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STATE-OF-THE-ART REVIEW: AERATION

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PULP AND PAPER POLLUTION ABATEMENT

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FOREWORD

This report covers work done on a project sponsored by the Cooperative Pollution Abatement Research (CPAR) program of the federal government and the Canadian pulp and paper industry.

The program was first announced in August, 1970 by the Minister of Fisheries and Forestry and the Minister of Energy, Mines and Resources, to provide for the funding of research contracts aimed at reducing water pollution from Canadian pulp and paper operations. Various elements of these Departments were combined with the formation in 1971 of the Department of the Environment, which assumed the responsibility for the operation and funding of the program. In November, 1971 the Minister of the Environment announced that support of pulp and paper air pollution abatement research projects would be added in the next fiscal year. A five-year extension of the program to March 31, 1981 was authorized in 1975.

The program administration and Secretariat are provided by the Environmental Protection Service, Department of Fisheries and Environment. Development and guidance of the program are the responsibility of a joint government-industry committee known as the Committee on Pollution Abatement Research. The members represent Fisheries and Environment Canada, the Department of Industry, Trade and Commerce, the Department of Supply and Services, the Canadian Pulp and Paper Association, the Pulp and Paper Research Institute of Canada and the pulp and paper companies in eastern and western Canada.

The Committee plans the program, assesses priorities, reviews progress and advises on the allocation of funds and awarding of contracts for research proposals from pulp and paper companies and any other recognized research institutions. Based on the Committee's recommendations, the federal government enters into contract agreements with the organizations concerned for the conduct of approved projects.

In the fiscal year 1970/71 funds in an amount up to $500,000 were authorized to finance approved water pollution abatement research projects. From 1971/72 through 1975/76 up to $1,000,000 was made available each year for water pollution research, and beginning in 1972/73 a further $200,000 was provided annually for the support of air pollution research projects. During the fiscal year 1976/77 through 1980/81 up to $1,500,000 per year will be made available for the support of research falling within the priorities identified by the Committee.

SUMMARY

The present state of controversy and confusion in the literature over the various aspects of aeration demonstrate a need for a document to cover in detail the performance characteristics of aeration systems along with the theory necessary to evaluate trade name products. This report attempts to fulfill the requirement by describing at length the state of the art of aeration systems. The literature review contained in this report examines all major types of aeration equipment with special emphasis on comparing submerged and surface aeration. To do so, basic oxygen transfer and fluid mixing theories are developed together with detailed analyses of testing procedures. Aerated lagoons at 25 pulp and paper mills were reviewed to summarize operational experiences with various aeration systems. While this report in no way qualifies as an aeration system buyers guide, especially considering that no trade names are mentioned, it does discuss and compare the theoretical and practical advantages of generic types of aeration equipment.

Conclusions based on the literature review lack true originality, but serve to reiterate important concepts. The major conclusions of this report include:

1. An intensive review of the literature and an operational history survey fail to show one type of aeration system as being the most cost effective in all instances. Instead what can be said is that many aeration systems when properly applied will yield a feasible and economic source of dissolved oxygen and mixing.

2. Surface aeration continues to be an attractive method of aeration for shallow and medium depth lagoons (less than 20 feet deep). The controversy of high speed versus low speed will continue because of the difficulty in justifying the initial higher cost of low speed aerators. Although low speed units have more efficient clean water reaeration test oxygen transfer rates they have not clearly shown that they can remove more BOD_5 per nameplate HP. Both the literature and the field performance review confirm that proper installation of recent aerator models minimizes icing and maintenance problems.

3. Submerged aeration, particularly static air-gun tubes, can be competitive in medium depth basin applications and are superior in deep basin lagoons (more than 25 feet deep) by virtue of the fact that their oxygen transfer rate is enhanced and their mixing is not deteriorated by greater submergence. Surface aerators are unable to adequately mix deep basins even with draft tubes.

4. The clean water non steady-state reaeration test as described in the report is the only test which should be accepted as an equipment specification or as a means of comparing various aeration systems.

5. The dissolved oxygen saturation concentration to be used in the analysis of reaeration test data must be based on a flexible approach as described in the report. Reliance on saturation concentration tables for surface aeration and geometrically defined effective saturation depths for submerged aeration will not always yield a representative transfer efficiency.

6. Power density (aerator HP/unit of basin volume) effects are very important when considering aeration systems for aerated lagoons. More research is necessary to describe the extent of aeration efficiency reduction due to lower than "standard or tested" power densities.

7. The maintenance costs for aeration systems are directly tied to the level of preventative maintenance performed. A strong preventative maintenance program has a significant cost, but also high operating reliability. A low emphasis on preventative maintenance is associated with lower maintenance costs, but mechanical reliability is also low.

It is hoped that this report will provide relevant and interesting information to design engineers and purchasers of aeration equipment.

INTRODUCTION

INTRODUCTION

This project commenced with several objectives within the scope of work:

a. To provide a comprehensive document which would serve as a guide in the selection and operation of aeration systems.

b. To provide description, design and cost data on the various types of aeration systems available with specific reference to operation in cold weather climates.

c. To provide a comparison between surface and submerged aeration systems with specific reference to capital and operating costs, operation and maintenance and oxygen transfer efficiency.

It was intended that a state-of-the-art review would provide the pulp and paper industry with a concise one volume manual incorporating information that was currently dispersed throughout the literature.

Soon after beginning the literature review it became apparent that not only was vital information dispersed throughout years of journals and conference proceedings, but also the information was contradictory and confusing. Manufacturers of aeration equipment had been enveloped in a cloud of controversy dealing with proper aeration performance testing and data analysis procedures. Even at the time of this writing there is no industry regulation body and although standards have been proposed the manufacturers are under no obligation to follow them. Consequently, the scope of work was enlarged to encompass the basic theory of aeration, the proper test procedures for aeration system testing, and the proper data analysis procedures for performance capability reporting. In short, the information provided in this report should provide sufficient background to assist aeration system operators, process engineers, and purchasers of aeration equipment to be able to deal on an even ground with aeration manufacturers. For those people interested in testing the performance capabilities of an aeration device or sizing an aeration system for a biological treatment system the text will serve as a summary of, and introduction to, the vast storehouse of information available in the references.

The report is divided into two basic sections: first a relatively detailed account of aeration theory, testing procedures, data analysis, and aeration device operation; second, a general field review of operating aerated stabilization basins (aerated lagoons). The review of operating aeration systems in Canada provides information on the operating reliability, maintenance requirements, and susceptibility to icing problems of different aeration systems.

The report as a whole is relatively long and detailed. This was not done to impress or discourage the reader, but to provide him the information necessary for aeration system testing, evaluation, and sizing. The order of presentation of the material is from basic oxygen transfer and fluid mixing theory to evaluation of aeration systems. The only item which may appear misplaced is the summary of typical aeration performance characteristics found at the end of the aeration performance testing and evaluation section, and not at the end of the aeration device description section. This was done to give the reader a summary of the relative performance of all aeration devices prior to beginning the detailed description of each.

Although this report has been written to be a comprehensive document there are several things which it does not discuss. Since trade or brand names have not been used the report is not a buyers guide to aeration systems. It presents information solely on the basis of generic types i.e. high speed surface, low speed surface, static air-gun submerged, etc., so that after deciding what type of system would be feasible a valid comparison of tenders can follow. The mechanical service factor rating of aeration system components has not been discussed, not because it is not important, but because the scope of this report was process related and not mechanical design related.

The units used in the report reflect the commonly reported unit system in use today. Typically the results of laboratory analysis and most temperatures are stated in metric and degrees celsius, respectively. Distances, velocity, volume, weight, and work are normally still found in English units. Therefore, it was felt that the document would be most practically useful if it made use of the units systems currently employed i.e. a mixture of English and metric. So that the information will still be useful after Canada's metric conversion Appendix two has been provided to give commonly needed conversions.

In the initial stages of information gathering a questionnaire was sent to manufacturer's of aeration equipment requesting installation lists in Canada and northern U.S. and typical performance characteristics (including test conditions) of their products. Of the 49 letter/questionnaires sent only 20 replies were received and of those only 4 returned a completed questionnaire.

Further communications revealed that the current state of confusion in aeration today i.e. no officially recognized testing procedure or data analysis method, places the manufacturer in an awkward position when he is asked to report test results. Therefore, many manufacturers choose not to participate in a "numbers game" and to maintain total silence. Hopefully this report will help to confirm and clarify the present state of contradiction and confusion, and to provide information needed to assist process designers and purchasers in evaluating the true capabilities of aeration equipment.

LITERATURE REVIEW

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SUMMARY

A B S T R A C T

This report presents an in-depth review of the state-of-the-art of aeration. The literature review begins by discussing the fundamental theories of oxygen transfer to water and of fluid mixing by aeration devices. Environmental and fluid properties which affect the rate of oxygen transfer are analyzed. Aeration system testing procedures and data handling techniques are critically reviewed. Finally, the operation and maintenance characteristics of the major types of aeration systems are described.

A field review of operating aeration systems in aerated stabilization basins in Canada and the northern U.S. is reported. Operation and maintenance data for 25 surveyed facilities are summarized.

Major conclusions and literature review findings are provided to summarize important aspects of oxygen transfer efficiency, aerator testing, operation and maintenance requirements and icing problems.

RÉSUMÉ

Le présent rapport est un exposé détaillé de l'état actuel des techniques d'aération. L'étude bibliographique commence par la discussion des théories de base du transfert de l'oxygène dans l'eau et du mélange des fluides par les dispositifs d'aération. Les propriétés du milieu et des fluides qui influent sur la vitesse du transfert de l'oxygène sont analysées. Les méthodes d'essai des dispositifs d'aération et les techniques de traitement des données font l'objet d'une analyse critique. Enfin, les caractéristiques de fonctionnement et d'entretien des principaux types de dispositifs sont exposées.

Le rapport fait le compte rendu de l'étude sur place des dispositifs d'aération utilisés au Canada et dans le nord des États-Unis dans les bassins de stabilisation. Il résume les données de fonctionnement et d'entretien de 25 installations.

Les conclusions principales et les résultats de l'étude bibliographique sont fournis afin de résumer les principaux aspects de l'efficacité du transfert de l'oxygène, de l'essai des dispositifs d'aération, et des conditions de fonctionnement et d'exploitation ainsi que des problèmes que cause le givrage.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

FIELD PERFORMANCE REVIEW

LITERATURE REVIEW

The literature review section of this report is a condensation of technical journals, proceedings of conferences and seminars, and textbooks. Where deemed necessary additional explanatory material has been given and several examples have been provided. The purpose of the literature review is several-fold: it is intended to provide the reader with a good foundation of aeration and mixing theory; describe the many interferences in the gas-to-liquid transfer process as applied to biological treatment aeration; familiarize the reader with the different testing and data handling methods, along with their limitations; and finally, describe the operation of the various oxygenation devices. The text is not for the casual reader; it is intended to provide all the technical information a purchaser of aeration equipment need know and is therefore necessarily detailed and theoretical.

Conclusions from just a review of the literature are difficult and often mean little unless correlated by research data. Therefore, this literature review is intended to enlighten the reader on both sides of the important issues and where possible to highlight recommended procedures and practices.

1.0.0 MASS TRANSFER THEORY

Oxygen in a gaseous state disperses itself through a body of liquid by the process of diffusion which tends to produce a stable state of uniform concentration. Mass transfer by diffusion occurs between the gaseous phase and the liquid phase when a driving force is created by a departure from equilibrium. This driving force is a partial pressure gradient in the gas phase and a concentration gradient in the liquid phase. The rate of mass transfer of a dissolved gas in a liquid is dependent on the characteristics of the gas and the liquid, the temperature, the concentration gradient and the cross-sectional area through which diffusion occurs.

Numerous theories have been put forward to interpret the mass transfer of a sparingly soluble gas such as oxygen to water. However, all these theories are approximations of the physical process as none completely accounts for all observed phenomenon. Of the three to be discussed, the first, the Whitman two-film theory [1,2], is the most widely accepted and used in commercial aeration analysis today.

The following are theories regarding mass transfer of a sparingly soluble gas such as oxygen in water:

1.1.0 FILM THEORY

The film theory is based on a model where two films exist at the gas/liquid interface. The resistance to gaseous molecules transferring from the bulk-air to the bulk-liquid state occurs in the films. In considering the transfer of gas molecules from the air to the liquid, soluble gasses encounter major resistance from the gaseous film and slightly soluble gasses, such as oxygen, find the major resistance from the liquid film. Gasses of intermediate solubility find significant resistance from both films [3].

This theory first proposed by Whitman [1,2] pictures a stagnant film of thickness Z at the surface of the liquid next to the gas. While the rest of the liquid is kept uniform in composition by agitation, the concentration in the film falls from C_s at the gas interface to C at the liquid surface (there is no convection in the film) and the dissolved gas crosses it by molecular diffusion alone. Mathematically

$$\frac{dm}{dt} = D\,(C_s - C)\ /\ Z = K_L(C_s - C)\ldots\ldots\ldots(1)$$

where $\frac{dm}{dt}$ is the average rate of solute transferred/unit time, C_s is the saturation concentration of the dissolved gas, and C is the average bulk liquid concentration. The liquid film coefficient K_L is defined as the diffusivity D divided by the hypothetical film thickness Z and in general K_L can be related to resistance from the liquid film, interface renewal and turbulence. In practice it is not possible to measure K_L directly, so K_La the overall mass transfer coefficient is measured. K_La is the product of the liquid film coefficient, K_L, and the interfacial surface area generated per unit of volume of liquid.

This theory is not very realistic as it assumes a layer of uniform thickness. Nevertheless, this theory incorporates an essential feature in the real system, namely that the gas must get into the liquid by dissolution and molecular diffusion before it can be transported by convection. The Whitman two film theory, despite its deficiencies, is the theory most accepted and used in commercial aeration analysis today.

1.2.0 STILL - SURFACE THEORY

Instead of the discontinuity implicit in the film theory, there may be a progressive transition from purely molecular transport to predominantly convective transport as the distance from the gas interface increases. King [4] has considered this possibility and assumed that transport is the combined result of molecular and eddy diffusivity. He showed that the transfer coefficient may be proportional to any power of diffusivity between 0 and 1 and not necessarily 1 as given by the film model.

He also provides an expression for K_L which contains two parameters related to the hydrodynamic conditions, whereas the film model uses only one i.e. Z. Some variations of this model have been suggested by Andrew [5] and Danckwerts [6].

1.3.0 SURFACE - RENEWAL THEORIES

These theories assume that during time intervals elements of liquid at the gas interface are replaced from the interior of the volume which is assumed to have the composition of the bulk average. The replacement of liquid at the surface is caused by turbulent motion of the body of the liquid. While the element of liquid is at the surface and is exposed to the gas, it absorbs as though it were quiescent and infinitely deep.

Different theories have been suggested depending upon the different surface age distribution function of the elements. For example Higbie [7], who originally proposed this theory, assumes that every element of surface is exposed to the gas for the same length of time 't' before being replaced by liquid of bulk composition. The adsorption rate may be determined by solving the following unsteady state equation:

$$\frac{dc}{dt} = D \frac{d^2c}{dx^2} \quad \ldots\ldots (2)$$

The solution of equation (2) may be obtained by Laplace transformation to give

$$K_L = 2\sqrt{\frac{D}{\pi t}} \quad ....\ (3)$$

Danckwerts [6] modified Higbie's assumption regarding surface renewal and supposed instead that the chance of an element of surface being replaced with fresh liquid is independent of the length of the time for which it has been exposed. This leads to a stationary distribution of surface ages in which the fraction of surface which at any given instant has been exposed to the gas for times between t and t + dt is $s\,e^{-st}\,dt$, where 's' is the fraction of the area of the surface which is replaced with fresh liquid in unit time't'. With this new assumption the average rate of mass transfer was shown to be:

$$\frac{dm}{dt} = (C_s - C)\sqrt{D\,s} \quad ....(4)$$

Accordingly $K_L = \sqrt{D\,s}$ ....(5)

1.4.0 MASS TRANSFER COEFFICIENT

Since 'K_L', the liquid film coefficient, and 'a', the interfacial surface area generated per unit of volume of liquid, are not determinable separately, in evaluating the performance of commercial aeration equipment it has been a general practice to consider the aeration process in terms of the overall oxygen transfer coefficient K_La. A number of correlations have been proposed to estimate K_La and these are summarized in Table 1.1.

TABLE 1.1

OVERALL OXYGEN TRANSFER COEFFICIENT CORRELATIONS

Equation	Reference	Remarks
$K_La = \frac{dC}{dt} \frac{1}{(C_s-C)}$	Eckenfelder [8,9,10]	Basic equation resulting from Lewis & Whitman [1,2] two-film theory.
$K_La = \frac{r}{C_{sw}-C}$	McWhirter [11]	Steady-State equation for K_La determination when oxygen demand is present.
$K_La = \frac{\ln\left(\frac{C_s-C_1}{C_s-C_2}\right)}{t_2-t_1}$	McWhirter [11]	Unsteady-State equation from clean water reaeration test.
$K_La = \frac{Q\ (C_d-C_u)}{(C_s-C)}$	McWhirter [11]	Steady-State relationship for aeration of stream flows.
$K_La = \frac{(D_LU)^{\frac{1}{2}}}{H^{3/2}}$	O'Connor and Dobbins [12]	Reaeration correlation for natural streams.
$K_La = \frac{KG_s^{(1-n)}H^{2/3}}{V_d}$	Eckenfelder [13]	General relationship for oxygen transfer from air-diffusion systems.
$K_La = 7.8 \times 10^{-3}\ (U_g)^{0.67}(P/V)^{0.95}$	Cooper, et. al. [14]	Empirical correlation for a bench scale vaned disc agitator.
$K_La = \frac{(K')(P/V)^{0.95}(V_s)^{0.45}}{(N_r)^{0.5}(D_L)^{0.52}}$	Richards [15]	Empirical correlation for a bench scale vaned disc agitator.
$K_La = 1.1\ (-V_s)^{0.67}(N_r)^2(L)^{4/3}$	Yoshida et. al. [16]	Empirical relation using turbine impellers.

KEY TO VARIABLES IN TABLE 1.1

K_La = Overall oxygen transfer coefficient - The product of K_L, the liquid film coefficient, and a, the interfacial area of air bubbles in the water per unit volume of liquid, hrs^{-1}

$\frac{dC}{dt}$ = Rate of oxygen transfer, change of dissolved oxygen concentration with respect to time

C_s = Dissolved oxygen saturation concentration, mg/l

C = Dissolved oxygen concentration of the liquid entering the aerator (operating or at a given time), mg/l

C_{sw} = Dissolved oxygen saturation concentration for wastewater mixed liquor at operating conditions, mg/l

r = Oxygen uptake rate or demand, mg/l-hr

$C_{1,2}$ = Dissolved oxygen concentration at times, t_1 and t_2, during non steady-state reaeration test, mg/l

Q = Stream flowrate under aeration, lbs/hr

C_u = Dissolved oxygen concentration of upstream or influent streamflow, mg/l

C_d = Dissolved oxygen concentration of downstream or effluent streamflow, mg/l (Note: For completely mixed tanks C_d = C)

D_L = Diffusion coefficient

U = Average velocity of streamflow, ft/sec

H = Average stream or tank water depth, ft

K = Constant

G_s = Air flow rate per diffuser, SCFM

(1-n)= Gas rate exponent characteristic of diffuser type

V_d = Basin volume per diffuser, ft^3

U_g = Superficial gas velocity, ft/sec

P = Power consumption

V = Basin volume, ft^3

K' = Constant

N_r = Impeller speed, rev/min

D_L = Impeller diameter, ft

L = Characteristic length of turbine, ft.

The equations in Table 1.1 need a great deal of discussion which will be provided in this and later sections. Briefly, the first five equations are used frequently in full scale aeration analysis and prediction while the last four are general and empirical relationships derived in laboratory research.

The mass transfer data shown in literature is in general based on the Whitman two film theory and the corresponding general expression of oxygen transfer, equation (6).

$$\frac{dc}{dt} = K_L a \, (C_{se} - C) \quad \ldots\ldots\ldots \quad (6)$$

where: $\frac{dc}{dt}$ = Rate of oxygen transfer, change of oxygen concentration (c) with respect to time (t), mg/l/hr.

K_L = The liquid film coefficient.

a = A/V, the interfacial surface area of the air (A) through which diffusion can occur generated by the particular aeration system per unit volume (V) of water.

$K_L a$ = Overall oxygen transfer coefficient, hrs^{-1}.

C_{se} = Effective saturation value of dissolved oxygen concentration at given temperature and atmospheric pressure, mg/l.

C = Average concentration of dissolved oxygen in liquid, mg/l.

NOTE: The literature is full of various systems for describing the saturation concentration. The following define and describe the system that will be employed in this report. While the writer understands that it is bulky for equation writing, it offers a precise way to describe the saturation concentration.

C = Average bulk liquid or sampling point concentration of dissolved oxygen, mg/l.

C_s = Abbreviation for saturation concentration of dissolved oxygen in water.

C_{se} = Effective saturation concentration of dissolved oxygen in the test or field liquid at the ambient atmosphere, hydrosatic pressure and water temperature, mg/l.

C_{ss} = Standard surface saturation concentration of dissolved oxygen in pure water at 760 mmHg (14.7 psia) atmospheric pressure and 20°C water temperature, 9.2 mg/l.

$C_{ss(t,p)}$ = "Book" or standard surface value of the dissolved oxygen saturation concentration for pure water at the given temperature (t) and/or atmospheric pressure (p), mg/l.

C_{sm} = Dissolved oxygen saturation concentration at the effective mid-depth of the water under aeration for an atmospheric pressure of 760 mmHg (14.7 psia) and a water temperature of 20°C. The effective mid-depth is used as a general term here to describe a depth somewhere between the surface and the air outlet, mg/l.

$C_{sm(t,p)}$ = Dissolved oxygen saturation concentration at the effective mid-depth of the water under aeration at given water temperature (t) and/or atmospheric pressure (p), mg/l.

C_{sb} = Dissolved oxygen saturation concentration at the bottom of the water being aerated with the atmospheric pressure over the liquid of 760 mmHg (14.7 psia) and the water temperature at 20°C. Adding (t,p) adjusts the value for water temperatures and/or atmospheric pressures of other than standard, mg/l.

C_{sw} = Dissolved oxygen saturation concentration for a wastewater or mixed liquor. The notation s (surface), m (mid-depth), and b (bottom) would be added as necessary, i.e. C_{sws}, to describe where in the tank the value applies and (t,p) will adjust the value for waste temperatures and/or atmospheric pressures of other than standard, mg/l.

Finally the total transfer of oxygen into water,

becomes $R = K_La\ (C_{se} - C)\ W$ ....(7)

R = Overall mass transfer coefficient, lbs oxygen/hr/mg/l driving force.

where W = Weight of water, millions of pounds.

To introduce efficiency, pounds of O_2 supplied per unit of power, equation (7) is divided by the horsepower (HP) consumed by the aeration system, which yields:

$$N_o = \frac{K_La\ (C_{se} - C)\ W}{HP} \quad \text{.......... (8)}$$

where N_o = Standard conditions oxygenation capacity of the aeration system, lbs O_2/hp-hr.

Of course this equation is only applicable at standard conditions i.e. 1 atmosphere pressure, 20°C, and 'clean' water. Interferences and correction factors are covered in Section 3.0.0.

2.0.0 THEORY OF FLUID MIXING BY AERATION

In order for an aeration system to be effective it must not only transfer the required amounts of dissolved oxygen to the water in the aeration basin, but it must also disperse the oxygen throughout the basin and provide sufficient turbulence to maintain solids in suspension. Aeration systems differ in the method in which mixing energy is applied. Mechanical aerators are point sources of very intense energy that must penetrate the basin volume. Submerged compressed air systems vary from multiple point sources of turbulence as typified by the static air-gun units, to rather uniform mixing inputs in the diffused air units which occupy a large portion of the basin bottom. However, no matter what system is employed the mixing functions it must provide include:

(a) the mixing of the basin biomass contents with the incoming wastewater,

(b) the bulk liquid mixing of the basin contents to the extent of "complete mixing" desired,

(c) transport of oxygenated water away from the aerator unit and the cycling back of deoxygenated water,

(d) mixing turbulence (large scale) for the suspension of biological solids, and

(e) mixing turbulence (small scale) to promote the transfer of dissolved oxygen and organics into the bacterial cell and to carry bacterial wastes away from the cell.

The first four mixing functions can be accomplished by large scale eddy turbulence, macromixing [17,18]. The fifth mixing function requires mixing turbulence that is characterized by eddies smaller than the bacterial floc particles, so called, micromixing [17,18,19].

The controversy over the macromixing abilities of the various types of aeration equipment is largely centered around how much mixing input is required and which system can provide it most efficiently.

Kalinske [20] presented a thorough analysis on the fundamental principles of fluid mechanics as they apply to mixing. The analysis of mixing energy reveals that large scale eddy turbulence which is important in the diffusion process is relatively unimportant so far as energy dissipation is concerned; it is the viscosity of liquid and the small scale eddy turbulence which are the controlling factors. Fluids rapidly dissipate energy into heat when small scale, intense eddies are produced. Orlob [21] proposed the following equation for relating the rate of energy dissipation to eddy turbulence:

$$D_t = KE^{1/3}L^{4/3} \quad \text{.............(9)}$$

where D_t = Eddy diffusion coefficient

E = Rate of energy dissipation per unit of mass.

L = Scale of eddies participating in turbulence diffusion.

K = Constant of proportionality.

This equation suggests the following: Turbulence, diffusion or mixing can be increased by adding energy to the fluid mass in the form of large scale eddies; if small scale eddies are produced rapid energy dissipation into heat will occur.

Because it is normally impractical and uneconomical to fill a basin with mixing devices, turbulence and mixing energy is provided by point sources. These point sources provide a localized origin of relatively high intensity turbulence which is directed to penetrate the mass of liquid. The intensity and scale of turbulence produced in the volume adjacent to the unit will be proportional to the velocity of the stream and its relative size.

2.1.0 MECHANICAL SURFACE AERATION

The pumpage and issuing stream of a mechanical surface aerator may be analyzed using the principles of submerged jet diffusion [22]. The characteristics of streams issuing into a mass of fluid were found by Albertson and Hunter [22] to be mathematically described by

$$\frac{V_x}{V_o} = 2.28\left(\frac{B_o}{x}\right)^{0.5} \quad \ldots\ldots\ldots\ldots\ldots(10)$$

where V_x = Centerline velocity at distance x downstream, ft/sec.

V_o = Initial velocity of issuing stream, ft/sec.

B_o = Height of issuing two-dimensional stream, ft.

x = Distance downstream, ft.

Since the flow, Q_o, per unit width of stream equals V_oB_o, equation (10) may be written as:

$$V_x = 2.28\left(\frac{V_oQ_o}{x}\right)^{0.5} \quad \ldots\ldots\ldots\ldots\ldots(11)$$

The power, HP, that must be applied to the liquid stream can be written as:

$$HP = KQ_oV_o^{\,2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

where K = Proportionality constant.

