0.904	2.17
4	0.86	1.13	1.314	1.00
5	19.5	23.2	1.190	21.3
6	7.1	7.1	1.000	7.1
Average			1.040	

Clearly, the samples varied considerably in their biodegradability. Regardless, as column 4 of Table 4 shows, no improvement is obtained by the use of oxygen in place of air as far as rate of removal is concerned.

Using t to represent the time of aeration in days, the average values of $t_{1/2}$ from column 5 of Table 4 along with column 2 of Table 3 were used to calculate the ratio $t/t_{1/2}$ given in column 10 of Table 3. The average of columns 8 and 9 of Table 3 is plotted in Figure 2 versus column 10 of Table 3.

Because, from the foregoing discussion, the use of oxygen does not increase the rate or oxygen demand removal, it would appear that the most beneficial use of oxygen in wastewater treatment is where conventional methods of aeration can maintain minimum DO concentration only with great difficulty. In the constact-stablization activated-sludge wastewater treatment plant, there are two possible uses of oxygen that may compare favorably with conventional methods of aeration. One application of oxygen would be in the activated-sludge stabilization basin where part of the underflow from the secondary sedimentation basin is aerated separately before being returned to the activated sludge contact basin. The other application of oxygen would be in the activated-sludge contact basin itself in order to permit much higher concentrations of mixed-liquor suspended solids and consequently greater oxygen demand removal. Use of oxygen in the activated-sludge stabilization basin permits addition of sludge digester supernatant as a nutrient.

While air is 20.9% oxygen by volume, it is 23% oxygen by weight. As a result, one might expect that in Table 1, division of column 7 by the corresponding value in column 8 would yield a constant value of 0.23. Column 2 of Table 5 shows that this is the case with the exception of test number 6.

