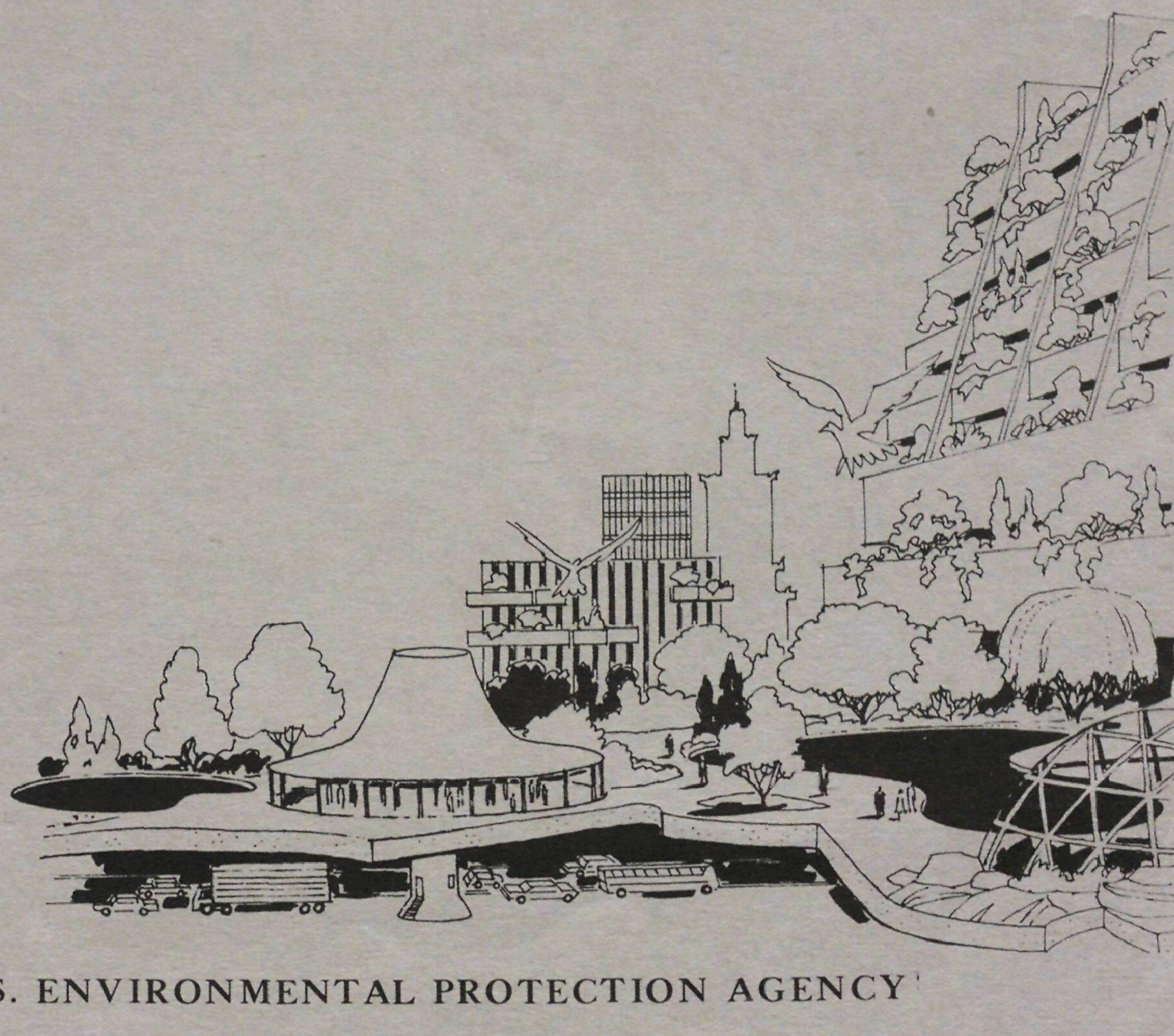
CLEAN WATER
WATER POLLUTION CONTROL RESEARCH SERIES • 16080FSN10/71

ENGINEERING METHODOLOGY FOR RIVER AND STREAM REAERATION



U.S. ENVIRONMENTAL PROTECTION AGENCY

WATER POLLUTION CONTROL RESEARCH SERIES

The Water Pollution Control Research Reports describe the results and progress in the control and abatement of pollution in our Nation's waters. They provide a central source of information on the research, development, and demonstration activities in the Office of Research and Monitoring, Environmental Protection Agency, through inhouse research and grants and contracts with federal, state, and local agencies, research institutions, and industrial organizations.

Inquiries pertaining to Water Pollution Control Research Reports should be directed to the Chief, Publications Branch (Water), Research Information Division, R&M, Environmental Protection Agency, Washington, D. C. 20460.

- about our cover

The cover illustration depicts a city in which man's activities coexist in harmony with the natural environment. The National Water Quality Control Research Program has as its objective the development of the water quality control technology that will make such cities possible. Previously issued reports on the National Water Quality Control Research Program include:

Report Number	Title
16080---06/69	Hydraulic and Mixing Characteristics of Suction Manifolds
16080---10/69	Nutrient Removal from Enriched Waste Effluent by the Hydroponic Culture of Cool Season Grasses
16080DRX10/69	Stratified Reservoir Currents
16080---11/69	Nutrient Removal from Cannery Wastes by Spray Irrigation of Grassland
16080DO007/70	Optimum Mechanical Aeration Systems for Rivers and Ponds
16080DVF07/70	Development of Phosphate-Free Home Laundry Detergents
16080---10/70	Induced Hypolimnion Aeration for Water Quality Improvement of Power Releases
16080DWP11/70	Induced Air Mixing of Large Bodies of Polluted Water
16080DUP12/70	Oxygen Regeneration of Polluted Rivers: The Delaware River
16080FYA03/71	Oxygen Regeneration of Polluted Rivers: The Passaic River
16080GPF04/71	Corrosion Potential of NTA in Detergent Formulations
16080GGP07/71	Effects of Feedlot Runoff on Water Quality of Impoundments

ENGINEERING METHODOLOGY FOR RIVER AND STREAM REAERATION

by

JBF Scientific Corporation
2 Ray Avenue
Burlington, Massachusetts 01803

for the

ENVIRONMENTAL PROTECTION AGENCY

Project #16080 FSN

October 1971

EPA Review Notice

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price $1.25

ABSTRACT

Results of recent activities in river and stream aeration by artificial techniques are reviewed, and a rational engineering methodology is developed for future river and stream aeration projects.

The development of the methodology follows from a thorough review of the oxygen dynamics in rivers and streams and the capabilities of aeration systems within the present state of the art. The report shows how the theoretical work can be simplified considerably and applied to the solution of river and stream water quality problems. It is assumed that aeration would only be used as a "polishing" action after all identifiable waste sources have received at least secondary treatment.

The results indicate that, with careful consideration of site factors, artificial aeration can be applied successfully to raise dissolved oxygen to 5 ppm, using mechanical surface aerators, diffusers, downflow contactors, and sidestream mixing. However, since the transfer of oxygen from air into water is relatively inefficient above 5 ppm DO, the introduction of molecular oxygen through sidestream mixing, U-Tubes, and possibly diffusers should be considered, depending on the volume of water to be aerated. In cases where DO may be maintained at levels lower than 5 ppm, systems using air are competitive with molecular oxygen, depending on site conditions.

This report was submitted in fulfillment of Project Number 16080 FSN under the partial sponsorship of the Environmental Protection Agency.

CONTENTS

SECTION		Page

FIGURES

TABLES

SECTION I

CONCLUSIONS

1. A review of the present state of the art in river and stream aeration indicates that the performance of aeration systems is strongly related to the minimum DO level set as a standard on any particular river or stream.

2. When a minimum level of 5 ppm is set, any system not using molecular oxygen will be relatively inefficient and, unless unusual site conditions prevail, will probably not be suitable. This is particularly true in summer months, when the saturation concentration for DO is at its lowest value.

3. The most efficient location for mechanical surface aerators and diffusers using air is at the point of maximum oxygen deficit. In order to maintain some established minimum DO level, however, these devices must be located wherever that minimum is approached, resulting in a significant loss of transfer efficiency. Based on presently available transfer rate data, mechanical surface aerators and diffusers using air are not efficient for maintaining DO levels above 4 ppm.

4. Downflow contactors provide a higher transfer efficiency than surface aerators or diffusers but can only be used where sufficient water depth is available. Nitrogen supersaturation may also be a problem but can be avoided by limiting the depth of the down leg of the tube. Since maximum transfer efficiency occurs at depths greater than 40 feet, there will always be some loss in efficiency if nitrogen supersaturation is to be avoided.

5. The lack of mobility and dependence on water depth limit the usefulness of downflow contactors in problems requiring the maintenance of a minimum DO level. These systems may be considered only if an injection point for oxygen occurs at a compatible location.

6. A relatively simple methodology can be developed for treating river and stream aeration problems. In this methodology the DO profile for "worst conditions" is used to determine alternative locations for aeration units in order to maintain some specified minimum DO level. Loss in natural aeration due to the oxygen addition must be taken into account. Alternative locations are required because site conditions may preclude the use of some types of aeration systems. There may also be cases where a trade-off is necessary between the injection of large amounts of oxygen at one location versus smaller amounts at several locations.

7. For large rivers where more than 50,000 lbs/day of oxygen is required, the use of molecular oxygen applied through side stream mixing should definitely be considered. Whether or not the oxygen is supplied from a generating plant located on the site, or delivered to the site as liquid oxygen will depend on the length of time over which oxygen is required. For continuous year-round operation, gaseous oxygen should be generated on the site. For intermittent periods and for volume requirements of less than 50,000 lbs/day, liquid oxygen trucked to the site may be more economical.

8. The transfer processes of various aeration systems in rivers and streams are not as well understood as in treatment facilities or even lakes and impoundments. The superimposed flow field creates some uacertainty in handling the analytical details, and a wide range of efficiencies has been reported. The range for surface aerators after conversion to standard conditions is 1.2 to 4.5 lbs O_2/hp-hr. Thus, depending on the number chosen, cost estimates may be off by as much as a factor of three.

9. The mathematical models of stream processes are generally adequate for the engineering design of a river or stream aeration system. The major inadequacy lies in the prediction of natural aeration coefficients from empirical methods. If measurements of the reaeration coefficient cannot be made at the site and an empirical method must be selected, the stream conditions from which that particular derivation was made should be reviewed to determine suitability for the particular application.

10. A review of current techniques for measuring rate processes which control DO and BOD in rivers and streams indicates that the present state of the art offers sufficient accuracy for the design of stream aeration systems. Additional refinements can be made; however, the results may offer a precision greater than the variations in the processes being measured.

11. Differences in longitudinal dispersion coefficients for a stream have been reported. Such differences may be due to whether or not measurements were made with the aeration system in place and operating. Knowledge of the dispersion characteristics are particularly important for large river systems where the aerator system is a relatively localized source. Measurements of the dispersion coefficient should be made with the device in place.

SECTION II

RECOMMENDATIONS

Artificial aeration of rivers and streams should not be used as a direct substitute for waste treatment at the source. There may be cases, however, where aeration can be used as a "polishing" action during periods of high temperature and low flow. Until advanced waste treatment methods are fully developed and implemented, public opinion may require an interim solution. Artificial aeration is at a state of development now where it can be applied to specific river and stream problems.

Although artificial aeration is technically feasible, cost estimates are still not sufficiently accurate, due to problems in predicting the transfer efficiency of a system in a stream. This deficiency will probably not be corrected by performing more tests. The primary need is to define the conditions under which aeration devices should be tested if they are to be used in a river or stream environment. A laboratory program should be undertaken to standardize measurement conditions for a variety of hydraulic parameters which might be encountered in the field. The results of this program should then be cross-checked to determine compatibility with field conditions.

The results of this study have indicated that the maintenance of a 5 ppm DO requirement will be difficult unless molecular oxygen is employed, and methods for delivering molecular oxygen to the water need additional development. The sidestream pressurization method is oriented toward large rivers where only a portion of the flow can be diverted. Work should be done on using gaseous oxygen, delivered to a site by truck, to supply a fine-bubble-size diffuser. The gas would be delivered under pressure, and this might reduce the possibility of internal clogging. A system like this would have application in small, shallow rivers or streams.

The conclusion has been made that surface aerators will not be effective in maintaining a DO level above 4 ppm. In cases where a level less than 4 ppm is acceptable, the design of the aerator should be modified to promote mixing of air and water downstream of the aerator. The symmetrical radial mixing zone of present aerators can be made asymmetrical by adding baffle plates or flow guides.

The design of an aeration system for a river or stream requires consideration of a number of factors. The system can be designed successfully by following an orderly procedure which highlights all of the considerations. The procedures should be formalized to the extent that design errors due to a lack of knowledge about river and stream processes are minimized.

In summary, the following areas are most in need of additional research and development:

1. Uniform standards for the measurement of transfer efficiencies of various aeration devices under flow conditions.

2. Improved devices for the diffusion of gaseous oxygen in the water.

3. Enhancement of surface aerator performance through the use of flow guides or baffles.

SECTION III

INTRODUCTION

Scope and Purpose

Present aeration technology for rivers and streams has developed primarily from waste treatment applications and from a limited number of field tests in lakes and rivers. The purpose of this study was to review the results of recent activities in river and stream aeration by artificial techniques and to assess the present state of the art. A direct result of this review has been the development of an engineering methodology for river and stream aeration systems.

The major objective in any aeration system design is to add oxygen to the water. In waste treatment applications this is done to satisfy a high biochemical oxygen demand (BOD), while in lakes and rivers one wishes to maintain a high-enough dissolved oxygen level to support a healthy aquatic population. There are other differences affecting system design, including the need to promote mixing of suspended solids in an aerated lagoon versus the desire to minimize excessive turbulence in lakes for aesthetic reasons. In rivers and streams natural flow conditions provide mixing, and new water is always being exposed to the aeration system. In lakes where there is no natural flow condition the most efficient aeration system is one which provides continual recirculation with minimum power. This results in the exposure of new water surfaces to the air and promotes diffusion and mixing.

In order to efficiently design an aeration system for rivers and streams the oxygen balance for the stream must be understood. The primary source of oxygen for a stream is natural reaeration at the surface, which is aided by the velocity and turbulence of the stream. If a stream is artificially aerated, there will be some loss in the natural aeration capability, and this must be compensated for by the engineer in estimating the additional oxygen required to meet a specified water quality condition. Additional contributions come from photosynthesis, ground water, drainage, and flow augmentation.

The remainder of the report is organized as follows. In Section III the scope and purpose, background, and approach methods are introduced. Section IV includes a review of the oxygen dynamics in rivers and streams and a section on the measurement of parameters in the oxygen-balance equation. Section V is a review of the use of surface mechanical aerators, diffusers, downflow contactors (U-Tubes), and sidestream mixing in river and stream applications. Also included in Section V is a discussion of the possible benefits of using pure oxygen instead of air. In Section VI the methodology for designing the aeration system is developed.

Background

Over the last 50 years an extensive body of literature has accumulated on the application of aeration in waste treatment. Recently, interest has developed in the use of aeration technology for destratifying lakes and reservoirs and in artificially improving the assimilative capacity of rivers and streams.

Serious consideration of artificial aeration for rivers and streams appears to have been first initiated by Tyler [1] in the early 1940's. He proposed that under certain conditions it might be economically advantageous to treat waste in a stream rather than in concentrated form as would be the case in a treatment pond. This philosophy has apparently interested a number of investigators, as there have been many tests of this concept in the last 5-10 years.

A second philosophy on the use of artificial stream aeration assumes that all possible waste material entering a stream is first treated in a waste treatment plant, resulting in the removal of 90-99% of the BOD. The aeration system would then be used as a supplement where DO levels on the order of 5 ppm are required to support a viable aquatic life and its attendant recreational benefits. In this case the aeration system would probably be operated on a seasonal basis when DO levels fell below 5 ppm. As will be shown later, much more work is required to maintain a 5 ppm level than would be needed for a 3 ppm level; thus relative transfer efficiencies of aeration devices are an important consideration.

Many of the aeration tests conducted have used site-dependent techniques, such as turbine venting, weirs, and dams. Although these techniques have demonstrated reasonable transfer efficiencies, their dependence on site conditions limits general application. Consequently, the emphasis in this study has been on more flexible systems, such as mechanical surface aerators, diffusers, downflow contactors, and sidestream mixing.

Since 1966, a number of tests have been conducted using mechanical surface aerators. A fewer number have used diffusers and sidestream mixing. No tests using U-Tubes in a flowing river were found, although there is reason to believe from results obtained in lakes and impoundments that these devices can be used on rivers and streams, given sufficient water depth. In several tests of diffusers, U-Tubes, and sidestream mixing, molecular oxygen has been substituted for air.

In many of the test programs the aeration systems were evaluated under a variety of actual or simulated stream conditions. Performance data in most cases was converted to a set of standard conditions, with the transfer efficiencies stated in pounds of oxygen transferred per horsepower hour.

Although the economics of river and stream aeration favor a high oxygen transfer rate, site conditions also restrict the use of particular aeration devices, for reasons other than cost. Many rivers are navigable both to shipping and recreational boating; others are used for recreational boating and water sports. Where public use is extensive, surface aerators using turbulent mixing would be restricted. In cases where a channel is maintained by dredging, diffuser systems cannot be located in the channel. Designs of aeration systems must also consider aesthetic conditions at the site. Large, unsightly structures with extensive surface agitation may not be acceptable to the public.

Approach

An extensive survey of the literature was conducted, with particular emphasis on reports of field tests with mechanical surface aerators, diffusers, U-Tubes, and sidestream mixing. Although necessary in the development of a total river basin system, reports dealing with mathematical and simulation models were reviewed only for background information. Each aeration field test was reviewed for engineering design, continuity of results, and efficiency.

In addition to a state-of-the-art review, emphasis was placed on the development of an engineering methodology for river and stream aeration which could be used by an engineer charged with the development of a system for a particular location.

In the course of the study it was evident that some aspects of river and stream aeration require additional research. Although large-scale projects may be possible within the present state of the art, additional research should result in better system effectiveness. Recommendations for further research are included in this report.

SECTION IV

DISSOLVED OXYGEN DYNAMICS IN RIVERS AND STREAMS

Oxygen Balance

Artificial aeration of a body of water, whether it is a lake or a stream, will have some effect on the natural oxygen balance. An understanding of the natural processes controlling oxygen concentration is therefore necessary before the design of an artificial aeration system can be undertaken.

There are four main processes controlling oxygen concentrations in naturally aerated streams:

1. Consumption of oxygen as a result of respiration of benthic and planktonic organisms, and chemical oxidation;

2. Exchange of oxygen as a result of atmospheric reaeration;

3. Photosynthetic production of oxygen during the day by benthic plants and phytoplankton; and

4. Oxygen contribution from ground water, surface drainage, and storage.

In the first case, consumption of oxygen by respiration is expressed as a biochemical oxygen demand (BOD) in pounds of oxygen per unit time. For DO levels below 1 ppm the rate of consumption has been found to be dependent on the DO concentration [2]; thus, in highly polluted streams there may be a diurnal variation in BOD if the stream becomes oxygen depleted in any particular area. For higher DO concentrations there does not appear to be the same dependence. Hence, for rivers or streams in which the minimum DO levels are on the order of 2 or 3 ppm it is sufficient to assume that the oxygen demand is a function only of the remaining BOD.

The oxidation of the organic load may occur in the stream or on the bottom, depending on the physical nature of the material. Because the rate of demand of the finely dispersed material in the stream differs from the demand of the larger particles, which settle to the bottom, the two components are often treated separately.

Also included in the respiration process is the oxygen uptake caused by nitrification, which is the oxidation of ammonia and nitrites to nitrates. These compounds are common in the effluents of secondary waste-treatment plants. Because nitrification is an autotrophic process carried out by relatively few organisms, an appreciable time lag may exist between the introduction of ammonia and the point at which measurable nitrification occurs. Because of the difference in rate and time, nitrification is often treated separately from BOD.

The second process is the primary natural mechanism for oxygenating a stream. Oxygen diffuses from the atmosphere directly into the water, with the exchange rate depending on the rate of renewal of new water surfaces and on the percentage saturation of oxygen in the water. Turbulent stream conditions facilitate a higher oxygen transfer than do quiescent conditions. If the water becomes supersaturated with oxygen, the direction of transfer may actually be to the atmosphere. Figure 4.1 shows typical diffusion rates for a stream in which there is significant photosynthetic oxygen production. In this case, oxygen is released to the atmosphere when photosynthesis during the day results in supersaturation.

The production of oxygen by photosynthesis is the third process in the oxygen balance. In this process, carbohydrates are synthesized from carbon dioxide and water, with a subsequent release of oxygen. This process requires radiant energy from the sun and is consequently diurnal in nature. The greatest rate of production occurs around noon and drops to zero at night, as is shown in Figure 4.2. The rate and total production will depend on the depth of penetration of sunlight, which is, in turn, dependent on water clarity or turbidity. Maximum daily production occurs at about 1800 hours, as opposed to the maximum rate of production, which occurs around noon.

The fourth process is the accrual of oxygen from ground water, drainage, and storage. This is a site-dependent contribution whereby incoming waters containing higher (or lower) concentrations of dissolved oxygen produce changes in the stream DO. This contribution is usually negligible except when it involves flow augmentation from hydroelectric storage impoundments.

The dissolved-oxygen level in a stream, therefore, is the net result of several dynamic processes occurring simultaneously. The processes interact to produce variations in DO along the length of a stream, the graphic representation of which is usually called the DO profile or "oxygen sag curve."

These processes can be quantized on an area basis, e.g., $g/m^2/hr$, or on a volume basis as $g/m^3/hr$, which is also ppm/hr. The summation of these processes can be expressed as follows:

$$q = d + p - r + a \tag{4.1}$$

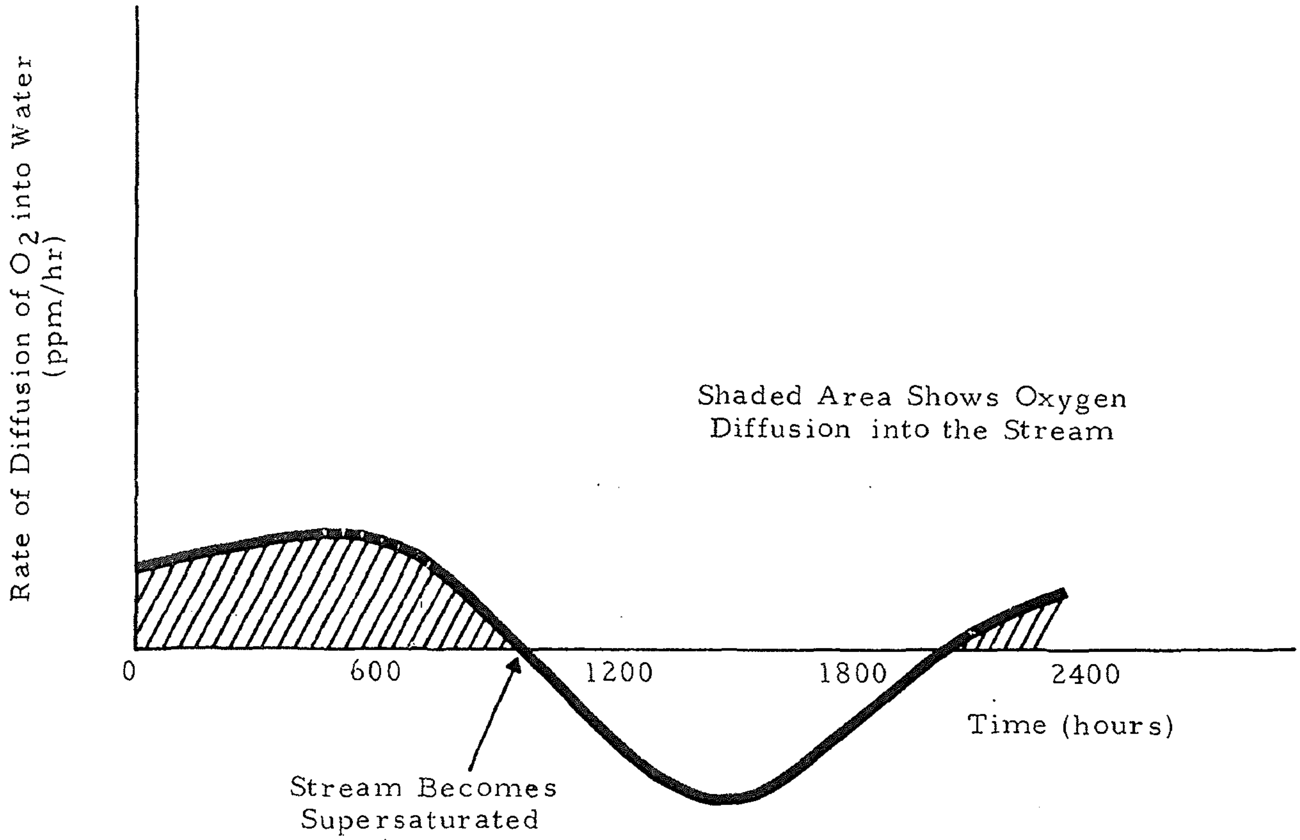


Figure 4.1. Typical Rate-of-Diffusion Plot

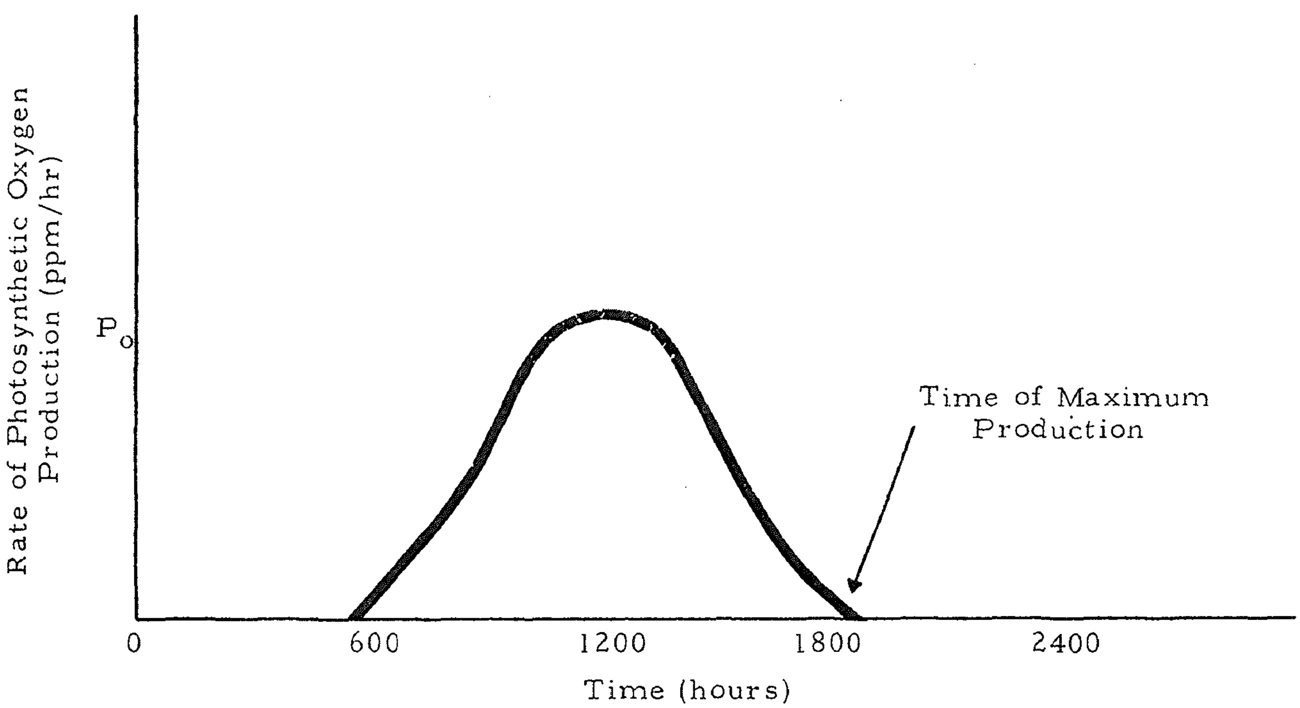


Figure 4.2. Typical Plot of Photosynthetic Oxygen Production

where

q = rate of change of dissolved oxygen per unit volume (ppm/hr

r = rate of respiration, including oxygen demands by plants, animals, and aerobic bacteria (ppm/hr)

d = rate of diffusion from the air if the concentration of dissolved oxygen is below saturation (ppm/hr)

p = rate of production of oxygen by photosynthesis (ppm/hr)

a = rate of accrual from drainage, ground water, or storage (ppm/hr)

If an oxygen sag curve shows low DO levels at certain stream locatio or if DO is lower than desired over a particular reach of a stream, artificial aeration systems may be used as a supplemental source of oxygen. The fate of the added oxygen will depend on the natural stre processes.

In designing an aeration system it is necessary that a new oxygen sa curve be calculated after oxygen is added artifically to raise the DO level. The shape of the curve will indicate how many aeration devic are required and their spacing, in order to keep the DO level above some specified minimum. In Section VI the specific techniques for determining the number and spacing of aerators are developed. In this section it is sufficient to note that the artificial aeration will hav some effect on the natural balance, and any decrease in the ability o the stream to reaerate naturally must be compensated for by the aeration system.

In order to obtain a numerical solution to the oxygen balance equatio a one-dimensional representation of each of the rate processes in Equation 4.1 is developed as expressed in Equation 4.2.

$$\frac{\partial C}{\partial t} = D_L \frac{\partial C}{\partial x^2} - U\frac{\partial C}{\partial x} + K_a(C_s - C) + P - K_cL - K_nN + A - S \quad (4.$$

where

A = rate of accrual of O_2 from drainage, ground water, etc. (ppm/day)

C = DO concentration (ppm)

C_s = saturation value of DO (ppm)

D_L = turbulent diffusion (dispersion) coefficient (ft^2/day)

K_a = aeration constant (1/day)

K_c = instream carbonaceous oxidation constant (1/day)

K_n = instream nitrogenous oxidation constant (1/day)

P = photosynthetic production rate (ppm/day)

S = benthal demand rate (ppm/day)

U = mean stream velocity (ft/day)

t = time (day)

x = distance along the stream (ft)

and

L and N are given by the solutions to

$$\frac{\partial L}{\partial t} = D_L \frac{\partial^2 L}{\partial x^2} - U\frac{\partial L}{\partial x} - K_c L + L_a \qquad (4.3)$$

and

$$\frac{\partial N}{\partial t} = D_L \frac{\partial^2 N}{\partial x^2} - U\frac{\partial L}{\partial x} - K_n N + N_a \qquad (4.4)$$

where

L = carbonaceous BOD (ppm)

L_a = uniform rate of addition of carbonaceous BOD (ppm/day)

N = nitrogenous BOD (ppm)

N_a = uniform rate of addition of nitrogenous BOD (ppm/day)

Equations 4.2 through 4.4 form a system of coupled, second-order, partial differential equations, the solution of which results in DO and BOD profiles along a stream. The equations are for general non-steady-state conditions and can be simplified for many stream conditions. Considerable simplification can be achieved, for example, when steady-state conditions are assumed or if diffusion effects are small. If simplification is not possible, a digital computer greatly eases the computational burden.

The first step in the solution is to partition the river reach under consideration into a number of sections, each of which is assumed to be completely mixed or homogeneous. A finite-difference method is then used to express the derivatives of the dependent variables C, L, and N. Details of the numerical producer can be found in references 3 and 4.

Although each of the rate terms and constants appearing in Equations 4.2 through 4.4 may be different for each section, they are often essentially equal and additional simplification can be achieved.

In order to obtain numerical values for terms appearing in Equations 4.2 through 4.4, a number of laboratory and field techniques have been developed. These techniques are discussed in the next subsection along with the practical assumptions that can be made and the relative orders of magnitude of the measured values.

Evaluation of Stream Parameters in Oxygen-Balance Equation

Saturation Values of C_s

The solubility of oxygen in water is primarily influenced by temperature and salinity. According to SED-ASCE [5] , the saturation value of oxygen concentration at sea level can be expressed as

$$C_s = 14.625 - .41022T + .0799T^2 - .000077774T^3$$

where

T = temperature in °C.