Equations (11) and (12) have great significance when applied to mechanical aerators. They predict that if one doubles V_o without changing Q_o (by reducing B_o) the downstream velocity V_x increases by 1.4 times, but requires a power increase of 4 times. If, however, one doubles Q_o without changing V_o (by increasing B_o) V_x is again increased by 1.4 times, but the power is only increased by 2 times. Thus it is apparent that a large power advantage is gained by increasing flow and decreasing velocity when mixing turbulence is desired. Also, by increasing the size of the issuing stream larger scale eddies will be produced which according to equation (9) increases diffusivity without generating great amounts of heat.

This analysis shows that for mixing, a great power advantage exists when a slow moving impeller which issues a huge volume of water is employed. However, there is a minimum acceptable velocity which is dictated by the solids which are to be kept in suspension. For biological solids the range of 0.4 - 0.5 ft/sec has been suggested as the minimum velocity for suspending biological solids in activated sludge [17,23,24]. Unfortunately, specifying a minimum velocity does not necessarily provide adequate mixing turbulence and many authorities suggest a minimum power density in terms of horsepower per unit volume. See Section 5.2.4 for suggested power densities.

2.2.0 MIXING WITH SUBMERGED AIR

In addition to providing dissolved oxygen to the mixed liquor the bubbling of air or other gases into the liquid provides an uplift force and mixes the liquid volume. This mixing occurs whether the air is introduced through small openings or diffusers without confinement or through a submerged riser pipe; however, the efficiency of the pumping action is enhanced by confining the bubble rise within a confined tube as it provides a better "grip" on the fluid.

The power required to supply air to the basin diffusers is given by the adiabatic equation:

$$HP = \frac{WRT_1}{550ne}\left[\left(\frac{P_2}{P_1}\right)^n - 1\right] \quad (13)$$

where HP = Brake Horsepower.

W = Weight of air flow, lbs/sec.

R = Gas constant, 53.5.

T_1 = Absolute inlet temperature, °R.

P_1 = Absolute inlet pressure, psia.

P_2 = Absolute outlet pressure, psia.

n = $(K-1)/K$ = .283 for air.

K = 1.395 for air.

e = Efficiency of the blower and motor.

If a standard condition of 68°F (496 °R) and motor-blower efficiency of 70% is assumed, equation (13) can be simplified to

$$HP = 0.30\, Q_1 \left[\left(\frac{P_2}{P_1}\right)^{0.283} - 1\right] \quad (14)$$

where Q_1 = Inlet air flow, SCFM.

The pumping ability for air-lifts can be analyzed by using the head relation or the energy equation as a starting point [25,26,27]. Kalinske [20] suggests the following analysis based on the energy equation. In the energy relation the assumption is made that the energy in the compressed gas will be used up in accelerating the liquid to a velocity, V_w, and overcoming any frictional resistances. The derived equation after some simplification becomes:

$$32\left(\frac{Q_1}{Q_w}\right)\ln\left(\frac{P'_2}{P_1}\right) = C\ \frac{V_w^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

where Q_w = Liquid pumped, ft^3/sec

Q_1 = Inlet air flow, SCFM

P'_2 = Absolute pressure of gas as it enters the liquid (accounts for frictional losses from compressor to liquid, but these losses are normally small and have been neglected in this analysis-yielding $P'_2 = P_2$ as in equations (16) and (17))

C = Coefficient, greater than unity. For example, a simple tube suspended over a gas outlet would have a value of approximately 1.5

V_w = Mean liquid velocity, ft/sec.

By combining equations (14) and (15) and rearranging, a relation is obtained which gives the liquid pumpage in terms of power to compress the gas, and the gas pressure as shown in equation (16).

$$Q_w = \frac{115\ HP}{YZ\ H_w} \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

where $Y = \left(\frac{P_2}{P_1}\right)^{0.183} - 1$

$Z = C/\ln\left(\frac{P_2}{P_1}\right)$

$H_w = V_w^2/2g$

$g = 32.2\ ft/sec^2$

2.3.0 COMPARISON OF MECHANICAL MIXING IMPELLER AND AIR-LIFT PUMPS

Assuming a basin 15 ft deep is to be mixed what are the relative power requirements for a mechanical impeller and an air-lift pump? Using atmospheric pressure of 14.7 lbs/in^2, taking C = 1.5 and assuming that V_w has a value of 6 ft/sec., equation (16) yields:

$$Q_w = 435 \text{ BHP}$$

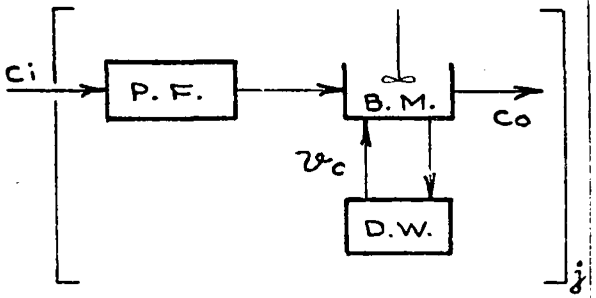
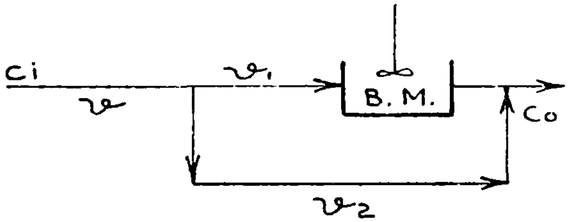
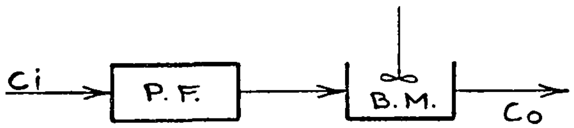
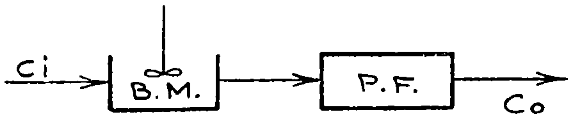
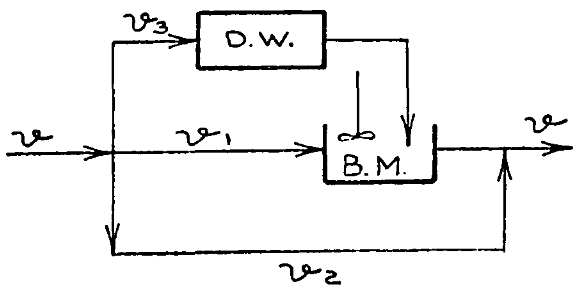
Rewriting equation (12) and using a turbine tip speed of 4 ft/sec and a $K = 0.376 \times 10^{-4}$ yield:

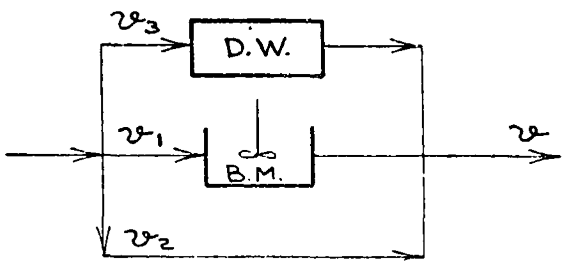
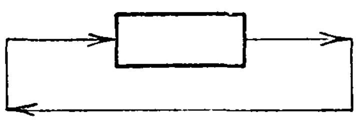
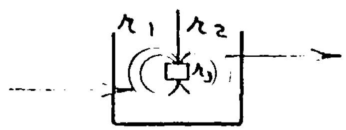
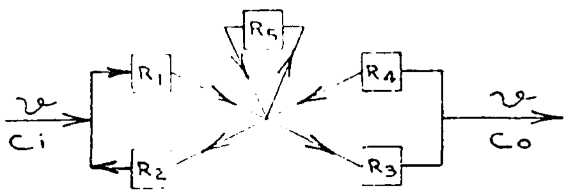
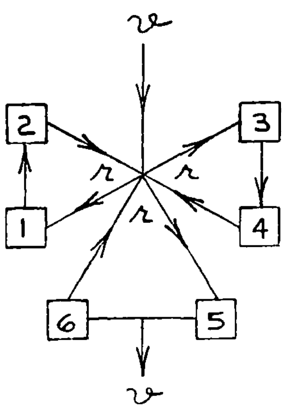
$$Q_w = 1700 \text{ BHP}$$

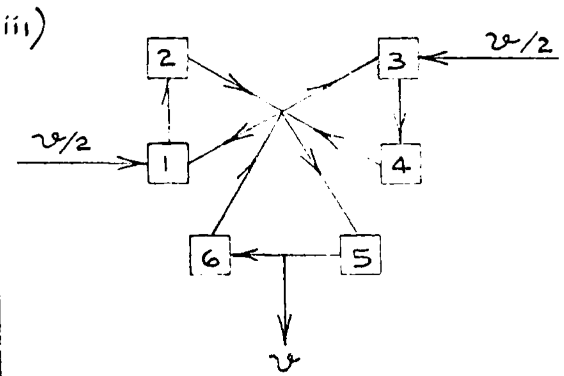
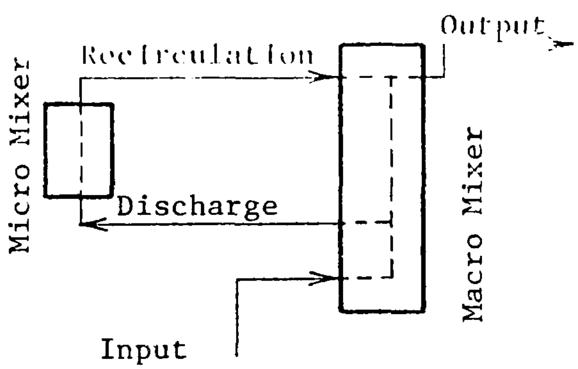
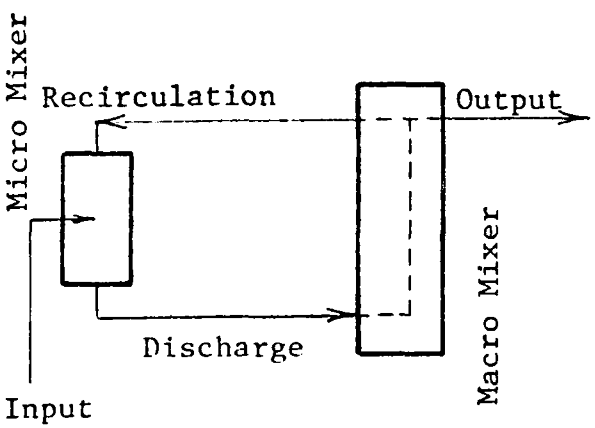
Essentially this finding confirms that the most efficient device for creating large scale turbulence is a slow moving impeller. This finding is not revolutionary, in fact, it is merely consistent with the mixing practices in the chemical and food processing industry and coagulant/floculation basins in wastewater treatment. However, it should be noted that large scale eddies do not promote efficient oxygen transfer and therefore aeration devices must create some small scale turbulence. It follows that aeration systems which must supply dissolved oxygen and mixing turbulence from relatively isolated sources must be a compromise between mixers and oxygenators.

In aeration theory it is assumed that perfect mixing exists within the volume of liquid undergoing aeration. In actual practice real aeration tends to deviate from this ideal condition of perfect mixing and dissolved oxygen gradients exist as a consequence of transporting dissolved oxygen by bulk pumping to significant distances from the point source of transfer. A number of mathematical models have been proposed to simulate the mixing in an actual aeration tank, and these are summarized in Table 2.1.

TABLE 2.1 - MIXING MODEL THEORIES

	Model Representation	Defining Equation	Method Used	Reference
1.	 P.F. = Plug Flow B.M. = Back Mix D.W. = Dead Water	$\frac{C_o}{C_i} = \frac{e^{-K\phi_P}}{K_1\phi_B + 1 + \frac{\nu_c}{\nu} - \frac{1}{\left(1+\frac{\nu}{\nu_c}\right)\phi_D K_1}}$	Tracer curve with different j values are matched with experimental C-curve.	Adler & Havorka [28]
2.		$\ln\frac{C_o}{C_i} = \ln\frac{\nu_2}{\nu} - \frac{\nu_1(t)}{(\phi_B)V}$	Material balance for a differential time dt, and solution of resulting differential equation	Cholette and Cloutier [29] Levenspiel [30] Cholette, Blachet and Cloutier [31]
3.		$\ln\frac{C_o}{C_i} = \frac{-1}{\phi_B}\left[\frac{\nu t}{V} - (1-\phi_B)\right]$	Material balance for a differential time dt, and solution of resulting differential equation	Cholette and Cloutier [29] Levenspiel [30] Cholette, Blanchet and Cloutier [31]
4.		i) $\frac{C_o}{C_i} = \frac{\nu_3}{\nu} + \frac{\nu_1}{\nu}e^{-(\nu_3+\nu_1)t/\phi_B V}$ ii) $\frac{C_o}{C_i} = \left[\frac{\nu_1}{\nu} + \frac{\nu_3}{\nu}e^{\left(\frac{\nu_1+\nu_3}{\nu}\right)(1-\phi_B)\frac{\nu}{\nu_3\phi_B}}\right]$ $\times\left[e^{-(\nu_3+\nu_1)t/\phi_B V}\right]$	i) $0 < t < (1-\phi_B)V/\nu_3$ ii) $t > (1-\phi_B)V/\nu_3$	Cholette and Cloutier [29]

	Model Representation	Defining Equation	Method Used	Reference
5.		i) $\frac{C_o}{C_i} = \frac{v_3}{v} + \frac{v_1}{v} e^{-v_1 t/\phi_B V}$ ii) $\frac{C_o}{C_i} = \frac{v_1}{v} e^{-v_1 t/\phi_B V}$	i) $0 < t < (1-\phi_B) V/v_3$ ii) $t > (1-\phi_B) V/v_3$	Cholette and Cloutier [29]
6.		$\frac{C}{C_\infty} = \sqrt{\frac{Bo}{4\pi\theta}} \sum_{j=1}^{\infty} \exp\left[-\frac{Bo}{4\theta}(j-\theta)^2\right]$	Solution of a differential equation for axial dispersion in a tube with infinite recirculation	Holmes, Voncken and Dekker [32] Voncken, Holmes and Den Hartog [33]
7.	i)   Three loops and 5 mixing stages	$C_{(b)} = \frac{v}{(r+v)\left[1+(p\, t_c/n)\right]^{n}}$	Material balance on various loops and solution of resulting equation by Laplace Transformation	Van de Vusse [34] Wen and Chung [35] Gibilaro, Kropholler and Spikins [36]
	ii)  Three loop six stage model with inflow direct to impeller	$s_j(n+1) = \sum_{i=1}^{N} s_i(n)\, p_{ij}$ $s(n+1) = s(n)\, p$	Probability method is used considering mixing stages to be tanks in series with recirculation	

	Model Representation	Defining Equation	Method Used	Reference
	iii)  Three loop, six stages with inflow divided equally between upper two loops	$s_j(n+1) = \sum_{i=1}^{N} s_i(n) p_{ij}$ $s(n+1) = s(n) p$	Probability method is used considering mixing stages to be tanks in series with recirculation	
8.		$\frac{c_q}{c_i} = \int_0^\infty \frac{1}{c_Q}\left(c_q(t)_{batch}\right)E(t)\,dt$	Material balance assuming macro mixed feed	Manning, Wolf and Keairns [37], and Keairns and Manning [38]
		$\frac{c_o}{c_Q} = \int_0^\infty \frac{1}{c_Q}\left(c_q(t)_{batch}\right)E(t)\,dt$	Material balance assuming micro mixed feed	

PARAMETER LISTING FOR TABLE 2.1

C_i = Inlet concentration

C_o = Outlet concentration

v = Flow rate

v_c = Cross flow rate

K = Constant

ϕ_P = Fraction of Total Volume in Plug Flow Zone

ϕ_B = Fraction of Total Volume in Perfectly Mixed Zone

ϕ_D = Fraction of Total Volume in Dead Water Zone

K_1 = $\frac{v_c (V) L}{v}$

V = Volume of tank

L = Characteristic length

$v_{1,2,3}$ = Fractional flow rates

t = time (duration)

C = Concentration at distance x=jL in tube with recirculation

C_∞ = Concentration at infinite time in tube with recirculation

B_o = Bodenstein number = $L\bar{v}/D_1$ (Dimensionless)

$\bar{v}$ = Average velocity

D_1 = Dispersion coefficient (L^2/time)

θ = Dimensionless time = t/t_c

t_c = Circulation time

C(b) = Transfer function

λ = Circulation rate

n = Number of mixing stages

p = Laplace parameter

N = Total number of states

$p_i(n)$ = State probability, defined as the probability that the system will be in the state i after n transitions from a given starting point.

p_{ij} = Probability of a transition from state i to state j

$s(n)$ = State probability vector : a line vector composed of elements $p_i(n)$

p = Probability

C_q = Impeller discharge concentration when it leaves the mixing vessel

C_Q = Impeller discharge concentration when it leaves the impeller

$E(t)$ = Residence time distribution function

3.0.0 OXYGEN TRANSFER CORRECTION FACTORS AND INTERFERENCES

At the end of Section 1.4.0 equation (8) was introduced as describing the oxygenation capacity of an aeration system. However, the oxygen transfer process is affected by many environmental and fluid variables including:

a. Atmospheric pressure
b. Partial pressure of oxygen
c. Liquid temperature
d. Presence of dissolved solids
e. Presence of suspended solids
f. Presence of surface active agents
g. Fluid turbulence
h. Basin geometry and power densities

All of these variables influence the overall oxygen transfer coefficient, K_La, and the standard oxygen transfer efficiency, N_o. Since it is desirable to have K_La and N_o as standard values, comparable to other devices tested under varying conditions, the environmental and fluid variables have been resolved into several correction factors. The effect of the first three variables can be analyzed separately, but the last five are grouped into overall factors which must be estimated or determined from testing. The following section discusses the influences of and corrections for the 8 variables listed above.

3.1.0 CHANGES IN ATMOSPHERIC PRESSURE AND THE PARTIAL PRESSURE OF OXYGEN

Changes in elevation directly alters barometric pressure. Variations in barometric pressure change the partial pressure of oxygen which alters the saturation value of dissolved oxygen in water, the driving force in aeration. The dissolved oxygen saturation concentration in distilled water is directly proportional to atmospheric pressure in accordance to Henry's law and this relationship is shown in equation form in reference [39],

$$C_{ss(t,p)} = \frac{(P-p) \times 0.678}{35+T} \quad \text{..................(17)}$$

where $C_{ss(t,p)}$ = Dissolved oxygen saturation concentration at the water surface for a given atmospheric pressure and water temperature, mg/l

P = Barometric pressure, mm of Hg

p = Saturated water vapor pressure, mm of Hg

T = Water temperature, °C where $0 \leq T \leq 30°C$.

$$C_{ss(t,p)} = \frac{(P-p) \times 0.827}{49+T} \quad \text{...................(18)}$$

where $30 \leq T \leq 50°C$.

Gameson and Robertson [40] have reported the following equation to apply to mixtures of pure water and sea water:

$$C_{ss(t)} \text{ (760 mmHg)} = \frac{475 - 2.65\ S}{33.5+T} \quad \text{..............(19)}$$

where S = Salinity, parts per thousand (ppt). May also be interpreted as total dissolved solids (ppt) in wastewater with reasonable accuracy [40].

T = Temperature, °C.

Solubility of oxygen in water Tables are available. To convert the saturation value at any temperature at sea level to a given barometric pressure the following equation is used:

$$C_{ss(p)} = C_{ss} \text{ (sea level) } \frac{P-p}{760-p} \quad \text{...............(20)}$$

Table 3.1 shows saturated water vapor pressures at various temperatures [13].

TABLE 3.1

SATURATED WATER VAPOR PRESSURE AT GIVEN WATER TEMPERATURES

Water Temperature (°C)	Saturated Water Vapor Pressure	
	mmHg	psia
0	5	0.097
5	7	0.135
10	9	0.174
15	13	0.251
20	18	0.348
25	24	0.464
30	32	0.619

NOTE: In equation (20) for elevations less than 1000 m (approx. 3000 ft) and temperatures below 25°C, p may be ignored without a significant loss in accuracy.

When the K_La of an aeration system is known for 0°C, the effects of elevation, temperature, and basin dissolved oxygen concentration changes can be calculated. Hunter and Ward [41] reported that these variables are related by equation (21) which is used to calculate the relative aeration efficiency, E, of an aeration system:

$$E = \frac{K_La \text{ (at } T°C)}{K_La(0°C)} \times \frac{(PC_{ss(T)} - C)}{14.652} \quad \ldots\ldots\ldots\ldots\ldots(21)$$

where P = Atmospheric pressure at a given elevation; atmospheres.

The authors [41] also derived an equation to calculate P, in atms., for a given elevation:

$$P = \left(1 - \frac{1.98 \times 10^{-3} A}{T_A}\right)^{5.29} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(22)$$

where A = Altitude of given elevation, feet

T_A = Air temperature at altitude A, °K

The above analysis applies primarily to surface aeration where the source of oxygen is the open atmosphere. Submerged aeration systems discharge air or oxygen enriched gas under the liquid surface. The hydrostatic pressure of the liquid and possibly positive pressure over the liquid (enclosed + pressurized aeration tanks as with oxygen activated sludge) both serve to increase the oxygen saturation concentration and thereby increase the driving force for oxygen transfer. The effect of hydrostatic pressure on the oxygen transfer equation will be covered in Section 4.1.1, 5.1.0, and Appendix 1.

3.2.0 EFFECT OF TEMPERATURE

The transfer of oxygen, a process dependent upon the resistance in the liquid film, is affected by changes in water temperature due to changes in water viscosity and diffusivity. The literature suggests a large number of recommended correction factors based on the exponential equations,

$$K_La(T) = K_La(20°C)\,(\theta)^{T-20} \quad (23)$$

and

$$K_La(20°C) = K_La(T)\,(\theta)^{20-T} \quad (24)$$

where $K_La(T)$ = Overall oxygen transfer coefficient at any given temperature (T °C)

$K_La(20°C)$ = Standard overall oxygen transfer coefficient for water at 20°C

θ = Temperature coefficient

Equation (23) is used to extrapolate standard K_La values to other temperatures, especially to field conditions, and equation (24) is used to standardize transfer values.

The temperature coefficient θ has been reported to vary from 1.016 to 1.047 [42,43,44] although recent literature supports a value near 1.024 [10,45,46,47, 48]. In an independent regression analysis of 26 data points generated by the testing of a single surface aerator Landberg et.al. [49] found $\theta = 1.012$ to yield a best fit for water temperatures between 5°C - 25°C. Gloppen and Roeber [50] suggest that the value of 1.024 is applicable to all but very cold water. Close to freezing they report a better value of the constant to be 1.030. Bewtra, Nicholas, and Polkowski [47] tested diffused air contactors at temperatures between 10° - 30°C and at varying air flow rates. The regression analysis of 81 individual reaeration tests showed θ to be a constant = 1.02, the figure also used by Eckenfelder [10] for diffused air systems. Hunter and Ward [41] ran lab scale submerged turbine reaeration tests at various temperatures between 0°C and 50°C and arrived at a linear relationship for K_La at different temperatures. Their equation which follows is based on a regression analysis of 68 data points and a base temperature of 0°C,

$$K_La(T) = K_La(0°C)\ (1 + 0.0284T) \quad \ldots\ldots(25)$$

or with a base temperature of 20°C equation (25) becomes:

$$K_La(T) = K_La(20°C)\ (0.6375 + 0.0181T) \quad \ldots\ldots(26)$$

The use of a linear relationship is supported by Hull and Carbaugh [51] who found that for large temperature changes extrapolation with the exponential equation did not have the same accuracy as the linear relationship. However, for a moderate temperature range between 10 - 25°C there seems to be little difference between the exponential θ and the linear θ.

Because of its wide acceptance in the literature and apparent accuracy within a moderate temperature range the exponential θ will be used in this text; however, when dealing with very low or high temperatures the linear model should be checked and the more conservative factor should be used. The temperature correction factor is used to adjust standard oxygen mass transfer equation (8) which now becomes:

$$N_o = \frac{K_La(T)\ (\theta)^{20-T}(C_{se}-C)\ W}{HP} \quad \ldots\ldots(27)$$

where N_o = Standard oxygenation capacity of the aeration system (at 1 atm, 20°C, and clean water), lbs O_2/hp-hr

C_{se} = Effective oxygen saturation value at field pressure and temperature (clean water), mg/l.

C = Average concentration of dissolved oxygen maintained in operating system, mg/l.

W = Weight of basin water, millions of pounds.

HP = Brake horsepower.

θ = Temperature correction coefficient (see text for values).

NOTE: Equation (27) does not incorporate wastewater correction factors.

3.3.0 WASTEWATER VARIABLES

One of the most important factors in the design and testing of aeration systems (see Section 4.0.0 for a discussion of aeration testing procedures) is the oxygen transfer rate in the biological treatment basin or "clean" water test tank relative to "pure" water. A distinction should be made between "clean" water test results using tap water and the test results that would be obtained using "pure" or distilled water, because "clean" water contains various dissolved solids and traces of other chemicals (both naturally occurring in the tap water and added for the purpose of deoxygenation) which may interfere with oxygen transfer rates and dissolved oxygen measurement. In addition, the degree of interference will vary depending on the quality of the local tap water and the quantity and quality of deoxygenation chemicals.

Assuming for a moment that clean and pure water test results are equivalent, it is necessary to be able to predict the oxygen transfer rate of an aeration system in any liquid. Previously (Sections 3.1.0 and 3.2.0) the effects of and correction procedure for elevation and temperature were given. The following discussion is presented to show the effects on oxygen transfer rates of various impurities, salts, and surfactants.

3.3.1 Effect of Total Dissolved Solids

The presence of electrolytes is known to reduce the solubility of gases. This effect can be noted by the reduction in the oxygen saturation concentration in the Standard Methods [39] table showing oxygen solubility as a function of temperature and chloride concentration. In general as the electrolyte concentration increases the oxygen diffusivity decreases and solution viscosity increases. These effects tend to combine to reduce K_L, but the increase in viscosity tends to increase interfacial area per unit volume, a [52]. The net effect is that the relative decrease in K_L is greater than the increase in interfacial area and the overall oxygen transfer coefficient, K_La, should decrease with an increase in viscosity. Robinson and Stokes [53] related changes in viscosity with electrolyte concentration and Ratcliff and Holdcroft [54] related diffusivity reduction with viscosity increase. In addition electrolytes tend to increase the surface tension of water, although relatively large quantities are required for small changes in surface tension. Nonetheless, a small change in surface tension can prevent bubble coalescence which increases interfacial area [55].

The addition of Na_2SO_3 during lab scale aeration evaluation tests increased K_La [55]. This increase was negligible when the Na_2SO_4 concentration was less than 1000 mg/l (approximately 10 additions of Na_2SO_3 at 100 mg/l per test run), but became significant when multiple tests were performed on the same water or at the usual sulfate ion concentrations of the sulfite oxidation test (approximately 20,000 mg/l or greater). Small variations in the total dissolved solids level of tap water was found to have little if any influence in K_La values.

3.3.2 Effect of Total Suspended Solids

Baker et.al. [56] found that high total solids concentrations in a poultry manure oxidation ditch, reduced K_La when the concentrations exceeded 2%.

Viscosity was hypothesized as being responsible for the decrease in K_La. Other studies investigating aeration in fermentation mixtures have also indicated reduction in oxygen transfer with increasing viscosity. A 95% reduction in K_La was observed in a fermentation solution with a viscosity of 150 centipoise [57]. An 80% decrease in K_La was observed with a penicillin fermentation that had an apparent viscosity of 300 centipoise [58]. The latter study suggested that the decrease in K_La was logarithmic with the increase in viscosity.