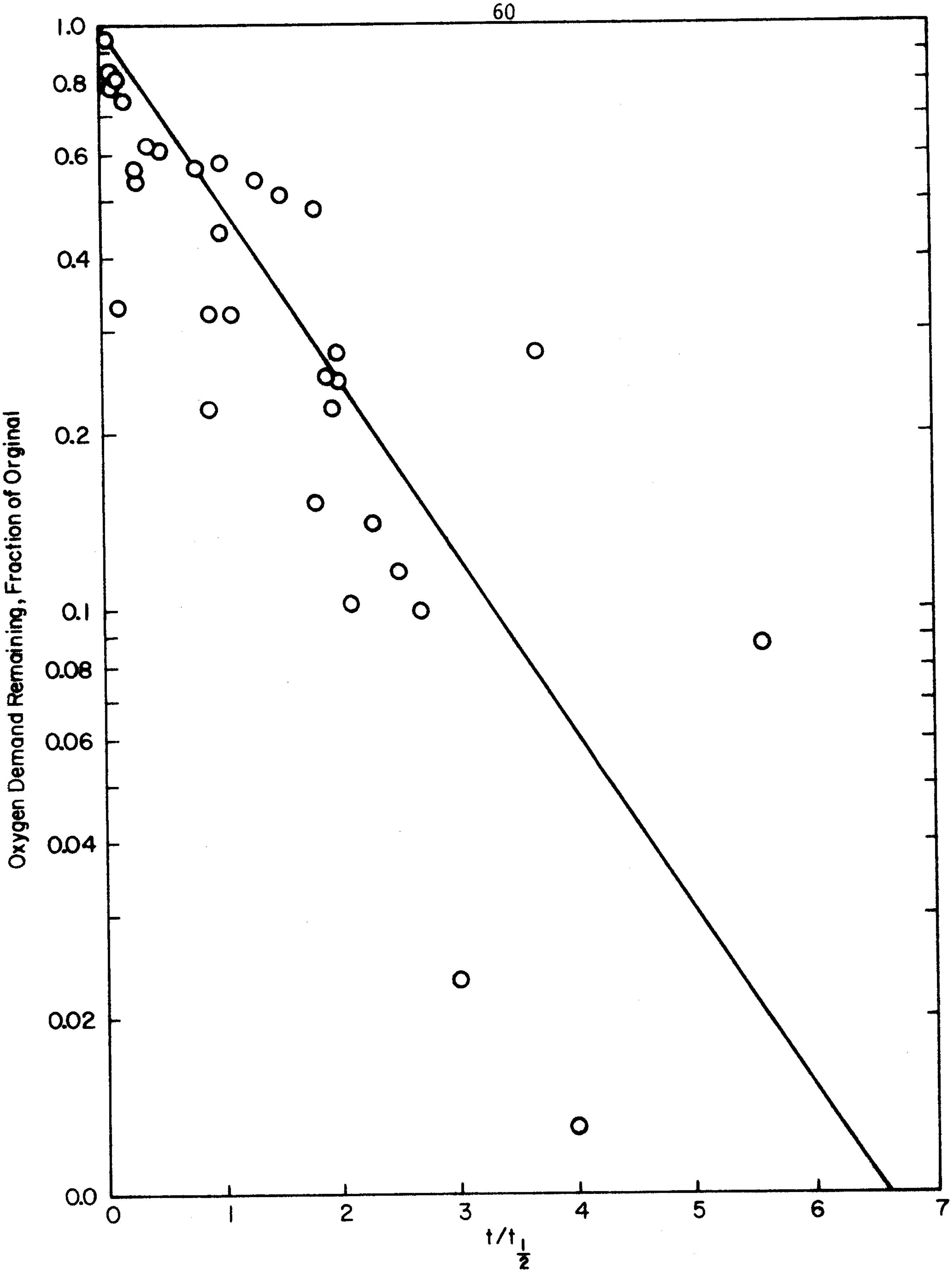


Fig. 2 - Fraction of Oxygen Demand Remaining Versus $t/t_{\frac{1}{2}}$

Table 5 - ANALYSIS OF EXPERIMENTAL CONDITIONS

Test Number	$\frac{\text{DO Air}}{\text{DO Oxygen}}$	Test Duration, $t/t_{1/2}$	Average OD Remaining, grams		Gas Flow Rate, Liters per Hour per Gram OD Remaining (Average)		Fraction of Saturation DO Concentration	
			Air (4)	Oxygen (5)	Air (6)	Oxygen (7)	Air (8)	Oxygen (9)
(1)	(2)	(3)						
1	0.23	2.49	0.750	0.750	106	106	0.880	0.810
2	0.23	3.74	0.286	0.228	280	350	0.933	0.839
3	0.22	5.62	0.345	0.325	232	145	0.920	0.894
4	0.24	4.03	0.654	0.516	23.0	29.0	0.933	0.810
5	0.24	2.06	1.320	1.210	3.03	3.30	0.693	0.615
6	0.18	1.28	1.953	2.01	2.04	1.99	0.454	0.531

Table 6 - EFFICIENCY OF OXYGEN TRANSFER

Test Number	Initial Oxygen Consumption Rate, Grams per Hour		Oxygen Supply Rate, Grams per Hour		Oxygen Supply Rate ÷ Initial Oxygen Consumption Rate		Efficiency of Oxygen Transfer, Percent	
(1)	Air (2)	Oxygen (3)	Air (4)	Oxygen (5)	Air (6)	Oxygen (7)	Air (8)	Oxygen (9)
1	0.0228	0.0228	16.8	88	738	3860	0.136	0.0259
2	0.0217	0.0174	16.8	88	775	5060	0.129	0.0198
3	0.0183	0.0146	16.8	55	919	3410	0.109	0.0293
4	0.0565	0.0445	3.15	16.5	56	371	1.785	0.269
5	0.0034	0.0031	0.84	4.4	248	1422	0.404	0.0704
6	0.0121	0.0124	0.84	4.4	69	355	1.357	0.282

For a test of duration $t/t_{1/2}$, the average oxygen demand (OD) remaining expressed as a fraction of the initial oxygen demand is

$$\frac{\text{average oxygen demand}}{\text{initial oxygen demand}} = \frac{1 - 10^{-0.3\ t/t_{1/2}}}{0.695\ t/t_{1/2}} \qquad (1)$$

Equation 1 gives the average fraction of the initial oxygen demand remaining and is plotted in Figure 3. The average oxygen demand remaining (given in columns 4 and 5 of Table 5) is the product of the initial oxygen demand (given in Table 3) times the average fraction of initial oxygen demand remaining (given in Figure 3) corresponding to the $t/t_{1/2}$ values given in column 3 of Table 5. The gas flow rate given in columns 6 and 7 of Table 5 are the values given in columns 5 and 6 of Table 1 divided by the average oxygen demand remaining given in columns 4 and 5 of Table 5. The fraction of saturation dissolved oxygen concentration given in columns 8 and 9 of Table 5 are the values given in columns 7 and 8 of Table 1 divided by 7.5 mg/ℓ and 35.8 mg/ℓ, respectively.