In studies conducted on the Passaic River, organic pollution did not appear to have a discernible effect on the saturation values [6] . It is reasonable, therefore, to assume that, unless one is dealing with extremely high organic loadings, the values of C_s given by the above equation are applicable. Values of C_s for the temperature range of 0°C to 40°C are given in Table 4. 1.

Aeration Constant— K_a

The natural aeration rates that occur in streams depend directly on the amount of turbulence and consequently are related to hydraulic parameters, such as velocity and depth of flow. Temperature and

TABLE 4.1

Saturation Values of Oxygen in Clean Water at One-Atmosphere Pressure

Temperature		
^{o}F	^{o}C	C_s
32.0	0	14.6
35.6	2	13.8
39.2	4	13.1
42.8	6	12.5
46.4	8	11.9
50.0	10	11.3
53.6	12	10.8
57.2	14	10.4
60.8	16	10.0
64.4	18	9.5
68.0	20	9.2
71.6	22	8.8
75.2	24	8.5
78.8	26	8.2
82.4	28	7.9
86.0	30	7.6
89.6	32	7.4
93.2	34	7.2
96.8	36	7.0
100.4	38	6.8
104.4	40	6.6

the type and concentration of pollutants in solution also affect aeration but to a lesser degree.

The aeration constant for a stream in which there is little biological and chemical activity can be readily evaluated. The temperature (to determine C_s) and DO measurements are taken at two stream locations where relatively steady-state conditions exist. An average value of K_a can then be calculated using Equation 4.5.

The rate of atmospheric aeration has been demonstrated to be proportional to the oxygen deficit $(C_s - C)$ [7], i.e.,

$$\frac{dC}{dt} = K_a(C_s - C)$$

Letting $C_s - C = D$,

$$- \frac{dD}{dt} = K_a D$$

which upon integration results in

$$\frac{\ln \frac{D_1}{D_2}}{\Delta t} = K_a \qquad (4.5)$$

where

D_1 = upstream deficit (ppm)

D_2 = downstream deficit (ppm)

Δt = time of travel between stations (days)

As mentioned previously, if the DO concentration in a stream is strongl influenced by biochemical oxygen demans, photosynthesis, nitrification, etc., the above approach is questionable. To minimize these effects, the time of observation between stations should be minimized; however, caution must be exercised in order to avoid conditions which may reflec small differences of small numbers.

Since natural aeration is a function of surface renewal, which, in turn, depends on hydraulic parameters, a number of empirical and theoretical formulations have been proposed for determining K_a. Many of the theoretical studies are based on transport phenomena and consider, for example, effects of surface tension, molecular diffusivity, and turbulence. In general, for stream applications these approaches reduce to formulations which express K_a in terms of two readily determinable stream parameters, viz, depth and velocity. The general form of the equation is

$$K_a = C \frac{V^{k_1}}{H^{k_2}} \qquad (4.6)$$

Table 4.2 contains values of the various constants in Equation 4.6 determined by different investigators.

Observation of the values given in Table 4.2 indicates that each formulation will result in a different value for K_a. It should be realized that each formulation has its limitations. In the case of a theoretical formulation [9] verification with stream conditions is needed. And for the remaining empirical equations caution must be used in applying results to stream conditions other than those from which the observations were made.

TABLE 4.2

Aeration Parameters for Determining K_a.

Investigator	C	k_1	k_2
Churchill et al. [8]	11.56	.969	1.673
O'Connor & Dobbins [9]	1.291	.5	1.5
Gameson [10	23.17	.73	1.5
Langbein & Durham [11]	7.59	1.0	1.33
Owens et al [12]	21.62	.67	1.85

Usually both the depth H and the velocity V can be obtained as a function of stream flow (Equation 4.7a), which would then permit the aeration constant to be expressed as a direct function of flow, as shown in Equation 4.7b.

$$H = f_1(Q) \qquad V = f_2(Q) \tag{4.7a}$$

From Equation 4.6

$$K_a = C \frac{V^{k_1}}{H^{k_2}} = f_3(Q) \tag{4.7b}$$

For the Passaic River [6] this type of analysis resulted in the following expressions for depth and velocity:

$$H = 0.746Q^{.398}$$

$$V = 0.020Q^{.524}$$

The above expressions were used in Equation 4.6 for the various values of C, k_1, and k_2 given in Table 4.2 The resulting predictions of K_a are shown in Figure 4.3, indicating that values of K_a differ widely according to the various formulations. (The precise reasons for such a spread are not clear, although the investigators speculated that perhaps it is because the Passaic is an unusually slow river and may be out of the range of the formulations.)

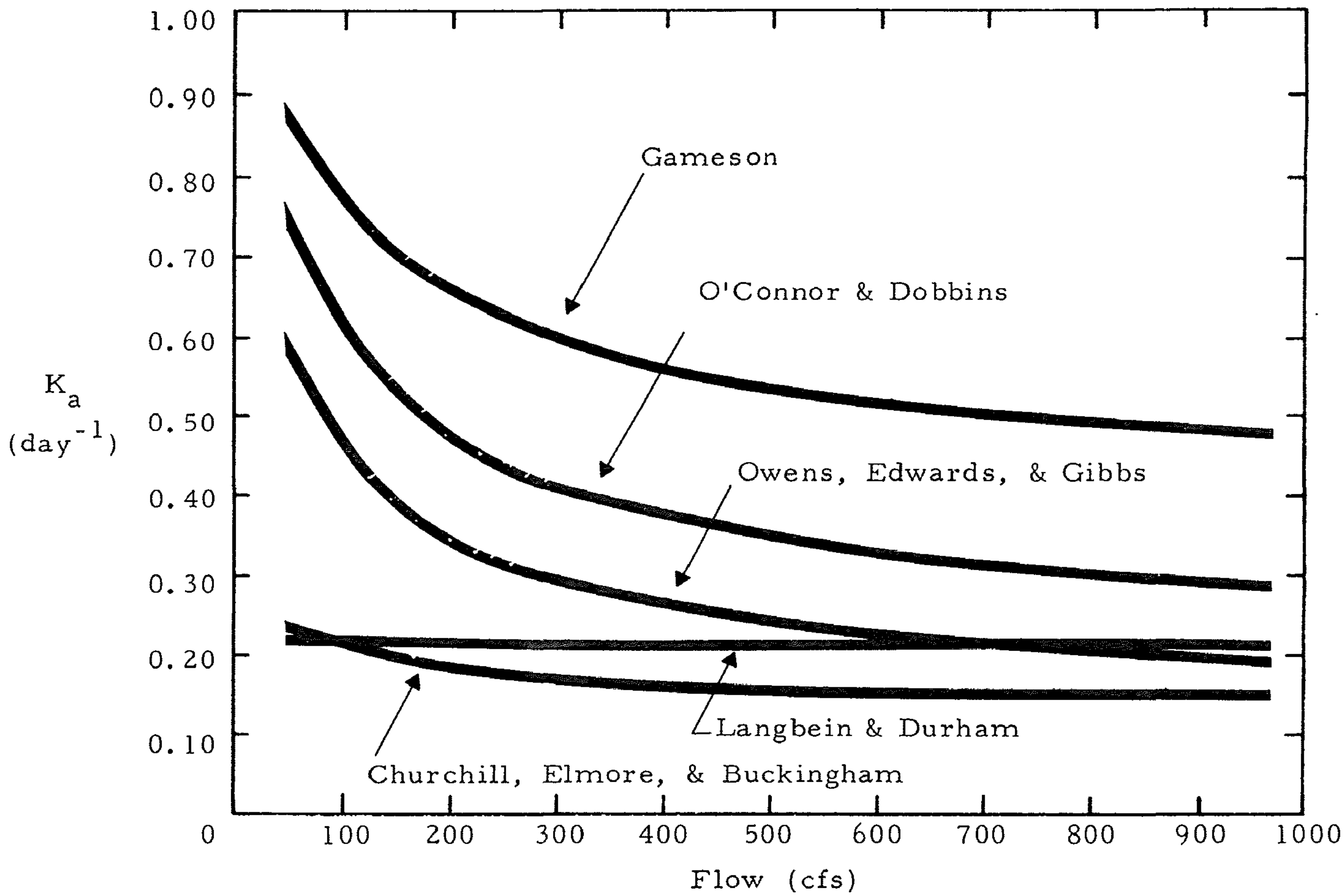


Figure 4.3. K_a vs Flow, as Calculated by Various Prediction Equations (Whipple et al. [6])

Because of the significant spread in the predicted values of the aeration constant, a serious question arises as to the general applicability of the formulations. The formulation of O'Connor and Dobbins (see Table 4.2) seems to provide an adequate description of aeration in natural waterways, since good agreement was found by the authors between measured and predicted values for several rivers [9]. Their formulation was also considered to be the most representative of aeration of the Passaic River. Other equations, e.g., that of Churchill et al., also provide good results for several rivers [8].

Since the natural aeration capability is affected by many chemical, biological, and physical factors, it is quite possible that no one formulation will be universally applicable. Thus, the above formulations should be used with discretion, particularly where "white water" turbulence or vertical stratification is evident. Furthermore, the predictions are for clean water, and if polluted water is to be aerated, adjustments on a percentage basis must be made, to account for the effect of the pollutants.

Since natural aeration is the most significant contributor in maintaining the DO level in a stream, it is advisable to measure the natural aeration coefficient before completing the final design of an aeration system. For preliminary design estimates, either the method of O'Connor and Dobbins or that of Churchill et al. is probably equally applicable.

Aeration transfer rates are quite sensitive to water conditions. Table 4.3 shows the large range of aeration transfer rates that have been measured for different water conditions. (Values given are mass transfer per unit of surface area per unit time.) For still water, values are on the order of .034 $g/m^2/hr$; while for water conditions involving small droplets, rates can be as high as 34 $g/m^2/hr$. Values for flowing water lie between these two bounds, which encompass three orders of magnitude.

The aeration constant is also a function of temperature. Reported values are usually given in the form

$$K_a(T) = K_a(20) \times \theta^{(T-20)}$$

where

$K_a(T)$ = aeration constant at temperature $\underline{T}$

$K_a(20)$ = aeration constant at $20^{\circ}C$

and θ is a factor ranging from 1.015 to 1.047. A commonly used value is 1.024.

TABLE 4.3

Transfer Rate of Oxygen into Water from Air for Various Flow Conditions (Odum [13])

	Velocity (m/sec)	Depth (m)	Temp. (°C)	K (g/m²/hr at 10% saturation)
Still water	0.0	-	20-25	.034
	0.0	-	-	0.03-0.08
Moving water				
Stirred water	-	-	25	0.09-0.74
Shallow circulating trough	0.01	0.1	0-10	0.037
	0.01	0.1	10-20	0.043
	0.01	0.1	20-30	0.47
	0.013	0.1	12	0.12
	0.070	0.1	17	0.52
	0.119	0.1	14	1.12
	0.20	0.1	13	3.8
Sewage in circulating trough	0.05	0.45	25-26	0.38
	0.15	0.45	25-26	1.5
Stream and ponds	-	-	-	0.08
New York Harbor	tidal	-	-	0.23
Tank with a wave machine	-	1.8	-	0.31
Sea Surface				
Summer	-	-	12-20	1.1
Winter	-	-	2-7	5.2
Silver River, Florida				
Subtraction-of-respiration method	0.21	2.77	23	0.92
Dye-measured-turnover method	0.21	2.77	23	1.00
Green Cove Springs, Florida. From carbon dioxide by respiratory-quotient method	0.3	0.23	24	0.55
Small rivers, diurnal oxygen curve analyses	-	0.5-3.	2	0.6-4.3
Ohio River below Cincinnati	0.05-0.09	4.8	15-25	1.5-5.0
Bubbles and drops (K given per area of drop or bubble)				
Air bubble	-	-	37	13.1
Air bubbles	-	-	20-25	2.8-28.
Water drops	-	-	24	22-34.

Biochemical Oxygen Demand (BOD)

Since the various oxygen demands in a stream or river depend on processes which proceed at different rates, each one should be described separately. For example, depending on the physical nature of organic loadings, the fine particulate matter will oxidize in the stream, while the larger particulates will tend to settle, forming the benthos, and will oxidize at a different rate. Furthermore, if the loading contains ammonia or nitrites, oxygen demands again occur at different rates, and separate rate constants are needed to describe each of the processes, which are commonly referred to as carbonaceous, nitrification, and benthol oxygen demand.

The oxidation of organic matter is essentially a chemical reaction, initiated either directly by bacteria or indirectly by their enzymes. As previously stated, the oxygen demand is exerted by two classes of materials: carbonaceous organic matter and oxidizable nitrogen, both of which may occur simultaneously [14-18] . Figure 4.4 illustrates the two processes and the clear distinction that they proceed at different rates. It can be seen in this case that a period of at least 19 days was required before oxidation was essentially completed. The upper curve represents the total BOD of the water (first and second stage). This is readily obtained by measuring the oxygen uptake of stream samples as a function of time (see reference 11). The lower curve represents only the carbonaceous BOD and can normally be obtained by following the methods given in Standard Methods [19], which call for the measurement of the oxygen uptake as methylene blue or allylthiourea. The tests are usually performed in a laboratory at 20°C. By taking the difference between the two curves, a curve representing the nitrogenous BOD is obtained. (In both of these tests, time and temperature can be closely controlled, but it is difficult to simulate the dynamics of the river environment, including the biological chain.)

The carbonaceous BOD follows a first-order reaction process, viz, the rate of biochemical oxidation is proportional to the remaining concentration of unoxidized substance. Such a process is described mathematically by

$$-\frac{dL}{dt} = K_c L \qquad (4.8)$$

which yields, upon integration,

$$L = L_o e^{-K_c t} \qquad (4.9)$$

where

t = time (days)

L = carbonaceous BOD at time t (ppm)

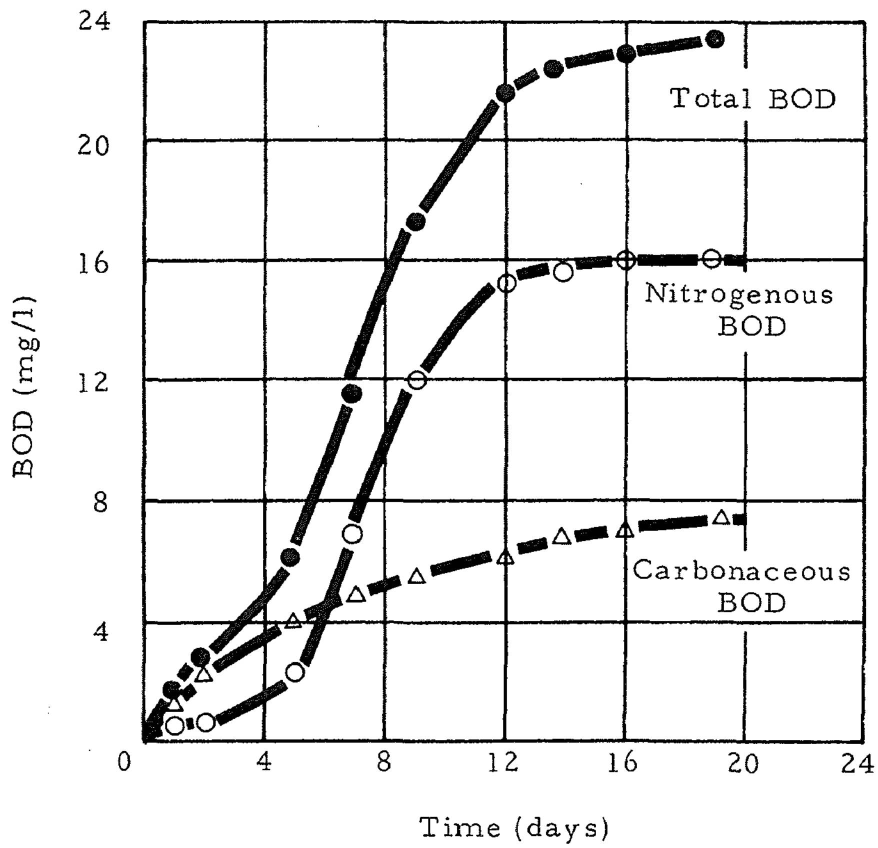


Figure 4.4. Grand River BOD Curve (Courchaine [18])

L_o = ultimate carbonaceous BOD (ppm)

K_c = carbonaceous deoxygenation constant ($\frac{1}{day}$)

K_c can be obtained from the slope of a semilog plot of Equation 4.9 and is usually on the order of .1/day at 20°C. In order to evaluate K_c for a stream it is not necessary to conduct the test for 20 or more days, since the slope of a semilog plot of Equation 4.9 can be quite accurately determined over a time period of 5 days. However, the ultimate carbonaceous demand L_o must be correctly stated. This can be clearly illustrated by examining Table 4.4 below. It can be seen that for K_c = .1/day, at the end of 5 days only 68.4% of the carbonaceous BOD has been consumed; hence, the ultimate carbonaceous BOD would be

$$BOD_{ult} = L_o = \frac{BOD_{5\ day}}{.684}$$

TABLE 4.4.

Percentages of Carbonaceous BOD as a Function of Time for K_c = .1/day

Time (days)	Remaining BOD (%)	Consumed BOD (%)
0	100	0
1	79.4	20.6
2	63.0	37.0
5	31.6	68.4
10	10.0	90.0
20	1.0	99.0

Both K_c and L_o depend on temperature. The following expressions were extracted from a recent study [54].

$$L_o(T) = L_{o(20)}\ (1 + 0.0113\ (T - 20)) \quad \text{range } 20^\circ - 35^\circ C$$

$$L_o(T) = L_{o(20)}\ (1 + 0.0033\ (T - 20)) \quad \text{range } 2^\circ - 20^\circ C$$

$$K_c(T) = K_{d(20)} \ (0.896)(1.126^{T-15}) \quad \text{range } 2^\circ - 32^\circ C$$

$$K_c(t) = K_{d(20)} \ (1.047^{T-20}) \quad \text{range } 15^\circ - 32^\circ C$$

$$K_c(T) = K_{d(20)} \ (1.728)(0.985^{T-32}) \quad \text{range } 32^\circ - 40^\circ C$$

The oxidation of carbonaceous matter is a heterotrophic process carried out by a great variety of different organisms and having optimum temperatures ranging from 18° to 25°C. Many of the bacteria obtain their food and energy requirements from the organic matter present in the water and have generation times on the order of 20 to 30 minutes [14]. On the other hand, nitrification is an autotrophic process, i.e., one which is carried out by specific bacteria which obtain food and energy from oxidation of ammonia and nitrites. The nitrogenous oxidation process involves two genus organisms, Nitrosomonas and Nitrobacter, each of which have an optimum growth temperature range of 25° to 28°C [20]. Furthermore, generation times on the order of 31 hours are necessary for nitriting cells to develop [14]. Often nitrification may not occur for several days, e.g., in a study on the Passaic River [6] nitrification did not begin until 3 days had elapsed and, in the case of the Grand River, a situation was found in which nitrogenous BOD did not occur until after 9 days (see Figures 4.5 and 4.6 [18].

Thus, it can be concluded that BOD tests should be conducted over a long-enough period to determine if and to what extent nitrification processes will occur. This is especially important if a river or stream may receive the effluents from a secondary treatment plant.

The ultimate oxygen demand due to nitrification is directly limited by the amount of oxidizable nitrogen available. The process involves the oxidation of ammonia to nitrite, which is carried out by the genus Nitrosomonas, and the second phase, the conversion of nitrite to nitrite, which is carried out by the genus Nitrobacter. The overall stoichiometric relation is given below:

$$NH_3 + 2O_2 \rightarrow HNO_3 + H_2O$$

$$(\text{M.W.}) \rightarrow 14 \qquad 64 \qquad 62$$

By comparing molecular weights, one finds that 1 part of NH_3 will consume 4.57 parts of O_2 by weight. Thus, 1 mg/l of ammonia is equivalent to 4.57 mg/l of BOD, and 1 mg/l of nitrate produced by

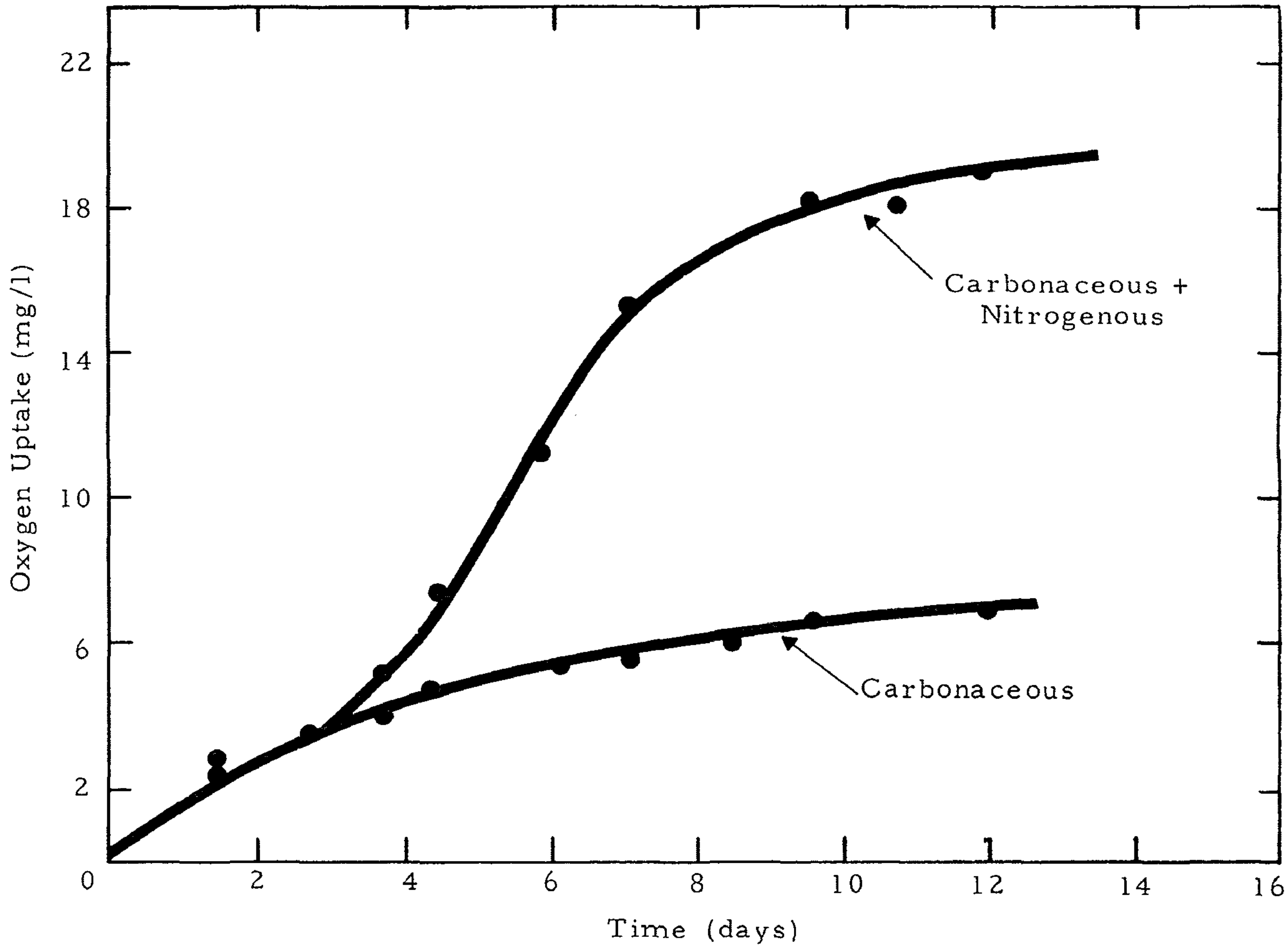


Figure 4.5. Total Carbonaceous and Nitrogenous BOD as a Function of Time (Whipple [6])

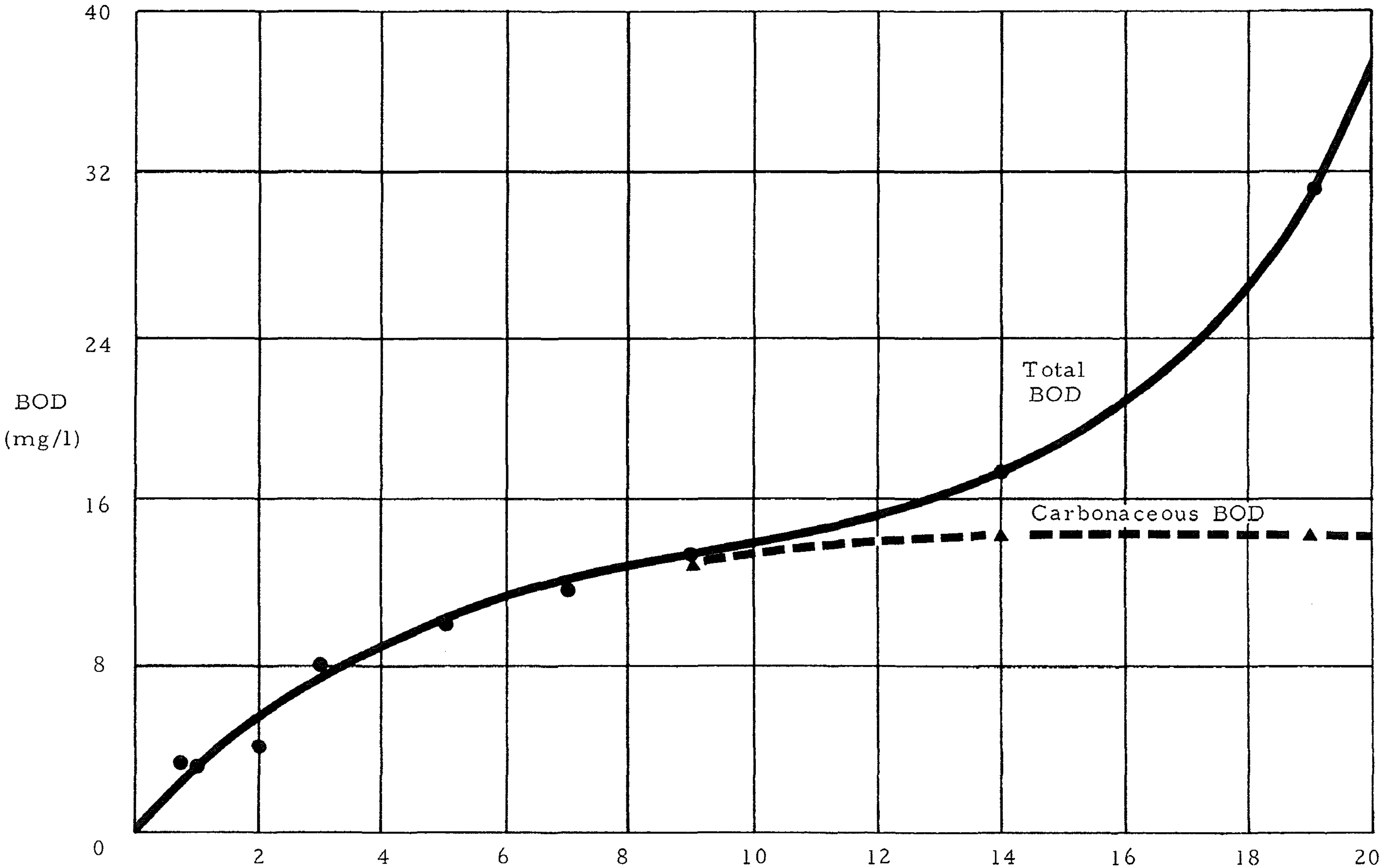


Figure 4.6. BOD Curve, Lansing Wastewater Treatment Plant, 24-hr Composite Sample, Taken July 12, 1960.

the oxidation of ammonia is equivalent to 1.03 mg/l of BOD. It is expected that some variation from the above ratio will exist because of fixation by carbon dioxide, lowering the ratio of 4.57 to perhaps 4.3 or 4.4 [21].

The rate of oxygen consumption by ammonia and nitrogenous matter is directly related to the multiplication of the nitrifying bacteria. It can clearly be seen from Figure 4.6 that the nitrogenous BOD curve consists of two phases. In the first phase the nitrifiers are lagging; the bacteria are undergoing multiplication, building up to a maximum population. Once this maximum is reached, the process enters the second phase (corresponding to the point of inflection), which is similar in shape to curves obtained for carbonaceous BOD. Such a process is clearly not first order. However, for mathematical expediency in predicting oxygen sag curves for a stream, the process is frequently assumed to be a first-order reaction [6, 22, 23], i.e., one in which

$$\frac{dN}{dt} = K_n N = K_n(N_o - N_t) \qquad (4.10)$$

where

N = nitrification demand (ppm)

t = time (day)

K_n = nitrification constant (day^{-1})

N_o = ultimate nitrification demand (ppm)

N_t = nitrification demand at time _t_ (ppm)

and which integrates to

$$N_t = N_o(1 - e^{-K_n t}) \qquad (4.11)$$

In order to take into consideration the lag time associated with the nitrification process, Whipple et al. [6] found it advantageous to include a lag-time term t_a in the following manner

$$N_t = N_o(1 - e^{-K_n \langle t - t_a \rangle}) \qquad (4.12)$$

where the triangular brackets represent the singularity function such that

$$\langle t - t_a \rangle = 0 \quad \text{for } t < t_a$$

$$\langle t - t_a \rangle = t - t_a \quad \text{for } t \geq t_a$$

An important point when evaluating the various constants is the fact that the time lag t_a can be a function of where and when a stream sample is taken. If oxidizable nitrogen was introduced near the point at which the sample was taken, long lag times can be expected. However, if the sample was taken a considerable distance downstream from the introduction of nitrogenous matter, short lag times may result, since incubation may have initiated during the transit time.

By describing the nitrification process as a first-order process, an upper bound is obtained on the BOD, since such a representation results in BOD values larger than those actually occurring (see Figure 4.7).

As mentioned earlier, the effect of temperature is quite significant. According to O'Connor [24], the temperature dependence is given as

$$K_n = K_n(20)\ 1.09^{(T - 20)} \qquad (4.13)$$

More detailed investigations of the twofold nitrification process have been conducted by several authors [25-28], in which the rate of change of nitrogenous BOD is expressed in terms of ammonia oxidation and nitrite oxidation. The expressions are relatively complex, nonlinear in nature, and, to be of practical use, they often require the assistance of a digital computer. In view of the many environmental conditions affecting nitrification (temperature, pH, chemical composition of the water, the specific genus of nitrifying organism present, etc.) and the variability of determining other terms in the equations used to predict the oxygen profile of a stream (Equations 4.2 through 4.4), it may be concluded that the effort involved in obtaining the precision offered by the more refined approaches is questionable. For stream aeration design purposes, the use of Equation 4.12 will result in oxygen demands in excess of what actually is required for nitrification. However, in view of the many variables affecting stream aeration, its predictions are perhaps as good as any others.