A recent study which included an extensive literature review on the subject attempted to resolve the question of suspended solids influence on oxygen transfer. In this study Casey and Karmo [59] used a lab scale surface aerator to measure the effects of non-flocculent inorganic and organic suspensions and flocculent suspensions of activated sludge and "synthetic" (soya bean meal and aluminum hydroxide) sludge. They found that the non-flocculent suspensions had a negligible effect on K_La, while the activated sludge flocculent suspensions significantly increased K_La at concentrations of 0 - 2000 mg/l for one and of 0-8000 mg/l for another, although both were taken from an oxidation ditch. The "synthetic" flocculent sludge had inconsistent influence below 2000 mg/l, but increased K_La significantly and constantly from 2000 - 8000 mg/l. It was hypothesized that while the non-flocculent suspensions must obviously alter the bulk-liquid density and viscosity they do not affect to a significant extent interfacial conditions i.e. mean air-water interface area, mean interface age and oxygen-solution resistance characteristics of the liquid interface. On the other hand, the flocculent suspensions do affect the oxygen transfer rates and it must be due to their influence on interfacial conditions. Casey and Karmo [59] concluded that the influence on K_La may be as dependent on the type of aeration system as it is on the type of suspension.

3.3.3 Effect of Surface Active Agents

From the time that detergents replaced soap as the principal washing additive the affects of surface active agents (SAA) on aeration have been studied with great interest. The results of these studies, however, have been very contradictory. Investigators have reported that oxygen transfer rates in the presence of SAA decrease [60,61,62,63,64], increase [6‿,66], and are unaffected [67,68].

Water is composed of polar molecules, such that, at the gas surface the negative ends of the molecules point towards the interface. Because of the lack of symmetry at the surface there is an excess of free energy (known commonly as surface tension) which makes the water surface elastic with a tendency to contract. When a SAA is added to water, the material is absorbed at the water surface with their hydrophilic ends anchored in the water phase and the hydrophobic (paraffin) part facing the air. This results in an increase in surface viscosity and a loss of elasticity because random surface motion is eliminated and the surface is stagnated. Thus the SAA acts like an insulating membrane separating the gas and aqueous phase. This effect is strong enough to retard bubble rise and to prevent bubble distortion as it rises [64,69].

Mancy and Barlage [70] have separated the effects of SAA into two parts. The first effect is caused by the adsorption of the SAA film, which may partially or totally cover the water surface, block dissolution sites at the interface, or distort intermolecular forces between the gas molecule and the water surface that are necessary in the dissolution process. The second effect is related to the increase in water surface viscosity, suppression of the hydrodynamic activity of the interface, and formation of a viscous subsurface hydration layer. In general it was found that regardless of the mechanism, the presence of SAA reduced the rate of oxygen transfer, the extent of which is dependent on the turbulence characteristics of the aeration system and the chemical properties of the SAA present.

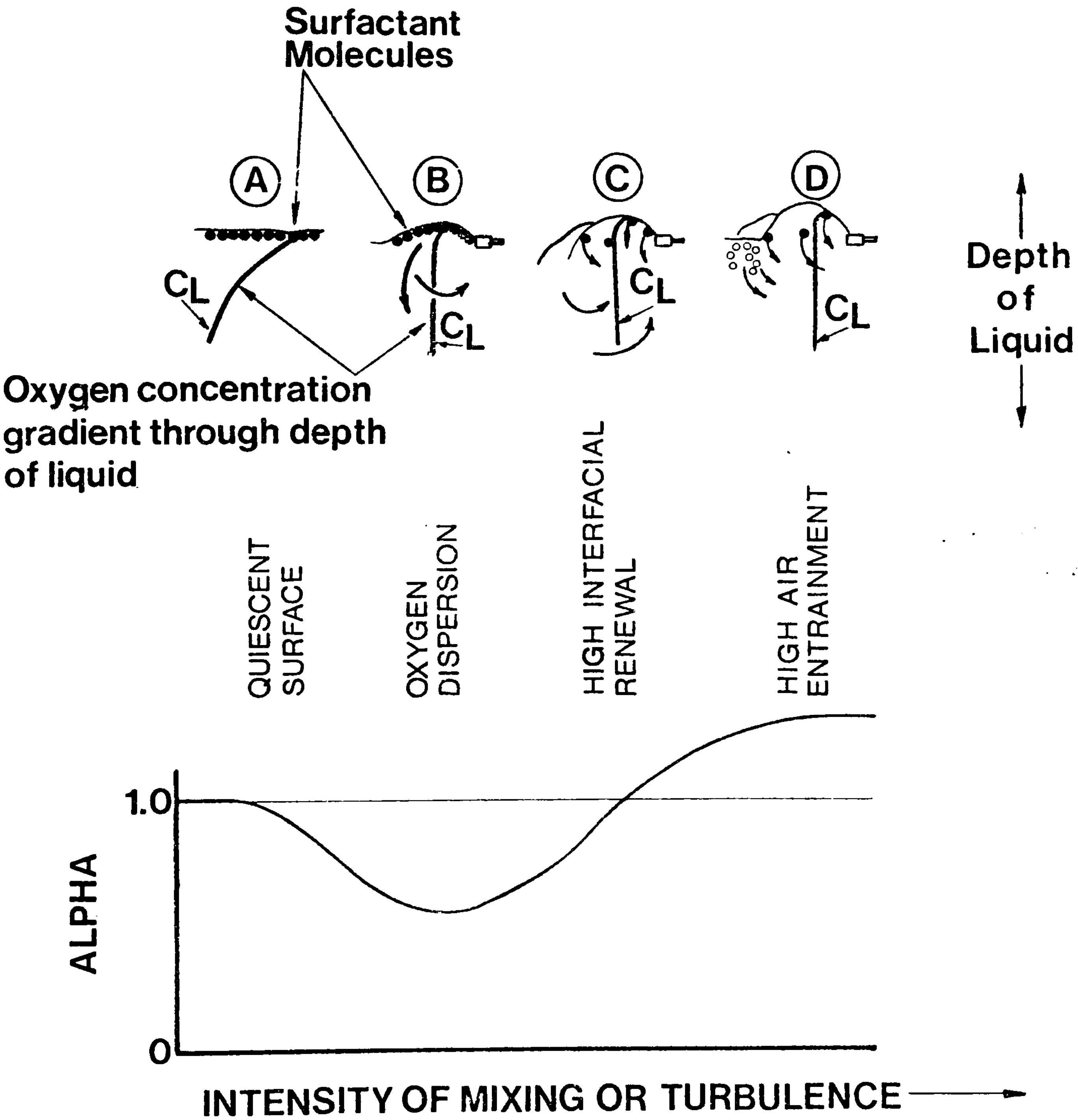
3.3.4 Alpha Correction Factor

The fluid variables of dissolved and suspended solids, surface active agents, and other organics mentioned above do not have independent correction factors for their effect on oxygen transfer in common usage. Instead these are all lumped together in a single factor called α (alpha). Mathematically it is defined as

$$\alpha = \frac{K_L a \text{ (Wastewater)}}{K_L a \text{ (Pure Water)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (28)$$

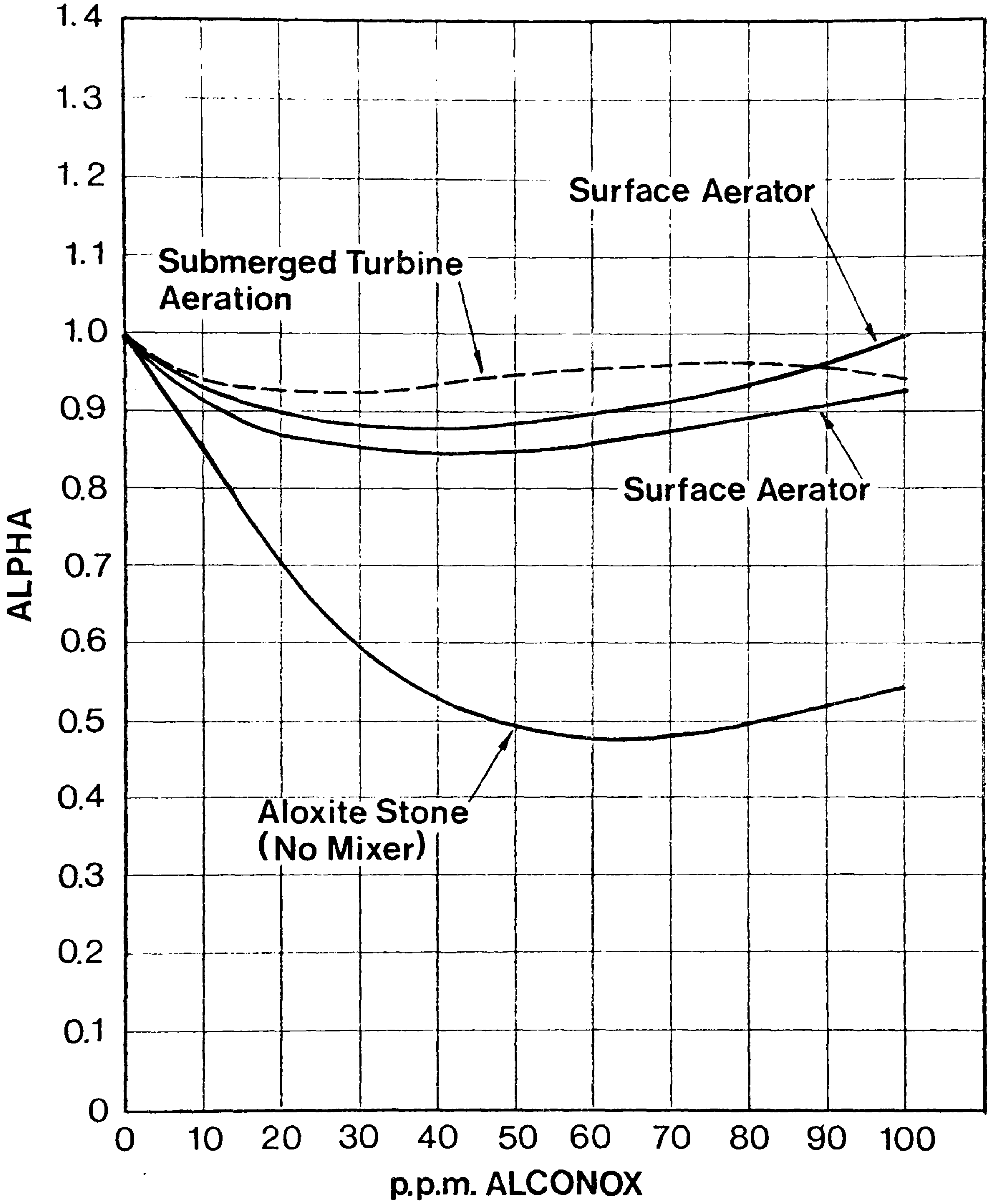
The influences of dissolved and suspended matter generally decrease the $K_L a$ of a liquid as was described above. The dissolved matter reduces K_L, but often the presence of surface active agents which reduce surface tension permits smaller bubbles to be produced and this increases a. Since $K_L a$ generally decreases with the presence of contaminants, K_L normally decreases at a faster rate than a increases; however, this is dramatically dependent on turbulence. When turbulence increases greatly, adsorbed surfactant molecules are swept back into the body of liquid, no interfacial barrier is permitted to be established and fine air bubbles are entrained creating a greater interfacial area. With high levels of turbulence values for alpha frequently exceed 1.0.

During the process of biological oxidation the value of alpha for the wastewater can be expected to change because those substances which cause the alpha value to deviate from 1.0 are being oxidized and stripped in the treatment process. One of the most disturbing aspects in defining and measuring alpha is that the value of this factor depends upon the concentration of waste constituents and the turbulence regime of the aeration system in a particular basin geometry and is therefore judged not to be an accurate and constant characteristic of the wastewater [23,48,71,72]. In fact it has been shown that diffused aeration suffers markedly from the presence of surfactants, but some types of aeration systems (those producing high shear intensities) may benefit [73]. See Figures 3.1 and 3.2 for graphical representations of the influence of turbulence on the value of alpha.



RELATIONSHIP BETWEEN THE COEFFICIENT ALPHA AND THE DEGREE OF TURBULENCE [23]

COOPERATIVE POLLUTION ABATEMENT RESEARCH C. AR P. OJ_ T NO. 542	beak	BY BG; DATE 17 MAR 77; DWG NO A1269-1	FIG. 3.1



ALPHA FACTOR VERSUS CONCENTRATION OF "ALCONOX" FOR VARIOUS SYSTEMS [94]

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	beak	BY BG	DATE 18 MAR 77	FIG. 3.2
		DWG NO A1269 - 2		

Despite the apparent shortcomings of the alpha factor, the fact remains that wastewater generally has a K_La different from the K_La of the test water used to evaluate the aeration system and there is no other way to express it than the alpha factor. With this in mind laboratory scale alpha tests must be viewed not as an absolute indicator of alpha, but as an approximation to what can be expected in the field. Certainly all attempts should be made to produce similar Froude and Reynolds numbers in the scaled-down alpha tests i.e. use a lab scale system with the same K_La as the full scale system; however, it can be reliably predicted that the alpha value observed will be in variance with the "true" value that will be produced in the field. Therefore, Eckenfelder and Ford [23] suggest that the laboratory studies should be run using an equipment set-up that allows the turbulence to be varied. The minimum observed alpha should then be used unless better information is available.

The literature seems to fall short of providing an answer to this dilema. Eckenfelder [74] reports that lab scale testing on pulp and paper effluents yields alpha values between 0.65 to 0.95. Several investigators report an alpha value of 0.80 [75,76,77] and 0.85 [78] for domestic sewage, although the laboratory testing procedures varied markedly. Often aerator testing is performed with river water as the "clean" water; several studies reported alpha values for river water based on lab tests of 0.75 - 0.78 [79], 0.85 [80], and 1.0 [81]. Finally, assumed alpha values have been reported for domestic wastewater of 0.85 [3,82,83] and 0.90 [84]. When reliable data is not available a conservative estimate of the alpha value should be used and a clear advantage should be given to aeration systems which produce high shear intensities in the aeration volume.

The introduction of alpha adds an additional factor to the temperature corrected transfer equation (27) which becomes (see equation (27) for explanation of terms):

$$N_o = \frac{\left[\dfrac{K_La(T)\ \theta^{20-T}}{\alpha}\right](C_{se}-C)\ W}{(HP)} \qquad \text{.............(29)}$$

NOTE: Equation (29) is not fully developed and is seldom employed to establish standard transfer capacity i.e. standard oxygenation capacities are usually performed in "clean" water where no alpha correction factor is required.

3.3.5 Beta Correction Factor

As with the alpha correction factor discussed in the previous section the β (beta) correction factor is a lump sum factor which incorporates all oxygen solubility reducing variables into a single compensating term. Essentially, it accounts for the reduction in the oxygen saturation concentration caused by various dissolved solids and organic substances.

Mathematically it is defined as

$$\beta = \frac{C_{sw(t,p)}\text{(wastewater)}}{C_{ss(t,p)}\text{(pure water)}} \qquad \text{.......................(30)}$$

where both saturation values are at the same temperature and pressure.

The factor is developed by aerating a sample of "clean" water and a sample of the wastewater in question for an extended period of say 2-4 hours. Stukenberg and McKinney [85] suggest that an aeration period of six times $1/K_La$ should be adequate to reach saturation in the test water. The long time is necessary because as saturation is approached there is very little driving force. There are a few considerations for this correction factor test. The first is that the "clean" water used in the beta test should be as close as possible to the "clean" water used by the manufacturers for the aeration test of the selected equipment or at least there should be no significant differences that would produce an incorrect saturation value. Secondly, the wastewater sample should not be aerated so violently so as to strip organic substances that would ordinarily be present in a full scale basin. Finally, the dissolved oxygen measurement must account for chemical interferences with the wet chemical Winkler test.

The beta test is relatively easy to perform with reasonable accuracy and therefore references to it in the literature are more general. The literature values for beta determined by test include 0.90 [78], and 0.95 [76,77] for mixed liquor samples (domestic sewage), 1.0 [81,86] for river water. Common assumed values for beta for domestic wastewater are 0.90 [83]. 0.90-1.0 [82], 0.95 [84], and 1.0 [3].

The inclusion of beta into the standard oxygenation capacity equations (8,27, 29) results in (see equation (27) for explanation of terms):

$$N_o = \frac{\left[\frac{K_L a(T)\ (\theta)^{20-T}}{\alpha}\right] \frac{C_{se}}{\beta} - C \quad W}{HP} \quad \ldots\ldots\ldots\ldots (31)$$

NOTE: This equation will convert oxygen transfer test data taken under any conditions to standard conditions. However, it should be noted that tests are normally performed at 20°C, 1 atm, and on "clean" water where no correction factors (alpha and beta) are required. Therefore, this equation is seldom used. The equation will be further developed for surface and submerged aeration systems in later sections.

3.4.0 FLUID TURBULENCE, POWER DENSITY AND BASIN GEOMETRY

Fluid turbulence in the form of small scale eddies is an important characteristic in oxygen transfer. High turbulence promotes rapid surface renewal and thereby increases K_La. In aeration the basin geometry and power applied per unit volume are important factors. Eckenfelder [23] noted in one test with a surface aerator that approximately 60 percent of the oxygen transferred was by liquid spray and 40 percent from turbulence and entrainment. As the volume under aeration increases for a given aerator, the larger volume will dissipate the energy faster yielding less turbulence, less entrainment, and a lower transfer rate. As the volume approaches infinity virtually all transfer would be in the aerator spray.

This dependence upon turbulence makes testing and reporting of aerator oxygen transfer capabilities a critical process. It is generally known that the amount of horsepower per unit volume will affect the K_La value. At aeration intensity levels between 10 HP/MG and 300 HP/MG (aerated lagoon and high-rate activated sludge, approximately) the effect of increasing the power per unit volume is to increase the transfer rate. Below the aerated lagoon level the transfer seems to remain constant and relatively stable and above the high power density level the transfer rate becomes highly unstable and depends upon basin baffling and tank geometry. As can be imagined a manufacturer wishing to maximize his products' capabilities will report, and truthfully so, the transfer rates associated with optimized power to volume test conditions. In fact, there are no test facilities in which a 150 HP aerator can be tested at low power densities; it requires an impractically huge basin and, as will be seen later, it might also lead to inaccuracies in test results. So, depending on the intended use of the aeration system, the field transfer rate can be significantly lower than the "standardized" results. Submerged aeration systems such as rising bubble contactors and submerged turbines are not generally affected greatly by this power density effect, because the systems are usually restricted to activated sludge applications where "complete mix" (reasonably high power per unit volume) turbulence regimes exist which is similar to the test turbulence. However, for surface aerators, submerged static tubes, and aerated fluid jets, which tend to be point sources of power input there can be significant differences in the oxygenation capacity for a given aeration system depending on the power input per unit volume.

Recognizing that the oxygenation capacity of a localized aerator varies with the liquid volume in the basin in which the aerator is installed, Kalinske [87] has proposed that a new aeration constant be introduced to replace K_La, a term which includes geometry effects. The constant proposed is Q_wK where Q_w is the rate of liquid flow through the aerator (vol/unit time) and, K is a dimensionless coefficient which is related to the interfacial area and turbulence generated by any particular aerator and to the variation of dissolved oxygen concentration in the liquid as it passes through the aerator. Q_wK would be equal to K_La divided by the aeration basin volume, ft^3, and would be a characteristic of an aerator unchanged by differences in basin geometry.

3.4.1 Power Per Unit Volume

Eckenfelder [23] proposed an equation which would account for the oxygenation as a function of liquid volume:

$$N_o = K\ HP_v + N_s \quad \ldots\ldots\ldots\ldots\ldots\ldots (32)$$

where N_o = Total oxygen transferred under standard conditions per unit horsepower, lbs O_2/hp-hr

HP_v = Horsepower per 1000 gals of basin liquid

N_s = Oxygen transferred from liquid spray

K = Constant characteristic of the aeration device, slope of line in Figure 3.3.

In support of this relationship several figures were presented which showed N_o as a function of HP_v. Figure 3.3 shows aeration performance data in water for several types of surface aerators.

3.4.2 Power Per Unit Area

In examining Figure 3.3 it is readily apparent that a fair degree of data scatter exists (to the extent that a supplementary line was added) and since the major source of oxygen transferred is at the surface the authors Kormanik et.al. [88] undertook a study to investigate the relationship between N_o and HP_a, the horsepower per unit area. Their tests were done on several types of surface aerators in many different basin geometries. The results of the study show an excellent data fit for N_o as a function of HP_a. As well, smaller horsepower units were significantly more affected by changes in HP_a than larger units as shown in Figure 3.4. For all the tests, changes in basin depth did not prove to be a significant factor; this is in direct conflict with the N_o - HP_v theory. The authors also noted that the low-speed open impeller surface aerator test results did not indicate a N_o - HP_a relationship as was indicated with the high speed surface aerator. Figure 3.5 shows the flatness of the low speed curve. This observation is not without support as data obtained by Knop, et.al., in 1964 also shows a lack of correlation with the low speed aerator between N_o and HP_v. (See Figure 3.3 and note the flatness of the dotted line). Because of the apparent good fit of the data Kormanik et.al. [88] proposed the following equation to describe N_o

$$N_o = K_a HP_a + N_s \quad \text{.....................(33)}$$

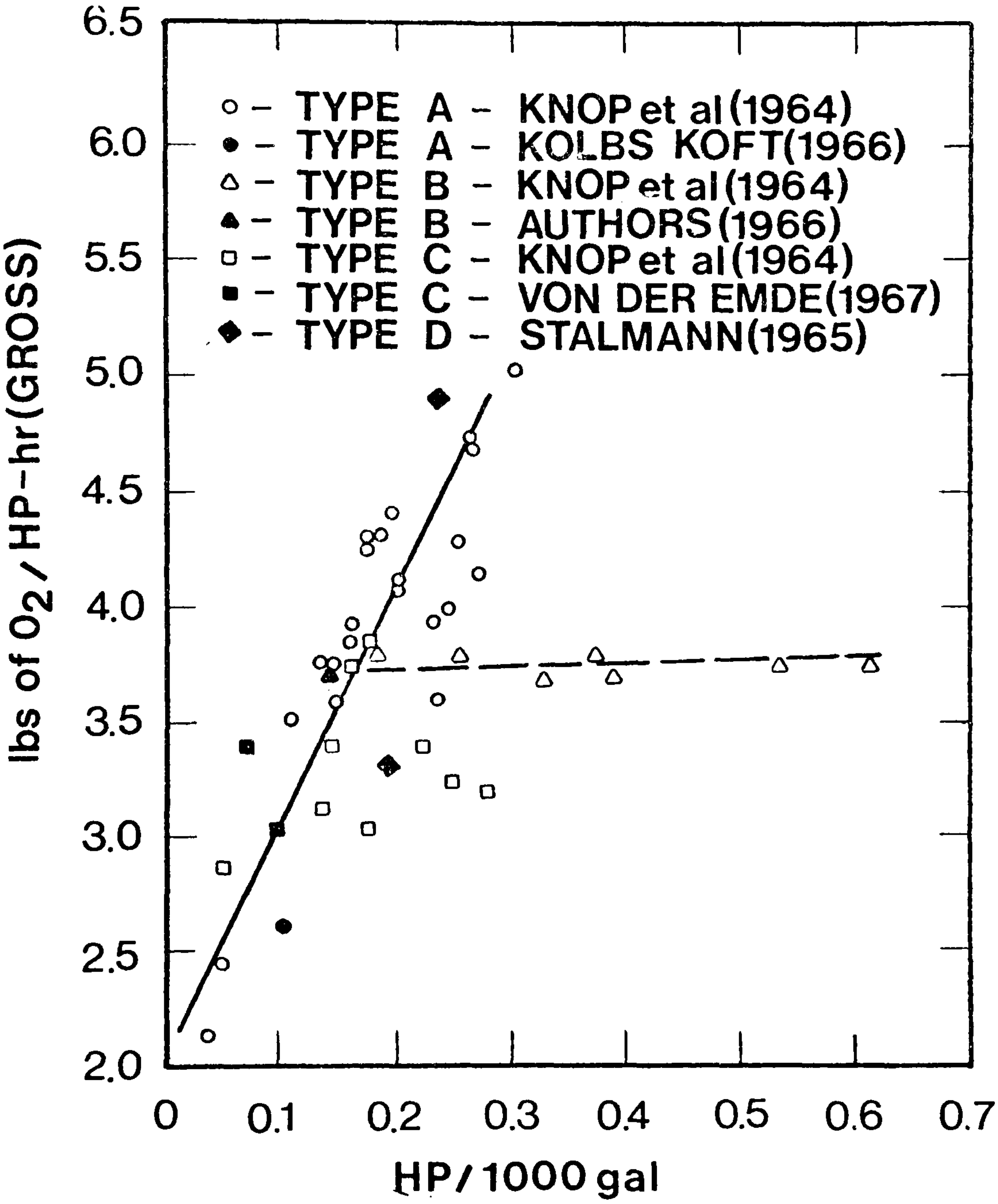
where HP_a = Horsepower per 100 ft^2 of basin surface area

K_a = Constant for the aeration device, slope of the lines in Figure 3.4, and 3.5.

The criticism that power per unit volume is not as good as power per unit area seems to have merit especially when varying the depths of a basin while maintaining the same surface area did not alter the transfer rate. However, the fact that there was a fair degree of data scatter in Figure 3.3 does not necessarily discredit the the N_o-HP_v relationship. The data in Figure 3.3 were for different types of surface aerators and for various horsepower units. With this in mind, if one considers the N_o-HP_a data in Figure 3.4 and disregards the iso-horsepower lines, then the data plot would be very non linear. Therefore the validity of N_o-HP_v or N_o-HP_a is not clearly evident by the Figures alone.