In Figure 4, the fraction of saturation dissolved oxygen concentration achieved (columns 8 and 9 of Table 5) is plotted versus the gas flow rate (columns 6 and 7 of Table 5). Because the rate of oxygen demand removal has been shown to be independent of the dissolved oxygen concentration, one might as well use relatively low dissolved oxygen concentrations and achieve the same results. In any event, Figure 4 suggests that attempting to maintain dissolved oxygen concentrations greater than about 70% of saturation requires excessive gas flow rates.

Under the test conditions, each liter of air contained 0.21 grams of oxygen, and each liter of oxygen contained about 5 times this amount or 1.1 grams of oxygen. The rate at which oxygen was being consumed was

$$\text{oxygen consumption rate} = \frac{(0.693)(\text{oxygen demand remaining})}{t_{1/2}} . \qquad (2)$$

A special case of Eq. 2 is the following

$$\text{initial oxygen consumption rate} = \frac{(0.693)(\text{initial oxygen demand})}{t_{1/2}} . \qquad (3)$$

Equation 3 was used along with the data in Tables 3 and 4 (column 5) to calculate the initial oxygen consumption rates given in columns 2 and 3 of Table 6. The data in columns 5 and 6 of Table 1 was used to calculate the data in columns 4 and 5 of Table 6. Columns 6 and 7 in Table 6 were calculated using the data in columns 2, 3, 4, and 5 of Table 6. Columns 8 and 9 of Table 6 are the recipricals of columns 6 and 7 multiplied by 100%. The data in columns 6 and 7 of Table 6 and columns 7 and 8 of Table 1 are plotted in Figure 5.