Benthal Demands $\underline{S}$

One of the best methods of determining benthal demands $\underline{S}$ is to measure the oxygen consumption of the deposit "in situ." This can be effectively performed by using an opaque respirometer which is only open to the stream's bottom surface. By monitoring DO levels and subtracting the oxygen consumed by carbonaceous oxidation and nitrification at the same time and temperature, the net oxygen demand due to the benthos can be determined. Given the time period over which the consumption occurred, one can determine the benthal oxygen demand on a rate basis, usually expressed as ppm/day, or, when multiplying by the stream height $\underline{H}$, as $g/m^2/day$. Having the results in the latter form and knowing the percentage of the river bottom covered with

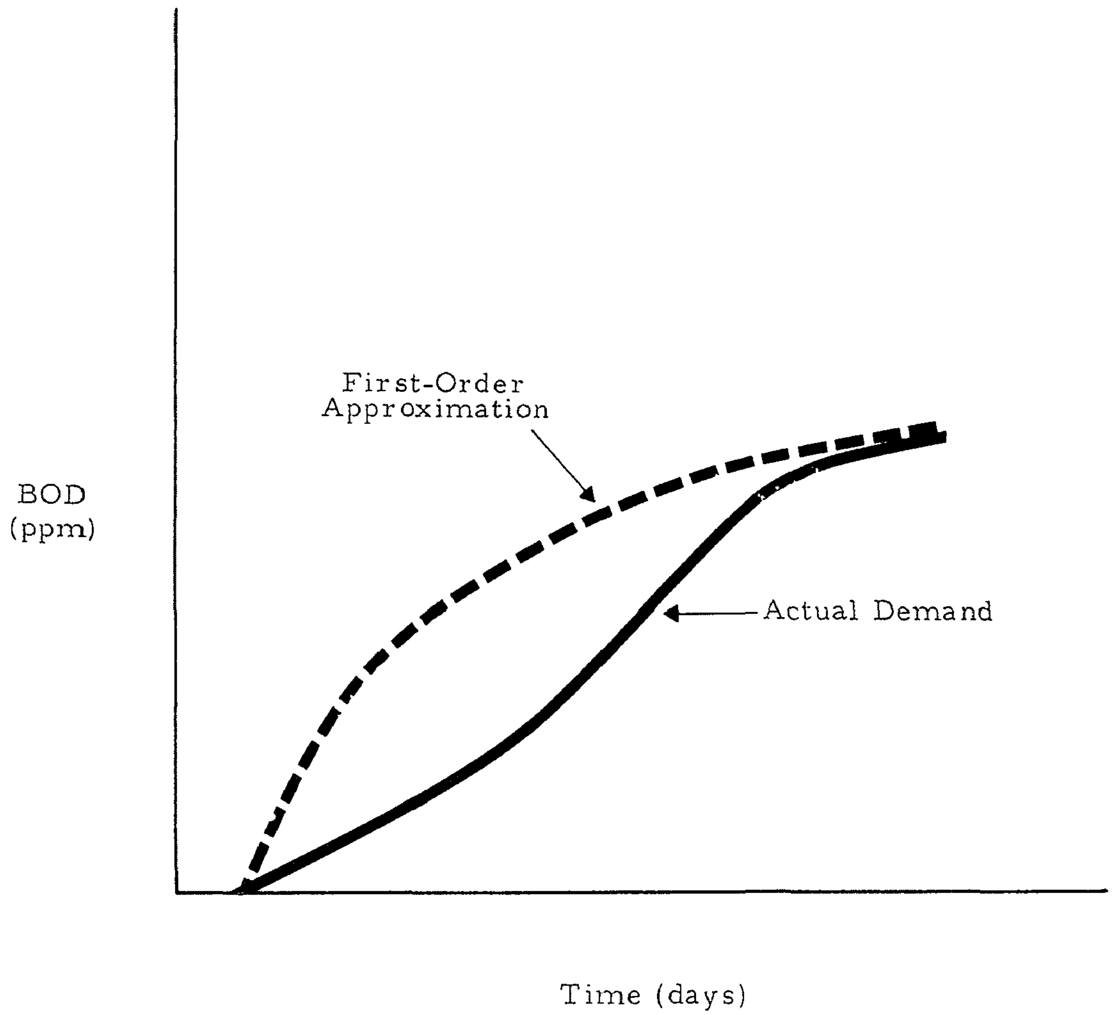


Figure 4. 7. First-Order Representation of a Nitrification Process

similar mud deposits permit the determination of the river demand on a daily basis. This approach gives an oxygen demand rate which is indicative of the steady-state consumption of the benthos. Making these measurements during summer months as opposed to other times of the year eliminates the need for temperature corrections when determining the needs of an artificial aeration system, even though such biological uptakes are temperature dependent. Since benthal demand rates are generally fairly constant and low, the "steady-state" value associated with the higher consumption rates during the summer months is a safe value to use for aeration system design.

Net Photosynthetic Oxygen Production P

The production of oxygen by photosynthesis in streams has been considered by several investigators [6, 13, 29-35]. Depending on the type of stream and associated climatological conditions, the contribution can be significant. Relevant parameters include presence of aquatic plants, especially free-floating and benthic algae; stream clarity; intensity of sunlight; stream temperature; and stream velocity. A study conducted on the Passaic River in New Jersey [6] indicated that the eutrophic zone was found to be limited to 50 centimeters, while investigations conducted on streams in Oklahoma [31, 35] which have relatively low turbidity have indicated that photosynthetic productivity in the benthos is considerable and at times in excess of that which is free-floating. Other studies, conducted on the Sirsloch River [29] in the U.S.S.R. and on the Rhine River in Germany [36], have also substantiated the finding that photosynthetic production of oxygen can be significant. In general, it can be concluded that the contribution of photosynthetic aeration should be considered when designing an aeration system.

Photosynthetic oxygen, by its nature, is diurnal in production and consequently is reported as a net production per 24-hour period, usually expressed in mg/ /day. A widely known method for measuring photosynthetic oxygen is the light-dark bottle technique. The measurement procedure requires one clear and one opaque bottle filled with stream water, which are incubated at several depths in the stream. At the end of the incubation period, which may run from one to several days depending on the rate of oxygen production, the difference in oxygen concentration between the water in the two bottles is assumed to be equal to the photosynthetic oxygen production.

The light-dark bottle technique requires the assumption that biological processes in the bottle are the same as those in the stream. This is not a completely valid assumption because the quiescence imparted to the samples affects the natural exchange of food and waste products to and from the organisms, and also because a higher surface-to-volume ratio is introduced in the sample bottles. In addition, this technique neglects photosynthetic oxygen from benthic algae or attached plants, an assumption which can only be made in relatively deep or turbid streams, where sunlight cannot penetrate to the benthos. If measurements are being made on a relatively clear, shallow stream, they could easily be in error. For this type of stream, Stay et al. [31] have developed a method which uses three plastic chambers placed over the stream bottom. Two sets of measurements are required, the first with plastic bottom plates covering the benthos and the second set without plates. Each of the three chambers is employed differently. One is clear and closed to the atmosphere, the second is clear and open to the atmosphere, and the third is black and closed. The oxygen concentration in the closed, clear chamber is affected by photosynthesis and respiration, while the oxygen in the black chamber is affected only by respiration. The clear chamber open to the atmosphere is a control. The tests are run with and without bottom plates, in order to account for respiration and photosynthesis of the benthos. The differences in concentration between the clear and dark chambers is the photosynthetic contribution.

The oxygen production should be expressed in terms of daily average rate (ppm/day). A more precise expression can be derived to account for the variation in sunlight intensity during the day. This precision is not required, however, when the object is to design an aeration system.

Longitudinal Dispersion

Longitudinal dispersion is the process of spreading and distributing a mass of pollutant or oxygenated water along the length of the stream. The spreading is a result of two diffusion processes, molecular diffusion and eddy diffusion. In turbulent flow the effect of molecular diffusion is negligible compared to that of eddy diffusion and consequently can be neglected.

In aeration system design, the rate of spreading and the resulting distrubition are important. The dispersion characteristic of flowing water has been found to vary greatly [36-42]. Table 4.5 contains values of dispersion coefficients D_L determined by various investigators for different rivers.

Examination of the table shows that longitudinal diffusion coefficients are larger for estuaries than for a conventional stream or river. This is primarily due to the mixing effects that occur in estuaries. An interesting point is the considerable increase in the diffusion coefficient of the Delaware River as a result of using a diffuser aerator (141,000 ft^2/sec, compared with 1075 ft^2/sec). The investigators speculated that the large value of the dispersion coefficient was a consequence of turbulence caused by the large bubbles emitted by the diffuser, and that a small-bubble diffuser might give smaller values.

Several approaches have been devised to predict the magnitude of the longitudinal diffusion coefficient. Some of the schemes have only

TABLE 4.5

Typical Longitudinal Dispersion Coefficients for Rivers

	Depth (ft)	Width (ft)	Discharge (ft^3/sec)	D_L (ft^2/sec)
Delaware (estuary) [40]	---	--	---	195-350
James (estuary) [49]	---	--	---	325
Hudson (estuary) [40]	---	--	---	4,850-16,100
Delaware (estuary) [37]	---	--	---	1075
Delaware (estuary) [44]	---	--	---	141,000*
Copper Creek, Virginia	1.6	52	54	210
[42]	2.8	60	300	230
	1.6	53	48	102
	1.3	61	483	106
Clinch River, Tennessee	2.8	154	323	150
[42]	7.0	195	3000	580
	6.9	175	1800	500
	1.9	118	240	87
Powell, Tennessee [42]	2.8	111	140	102
Coachella Canal, California [42]	5.1	80	950	103

*with artificial aerator in operation

been applied to laboratory channel conditions, while others have been verified with natural stream data. The "routing procedure" as described by Fischer [42] appears to give the best predictions when compared to dye-concentration measurements. However, this approach requires the use of tracer dyes and is mathematically involved to the extent of requiring the use of a computer. If cost and personnel limitations do not permit use of the routing technique, the disperson coefficient can be estimated from field measurements of velocities and water-surface slope. This technique has also been developed by Fischer [41] and will only be briefly described here. (If one is faced with evaluating the diffusion coefficient of a stream, references 41 and 42 should be consulted.)

The procedure involves measuring the slope of the stream and the cross-sectional geometry and velocity distribution at one or more typical cross sections. For many stream situations these field measurements can usually be completed in a day by a three- or four-man crew.

Equation 4.14 is used to calculate D_L for streams having a width-to-depth ratio equal to or greater than 6.

$$D_L = -\frac{1}{A}\int_0^b (q'(z)d(z) \int_0^b \frac{1}{E_z d(z)} dz \int_0^z q'(z)d(z) \qquad (4.14)$$

where

$$q'(z) = \int_0^{d(z)} u'(y, z)\, dy$$

E_z = $.23\, dU^*$ transverse turbulent mixing coefficient [42]

$u'(y, z)$ = velocity at any point relative to the mean flow velocity, i.e., $u'(y, z) = u(y, z) - \overline{u}$, where $u(y, z)$ is the actual velocity

$q'(z)$ = depth of flow at any point on the cross section (ft)

A = area of flow (ft^2)

b = width (ft)

y = vertical coordinate

z = transverse coordinate

U^* = $(grSe)^{1/2}$ function velocity, where g = acceleration of gravity, r = hydraulic radius, and Se = slope of the energy gradient

Although the calculation of D_L appears complicated and evaluation by hand is tedious, the equation can easily be programmed for a computer. Normally, depth and velocity measurements are taken at a minimum of 20 vertical sections across the stream. The integrals in Equation 4.14 are then approximated by summations, viz,

$$D_L = -\frac{1}{A}\sum_{k=2}^{n} q'_k \; z \left[\sum_{j=2}^{k} \frac{\Delta z}{E_{z_j} d_j} \left(\sum_{i=1}^{j=1} q'_i \; \Delta z\right)\right] \qquad (4.15)$$

where

$q'_i = \frac{1}{2}(d_i + d_{i+1})u'_i$

u_i = velocity in the i^{th} vertical slice (ft/sec)

$u'_i = u_i - \bar{u}$ (ft/sec)

$\bar{u}$ = mean velocity of the flow within the entire cross section (ft/sec)

d_i = depth at the i^{th} vertical slice (ft)

Δz = width of vertical slice (ft)

n = number of vertical slices (usually more than 20)

E_{z_i} = $.23 d_i U^*$ transfer coefficient between i-1 and the i^{th} vertical slice

Table 4.6 has been reproduced from reference 42 and illustrates the procedure to be followed.

Simplification of the Oxygen Balance Equations (4.2-4.4)

Equations 4.2 through 4.4 describe the temporal and spatial distribution of BOD and DO. The flow volume and the cross-sectional area are functions of both space and time. In order to simplify the treatment, the assumption is usually made that the most severe condition for design purposes is the one which can be made to approach steady state. Although steady-state conditions are seldom, if ever, attained, the errors introduced by this assumption are minor compared to variations occurring in the physical stream and in measurement procedures.

If, in addition to the steady-state conditions, the following assumptions are applicable:

1. Stream flow is uniform.
2. Carbonaceous and nitrogenous BOD are first-order reactions.
3. Photosynthetic oxygen, benthal demands, and accrual processes are uniform along a stream section and are determined on an average daily basis.
4. Vertical and transverse variations are negligible.

TABLE 4.6

Sample Calculation of Dispersion Coefficient from Field Data Test [41]

Data				Computed Quantities		
Vertical slice (1)	Distance from left bank to start of slice (ft) (2)	Depth at left side of slice d_i (ft) (3)	Mean velocity in slice μ_i (ft/sec) (4)	Discharge through slice relative to mean velocity $q'_i \Delta z$ (ft/sec) (5)	Cumulative relative discharge $\sum_{i=1}^{j} q'_i \Delta z$ (ft^3)/sec) (6)	$\sum_{j=z}^{k} \frac{\Delta z}{E_{z_j} d_j} \sum_{i=1}^{j-1} q'_i \Delta z$ (ft) (7)
1	0.0	0.00	0.15	-2.00	-2.00	0.0
2	2.5	1.00	0.25	-5.89	-5.89	-65.7
3	5.0	2.15	0.35	-8.31	-16.20	-121.9
4	7.5	2.61	0.42	-9.80	-26.00	-200.2
5	10.0	3.30	0.65	-9.20	-35.19	-278.9
6	12.5	3.41	1.35	-3.33	-38.53	-378.5
7	15.0	3.32	1.80	0.43	-38.09	-493.7
8	17.5	3.14	2.30	4.25	-38.84	-620.9
9	20.0	3.00	2.35	4.53	-29.31	-744.8
10	22.5	3.01	2.40	4.99	-24.32	-851.2
11	25.0	3.10	2.50	5.74	-18.58	-934.2
12	27.5	2.99	2.55	5.80	-12.79	-1,003.2
13	30.0	2.78	2.70	6.46	-6.33	-1,057.7
14	32.5	2.64	2.75	6.56	0.24	-1,087.6
15	35.0	2.59	2.65	5.93	6.17	-1,086.4
16	37.5	2.66	2.45	4.90	11.05	-1,057.7
17	40.0	2.90	2.30	4.07	15.12	-1,014.4
18	42.5	2.98	2.15	2.94	18.06	-958.3
19	45.0	2.84	1.85	0.73	18.79	-884.6
20	47.5	2.78	1.50	-1.69	17.09	-804.5
21	50.0	2.72	1.10	-4.13	12.96	-728.4
22	52.5	2.39	0.70	-5.51	7.46	-653.6
23	55.0	1.82	0.40	-4.48	2.98	-579.5
24	57.5	0.84	0.20	-2.28	0.70	-440.3
25	60.0	0.34	0.10	-0.70	0.00	-241.0

$$D = \frac{-\Sigma[\text{column (5)} \times \text{column (7)}]}{\text{total area}} = \frac{34,800 \text{ ft}^4/\text{sec}}{149 \text{ ft}^2} = 234 \text{ ft}^2/\text{sec}$$

then considerable simplification of Equations 4.2 through 4.4 results:

$$D_L \frac{d^2 C}{dx^2} + K_a(C_s - C) - U \frac{dC}{dx} - K_c L + P - K_n N + A - S = 0 \qquad (4.16)$$

$$D_L \frac{d^2 L}{dx^2} - U \frac{dL}{dx} - K_c L + L_a = 0 \qquad (4.17)$$

$$D_L \frac{d^2 N}{dx^2} - U \frac{dN}{dx} - K_n N + N_a = 0 \qquad (4.18)$$

Dobbins [45] has shown that, for freshwater streams, neglecting the longitudinal diffusion terms results in a prediction which is at most a few per cent different from a solution which includes the effects of diffusion. If the value of $\frac{U^2}{2K_a D_L}$ is on the order of 100 or more, neglecting the diffusion term results in a negligible difference. It should be noted, however, that the value of D_L should include the effects of the aerator system (see Table 4.5.)

If one is dealing with an estuary, the ratio of $\frac{U^2}{2K_a D_L}$ may be quite small, meaning that the diffusion is significant. This would be indicative of a relatively slow-moving body of water which experiences good mixing (e.g., tidal effects). If one concludes that the diffusion terms are negligible, Equations 4.16 through 4.18 reduce to

$$U \frac{dC}{dK} - K_a(C_s - C) + K_c L + K_n N - P - A + S \qquad (4.19)$$

$$U \frac{dL}{dx} + K_c L - L_a = 0 \qquad (4.20)$$

$$U \frac{dN}{dx} + K_n N - N_a = 0 \qquad (4.21)$$

Equations 4.20 and 4.21 can be integrated to give

$$L = L_o e^{-\frac{K_c}{U} x} + \frac{L_a}{K_c}$$

$$N = N_o e^{-\frac{K_n}{U} x} + \frac{N_a}{K_n}$$

which can be substituted into 4.19 to give

$$\frac{dC}{dx} - \frac{K_a}{U}(C_a - C) + K_c L_o e^{-\frac{K_c}{U} x} + K_n N_o e^{-\frac{K_n}{U} x} = P - L_a - N_a + A - S \qquad (4.22)$$

or

$$\frac{dD}{dx} + \frac{K_a}{U} D = K_c L_o e^{-\frac{K_c}{U} x} + K_n N_o e^{-\frac{K_n}{U} x} + L_a + N_a - P - A + S \qquad (4.23)$$

where D represents the oxygen deficit (C_s - C).

If nitrogenous BOD is small compared to carbonaceous BOD, the two can be combined in a single expression for BOD. Hence, Equations 4.4, 4.18, and 4.21 may not be needed in many stream analyses. The effects of nitrification would be contained in K_c, L, and L_a and would not be differentiated from carbonaceous consumption of oxygen. This has often been done in many of the analyses that appear in the open literature.

SECTION V

AERATION SYSTEMS FOR RIVER AND STREAM APPLICATIONS

Introduction

Various types of mechanical surface aerators, diffusers, and sidestream mixing systems have been used in experimental river and stream aeration projects. Downflow contactors (U-Tubes), although not used previously for river and stream aeration, have been used successfully in impoundments and lakes and should be adaptable to river and stream applications.

In this section the aeration systems which could be used for rivers and streams are described, and results of recent tests using these systems are evaluated. The specific application of any of these systems is extremely site dependent, thus site considerations are included in the discussion of each system. In most cases, aeration devices designed specifically for waste treatment have been used without modification in the stream application. Some improvements, particularly for surface aerators, can be made to enhance their performance when used in stream environments, since strong pumping action is not as important there as it is in waste treatment.

Downflow contactors, diffusers, and sidestream mixing systems can be used with both air and pure oxygen, and the relative merits of the two approaches are discussed in this section. Since the efficiency of diffuser systems depends strongly on the diffusion mechanism for small bubbles, this subject is included in the discussion of diffusers.

Mechanical Surface Aerators

A variety of designs for mechanical surface aerators are available from a large number of manufacturers. There are no designs of surface aerators specifically for river and stream aeration, available systems being used only in waste-treatment applications. A comprehensive description of surface aerators can be found in Manual of Practice No. 5, published by the Water Pollution Control Federation [47]. Some of that information is included in Appendix A.

For river and stream applications, it is desirable that the system be float-mounted, so that a wide range of flow conditions can be accommodated.

The following types of surface aerators have been developed. (See Appendix A for more details:

Rotating Plate	-	Creates a peripheral hydraulic jump that accomplishes oxygen transfer through entrainment.
Updraft	-	Pumps large quantities of water at the surface at relatively low heads. Aeration efficiency related closely to efficiency as a pump.
Downdraft	-	Oxygen is supplied by air self-induced by negative head produced by rotating element.
Combination	-	A rotating element and a sparge ring are combined to transfer oxygen by dispersing compressed air fed below the surface to a rotating agitator or turbine.
Brush	-	A horizontal revolving shaft with attached brush-like elements extending slightly below the surface.

The transfer of oxygen by surface aerators to a body of water is a direct result of breaking the water into small droplets and inducing turbulent mixing on or near the water surface. Each process causes new unsaturated water surfaces to be exposed to the air, resulting in their becoming saturated and subsequently mixed with the bulk of the water.

A significant difference between using surface aerators in streams and using them in lakes or still bodies of water is the superimposed effect of the stream current. The current provides the aerator with a supply of water low in DO compared to water in the mixing zone of influence of the aerator. Hence, the DO deficit will tend to be greater, enhancing the transfer of oxygen. Furthermore, since part of the energy consumed by surface aerators is in the pumping of water, aerators which expend relatively low pumping energy should be considered for stream applications. The pumpage associated with surface aerators should be supplied by the manufacturers. For example, the pumping rates published by two manufacturers for various horsepower units are listed in Table 5.1.

In a recent study, McKeown [47] measured velocity profiles and DO concentrations in stabilization basins as affected by surface aerators. Although the study dealt with basins and not streams, the results are characteristic of surface aerators and can provide preliminary information for stream applications. The investigation included a number of different sizes of surface aerators. Figure 5.1 shows the extent of influence of a 75-hp unit. The profiles shown are typical of surface aerators.

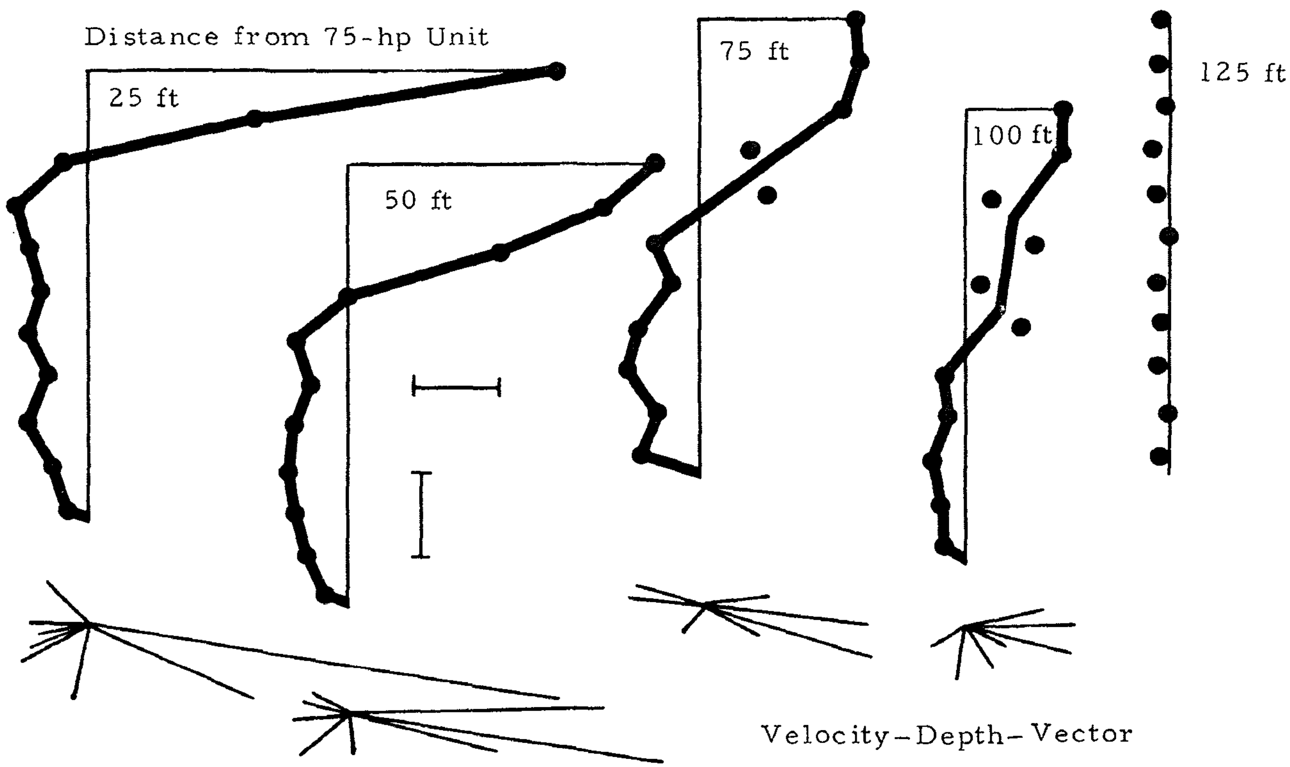


Figure 5.1. Example of Velocity Profiles at Various Distances from a 75-hp Aerator (McKeown [47])

TABLE 5.1

Surface Aerator Pumping Rates

Horsepower	Manufacturer A "Aqua-Jet"*	Manufacturer B "AQUARIUS"**
5	3400	2000
7.5	3800	3400
10	5000	4000
15	6100	5000
20	8300	6500
25	9800	7500
30	12,500	8000

*Aqua Aerobic Systems, Inc., Rockford, Illinois

**Keene Corporation, Aurora, Illinois

Table 5.2 [47] lists for various size aerators the depth of penetration of outward flow, the radius at which this depth is reached, and also the radius at which all discernible outward flow at the surface ceases. The position of the aerators was such that there was no interference from adjacent aerators or basin banks. It is interesting to note that the depth of penetration of the crossover point rarely exceeded 50% of the basin depth.

Table 5.3 [47] contains data on influence of flow and the net DO concentration changes at each foot of depth and at varying distances from the aerator.

It was concluded that the maximum zone of influence for different-size aerators was 300-400 feet for 100-hp units, 200-250 feet for 75-hp units, 150-250 feet for 40- to 60-hp units, and out to 150 feet for 10- to 25-hp units.

Attempts to compute the pumpage associated with the various aerators were not successful, primarily because the flow associated with the surface aerators is three-dimensional and the data collected did not consider the vertical dimension.

In another study conducted by Burns et al. [48], two 15-hp surface aerators were used to raise the DO in the Jackson River near Covingto[n] Virginia. It was reported that, by placing the aerators at sag points, transfer efficiencies on the order of 2.2 pounds O_2/hp-hr (20°C and 0 upstream DO) were obtained. Average stream velocities were approximately 3/8 ft/sec.

Kaplovsky et al. [49] conducted an investigation on aerating the foreba[y] of a canal at Lockport, Illinois, using two model 100 Hi CoWave

TABLE 5.2

Zone of Outward Aerator Influence* (McKeown [47])

Type	NPHP	DHP	D (ft)	d (ft)	r_1 (ft)	r_2 (ft)
L	10	8	11	5	50	110
L	10	8	12	3	50	80
L	10	8	11	4	75	100
H	25	21	10	2	40	60
L	40	41	8	2	50	80
L	40	27	8	2	50	80
L	40	34	8	3	50	80
L	40	26	8	2	50	80
H	50	47	13	7	50	100
H	50	47	14	6	50	80
H	50	50	9	3	50	60
L	50	-	12	5	60	110
L	50	-	11	6	60	110
L	60	52	11	6	75	110
L	60	52	14	3	50	75
L	60	49	14	3	75	110
L	60	49	12	4	100	125
L	75	54	8	2	100	110
L	75	64	14	5	75	125
L	75	55	14	4	75	110
H	75	64	10	2	40	60
L	75	59	10	5	60	100
L	100	-	18	9	150	200
L	100	-	18	9	100	150
L	100	-	18	7	100	175

*NOTE: (1) Nearest restriction (bank or aerator) at least $2.5r_2$ distant from aerator reported.

(2) Symbols:

L = low speed aerator
H = high speed aerator
NPHP = name plate horsepower
DHP = drawn horsepower
D = basin depth
d = maximum depth of penetration of outbound flow
r_1 = radius from aerator shaft to point of maximum depth (d)
r_2 = radius from aerator shaft to point where surface outward flow blends with background

TABLE 5.3

Sample DO Profiles at Various Distances from Aerators (McKeown [47])
(values shown in mg/l)

60-hp Unit	Radial Distance Depth	25 ft	50 ft	75 ft	100 ft
	0	2.4	2.1	2.0	1.7
	1	2.4*	2.0	1.8	1.5
	2	1.9	2.0	1.7	1.4
	3	1.8	1.8	1.7	1.3
	4	1.5	1.5	2.0	1.0
	5	1.4	1.4	1.6	1.2
	6	1.4	1.4	1.9	1.2
	7	1.2	1.4	1.5	1.2
	8-10	1.2	1.4	1.4	1.2
	11-13	1.2	1.3	1.2	1.2
100-hp Unit	0	2.0	1.0	0.4	0.0
	1	1.4	0.4	0.1	0.0
	2	0.2	0.2	0.0	0.0
	3	0.0	0.0	0.0	0.0
	4	0.0	0.0	0.0	0.0
	5-12	0.0	0.0	0.0	0.0
25-hp Unit	0	2.7	2.7	2.2	
	1	2.3	2.6	2.1	
	2	2.2	2.4	2.0	
	3	2.2	2.3	1.9	
	4	1.9	2.4	2.0	
	5	1.9	2.2	1.9	
	6-10	1.4	1.9	1.7	
50-hp Unit	0	2.5	1.5	1.6	1.9
	1	1.7	1.5	1.4	1.4
	2	1.5	1.3	1.4	1.5
	3	1.4	1.3	1.3	1.4
	4	1.1	1.1	1.3	1.4
	5	0.8	1.0	1.3	1.4
	6	0.6	1.0	1.3	1.3
	7-10	1.0	1.0	1.3	1.3
10-hp Unit	0	2.0	1.9	1.7	1.6
	1	2.0	1.7	1.5	1.5
	2	1.9	1.6	1.6	1.5
	3	1.6	1.5	1.5	1.4
	4	1.5	1.5	1.5	1.5
	5	1.5	1.5	1.5	1.5
	6-10	1.5	1.5	1.4	1.3

*Velocity crossover zones are underlined

Aerators (73 hp each). Flow rates varied from 800 cfs to 5600 cfs, and the average depth of the bay was 15 ft.

It was found that at low flow rates (1000-3000 cfs), transfer efficiencies on the order of 1.8 lbs O_2/hp-hr were obtained, while for high flow rates (4000-6000 range), efficiencies increased to on the order of 4.4 lbs O_2/ hp-hr (see Figure 5.2). The values quoted above have been correctec to standard conditions, using the average of upstream and downstream concentrations.

Figure 5.2 illustrates the differences in oxygen transfer at different rates of flow. The rapid transition shown is likely to occur if flow conditions changed, e.g., laminar to turbulent. However, from the data presented in the report no evidence of such a phenomenon could be found. It is quite possible that a more realistic curve of increasing efficiency would show a gradual increase, rather than an inflection.

The authors speculated that the appreciable increase in efficiency might be attributable to increased shearing of bubbles in the upstream region or greater retention time of the bubbles in the water. However, it is more likely that, as the stream velocity increases, more unoxygenated water is fed to the aerators, resulting in a greater O_2 deficit and a greater rate of transfer.

Whipple et al.[6] also found from studies using surface aerators on the Passaic River (average width 100 ft, average depth 7 ft in low flow) that an increase in efficiency occurred with flow rate, as shown in Figure 5.3. The efficiency increased from about 1.2 lb O_2/hp-hr at 120 cfs to approximately 2.8 lb/O_2/hp-hr at standard conditions. These values are consistent with those of Kaplovsky. However, the transition to higher efficiencies is more gradual and perhaps more representative of the actual situation. Some question remains as to what happens to the efficiency when the discharge approaches zero.

In contrast to the results of Kaplovsky and Whipple, Susag et al. [50] found in a series of laboratory tests that very little difference in oxygen transfer efficiencies occurred between flow and non-flow conditions. His average results, corrected to standard conditions (according to the aeration equation) for a 9-in. and a 12-in. unit, are contained in Table 5.4.

In the authors' opinion the values associated with the 9-inch unit were more representative, since very little splashing on the sides of their test tank occurred during that test. The velocity range investigated was from about .1 ft/sec to .65 ft/sec for the flow-through tests.