For both relations, equations (32) and (33), it is possible to calculate the theoretical oxygen transfer due to the liquid spray from the following equation [88]:

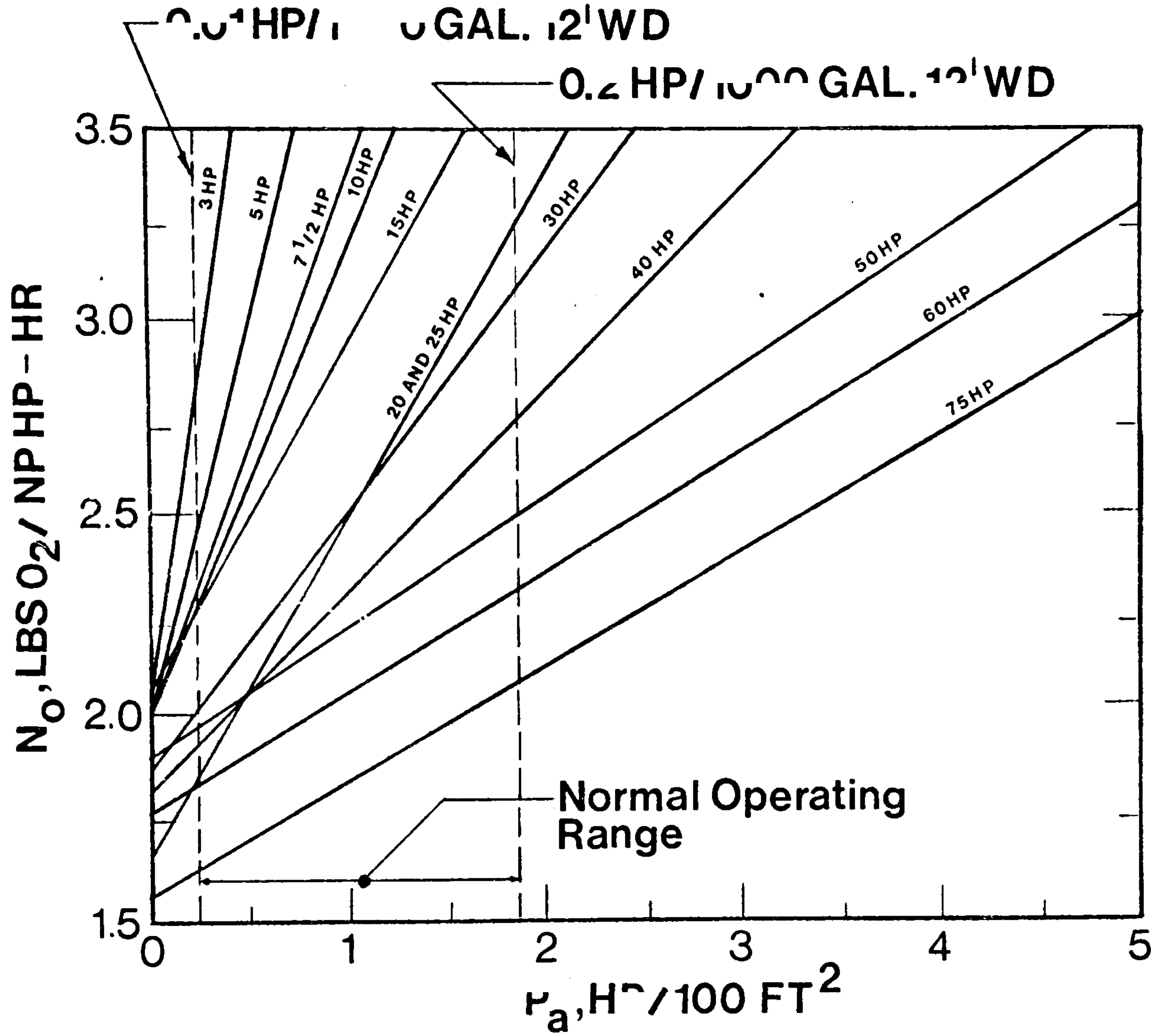
$$N_s(\text{THEO}) = Q_p \times 60 \frac{\text{min}}{\text{hr}} \times 8.34 \frac{\text{lbs}}{\text{gal}} \times \frac{C_{se}-C}{10^6} \quad \text{.........(34)}$$



Basin volume effect on oxygen transfer rate by surface aerators

AERATION PERFORMANCE DATA [23]

COOPERATIVE POLLUTION ABATEMENT RESEARCH C. AR P. J. 542	beak	BY BG / DATE 18 MAR 77 / DWG NO A1269-3	FIG. 3.3



Surface area effect on oxygen transfer rate by high speed aerators [88]

OXYGENATION RATE VERSUS AREA

COOPERATIVE POLLUTION ABATEMENT RESEARCH
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BY BG	DATE : 21MAR77	FIG. 3.4
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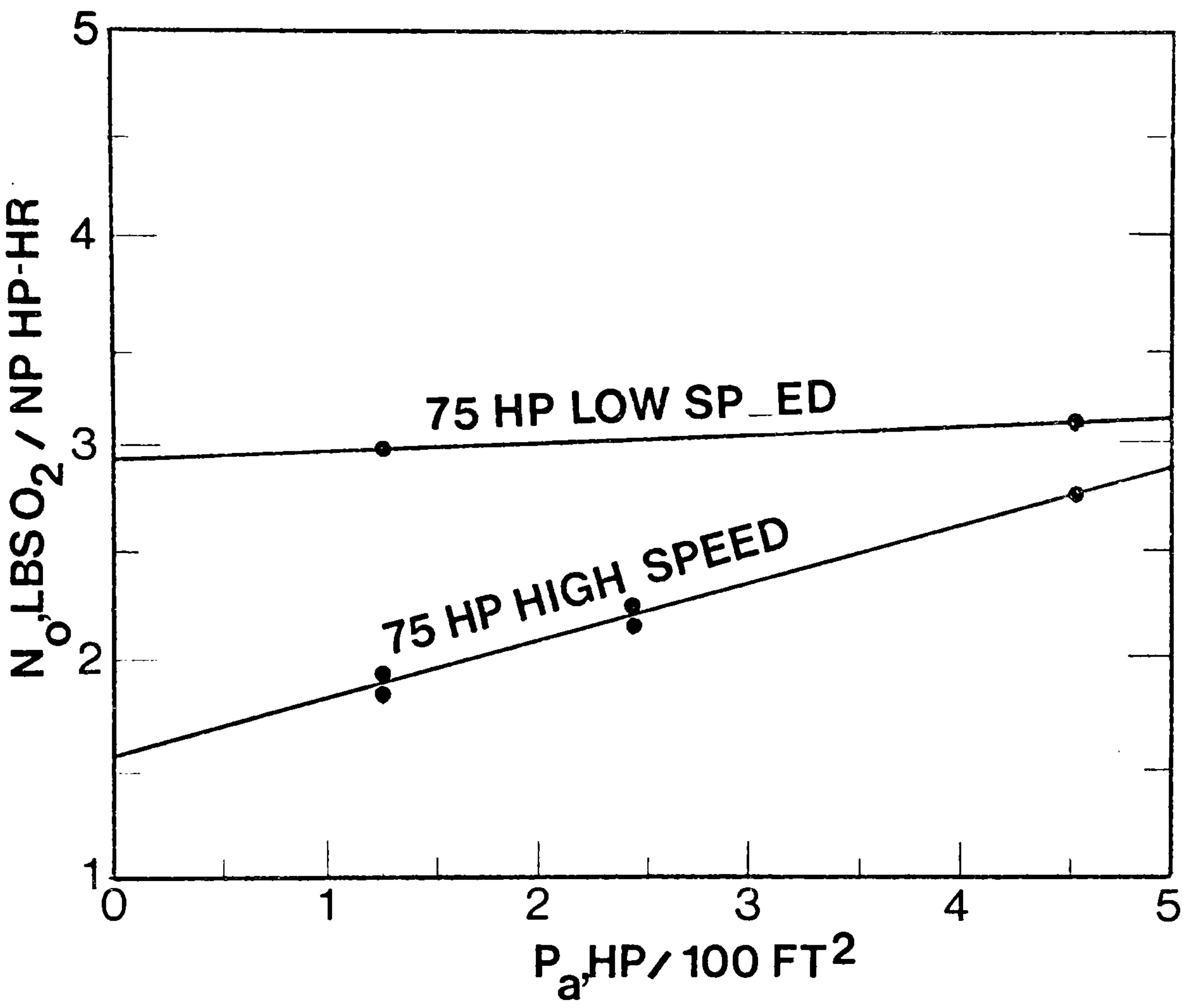


Comparative effect of surface area on high and low speed mechanical surface aerators [88]

OXYGENATION RATE VERSUS AREA

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	beak	BY BG DATE: 22 MAR 77 DWG. NO. A1269-5	FIG. 3.5

where N_s(THEO) = Theoretical maximum oxygen transfer in liquid spray, lbs O^2/nameplate (NP) hp-hr.

Q_p = Actual pumping rate of aerator, gpm/NPhp (not induced pumpage).

and since it is difficult to saturate the liquid spray in the short time it is in the air, the theoretical maximum must be multiplied by some percentage of saturation to reach the actual N_s observed in testing. Because a low speed aerator does not actually spray the liquid its percentage of saturation is much less than the high speed aerator. For high speed aerators aerating 0.0 mg/l water at 20°C the percentage of saturation will be approximately 85 - 100% and for low speed aerators it will be approximately 50 - 65%.

3.4.3 Aerator Interactions

Figures 3.3, 3.4 and 3.5 fail to show any limit to the oxygen transfer as the power per unit area/volume increases. As mentioned before the point at which the curve becomes unstable is a function of both the aeration system and the basin baffling characteristics, but a significant reduction in oxygen transfer efficiency and mixing ability was noted in two activated sludge basins [17] because of surface aerator interactions. In these basins surface aerators were installed in a geometrically uniform pattern; the number of aerators installed was based on oxygen requirements and the resulting horsepower per unit volume, 280 HP/MG and 60 HP/MG, was well within the suggested range for suspension of biological solids. The most significant interference resulted in the higher power density basin with sludge accumulations amounting to an average depth of 2.5 ft. The problem was solved by placing five downward pumping mixers at points of maximum interference; however, if draining the basin had been an acceptable alternative upward pumping impellers on extended shafts or draft tubes might have been the most economical solution. Velocity profiles before and after solving the mixing problem revealed that horizontal velocities were at best only a general indication of adequate mixing. It was concluded, however, that biosolids in concentrations up to 5000 mg/l could be kept in suspension with velocities between 0.4 - 0.5 ft/sec, but that velocities in a clean water tank will be significantly different than with a mixed liquor solution because of the increased viscosity of a biosolids liquor.

4.0.0 EVALUATION OF AERATION PERFORMANCE

The previous sections discussed how gaseous oxygen is dissolved in liquid and how various liquid constituents and basin characteristics influence the rate of transfer. This section deals with how one measures the effectiveness of an aeration device. First, the procedural and analytical problems involved with aeration system testing are discussed. Recommended methods for aeration testing are given. Mixing by aeration systems is examined in relation to pumpage and basin liquid velocity. Finally, typical aeration performance characteristics are summarized.

The purpose of summarizing aeration characteristics before having discussed the operation of the various types of aeration devices is simply an attempt to establish reasonable ranges of efficiency before the reader is influenced by the efficiencies shown in Section 5.0.0. The values shown in Section 5.0.0 are the result of different test procedures and data analysis methods; there is little agreement. In contrast the values shown in Section 4.3.0 are more closely in agreement, because the test procedures and data analysis used were similar.

When measuring the effectiveness of an aeration device the basic and only unit of measure applicable to all types of aeration devices is the weight of oxygen dissolved per unit of power consumed, lbs O_2/hp-hr [89]. Nearly everyone accepts this concept, but the way in which the efficiency should be evaluated is hotly contested.

4.1.0 TESTING PROCEDURES FOR OXYGEN TRANSFER

In 1960, Morgan and Bewtra [89] wrote that as of the date of their report there was still no generally agreed upon standard aerator test procedure. While they agreed that the testing of aeration devices in activated sludge basins gave useful information it by no means provided "standard" data which could be used to compare one system against another. What they and others wished to establish was a standard test that would be both easy and reliable to perform and would yield data that could be extrapolated for field applications. As of 1977 the literature shows a clear preference for the non steady-state reaeration of clean water at 20°C as the only specification of aeration performance [10,11, 48,49,55,75,77,79,83,89,95], although there are those who still feel that the steady-state aeration of mixed liquor is valid for confirmation of equipment performance [72,79,85,96,97]. Very few, if any, support the steady-state oxidation of sulfite as a realistic indication of aeration performance. What is definite, however, is that each test may serve a useful purpose and all suffer major problems.

4.1.1 Non Steady-State Reaeration Test

This test procedure has been more or less adopted as the industry standard for reporting oxygenation capacity. Simply, the test is performed as follows:

1. An appropriately sized basin is cleaned and the aeration system is installed.
2. The basin is filled with tap water and the aeration system is started to establish a mixing pattern.
3. After the system has reached a hydraulic steady state the water is deoxygenated. Various deoxygenation methods are discussed later.
4. As the dissolved oxygen concentration rises from zero to near saturation samples are taken and the dissolved oxygen concentration is recorded with the time of the sample.
5. The data is plotted on a semi-log graph as the oxygen deficit $(C_{se}-C_{time(t)})$ versus time. A best fit line is drawn through the points, the slope of which is K_La. By introducing the weight of water under aeration and the horsepower used to drive the aeration system a transfer efficiency can be computed.

The reason that this test has become a standard is due to the fact that it is simple to perform and when care is taken to minimize interferences the results are reasonably accurate. By using clean water the transfer process involves only diffusion and therefore the analysis is not complicated by biological or chemical reactions. The standard conditions for the test include: water temperature of 20°C, an atmospheric pressure of 760 mm Hg (14.7 psia), an initial dissolved oxygen level of 0.0 mg/l, and a water purity of "clear, clean, or tap". If the test is conducted under different conditions than those specified, the test results must be corrected to standard conditions by the factors mentioned in Section 3.0.0.

Because this test procedure is widely accepted it is necessary to understand how it is performed and what can go wrong. The following discussion is a detailed analysis of the reaeration test. Where possible interferences are identified and recommended procedures given.

REAERATION TEST THEORY

The analysis of the non steady-state test is based on the first order differential equation, equation (7),

$$\frac{dC}{dt} = R = K_L a\,(C_{se} - C)W \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The use of this equation to analyze the test data implies the following assumptions:

1. The Whitman two-film theory is assumed to describe the overall mass transfer process and the primary resistance to mass transfer is in the liquid phase. Therefore, $K_L a$ depends only on the liquid properties.
2. The entire test basin contents are perfectly mixed (concentration gradients negligible) for all periods during the test.
3. The $K_L a$ of the aeration system is a constant throughout the test; it is independent of the test duration and dissolved oxygen level.
4. Environmental conditions including air temperature, wind velocity, and humidity may be ignored due to assumption that all transfer resistance lies in the liquid film.
5. The dissolved oxygen saturation concentration is a constant during the experiment and changes only with variations in liquid temperature, salinity, and atmospheric pressure.

If these assumptions are valid, then the equation may be integrated to obtain a solution for K_La,

$$K_La = \frac{\ln \frac{C_{se} - C_1}{C_{se} - C_2}}{t_2 - t_1} \quad \text{.........................(35)}$$

where C_1 occurred at t_1 and C_2 occurred at t_2. Mathematically, the oxygenation capacity of the aeration system is described by equation (35).

As for the validity of the assumptions it is obvious from the overwhelming acceptance of this test procedure that for the most part the conditions assumed occur in the test. In general, the literature supports the use of the Whitman film theory as being adequate. However, it is possible to run the test improperly such that the test data are next to meaningless.

BASIN SIZE AND MIXING

One of the first critical items is the test basin in relation to the aeration system. To meet the assumption that the basin is uniformly and completely mixed so that dissolved oxygen gradients are minimal the basin size must be neither too large nor too small for the mixing capabilities of the aeration system. Some authorities have tried to specify a horsepower per unit volume, 1 HP/1000 ft^3, [91] to provide the correct mixing. Unfortunately, equal power inputs does not mean equal mixing as was discussed in Sections 2.0.0 and 3.4.0. A more reasonable approach would appear to be a specified time to aerate the water from no oxygen to near saturation. Landberg [94] suggests 0-90% of saturation in 15-45 minutes. McWhirter [11] found 0-90% of saturation in 10-15 minutes to be satisfactory. To reach 80% of saturation Kalinske [92] recommends 10-30 minutes. If the dissolved oxygen readings from the various sample points vary more than .25 mg/l from the average it is an indication that the mixing is inadequate and significant gradients in the dissolved oxygen concentration exist; the test results should probably be invalidated [48].

Since it is necessary to create "complete mix" conditions throughout the entire test period the aeration system must be turned on well in advance to bring the system to a hydraulic steady state. For example, a leading manufacturer has found it necessary to have a 75 HP low speed surface aerator operate for about 30 minutes to achieve a hydraulic steady state in a 500,000 US gallon tank [94]. If the aeration system is simply turned on after the addition of the deoxygenation material, the test results will reflect the intense gradients that will result.

CONSTANT K_La

When the reaeration data is plotted as the oxygen deficit versus time on semi-log graph paper the theory implies that a straight line will occur. Unfortunately reaeration data plotted on semi-log graph paper seldom plots exactly as a straight line. Usually the non-linearity or randomness occurs at the beginning of the test where very slight time errors can introduce large displacements and at the end of the test where a slight difference in the real water saturation concentration from the assumed value will curve the plot. No pattern of a time or concentration dependent K_La has been found to date in the literature.

ENVIRONMENTAL CONDITIONS

The environmental conditions which may vary from test to test include:

a. Air temperature
b. Humidity
c. Wind velocity
d. Solar radiation
e. Atmospheric pressure
f. Water vapor pressure

While these conditions might all influence oxygen transfer, the fact that for slightly soluble gases such as oxygen all of the resistance to transfer lies in the liquid film, negates the possibility that factors which only affect the gaseous film could influence the rate of oxygen transfer. Therefore, only atmospheric pressure and saturated water vapor pressure at the temperature of the test water should be considered. Water vapor pressure should be subtracted from the local atmospheric pressure for the computation of C_{se}, although for elevations below 1000 m (3000 ft) and water temperatures below 25°C (77°F) it may be neglected [39]. Atmospheric pressure must always be checked as it directly influences C_{se} (see Section 3.1.0).

DISSOLVED OXYGEN SATURATION CONCENTRATION

The assumption that the dissolved oxygen saturation concentration remains constant is rather limited. For surface aeration it is reasonable to assume that the only source of oxygen is the atmosphere, which represents an infinite supply that can replace the dissolved oxygen faster than it can dissolve. Considering that only changes in liquid salinity and temperature, and the partial pressure of oxygen can change the saturation concentration, the relatively short test period and large water mass confirms the use of a constant C_s for surface aeration. However, it has been a relatively common event for directly observed C_s determinations to be higher than the book values. This phenomenon has been attributed to the entrainment of air bubbles in liquid transported to deep areas of the tank resulting in an increased partial pressure of oxygen and larger driving force (C_s) than would be present at the atmospheric pressure surface [49]. This would tend to indicate that when large amounts of entrained air bubbles can be transported to significant depths such as when a large horsepower aerator is tested in a relatively small surface area or volume tank the true C_{se} value although it is probably constant will be higher than the standard surface saturation value C_{ss}. In instances where this occurs it is necessary to determine the C_{se} by direct observation.

When the method of aeration is sub-surface modern gas-liquid theory quickly negates the assumption of a constant C_s value. As an air bubble is released somewhere below the tank surface it "sees" an apparent pressure due to atmospheric pressure and hydrostatic pressure and it has an oxygen content (mole fraction) equal to the atmosphere, 21%. As the bubble rises the bubble experiences decreases in both pressure and, because the bubble does not contain an infinite supply of oxygen, oxygen content. It is clear that C_{se} for a submerged aeration system is not a simple constant. In fact, the C_{se} not only changes with depth, but also with duration of the test, because as the oxygen deficit becomes small the rate of transfer from the bubble in the lower regions of the tank decreases and actually begins to transfer from the liquid to the gas in the upper tank area [91,93]. This phenomenon of oxygen absorption near the bottom and out-gassing near the surface that varies with time simply tells us that the C_{se} is not a constant but is instead a constantly varying value.

This observation that C_{se} is not a constant does not preclude the use of equation (7), but it does require that either one assumes a constant value (hopefully accurate or at least conservative) or undertakes a rather long and tedious data analysis, usually by computer, to determine the C_{se} at all times during the reaeration. The choices of constant C_{se} values and their consequences have been covered well in [93,98]. The alternative methods of computing the varying C_{se} are covered in [93]. See Appendix 1 for the Non Steady-State test example for the effect of C_{se} on K_La.

EXPERIMENTAL PROBLEMS AND SOLUTIONS

To obtain meaningful and consistent test results from the unsteady-state test the following conditions and procedures must be observed:

1. As mentioned earlier the testing basin must be appropriately sized for the aeration system to be tested. The volume utilized should be such that the liquid can be brought to 90% of saturation in about 10-30 minutes. The basin must be baffled to prevent a stirring action by

turbine impellers and to enhance complete mixing. It must be remembered that velocity does not necessarily ensure mixing, large scale turbulence does. To avoid chemical effects (to be discussed later) the basin should be cleaned of any material i.e. sodium sulfate residue and catalyst, before filling the basin.

2. The number and location of sampling points depends on the basin geometry, but a minimum of 3 points is considered necessary in ideal basins, 5 to 7 points for average conditions, and in some extreme cases (irregular basin geometry) as many as 10 points are required to adequately monitor the basin [85]. When point sources of aeration are being tested, such as a surface aerator, the oxygen is not transferred to the average basin water as would be calculated from the average values of all the sample points; it would be transferred to the water pumped by the device. (This statement assumes bubble transport is negligible). Since this liquid is at a minimum dissolved oxygen concentration just before entering the aerator inclusion of data from this sample point would tend to increase the apparent driving force and result in a more conservative and possibly more realistic value of K_La [85]. As a brief guide to sample point location Figure 4.1 is provided to show recommended locations.

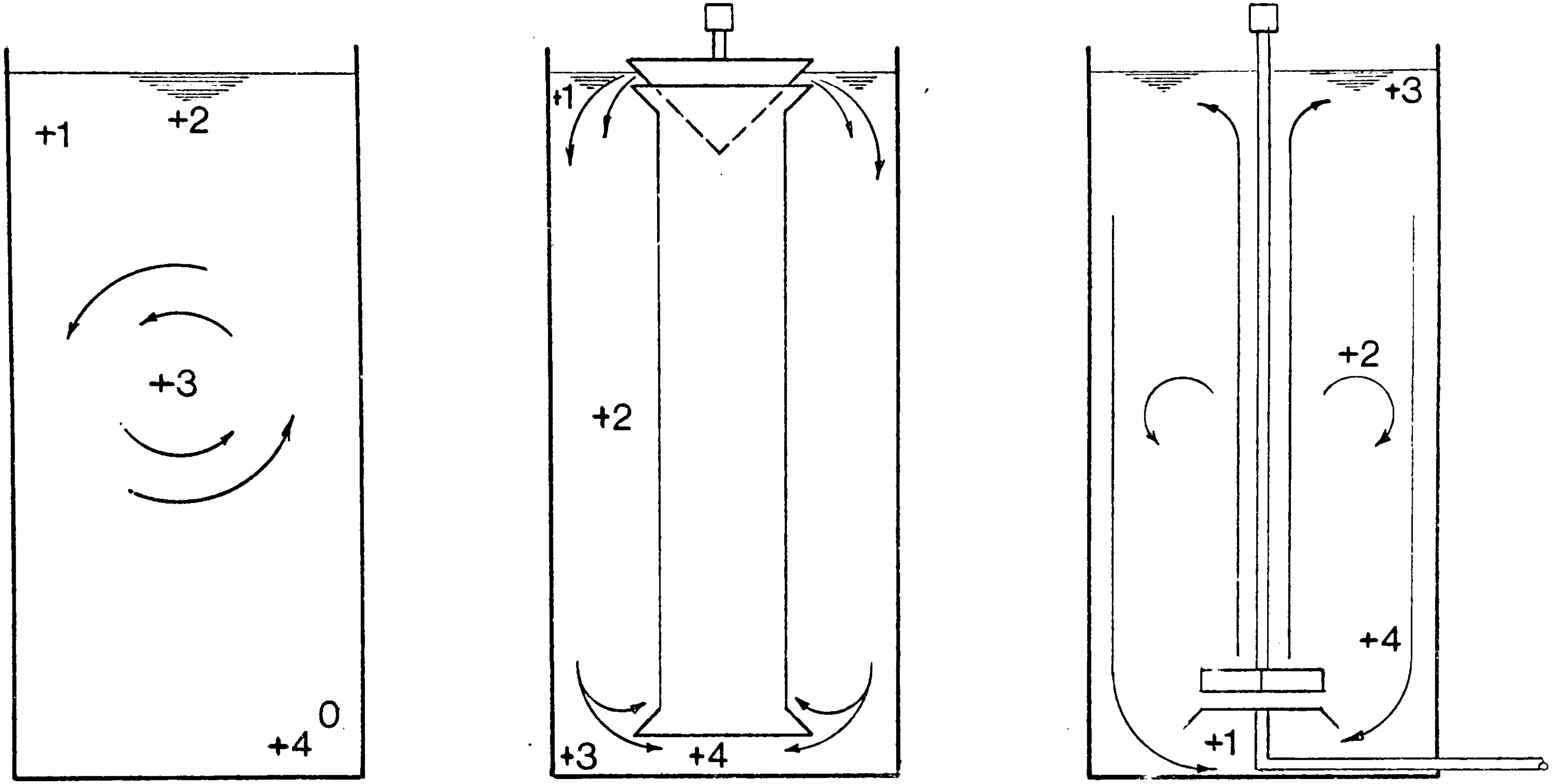
   After the number and placement of sampling points has been decided, the method of sample conveyance must be considered. If sufficient head is available gravity feed is a good method; however, large siphoning lifts should be avoided due to reduced pressure on the suction side that can cause out gassing of the dissolved oxygen especially at low oxygen deficit conditions. When the physical conditions do not permit direct gravity discharge, submerged pumps offer an excellent delivery system as long as there is no throttling of the discharge.

Either of these methods provides consistent results and a minumum lag time in sample delivery. The use of a suction lift pump is not recommended as the reduced pressure on the suction will cause out gassing and erroneous results. For the two acceptable methods it is also important to provide effective equal delivery line lengths to ensure that the samples are arriving at the same time.

An additional complication in sample collection is air bubble entrainment. Many investigators have reported that suspected high dissolved oxygen readings may have resulted from the inclusion of fine air bubbles in the sample and that these samples both aerate the oxygen deficit samples and may titrate as dissolved oxygen with the Winkler test. Anti-air entrainment devices on the sample point inlet have been found effective in eliminating this problem [83,99]. As a further protection, oxygen probes have been shown to be relatively insensitive to the presence of non-dissolved oxygen.

The sample bottles used for collection are usually BOD bottles with air tight ground glass stoppers. It is usually not acceptable to fill a bottle by placing the sample line into an empty bottle and filling it for a given sample time. The recommended procedure where sufficient test volumes exist would be to allow the sample lines to run freely into the bottles such that the contents of the bottles and the aeration tank contents are as nearly the same as possible, except for a small time lag. Then at the predetermined sample time the lines are removed, the bottles stoppered, and a new set of bottles are placed under the delivery lines.

To provide adequate data 6 sets of samples should be taken between 10 and 90% of saturation [48].



A. DIFFUSED AERATION

B. SURFACE AERATION

C. SUBMERGED TURBINE AERATION

LEGEND

+2 – SAMPLING POINT (TYPICAL)

SUGGESTED SAMPLING LOCATIONS FOR TYPICAL AERATION METHODS [85]

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542		BY BG DATE 23 MAR 77 DWG NO. A1269 – 6	FIG. 4.1

3. Determination of dissolved oxygen may be by either the Winkler wet chemical method (including appropriate variations such as the Azide modification) or by a polaragraphic oxygen probe according to Standard Methods [39]. Unfortunately, while it is relatively easy to perform the tests, uncorrected interferences can result in poor determinations. Recent articles have devoted a considerable amount of time debating the problems involved with obtaining accurate dissolved oxygen concentrations.