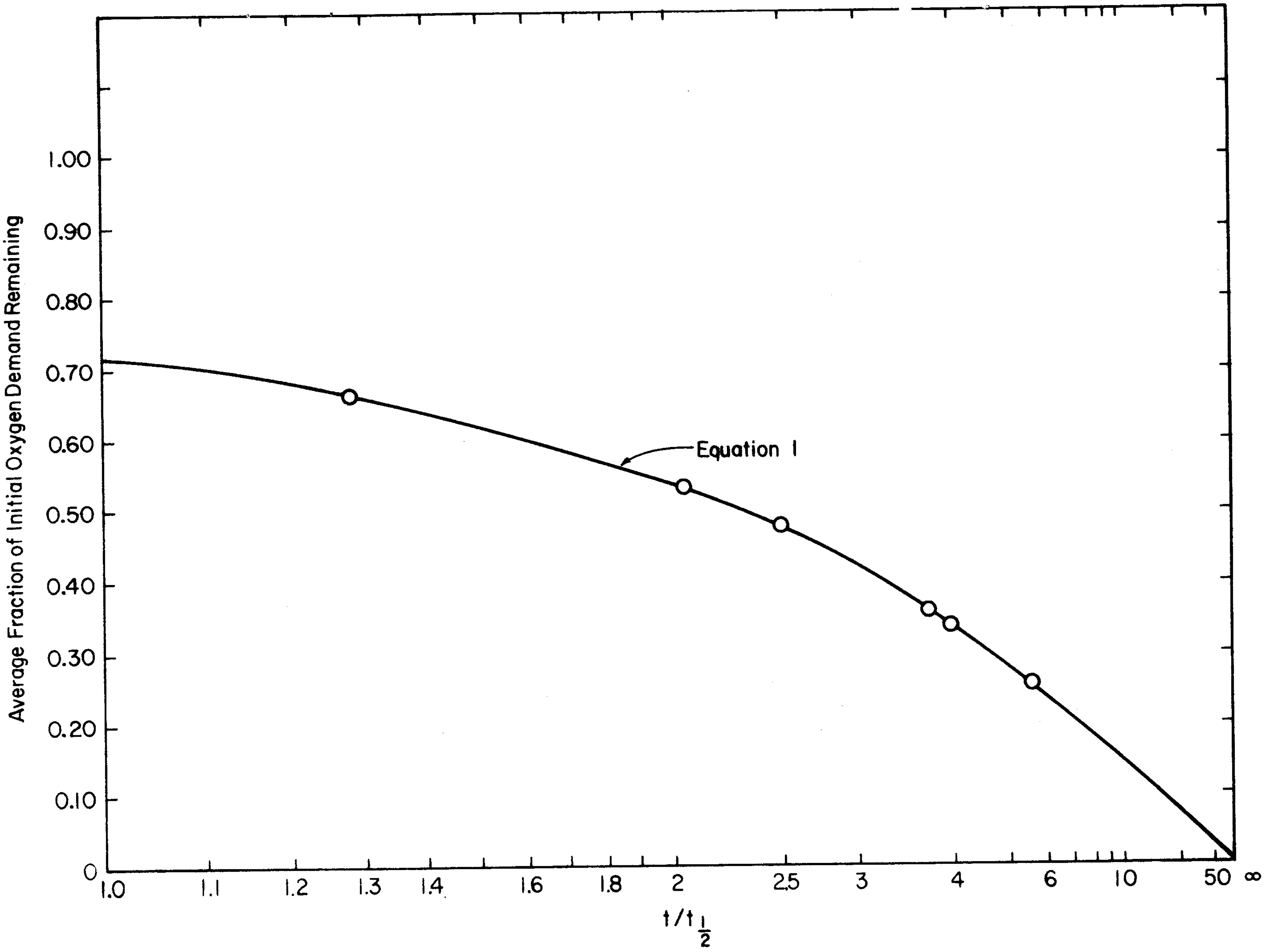


Fig.3- Average Fraction of Initial Oxygen Demand Remaining.