In addition to his tests on the Passaic River[6], Whipple directed a series of tests of surface aerators and bottom diffusers on the Delaware River near Philadelphia in order to determine the practicality of oxygenating a deep, navigable river [44]. The intent of the study was

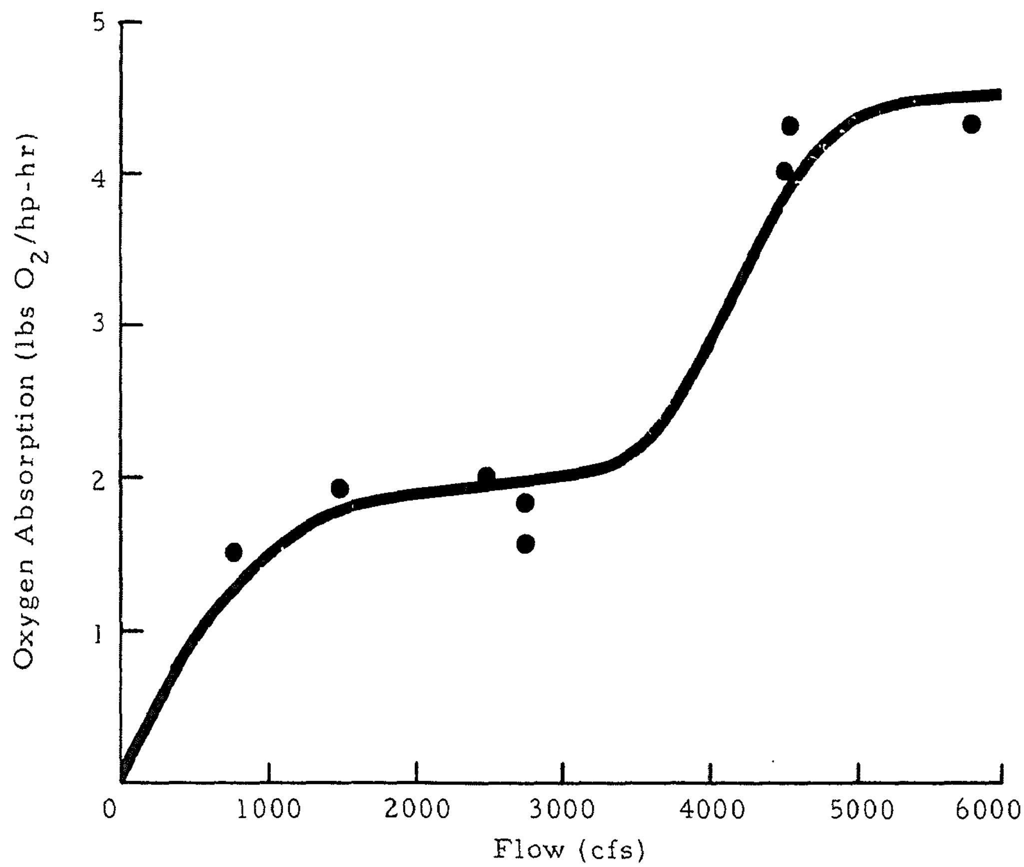


Figure 5.2. Mean Rate of Oxygen Absorption at Steady-State Operation Under Standard Conditions (Kaplovsky et al. [49])

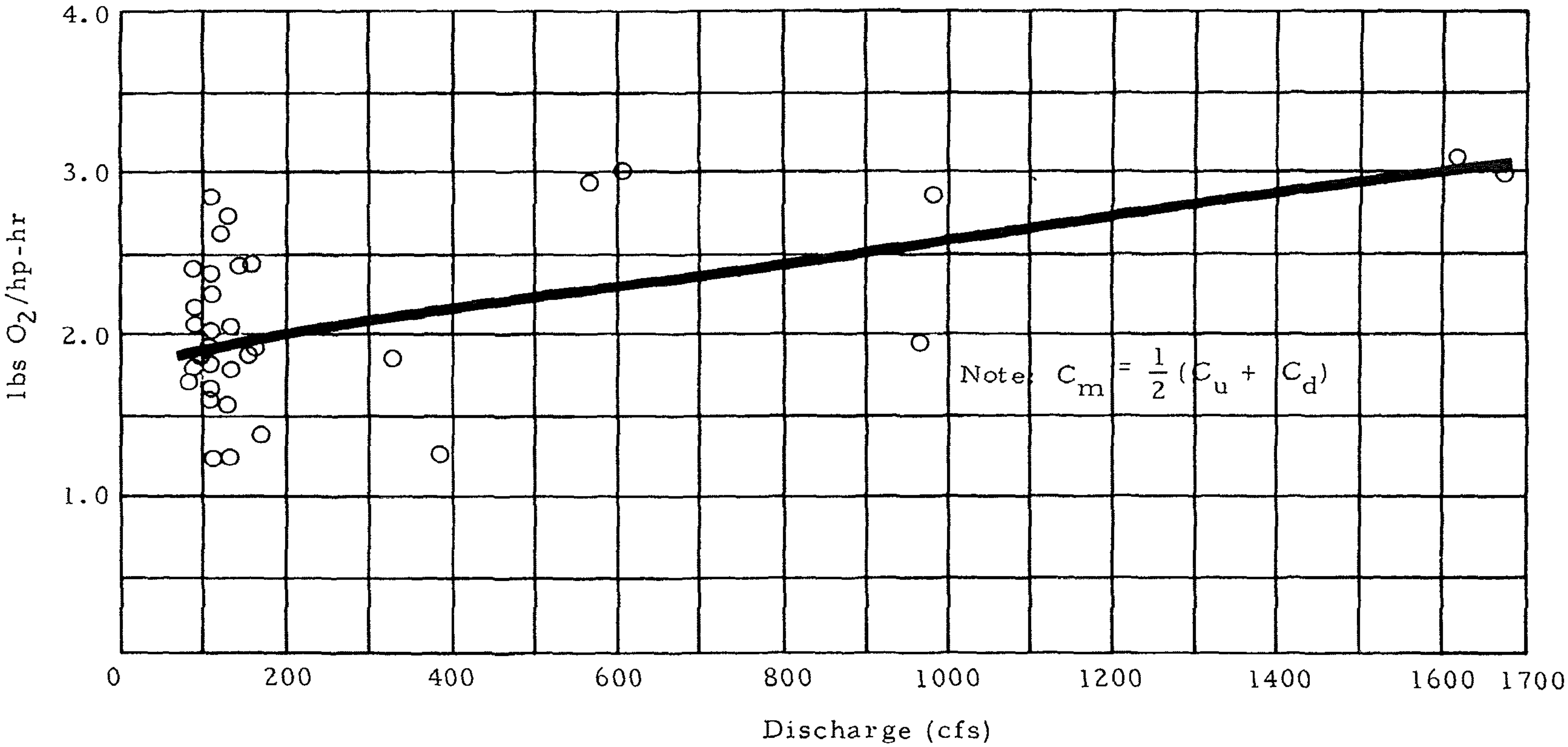


Figure 5.3. Oxygen Transfer Rate vs Flow for Mechanical Aerator (Whipple [6])

TABLE 5.4

Average Oxygen Transfer Efficiencies, in lbs O_2/hp-hr (Susag [50])

Turbine Size	Flow	No Flow
9 inch	3.73	3.89
12 inch	4.11	4.86

to test systems on a wide, deep, navigable stream to determine efficiency, economy, and operating characteristics and to prepare prototype designs and cost estimates for installations appropriate to such rivers. This is in contrast to the study on the Passaic River, which is a relatively small river.

The oxygen deficiency on the Delaware extended over a distance of about 40 miles, including areas containing heavy industry. The river is characteristically 2000 to 2500 ft wide above the confluence of the Schuylkill and somewhat wider below this point. The main channel is 40 ft deep, with adjacent anchorage areas of about 30 ft. Normal velocity range is 1 to 1-1/2 ft /sec.

Oxygen transfer rates were reduced to standard conditions. The α and β values were found to be equal to 1. Before being reduced to standard conditions, the surface aerator transfer rates varied from 1.18 lbs O_2/hp-hr to 3.78 lbs O_2/hp-hr, with an average of 2.56 lbs O_2/hp-hr; after conversion, the range became 1.29 to 4.50, with an average of 3.06 lbs O_2/hp-hr.

These values are substantially higher than the average transfer rates for the mechanical aerator tests conducted on the Passaic River [6]. The average field condition of 2.56 lbs O_2/hp-hr on the Delaware compared to 1.04 lbs O_2/hp-hr on the Passaic, and under standard conditions the averages were 3.06 lbs O_2/hp-hr and 2.12 lbs O_2/hp-hr, respectively. The above results are within the range of values obtained by other investigators for flow conditions (Table 5.5).

In a study conducted by Brookhart [5] on the Miami River, floating mechanical aerators were located at an oxygen sag point occurring in an impoundment. Four 20-hp high-speed surface aerators were selected (Welles Products Company, Roscoe, Illinois), and were placed across the channel so that each aerator would handle equal amounts of discharge. The channel was approximately 300 ft wide and the depth about 7 ft. Water temperatures were approximately 25°C. The average transfer rate, computed for tests in which the incoming water had a DO of approximately 3 ppm, was 1.0 lbs O_2/hp-hr (corrected only to standard temperature) in a discharge range of 400 to 800 cfs (velocity . 1/3 fps).

TABLE 5.5

Average Oxygen Transfer Rate Obtained by Different Investigators for Surface Aerators

River	Investigator	Standard Conditions (Av. lbs O_2/hp-hr)	Velocity Range (fps)
Delaware River	Whipple et al. [44]	3.16	1 → 1-1/2
Passaic River	Whipple et al. [6]	2.1	1/5 → 2/5
Laboratory Channels	Susag et al. [50]	≈ 4.0	1/10 → 2/3
Chicago Canal	Kaplovsky et al. [49]	1.5 → 4.5	1/4 → 1/2
Miami River	Brookhart [51]	≈ 1.0*	1/3
Jackson River	Burns et al. [48]	2.2	3/8
Flambeau River	Lueck et al. [53]	.44 → .90**	-

*Only corrected to standard temperature
**Not at standard conditions (T ≈ 25°C, Incoming DO ≈ 2 ppm)

In a surface-aerator study similar to the one conducted by Brookhart, McKeown installed three 50-hp surface aerators in Gulf Island Pond on the Androscoggin River in Maine [52]. The pond resembled a sluggish river, and the BOD_5 was generally between 2 and 4 ppm. The three 50-hp aerators were used with incoming DO levels in the water of less than 1 ppm. Transfer efficiencies of 1.7 lbs O_2/hp-hr were obtained. It was speculated that if the spacing between aerators had been increased, somewhat higher efficiencies would have resulted.

A comparison of spray aerators and turbine venting aeration was made in studies conducted on the Flambeau River in Wisconsin[53]. The spray aerators were furnished by Welles Products Company and were known as "Aqua-Lators." Four Aqua-Lators were installed in the tailrace of the Pixley Dam powerhouse and used to create a spray by pumping river water through a slotted disc. Each unit covered an area approximately 35 ft in diameter and sprayed water in the vicinity of 8 to 10 ft high. It was reported that droplets in the spray were rather large.

The efficiencies of the spray aeration device are relatively low and are compared to results obtained from turbine venting at the same site (Pixley Dam).

The turbines added 1.9 to 2.1 lbs O_2/hp-hr with oxygen saturation levels ranging from 3% to 12% and stream flow of 464 to 517 cfs, while for similar conditions the aerators only added from .44 to .90 lbs O_2/hp-hr.

In the tests only about 7.5% of the total flow was pumped by the aerators, and, except for minor leakage, all of the flow passed through the turbines.

From the limited number of tests, the turbines were 2-1/2 to 5 times more efficient than the spray aerators.

A summary is presented in Table 5.4 of the transfer efficiencies for surface aerators found by several of the investigators mentioned in this section. Most of the tests were conducted with updraft-type aerators, thus the variations in results do not appear to be attributable to the type of aerator used. All of the transfer efficiences have been corrected to standard conditions, except for the results reported by Brookhart [51], which have only been corrected to standard temperature, and those of Lueck [53], which are reported for a temperature of 25°C and an incoming DO concentration of 2 ppm.

Diffuser Systems

In diffuser systems, air or molecular oxygen is piped to a distribution system where it is introduced directly into the water through porous ceramic heads (usually silicon dioxide or alumina), finely perforated tubing, networks of nozzles, orifices, or jets. The diffuser heads can be installed at various depths below the water surface. Increasing the height of water above the system provides greater contact time between the gas bubbles and the water, thus increasing oxygen absorption. However, by increasing the height of water, one also increases the hydrostatic head against which the gas must be pumped.

If an air diffuser system is being used, higher operating pressures are then required, resulting in an overall decrease in transfer efficiency measured in lbs O_2/hp-hr absorbed. If, on the other hand, the diffuser system utilizes gaseous oxygen, an increase in the hydrostatic head does not present a problem, since the source would be under high pressure. Furthermore, when using oxygen instead of air, absorption rates will increase by up to a factor of five because of the increase in partial pressure.

In general, the porous-ceramic and perforated-plastic-tubing diffusers produce smaller bubbles than the other system types and consequently allow for a greater percentage of oxygen to be transferred to the water, due to the increased area-to-volume ratio of smaller bubbles. However, associated with these systems are greater head losses, which for air diffusers produce lower system efficiencies as measured in lbs O_2/hp-hr. Furthermore, the fine-pore diffusers are more susceptible to clogging.

The total rate of oxygen transfer is associated with three different components: bubble formation, bubble ascent, and the breaking of the bubble at the water surface. For small diffuser openings and low air-flow rates, oxygen transfer during bubble formation is appreciable. Conversely, for large aperture diffusers with high air-flow rates, little transfer occurs during bubble formation, primarily because the bubbles are formed while rising in the water. The aeration during bubble bursting at the water surface is primarily due to turbulence. The oxygen transfer during ascent depends on such factors as size of the bubble, depth, terminal velocity, etc.

Diffuser System Tests Using Air

Diffuser tests using air have been conducted as early as 1943 in the Flambeau River at Pixley, Wisconsin. Those tests have been described by Tyler [54] and Wiley et al. [55] . Noticeable improvement in DO concentration was obtained for several miles along the river by introducing air through carborundum plates and porous tubes located under 12 ft of water in the headrace and tailrace waters of the Pixley Dam. Absorption efficiencies were on the order of 7%. (The efficiencies for diffuser systems are often reported as the percentage of oxygen absorbed by the water.) Results of subsequent tests on the Flambeau River, using drilled pipe (1/8-in. holes) as diffusers under 4 to 5 ft of water, were reported by Palladino [56]. Considerably lower absorption efficiencies (1.7%) were obtained for incoming water having DO levels from 2 to 3 ppm. Operating efficiency was about .38 lbs O_2/hp-hr.

Low absorption efficiencies have also been reported by Böhnke for fine and coarse diffusers using air to aerate the Lippe River at Heil, Germany[57] . Diffuser depth was about 3 ft, and the incoming water was nearly depleted of oxygen. The river depth was approximately 12 ft at the installation. An absorption efficiency of 1.7% was obtained with the fine-bubble diffuser while the coarse-bubble diffuser (≈ 1/4-in. nozzles) yielded an absorption efficiency of only 1.0%. Subsequent tests using diffusers located on the stream bottom increased the absorption efficiency to 1.5% and the system efficiency to approximately 1.65 lbs O_2/hp-hr [73]. The importance of depth was emphasized in each of the above river applications; the greater the depth of the diffuser the greater the absorption efficiency, i.e., the percentage of oxygen absorbed.

More recent studies using air diffusers have been conducted in the Passaic [6] and Delaware [44] Rivers in New Jersey. Similar diffuser systems were used in each case. The system consisted of two 8-in. underwater heads with a total of 160 diffuser nozzles, each having twelve 5/32-in. ports. The tests were conducted at various depths in the Delaware and for a single depth in the Passaic River. Table 5.6 summarizes the results.

TABLE 5.6

Diffuser Results from the Passaic and Delaware Rivers

Mean Depth (ft)	Location	Approximate Mean Water Velocity (ft/sec)	Air Flow	Average Absorption of O_2 %	Average Efficiency (Std. Cond.) (lb O_2/hp-hr)
7.2	Passaic River		16	2.7	
7.2	Passaic River	1/4	12.6	2.0	1.20
7.2	Passaic River		9	4.2	
13.2	Delaware River	1	12	5.0	1.36
25.0	Delaware River	1	12	6.3	.93
38.3	Delaware River	1	12	7.0	.68

In comparing the results, it should be realized that the diffuser systems are essentially the same, the air flow rates being quite similar, and the only significant difference other than diffuser depth is the lower water velocity of the Passaic River. The conclusion can be reached from the table that oxygen absorption increases substantially with depth. However, the operating efficiency in lbs O_2/hp-hr increases from the 7.2-ft depth to the 13.2-ft depth, after which it decreases.

The above comparisons for different depths can be made because the diffuser systems were essentially the same. However, there are a large number of factors affecting absorption of oxygen from a diffuser system, and caution must be exercised when conclusions on diffuser performance are made by comparing results of entirely different systems. For example, one might consider diffuser test results from two different types of systems in which the air flow rates, water velocities, and depths of submergence were the same. The oxygen absorption efficiency and system efficiency in terms of lbs O2/hp-hr might differ considerably, since the mean air bubble sizes emerging from the diffusers could be quite different. The bubble size would, among other factors, depend on the size and number of diffuser openings, which would not be the same unless similar equipment was used.

Additional useful results could have been obtained in the Delaware River study if the air-flow rate had been varied at the different depths. This would have provided information for optimizing system efficiency in terms of lbs O_2/hp-hr and air flow versus the number of nozzles.

The efficiency of diffuser systems should not be a strong function of stream velocity unless large eddies entrain the air bubbles so as to increase the air-water contact time. If air bubbles require longer time to surface because their mean ascent velocity is lowered by eddies, then higher absorption efficiencies would be expected. However, if flow conditions significantly affect rise time, the stream would, in all probability, have adequate natural aeration to correct problem conditions.

For the types of diffuser systems used in the above river studies, the maximum absorption efficiency was 7.0% (Table 5.7). Test results reported by Imhoff [58], using finely perforated (.02 in-to .028 in.-diameter holes) tubing in the Ruhr River (West Germany), indicated the following absorption efficiencies:

8% @ 8-foot depth
17% @ 16-foot depth
15% @ 20-foot depth

Even higher absorption efficiencies have been obtained from laboratory tests using 1/2-in. polyethylene tubing having die-formed slits 1-1/2 in. on center. Tests were conducted for low air flows and non-flow conditions at 23°C. Results have shown that, for 1-cfm air flow with 100 ft of tubing, absorption efficiencies in oxygen-depleted water have ranged from 14 to 44% at 3- and 10-ft depths, respectively [59].

In view of the relatively high efficiencies obtained by Imhoff for stream conditions and the even higher values obtained with the 1/2-in. polyethylene tubing for non-flow situations, it is possible that a poly-ethelene tubing system might be adaptable to stream applications. Further study would be required to determine whether or not the system would have similarly high absorption efficiencies for flow conditions as it does for non-flow conditions. Specifically, further investigation of its performance as a function of air flow, water velocity, and depth is needed. In addition, it would be of interest to use this type of system with molecular oxygen. The following discussion considers previous tests of diffuser systems with gaseous oxygen.

Diffuser System Tests Using Molecular Oxygen

The results of a series of experiments using pure oxygen in a shallow diffuser system have been reported by McKeown [60]. Fifteen ceramic diffusers were evenly spaced along a 4-in. diameter header, 100 ft long, which was submerged 3 ft below the stream surface. Dissolved oxygen levels of incoming water varied from 0-1 ppm, and stream depth in the vicinity of the tests varied from 3 to 5 ft. It was found that at a feed rate of 300 scfm absorption was only 1.1%, while at 10 scfm absorption efficiency was increased to 12%.

In a somewhat limited study conducted by Amberg et al. [61] on the Pearl River near Bogalusa, Louisiana, molecular oxygen was diffused through a multiport feeder placed on the bottom. In this test the oxygen was produced in a pilot plant on the site.

The multiport diffuser consisted of two 4-in. pipes, 36 in. on center, and equipped with Walker Process Company's "Sparjets." The Sparjets on one pipe had 1/32-in. holes and those on the other had 3/64-in. holes.

During the tests, water flow rate over the diffuser section was approximately 2440 cfs, with an average depth of 19 ft, and a temperature of 22°C. The incoming water was moving at an average of 2.14 ft/sec and had a DO of 7.7 ppm. A summation of five trials is presented in Table 5.7. Oxygen efficiencies varied from 14.6% to 21.5%. It was found that a single header with 1/32-in. orifices was as effective as the multiple header with two different-size orifices. The observation was made that, even with the small orifice size and low aeration rates, a great number of oxygen bubbles were breaking at the water surface, indicating waste of oxygen.

The efficiency might have been increased by using carborundum or Saran-wrapped diffusers, commonly used in sewage treatment. However, such systems may become clogged when immersed in a river and not used on a continuous basis.

The Effect of Flow on Dispersion of Oxygen from Diffusers

A study of the effects of flow on dispersion has been conducted by Whipple et al. [44], in which Rhodamine-B dye was injected through a diffuser system into the Delaware River. By measuring the dispersion of the dye as it travelled downstream and using curve-fitting techniques, the longitudinal dispersion coefficient was obtained. According to

TABLE 5.7

Reaeration Data for the Pearl River, Louisiana Using a Double Aeration Header with 1/32-in. and 3/61-in. Orifices (Amberg [61])

Oxygen feed rate scfm	Oxygen feed rate lb/day	Oxygen increase in stream (lb/day)	Oxygen absorption efficiency (%)
100	11,900	2550	21.4
200	23,800	4250	17.8
300	35,800	5230	14.6
400	47,700	7850	16.5
Single Header (1/32-in. Orifices)			
100	11,900	2620	22.0

one-dimensional-dispersion theory, the coefficient was found to be 8.5×10^6 ft^2/ min or 1.41×10^5 ft^2/sec. Data on the surface aerator was found to be incomplete, due to equipment failures. This value is an order of magnitude larger than the largest "natural" coefficient for a similar river. It was felt that the large value was primarily due to turbulent mixing induced by the aeration system. Furthermore, although this value is characteristic of a given installation, the authors believed that it constitutes a decent first-order approximation to other reaches in similar rivers being aerated. It was also concluded that the DO disperses in a manner similar to the dispersion of the dye. Such an assumption is reasonable, since changes in the stream characteristics due to such a dye or oxygen are negligible.

A transverse-dispersion coefficient was not reported. However, the transverse spreading effect was presented in an equation relating the area affected as a function of distance downstream. The equation was developed from data on the dye cloud geometry and is shown in Figure 5.4.

It was noted that, from similar tests using surface aerators, lateral dispersion was observed to be approximately the same as for the diffuser system.

Downflow Contactors

The downflow contactor category includes the more widely known U-Tube System first reported in the Netherlands by Bruijn and Tuinzaad [62]

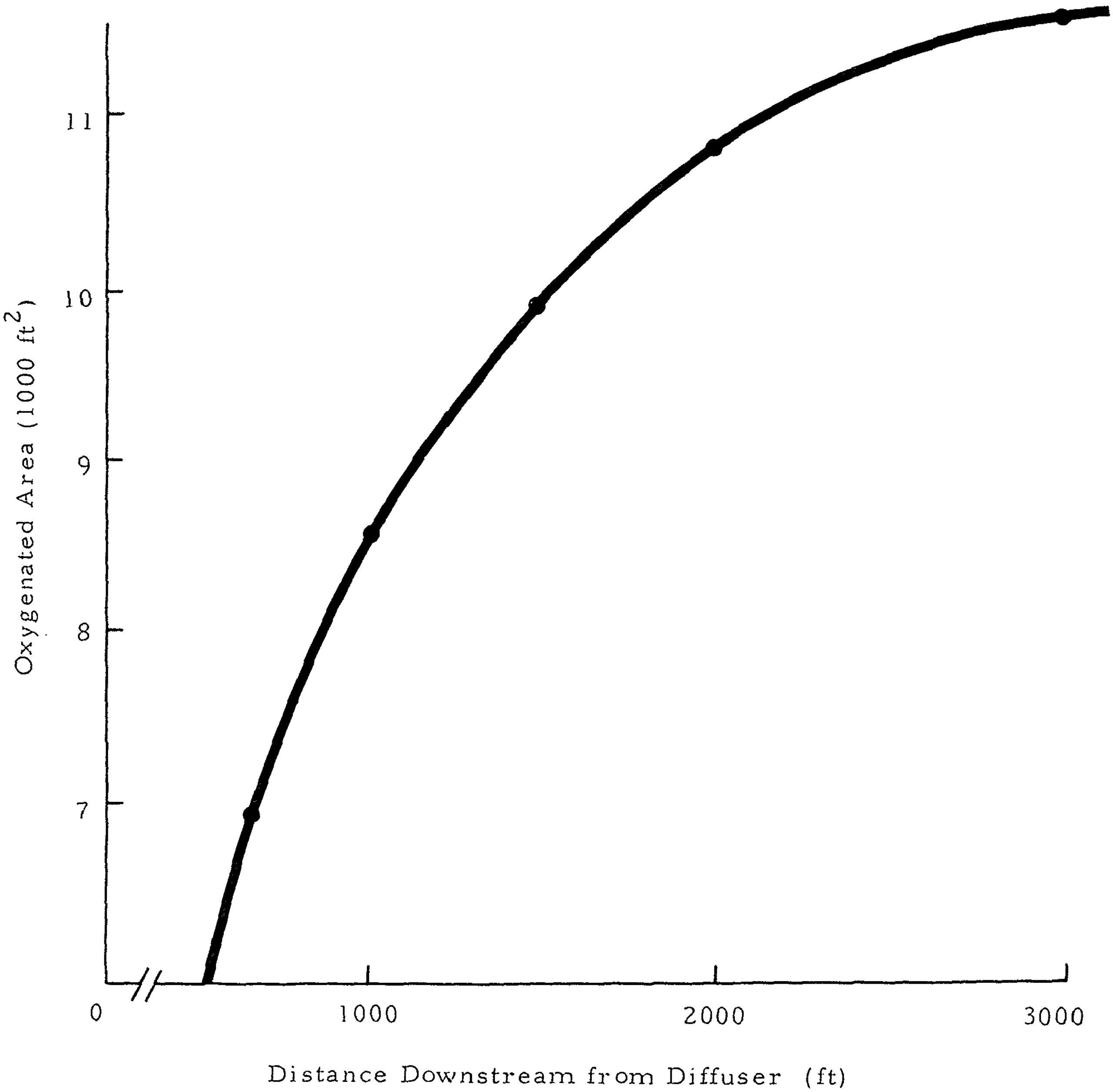


Figure 5.4. Graphical Results of Cross-Sectional Area Distribution (Whipple [44])

and more recently in this country by Speece[63]. Aeration by systems in this category is accomplished by temporarily pressurizing an air-water mixture as it is forced downward by a slight head over a vertical tube. More oxygen is transferred near the bottom of the tube by virtue of increased pressure and lower temperature, which increases the DO deficit. This relationship is illustrated in Figure 5.5. In a U-Tube the mixture is released from the tube near the surface, whereas in a straight downflow contactor it would be released near the bottom.

Several different types of U-Tube systems can be designed[65]. In Figure 5.6 a system is illustrated where oxygen is injected into the inlet water by a blower. Since only low pressures are required at the point of injection, centrifugal blowers may be used, which reduce cost and maintenance requirements. Good control over the air-water ratio, which ranges between 0 and 20% (by volume), is maintained by adjusting the air-intake lines.

A second type of U-Tube system is shown in Figure 5.7. In this system the head is provided by a natural cascade. The system shown has been used in a fish hatchery where 400 gpm of water at 75% DO saturation cascades 3 ft into the inlet of a 40-ft-deep U-Tube and emerges at 120% DO saturation [63].

In still another type of U-Tube, air is introduced by a venturi which is vented to the air as shown in Figure 5.8. The venturi system has a somewhat larger head loss than the blower system described above. The air-water ratio can be controlled by valving the air-intake port. This system has the advantage of not requiring external power.

Where stratified impoundments are a problem, U-Tubes can effectively reaerate the water by selective withdrawal of the hypolimnion water. Such a system has been proposed for the Snake River and is shown in Figure 5.9. This system is capable of raising the DO from 40% to 95% saturation. The U-Tube would be a 40-ft-deep trench, 160 ft long and 10 ft wide, on each side of the center baffle.

The transfer of oxygen to water is more effective the deeper the U-Tube; however, the saturation of dissolved nitrogen (DN) also increases. This may be a critical factor since fish are adversely affected when nitrogen super-saturates. For example, it is cited in reference 63 that a tolerable dissolved nitrogen level for salmon is about 105% saturation at the water surface. If U-Tubes are restricted to a water depth of 10 ft, the maximum possible supersaturation is 106%, and acceptable nitrogen levels would exist. The mixture of air and water could then be passed through several 10-ft stages which would increase the DO concentration but not the DN.