The main debate centers on the interference, in this case enhancement, of sodium sulfite, Na_2SO_3, and cobalt catalyst, a commonly used deoxygenation material. It is claimed by Kalinske et.al. [90] that normal concentrations of Na_2SO_3 can interfere to a significant extent with the Winkler test depending on the cobalt catalyst concentration. The interference appears to be caused by a precipitant complex of cobalt and sulfite which titrates as dissolved oxygen in the Winkler analysis. The chemical precipitate seems to be pH dependent as well, as it forms readily above pH 7 and will not form at all below pH 5. The effect is claimed to be negligible with a cobalt concentration of 0.05 mg/l and to be very large at the levels considered normal by some aeration manufacturers i.e. 2-5 mg/l. Their findings are based on extensive laboratory testing and are substantiated by the fact that many authors have reported apparent interferences in test samples, often resulting in dissolved oxygen concentrations well in excess of standard values.

The obvious solution is to reduce the catalyst concentration to 0.05 mg/l or lower and avoid the interference problems. However, there is much disagreement on the adequate level of the catalyst. If an insufficient concentration of cobalt is used, the deoxygenation reaction will not go to completion and as the oxygen level tries to rise unreacted sulfite will then combine creating interferences in the determination of the value of K_La and will result in a lower K_La. In general, the literature supports the use of cobalt concentrations of less than or equal to 0.05 mg/l as being adequate to catalyze the sulfite to sulfate reaction (Pye, 1947; Zieminski et.al., 1958; and Krenkel and Orlob, 1962), but manufacturers tend to be skeptical since insufficient catalyst only detracts from their equipment performance.

If Na_2SO_3 is used as the deoxygenating material the following appear to be acceptable methods of obtaining accurate dissolved oxygen concentrations:

a) The chemical effect can be avoided altogether by using a fast response polaragraphic probe instead of the Winkler analysis. But, the probe does have an inherent delay that can cause a small error in the determination of K_La if the probe is placed in the test tank, a previously specified procedure [10]. This lag error can be eliminated, however by taking the samples in BOD bottles and placing the probe in them. In this way one obtains multiple data points at each sample time, with no error in oxygen determination [100], and only one probe is needed.

If the investigator wishes to use a probe in the tank (especially if a recorder will be used), the probe response time delay can be mathematically predicted if the probe membrane coefficient, Kp, is known. When $Kp > 10\ K_La$ any correction is insignificant, but for instances where $Kp < 10\ K_La$ the corrected K_La value due to probe response time may be calculated by the following equation [101,102]:

$$Cp = C_{se}\left[1 + \left(\frac{K_La}{Kp-K_La}\right)e^{-Kpt} - \left(\frac{Kp}{Kp-K_La}\right)e^{-K_Lat}\right] \quad \ldots\ldots\ldots\ldots\ldots (36)$$

where Cp = Dissolved oxygen concentration as measured by the probe, mg/l

Kp = Probe membrane coefficient, hr^{-1}

t = Any time during the test with zero at the point of initial D.O. increase, hr.

The effect of Kp on the response curve is shown graphically in Figure 4.2.

When Kp is much greater than K_La, equation (36) reduces to:

$$C = Cp = C_{se} (1-e^{-K_L at}) \quad \text{.............(37)}$$

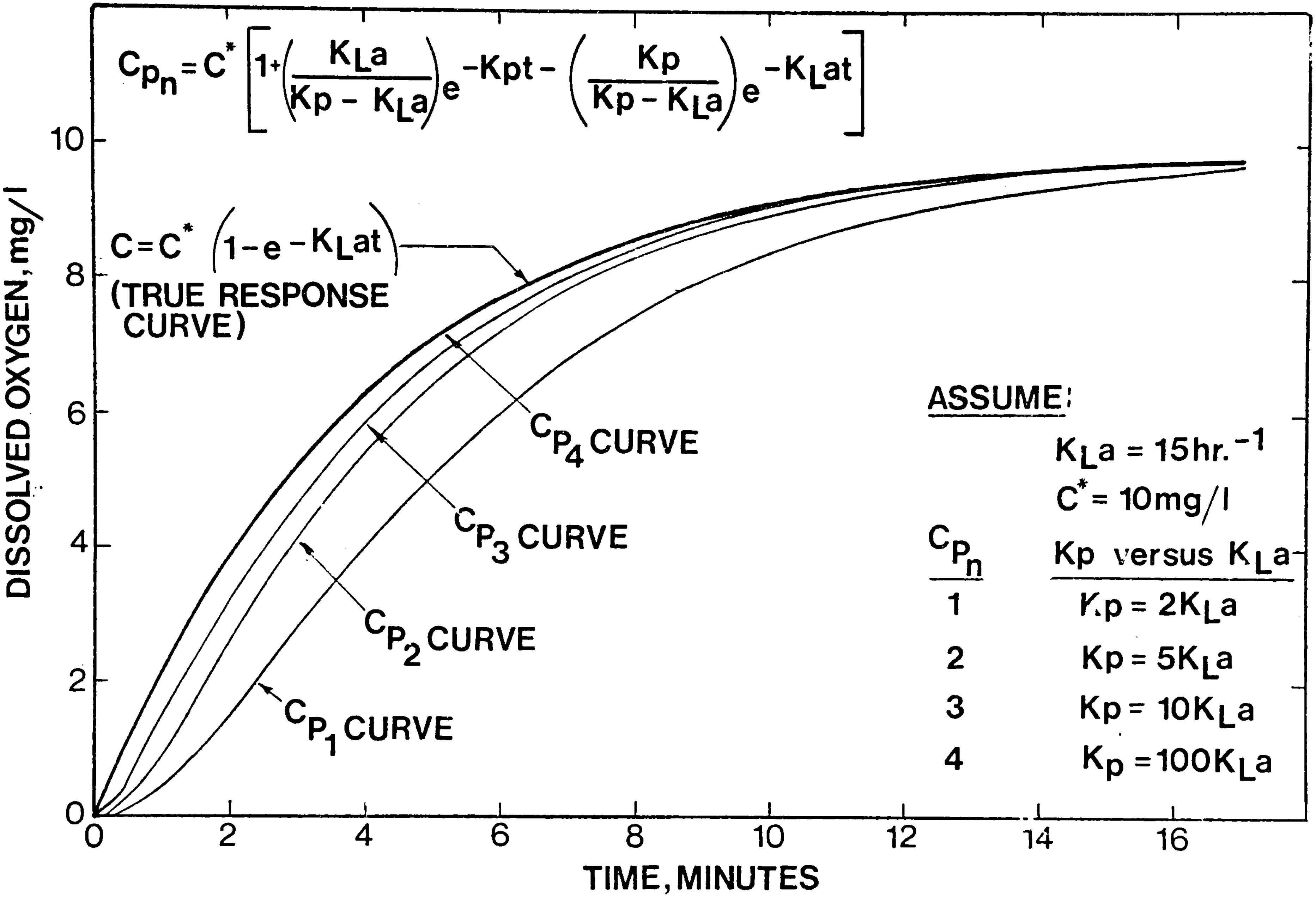
which is the integrated form of the general expression for oxygen transfer, equation (6). Therefore, when the Kp of the probe membrane exceeds 10 $K_La(hr^{-1})$ the response time delay may be neglected and the probe may be placed in the tank directly without incurring significant error. Generally, probes which reach 99 percent of the true value of C_s in less than 30 seconds [102] or 15 seconds [90] can be used without correction for time delay.

b) If the Winkler procedure is used for dissolved oxygen determination of the test water (Azide modification for wastewaters or mixed liquor), then two possible solutions are available. One, is to limit the use of the cobalt catalyst to 0.05 mg/l. This forces the acceptance of the minor positive interference that results and some slight non-linearity in the high deficit region from small amounts of unreacted Na_2SO_3 still remaining as the dissolved oxygen concentration rises. The second solution is that proposed by Stanton and Bradley [93] and Lakin [103]. Their proposal is to use an "adequate" amount of cobalt catalyst, say 2 mg/l, and to subtract the chemical interference by the use of a chemical blank.

They suggest that the chemical precipitate, which may be related to the brownish color found in aeration basins after several trials, acts as an oxidant similar to dissolved oxygen after acidification and increases the amount of free iodine released and measured by titration in the Winkler procedure. To measure this positive interference two samples are withdrawn from the test tank at any time during the reaeration test. The first is analyzed by following the complete Winkler analysis procedure while the second has the addition of manganese sulfate solution withheld but otherwise tested the same. If the second sample has any reading it is due to the oxidizing property of the chemical precipitant and other oxidants in the "clean" water. The reading of the second sample is then the positive interference of the catalyst and Na_2SO_4 and should be deducted from the other dissolved oxygen concentrations of the test. Cross checks with an oxygen probe have confirmed the accuracy of this procedure. It is necessary to test for chemical interference after each addition of Na_2SO_3, but the effect has been found to remain constant during a given test run.

4. Before the reaeration part of the non steady-state test can be run, the test water must first be deoxygenated. There are two methods in use today: sodium sulfite with catalyst and nitrogen gas.

   Using nitrogen gas to strip all the oxygen out of the test water is relatively difficult and expensive to employ. It requires using an underwater distribution system and may not be able to completely deoxygenate the water while a surface aerator is mixing the liquid. It would seem to be better suited to a submerged aeration system where it could be distributed through the air supply system, effectively mixing the contents, and then turned off to allow the air/oxygen to be sent down. However, it does have the advantage of not creating any interference with the dissolved oxygen determination.



AFFECT OF Kp ON RESPONSE CURVE [103]

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	BY BG DWG. NO. A1269-7	DATE: 24 MAR 77	FIG. 4.2

Sodium Sulfite, Na_2SO_3, is the most often used oxygen scavenging agent. It is readily available as various forms of it are used for removing oxygen from circulating water systems such as boilers. The reaction of sulfite is described by

$$Na_2SO_3 + O_2 \rightarrow Na_2SO_4 \ldots\ldots\ldots\ldots\ldots (38)$$

Theoretically, 7.9 mg/l Na_2SO_3 is needed per mg/l dissolved oxygen. This means that for saturated water at 20°C (C_s = 9.18 mg/l) approximately 70 mg/l of Na_2SO_3 is required to deoxygenate the liquid. However, because the aeration system is used to mix the basin and the sulfite solution is partially oxidized during the mixing period it is necessary to add approximately 1.5 times the theoretical quantity such that 100 mg/l of Na_2SO_3 is the typical addition [48,85,90.92].

The sulfite is added to the test tank after a hydraulic steady-state has been reached. The sulfite should be predissolved in a concentrated slurry or it is probable that the dry material will form lumps in the basin. At least two addition points should be used to disperse the sulfite solution as quickly as possible.

Unfortunately, Na_2SO_3 by itself will not completely deoxygenate water as quickly as is needed for the non steady-state test. Therefore, a catalyst is needed to help the reaction to its end point. The universally accepted catalyst is cobalt either in combination with chloride or sulfate. Cobalt chloride is typically supplied as a hydrate in the form ($CoCl_2 \cdot 6H_2O$). The amount of catalyst used depends to some extent on the oxygen determination method (see item 3 above), but will generally be around 0.05 mg/l for straight Winkler determinations and 2.0 mg/l for Winkler compensated or oxygen probe determinations. There does not appear to be any substantiated reason for ever using more than 2.0 mg/l and in fact, the bulk of the literature shows that cobalt catalyst additions in excess of a few tenths of a milligram are unnecessary [85]. The catalyst is added directly to the test basin before starting the aeration system to begin mixing. The catalyst is not consumed in the reaction and need only be added once.

The above statement may seem a bit obvious, but some authors have suggested mixing the catalyst with the sulfite solution and adding the two together, which is fine for one test run on a batch of clean water, but is definitely not acceptable for multiple runs as the catalyst concentration will rise. Related to this is the use of commercial grade sodium sulfite which contains small amounts of catalysts.

Although the concentration of these catalysts is small especially for the first addition, Kalinske et.al. [90] found that after 10 additions the Winkler analysis was reading 0.6 mg/l high which can inflate the resulting K_La value about 20 percent. Technical grade sodium sulfite that does not contain catalysts should be used or the interference will have to be determined. Also note that alternative forms of Na_2SO_3such as $N_2S_2O_5$ (sodium metabisulfate) are unacceptable as deoxygenating agents because of an unfavourable equilibrium which limits the rate of deoxygenation.

Other catalysts are available that do not interfere with the Winkler analysis, most notably copper, but they are relatively less efficient. The copper catalyst is generally slower acting and requires between 25-50 mg/l as copper to effectively catalyze the reaction and therefore tends to cost much more.

•

Even when low amounts of catalyst are used it has been noted that as the number of test runs performed on a single batch of water increases the K_La increases. Because of this it is recommended that a maximum of ten tests be performed on a single batch of water or that the rise in K_La be recorded and graphed so that a correction factor may be derived [49,55,90,91,100].

DATA ANALYSIS

Unfortunately, the test procedure is not the only area in which inaccuracies abound. Once the investigator has properly performed his reaeration test several times to develop adequate test data he is now faced with enough inconsistencies and irregularities in common data reduction/analysis procedures to alter the true oxygenation capacity of the subject aeration system by $\pm$ 25%. Mechanistically, the approach is simple; average the data, plot the log of the oxygen deficit versus time and draw a best fit line through the points. The slope of the line i.e. equation (35) is K_La. The problems develop through the improper selection of C_{se}, and truncation of data, not to mention the fact that semi-log plots always weight the data. This last subject does not have any astounding practical significance, but it was correctly questioned by Boyle et.al. [104] who pointed out that it is only when the larger errors in measurement are in the large oxygen deficit region that the data is properly weighted by the logarithmic transformation. If the data are equally in error a non-linear plot on arithmetic paper will probably result in the best fit by a least squares analysis. But, for the convenience of having a final plot which is in the form of y = mx+b the semi log plot has become the most accepted analysis method.

Selection of C_s

The value to be used for the dissolved oxygen saturation concentration in aeration testing is very probably the most difficult subject to have any two aeration authorities agree and it is critical to obtaining an accurate estimate of K_La. Many methods have been discussed in the literature on how to properly select/determine C_{se}: (a) one can find it in a table of $C_{ss(t)}$ values, such as Standard Methods [39] or the ASCE tables [105] and use it directly for surface aeration or compute an average C_{se} for submerged aeration; (b) one can measure it directly by aerating the test water with the aeration system for an extended time; (c) one can find it indirectly by plotting the test data with assumed C_{se} values until the data plots straight i.e. best fit of data; or finally (d) one can employ the procedure suggested by Stukenberg and McKinney [55] and plot the aeration test data directly onto arithmetic paper as oxygen transferred (mg/l/hr) versus dissolved oxygen (mg/l) which reveals not only the effective C_{se}, but also the maximum oxygenation capacity, the K_La (at test temperature) and hydraulic characteristics of the test basin and aeration system.

a) Published Values

Values for the $C_{ss(t)}$ in water have been published in references [39] and [105]. The two tables were developed separately and are not in complete agreement. Investigators have found the values published in the ASCE tables [105] have generally been more accurate especially between the temperatures of 10°C to 30°C. As long as the surface aeration device does not entrain large quantities of air and transport it to great depths the table values will probably be sufficient. But, if the aerator does entrain air and transport it down to the tank bottom, because of a small tank surface area or small volume, the table value will be low. In this case it is probably better to run the risk of incurring some experimental error in determining the C_{se} by extended aeration (direct determination). The use of the table values for surface aerators has been an accepted practice, but the compounded positive error of using a table value of $C_{ss(t)}$ (creating a smaller driving force $C_{se}-C$) along with a cobalt catalyst inflated Winkler analysis result (creating a still smaller driving force) can be significant. This can produce seriously inflated values of K_La for the aerator being tested.

For submerged aeration, depth adjusted table values of $C_{ss(t,p)}$ have been used almost universally. As described earlier this is wrong, but if the air release depth is not great, then a reasonable approximation can be calculated. The example problem which is shown in Appendix 1 discusses the choices and results of the different depth corrected saturation concentration calculations. If a computer is readily available or if the investigator is willing to spend the time it is possible to obtain the constantly varying value of C_{se} all through the aeration test, a procedure that should result in the most closely correct analysis of the data. However, if the submergence of the diffuser is less than 20 ft using one of the constant C_{se} calculations may be justified [93].

b) Extended Aeration

This method is useful when testing surface aerators which entrain and transport air to the lower regions of the tank and all submerged systems. It is also useful when positive uncorrected interference is suspected in the Winkler analysis. The problem is that it is very difficult to know when a body of liquid is saturated. Estimates of $6/K_La$ [85], 15-20 minutes after not more than 0.05 mg/l change in dissolved oxygen concentration at a power density of 0.1 shaft HP/1000 gal [100], and several hours [92] have been given in the literature.

Another problem is that of accurately measuring the C_{se}. The presence of microscopic air bubbles in the liquid will probably titrate as dissolved oxygen in the Winkler test even though they are not in the true sense dissolved nor create a larger driving force. The polaragraphic oxygen analyzer will accurately determine the dissolved oxygen concentration if the probe has been accurately calibrated. This calibration is often done by standardizing the probe against a "saturated" distilled water sample analyzed by the Winkler procedure, which may have some interference from sub-optical air bubbles, but at least the error is on the conservative side. The literature clearly shows that there is merit in determining the C_{se} by direct observation because at the very least it helps to gain better insight into the dynamics of the system and more objectivity in oxygen transfer rate reporting.

If the direct observation value of C_{se} is significantly different from the calculated or assumed C_{se} then the investigator must be able to account for the variance or arbitrarily accept one value over the other [102,104].

Direct observation of C_{se} has shown low speed surface aerators to create C_{se} values significantly above table values while high speed surface aerators were not significantly different than the table values [104]. For submerged systems direct observation usually shows C_{se} equivalent to .22 to .33 of the side wall depth from the surface to the air outlet level [77,83,91,102].

c) Curve Fitting

This technique is based on the fact that the oxygen deficit versus time should plot as a straight line on semi-logarithmic paper. For this determination of C_{se} different values of C_{se} are assumed and the data plotted until a "best fit" or straight line results. In theory this sounds good but in practice there is little sensitivity in this method, especially when low deficit data is truncated. The problem is that non-linearity usually only occurs at low deficit values ($C_{se}-C < 1.0$ mg/l). Since the values are small, great accuracy is required or large displacements of the plotted points will result.

For submerged aeration C_{se} is known not to be a constant especially in the low deficit time period of the test when both oxygen transfer and stripping occur simultaneously. Therefore, this method for C_{se} determination which assumes linearity at low deficit values where the mass transfer equation is compromised, is not recommended [91].

The method was examined for surface aeration by Boyle, et.al. [104]; they found that by applying a non-linear least squares analysis to the plots resulting from different assumed C_{se} values there was no statistical difference at the 95% confidence level between C_{se} values between 8.6 mg/l and 9.6 mg/l when high end truncation of the data was allowed. Their conclusion was that this method is relatively insensitive and subject to considerable bias especially when data truncation occurs.

d) Direct Analysis of Test Data

A method has been proposed recently by Stukenberg and McKinney [85] that provides C_{se} without assumptions or measurement by direct data evaluation. With this method the data is analyzed at each sample time so that for each period an average dissolved oxygen level (abscissa) in the tank is paired with the amount of oxygen supplied (ordinate) during that period (mg/l/hr) and the pairs are plotted on rectangular coordinates. A best fit line is drawn through the data points and extended to intercept the axes. The x-intercept is the C_{se} and the y-intercept is the maximum rate of oxygen transfer possible with the C_{se} value for the particular sample point. While the normal oxygen deficit plot versus time tends to be very smooth and linear the direct method has a tendency to be very non-uniform. The non-uniformity (randomness) is an indication that hydraulic surging was taking place during the test because of aerator interference, poor baffling, or other geometry related problems. In this way the authors suggest that the direct method provides a very useful tool in assisting in the interpretation of test results.

This method has just been recently published and therefore there has been little response to it. However, it should be pointed out that the non-uniformity (randomness of data points) which may well indicate hydraulic characteristics of the test tank makes it difficult to obtain a best fit line, and therefore compromises the accuracy of the value of C_{se} which results.

Certainly a linear least squares analysis would be an asset as lines drawn by eye would not generate much confidence. As a final comment an example given in the text shows a higher C_{se} value for a surface aerator than for diffused aeration or submerged turbine aeration systems and this would be difficult to substantiate (although the figure may be non-representative of the merit of the data analysis method i.e. it may be the exception and not the rule).

See Appendix 1 for an example problem covering the effect of various C_{se} values on K_La.

From the preceding discussion and the Appendix 1 example problem the dramatic effect of C_{se} on K_La is readily apparent. Certainly the design engineer and customer would be well served if a fixed and correct method of determining C_{se} for aeration devices could be provided such as has been attempted by Berk, et.al. [95], Eckenfelder [8,10,13,109] and Shell et.al. [91,112] in their proposed use of the mid-depth corrected model for submerged aeration and a book value for surface aeration. However, the diverse aeration and mixing characteristics of aeration devices in various geometries dictates against finding such a fixed method. Consequently a flexible method, one which determines C_{se} from the data or directly from extended aeration, then has merit in aeration analysis.

For submerged aeration no one method has yet been identified that clearly shows it to yield consistent results that allow direct comparison with surface aerators. The following procedure would seem to offer the best solution by determining C_{se} by several different methods and reporting them all. During the reaeration test, run the test until an asymptotic value for C_{se} is reached and then use this value and all the data points to determine K_La. Plot the data directly as suggested by Stukenberg and McKinney [85] and determine the

C_{se} from the best fit line through the data. Especially for deep submergence tests, analysis of all the data by the log mean driving force model should be performed to determine K_La. Finally, the mid-depth corrected model as well as the best fit line analysis of the deficit plot using all the data up to an asymptotic C_{se} should be tried. If after determining C_{se} and K_La from these various methods close agreement between all the methods is noted, one can be reasonably confident of the test procedure and the resulting value of K_La. However, if on the other hand, the various methods yield significantly different C_{se} and K_La results, either the divergent methods must be accounted for and neglected or all the test results must be reported because no valid reason for arbitrarily ommitting one method and accepting another could be found.

For surface aeration the flexible approach must include C_{se} determination by the tables [39,105], by direct observation of the asymptotic C_{se} value, by direct analysis of the data [85], and by the best fit line analysis of the deficit plot using all data up to an asymptotic value of C_{se}. The same comparison and reporting of results applies to surface aeration as well as submerged systems.

Since the Whitman two-film theory is universally accepted, the linearity of the deficit versus time plot must also be accepted as evidence of a correct value of C_{se}. Slight non-linearities are to be expected in the low deficit area ($C_{se}-C < 1$ mg/l) because of the high degree of accuracy needed in C determination or conversely because of the high probability that C values in that region will be in variance with the true value. However, there is little reason to accept the C_{se} that is determined by an assumed condition or calculated by a static geometry relationship if this method generally yields a non-linear deficit plot. Therefore, to accept the surface saturation $C_{ss(t,p)}$ as the only correct value for a surface aeration and to accept the mid-depth corrected method determination of C_{se} as the only correct value for a submerged system when the data always plot in a non-linear manner for that particular surface aerator or submerged system is to be blind to the possibility that the dynamic conditions during the reaeration test negate the C_{se} values derived from the static geometry. This is why it is suggested to use and report multiple C_{se} and K_La determination methods even though it is not a simplification of the problem.

Test Data Truncation

It is a common occurrence for a test specification to mention the interval over which the test results shall apply i.e. 20%-70% of saturation or 10%-90% of saturation. The reason for this is none other than ensuring that the data will plot straight, although the reason most often given is that the data on the extremes are unreliable and should not be included.

First let us consider truncation of low end data. It is true that the initial dissolved oxygen levels are influenced in some cases by residual unreacted sulfite and are very time sensitive. Slight time lags in sample transport will suggest a lower K_La value initially, so in terms of reliability the current testing methods do not provide initial data in which one can place high confidence. As well it does not seem worthwhile to improve the testing procedure to yield more reliable initial data, because the critical part of the test for determining K_La is approximately 2/3 C_{se} [104]. Truncation of the first 10-20% of the data does not markedly affect K_La and therefore may be dropped.

Although numerous explanations have been brought forth favoring high end data truncation, there is little hard evidence available to support the indiscriminate truncation of data in the low deficit region. The data although dependent on an accurate determination of C are not subject to any test related problems such as residual unreacted sulfite or high time sensitivity. The problem here is that the greater the difference between the real C_{se} and the assumed/observed/calculated C_{se} the greater the non-linearity the K_La plot displays. Boyle, et.al. [104] analyzed this fallacy in detail and could not find any support for high end truncation. The region critical to K_La determination was found to be

2/3 C_{se} so that data in the 70%-90% range are necessary. They found that by truncating at 70% a well fitting (by eye and by statistics) K_La plot could be drawn that was 15% higher than by truncation at 90%. Truncation of data permits a K_La to be determined that fits the truncated test data very well, but it does not necessarily provide a true value of K_La.

Essentially, truncation of high end data allows the use of many C_{se} values which are all equally statistically valid; there is little evidence to support one over another. However, substantial differences in K_La are produced by different values of C_{se} (and K_La varies more rapidly than C_{se}).

This makes a strong argument in favor of eliminating all high end truncation of data and simultaneously suggests the use of the correct value of C_{se}, if a precise estimate of K_La is desired.

NON STEADY-STATE TEST SUMMARY

According to Landberg et.al. [49], the first concept investigators and aeration equipment users must realize is that the test does not have a high degree of accuracy. They show the results of 26 separate aeration tests performed over 9 months with the only variables being water temperature, environmental conditions, and residual sulfate levels. After using all correction factors to bring the data to standard conditions the 26 K_La values ranged from 22 hr^{-1} to 29 hr^{-1} with a mean of 25.1 hr^{-1} and a standard deviation of 1.57. What kind of accuracy can one expect from a well run, properly analyzed series of tests? It would seem reasonable to expect an accuracy of approximately $\pm$ 5% of the true value [102]. An improperly tested and analyzed test result may be in variance with the real value by as much as 50%.

One also has to be aware that test results from small scale units must be evaluated closely. Kalinske [92] reports that lab scale low speed surface aerators have provided up to 8 lbs O_2/hp-hr while an acceptable figure for a full scale field unit ranges between 2.8 to 4.5 lbs O_2/hp-hr.

Finally, what can be said about the non steady-state test is that it is still the best test for realistic comparison of all types aeration devices. What is needed is not to have all agree that one method of testing and data analysis is the correct way, but merely to establish a reasonable standard procedure that all can follow and that is fair to both surface and submerged aeration equipment. Many standard procedures have been suggested, but all fail to adequately handle testing interferences and data analysis biases.

4.1.2 Steady-State Aeration of Mixed Liquor

The second aeration test procedure that has been used extensively is the steady-state aeration of mixed liquor. The test has been used because it enables the tester to measure the capabilities of the aeration device directly in a biomass suspension rather than extrapolate from a clean water test to the field application. The test has not been accepted as the best method to specify and compare equipment performance because of difficulties in obtaining reproducible results; however, it has been suggested as a good method to evaluate the equipment once it is installed and operating in the field.

Mathematically, the steady-state test is described by equation (7) with an additional factor for the oxygen uptake rate, r, which depletes dissolved oxygen:

$$\frac{dC}{dt} = K_L a\,(C_{se} - C) - r \quad \ldots\ldots\ldots\ldots\ldots\ldots (39)$$

When the system is indeed running at steady-state conditions i.e. constant dissolved oxygen level and oxygen uptake rate, equation (39) can be simplified because $\frac{dC}{dt} = 0$

$$K_L a \text{ (Test Conditions)} = \frac{r}{C_{se} - C} \quad \ldots\ldots\ldots\ldots\ldots (40)$$

where $C_{se} = C_{sw(depth,t,p)}$ = Oxygen saturation concentration of the waste at operating conditions, mg/l.