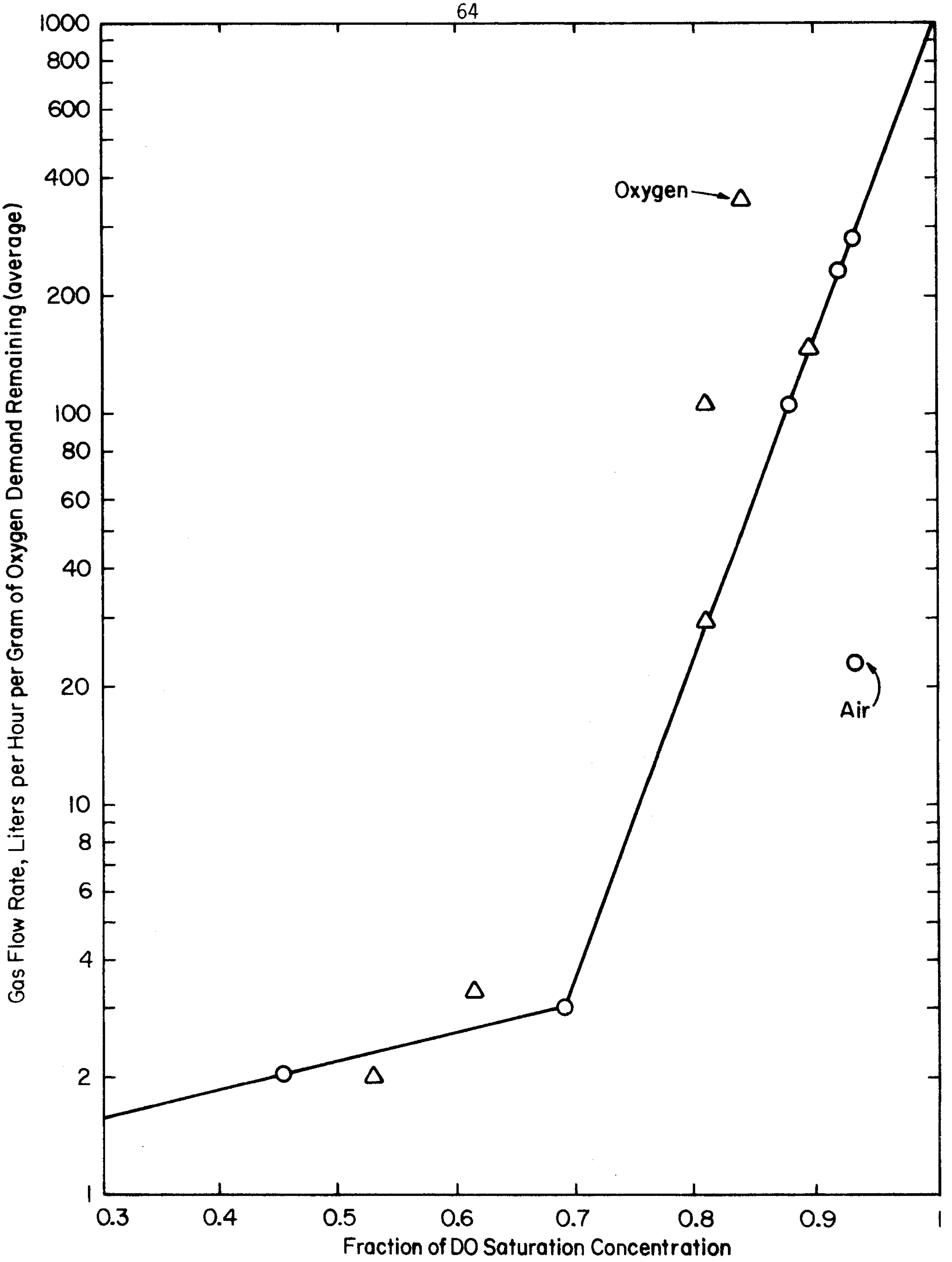


Fig. 4- Effect of Gas Flow Rate on Fraction of Dissolved Oxygen Saturation Concentration.