Any time U-Tubes are considered for an aeration application, attention must be given in the design to the avoidance of nitrogen supersaturation. The prime design consideration, of course, is the DO concentration

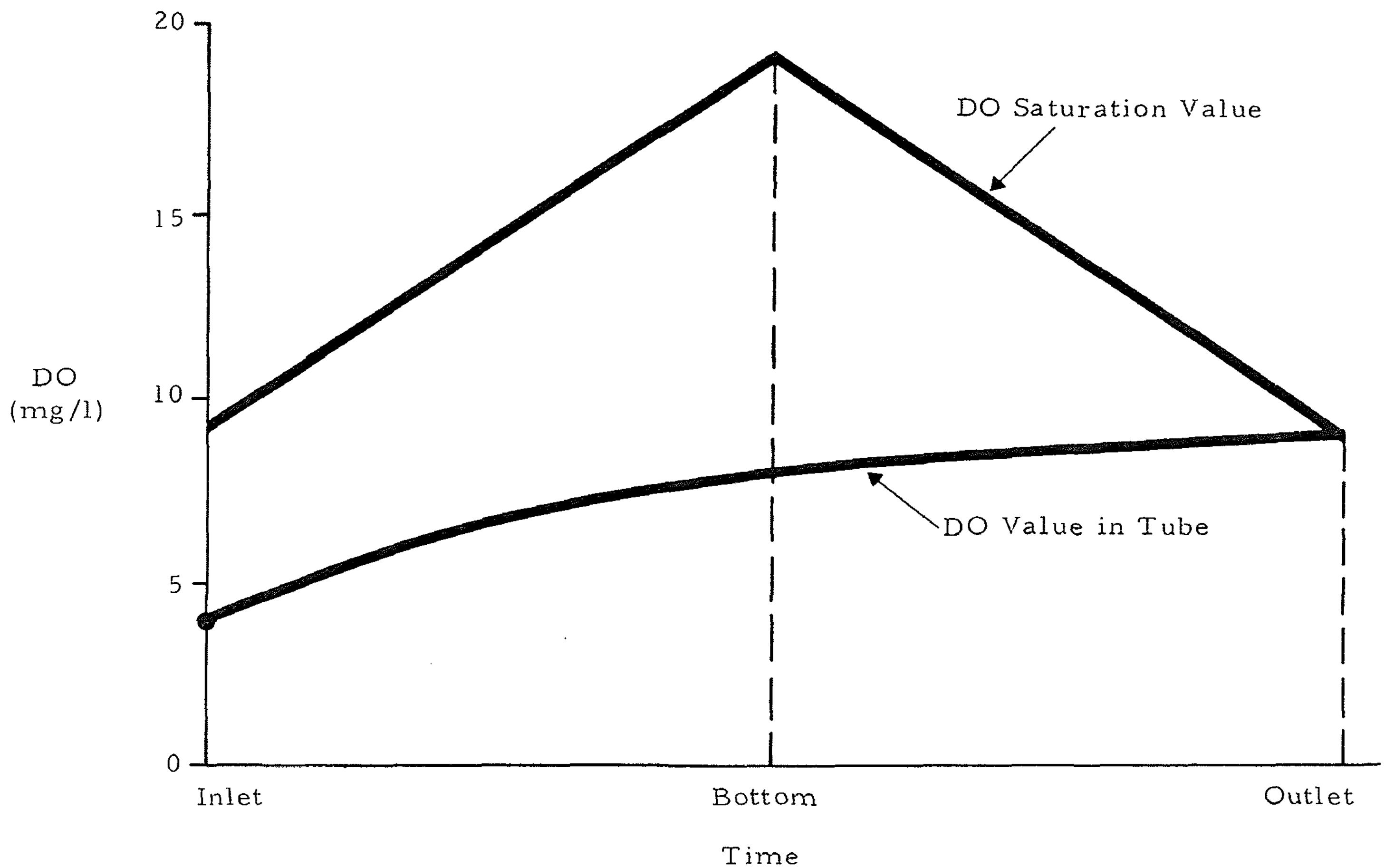


Figure 5.5. DO Deficit in 40-Ft-Deep U-Tube (Speece [65])

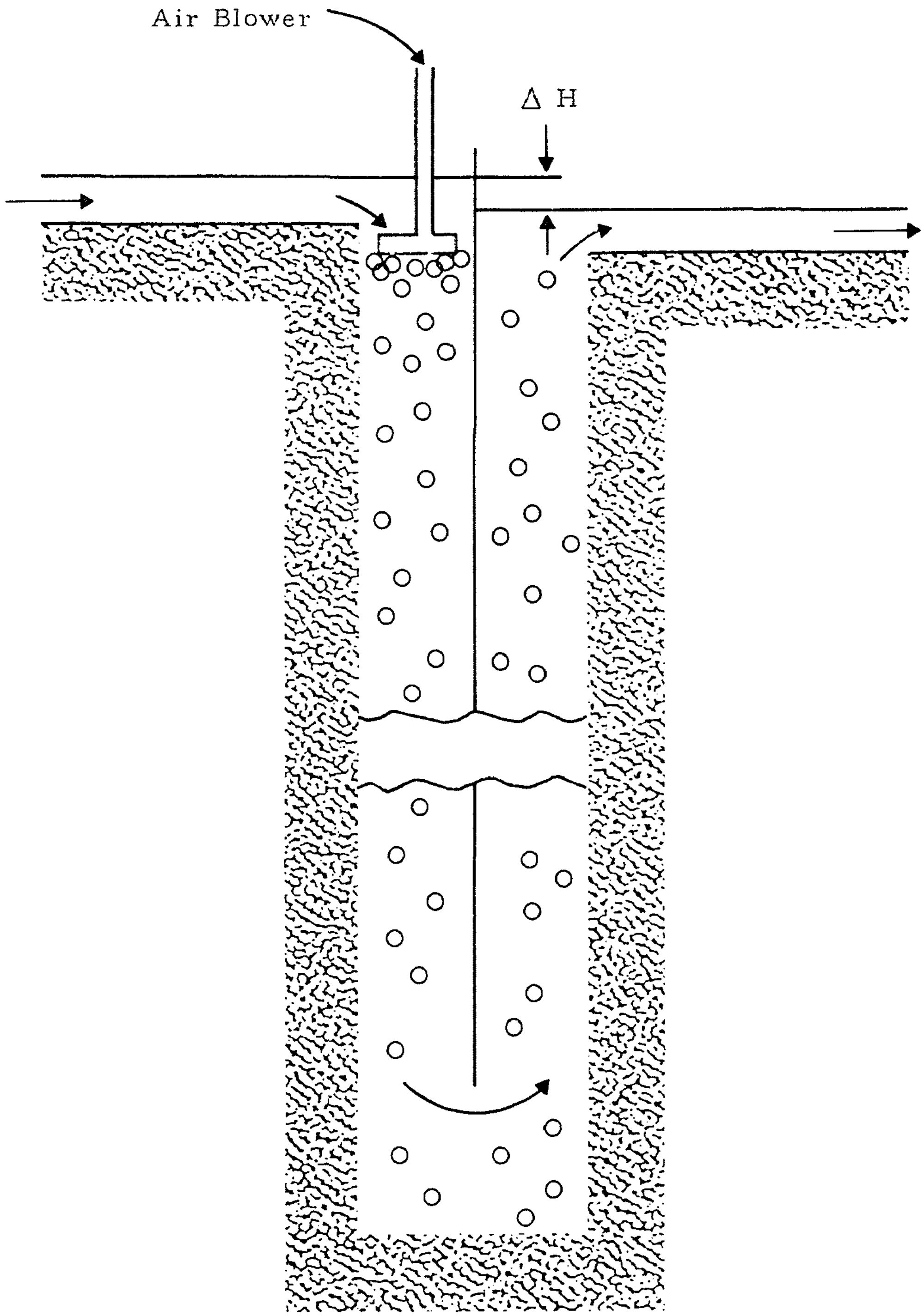


Figure 5.6. Air Blower Injection Modification of U-Tube System (Speece [65])

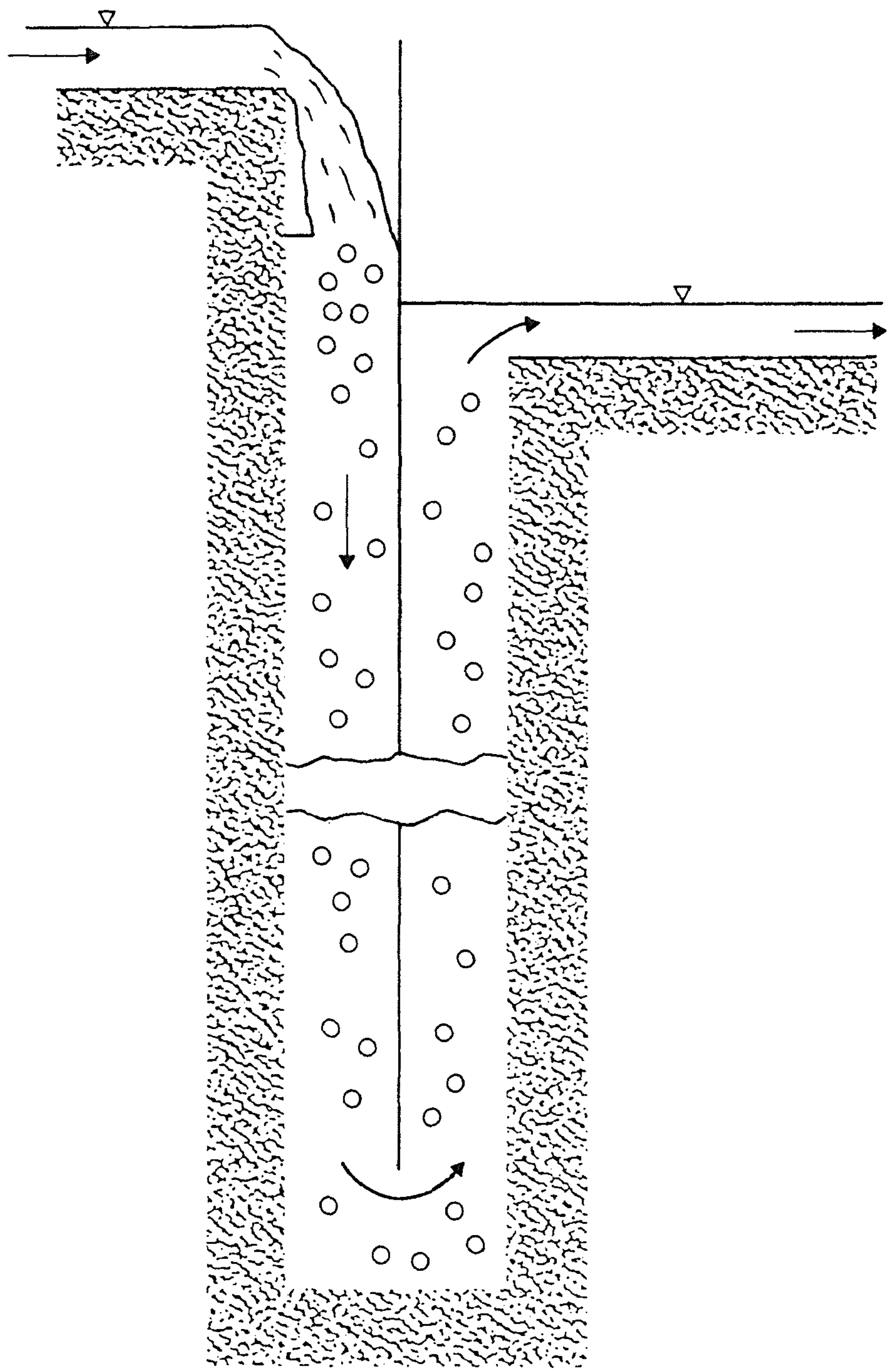


Figure 5.7. Cascade Air Injection (Speece [65])

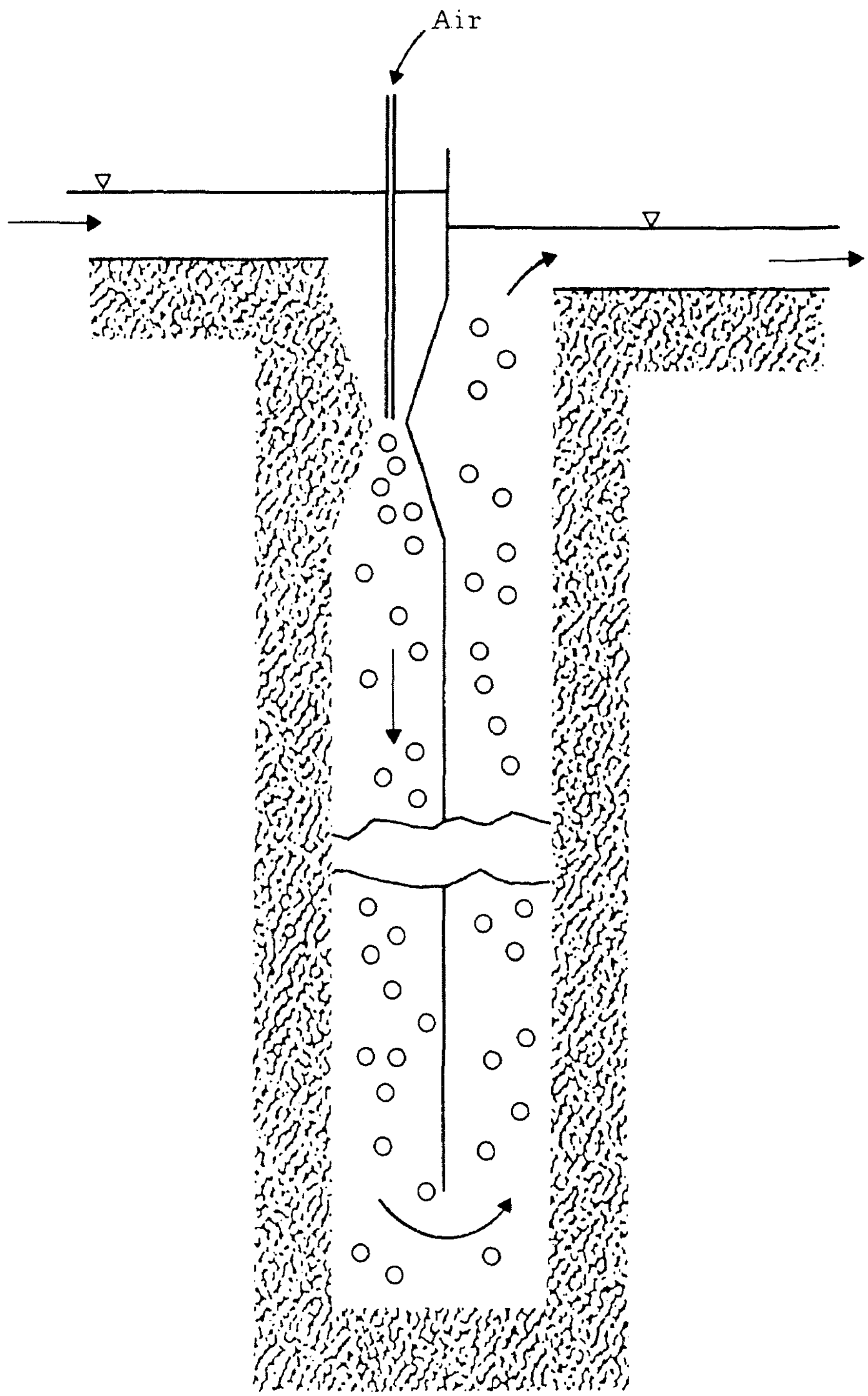


Figure 5.8. Venturi Air Injection (Speece [65])

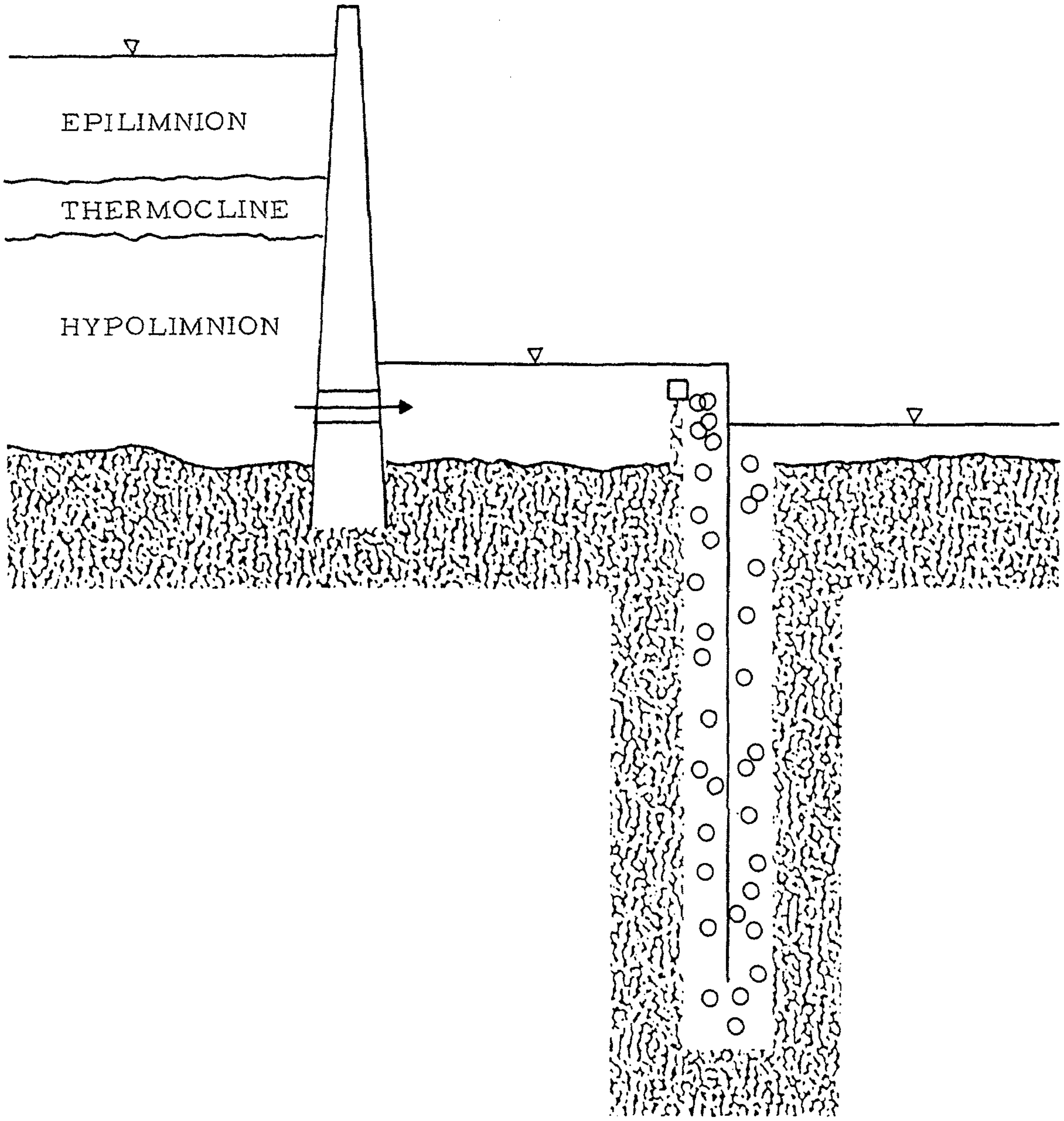


Figure 5.9. Schematic Installation of U-Tube Oxygenation of Stratified Impoundment Releases (Speece [63])

entering and leaving the tube. However, in achieving a desired DO level the effluent should be checked for possible supersaturation of nitrogen.

In general, high air-water ratios and deeper depths are required to obtain DO saturation, as is shown in Table 5.8 [64]. According to gas transfer theory, the associated air-water ratios that will saturate the water with nitrogen are those given in Table 5.9.

TABLE 5.8

Air-Water Ratio Required
for Oxygen Saturation (%)
(Speece [64])

Inlet DO	U-Tube Depth (ft)				
(% saturation)	20	30	40	50	60
0	--	23	18	15	13
20	--	20	16	13	11
40	--	18	14	12	10
60	22	14	11	9	8
80	14	9	8	7	5

TABLE 5.9

Air-Water Ratio Required
for Nitrogen Saturation (%)
(Speece [64])

Inlet DO	U-Tube Depth (ft)				
(% saturation)	20	30	40	50	60
0	--	--	21	17	15
20	--	23	18	15	13
40	--	21	16	14	11
60	--	16	13	10	9
80	16	10	9	8	6

If the required air-water ratio to saturate the water with oxygen exceeds the air-water ratio for nitrogen saturation, then nitrogen supersaturation will occur.

Another possibility for avoiding nitrogen supersaturation is to use pure oxygen in place of air. With such a system, initial DN would not be altered, but the DO would increase. Another advantage of an oxygen injection system is that the change in DO is approximately five times that of air (Figure 5.10).

Tests conducted by Speece[65] using a variety of parameters for 4-in. diameter U-Tubes resulted in the following significant trends:

1. Increasing the air-water ratio increases the change in DO at a diminishing rate.

2. Increasing the depth at which air is introduced results in a reduction of change in DO for a given air-water ratio.

3. Increasing the depth at which air is introduced reduces the head loss due to air injection in the system for a given air-water ratio.

4. There is an equilibrium air-injection depth at which the air injection head loss is zero.

5. Higher water velocities reduce the head loss due to air injection and decrease the change in DO through the U-Tube. These changes are a consequence of the more nearly equal bubble residence times in both legs of the tube and the reduced time for oxygen transfer to occur.

6. The head loss due to air injection is proportional to the U-Tube depth.

7. Minimum diffuser submergence gave maximum transfer economy.

The authors extrapolated their findings to a 60 in.-diameter U-Tube and found that transfer economies in excess of 3 lbs O_2/hp-hr could be obtained (Figure 5.11). Furthermore, it was determined that minimum air injection submergence resulted in maximum transfer economy. Figure 5.11 shows that associated with each U-Tube depth and velocity there is an optimum outlet DO. The optimum outlet DO was found to be dependent on the velocity, as indicated in Figure 5.12.

Figure 5.12 also indicates that the lower velocity of 3.5 ft/sec gives rise to more efficient oxygen transfer. However, if one is interested in transferring a given amount of oxygen into water, it may be more economical to use smaller U-Tubes with higher velocities, in which lower operating efficiencies are offset by lower capital expenditure.

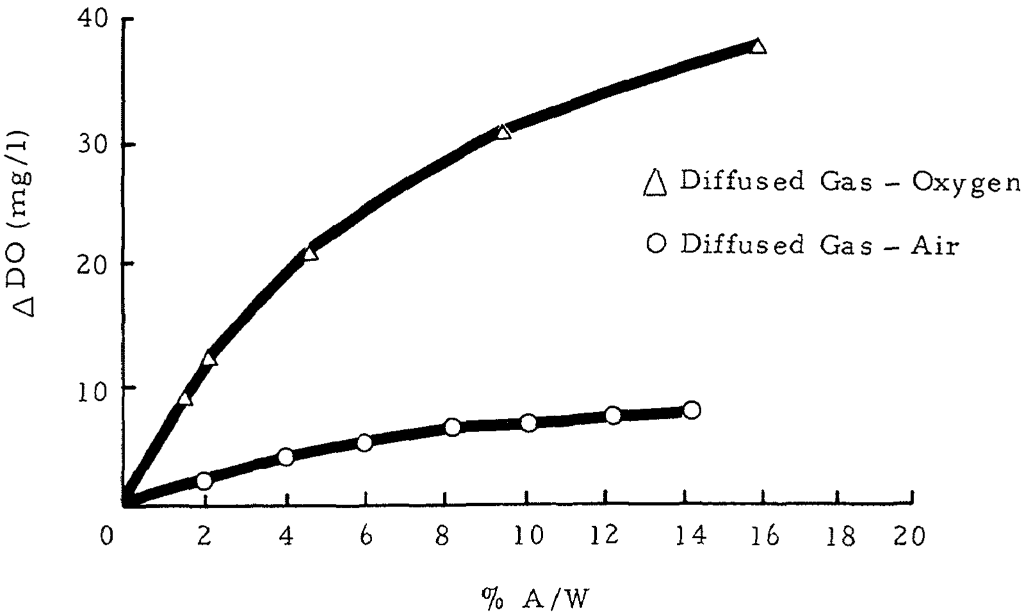


Figure 5.10. Increase in DO vs Per Cent A/W for Diffusion of Oxygen and Air

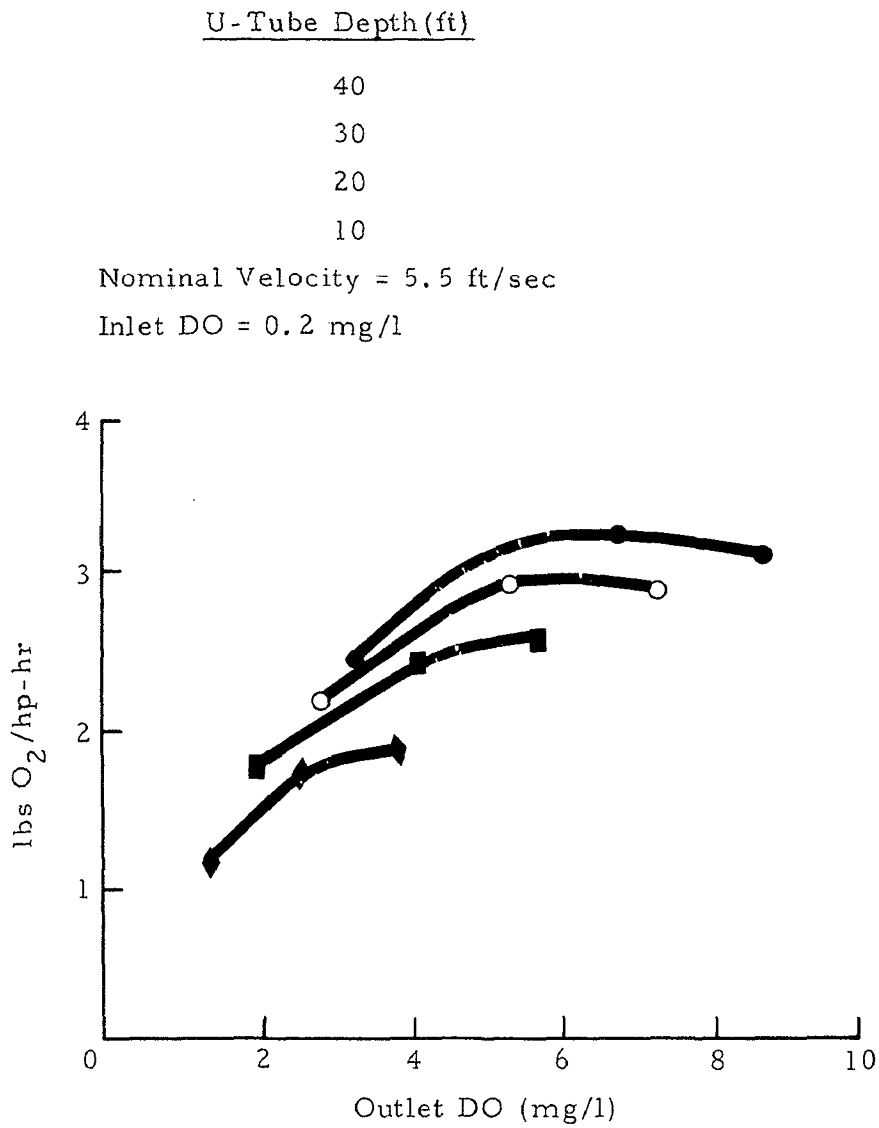


Figure 5.11. Effect of Depth on Oxygen Transfer Economy in 60-in. U-Tube

From the work of Speece and Adams [65] it has been concluded that initial bubble size has no noticeable effect on the change in DO in a U-Tube. The diffusers used in the tests consisted of a nylon cloth and perforated units with 1/32-in. and 1/4-in. holes.

An exhaustive U-Tube testing program has recently been completed by Rocketdyne, in which a 2-in.-diameter U-Tube system was used [66]. Variables investigated included depth, water velocity, air-water ratio, and aspirator configuration:

Depth	-	9 to 45 ft
Velocity	-	1.4 to 3.4 ft/sec
Air-Water	-	0 to .2 (volume ratio)
Aspirator	-	center-plug and venturi type

Quantitative analyses for rate of nitrogen transfer relative to that of oxygen were conducted by a combination of vacuum degassing and mass spectrometry. The results are interesting in that the ratios of DN to that of DO were found to have an average value of 2.4. Table 5.10 contains the results from the samples investigated.

TABLE 5.10

Results of Chemical Analysis for
Dissolved Nitrogen (Rocketdyne [66]

	Run Number	
	293	375
Superficial water velocity (ft/sec)	1.9	1.4
Air/water at 1 atm (68°F)	5.8	7.0
DO concentration (mg/l):		
Entrance	2.2	1.1
Exit	7.4	5.6
DN concentration (mg/l):		
Entrance	3.8	2.6
Exit	16.8	12.9
DN change/DO change	2.5	2.3

This result is in contrast to the findings of Speece [65] which, for the conditions investigated, indicated that the nitrogen gas transfer out of the bubbles was insignificant.

The discrepancy between Rocketdyne's and Speece's investigations lies in the fact that the test water used by the former was subjected to vacuum degassing and, in so doing, nitrogen as well as oxygen was stripped from the water, which resulted in a large nitrogen deficit and consequently a large nitrogen transfer. In the case of Speece's work, well water was used, which is characteristically high in DN. Hence, only a small amount can be transferred at a relatively low rate.

Usually, in a stream or river the DN level is expected to be near saturation, since there are virtually no nitrogen sinks and the water surface quickly establishes equilibrium with the atmosphere. Hence, the nitrogen-oxygen transfer results in the Rocketdyne report can be misleading when applied to a stream or river situation.

These tests also indicated that pressure losses in a venturi aspirator were considerably lower than losses from center-plug aspirators (Figure 5.13), and also that the minimum flow passage for the venturi remains higher than for the center-plug aspirator, thus reducing the chance for plugging.

A modification of the U-Tube into a straight downflow contactor has been investigated recently by McKeown in the Androscoggin River in Maine [52]. The modification consisted essentially of removing the return leg of the U-Tube, which then permitted the oxygenated water and remaining air bubble to rise freely.

Extensive testing involved collecting DO and velocity profiles in the vicinity of the contactor, which defined the zone of influence. The site was a deep pond, formed by a power dam, with a span of about 1300 ft. Water depth was over 60 ft, and the general character resembled a sluggish river.

The aeration system consisted of an axial flow pump with intake 4 ft below the surface and whose turbulent discharge, containing large quantities of entrained air, flowed through a header box into an 18-in. corrugated pipe. Nominal liquid velocities in the pipe were on the order of 6 ft/sec, and depths up to 40 ft were investigated. Since there was no direct method of calculating how much air became entrained, the discharge from an auxiliary air blower was also fed into the head box. Sparge rings or diffusers were not used to form small bubbles, since sufficient turbulence existed in the header box, and the associated sheer force was adequate to produce small bubbles.

The velocity profile associated with a 10-ft downdraft bubble contactor is shown in Figure 5.14.

Mixing was observed to occur some 15 ft below the discharge, and the representation of the rising bubbles (Figure 5.14) is based on visual observation. The vertical area zone of influence was estimated to be approximately 800 ft^2 (40 ft wide by 20 ft deep). The major

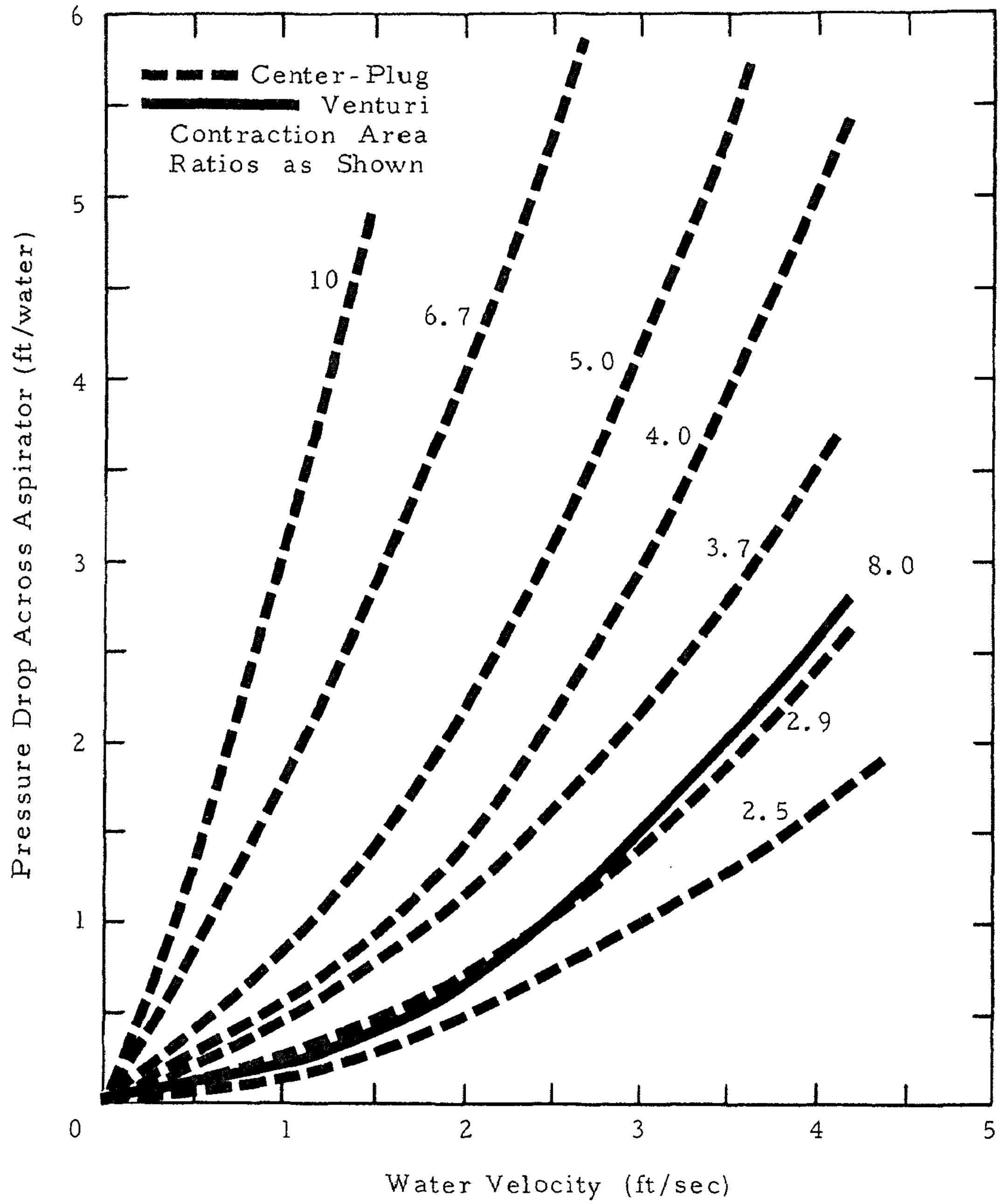


Figure 5.13. Comparison of Pressure Drop Across Center-Plug and Venturi Aspirators (Rocketdyne [66])

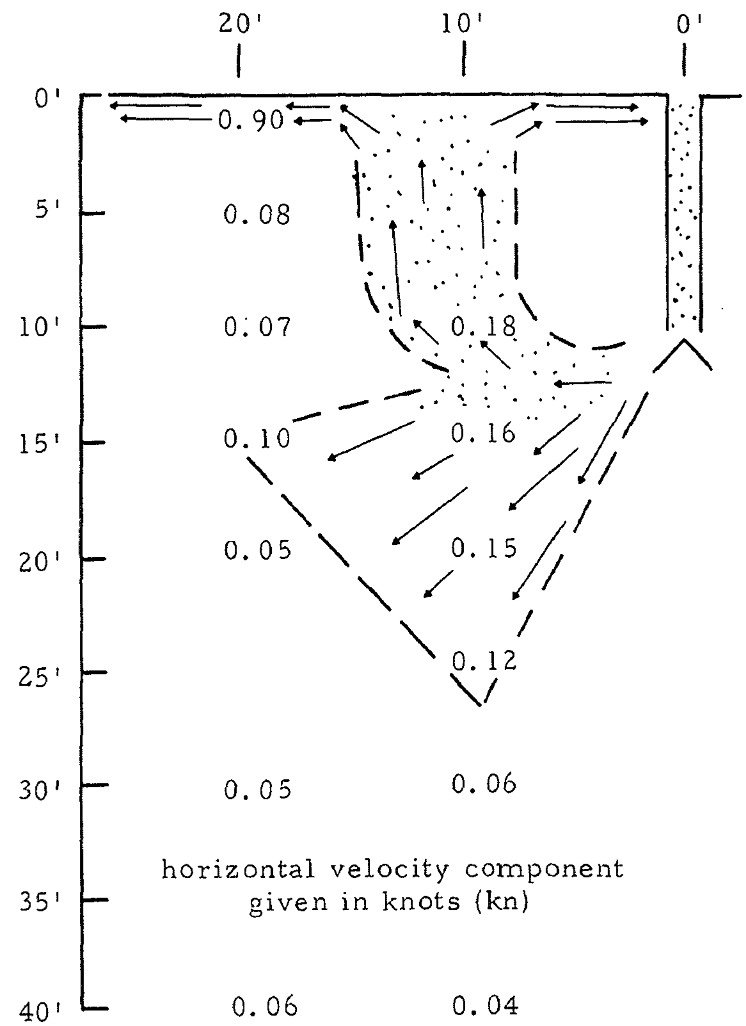


Figure 5.14. Zone of Influence of the Downdraft Bubble Contactor on the Surrounding Water (McKeown [52])

difference in the area of influence for different depth tubes was that of depth.