Equation (40) may be brought to standard conditions by applying the correction factors as mentioned in Section 3.0.0.

TEST PROCEDURE

The test is simple to describe and analyze, but as will be described later several of the test determinations are difficult to perform with great accuracy. To perform the test one finds an operating mixed liquor system where the dissolved oxygen concentration is relatively stable. To find the K_La at the test conditions one obtains the following data:

1. Oxygen uptake rate, r, mg/l/hr.
2. Dissolved oxygen concentration, c, mg/l.
3. Wastewater saturation concentration, C_{se}, mg/l.

To compute the oxygen transfer efficiency in terms of lbs O_2/hp-hr at the test conditions additional data is required:

1. Weight of water under aeration, Millions of lbs.
2. Operating horsepower, HP, be sure to specify nameplate, electrical, shaft or adiabatic HP.

Finally, to compute a transfer efficiency at standard conditions one must measure:

1. Relative transfer coefficient, α.
2. Relative saturation concentration coefficient, β.
3. Mixed liquor temperature, °C.
4. Site barometric pressure, mm Hg (psia).

The assumptions made in using equation (40) and this test include: that it is possible to measure accurately the biomass activity in terms of oxygen uptake rate; that the basin dissolved oxygen concentration is a uniform constant; that a representative C_{se} can be measured or computed; and that the biomass does not interfere or enhance oxygen transfer.

Oxygen Uptake Rate

To measure the oxygen uptake rate one removes a representative sample of mixed liquor and monitors dissolved oxygen depletion as a function of time while mixing the contents and preventing aeration of the sample, although Conway and Kumke [79] suggest several other possible methods. The problems in obtaining an accurate measurement are severalfold.

First, as soon as the sample is removed a rapid initial depletion of dissolved oxygen is found followed by changes in the metabolic rate as the available substrate and dissolved oxygen levels are removed. Depending on the amount of oxygen and substrate to begin with the metabolic rate measured after a short period may approach endogenous respiration rates, several times lower than normal substrate oxidation rates. Second, as confirmed by Richard and Gaudy [106], the uptake rate is affected by the agitation level, and any externally determined value for an uptake rate can not adequately indicate the rate that will be achieved at the oxygen and substrate level found in the actual aeration basin. Error in the first part can be minimized if the flow of wastewater is cut at least 60 min. prior to the test. By doing so the biomass uptake rate will be principally the rate of endogenous respiration which is very close to a constant [85].

Dissolved Oxygen Concentration Uniformity

It is improbable for an entire basin to be at a uniform dissolved oxygen concentration even if the oxygen uptake is small, especially for point sources of aeration input. The best that can be done in this test is to monitor the dissolved oxygen at several points in the basin and take an average. One of the monitoring points should be in the intake flow to the aerator or diffuser. See Figure 4.1 for recommended monitoring points.

Oxygen Saturation Concentration

As shown in the earlier Section 4.1.1, the correct value for C_{se} in aeration is rather difficult to estimate or measure. To obtain a C_{se} for the mixed liquor basin two methods are available. The simplest method is to take a sample of the mixed liquor, aerate it for several hours or 6 times $1/K_La$ and record the C_{se}. The difference between $C_{ss(t,p)}$ (table value) and C_{se} will be a function of β. However, as the mixed liquor is aerated the organic compounds which cause the β factor to occur will be partially oxidized so that this result is only approximate. The other method is one developed by Stukenberg and McKinney [85]. Their method of direct data analysis permits the estimation of C_{se} by the x-axis intercept of a line fit through the data points by regression analysis. Again, although regression analysis provides a valid means of locating the best fit, the confidence in the intercept value should be judged by the strength of the correlation coefficient.

Biomass Interference in Oxygen Transfer

The classical concern over biomass interference with oxygen transfer was viscosity increase. But, for the most part the MLSS concentration in aeration basins is not great enough to significantly affect viscosity. A new complicating factor has been proposed, however, which shows that biomass when in an environment that lacks sufficient dissolved oxygen are able to absorb oxygen directly from air bubbles [96, 107]. If true, this means that significantly higher levels of oxygen transfer are capable in an aeration basin, than in the non-aerated oxygen uptake measurement unit.

Miscellaneous Considerations

If the problems involved in determining a K_La (test conditions) were not great enough, then the further complication of having to analyze an accurate alpha value for the wastewater mixed liquor helps to explain why this test procedure is not considered an adequate test of standard aerator performance. Basically, the problem involved with determining an alpha value is that it is an imprecise test. Even if the alpha test tank has approximately the same K_La as the full scale system, the scale factors involved compromise the accuracy.

Another means of determining the oxygen transfer rate of an on-line system has been to use BOD_5. The theory behind this is that by computing the BOD_5 reduction in pounds in place of an uptake rate determination and measuring the other environmental and mixed liquor characteristics an estimate of the aeration system's oxygenation capacity could be made. In addition to all the other accuracy problems mentioned before, this test procedure assumes that BOD_5 input is constant, that there is no oxygen demand from bottom sludge, and that no oxygen is transferred from the atmosphere to the still water surface which in some aerobic-facultative lagoons can approach 10-20 percent of the oxygen requirement. In summary, Busch [72] adds that because of the various biological interferences with the elementary oxygen transfer process "BOD_5 is not an adequate or valid parameter of process performance and BOD_5 removal is not an adequate or valid indication of oxygen transfer or aerator efficiency."

SUMMARY OF MIXED LIQUOR STEADY-STATE TEST

This test procedure provides a relatively easy check on aeration performance in the field when non steady-state tests are impractical. However, the questionable accuracy of the various required measurements limits the usefulness of the test and certainly restricts its use as a means of obtaining a performance specification.

4.1.3 Steady-State Oxidation of Sulfite

This test technique was first used by Cooper et.al. [14] in 1944 to determine the mass transfer characteristics of submerged turbine impellers. The test was originally developed to provide a consistent and reliable approach to oxygen transfer measurements. The test although easily performed gives unrealistically high values of K_La, but is included here to inform the reader.

In this method, sulfite is added to water in a test tank in quite high concentrations so that when an aeration device is run all the oxygen is reacted with sulfite to form sulfate. The overall sulfite-sulfate reaction is quite simple,

$$SO_3^{=} + 1/2\ O_2 \xrightarrow{\text{catalyst}} SO_4^{=} \quad \ldots\ldots\ldots\ldots\ldots(41)$$

Using the standard iodometric titration of the unreacted sulfite before and after aeration can then reveal the amount of oxygen transferred according to the following equation [11],

$$N = \frac{N_{SO_3^=}(\text{initial}) - N_{SO_3^=}(\text{final})}{t_2 - t_1} \times \frac{7.9 \text{ gm}}{\text{gm equiv.}} \times \frac{V}{454} \quad \ldots(42)$$

where N = Lbs of oxygen absorbed per hr

N_{SO_3} = Normality of sulfite solution being aerated

t = Time, in hrs

V = Volume of test liquid, litres.

The bulk liquid dissolved oxygen concentration remains at zero and by inserting the applicable test water oxygen saturation concentration value the overall liquid phase oxygen transfer coefficient can be calculated

$$K_L a = \frac{N}{C_{se} - C} = \frac{N}{C_{se}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(43)$$

The true kinetics of the sulfite reaction although extensively studied are as yet unknown. The sulfite oxidation method involves simultaneous gas absorption and chemical reaction and is extremely sensitive to the type and quantity of catalyst used. McWhirter [11] cites many conflicting reports concerning the results of sulfite oxidation.

Basically what can be said about the sulfite oxidation test is that it is simple to perform and when care is taken to minimize temperature and catalyst changes between different runs, it is a good means for comparing devices. However, it gives a result that has little to do with the oxygen transfer capabilities of an aeration device in clean water or in mixed liquor. The results given by the test are always higher than the results given by the more accepted clean water test. An example of this increase in oxygen transfer as well as the dependence on the catalyst is given in Figure 4.3. The increase in oxygenation capacity resulting from this test using the non steady-state reaeration test as a base line has been reported to be as much as 44 percent [79] and 50 percent [92].

4.1.4 Miscellaneous Testing Methods

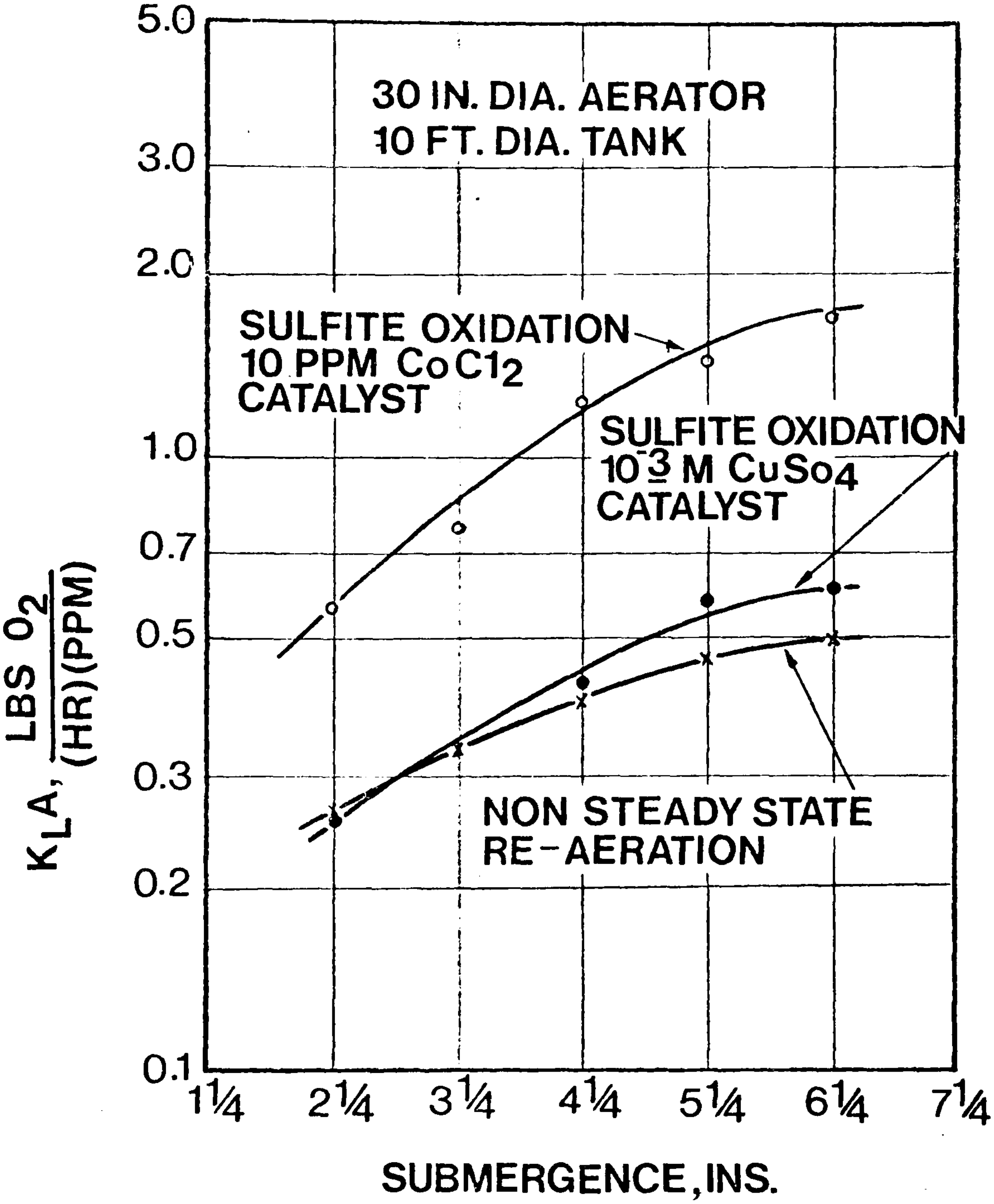
The following methods are included to fully cover the testing methods that have been employed in the past, but they are not considered either practical or reliable for various reasons

a. Steady-State Aeration of Clean Water

This test procedure is divided into two segments: first, where one places an aeration system in a small slow river and measures the upstream and downstream dissolved oxygen concentrations, and second, an attempt to simulate this field test in a controlled test tank where a large quantity of low oxygen content water is pumped into a small reactor where an aeration device adds oxygen before discharge.

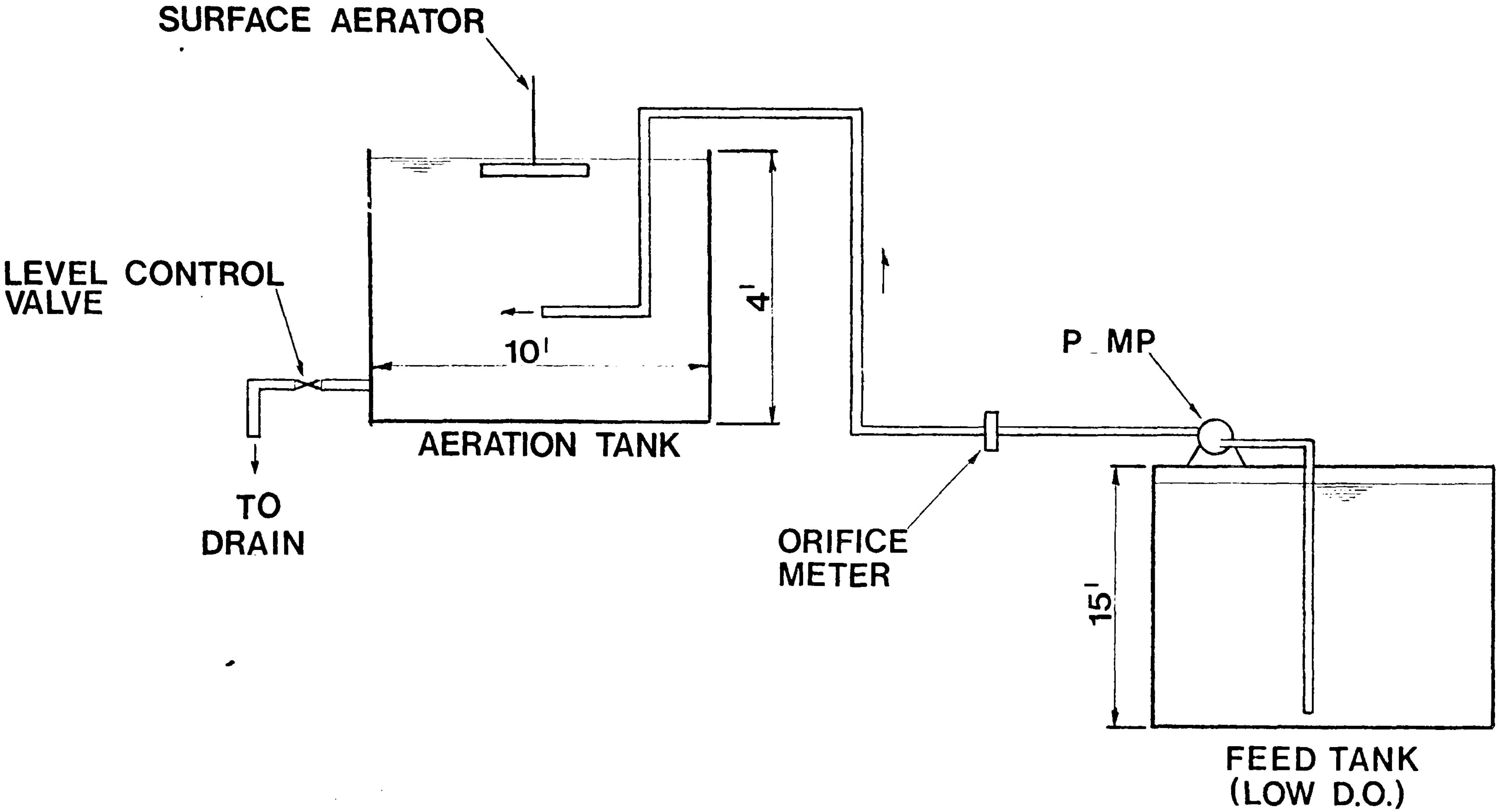
The testing of aerators in rivers has been used more as a means of examining the feasibility of assisting pollution abatement in non-turbulent, low D.O. rivers than an attempt to establish a standard oxygen transfer test procedure. The test is subject to many inaccuracies especially concerning precise estimates of flow and average D.O. concentration. One of the first tests involving mechanical surface aerators in a navigable channel was in the canals of Chicago by Kaplovsky, et.al [80]. More recently two studies were done on large polluted rivers using both mechanical surface aerators and submerged systems [81,86]. These reports include very good reference lists concerning river aeration.

The testing of an aeration system in a small basin with influent and effluent flows would be similar to Figure 4.4. The test makes all the same assumptions as for the non steady-state test, but it has the advantage of being able to use smaller test tanks thereby reducing concentration gradients. The test result is accurate and very close to the unsteady state, however, it is rather expensive to perform. McWhirter [11] reports that for a 1 HP, 30 in diameter surface turbine a flow of approximately 250 gpm was required. The flows required for a commercial sized aerator then become impracticable.



COMPARISON OF SURFACE AERATOR MASS TRANSFER COEFFICIENTS USING SULPHITE OXIDATION AND NON STEADY STATE REAERATION TECHNIQUES [11]

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	beak	BY B G	DATE 25 MAR 77	FIG. 4.3
		DWG NO	A1269-8	



SCHEMATIC DIAGRAM OF EXPERIMENTAL APPARATUS FOR STEADY-STATE REAERATION STUDIES [11]

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	BY BG	DATE 25 MAR 77	FIG. 4.4
	DWG. NO. A1269-9		

b. Gas Stream Oxygen Balance

This is a little known oxygen transfer test for submerged diffuser aeration systems. The test involves the capturing of rising gas bubbles at various levels in the test tank. The oxygen content is measured and a transfer efficiency can be computed. The test has not been found extremely useful and as compared to the non steady-state test it was found to give higher results by approximately 28 percent [79].

4.1.5 Interpreting Aeration Performance Test Results

With the universal acceptance of the non steady-state test procedure as a standard method of determining oxygen transfer capacity a person may compare the relative efficiencies of the various types of aeration equipment. However, one must be cautious in using the results of the standard test directly because they are only applicable to standard conditions of clean water at 20°C, atmospheric pressure = 760 mm Hg (14.7 psia), and dissolved oxygen concentration = 0.0 mg/l. In addition, the figure which the manufacturer reports as the standard oxygen transfer rate may be a result of adjustments in the applied HP to volume or area ratio, or in the baffling of the test vessel that was optimized to obtain the maximum oxygenation efficiency from the device.

The following equation is used to estimate the oxygen transfer efficiency of a surface aerator in the field when the standard transfer efficiency is known.

$$N = N_o \left(\frac{C_{se} - C}{C_{ss}} \right) \theta^{(T-20)} \qquad \text{.................(44)}$$

where N = Expected field oxygen transfer efficiency, lbs O_2/hp-hr

N_o = Standard oxygen transfer efficiency for clean water at 20°C, at- atmospheric pressure = 760 mm Hg (14.7 psia) and dissolved oxygen = 0.0 mg/l, lbs O_2/hp-hr

C_{se} = Effective dissolved oxygen saturation concentration of waste water in the field at field temperature, pressure, and salinity, mg/l. When beta is known the term is usually shown as $\beta C_{ss(t,p)}$ where $C_{ss(t,p)}$ is the dissolved oxygen saturation concentration for tap water at field wastewater temperature and atmospheric pressure

C_{ss} = Dissolved oxygen saturation concentration for the surface of clean water at 20°C and 760 mm Hg (14.7 psia), mg/l

C = Average operating level of dissolved oxygen concentration in aeration basin, mg/l

$\theta^{(T-20)}$ = Temperature correction for standard oxygen transfer rate, T°C

α = Ratio of K_La(wastewater)/K_La(tap water).

To exemplify what happens when a standard oxygen transfer rate is adjusted to field conditions without considering any other effects the following surface aerator example is given:

N_o = Standard oxygen transfer efficiency = 3.0 lbs O_2/hp-hr

Field Conditions:

Wastewater Characteristics

- temperature = 10°C (temperature correction factor θ = 1.024)
- alpha = 0.80
- beta = 0.95
- C operating level = 2.0 mg/l

Environmental Conditions

- pressure = 750 mm Hg
- saturated water vapor pressure at 10°C = 9 mm Hg

from Standard Methods [39]

$C_{ss} = 9.2$ mg/l

$C_{ss(10°C)} = 11.3$ mg/l

1. Compute C_{se} of wastewater = $\beta\ (11.3)\ \frac{750-9}{760-9} = 10.6$ mg/l

2. Compute temperature correction = $\theta^{(T-20)} = 1.024^{(10-20)} = 0.789$

3. Compute $N = (3.0)\left(\frac{10.6-2.0}{9.2}\right)(0.789)(0.80) = 1.8$ lbs O_2/hp-hr

So the 3.0 lbs O_2/hp-hr at standard conditions has been reduced to 1.8 lbs O_2/hp- hr at field conditions, a reduction of 40%. If an operating dissolved oxygen level of 1.0 mg/l could be accepted then the field oxygenation rate would be 2.0 lbs O_2/hp-hr a reduction of 33%.

POWER CONSUMPTION

A very important item when analyzing oxygen transfer efficiency rates is to be sure of the type of horsepower reported. The purchaser is usually interested in what the electrical horsepower is, because he must pay for the kilowatt hours consumed. Electrical horsepower is also known as gross, line or wire horsepower. The nameplate horsepower can be used in the efficiency figure, but it does not necessarily correlate to the amount of horsepower consumed or delivered to the water so it should be avoided. Shaft or delivered horsepower is power actually used to drive an aerator impeller, but it does not include motor or gear box losses. Adiabatic horsepower is the theoretical power used to deliver air to the outlet near the basin bottom and it does not include motor or blower losses although it may be included. It is reasonable for manufacturers to report efficiencies in terms of shaft or adiabatic horsepower, because they may not manufacture and market the motors and/or blowers to drive the aeration system and can not be responsible for losses in them. So as long as the purchaser is aware of the losses normally involved a reasonable comparison is possible. Table 4.1 summarizes normal efficiencies found in aeration components.

TABLE 4.1

EFFICIENCIES OF AERATION COMPONENTS

Item	Average Efficiency, %
Motor 100 HP (full load)	92
10 HP (full load)	85
Reducing Gear Box, 2 stage	97
3 stage	95
Blower, centrifugal	75
Blower, positive displacement	70

STANDARD GEOMETRY VS. FIELD GEOMETRY

Since the K_La of an aeration device has been reported to vary with the HP/unit volume [23] and HP/unit area [88], the relation of the standard test tank geometry and baffling to the field conditions is extremely important. Usually, the manufacturers perform non steady-state tests at reasonably high HP/unit volume or area, so that the purchaser must realize that if his application is an aerated lagoon, the performance of the aerator will be somewhat less (see Section 3.4.0).

BIOLOGICAL FACTORS

The standard oxygen transfer rate is based on pure physical diffusion into clean water, but in any biological treatment process there is a concurrent biochemical uptake of oxygen by bacteria in addition to the diffusion process. It has been noted that the rate of oxygen transfer in the steady-state sulfite oxidation test was directly related to the rate of the chemical reaction.

Similarly, Busch [72] and Albertson and DiGregorio [96] have proposed that the rate of oxygen transfer can not proceed faster than it is used and therefore the oxygenation capacity in mixed liquor is determined by the rate and net stoichiometry of the biological reaction in a particular system. And since the rates normally found in mixed liquor systems are limited, the actual oxygen transfer efficiencies are also limited and nearly equal. Albertson and DiGregorio [96] also report that in full-scale activated sludge tests oxygen transfer rates were measured far in excess of the rates normally considered standard which was attributed to direct transfer of oxygen from bubbles to the microorganisms. The concept of a biological uptake controlled oxygen transfer rate has been severely criticized by Kalinske [108].

From this discussion of field interferences, one concept is reasonably clear, and that is the accuracy of equation (44) in describing completely the expected performance of a surface aeration device is limited. This is not to say that precise testing methods and data analysis procedures are not warranted, but that when the standard oxygen transfer rate is extrapolated to the field, a high degree of confidence in the result is not possible and a conservative approach is necessary.

4.2.0 DETERMINING MIXING CAPABILITIES

Mixing in biological waste treatment aeration basins is necessary for oxygen dispersion throughout the liquid volume, for suspension of active biological solids, and for turbulence to promote a high rate of biological activity. The mixing capability of a given aeration device is fundamental to its effectiveness, but being able to quantify its mixing characteristics is not always easy.

There is no readily accepted standard for determination of mixing performance in the aeration industry today. The literature is filled with different descriptions of what constitutes adequate mixing, such as:

a. Horsepower per unit volume, HP/MG
b. Mixing radius (velocity)
c. Radius of Influence (oxygen dispersion)
d. Direct pumping rate
e. Induced pumping rate

It is obvious from the items above that they refer only to mechanical aerators. Mechanical aerators, especially surface aerators, have always been highly suspect as to their mixing ability because they are point sources of. power input that must pump the oxygenated liquid to the farthest reaches of the basin. Submerged aeration systems, such as diffused aeration on the other hand are not point sources of power, but are instead uniformly dispersed on the basin floor. Historically, submerged aeration systems have provided adequate solids suspension when sized for the oxygen requirements, so they have not received the same skepticism as their mechanical counterparts.

For either type of aeration system the desired result is oxygen dispersion and biological solids suspension. The best test method would be one where these characteristics could be measured. It has been suggested that bid requests require the suspended solids concentration of mixed liquor within the zone of influence of the aerator to show less than ± 10 percent variation from the mean [72] or less than ± 20 percent variation from the mean when the basin as a whole is considered [94]. This is a valid way to ensure that the aeration device meets the system requirements, but it has the disadvantage of being an after installation and start-up test. Therefore, it would be desirable to adopt a test method and a reporting system that would enable a manufacturer to inform the prospective client of the device's capabilities before purchase, such as is done with oxygen transfer. However, no uniform and fair system is now available and it appears one will not be forthcoming. This is the reason that claims of mixing are so contradictory and inconsistent.

There has been an attempt to describe adequate mixing in terms of horsepower per unit volume; in aerated lagoons it is usually reported as HP/MG. Unfortunately, as seen in Section 2.0.0 equal power application does not ensure equal mixing. What is necessary for this standard to become usable is to specify a power per unit volume for each type of aeration device.

Another system of mixing evaluation is based on the maintenance of a minimum solids suspension velocity of approximately 0.45 ft/sec. This system also falls short of defining mixing also because at some point in a recirculated system the horizontal and/or upward component of velocity must be zero; a single velocity figure is inadequate to describe the turbulence required to transport biological solids from the farthest reaches of the basin back to the aeration device [72].