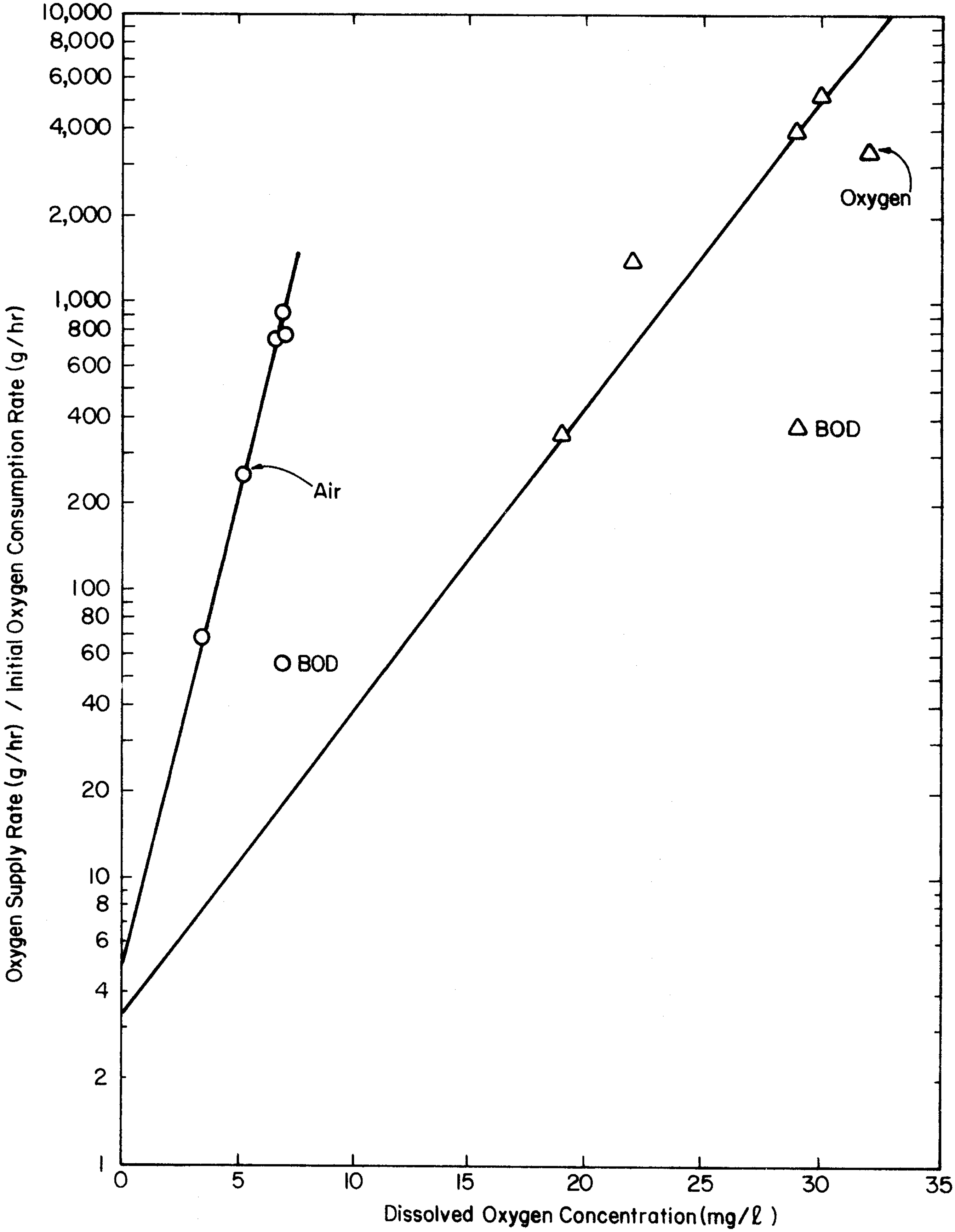


Fig. 5- Dissolved Oxygen Concentration Resulting from a Given Ratio of Oxygen Supply Rate to Oxygen Consumpution Rate (by weight).

Figure 5 indicates that the maximum possible efficiency using air is about 20%, while the maximum possible efficiency using oxygen appears to be about 28%. The minimum concentration of dissolved oxygen ordinarily needed in aeration units is about 1 mg/ℓ. At this concentration, the efficiency using air is about 9% (the oxygen-transfer efficiency of bubble aeration is usually between 5 and 15%), while the efficiency using oxygen is about 22%.

Most of the plotted points in Figure 5 lie close to the empirical straight lines with the exception of the 2 points (labeled BOD) from test 4, which was the only test where the oxygen demand was measured in terms of BOD.

If oxygen is used, the effluent to be discharged could be saturated with dissolved oxygen (the saturation concentration of dissolved oxygen under the conditions of these 6 tests is about 7.5 mg/ℓ) and still have an efficiency of about 5%.

CONCLUSIONS

The first-stage BOD has generally been formulated as a first-order reaction. The concentration of oxidizable organic material present is the rate-determining factor, provided that the dissolved oxygen concentration is greater than a critical value of about 4 mg/ℓ at 20°C, for example. This work has shown that this statement is true (at 20°C) for dissolved oxygen concentrations all the way from 3.4 mg/ℓ up to at least 32 mg/ℓ. The use of oxygen for aeration does not have an effect on the rate of oxygen demand removal by aeration.

The rate of oxygen demand removal by aeration can vary enormously (by a factor of 27 in this study) for different samples of the same municipal effluent. In this study, it was shown that the oxygen demand rate constant could vary from 0.807 per day at 20°C (for BOD removal) down to as low as 0.0298 per day at 20°C (for COD removal) for a given municipal wastewater. For this reason, oxygen demand as a function of time for different samples is best compared as illustrated in Figure 2. The use of the 5-day, 20°C BOD is clearly of little value. Oxygen demands should either be expressed in terms of COD and/or in terms of ultimate BOD at a given temperature. Manometric and/or electrolytic respirometric determination of BOD is clearly preferable to other methods, because both the ultimate BOD and the BOD rate constant at a given temperature are necessary for stream pollution work.

Even when 90% of the oxygen demand is removed by aeration (see Figure 2), the average oxygen demand during the aeration period is about 40% of the initial oxygen demand (see Figure 3). Attempting to maintain a dissolved oxygen concentration greater than about 70% of saturation appears to require excessive gas flow rates (see Figure 4). Maintaining 4 mg/ℓ (at 20°C) of dissolved oxygen in a wastewater can be accomplished with 1% efficiency using air and 11% efficiency using oxygen (see Figure 5).