The effects are shown in Table 5.11.

TABLE 5.11.

Vertical Area Affected by Bubble Contactor

Depth of Tube (ft)	Vertical Area Affected Width Depth
10	40 ft x 20 ft (800 ft^2)
20	45 ft x 35 ft (1575 ft^2)
40	50 ft x 60 ft (3000 ft^2)

In general, McKeown's findings can be summarized as follows:

1. The blower produced no increase in DO or economy.

2. The average efficiency for all the tubes is above 1.4 lb O_2/hp-hr (converted to standard conditions).

Sidestream Pressurization

Sidestream pressurization is a technique for oxygenating river water, in which a small percentage of the flow volume is drawn off, mixed with oxygen under pressure, and the resulting supersaturated mixture diffused back into the river. There have been very few tests of this technique, although the concept is promising, particularly for large rivers where the oxygen requirement is great enough to justify the cost of constructing on site a gaseous-oxygen generating plant. In the preceding subsections, cost has not been considered in the discussions, primarily because site conditions have a significant affect on cost. For sidestream mixing, however, the cost of oxygen is a major factor and is discussed in this subsection.

In one of the sidestream pressurization studies conducted by Amberg et al. [61], water entering the Pearl River was pumped through an oxygen-diffusion system operating at a pressure of 68 psig. The system was designed to pump 10,000 gal/min under a 204-ft head through a 150-ft-long, 14-in.-diameter pipe where oxygen was added through spargers. In this process the water became supersaturated with oxygen and was returned to the river through a diffuser header placed across the bottom of the river. The diffuser header was equipped with twelve 2-in. nozzles and fifteen 1-1/2-in. nozzles, and was tapered from a 14-in.- to an 8-in. diameter.

Initially, considerable trouble was experienced from clogging of pumps and diffuser nozzles with debris carried in the river. However, these difficulties were overcome with appropriate modifications (screens and increasing nozzle sizes to 1.5 in.). Table 5.12 illustrates the effects of adding 30,000 lbs of oxygen. It can be seen that about 2 ppm or 16,400 lbs of oxygen was added to the Pearl River at the first station, where mixing was considered to be complete. The oxygen absorption efficiency for the system when aerating 25 cfs of the total stream flow (1.64% of the total) was 54.6%.

The oxygen was released in very small, discrete bubbles through the return header. The small bubbles permit considerable oxygen absorption in the water as they rise. The average head of water over the diffuser was 9 ft.

The daily cost of adding 16,400 lbs of oxygen (54.6% of 30,000 lbs) based on $30/ton (delivered) was:

$450 for oxygen
$ 59 for power ($.005/kw-hr)
$509

This resulted in adding 1.5 to 1.6 ppm oxygen over a 9-mi. stretch.

The above costs do not include capital, maintenance, etc., and thus do not provide a true picture. In addition, the system study was only conducted for a limited set of conditions which were probably not optimum.

The above sidestream oxygenation system was designed by the Linde Division of Union Carbide Corporation and is referred to as the "LINDOX" System.

A smaller system was tested in Brewton, Alabama. The system was designed to inject 3000 lbs of oxygen per day into the effluent of a paper mill of the Container Corporation of America. Union Carbide claims that injection efficiencies of from 55 to 75% were achieved [67].

According to Union Carbide Corporation, preliminary capital cost estimates for sidestream aeration can be made on the basis of $4000 per daily ton of oxygen injected. This price includes pump installation, concrete pad, control panel, injection thimble, dispersion header, etc.

Oxygen costs will vary according to the installation and depend on such factors as quantity used, transportation costs, etc. Typical prices, according to Union Carbide Corporation (Spring 1971), vary from $35 to $50 per ton. They also suggest that power costs for pumping can be estimated to be approximately 15% of the total oxygen cost.

In other investigations conducted by Linde, parameters have been established for the following process variables:

TABLE 5.12

Dissolved Oxygen Added to the Pearl River at an Oxygen Addition Rate of 30,000 lb/day by Sidestream Oxygenation (Amberg et al. [61])

(Water temperature was 25.5°C)

Station	Before oxygenation Flow (cfs)	Before oxygenation DO (ppm)	Before oxygenation DO (lb/day)	After oxygenation Flow (cfs)	After oxygenation DO (ppm)	After oxygenation DO (lb/day)	DO increase (ppm)	DO increase (lb/day)
Lakeview (above mill)	1528	7.5	61,600	1524	7.5	61,600	....	...
1.5 miles (below mill)	1528	5.0	41,100	1524	7.0	57,500	2.0	16,400
3.0 miles (below mill)	1528	4.2	34,600	1524	6.0	49,250	1.8	14,650
6.0 miles (below mill)	1528	3.1	25,500	1524	5.0	41,100	1.9	15,600
9.0 miles (below mill)	1528	2.7	22,200	1524	4.3	35,300	1.6	13,100

1. Equilibrium oxygen concentration in water versus O_2 partial pressure.

2. DO at various pressures in the pumped stream versus efficiency.

3. Bypass line pressure and input oxygen concentration versus overall efficiency.

4. Velocity (Reynolds Number) in bypass versus overall efficiency.

5. Contact time and oxygen input concentration versus DO in pumped stream.

6. Fraction bypassed and input oxygen concentration versus overall efficiency.

7. Cost of pumping.

Use of Pure Oxygen

Pure (molecular) oxygen can be used to replace air in several aeration systems, such as U-Tubes, diffuser systems, venting of turbines, and sidestream pressurization. The form of the oxygen can either be gaseous or liquid, although oxygen in the gaseous form is more easily injected. The following discussion deals with various applications and the relevant findings.

The only liquid oxygen (LOX) test reviewed in this study was conducted by Midwest Research Institute and reported in July, 1970 [68]. In that study, the investigators dealt with injecting LOX into both static and flowing water which was vacuum-stripped of oxygen. The water was then stored under a nitrogen blanket.

The rationale behind using LOX was the following:

1. LOX is the most economical form for transportation of oxygen.

2. LOX is more dense than water, hence it sinks and prevents losses.

3. Evaporation of LOX in water could be at rates that would produce high-pressure bubbles.

4. The cooling is localized, thus increasing the driving force.

5. LOX introduction imparts turbulence.

The program encountered considerable difficulty, and consequently a definitive assessment of the aeration process was not able to be given. However, based on the work carried out, certain trends were observed, and a limited number of conclusions were drawn by the investigators. Among those conclusions were the following:

1. Based on mass transfer, LOX is at least as attractive as gaseous oxygen if the quantities are less than those necessary to require construction of a production plant on site.

2. If the oxygen consumption is such that on-site production must be considered, then gaseous oxygen would be more economical.

3. When the flow was turbulent, absorption appeared to be more effective, and DO concentrations up to 30 ppm were obtained.

4. Increasing the contact time of the LOX with water increased the efficiency of absorption but not the mass-transfer coefficient.

5. Varying the water temperature from 7^{o} to $30^{o}C$ had no apparent effect on the absorption efficiency.

6. The initial DO content of the water did not affect the mass-transfer coefficient significantly.

These results would tend to indicate that the injection of LOX into water is a difficult problem, and a better alternative would be to transport oxygen as LOX but deliver it to the water in gaseous form.

Since the cost of pure oxygen is based on rate of consumption and distance from the source, the prediction was made that, when the consumption rate exceeded 25 tons/day, a separation plant should be erected at or near the site. If the demand exceeds 25 tons/day, the oxygen should be piped as gaseous oxygen, and if the rates were smaller, the oxygen should be transported as LOX. This conclusion is based on pricing schedules from four major industrial gas suppliers for supplying oxygen to ten different locations. Figure 5.15 illustrates the results, indicating that the four companies quoted similar prices. The prices include delivery within a 100-mi. radius of the separation plant.

The minimum price of pure oxygen is directly a function of the cost of power. To produce one ton of oxygen, 350 kwh are required. It was pointed out that a lower bound would be about $7/ton of oxygen. This is based on an industrial rate of slightly under $.02/kwh. Consumption rates of 1000 tons/day would be required to drop the cost to $10/ton. Such a consumption rate is atypical, since this rate would be indicative of the domestic waste requirements of metropolitan New York City.

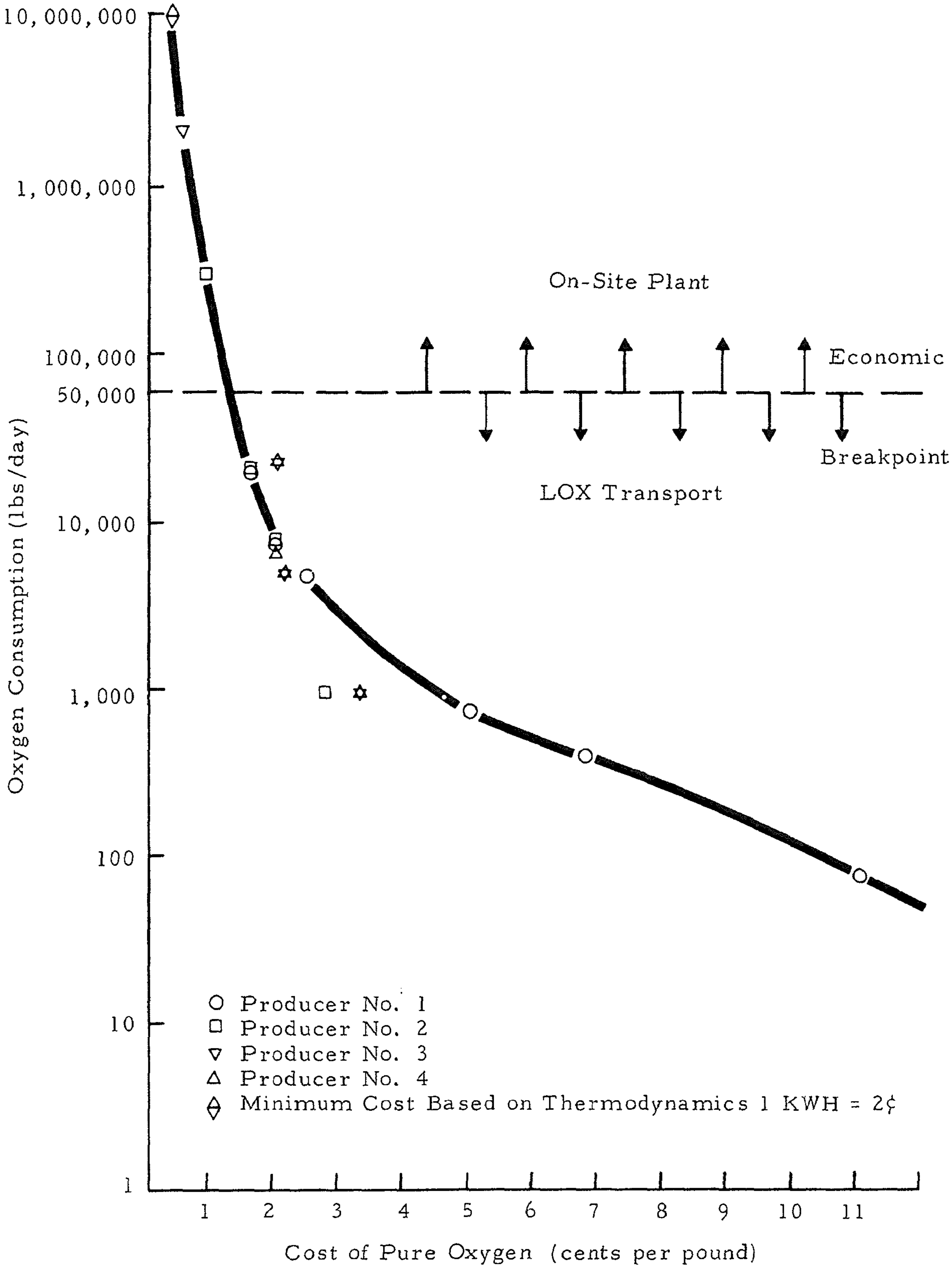


Figure 5.15. Cost of Pure Oxygen (Both [60])

An interesting and valuable theoretical study has been conducted by Speece [69] to predict the transfer of oxygen out of a bubble of oxygen and the transfer of nitrogen from water into an oxygen bubble. The results of this study are important, since a knowledge of conditions which enable efficient oxygen absorption is necessary in order to design an economically competitive oxygen injection system. The significant findings of his study can be summarized as follows:

1. When small bubbles of approximately 2-mm diameter are released from depths in excess of 100 ft, essentially all of the oxygen is transferred.

2. The initial concentration of DO in the water has very little effect on the absorption of pure oxygen.

3. The absorption of oxygen is greater for 2-mm bubbles than it is for 4-mm bubbles. At 40 ft there is approximately a 100% difference.

   Findings 1 and 3 above are illustrated in Figure 5.16.

In another test concerned with the feasibility of using pure oxygen, Amberg et al. [70] added substantial quantities of oxygen to water passing through a power turbine at Willamette Falls on the Willamette River in Oregon. The turbine was vented with pure oxygen and also with air. In this test the goal was to achieve a 5 ppm concentration of DO to meet a state standard. It was found that aeration with air did not offer a practical solution. Through the use of a sparge ring and pure-oxygen absorption, efficiency on the order of 40% was obtainable. The relative cost of air and oxygen for this test are shown in Table 5.13, where it can be seen that at high DO levels of the intake water the use of pure oxygen is more economical.

In a study conducted by Pfeffer and McKinney [71] using oxygen-enriched air to aerate industrial wastes, it was indicated that the rate of oxygen transfer is considerably increased as the oxygen content of the gas increases. Upon examination of Figure 5.17 it can be seen that at a given DO level the rate of oxygen transfer (slopes of the curves) increases significantly with increase in oxygen content of the gas.

In oxygen-absorption tests conducted by Carver [72] it was found that, when pure oxygen was used for aeration, the rate of oxygen transfer was independent of the DO content in the liquid between 0 to 12 mg/l.

Hybrid or Mixed Systems

A "mixed" system would be two different types of systems in combination. Such a system might be economically feasible when large changes in DO are needed, when considerable shifting of the DO sag point occurs with

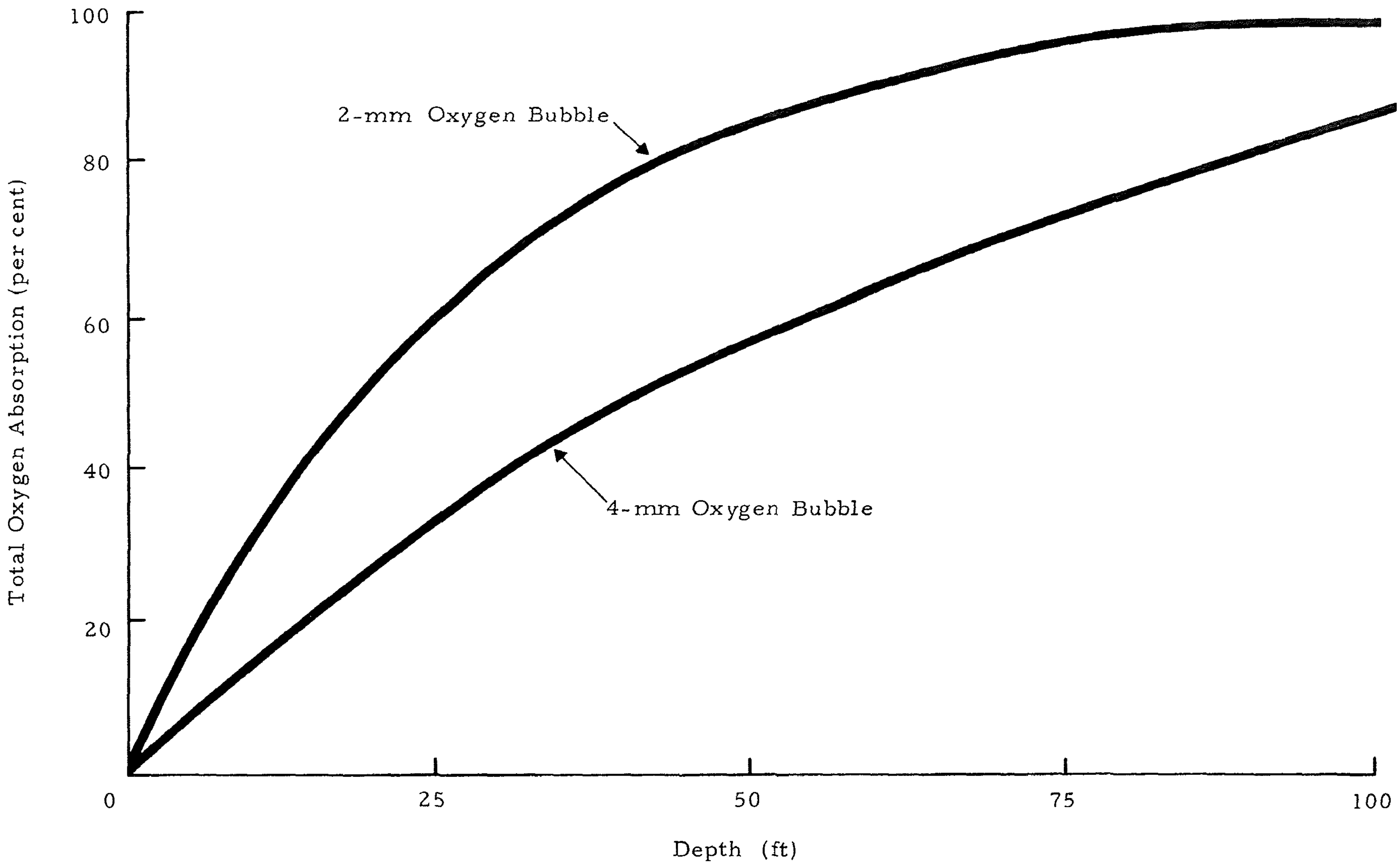


Figure 5.16. Total Oxygen Absorption vs Depth of Injection (Speece [69])

TABLE 5.13

Comparison of Reaeration Studies with Air and Oxygen

Location	Gas Used	DO to Turbine (ppm)	Oxygen Absorption Efficiency (%)	Oxygen Exchange (lb/kw-hr)	Power Cost per 1000 lb Oxygen Dissolved (dollars)
Willamette Falls	Air	7.8-8.0	6.0	0.53	9.52
Willamette Falls (a)	Oxygen	7.2	33.9	13.9	0.36
Willamette Falls (b)	Oxygen	7.8	39.0	9.5	0.53

(a) Trial No. 1, Single-Opening Vent to Turbine
(b) Trial No. 2, Sparge Ring to Turbine

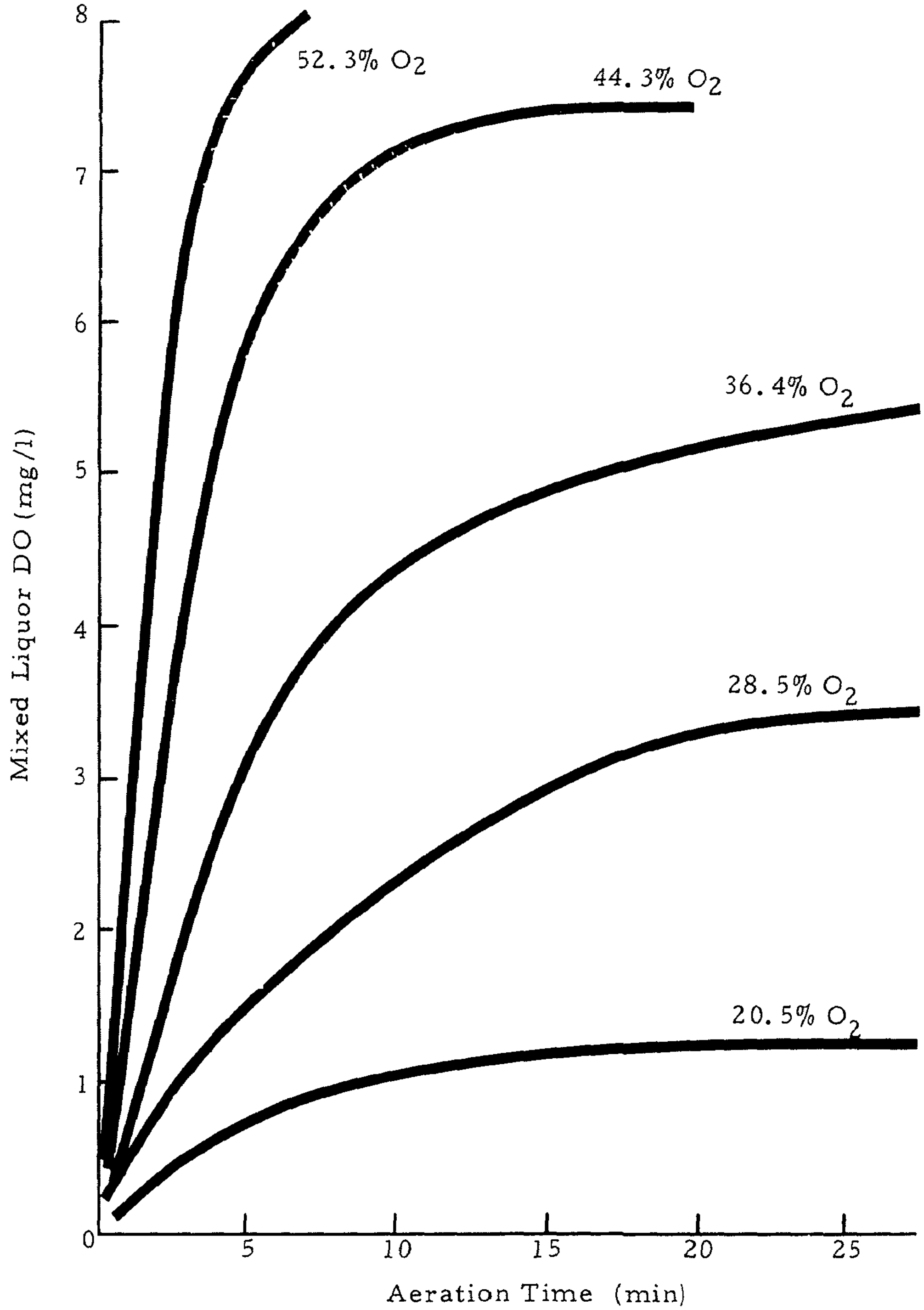


Figure 5.17. Effect of Percentage Oxygen in Aerating Gas on the Rate of Oxygen Transfer (Pfeffer & McKinney [71])

different seasons, or if unusual conditions are associated with a stream. For example, if the water level in an impoundment where a U-Tube is normally used drops significantly, surface aerators might be used to temporarily continue oxygen delivery until water depth again increases.

If a mixed system is to be considered, there are several natural combinations which can be made. Reasonable combinations would be units which work efficiently at low DO levels followed by units which operate well in surface aerators or air diffusers acting as the primary system, and the U-Tube, sidestream pressurization, or diffusers using pure oxygen as a secondary fixed system.

When considering a mixed system, it should be kept in mind that a system which operates well in the 3 to 5 ppm DO range will also work well in the 1 to 5 ppm DO range. Hence, although in a particular application it may be found that a mixed system is more economical, in general, a non-hybrid system offers fewer complications and will, in most cases, be less expensive.

SECTION VI

ENGINEERING METHODOLOGY FOR RIVER AND STREAM AERATION

In the previous sections the present state of the art in river and stream aeration was reviewed. The oxygen balance in a river or stream has been shown to be relatively complex. In this section a methodology is developed for the design of an aeration system. It will be shown that from an engineering viewpoint much of the rigor required in the understanding of aeration and of oxygen balance can be simplified considerably in the system design.

An outline of the steps required in the design process is shown in Figure 6. 1. In the following paragraphs each one of the steps will be discussed, with supporting calculations and examples given where necessary. It should be noted that additional refinement can be added to the procedure, but in this section it is only intended to present the framework of the methodology.

Problem Recognition

The first step is a very obvious one, but one which may be difficult, in that artificial aeration of rivers and streams is not a generally accepted practice. This step requires the recognition that a problem in river water quality exists and that the problem can be solved by artificial aeration.

In some cases all known sources of industrial and municipal waste may have been treated to the degree that 90 to 99% of the BOD is removed. During some periods of the year, however, there may still be times when fish die off or there is a noticeable decrease in some of the more desirable forms of aquatic life. This is most likely to occur in the summer months, when flow volume decreases and temperatures rise. The condition may also develop during the winter, when ice cover on a river prevents natural reaeration through the surface. Extensive eutrophication is an indication that oxygen-depletion conditions may develop. In these cases the assimilative capacity of the river or stream may be increased by artificial aeration, and recognition of this fact constitutes the first step in the problem solution.

Preliminary Assessment

For a preliminary assessment of the problem, a profile along the critical reach in the river should be obtained. If profiles are available from past measurements and no significant changes in BOD loading or flow volume have occurred, these profiles can be used. The profiles should be for the worst case, i.e., low flow and high temperature. If

PROBLEM RECOGNITION

. Dissolved oxygen levels in river or stream are below acceptable levels.

PRELIMINARY ASSESSMENT

. Dissolved oxygen profile is obtained along critical reach. Profile should be obtained for worst conditions, i.e., low flow during summer months or possibly under ice in winter.

. Temperature, flow velocity, and depth are measured along critical reach. From these measurements flow rates are calculated, and reaeration coefficients are estimated from those empirical formulations most suited to the particular river or stream.

OXYGEN REQUIREMENTS

. Select firstpoint where DO decreases below the accepted minimim level (5 ppm).

. Determine step increase in DO necessary to bring DO above minimum requirements.

. Calculate daily loss of natural reaeration.

. Plot new DO profile from step increase data, old profile, and calculated loss of natural reaeration.

. Examine new profile for points where DO may again decrease below minimum.

. Trade off costs of making larger initial step increase of DO at one location versus smaller increases at several locations.

EQUIPMENT SELECTION

. Convert transfer efficiencies of several possible aeration systems from standard conditions to conditions present in the particular application at hand.

. Determine size and number of units necessary to supply required amount of oxygen.

. Determine cost per year for each system.

. Compare costs.

SITE CONSIDERATIONS

. Consider site factors which may eliminate any particular aeration systems from further consideration.

FINAL SYSTEM DESIGN

. Compare cost and site factors and select system.

. Refine system design.

Figure 6.1

Outline of Engineering Methodology

no profiles are available, or if the ones that are available are questionable, a survey of DO should be made over the critical reach. In either case, measurements should definitely be made of the flow velocity, temperature, and depth. These measurements are required for flow rate calculations and for estimates of reaeration coefficients which are used in the determination of oxygen requirements and in compensation for loss in natural aeration.

The flow rate is simply the velocity times the cross-sectional area. For the preliminary assessment the cross-sectional area can be estimated from the width and average depth. Whenever significant variations occur in cross-sectional area, a new flow rate should be calculated for that section. The aeration coefficient can be measured as described in Section IV, or it can be calculated using whichever of the empirical methods best fits the river or stream. The methods of Churchill [8] and O'Connor [9] appear to have wide application.

Determination of Oxygen Requirements

Once it has been determined that the DO levels in a stream or river must be increased by artificial aeration and a preliminary assessment of the problem has been made, the next task is to determine how much oxygen must be added and where to add it. To answer these questions it is first assumed that DO profiles of the river in question have been obtained for the worst set of conditions. The profile used to determine the critical reach of a river may not be a recently measured one but may be one associated with a one-in-twenty or one-in-thirty year low-flow situation.

In order to illustrate the methodology, we assume that the DO profile, upon which an artificial system will be designed, is the one given in Figure 6.2. For the purpose of illustrating a case of a "polishing" action, this profile shows a low point of only about 3 ppm.

Assuming it is required that the DO level should not drop below 5 ppm in the stream, it is then necessary to begin aeration artificially no further downstream than the one-mile station. Assuming then that artificial aeration would begin at this station, it is necessary to calculate the amount of oxygen that should be added. Since it has been assumed that the minimum DO level would be 5 ppm, it might seem logical to raise the DO level at this point by 2 or 3 ppm. However, the higher the DO level is raised, the less efficient the transfer of oxygen becomes, since the rate of transfer of oxygen is proportional to the oxygen deficit, i.e.,

$$\frac{dC}{dt} = K_L a(C_s - C) = (K_L a) D \qquad (6.1)$$

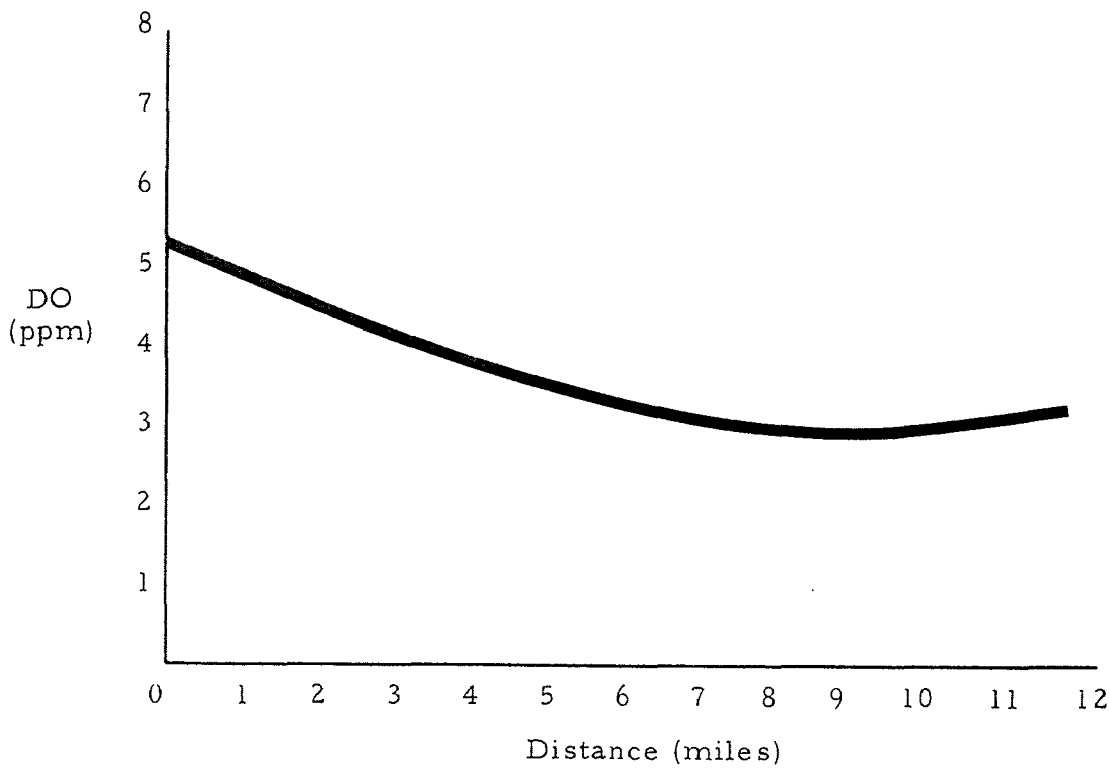


Figure 6.2. Example DO Profile

where

C = the O_2 concentration of the water (ppm)

C_s = the saturation level (ppm)

K_La = the overall transfer coefficient of an aerator (1/hr)

t = the time (hrs)

D = the oxygen deficit (ppm)

Equation 6.1 shows that the rate of change in oxygen concentration at any time is proportional to the magnitude of the deficit at that time. Hence, at low initial DO levels the operating efficiencies of a system are greater than for conditions where DO levels in the water are initially high. Figure 6.3 illustrates the work expenditure for step oxygen increases of 1 ppm, in water where the saturation value is 9.2 ppm. The work required is proportional to

$$\frac{C_s}{C_s - C_m}$$

where C_m = mean DO concentration at aerator

$$0 < C_m < C_s$$

This behavior is indicative of artificial aeration systems operating at a nominal pressure of 1 atmosphere, viz, surface aerators and shallow diffuser systems. When initial DO is on the order of 6 ppm or higher, systems which transfer oxygen from air into water become relatively inefficient. For instance, increasing the DO level from 8 to 9 ppm requires approximately 13 times as much work as raising the DO from 0 to 1 ppm.