The attempts to report a standard value led to the use of aerator pumping rate. This is based on the flow quantity pumped by the aerator and measured by multiplying the area of the intake or discharge stream times the stream velocity. The results of this type of measurement obviously favor low head, high volume pumps, but it does not necessarily indicate relative mixing capability. As a result of this, a term referred to as induced pumpage has been introduced which not only includes the liquid pumped through the aerator, but also includes the liquid movement induced by the issuing stream. For this number to be useful the induced pumpage rate must be accompanied by a description of the basin geometry in which this figure is valid and must specify the minimum velocity included in the liquid movement flow regime.

Finally, the concept of a radius or area of influence was introduced to the list of mixing terms in an attempt to describe the quantity of liquid affected by a point source aerator. This was supposed to end confusion about HP/MG, pumping rate, and velocity by combining all these variables into a single term that would describe how large an area a surface aerator would affect. The term was subdivided into two classifications, mixing radius and radius of influence, to account for the fact that a point source of power could disperse oxygen further into the basin than maintain solids in suspension.

The concept of mixing radius would seem to be the most valid method for describing the mixing capabilities of a surface aerator as long as the test procedures used to measure it are based on actual field results and not on extrapolations of small test tank velocity data. Therefore, while numbers like HP/MG may give approximate indications of how much aeration is needed in aerated lagoons, the detailed analysis and aerator placement must be based on accurate data derived from full scale tests. As stated previously, the criteria for defining a zone of influence should be based on maintaining a uniform suspended solids concentration and dissolved oxygen concentration.

4.3.0 GENERAL SUMMARY OF TYPICAL AERATION PERFORMANCE CHARACTERISTICS

When a prospective purchaser of aeration equipment wishes to compare different types of aeration systems he is faced with the incredible task of trying to sort out representative numbers for each type of device. The oxygen transfer rates from manufacturers are not necessarily based on the same test procedure or data analysis so that their figures are inconsistent even for the same type of equipment. What can be of help is to look to investigators who have tested most of the different types of aeration devices and can report the oxygenation capacity of each based on similar test procedures and data analysis methods. Table 4.2 has been adapted from similar tables found in references [72] and [91]. Additional figures have been added from several references to help complete the comparison. It is reasonable to expect slight differences among devices of the same type but from different manufacturers, but it must be emphasized that the differences will not be great. As an example, Shell and Stein [91] tested seven different commercial designs of static air-gun aerators and found that the range of transfer rates varied from 5 to 20 percent better than an open tube. Therefore, it is reasonable to consider for the purposes of a general comparison that all devices of the same type are similar. This assumption also makes no differentiation between small and large horsepower units of the same type although the smaller units are generally more efficient.

It is unfortunate that the values shown in Table 4.2 are so scattered. To add to the confusion some of the investigators who reported the figures did not state the test conditions or even what type of horsepower was used in the oxygen transfer rate except for Shell and Stein [91]. Their [91] numbers are probably a very good indication of relative performance, but tend to be slightly conservative. The values shown for diffused aeration do not include fine bubble serrated tubing that are used in long retention time aerobic oxidation lagoons. These diffusers are significantly more efficient in oxygen transfer, but are low rate and are incapable of maintaining average quantities of mixed liquor solids in suspension because of very low air flow rates which do not provide turbulent mixing.

GENERAL COMPARISON OF AERATION DEVICES

Characteristic	Low Speed Surface Aerator	Ref.	High Speed Surface Aerator	Ref.	Submerged Turbine	Ref.	Diffused Aeration	Ref.	Static Air-Gun Tubes	Ref.
Observed Oxygenation	up to 6.0	[72]	3.6	[72]	2.6	[72]	4.5	[72]		
Capacity at Standard	2.5	[91]a	2.0	[91]	1.9	[91]b	1.5	[91]c	1.8	[91]d
Conditions (lbs O_2/hp-hr)					1.6-2.9	[10]				
	3.2-3.8	[109]	3.2-3.8	[109]	2.5-3.0	[109]				
	2.8-4.5	[92]			2.5	[92]	1.8	[92]e	1.5	[92]
	(2.7-4.0)*		(2.0-3.0)*		(1.5-3.0)*		(1.5-3.0)*		(1.5-3.0)*	
Biological Process Rate Control-Observed Range of Performance, (lbs O_2/hp-hr)	2.1-2.4	[110]	2.0-2.5	[72]	1.7-2.5	[72]	2.3-2.5	[73]	-	
	2.9	[24]					2.6-3.7	[111]		
Pumping Capacity (cfs/hp)	4.5	[20]	0.85	[72]	1-10	[72]	4.7	[20]f		
	2-3	[91]	1.75	[91]	2-3	[91]	2-3	[91]	2-3	[91]

a. All test results from reference [91] based on 1.0 delivered HP/1000 ft^3, using 0.5 mg/l cobalt catalyst, and wire HF

b. Based on 20 ft side wall depth.

c. Based on coarse bubble diffuser at 20 ft side wall depth.

d. Based on 20 ft side wall depth with tubes on 15 ft centers.

e. Based on 15 ft side wall depth, and assumed absorption efficiency = 6%.

f. Based on 15 ft side wall depth, 65% efficiency for motor and blower.

* Numbers in parentheses are average ranges of relative performance based on author's experience. All values are for a power density and submergence range normally used in field applications, no chemical effects and 0 mg/l D.O.

5.0.0 AERATION DEVICE OPERATION

The purpose of this section is to describe in detail the method of operation, the applicability, and the performance capabilities of several types of aeration devices and systems. When possible independent research articles have been used as sources, but in many cases the manufacturer has been the only one to test and report the operational characteristics. Because different testing methods have been used for these various aeration systems (some at standard conditions, some at field conditions, and many with different data analysis procedures) caution must be exercised when comparing the performance characteristics of the aerators and systems which follow. See Section 4.3.0 for a summary of aeration device performance data.

5.1.0 SUBMERGED AERATION SYSTEMS

Submerged aeration systems have been used in the treatment of wastewater since the discovery of the activated sludge process by Ardern and Lockett in 1914 [114]. The first aeration systems were coarse bubble diffusers, but interest in reducing horsepower and compressor requirements led to the development of fine bubble diffusers. The fine bubble diffusers are capable of transferring more oxygen per unit of power consumed because of the increased bubble surface area created by the smaller bubbles; however, the small bubble systems require highly filtered air and are troubled by inorganic deposits and biological growths on the diffuser openings. The increased interest in aerated lagoons and deep tanks has led to the development of static tube aerators. These units use large air openings and various styles of riser tubes to promote oxygen transfer and mixing.

In submerged aeration, oxygen transfer takes place in three phases: first, there is a rapid transfer across the expanding bubble surface during formation; second, oxygen is transferred to the bulk liquid as the bubble rises; and third, the turbulence created by the bubble breaking the surface promotes surface aeration. The amount transferred during the first phase of bubble formation depends upon the type of diffuser unit being employed; fine bubble diffusers provide a great deal of oxygen transfer because of the frequency of bubble formation and surface area per unit volume of air. Coarse bubble units provide much less interfacial area. Sparger units and open holes in air pipes do not provide large amounts of oxygen transfer in this phase because they do not form individual bubbles on the diffuser, but instead issue an air stream which separates into bubbles after leaving the diffuser. As the bubbles rise after formation they are initially experiencing a high driving force due to the large value of the oxygen saturation concentration in the deeper regions of the basin. The transfer of oxygen is rapid at this point and the oxygen content within the bubble decreases. This transfer process rate decreases as the bubble rises until at some point near the surface a condition may occur where oxygen is stripped from the liquid back into the air bubble. This phenomenon usually occurs only in low oxygen deficit periods and is due to oxygen enriched water near the surface which contains dissolved oxygen in excess of the saturation concentration at that shallow depth. The amount of transfer in the rising phase is enhanced by small bubbles (large interfacial area per unit volume), high turbulence (rapid surface renewal), deep submergence (increased driving force due to larger saturation concentration), and long contact time. The surface turbulence created by the bursting bubbles exposes new surfaces of liquid to the atmosphere which allows oxygen transfer especially when the dissolved oxygen concentration is low.

There is no question that submerged aeration in its many forms has a place in wastewater treatment today. Increased land costs and, in some cases, scarcity of land has forced treatment plants to go deeper and be placed closer to living areas. Submerged systems offer the advantage of increased oxygen transfer as the air is released from greater depths and they do not create airborne particles of mixed liquor mist. This mist is particularly objectionable where it may be blown over land adjoining the treatment facility.

DATA ANALYSIS

While the value of submerged systems is well accepted the analysis of aeration test results for submerged aerators is most certainly a controversial issue as manufacturers of surface and submerged aeration equipment have not been able to agree on the proper C_{se} values to be used in K_La computation. As seen in the example problem in Appendix 1 the choice of C_{se} determines the K_La. This directly affects the electrical operating cost of the system which is a major consideration in an aeration system selection. As can be imagined it is in the best interest of a surface aerator manufacturer to stress the importance of a "mid-depth" C_{se} value while the submerged aeration manufacturers may have a tendency to use smaller C_{se} values based on off-gas considerations, observed C_{se} values, and straight line K_La plots. It is anticipated that the controversy over the proper C_{se} will continue for some time; therefore, it is suggested that manufacturers and investigators make use of seven C_{se} determination methods which have been shown in the example problem and elsewhere, to give closely correlated results. It would be difficult to recommend one model as always being better than another so it is recommended that all seven models be used and the results compared. If the results of the seven models compare favorably then the testor can have high confidence in the K_La computed. If the results are divergent then the assumptions for the divergent models may be badly compromised and can be neglected, but not without reasonable evidence. The chances are good that no substantiated reason to discard some of the models will be discovered, so the investigator may state his preference, but should show the results of all models. This method of reporting will increase the confidence of the designer and potential purchaser and will eliminate the claim that bias was used in the data analysis.

The seven suggested C_{se} models include:

1. Mid-Depth Corrected Model

   This method of C_{se} determination has been proposed by Eckenfelder [8,9,10, 13,109], Shell et.al. [91,112], and Berk et.al. [95]. It is based on the fact that the average C_{se} should be the mid-depth above the air outlet with an allowance for oxygen depletion in the rising bubbles (off-gas correction). It is defined by equation (45) and has been shown to give reasonable results for moderate and shallow submergences i.e. submergences of 20 ft or less.

$$C_{sm(t,p)} = C_{ss(t)} \left[\frac{P + .433(H) - p}{29.4 - 2p} + \frac{(P-p)\ O_r}{(14.7-p)\ (42)} \right] \ldots\ldots(45)$$

where P = Ambient barometric pressure, psia

p = Water vapor pressure at the temperature of the test water, psia. See Table 3.1 for values. For elevations less than 3,000 ft and water temperatures of less than 25°C, p may be neglected

H = Depth of liquid over the air outlet, ft

O_r = Oxygen content of the air leaving the liquid (expressed as a percent)

$$= \frac{21(1-E)100}{79+21(1-E)}$$

E = Decimal fraction of oxygen in the air bubbles transferred to the basin liquid.

2. Log-Mean Saturation Value Model

This model has been proposed by Stanton and Bradley [93] as a close approximation to the log mean driving force model. It assumes a constant C_{se} concentration during the test equal to the log-mean of the oxygen saturation at the tank bottom and the oxygen saturation at the surface corrected for decreased oxygen partial pressure in the rising bubble. It has also shown to be a reasonable approximation for submergences of less than 20 ft. It is defined by equation (46):

$$\ln C_{se} = \frac{\ln \left[C_{ss(t)} \left(\frac{P + 0.433(H) - p}{14.7 - p} \right) \right] + \ln \left[C_{ss(t)} \left(\frac{O_r}{21} \right) \right]}{2} \ldots\ldots(46)$$

see equation (45) for an explanation of terms.

3. 0.25 Submergence Model

This method of C_{se} determination is based on the fact that investigators who directly observed the C_{se} produced by a submerged aeration system reported that the value is equivalent to that calculated for a depth of 0.22 - 0.33 of submergence [77,83,102,115,116]. The 0.25 submergence is then only an approximation to the trend noted by many investigators. The exact value of effective depth must be determined from direct observation and will vary according to the dynamic characteristics of the system. For this model an equation may be written,

$$C_{se} = C_{ss(t)} \left(\frac{P + .433(H)(S)}{14.7} \right) \ldots\ldots\ldots\ldots\ldots\ldots (47)$$

where S = Decimal fraction of assumed or observed effective depth of submergence. For the example problem S was assumed to be 0.25.

4. Best Fit Model

This model has been proposed by Ball, et.al. [77] and Conway and Kumke [79] as a means of determining C_{se}. The procedure is to take the reaeration test data, assume a C_{se} and plot the deficit versus time. This method has been attacked because when truncated data is used the data may plot straight for a range of C_s values for which there is no indication which one is correct. If the reaeration test is described by first order kinetics, then this approach is on firm theoretical ground, but it is absolutely necessary to take the dissolved oxygen concentration to an asymptotic saturation concentration. The sensitivity of this method should then be adequate.

5. Directly Observed Saturation

If one is going to take the reaeration data to an asymptotic saturation concentration, then one has essentially directly observed the C_{se}. Therefore, methods 4 and 5 are essentially the same if the proper test procedures are observed. The only difference between the two would be to try under method 4 various values of C_{se} close to the observed value to see if a better fit of the data could be obtained. With method 5 no trial and error C_{se} plotting is permitted and any runs which do not plot straight are thrown out. Direct observation of C_{se} is supported in the literature [49,83,102,104].

6. Direct Analysis of the Data

Direct analysis of the data is a method for finding C_{se} that uses only the data from the reaeration test. It involves plotting the rate of oxygen transfer during a time interval (mg/l/hr) versus the average D.O. during the time interval (mg/l) on rectangular coordinate graph paper. A straight, best-fit line is drawn through the plotted points and the X-axis intercept is C_{se}. The confidence in the derived C_{se} increases with more data points in the low deficit region, so high end truncation should be avoided. The example problem in Appendix 1 shows how to perform this method which was recently proposed by Stukenberg and McKinney [85].

The direct analysis method in addition to providing C_{se}, also provides K_La, the slope of the straight line plot, and the maximum rate of oxygen transfer, $(K_La)(C_{se})$. Fluctuations in the plotted data indicate hydraulic non steady-state or surging conditions in the test tank. As can be seen by Figure A.4 there were no surging conditions in the example problem test as the plotted points are very smooth.

7. Log Mean Driving Force Model

Stanton and Bradley [93] discuss two data analysis methods, one of which is the log-mean driving force model, that incorporate the concept of a non-constant C_{se} during a submerged reaeration test. The methods are on firm theoretical ground, because during each time interval the rate of transfer indicates an absorption efficiency which in turn yields the approximate off-gas oxygen content. With this data for each time interval a log-mean driving force (LMD_t) is computed and plotted with the rate of transfer for the time interval. The example problem in Appendix 1 presents the tabular method of summarizing the data (Table A.3) and the derived graph (Figure A.3).

Because the model incorporates a changing C_{se} it should be particularly well suited for analyzing deep tank submerged aeration results because of the large range of absorption during the test. Stanton and Bradley [93] feel that this model offers a very good correlation to field results and, although somewhat laborious, is worth the effort.

All of the models which assume, compute or observe a constant C_{se} value are only an approximation to what is actually occurring during the test. The log-mean driving force on the other hand attempts to map the changing value of C_{se} by short line segment approximations to the curving trace of C_{se}. The shorter the time interval the better the result. However, the accuracy of the reaeration test may not be great enough to show with consistency the merit of a variable C_{se} analysis. For depths of less than 20 ft and average absorption rates all of the seven models should give the same answer $\pm$ 5%. For submergences of 25 ft or more and for high absorption rates divergency will be noted as the assumptions of the constant C_{se} models become less valid. For deep submergences the log-mean driving force model should be most accurate in describing the oxygen transfer efficiency.

Once the C_{se} is determined from each method the standard oxygen transfer efficiency, N_o, may be computed by the general equation (31):

$$N_o = \frac{\left[\frac{K_La(T)\ (\theta)^{20-T}}{\alpha}\right]\left(\frac{C_{se}}{\beta} - C\right)}{HP} W \quad \ldots\ldots\ldots\ldots\ldots(31)$$

where $K_La(T)$ = Overall oxygen transfer coefficient at T°C, hrs^{-1}

θ = Temperature correction coefficient, at moderate temperatures it is most often = 1.024 (see Section 3.2.0)

α = Alpha correction factor - for clean water α = 1.0

C_{se} = Effective dissolved oxygen saturation concentration as determined by the various methods, mg/l

β = Beta correction factor - for clean water β = 1.0

C = Test condition level of dissolved oxygen concentration, mg/l. For the non steady-state test C = 0 and for the steady aeration of mixed liquor C = average D.O. in the basin

W = Weight of water subject to aeration, 10^6 lbs

HP = Horsepower consumed. For submerged aeration adiabatic HP is used, but an efficiency must be included for losses in blower and motor to obtain an electrical or wire HP.

To estimate the oxygen transfer efficiency of a submerged aeration device in the field use equation (48):

$$N = N_o \left(\frac{C_{se} - C}{C_{sm}}\right)(\theta)^{T-20} \alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots(48)$$

where N = Expected field oxygen transfer efficiency, lbs O_2/hp-hr

N_o = Standard oxygen transfer efficiency, at 20°C, at atmospheric pressure = 14.7 psia (760 mm Hg) and a dissolved oxygen level = 0.0 mg/l, lbs O_2/hp-hr

C_{se} = Effective dissolved oxygen saturation concentration of wastewater in the field at field water temperature and salinity, and atmospheric pressure, mg/l. When beta is known the term is often shown as $\beta C_{sm(t,p)}$ where $C_{sm(t,p)}$ is the dissolved oxygen saturation concentration for tap water at field water temperature and atmospheric pressure at the basin effective mid-depth. Effective mid-depth will be determined by the C_s determination method which is being used.

C_{sm} = Dissolved oxygen saturation concentration at the effective mid-depth for clean water at 20°C and 14.7 psia (760 mm Hg), mg/l. It is the standard conditions C_s value as computed or assumed by the seven models previously described.

C = Average operating level of dissolved oxygen concentration in aeration basin, mg/l.

θ^{T-20} = Temperature correction factor to adjust K_La(20°C) to the field temperature with Θ = 1.024 for moderate temperatures (see Section 3.2.0 for more details) and T is the basin liquid temperature in °C.

α = Alpha correction factor = ratio of K_La (wastewater)/K_La (tap water).

THEORETICAL TRANSFER EFFICIENCY

Kalinske [18,20] reports that by knowing the oxygen absorption efficiency, release depth and atmospheric pressure a theoretical oxygen transfer rate can be computed from equations (13 or 14). Using equation (14) and including E, the absorption efficiency, one obtains equation (49):

$$N_o = 3.4\,E\Big/\left[\left(\frac{P_2}{P_1}\right)^{.283} - 1\right] \quad \ldots\ldots\ldots\ldots\ldots(49)$$

where N_o = Theoretical oxygen transfer rate, lbs O_2/hp-hr

E = Absorption efficiency expressed as a fractional decimal

P_2 = Absolute outlet pressure, psia

P_1 = Absolute atmospheric pressure, psia.

Note: Equation (49) contains a blower and motor efficiency factor of 70%.

Equation (49) will be used in Sections 5.1.1 - 5.1.4 to give theoretical estimations of the oxygen transfer efficiency of the various types of submerged aeration systems.

Being a theoretical equation one can expect that equation (49) would be optimistic in its predicted oxygen transfer rate. In addition experimental error in measuring off-gas concentrations and the error in estimating a single absorption efficiency value for a test would decrease the confidence in the calculated theoretical transfer efficiency. In fact, where both absorption efficiency and transfer rate are given the theoretical equation suggests a rate that is 25-50 percent higher than the reported figure. The actual reason for this magnitude in error is not known so that the theoretical transfer efficiencies must be viewed with caution. Included in performance summary tables which follow will be a bracketed range after a theoretical transfer rate to help give a more realistic picture of the performance capabilities of the aeration system.

5.1.1 Fine Bubble

Description

Fine bubble diffusers or porous media diffusers are generally either tubes or plates constructed of carborundum or tightly wrapped saran or nylon, or they are socks fabricated out of synthetic woven fabric.

Tubes and socks are usually placed at the side of an aeration tank, perpendicular to the wall creating a spiral roll motion with the mixed liquor as it flows down the tank. Alternatively, the tubes may be mounted on lateral rather than longitudinal headers making a cross roll system. The maximum spacing between tubes is limited by solid suspension requirements while a minimum spacing must be observed to prevent bubble coalescence as the air streams rise. Tube arrangements may locate the tubes on fixed headers or as in the case of modern systems on jointed swing-headers.

Plates are normally mounted on the aeration basin on air plenums. The patterns used in operating systems include:

a. Ridge and furrow - wide spaced transverse rows alternating with concrete ridges
b. "Crow's foot" placement
c. Modified "crow's foot"
d. Transverse row - closely spaced transverse rows
e. Longitudinal row - closely spaced longitudinal rows

During two full scale investigations of the above listed patterns at the Milwaukee Jones Island wastewater treatment system the ridge and furrow pattern and longitudinal row placements provided the best oxygen transfer. Spiral roll with tubes provided the least oxygen transfer [117,118].

Descriptions of proprietary tubes, plates, and socks are given in the WPCF Manual of Practice No.5 [48].

Operational Characteristics

Fine bubble diffusers were developed in an effort to provide a more efficient form of oxygen supply. The fine bubble diffusers produce more bubbles per SCF than coarse bubble and sparger units and therefore more interfacial area per unit volume, 'a', which increases K_La. This increase in transfer efficiency does not occur without some tradeoffs, however, since porous diffusers require highly filtered air and are affected by surface active agents more than coarse bubble diffusers [10]. Porous diffusers are also somewhat limited to their flow passing capacity because of back pressure as compared to coarse bubble diffusers.

Fine bubble diffusers are used exclusively in activated sludge basins primarily because they are not economically suitable for applications of other than complete mix biological systems. With porous fine bubble diffusers, cleaning of the tubes, plates or socks may be required. The cleaning requirement is a result of several blockages: first, some particulate matter does pass through the filtering process and lodges in the diffuser openings; second, biological and mineral deposits grow on the diffuser outside; and third, if the air supply system is shut down for any reason, the water that enters the submerged diffuser carries with it biological solids and particulate fines and usually some are left behind when the liquid is expelled by the turning-on of the air. As a general guide, reference [48] suggests that a fine bubble diffuser will require cleaning due to particulate solids after passing about 12 million ft^3 of well filtered air. The length of time is therefore dependent on the rate of air supply per diffuser. However, the length of time between cleanings as a result of mineral and biological growths and deposits is dependent on the strength and mineral composition of the wastewater. Chaswick [119] reports that saran diffusers clogged much more frequently than ceramic diffusers when both used the same air supply.

Performance

The literature values for porous-fine bubble diffusers and the manufacturers performance specifications for the same type of unit show a wide variation. However, at least one performance criteria, mixing, is well agreed upon by both sources; diffused aeration as applied to activated sludge provides adequate mixing with most aeration arrangements. This is a result of the fact that activated sludge requires high rates of oxygen for the biomass and the volume of air discharged to supply that oxygen even at high absorption efficiencies is usually sufficient to maintain suspended solids in solution by the air-lift pumping. Aeration basins must be designed properly to avoid dead spots by forming fillets in corners and restricting excessive width to depth ratios.

Oxygen transfer efficiencies for fine bubble diffused aeration systems are usually shown as absorption efficiencies or as lbs O_2/hp-hr where the horsepower is adiabatic without blower or motor losses. Table 5.1 presents some of the transfer efficiencies shown in the literature using equation (49) to convert absorption efficiency to N_o theoretical and it includes motor and blower losses.

TABLE 5.1

PUBLISHED TRANSFER EFFICIENCIES FOR
FINE BUBBLE DIFFUSER AERATION SYSTEMS

Item	Submergence, ft	SCFM per Diffuser Unit	Absorption, %	Theoretical N_o, lbs O_2/hp-hr*
Ceramic Flat Porous Plate, longitudinal pattern [118]	10	30	13.3	6.0 (4.0-4.8)**
	10	60	15	6.8 (4.5-5.4)
	15	30	14	4.4 (2.9-3.5)
	15	60	17.5	5.5 (3.7-4.4)
Saran Tube, Spiral Roll [121]	10	6	11	5.0 (3.3-4.0)
	10	12	9	4.1 (2.7-3.3)
Saran Tube, Spiral Roll [89]	12.75	6	12	4.3 (2.9-3.4)
	12.75	12	10	3.6 (2.4-2.9)

* Based on equation (49), assumed atmospheric pressure = 14.7 psia, and blower and motor efficiency at 70%.

**Bracketed range based on Theoretical N_o 25-50% higher than observed.

The values shown in Table 5.1 are higher than the values presented in Section 4.3.0 and this is an example of the conflicting performance ratings found in the literature and advertisements today. From the literature it is not possible to know which values for oxygen transfer efficiency are true, but the majority of the independent aeration test reports tend to indicate that the values presented in Table 5.1 are unrealistically high. As a further example, a well respected wastewater engineering design book [3] suggests that 8% absorption is a reasonable figure to use for porous tube diffusers for normal submergences. Therefore a range of 2.5-3.0 lbs O_2/hp-hr would be representative of this absorption efficiency.

5.1.2 Coarse Bubble

Description

It may not be justified to separate coarse bubble diffusers from fine bubble diffusers and spargers, but it has been done here due to some significant differences among the devices. A coarse bubble diffuser is defined here as a diffuser that consists of a tubular pipe with cast, drilled, or punched air outlets along its length. It is mounted in the same manner as porous tubes to either fixed or removable headers. The coarse bubble diffuser has larger holes than the fine bubble units so that air filtering requirements are not as strict, but the holes are still small enough to encourage separate bubble formation rather than the " jet-of-air" characteristic of the sparger group. The diffusers which require large particle filtration are able to pass small particulate matter that would clog a fine bubble unit, but are still susceptible to mineral and biological growths in some instances. The oxygen transfer is slightly less than the fine bubbles but more than the maintenance free spargers. The coarse bubble units are limited to activated sludge applications due to system economics and maintenance requirements.

Operational Characteristics and Performance

The literature does not generally subdivide this intermediate bubble size diffuser, but rather includes it either with the fine bubble or sparger systems.

Therefore, the operational characteristics in terms of maintenance requirements and oxygen transfer are not well documented. Schmit, et.al. [83,121] have reported on the oxygen transfer capacity of the diffuser units developed from full scale test tank investigations, a summary of which is presented in Table 5.2. They also have determined that a mid-width diffuser placement is more efficient than a side (spiral roll) arrangement.

TABLE 5.2

PUBLISHED TRANSFER EFFICIENCIES FOR
COARSE BUBBLE DIFFUSER AERATION SYSTEMS [83]

Submergence ft	SCFM per 1000 ft^3	Absorption %	Theoretical N_o, lbs O_2/hp-hr*
13	46.7	7.8	2.8 (1.9-2.2)**
13	81.7	8.6	3.0 (2.0-2.4)
18	47.3	11.9	3.2 (2.1-2.6)
18	81.4	12.9	3.4 (2.3-2.7)
22.3	44.1	14.9	3.3 (2.2-2.6)
22.3	61.4	16.2	3.6 (2.4-2.9)

*Based on equation (49), assumed atmospheric pressure of 14.7 psia and blower and motor efficiency at 70%.