Even when air is used for aeration, contact-stabilization appears to be the best type of activated-sludge treatment from the standpoint of cost effectiveness. Further, if oxygen can be used advantageously in wastewater treatment, the contact-stabilization activated-sludge wastewater treatment plant offers the best possibilities for the advantageous use of oxygen as shown in Figure 6. In regions where extended periods of extremely low air temperatures are encountered, small activated-sludge wastewater treatment plants are often entirely enclosed. The building size necessary to enclose an activated-sludge wastewater treatment plant is smallest when contact-stabilization is the type of activated-sludge treatment employed. Enclosure of the activated-sludge contact basin and the activated-sludge stabilization basin (see Figure 6) would permit the most economical use of oxygen, because the overlying enclosed atmosphere could be passed through a packed tower countercurrent to potassium hydroxide in order to remove the carbon dioxide produced by microorganism respiration. This gas stream could then be reused for aeration.

In Table 7, the data in columns 2, 3, and 4 were obtained from Table 3. Column 5 of Table 7 shows that the maximum oxygen demand removal percent is the same for both air and oxygen. Column 6 of Table 7 is the average of columns 3 and 4 and indicates that the maximum COD removal by aeration is likely to be roughly 90%.

Table 7

Oxygen Demand Removal

Test Number (1)	Test Duration, Days (2)	Oxygen Demand Removal, Percent		Removal Ratio, $\frac{\%\ O_2}{\%\ \text{air}}$ (5)	Average OD Removal, % (6)
		Air (3)	Oxygen (4)		
1	5	84.6	92.3	1.091	88.4
2	4	76.7	68.3	0.891	72.5
3	12.2	91.2	91.4	1.002	91.3
4	4.03	100	97.4	0.974	98.6
5	44	90.8	88.8	0.978	89.7
6	9.08	45.6	45.7	1.002	45.6
Average				0.990	

RECOMMENDATIONS

Research should be carried out at the earliest possible time to determine the economic feasibility of using oxygen in connection with an enclosed contact-stabilization activated-sludge wastewater treatment plant of the type discussed in the conclusions section above and