In order to illustrate the methodology for determining oxygen requirements and the spacing of aeration systems, the following case has been selected:

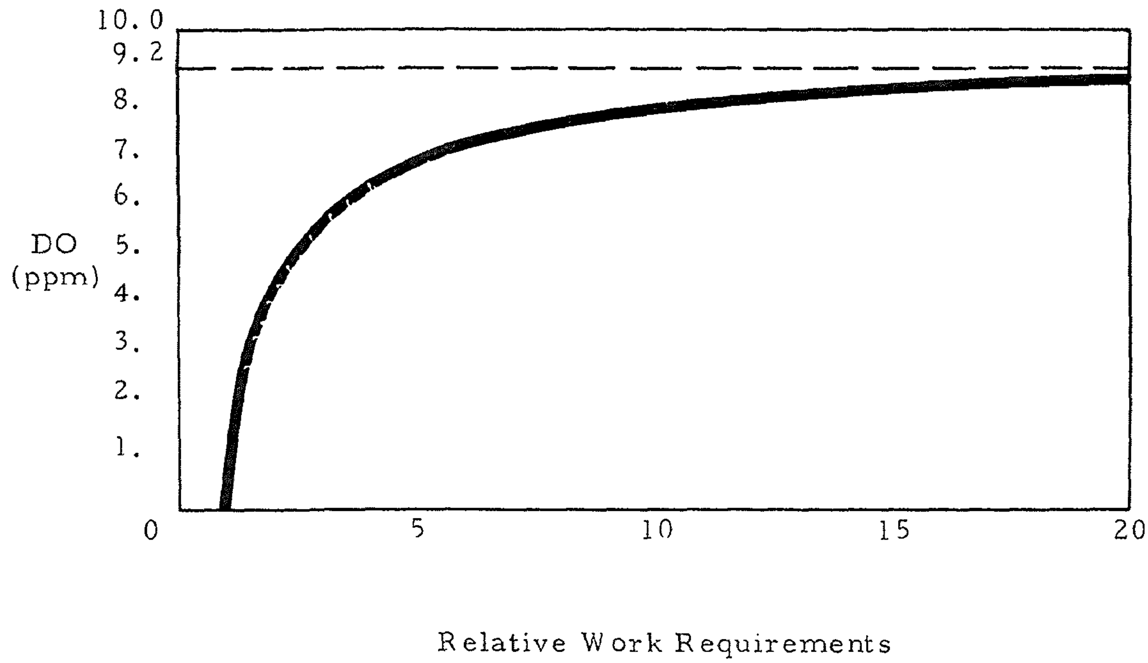


Figure 6.3. Relative Work Requirements for a Unit Increase in DO in Water Initially Having Different DO Levels

DO Profile - Figure 6.2

Flow Rate - 1000 cfs

Velocity - 0.5 mph

T - $24^{\circ}C$

K_a - 0.4/day

The values listed above are assumed to be constant over the 12-mile reach. This assumption is made for the purpose of illustrating the methodology rather than for indicating exact stream conditions within the section.

As discussed above, unless pure oxygen is being dissolved directly, the work required to transfer oxygen from air increases significantly for DO levels above 6 ppm. Since the objective is to prevent DO from decreasing below 5 ppm, the first aeration devices must be placed in the stream at mile 1. For a first cut, a step increase of 1 ppm is made at this point, raising the DO to 6 ppm. The loss in natural aeration due to the artificial addition must then be calculated.

As a consequence of increasing the DO level of the stream from 5 ppm to 6 ppm, the natural aeration rate will decrease. The decrease can be computed as follows:

$$\frac{dC}{dt}_{5\ ppm} = K_a(C_s - 5.0)$$

$$\frac{dC}{dt}_{6\ ppm} = K_a(C_s - 6.0)$$

Subtracting the above two equations,

$$\Delta \frac{dC}{dt} = \frac{dC}{dt}_{6\ ppm} - \frac{dC}{dt}_{5\ ppm} = 1.0\ K_a$$

Since the loss in natural aeration depends only on the increase of DO, an upper bound on the loss of oxygen from natural aeration can be established by assuming that the maximum loss occurred over the entire length. Hence, the upper bound for the loss in natural aeration at the 12-mile station is

12 mi. x (1/.5 mi./hr) x (1/24 hr/day) x 1.0 ppm x .4/day = .4 ppm

In Figure 6.4 the effect of the loss in natural aeration is shown at mile 12, where it is seen that instead of a 1.0 ppm step increase over the old DO profile there is only a 0.6 ppm increase. Now it is also noted that the new DO profile crosses the 5 ppm minimum level at mile 4. At this point a second set of aerators must be added and the loss in natural aeration again calculated. At mile 7 there is another crossover, but at this point it appears that a .5 ppm increase will be sufficient. The new profile shows that this is true. Thus a total of 2.5 ppm of DO has been added at three separate locations. The oxygen requirement for this case is:

$$\text{lbs } O_2 = 1000 \text{ ft}^3/\text{sec} \times 62.4 \text{ lbs}/\text{ft}^3 \times 3600 \text{ sec}/\text{hr}$$

$$\times 24 \text{ hr}/\text{day} \times 2.5 \times 10^{-6}$$

$$= 13,350 \text{ lbs } O_2/\text{day}$$

By making a larger initial increase in DO at mile 1, it may be possible to eliminate the need for additional sites downstream. It is also known that the work required to raise DO from 5 to 7 ppm is greater than twice that required to raise it from 5 to 6.

To pursue this further, two more sets of calculations are made. In Figure 6.5 the initial DO is raised from 5 to 7 ppm, and it is shown that a second set of aerators will be required at mile 5.7. The step increase required at this point is greater than .5, thus, for convenience, 1.0 is selected as the value.

The total oxygen needed in this case will then be 16,020 lbs/day, but only two locations are required. It is not known at this point which alternative is better, since the cost of constructing and maintaining three sites must be weighed against the transfer efficiency of the aerators employed in the two-site case illustrated in Figure 6.5.

There is still another alternative, which is to raise the DO from 5 to 8 ppm at mile 1, as shown in Figure 6.6. The only feasible way of doing this would be to use pure oxygen, since conventional surface aerators and diffusers become quite inefficient in this DO range. The costs associated with this alternative are discussed in Section V and also later in this section.

The above example illustrates the basic procedure for determining oxygen requirements and the spacing of aeration systems. There are several important factors which will affect the calculations. These include:

1. Value of aeration constant. A high value will lead to the requirement for a high initial step increase or more aerator sites downstream.

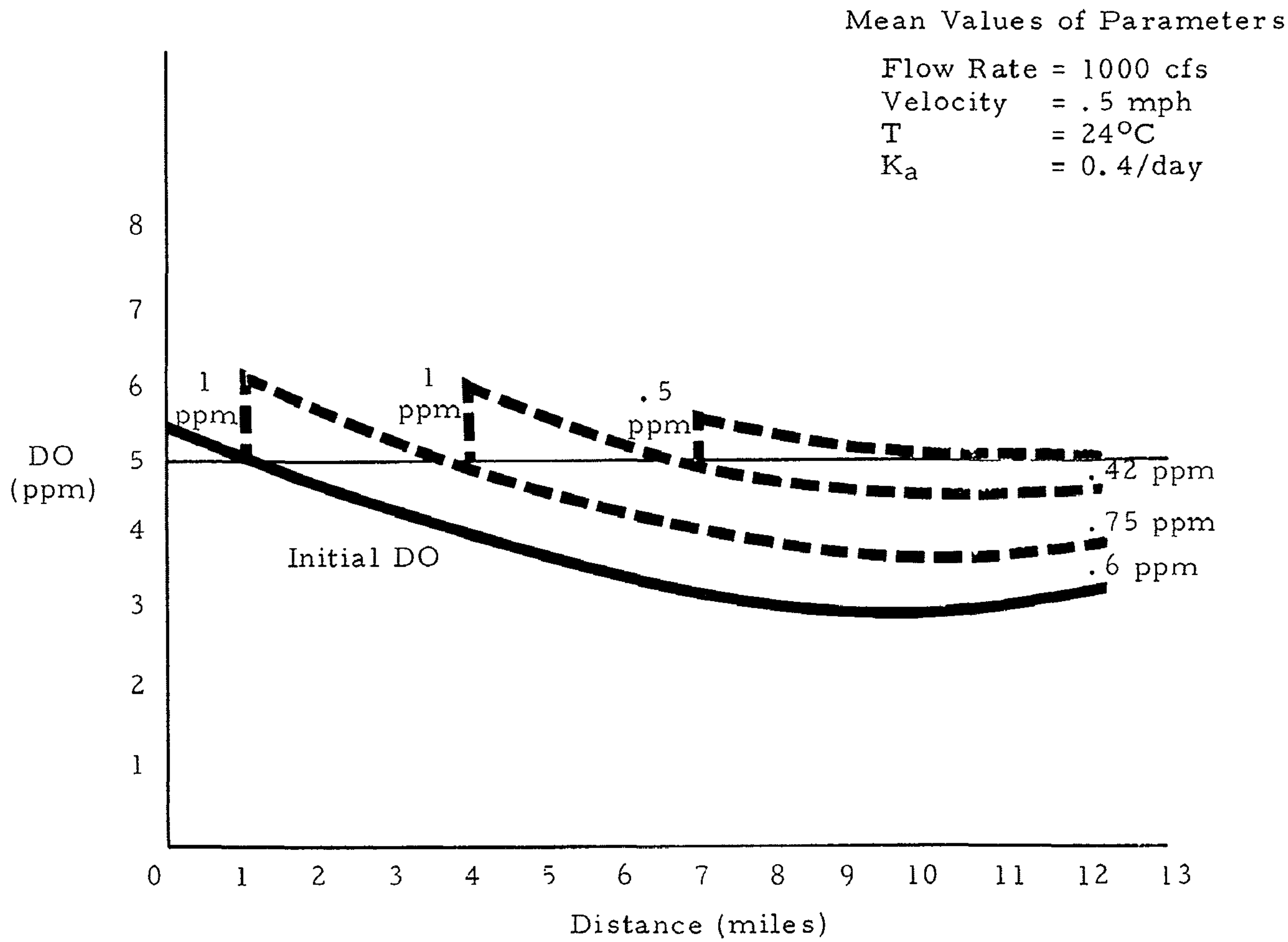


Figure 6.4. DO Profile Before and After Oxygen Addition at Three Locations

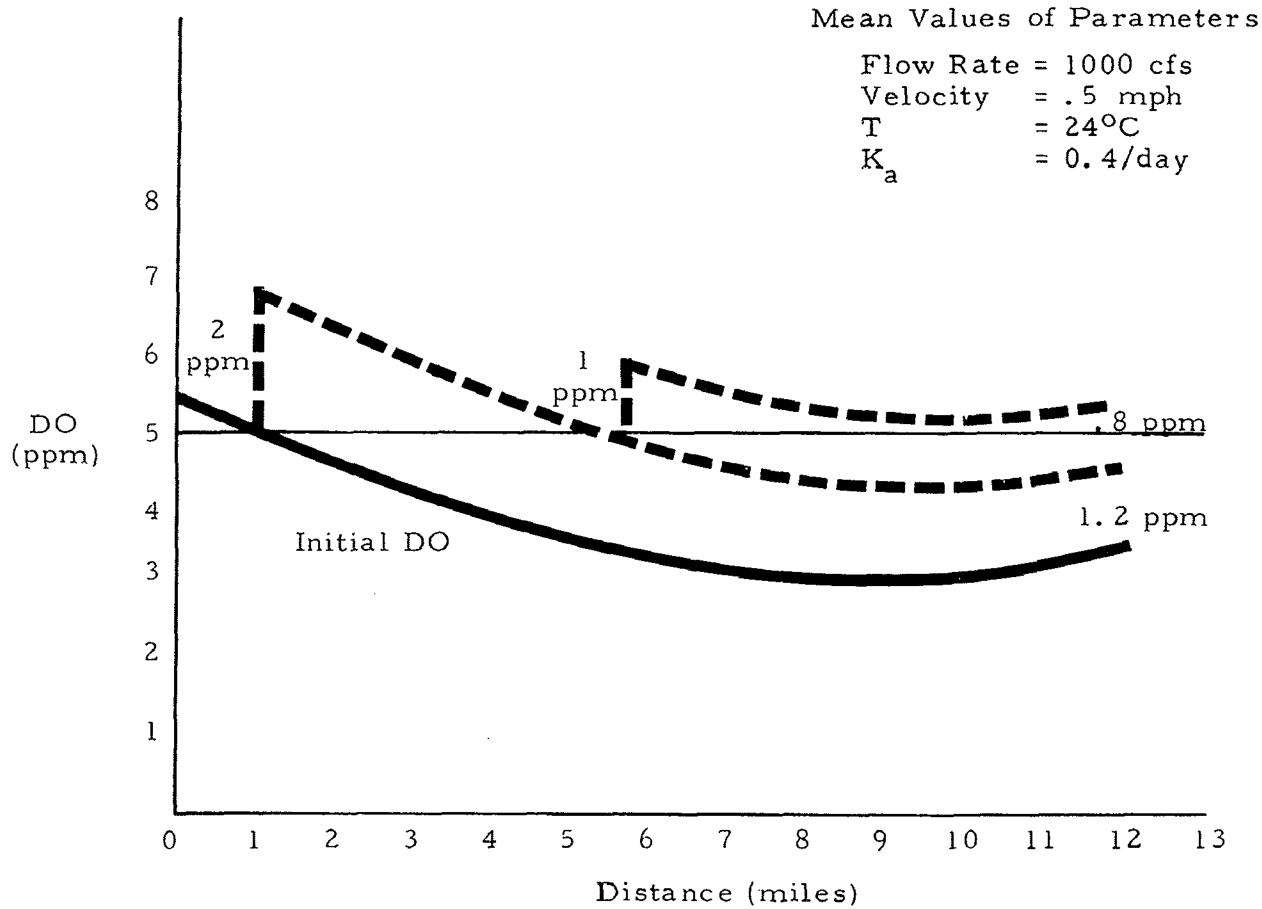


Figure 6.5. DO Profile Before and After Oxygen Addition at Two Locations

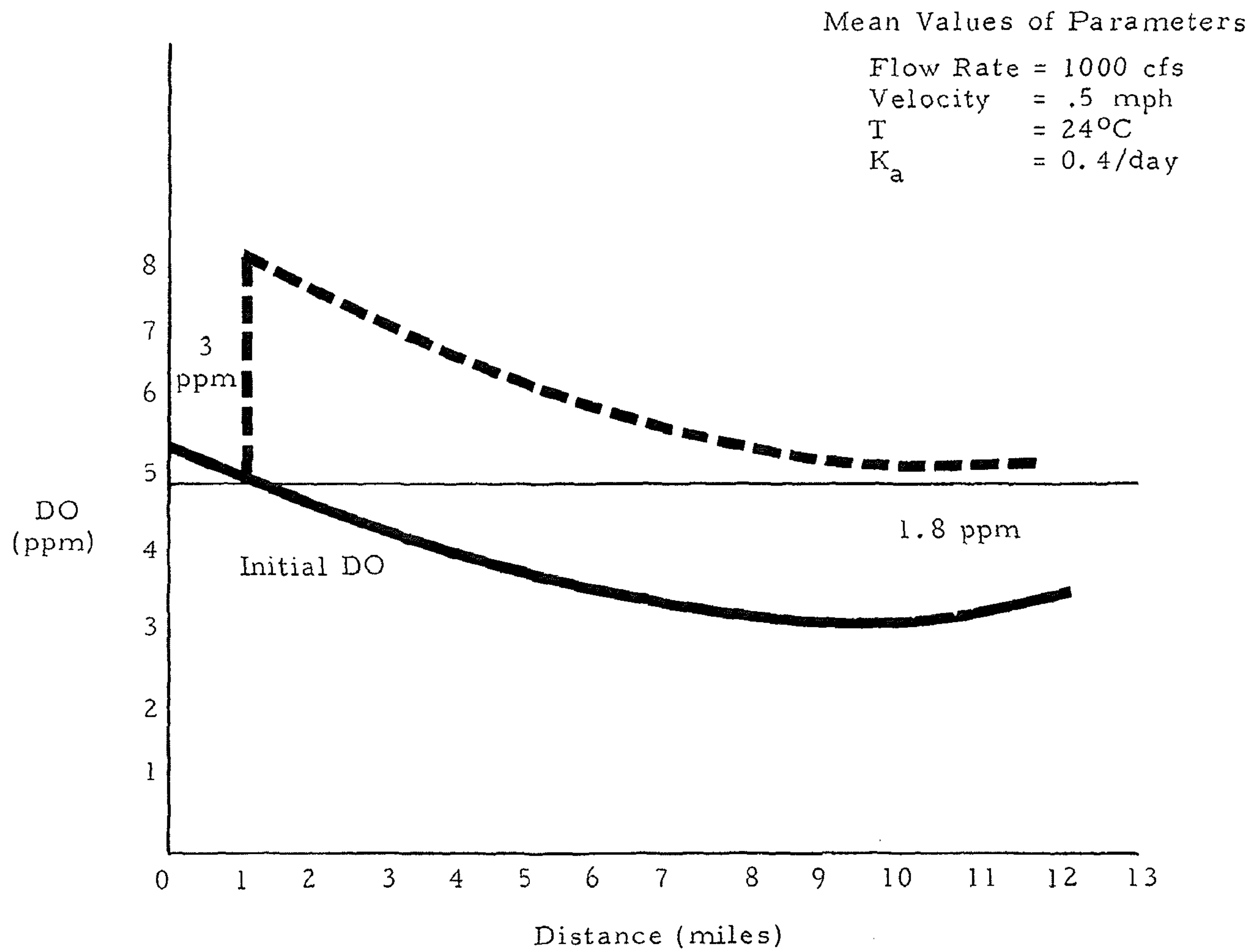


Figure 6.6. DO Profile Before and After Oxygen Addition at One Location

2. Flow rate. Large flows require a high oxygen input to increase the DO initially. Loss in natural aeration is less significant for large flow rates.

3. Pure oxygen versus air. If pure oxygen is available on the site, it is possible to make large initial increases in DO without suffering a significant loss in transfer efficiency.

As can be seen from the above discussion, the transfer efficiencies of the aeration devices play a significant role in system design. In the following step in the design methodology, the characteristics of specific aerators affecting the equipment selection are discussed. This is followed by a discussion of site factors, which may eliminate certain types of systems from consideration, depending on specific conditions at the site.

Selection of Aeration Units

As discussed previously in Section V, the currently available aeration systems are surface aerators, diffusers, downflow contactors (including U-Tubes), and sidestream mixing devices using molecular oxygen. There are also several other types which may be used with one of the above systems to form a "hybrid" system. The hybrid approach has not been explored in great detail but offers some promise with additional development.

The selection of a particular aeration system depends on a number of factors, including transfer efficiency, cost, maintainability, and site suitability. Site factors are very important, and it is quite likely that even if a system is suitable by virtue of its transfer efficiency and cost, it might be aesthetically displeasing within a particular area.

Engineering Considerations Affecting the Selection of an Artificial Aeration System

According to the laws governing the transfer of oxygen to water, it is desirable to locate the aeration system at the point of maximum oxygen deficit. This is particularly true when oxygen is being transferred from air, since the partial pressure of oxygen is then much less than it would be if pure oxygen were being transferred.

Unfortunately, it is not possible to locate the aeration system at this point if some minimum DO level must be maintained. If, for instance, the lowest DO concentration is 4 ppm and a level of 5 ppm must be maintained, the aeration system must be located where DO first drops below 5 ppm. This type of consideration tends to favor a system using pure oxygen, since the system using air cannot be located at its most efficient operating point.

In order to compare transfer efficiencies of the various aeration systems for the application at hand, they must first be converted from standard conditions to field conditions. For systems using air the field transfer rate can be calculated using Equation 6.2.

$$TR_f = \frac{TR[\beta C_s \frac{P}{760} - C_m] \, \theta^{(T - 20)} \alpha}{C_{st}} \quad (6.2)$$

where

TR_f = field transfer rate (lbs / hp-hr)

TR = transfer rate at standard conditions (lb / hp-hr)

C_m = DO level seen by aerator (ppm)

C_s = saturation DO level at stream water temperature (ppm)

C_{st} = saturation concentration at standard conditions = 9.17 ppm

P = pressure at which the system operations (mm of Hg)

$\alpha = \frac{\text{rate of transfer of } O_2 \text{ in stream water}}{\text{rate of transfer of } O_2 \text{ in clean water}}$

$\beta = \frac{\text{saturation concentration of } O_2 \text{ in stream water}}{\text{saturation concentration of } O_2 \text{ in clean water}}$

θ = temperature-dependent coefficient (average value is 1.024)

For a given river or stream α, β, θ, and C_s would be fixed, and

$$TR = k_1 [k_2 \frac{P}{760} - C_m] \quad (6.3)$$

where k_1 and k_2 would be calculated constants. Thus, the transfer rate for a system will depend on the DO in the water and on the operation pressure.

The exact evaluation of C_m is difficult to obtain, consequently, the transfer rate cannot be precisely determined. Susag et al. [50] have proposed three methods for estimating C_m. The first method assumes $C_m = C_u$, the upstream DO value; the second considers $C_m = 1/2\,(C_u + C_d)$, i.e., the average of upstream and downstream DO levels; and the third uses a logarithmic average based on the aeration equation. Based on laboratory tests using surface aerators, the proposers of these methods found the third technique to give the best results. However, this area warrants further investigation. The application of these methods for diffusers, U-Tubes, and sidestream pressurization systems should be verified.

For a surface aeration unit at or near sea level, the pressure is essentially 760 mm, and the transfer rate will depend inversely on C_m (the upper limit of $C_m = (\beta C_s) = k_2$). Hence, if it is desirable to raise the DO level C of the stream to a high value, the overall efficiency would drop off rapidly. However, if a pressurized system or a pure-oxygen system were used, high transfer efficiencies could be achieved. For example, if an air pressurized system were used at 70 psig, transfer efficiencies would increase significantly. If such a system used molecular oxygen in lieu of air, the transfer efficiency should increase by a factor of five compared to that of air, and perhaps on the order of twenty compared to the surface aerator system.

Each of the aeration systems has particular advantages and disadvantages relating to the river and stream application. A summary of these considerations is presented in Table 6.1

Economic Considerations Associated with an Aeration System

One of the most significant factors associated with an aeration system is transfer efficiency (lbs O_2/hp-hr). It has been shown in this section how to calculate oxygen requirements for a particular application. From these calculations it was considered that there are several possible alternatives and that the final selection will depend on transfer efficiencies of the available devices and on site factors at the point where oxygen should be added.

The cost of adding oxygen at one point, such as the case shown in Figure 6.6, will depend on the transfer efficiency of a device attempting to increase DO from 5 to 8 ppm. It will be shown in a design example that this can be achieved using pure oxygen but that the cost of using surface aerators would be prohibitive at this location.

Other alternatives are shown in Figures 6.4 and 6.5. In these cases, the cost of constructing additional systems at more than one location must be considered. These costs will depend on specific conditions at the site, such as:

1. Type of soil for supporting structures
2. Availability of power
3. Accessibility for maintenance

TABLE 6.1

Characteristic Features of Aeration Systems

Type of Aerator	Features	Disadvantages
Mechanical Surface Aerator	Wide choice of commercially available units. High-speed, lightweight, electrical units can provide portability. Most units do not require direct vertical support, i.e., they float. However, provision must be made for sudden increases in stream depth due to sudden storms. Ideal operating DO level is under 6 ppm. Range of instream transfer rates: 1 — 4 lbs O_2/hp-hr Range of cost: 10-hp unit, \$ 3,400; 75-hp unit, \$18,500 Total cost increases as the number of sites increases, because of electrical service and connections.	Mooring cables may restrict boating. Northern climates may cause freezing problems. Their presence may present aesthetic and/or noise problems. Being exposed, they are vulnerable to vandalism.
Diffuser	Can be used with air or molecular oxygen. Does not provide any surface obstructions. Not vulnerable to vandalism. Operates with a minimum of noise and aesthetic upset. Diffuser heads are often porous ceramic, however, perforated plastic tubing is also available. Range of absorption efficiencies (with air): porous ceramic: 3 — 10%; perforated tube: as high as 40% (when flow rate is low) Range of instream transfer rates (porous ceramic only): .7 — 1.4 lbs O_2/hp-hr Ideal operating range is usually under 6 ppm when used with air. Ideal operating depth: air, 10-15 ft; pure oxygen, stream depth	Internal clogging from dust particles in the air. Except for plastic tubing, installations are generally fixed. Cannot be used in a channel maintained by dredging. Long distance between compressor and diffuser results in large head losses.

TABLE 6.1

(continued)

Type of Aerator	Features	Disadvantages
Side-stream Mixer	Works efficiently with high initial DO in water. Does not interfere with boating. Oxygen-absorption efficiencies are normally over 50%. Is not seriously affected by cold weather climates. Requires a supply of pure oxygen.	Requires sophisticated equipment and continual maintenance. Relatively high initial cost Small installations are expensive to operate because of high cost of oxygen. Not portable. Limited number of commercial units available.
Down-flow Contactor (U-Tube)	If natural head is available and sufficient stream depth, this system offers maintenance-free operation. Can be located to the side of a main channel; does not restrict boating. Can be used with air or molecular oxygen. Ideally suited for high DO levels (near saturation).	Not portable. High initial cost compared to other systems. Requires depth of at least 10 ft, 30 to 40 ft for high efficiency. Possible problems with nitrogen saturation when used at depths in excess of 10 ft. Usually requires a custom installation.

After the sizes and number of units required to meet a given oxygen requirement have been determined, the capital, construction, and engineering costs can be computed. This cost is converted to an annual amortization rate to which are added operating and maintenance costs. Where there are several possible types of systems, a cost analysis should be performed for each one. The final selection may be based on factors other than cost, but it is important to have the cost information available.

Design and Cost Examples

The following two examples are offered as illustrations of the procedure for estimating costs and also to show some of the differences in approach using surface aerators and sidestream mixing with pure oxygen.

Figures 6.4 and 6.6 are graphic illustrations of the two examples. In Figure 6.4 oxygen is injected at three different locations, and in Figure 6.6 the same DO profile is treated at only one location. It is fairly obvious from the previous discussions in this section that pure oxygen can be injected efficiently at a point where the DO level in the water is fairly high. The transfer efficiency of a surface aerator, however, is best at a low DO concentration.

For the two cases, surface aerators will be used at each of the three locations in Figure 6.4 while a sidestream mixing system will be used at the single location shown in Figure 6.6.

The following design conditions apply to both examples:

Velocity	.5 mph
Discharge rate	1000 cfs
Length of critical reach	12 mi.
Temperature	24°C
Pressure	1 atmosphere
$\alpha = \beta$	.95
Aeration constant, K_a	.4/day

In the first example, surface aerators are used at two locations to raise DO from 5 to 6 ppm and at a third to raise DO from 5 to 5.5 ppm. The oxygen requirements at each location are

$$\text{lbs } O_2/\text{day}\Big|_{1,2} = 1000 \text{ ft}^3/\text{sec} \times 624 \text{ lbs/ft}^3 \times 3600 \text{ sec/hr} \times 24 \text{ hr/day} \times 1.0 \times 10^{-6} = 5,380 \text{ lbs } O_2/\text{day} = 222 \text{ lbs } O_2/\text{hr}$$

$$\text{lbs } O_2/\text{day}\Big|_{3} = 1000 \text{ ft}^3/\text{sec} \times 624 \text{ lbs/ft}^3 \times 3600 \text{ sec/hr} \times 24 \text{ hr/day} \times 0.5 \times 10^{-6} = 2,695 \text{ lbs } O_2/\text{day} = 112 \text{ lbs } O_2/\text{hr}$$

To determine how much horsepower is required at each location, the standard transfer efficiency for a surface aerator is converted to a field transfer rate using Equation 6.2.

$$TR_f = \frac{TR[\beta C_s \frac{P}{760} - C_m] \, \theta^{(T-20)} \, \alpha}{C_{st}}$$

For this example, surface aerators with a transfer efficiency of 2.2 lbs O2/hp-hr are selected. There will be two field transfer rates, one for the case where DO is increased from 5 to 6 ppm and the other when DO is raised from 5 to 5.5 ppm.

$$TR_{f_{1,2}} = \frac{2.2\,[.95 \times 8.5 \times \frac{760}{760} - \frac{5+6}{2}] \times 10^{-6} \times 1.10 \times .95}{9.17 \times 10{-6}}$$

$$= .64 \text{ lbs } O_2/\text{hp-hr}$$

$$TR_{f_3} = \frac{2.2\,[.95 \times 8.5 \times \frac{760}{760} - \frac{5+5.5}{2}] \times 10^{-6} \times 1.10 \times .95}{9.17 \times 10^{-6}}$$

$$= .71 \text{ lbs } O_2/\text{hp-hr}$$

The hp requirement at locations 1 and 2 will be

$$hp_{1,2} = \frac{222}{.64} = 347$$

At location 3

$$hp_3 = \frac{112}{.71} = 158$$

Cost estimates for 75-hp electrical surface aerators have been reported in a recent study[6] . The estimates include all costs necessary to install and operate the systems (cables, piling, lights, specially reinforced frames, etc.) and are given for single-mounted units and aerators mounted in clusters of two and three. (Prices are based on 135 days of annual use.)

Arrangement	Single	Double	Triple
Total Horsepower	75	150	225
Equipment and Construction	57,000	92,700	130,500
Engineering and Contingencies	11,400	18,500	26,100
	$68,400	$111,200	$156,600
Operation and Maintenance	20,000	26,500	33,000
Amortization & Interest (15 years @ 6%)	7,000	11,500	16,200
	$27,000	$38,000	$49,200

Assuming that the above costs are representative of the costs associated with the given example, the yearly expense of a system for the three locations can be estimated as follows:

> At the two sites requiring 347 hp, one triple cluster and one double cluster could be used at each location, while at the third site one double cluster could be installed. This results in a slight excess at the first and second locations and a slight deficit at the third location. The total provision is on the conservative side.
>
> The total annual costs would then be
>
> 2 x $49,200 + 3 x $38,000 = $212,400

In the second example, illustrated by Figure 6.6, the design conditions given for the previous example also apply. The oxygen in this case will be injected by sidestream pressurization at one location, raising DO from 5 to 8 ppm.

Based on correspondence with the manufacturer [67], it is estimated that installation costs will be approximately $4000 per daily ton of oxygen injected. This includes pump installation, concrete pad for oxygen supply system, fabrication of oxygen control panel, injection thimble, and dispersion header.

The operating costs for supplying oxygen at the site would be about $35 to $50 per ton. The power required to pump water at 100 psig is about 50 kw per 1000 gpm. (The oxygen and water are mixed at approximately 100 psig.) The injection efficiencies for the system should be on the order of 55-75% when 1 to 3% of the total flow is pumped to the sidestream unit.