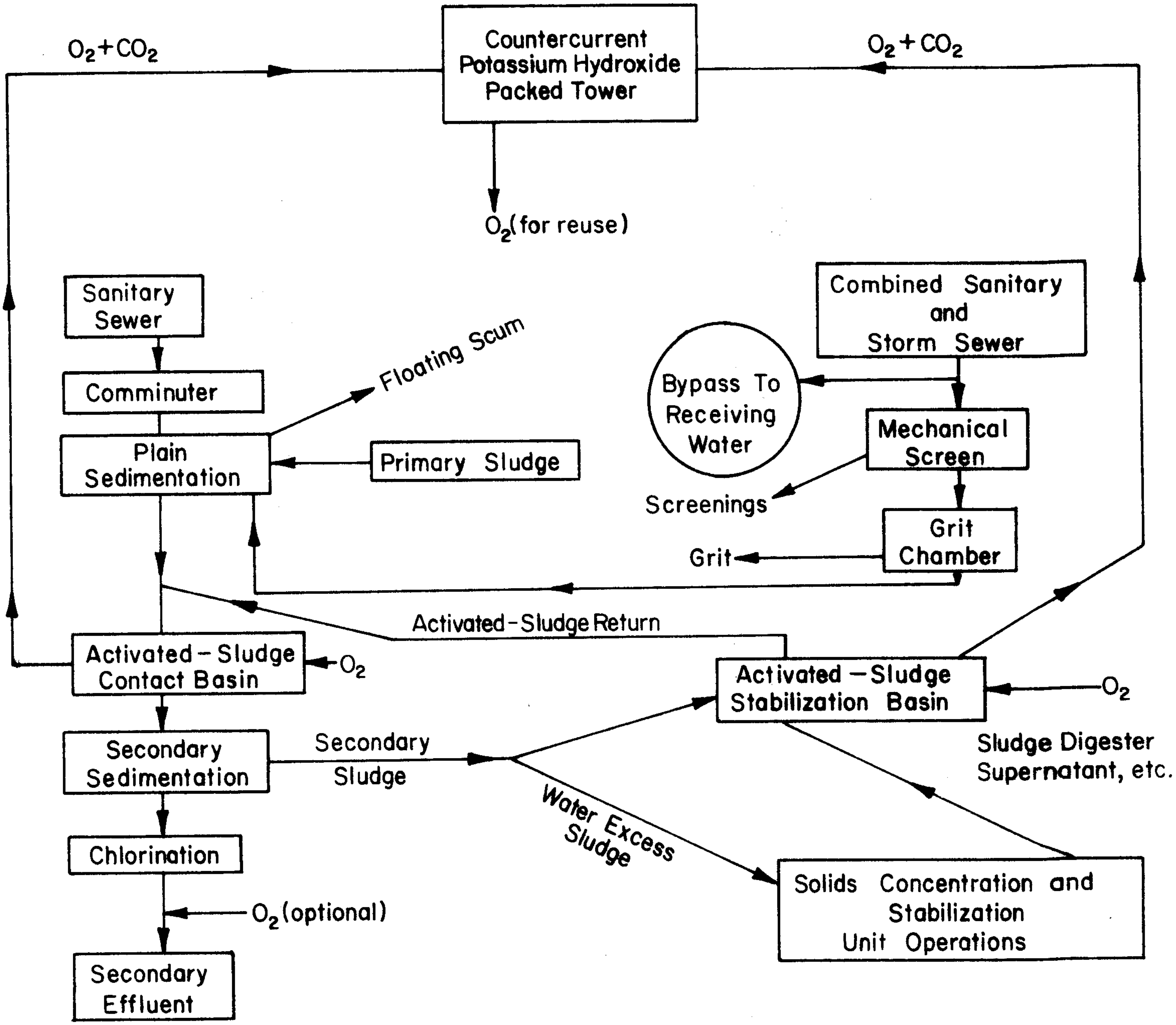


Fig.6- Enclosed Contact-Stabilization Activated-Sludge Wastewater Treatment Plant Using Oxygen Instead of Air for Aeration.

illustrated in Figure 6. This research sould be carried out in three phases as follows:

(1) Laboratory scale to determine the technical feasibility of the foregoing and to obtain design data for the second phase of the research which is;

(2) Pilot plant scale to estimate the economic feasibility of the foregoing and to obtain design data for the third phase of the research which is;

(3) Full scale plant to demonstrate the economic feasibility of the foregoing and to obtain accurate cost-effectiveness information.

SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

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3. Accession No. **W**

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15. Supplementary Notes: Part A by S. M. Morrison, G. C. Newton, G. D. Boone, and K. L. Martin, Microbiology

16. Abstract

Part 1 (The Effects of Water Temperature and Elevation upon Aeration): A laboratory-scale mechanical aeration system was used to examine the variation in oxygen transfer rates into water as a function of water temperature (0 to 40°C). The over-all volumetric mass transfer coefficient, liquid phase base, increased linearly with water temperature at a rate of 2.84% per $^{\circ}$C. The relative aeration efficiency decreases with increasing elevation, water temperature, and dissolved oxygen concentration. For zero dissolved oxygen and elevation, the rate of oxygen transfer per unit volume and time is independent of water temperature for 0 to 60°C. Equations were developed relating saturation dissolved oxygen concentration to temperature and atmospheric pressure to elevation and air temperature.

Part 2 (BOD and COD Removal from Wastewater by Aeration with Air and Oxygen): Both air and oxygen were used under identical conditions to determine the effect (if any) of dissolved oxygen concentration on the rate of oxygen demand removal. At 20°C, the rate of oxygen demand removal was independent of the dissolved oxygen concentration over the range 3.4 to 32 mg/ℓ. The use of oxygen in an enclosed contact-stabilization activated sludge wastewater treatment plant suitable for high altitudes and latitudes is shown.

17a. Descriptors: *Aeration, *Water Temperature, *Altitude, *Oxygen, Dissolved Oxygen, Chemical Oxygen Demand, Biochemical Oxygen Demand

17b. Identifiers: *Oxygen Transfer, *Low Water Temperature, *High Elevation, *Oxygen Aeration, *Mechanical Aeration, Atomospheric Pressure, Air Temperature

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