The oxygen requirement to raise DO by 3 ppm at the one location is:

$$\text{lbs } O_2/\text{day} = 1000 \text{ ft}^3/\text{sec} \times 62.4 \text{ lbs/ft}^3 \times 3600 \text{ sec/hr} \times 24 \text{ hr/day} \times 3 \times 10^{-6}$$

$$\doteq 16{,}020$$

Assuming an injection efficiency of 65%, the injection system should deliver

$$\frac{16{,}020 \text{ lbs}}{.65 \times 2000 \text{ lbs/ton}} = 12.3 \text{ tons } O_2/\text{day}$$

The installation costs would then be

$$12.3 \text{ tons} \times \$4000/\text{ton} = \$49{,}200$$

This cost can be amortized over 15 years at a 6% interest rate, yielding an annual cost of $4,700/year.

The operating costs are calculated as follows:

Assuming the cost of O_2 is $45/ton and that 3% of the river flow is pumped to the mixer:

$$O_2 \text{ costs (135 days)} = 12.3 \text{ tons} \times \$45/\text{ton} \times 135 \text{ day/yr} = \$74{,}800/\text{yr}$$

The cost of pumping water to the mixer over a 135-day period is:

$$\text{Power required} = 1000 \text{ ft}^3/\text{sec} \times 7.48 \text{ gal/ft}^3 \times 60 \text{ min/sec} \times .03 \times 50 \text{ kw}/1000 \text{ gal/min} = 675 \text{ kw}$$

$$\text{Power cost} = 675 \text{ kw} \times 24 \text{ hr/day} \times 135 \text{ day/yr} \times \$.015/\text{kw-hr} = \$32{,}800$$

Maintenance costs are estimated as follows:

Personnel – 2 men @ $8,000/yr =	$16,000
Equipment	5,000
	$21,000

The total annual cost is:	$ 4,700
	74,800
	32,800
	21,000
	$ 133,300

Summary

The cost of using surface aerators in this application is more than 1-1/2 times as high as that of using the sidestream system. The basic reason for this is the low transfer efficiency of the surface aerator when working with an incoming DO level of 5 ppm. The oxygen-injection system is not affected by the relatively high DO and thus performs the job at a much lower cost.

These two examples serve only to illustrate the methodology. For each case, the cost calculations should be made, but site factors will also influence the final result. These factors are considered next.

Site Factors

Depending on the uses of a stream or river, the application of certain aeration systems may be precluded or severely limited. For example, if the waterway is navigable and is used for shipping and pleasure boating, the placement of obstructions such as surface mechanical aerators or U-Tubes in the river would present an obvious problem. In this case, the tendency would be to select a diffuser or sidestream pressurization system. This situation does not completely eliminate the possible use of surface aerators or U-Tubes, since they can be installed outside of a main channel; although, this would not permit optimum utilization of the equipment. On the other hand, if a river channel is dredged periodically, the positioning of diffuser units or outflow lines from a sidestream pressurization system would also be constrained.

Aesthetic considerations and noise levels may also carry considerable weight when selecting a system. If the installation is to be near a town or city, opposition may arise if the units produce considerable foaming and frothing or a continuous whine or roar.

In some cases there may be shifting of the low points in the DO profile, and consideration must be given to a system which affords portability. Such a situation would favor the selection of high-speed surface aerators, which are relatively small and light compared to low-speed units. U-Tubes, sidestream pressurization, and diffuser systems are generally not portable or easily moved.

If artificial aeration is necessary during winter months, freezing may be a problem with surface aerators. When the surface of a river freezes, the aerator may be tilted or lifted and consequently may become ineffective. In this case, a diffuser or sidestream pressurization system would be favored, since they would not be affected by conditions on the surface.

Another factor that must be considered from a practical viewpoint is the vulnerability of the system to vandalism. For example, with a diffuser system, accessibility to any of the components can be minimized; the diffusers are under water, the feed lines and manifolds are submerged or buried, and the compressors can be located in a blockhouse. If sufficient natural head and water depth exist in a stream, a U-Tube system is also relatively impervious to vandals. The system in this case would essentially be a submerged concrete structure whose cross-sectional shape corresponded to that of a U-Tube.

Final Selection of an Aeration System

As discussed above, site considerations play a major role in the final selection of an aeration system. In the design examples, several possible solutions were shown for a selected DO profile, each having a different cost. The final choice must involve a trade-off between the costs of a system, the cost of construction and maintenance, and the aesthetic considerations at the possible sites.

For each of the possible technical solutions, the corresponding site problems should be listed. The site problems can be characterized as those affecting cost and those affecting aesthetic qualities. From each combination there will emerge a top candidate system. If several combinations appear to be satisfactory, the final selection will obviously be the one with the lowest estimated cost. In the examples discussed previously, the use of pure oxygen in a sidestream mixing system emerged as a top choice on a cost basis and would probably also be a better choice aesthetically.

However, further examination might have indicated that diffuser systems using plastic pipe were both less expensive and more acceptable aesthetically. Unless there are very obvious reasons not to do so, calculations and a trade-off should be performed for each possible alternative.

In this report it has been assumed that the minimum acceptable DO level is 5 ppm. The results of the design examples may differ considerably if this standard is lowered, for example, to 3 or 4 ppm. The methodology, however, would not be affected.

SECTION VII

ACKNOWLEDGEMENTS

The support and assistance of the Project Officer, Dr. Curtis C. Harlin, Jr., of the Robert S. Kerr Water Research Center, EPA, is acknowledged with sincere thanks. In addition, the assistance of Mr. Lowell Leach, of the Robert S. Kerr Water Research Center, and of Mr. James Basilico and Mr. Charles Myers, of the EPA, has been appreciated.

SECTION VIII

REFERENCES

[1] Tyler, R. G., "Accelerated Reaeration," Sew. Works J., 14, 4, 834, July, 1942.

[2] ZoBell, C. E., "The Effect of Oxygen Tension on the Rate of Oxidation of Organic Matter in the Sea," J. Mar. Res., 3, 211-223, 1940.

[3] Dresnack, R., and Metzger, I., "Oxygen Response and Aeration in Streams," Proc. 23rd Industrial Waste Conference, Purdue Univ., Lafayette, Ind., May, 1968.

[4] Dresnack, R., Transient Dissolved Oxygen Profiles in Streams, Doctoral Thesis, New York Univ., 1966.

[5] American Society of Civil Engineers, SED, Twenty-Ninth Progress Report of the Committee on Sanitary Engineering Research, 86, SA 4, 41, 1960.

[6] Whipple, W., et al., Instream Aeration of Polluted Rivers, Water Resources Research Institute, Rutgers Univ., August, 1969.

[7] Littleton Research and Engineering Co., An Engineering Economic Study for the Development of an Optimum Mechanical Aeration System for Quiet Rivers and Ponds, Report #G-182, July, 1970.

[8] Churchill, M. A., et al., "The Prediction of Stream Reaeration Rates," J. San. Eng. Div., Proc. American Society of Civil Eng., July, 1962.

[9] O'Connor, D. J., and Dobbins, W. E., American Society of Civil Eng., 123, 641, 1958.

[10] Gameson, A. L. H., and Truesdale, G. A., J. Institute of Water Eng., 13, 175-87, 1959.

[11] Langbein, W. B., and Durrem, W. H., Geological Survey Circular 542, U. S. Dept. of the Interior, Washington, D. C.

[12] Ownes, M., Edwards, R. W., and Gibbs, J. W., International J. of Air and Water Pollution, 8, 469, 1964.

[13] Odum, H. T., "Primary Production in Flowing Waters," Limnol. Oceanog., 1, 102-117, 1956.

[14] Buswell, A. M., Van Meter, I., and Gerke, J. R., "Study of Nitrification Phase of the BPD Test," Sewage and Industrial Wastes, 22, 4, 508, February, 1950.

[15] Gaffney, P. E., and Heukelekian, H., "Oxygen Demand Measurement Errors in Pure Organic Compounds - Nitrification Studies," Sewage and Industrial Wastes, 30, 4, 503, April, 1958.

[16] Sawyer, C. N., and Bradney, L., "Modernization of the BOD Test for Determining the Efficacy of Sewage Treatment Processes," Sew. Works J., 18, 6, 1113, November, 1946.

[17] Ruchhoft, C. C., Placak, O. R., and Ettinger, M. B., "Correction of BOD Velocity Constants for Nitrification," Sew. Works J., 20, 5, 832, September, 1948.

[18] Courchaine, R. J., "Significance of Nitrification in Stream Analysis-Effects on the Oxygen Balance," 30th Annual Conference, Michigan Water Pollution Control Assn., May, 1962.

[19] American Public Health Assn., Standard Methods for the Examination of Water, Sewage and Industrial Wastes, 13th Edition, New York, 1971.

[20] Salle, A. J., Fundamental Principles of Bacteriology, 3rd Edition, McGraw-Hill Book Co., New York, 1948.

[21] Velz, C. J., Applied Stream Sanitation, John Wiley & Sons, New York, 1970.

[22] O'Connor, D. J., "The Temporal and Spatial Distribution of Dissolved Oxygen in Streams," Water Resources Research, 3, 1, 65, 1st Quarter, 1967.

[23] Gameson, A. L. H., "Some Aspects of the Carbon, Nitrogen, and Sulphur Cycles in the Thames Estuary, Part II," in Effects of Pollution on Living Material, pp 47-54, Institute of Biology, London, 1959.

[24] O'Connor, D. J., "Stream and Estuarine Analysis," Manhattan College Summer Institute in Water Pollution Control, New York, N.Y.

[25] Buswell, A. M., Shiota, T., Lawrence, N., Van Meter, I., Applied Microbiology, 2, 21-5, 1954.

[26] Garrett, M. T., Proc. Industrial Water and Waste Conference, Rice Univ., Houston, Texas, 1961.

[27] Knowles, G., Downing, A. L., Barrett, M. J., J. General Microbiology, 38, 263-78, 1965.

[28] Stratton, F. E., and McCarty, P. O., "Prediction of Nitrification Effects on the Dissolved Oxygen Balance of Streams," Environmental Science and Technology, 1, 5, May, 1967.

[29] Winberg, G. G., and Sivko, T. N., "The Significance of Photosynthetic Aeration in the Oxygen Balance of Polluted Waters," International J. of Air/Water Pollution, 6, 267-75, 1962.

[30] Innjatovic, L. R., "Effect of Photosynthesis on Oxygen Saturation," J. Water Pollution Control Fed., May, 1968.

[31] Stay, F. S., et al., The Components of Oxygenation in Flowing Streams, U. S. Dept. of the Interior, FWPCA, April, 1967.

[32] Hull, C. H. J., "Photosynthesis as a Factor in the Oxygen Balance of Reservoirs," Symposium on Streamflow Regulation for Quality Control., PHS Pub. No. 999-WP-30, June, 1965.

[33] Hull, C. H. J., "Discussion of 'Effects of Impoundments on Oxygen Resources' by Churchill," Oxygen Relationships in Streams, W 58-2, pp 124-29, 1958.

[34] Copeland, B. J., and Duffer, W. R., "Use of a Clear Plastic Dome to Measure Gaseous Diffusion Rates in Natural Waters," Limnol. Oceanog., 9, 4, 494-499, October, 1964.

[35] Hornuff, L. E., A Survey of Four Oklahoma Streams with Reference to Production, Oklahoma Fishery Research Laboratory Reference to Production Report 62, June, 1957.

[36] Knöpp, H., "Investigation of the Oxygen Production Potential of River Plankton," Hydrology, 22, 152-66, 1960.

[37] Paulson, R. W., "The Longitudinal Diffusion Coefficient in the Delaware River Estuary as Determined from a Steady-State Model," Water Resources Research, 5, 1, 59, 1969.

[38] Harleman, D. R. F., and Ippen, A. T., "The Turbulent Diffusion and Convection of Saline Water in an Idealized Estuary, International Assn. Sci. Hydro. Publ., 51, 1960.

[39] Orlob, G. T., "Eddy Diffusion in Homogeneous Turbulence, Proc. American Society Civil Eng., 85, No. HY 9, September, 1959.

[40] O'Connor, D. J., "Oxygen Balance of an Estuary," Proc. American Society Civil Eng., 86, SA3, May, 1960.

[41] Fischer, H., "The Mechanics of Dispersion in Natural Streams," J. Hydraulics Div., Proc. American Society Civil Eng., p 187, 1967.

[42] Fischer, H., "Dispersion Predictions in Natural Streams," J. Sanitary Eng. Div., Proc. American Society Civil Eng., p 927, 1968.

[43] Elder, J. W., "The Dispersion of Marked Fluid in Turbulent Shear Flow," J. Fluid Mechanics, 5, 544-60, 1959.

[44] Whipple, W., et al., Oxygen Regeneration of Polluted Rivers: The Delaware River, Environmental Protection Agency Program No. 16080 DUP, December, 1970.

[45] Dobbins, W. E., "BOD and Oxygen Relationships in Streams," J. Sanitary Eng. Div., Proc. American Society Civil Eng., pp 53-78, June, 1964.

[46] Aeration in Wastewater Treatment, Water Pollution Control Federation Manual of Practice No. 5, 1971.

[47] McKeown, J. J., and Buckley, D. B., "Mixing Characteristics of Aerated Stabilization Basins," TAPPI 8th Water and Air Conference, 1971.

[48] Burns, O. B., et al., "Pilot Mechanical Aeration Studies of the Jackson River in Covington, Virginia," Proc. 21st Industrial Waste Conference, Purdue Univ., Lafayette, Ind., 799, 1966.

[49] Kaplovsky, A. J., et al., "Artificial Aeration of Canals in Chicago," 36th Annual Meeting of the Water Pollution Control Federation, Seattle, Washington, October, 1963.

[50] Susag, R. H., Polta, R. C., and Schroepfer, G. J., "Mechanical Surface Aeration of Receiving Waters," J. Water Pollution Control Fed., 38, 1, January, 1966.

[51] Brookhart, N. M., Mechanical Aeration Project Performance and Feasibility Study, Miami Conservancy District Report, November, 1969.

[52] National Council of the Paper Industry for Air and Stream Improvement, Results of a Cooperative Field Study of a Downflow Bubble Contactor and a Conventional Surface Aerator, Techn. Bull. #237, June, 1970.

[53] Lueck, B. F., et al., Evaluation of the Spray Type "Aqua-Lator" for River Aeration, State of Wisconsin Commission on Water Pollution, Bulletin No. WP-109, March, 1964.

[54] Tyler, R. G., "Polluted Streams Cleared up by Aeration," Civil Eng., 16, 348, August, 1946.

[55] Wiley, A. J., et al., "River Reaeration," Paper Trade J., 124, 12, 123, 1947.

[56] Palladino, A. J., "Investigation of Methods of Stream Improvement," Industrial Water and Wastes, 6, 3, 87, 1961.

[57] Bõhnke, B., "Effect of Organic Wastewater and Cooling Water on Self-Purification of Waters," Proc. 22nd Industrial Waste Conference, Purdue Univ., Lafayette, Ind., 752, 1967.

[58] Imhoff, K. R., "Oxygen Management and Artificial Reaeration in the Area of Baldeney Lake and the Lower Ruhr River," Das Gras und Wasserfoch, 109, Germany, 1968.

[59] Sellner, E. P., "Am-Aqua Aerated Lagoons," presented at the 38th Annual Conference of the Arizona Water and Pollution Control Assn., April, 1966.

[60] National Council of the Paper Industry for Air and Stream Improvement, Artificial Reaeration of Receiving Waters, Tech. Bull. #229, New York, May, 1969.

[61] Amberg, H. R., et al., "Aeration of Streams with Air and Molecular Oxygen,"

[62] Bruijn, J., and Tuinzaad, H., "The Relationship Between Depth of U-Tubes and the Aeration Process," American Water Works Assn. J., 50, 879-885, July, 1958.

[63] Speece, R. E., "U-Tube Stream Reaeration," presented at the 7th Annual Sanitary and Water Resources Engineering Conference, Vanderbilt Univ., May, 1968.

[64] Speece, R. E., "U-Tube Oxygenation for Economical Saturation of Fish Hatchery Water," presented at the American Fisheries Society Meetings, September 1968.

[65] Speece, R. E., and Adams, J. L., "U-Tube Oxygenation Operation Characteristics," Proc. of the 23rd Industrial Waste Conference, Purdue Univ., Lafayette, Ind., May, 1968.

[66] Rocketdyne (Division of North American Rockwell Corp.), The U-Tube for Water Aeration, Final Report, Project R-8043, Canoga Park, California, March, 1970.

[67] Union Carbide Corporation, private communication dated March 1971.

[68] Both, T. D., et al., Oxygenation of Aqueous Bodies Using Liquid Oxygen - Loxination, Midwest Research Institute, Kansas City, Missouri, March, 1970.

[69] Speece, R. E., "The Use of Pure Oxygen in River and Impoundment Aeration," Proc. of the 24th Industrial Waste Conference, Purdue Univ., Lafayette, Ind., May, 1969.

[70] Amberg, H. R., et al., "Reaeration of Streams with Molecular Oxygen," Industrial Water Engineering, pp 15-20, February, 1967.

[71] Pfeffer, J. T., and McKinney, R. E., "Oxygen-Enriched Air for Biological Waste Treatment," Water and Sewage Works, p 381, October, 1965.

[72] Carver, C. E., "Absorption of Oxygen in Bubble Aeration," Biological Treatment of Sewage and Industrial Wastes, Volume I: Aerobic Oxidation, Reinhold Publishing Corp., New York, 1956.

[73] Böhnke, B., Possibilities of Artificial Aeration of Streams and Waters, Illustrated by the Lippe as an Example, Lippe Association, Essen, Germany.

SECTION IX

APPENDICES

A. Diffusers and Mechanical Aerators [46]

Diffusers

Diffusers are devices which introduce air into liquids. They are installed in various locations below the liquid surface on either fixed or retractable mountings. Air is furnished by blowers, which are usually in a central location. The blowers operate at a pressure sufficient to overcome the static head of liquid above the diffusers and the distribution losses. In many large plants, gas engines operated from the digester gas are used to drive the blowers.

Diffusers may be classified as porous or nonporous (Table A. 1). Porous diffusers in the form of plates or tubes are either of the ceramic type, constructed of silicon dioxide or aluminum oxide grains held in a porous mass with a ceramic binder, or of the non-ceramic type, consisting of plastic-wrapped tubes or plastic-cloth tubes.

Nonporous diffusers may be of the nozzle, orifice, valve, or shear type. Nozzle and orifice-type diffusers are constructed of metal or plastic, have larger openings, and release larger bubbles than the porous-type diffusers. Valve-type diffusers have a disc or valve which closes when the air supply is shut off. They release larger bubbles than do porous diffusers.

Shear-type diffusers provide for the reduction of the bubble size by the shearing force of the water entering the diffuser at the open top in a counter-flow direction to the upflowing air. These diffusers are square in shape.

Other diffuser arrangements include water jets, which consist of combined air units, and perforated or slotted pipes, which are used occasionally as a temporary expedient or for unusual conditions. The perforated or slotted-pipe diffusers are not offered for deep-submergence diffusion, show a low oxygen absorption efficiency, and are readily clogged or corroded. Many of the diffuser applications in the past have been in treatment tanks, and much of the following discussion is in relation to that type of usage.

Diffuser mountings may be either fixed or retractable. Portable hoists may be used for raising the headers out of the tank for servicing. Sometimes porous plates are mounted in plate holders installed on the floor of the tank. The location of the diffuser in an aerator tank has a considerable impact on the efficiency of the device. Data are available from studies on the oxygen transfer of diffusers at various tank locations,

TABLE A-1

List of Diffuser Manufacturers

Manufacturer	Diffuser Type	Description
Aer-O-Flo Div. Clow Corp.	Nonporous	Stainless-steel-nozzle type with check valve
Carborundum Co.	Porous	Ceramic plates and tubes
Chicago Pump FMC Corp.	Porous plastic	Saran wrapped media, metal core with integral end caps and control orifice
	Porous plastic flexible media	Saran cloth flexible media, metal frame with integral end cap and orifice
	Nonporous	Plastic nozzle type with integral control orifice
	Porous	Ceramic tubes with cast-iron end caps and control orifice
	Nonporous	Plastic and metal valve type with integral control orifice
	Nonporous	Nonporous metal shear type with control orifice
Dorr-Oliver, Inc.	Nonporous	Tubular metal grid, nozzle-type diffusion, 0.5 to 1 m below water surface
Eimco Corp. An Envirotech Div.	Nonporous	Plastic base with elastomer cover
Filtros Plant Ferro Corp.	Porous	Ceramic plates and ceramic tubes with and without integral end caps and control orifice
FMC Corp. Link-Belt Division	Nonporous	Metal nozzle type, adjustable, with 4 to 12 openings; ball check valve
Fuller Co., Infilco Products	Porous plastic	Porous plastic media, plastic pan-type holder
Hinde Engr. Co.	Nonporous	Plastic aeration tubing
Keene Corp. (formerly American Well Works)	Nonporous	Variable-flow, multiple-orifice type, made of cast bronze or aluminum magnesium
Norton Co.	Porous	Ceramic plates and tubes
Ray Products Co.	Porous	Plastic media, various mountings
Rex Chainbelt Inc., Pacific Flush Tank Div.	Nonporous	Nonporous-metal-valve type with plastic ball valve
Walker Process Equipment Div. Chicago Bridge & Iron Co.	Nonporous	Plastic-nozzle type

water depths, numbers of diffusers, tank width, diffuser spacings, and air rates. Table A.2 reports the results of these studies. Similar studies have also been made of nonporous diffusers.

Mechanical Aerators

Over the past decade mechanical aerators have been widely used to supply oxygen to treatment plants treating a broad range of flows and organic loads, providing high removal efficiencies at comparable power costs.

Mechanical aerators can transfer atmospheric oxygen to liquid by surface renewal and interchange; and, when properly designed, mechanical aerators meet the mixing requirements at various single and multiple-unit installations for a broad range of tank sizes and configurations. Mechanical aerators can also transfer atmospheric oxygen by dispersing compressed air fed below the surface to a rotating agitator or turbine. In the former case for an updraft-type aerator, oxygen is introduced to the tank contents by lifting large volumes of liquid above the water surface and exposing it in thin films to the atmosphere. With the plate-type aerator a high degree of turbulence is generated. Both types of aerators transfer oxygen through incorporation and dispersion of air into the liquid because of high surface agitation.

In the latter case, air bubbles are discharged from a pipe or sparge ring beneath the turbine and are broken up by the hydraulic shearing action created by the high-speed rotating blades of the turbine moving through the liquid. The sparge ring is fed by compressed air; hence, this system is actually a combined mechanical diffused-air system.

In the downdraft system oxygen may be supplied by air, self-induced from the negative head produced by the rotor. With this system external blowers or compressors are not required.

Brush-type mechanical aerators consist of a horizontal revolving shaft with combs, blades, or circular discs with T-shaped bars attached, extending below the water surface.

Table A.3 lists some of the manufacturers of mechanical aerators.

The current trend is toward the use of mechanical surface aerators in larger basins. Today there are many installations throughout the world utilizing multiple units in large tanks. Mechanical aerators have been used in both small and large activated sludge plants and aerated lagoons treating domestic and industrial wastes.

Efficiencies up to 7 lb O_2/hp-hr have been attained for various aerators. Actually it has been found that very high efficiencies can be achieved on small pilot aerators but that for practical application, under normal conditions, the larger aerators have an efficiency range of 2 to 4 lb/O_2

TABLE A.2

Diffuser Efficiencies at Various Locations in Tank Under Standard Conditions

Location	Type	Depth (ft)	Air Rate	Efficiency (%)	Tank Width (ft)
Diffusers mounted on a header on the wall side	Porous	12.75	4 cfm/ft 8 cfm/dif.	9.7	24
			12 cfm/ft 8 cfm/dif.	11.5	
Diffusers mounted on both sides of a header near tank well	Porous	12.4	8 cfm/ft 8 cfm/dif.	12	24
			16 cfm/ft 8 cfm/dif.	12.8	
			20 cfm/ft 10 cfm/dif.	12.5	24
Diffusers mounted on both sides of a header located near both tank walls	Porous	12.4	16 cfm/ft 8 cfm/dif.	14	24
Diffusers mounted on both sides of multiple headers	Porous	12.4	72 cfm/ft 8 cfm/dif.	16	24

TABLE A-3

List of Mechanical Aerator Manufacturers

Manufacturer	Type	Aerator Characteristics
Chicago Pump FMC Corp.	Updraft	"Chicago"-propeller-driven flow discharged against diffuser cone at top
Dorr-Oliver Inc.	Combination	"D-O Aerator" -induced by sub-surface rotor and compressed air
Eimco Corporation, An Envirotech Division	Updraft	"Simcar"-induced by rotating impeller at top
Fuller Co., Infilco Products	Plate	"Vortair"-induced by horizontal, radially vaned impeller at top "Aero-Accelator"-induced by sub-surface rotor and compressed air
Keene Corp. (formerly American Well Works)	Plate	"American"-induced by horizontal vaned impeller at top
Lakeside Engineering Corp.		Horizontal rotating
Mixing Equip. Co. Inc.	Updraft	"Lightnin'"-induced by rotating impeller at top with rotor below surface
Permutit Co., Div. Ritter Pfaudler Corp.	Combination	"Permaerator"-induced by surface, sub-surface, and compressed air
Vogt Manufacturing Co.	Downdraft	"Aer-O-Mix" - Produced by impeller in tube; with radial inlet troughs.
Walker Process Equipment, Div. Chicago Bridge & Iron Co.		Induced by rotating updraft impeller
Welles Products Corp.	Updraft	"Aqua-Lator" -either submersible or non-submersible pump discharge through vertical tube
Yeomans-Clow	Updraft	"YeoCone"-induced by spiral vaned revolving cone at top and draft tube
	Updraft	Sigma-induced by scoop-type revolving blades at top

transferred under standard conditions per horsepower hour. This efficiency range normally covers the entire range of aerators marketed today.

Plate Types

Typical plate types are the "Vortair," manufactured by Infilco/Fuller, and the "American Aerator," manufactured by American Well Pump. The "Vortair" consists of a circular flat plate with vertical blades attached at the periphery of the plate. The "Vortair" uses a standard motor and gear-drive unit. The plate rotates in a horizontal plane a short distance below the normal water surface. When the aerator is in operation, the top of the plate is clear of water. The performance of the aerator depends on establishing proper design relationships to determine the effects of diameter, blade sizes, number of blades, speed of rotation, submergence, and other variables that affect horsepower requirements and oxygen transfer.

Updraft Types

There are a number of updraft types available, including the Yeomans-Clow "Sigma," the Eimco "Simcar," the Mixco "Lightnin," the Welles Products "Aqua-Lator," the Walker "Intens-Aer," and one manufactured by Chicago Pump, all of which are described below.

The Yeomans-Clow "Sigma" aerator operates on the updraft principle with an impeller located at the surface of the liquid, designed to pump large quantities of liquid at a low head. Individual blades, attached to the rotating drive ring, are designed specifically to insure maximum hydraulic efficiency. The use of individually mounted blades allows for great flexibility in changing the capacity of the unit on the job site at any desired future date. The unit is driven by a standard motor and gear drive and is adaptable to the use of a variable-speed drive.

The Eimco "Simcar" aerator consists of a standard motor and gear-drive unit, supported by walkway beams spanning the aeration tank. The impeller is a cone-shaped disc with square-bar blades radiating outward from the center. The blades are at or just below the surface of the liquid. Liquid is drawn upward and outward by the rotating impeller into a center cone and then is propelled outward in a low trajectory.

The Mixco "Lightnin" aerator is a pitched blade, open-style turbine utilizing a motor and gear-drive unit. The aerator is located at the surface of the liquid and operates on the updraft principle. The aerator usually consists of four blades pitched at a 45-degree angle. Operating speeds are generally between 30 and 60 rpm. At times, a smaller rotor is installed on an extended shaft near the bottom of the tank to increase turbulence and maintain solids in suspension.

The "Aqua-Lator" (Welles Products Corporation) is a relatively simple aerator, consisting of a special submersible or nonsubmersible pump, a riser tube, a fiberglass-covered float, and an orifice-diffuser assembly. Power is supplied from an on-shore control station by means of a submersible power cable. The "Aqua-Lator" is supported in the liquid by its own integral float, which automatically adjusts to water-level changes.

The Walker "Intens-Aer" aerator consists of an updraft unit pumping large volumes of liquid at low head by means of a slinging-blade impeller located near the surface of the liquid. Oxygen transfer ossurs from the large interfacial area created by the impeller discharge pattern, from high turbulence and surface wave action, and from entrained air bubbles carried down with the circulating tank liquid by the high tank-turnover rates established.

A mechanical aerator manufactured by Chicago Pump, FMC Corporation, consists of an impeller on a vertical shaft located near the top of a vertical draft tube, which is in the center of the tank. This impeller lifts the liquid up the tube and discharges it against a diffuser cone, which deflects it horizontally and down to the surface.

Downdraft Types

The Vogt Manufacturing Company makes the "Aer-O-Mix," in which an impeller in a vertical tube forces liquid from the top down through the tube to the bottom of the tank. The liquid entrains the air from above. The mixture expelled from the bottom of the tube rises through the tank. This system, in principle, is a "downflow contactor" as well as a surface aerator.

Combination Types

The "D-O" turbine (Dorr-Oliver, Inc.) is powered by a standard, direct-connected motor and gear drive that is secured to a beam structure spanning the tank. Two or more turbine impellers can be used, one usually located near the bottom of the tank above a sparge ring, and another located about 30 in. below the surface. The upper impellers, or any intermediate impellers located below the surface, serve as shearing devices for the compressed air released through the sparge ring.

The "D-O" aerator transfers oxygen through the emission of air at the sparge ring and the shearing action on the bubbles by the rotating impellers located above the sparge ring.

The Permutit "Permaerator" uses two motor-driven impellers and a sparge ring at the lower impeller. The Permutit aerator sparge ring is designed to release air within the diameter of the adjacent impeller. The upper impeller on the Permutit unit is located near the surface and functions as a surface aerator.

☆U.S. GOVERNMENT PRINTING OFFICE: 1972 484-482/20 1-3

1 Accession Number	2 Subject Field & Group	
	05G	**SELECTED WATER RESOURCES ABSTRACTS** INPUT TRANSACTION FORM

5 Organization

JBF Scientific Corporation
2 Ray Avenue, Burlington, Massachusetts 01803

6 Title

ENGINEERING METHODOLOGY FOR RIVER AND STREAM REAERATION

10 Author(s)

Murro, Ronald P.
Yeaple, Donald S.

16 Project Designation

16080 FSN 10/71

21 Note

22 Citation

23 Descriptors (Starred First)

*Water quality control, *Aeration, Dissolved oxygen, Oxygenation, River Basins.

25 Identifiers (Starred First)

*Induced aeration, *Oxygenation efficiency, Air distribution, Molecular oxygen, Surface aerators, Diffusers, Downflow contactors, U-Tubes, Sidestream mixing, Oxygen balance.

27 Abstract

Results of recent activities in river and stream aeration by artificial techniques are reviewed, and a rational engineering methodology is developed for future river and stream aeration projects.

The development of the methodology follows from a thorough review of the oxygen dynamics in rivers and streams and the capabilities of aeration systems within the present state of the art. The report shows how the theoretical work can be simplified considerably and applied to the solution of river and stream water quality problems. It is assumed that aeration would only be used as a "polishing" action after all identifiable waste sources have received at least secondary treatment.

The results indicate that, with careful consideration of site factors, artificial aeration can be applied successfully to raise dissolved oxygen to 5 ppm, using mechanical surface aerators, diffusers, downflow contactors, and sidestream mixing. However, since the transfer of oxygen from air into water is relatively inefficient above 5 ppm DO, the introduction of molecular oxygen through sidestream mixing, U-Tubes, and possibly diffusers should be considered, depending on the volume of water to be aerated. In cases where DO may be maintained at levels lower than 5 ppm, systems using air are competitive with molecular oxygen, depending on site conditions.

Abstractor	Institution
Donald S. Yeaple, Sr Stff Eng.	JBF Scientific Corporation

SEND TO: WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D. C. 20240

ENVIRONMENTAL PROTECTION AGENCY
Publications Distribution Section
Route 8, Box 116, Hwy. 70, West
Raleigh, North Carolina 27607

Official Business

CLEAN WATER

POSTAGE AND FEES PAID

ENVIRONMENTAL PROTECTION AGENCY