**Range based on N_o Theoretical 25-50% higher than observed.

These values are within the diffused aeration range shown in Section 4.3.0, although a little on the high side. One item of interest is that Schmit et.al. [83,121] have used an observed or measured C_{se} value which corresponds with approximately 0.25 of submergence. It is their opinion that the mid-depth corrected model does not always yield a correct C_{se} and that measuring it yields the best result. Additionally, the data shows a higher rate of absorption with increased air flow rates which is not in agreement with previous investigators [10,89,120].

5.1.3 Sparger Diffusers

Description

Sparger diffusers are a group of aeration devices which employ large holes, flexible seals, or mechanical check valved outlets for air ejection. The devices have rather low oxygen transfer efficiencies, but because of the large openings and high air flow rates they have very low maintenance requirements and do not require filtered air.

The spargers are generally saddle mounted on air distribution lines which are normally fixed because there is no need to pull the spargers out for cleaning. Because of this the spargers may be located anywhere in the aeration basin and have even been employed in aerated lagoons. Reference [48] presents a comprehensive description of many proprietary sparger devices.

Operational Characteristics

The spargers have been applied to both activated sludge systems and aerated lagoons. Oxygen absorption increases, as with most submerged devices, at greater depths, however, oxygen transfer efficiency does not increase with depth. Spargers generally are unaffected by increasing air flow rates and are less affected by alpha producing compounds than are fine bubble diffusers.

Although spargers do not have a high oxygen transfer efficiency, they are still attractive where maintenance costs for the fine bubble systems would be greater than the operating savings by using the more efficient system. This is particularly applicable to small treatment facilities.

Performance

Table 5.3 summarizes the oxygen transfer efficiencies for sparger diffusers as reported by various investigators.

TABLE 5.3

PUBLISHED TRANSFER EFFICIENCIES FOR SPARGER DIFFUSER AERATION SYSTEMS*

Reference	Submergence ft	Absorption %	Theoretical N_o, lbs O_2/hp-hr**
[120]	6.0	4	2.9 (1.9-2.3)***
	8.75	5.4	2.7 (1.8-2.2)
	11.75	6.9	2.7 (2.8-2.2)
[89]	12.2	6.2	2.3 (1.5-1.8)
[122]	12.0	6.4	2.4 (1.6-1.9)
	14.0	7.4	2.4 (1.6-1.9)

* For all references air flow rates between the ranges tested (0-30 SCFM/diffuser) had no effect on absorption efficiency.

** Based on equation [49], assumed atmospheric pressure of 14.7 psia and blower and motor efficiency at 70%.

*** Range based on N_o Theoretical 25-50% higher than observed values.

It is significant to note that increased submergence, while it does increase absorption, actually decreases oxygen transfer efficiency, a result of increased power requirements to compress the air.

5.1.4 Static Tubes

Description

Static tube mixers and aerators are a part of a general group of aeration devices which use both hydraulic and mechanical shear to effect oxygen transfer. Generally, the tubes are pipes with various arrangements of packing, spiral patterns, and venturi constrictions which are suspended over large holed air outlets in air distribution lines. The air stream is ejected into the bottom of the tube and the air-lift action entrains liquid. The internal configuration controls the rate of ascent, mechanical shear, and encourages hydraulic shear.

Closely related to the static tubes are their forerunners the hydraulic shear diffusers. These devices in the simplest form consist of a small, empty, five sided box into which air is introduced. The rising stream of air forces water to rush into the box resulting in hydraulic shear of the air stream into small bubbles. The hydraulic shear diffusers are applicable to activated sludge and aerated lagoons and have an oxygen transfer efficiency about the same as spargers.

The static tube mixers and aerators have received much attention since they have made their debut in the marketplace. The units offer several advantages over other submerged aeration systems: there is no filtration requirement and maintenance on underwater structures is nil as long as the tubes are not plugged. Oxygen transfer is comparable to diffused aeration. The tubes are applicable to all forms of biological treatment and are capable of mixing deep tanks effectively.

Operational Characteristics

Particular attention is being given these devices as alternate aeration systems for aerated lagoons. The surface aerators which predominate as the aeration system for aerated lagoons are not without operational and maintenance problems. For the northern latitude, winter icing has been a recognizable problem in the past with both fixed and floating aerators. When maintenance is required either the aerator must be pulled to shore, or the men must journey out onto the lagoon by boat or on catwalks to the platforms. Obviously the risk of accident working on or over water is greater than on land and this safety aspect has been a determining factor in the choice of submerged aeration for some installations. Submerged aeration systems are unaffected by all atmospheric conditions and when maintenance is required all moving parts are located inside a sheltered building. The only maintenance problems with the submerged parts are possible plugging by rags or paper and possible air line breakage due to vibration fatigue or manufacturing defects.

The problems of plugging are significant for some installations. Air-gun installations for unscreened wastewaters or where paper and fibrous debris can blow into the aerated lagoon have experienced considerable plugging problems [123,124]. The chances of plugging increase with increased packing and smaller tolerances inside static tube. Plugging due to biological growth inside the tube is not considered likely [125]. Unfortunately, cleaning blockages from the submerged devices requires divers and/or emptying of the lagoon.

Performance

Table 5.4 presents oxygen transfer data reported in the literature. The tubes are from different manufacturers and tested under different conditions so the values are expected to be divergent. However, Shell et.al. [91,112] tested six different types of static tubes and reported a variance of only 15% among all tubes tested so when values exceed ± 7.5% from the mean the difference is due to testing and data handling procedures.

TABLE 5.4

PUBLISHED TRANSFER EFFICIENCIES FOR STATIC TUBE AND HYDRAULIC SHEAR DIFFUSER AERATION SYSTEMS

Item	Submergence, ft	SCFM per Unit	Absorption %	Oxygen Transfer Efficiency, lbs O_2/hp-hr N_o* Theoretical	N_o Reported
Static Tube Aerators [91,112]	10	15	5.9	2.6	1.5
	10	40	5.2	2.3	1.4
	15	15	7.7	2.4	1.6
	15	40	7.5	2.3	1.5
	20	15	10.8	2.6	1.8
	20	40	10.5	2.6	1.8
Static Tube Aerator [77]	10	15	-	-	4.1
	10	40	-	-	3.1
	15	15	-	-	4.3
	15	40	-	-	3.4
	20	15	-	-	4.4
	20	40	-	-	3.6
Static Tube Aerator [126]	10	15	9	4.0	3.2
	10	40	7	3.1	2.3
	15	15	14	4.4	3.5
	15	40	11	3.4	2.6
	20	15	18	4.4	3.8
	20	40	14	3.4	2.8
Static Tube Aerator [98]	23	32	-	-	4.6
Static Tube Aerator [102]	10	28	-	-	1.9
	15	28	-	-	2.4
	20	28	-	-	2.9
	25	28	-	-	3.4
	30	28	-	-	3.9
	35	28	-	-	4.4
Venturi Diffuser [89]	13.6	10	7.6	2.6	(1.7-2.1)**
	13.6	30	6.9	2.4	(1.6-1.9)
Hydraulic Shear Box [89]	14.4	10	8.0	2.6	(1.7-2.1)
	14.4	30	7.6	2.5	(1.7-2.0)

* Based on equation (49), assumed atmospheric pressure of 14.7 psia and blower and motor efficiency at 70%.

**Range based on N_o Theoretical 25-50% higher than observed values.

The values reported for the static tubes are in much disagreement. Obviously some different methods of data analysis and test procedures account for some of the differences. Of the articles referenced, those by Shell, et.al. [91,112] and by Gilbert and Chen [102] are most interesting. The reported procedures used by these investigators conform very well to this text's recommended procedures and yet there is quite a discrepancy. The major difference between the tests is the choice of C_{se} and the power density. The lower figures given in [91,112] were a result of a power density of 1 HP/1000 ft^3 (133 HP/MG) and a mid-depth corrected C_{se} value. The higher numbers shown in [102] resulted from a power density of approximately 2 HP/1000 ft^3 (270 HP/MG) and a directly observed C_{se} value. The effect of the directly observed C_{se} value usually results in a slightly higher (5-10%) N_o than the mid-depth corrected model, but the major difference between the two must be due to the power density. Surface aerators are known to be dependent on power density, but very little is known about the influence of power density in submerged aeration. Gilbert and Chen [102] report that further studies are underway to help determine the effect of power density, which when reported should help to explain the variance in the reported values.

5.1.5 Serrated Tube Diffuser

Description

The serrated tube diffuser consists of specially formulated polyethylene flexible tubing with machine die formed slits at intervals along the top of the tubing. The size of bubbles is determined by the slit size, but they are generally fine bubbles. The tubes are placed in grids on the lagoon bottom the spacing of which is dependent on the oxygen requirements. The system has been used extensively for upgrading existing oxidation ponds and in long retention (30 days) aerated/facultative lagoons. In general, the serrated tube diffuser exhibits very good oxygen transfer and because the tubes are placed as required for oxygen demand the mixed liquor D.O. level is very uniform.

Operational Characteristics

As long as the system is clean and the influent organic loads are within design levels the serrated tube diffuser system accomplishes high absorption efficiency with a low power demand; however, the land requirements are reasonably high due to long retention time requirements as the overall K_La of the system is very low. The system can maintain a uniform D.O., but is not capable of maintaining a high concentration of mixed liquor suspended solids nor resuspending sludge solids.

The literature reveals that the system is very susceptible to clogging by mineral deposits in the slits which block the air passages and although the manufacturer suggests quarterly cleaning with anhydrous HCl this has been insufficient in many cases. The studies conducted in Winnipeg using the serrated plastic tubing tend to confirm the cleaning problems [123,124]. In fact, it was found necessary to hand punch the slits quarterly in conjunction with the acid cleaning. Christianson and Smith [78] reviewed the performance of diffused aeration systems in sewage lagoons serving Alaskan military bases. Their findings were that the serrated tubing was subject to frequent clogging and actually was covered by sludge in some older systems. Total dissolved solids whether derived from natural hardness or industrial discharges show a tendency to precipitate in the presence of air and the fine bubble diffusers with low air flows appear to be the most susceptible.

Performance

The oxygen transfer efficiency of the serrated plastic tube diffuser is generally higher than other aeration devices. However, it should be pointed out that while the serrated tube is very miserly on horsepower consumed it has a K_La an order of magnitude below other submerged systems. This means that a serrated plastic tube diffuser does not have a high rate capacity and is limited to long retention time lagoons.

5.1.6 Application to Aerated Lagoons

Application of submerged aeration to aerated lagoons has been limited almost entirely to static tube aerators, due to their very low requirement for cleaning and maintenance and competitive oxygen transfer rate and efficiency. Section 5.1.4 discussed the standard oxygen transfer capabilities and this section will attempt to present the field performance and applicability of the static tubes to aerated lagoons.

If it appears that rather a large amount of horsepower is required to accomplish the BOD reductions which will be discussed, be reminded that the standard oxygen transfer efficiency applies only to standard conditions. The values shown in Table 5.4 were developed from tests where the power density ranged from 133 HP/MG to 270 HP/MG and although the effect of power density is not as well documented for submerged aeration as for surface aerators, it is clear that a power density of 10-20 HP/MG found in aerated lagoons will effectively reduce oxygen transfer because of reduced turbulence.

Shell and Stein [91] have reported on the use of static tube aerators for pulp and paper mill aerated lagoons. They summarize the mixing ability of the aerators according to mixing power applied, as shown in Table 5.5.

TABLE 5.5

POWER REQUIREMENTS FOR EFFECTIVE MIXING AT VARIOUS MLSS LEVELS BY STATIC TUBE AERATORS

MLSS, mg/l	Delivered HP HP/1000 ft^3	Delivered HP HP/MG
10,000 - 20,000	1.0	133
5,000 - 10,000	0.8	106
3,000 - 5,000	0.6	80
1,000 - 3,000	0.4	53
500 - 1,000	0.2	27
less than 500*	0.1	13

* MLSS concentration for most aerated lagoons.

Comparatively, a leading manufacturer of static tube aerators has reported that a 13,000 mg/l suspension of powdered carbon-activated sludge mixture was maintained completely mixed with a power application of approximately 50 HP/MG (0.4 HP/1000 ft^3) [77]. However, it should be noted that the test tank was a relatively small vertical cylinder with one static tube in the center; this is an ideal mixing geometry for the static tube and probably resulted in a very low mixing power requirement.

Static tube aerators have been installed in successfully operating aerated lagoons and their reported design parameters include:

Board Mill [91]

Aerated lagoon volume = 7.2 MG
Retention time = 20 days
Power density = 17.5 HP/MG
Primary and secondary treatment system BOD_5 removal efficiency = 80%

Bleached Hardwood Kraft Mill [91]

Aerated lagoon volume = 175 MG
Retention time = 10.5 days
Power density = 8 HP/MG
BOD_5 applied = 51,500 lbs/day
BOD_5 removal efficiency = 82%

Pulp and Paper Mill [91]

Activated sludge basin volume = 43 MG
Retention time = 1 day
Power density = 70 HP/MG
BOD_5 applied = 147,000 lbs/day
BOD_5 removal efficiency = 83%

Soft Drink Bottling Plant [126]

Activated sludge basin volume = 0.22 MG

Retention time = 1 day

Power density = 155 HP/MG

Unfortunately, the literature does not provide in-depth coverage on field performance of static tube aerators due to their relatively recent entry into the aeration system market.

5.2.0 SURFACE AERATORS

Soon after activated sludge became a standard in high rate stabilization of sewage the efficiency and maintenance costs of the diffused aeration systems which supplied the oxygen requirements were studied in-depth to try to maximize the transfer efficiency and minimize the maintenance. It soon became apparent that the law of adiabatic compression was immutable and the absorption efficiency of even the fine bubble diffusers was limited at normal submergences. So a new concept emerged, that of using surface generated turbulence and the ever-present atmosphere as the source of oxygen.

For a long time the intense turbulence and air entraining properties of the hydraulic jump have been known. What the first mechanical surface aerators attempted to duplicate was a hydraulic jump by using a rotating turbine near the water surface. Since it was already known that large volume and low velocities mixed best, the first surface aerators were in essence low head, high volume pumps so located near the surface that the desired hydraulic jump was produced.

Since that time surface aerators have taken many different forms to try to maximize oxygen transfer and basin mixing and minimize maintenance costs. The resulting array of whirling and rotating water pumping and spraying devices shows that there are many feasible ways of introducing dissolved oxygen by surface generated turbulence. For surface aerators the design and positioning of the unit with respect to the surface can vary the water pumpage (mixing) with respect to air entrainment. Turbine and rotor surface aerators are most flexible in this respect with the ability to be very efficient in activated sludge where oxygen transfer is usually the limiting factor and long retention time systems where mixing is often an important factor. However, all surface aerators are a compromise between oxygenators and mixers. Usually, it is more energy efficient to add mixers to a basin rather than add aerators when the system is mixing deficient, but has adequate oxygen.

DATA ANALYSIS

The problem of proper C_{se} selection is not limited to submerged aeration as described in Sections 4.1.1 and 5.1.0; however, surface aeration is more easy to analyze, even if the assumption that $C_{se} = C_{ss(t,p)}$ will not always be true. For surface aeration, as well as submerged, a flexible approach would appear to be advantageous. Four determination methods should be used to find C_{se}:

1. $C_{ss(t,p)}$ Tables

   $C_{ss(t,p)}$ values are listed in tables in references [39,105]. For surface aerators operating in large area basins, or where the HP/unit area-volume is low this method should be correct. Eckenfelder [10,23,109] and Berk et.al. [95] suggest this method for all surface aerators.

2. Direct Observation of C_{se}

   This method as described in Sections 4.1.1 and 5.1.0 determines C_{se} by saturating the test basin liquid by an extended period of aeration. The asymptotic value of C_{se} should agree closely to $C_{ss(t,p)}$ except when large amounts of entrained air are pumped down to significant depths. Direct observation of C_{se} is supported by [49,83,102,104].

3. Direct Analysis of the Data

Stukenberg and McKinney [85] have presented this method for C_{se} and K_La determination and hydraulic flow pattern analysis (see Sections 4.1.1, 5.1.0 and the example problem in Appendix 1 for the methodology). Since the determination method uses the test data to find C_{se} any interferences both negative and positive should be reflected in the derived C_{se} value.

4. Best-Fit of the Data

Essentially, this method supported by Ball et.al. [77] and Conway and Kumke [79] assumes that since the log of the oxygen deficit versus time should be a straight line, the correct value of C_{se} is the one which makes the data plot straight. As described in Section 4.1.1 this method is only accurate and precise if the reaeration test is taken to an asymptotic C_{se} value although minor adjustments in the C_{se} value are permitted to make the data plot more linear.

All these methods should be employed when analyzing the data from a reaeration test. If close agreement is obtained then the value determined is most probably the correct one; however, if they are not, then the lack of agreement indicates interferences in the test basin or inaccuracies in the D.O. and C_{se} measurement. Usually, lack of agreement when it occurs will be between the table value and the rest of the methods, because of air entrainment. In any case, the non steady-state test should be run to an asymptotic C_{se} value and all data should be used in the various analysis methods. Reporting the oxygen transfer efficiency resulting from each C_{se} determined and then rejecting the ones which are obviously in error will create the best confidence in the reporting technique.

Once the C_{se} is determined from each method the standard oxygen transfer efficiency, N_o, may be computed by the general equation (31):

$$N = \frac{\left[\frac{K_La(T)(\theta)^{20-T}}{\alpha}\right]\left(\frac{C_{se}}{\beta} - C\right) W}{HP} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(31)$$

where $K_La(T)$ = Overall oxygen transfer coefficient at T°C, hrs^{-1}

θ = Temperature correction coefficient

α = Alpha correction factor - for clean water $\alpha = 1.0$

C_{se} = Effective dissolved oxygen saturation concentration as determined by the various methods, mg/l

β = Beta correction factor - for clean water $\beta = 1.0$

C = Test condition concentration of dissolved oxygen, mg/l. For the non steady-state reaeration test C = 0 and for the steady-state aeration of mixed liquor C = average D.O. in the basin

W = Weight of water subject to aeration, 10^6 lbs

HP = Horsepower consumed - wire, line or gross.

To estimate the oxygen transfer efficiency of a surface aeration device in the field use equation (44):

$$N = N_o \left(\frac{C_{se} - C}{C_{ss}}\right)(\theta)^{T-20} \alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(44)$$

where N = Expected field oxygen transfer efficiency lbs O_2/hp-hr

N_o = Standard oxygen transfer efficiency at 20°C, at atmospheric pressure = 14.7 psia (760 mm Hg), lbs O_2/hp-hr

C_{se} = Effective dissolved oxygen saturation concentration of wastewater in the field at field water temperature, and salinity, and atmospheric pressure, mg/l. When beta is known the term is often shown as $\beta\, C_{ss(t,p)}$ where $C_{ss(t,p)}$ is the dissolved oxygen saturation concentration for tap water at field water temperature and atmospheric pressure at the liquid surface. (Also see Note in C_{ss} below for occasions when the surface value of C_{ss} does not apply).

C_{ss} = Dissolved oxygen saturation concentration for clean water at 20°C and 14.7 psia (760 mm Hg) at the surface of the liquid, mg/l. NOTE: if the four suggested methods of C_{se} determination reveal that the surface aerator creates C_{se} values higher than C_{ss} for power densities close to the power density to be achieved in the field, then C_{ss} should be increased to reflect the effective depth of the C_s that will be achieved in the operating basin. It is necessary to be consistent in the effective depth used in the fraction numerator and denominator i.e. if the effective depth is the surface, then in the numerator use $C_{ss(t,p)}$ and in the denominator use C_{ss} for which both are at the surface.

C = Average operating dissolved oxygen concentration in the aeration basin, mg/l.

$(\theta)^{T-20}$ = Temperature correction factor to adjust $K_La(20°C)$ to the field temperature with $\theta = 1.024$ for moderate temperatures. T is basin liquid Temperature in °C. (See Section 3.1.0 for more details on choices of θ).

α = Alpha correction factor = ratio of K_La (wastewater)/K_La (tap water).

5.2.1 Low Speed

Description

Low speed aerators are a category of radial flow aerators which employ slow moving impellers or turbines at or near the liquid surface to create surface turbulence. The mechanical arrangement consists of a vertical or horizontal motor coupled to a reducer gear box connected to the impeller shaft. The assembly may be fixed-mounted on a stationary pile supported platform or may be incorporated onto a floating platform. "Low speed aerator" is a term which has received a fair amount of abuse due to its application to rather high rpm devices. In this report a range of 30-60 rpm is considered as appropriate for low speed aerators. The aerators which operate in the range of 100 rpm fall somewhere between high speed and low speed units and are not discussed in this review.

In terms of flow patterns there are two similar types of low speed aerators: plate impeller and turbine impeller. The plate impeller consists of a flat circular plate with radial blades fixed to the underside or periphery of the plate. The plate is mounted near the water surface and when rotated liquid is pushed radially such that a hydraulic jump is created. The positioning of the blade is crucial to the performance, because if the water level is too low the blades do not have a good grip and if too high the top surface of the plate is submerged, air cannot reach the low pressure area behind the blades, and the power draw is high. In other words, this type of impeller is level sensitive. The turbine impeller is a relatively non-level sensitive open bladed or finned cone low head, high volume pump which essentially moves the water radially but does not in a true sense produce a hydraulic jump. For both, the flow pattern created consists of an upward flow to the impeller and a radial flow in either a high or low trajectory away from the impeller. Mixing results from the push and pull of the direct water pumpage and induced pumpage due to the transfer of energy between the issuing stream and the liquid volume. Oxygen transfer results from spraying water into the air and from turbulence generated in the liquid surface. See reference [48] for descriptions of proprietary aerators.

Operational Characteristics

The plate impeller was the first type of low speed aerator produced and was a very efficient oxygen transfer device. However, because the plate impeller was level sensitive it was in practice difficult to produce in the field the transfer efficiency predicted by the clean water non steady-state test. In aerated lagoons and activated sludge basins not equipped with automatically adjusting weirs, level variations produced unwanted results: low oxygen input with low levels and possible motor overloading with high levels. Floating aerators solve this problem except when pontoons leak or the floating structure weighs down with ice or heels to one side because of high winds. The frequency of the problems occurring is not well documented, but the fact that low speed aerator manufacturers have gone to non-level sensitive turbines suggests that the plate type of impeller proved to be undesirable in many applications.

The turbine impeller was developed to overcome the level sensitive tendency of the plate impeller. Oxygen transfer is somewhat reduced, but the overall reliability is increased. This type of impeller is applicable to both floating and fixed-mounted platforms in both aerated lagoons and activated sludge systems.

Surface aerators are dramatically influenced by impeller size, rotational speed, submergence, scale and geometry. Studies on lab scale impellers have determined that K_La is proportional to the 1.5 power of the rotor speed, to the 1.2 power of the reciprocal of the water depth, and to the impeller diameter: tank diameter ratio [127]. Lab scale studies have shown oxygen transfer efficiencies as high as 8 lbs O_2/hp-hr with a 4 in impeller, but this is a result of the scale factor problem. This scale factor effect continues to be noticed even in commercial sized units where in general small horsepower units have a higher O_2 output per hp-hr than large horsepower units [92].

The effects of geometry have been previously discussed in Section 3.4.0, but briefly the larger the HP/vol or area the higher the O_2 output. Also, aerators placed within the hydraulic influence of another can result in substantial reduction in the mixing and oxygen transfer efficiency in high power density basins.

Maintenance of low speed surface aerators is generally limited to semi-annual oil changes of the gear box oil and periodic preventitive maintenance checks and motor lubrication. When this is done the literature indicates that the aerators operate satisfactorily. Without the necessary maintenance gear boxes will not operate indefinitely without problems. Gear box failures probably have accounted for many of the problems associated with low speed aerators. Part of the problem was poor maintenance, but many gear boxes in the 60's were failing even with proper lubrication. Many times these failures resulted from gear meshing frequencies that coincided with the impeller shaft resonance frequencies. Therefore, even though the gears were adequately designed to transmit constant torque loads, dynamic loads caused by vibration in the shaft overloaded the tear teeth. Garland et.al. [128] report that this problem has since been corrected by moving gear meshing frequencies (by changing the number of teeth on the gear) out of the shaft resonance frequency range and by stiffening the impeller shaft to change and reduce its resonance frequency.

Motor problems are generally associated with two conditions: the torque demand of the output shaft exceeds the capacity of the motor and high temperatures. The former condition referred to as overloading, is normally controlled at the motor control center where an ammeter detects abnormally high current draw which could burn out the motor and actuates a trip-out switch. The latter problem of overheating may also result in high current demand which could cause the power source to be disconnected; however, in many instances motor damage will result prior to excessive current draw. Therefore, a temperature sensing device, a thermistor, is commonly employed to protect against overheating. The thermistor is a bimetallic connection which is wired in series with the windings of the motor. The thermistor is set such that when the temperature in the motor begins to rise, the connection is opened which actuates the shut-down of the motor. Both of these motor protection devices are relatively inexpensive and are commonly included with both low speed and high speed aerator units.

Besides maintenance, gear box inadequacies, and motor failures the last obstacle has been icing. The Canadian winter provides harsh conditions for all surface aerators especially on long retention time (low basin liquid temperature) systems. Water spray and mist can freeze on above water unheated surfaces and build up a substantial thickness. The ice provides undesirable weight and wind catching surface on floating aerator structures making them unstable. In the past unprotected floating aerators have tilted due to eccentric ice loading, sometimes sunk, and even danced (repetitive process where one side of aerator becomes ice laden and tips toward warm liquid which melts the ice allowing it to return to near upright) [129]. Ice build up on fixed platforms has resulted in the lifting of the platforms [124], damage to the impeller including loss of blades due to ice build-up around and falling from the platform and piers, [123,124,129], gear box and motor damage due to ice blockage and impeller and shaft imbalance [123,124,129], reduced oxygen transfer and sometimes shutting down of the aerator [123,124,129]. The result of these difficulties has been a formulation of anti-icing strategies for both floating and fixed-mounted low speed aerators, which include:

1. Maintain the lagoon liquid temperature as warm as possible.

2. Floating aerators, if used at all, should be equipped with extended legs with feet near the lagoon floor to prevent tipping. Alternatively the aerator should be tethered with 3-4 short cables on slip rings to anchor posts, so called pinning. All extra above water appurtenances such as handrail and gratings should be removed. A stationary not rotating ice shield should be used to keep spray away from the platform. Finally, it may be necessary to heat trace the structural arms of the floating platform.

3. Fixed-mounted aerators should be placed on low, not high platforms. High platforms still ice-up with freezing mist and because of the long extended shaft are more likely to suffer from impeller imbalances. The low platforms should be within 3-4 ft of the water surface so that it can be washed with the warm effluent and be in the warmer air near the surface.

All surfaces should be as smooth as possible (steel is preferable to concrete) and protruding nuts, ledges, and other projections avoided. Tubular steel structural members although expensive are more desirable than flanged members, because they do not have corners and edges where ice can build-up. Support piers should be at a radius such that ice falling from or sliding down the piers will not strike the impeller.

The recent implementation of these designs and procedures has reduced icing maintenance problems to a minimum.

Performance

In general, the low speed surface aerator is considered one of the most efficient oxygenation and mixing devices yet devised for wastewater treatment. Table 5.6 summarizes some of the reported data found in the literature concerning oxygen transfer efficiencies. For further comparison of low speed aerator performance data see Table 4.2 in Section 4.3.0.

TABLE 5.6

PERFORMANCE DATA FOR LOW SPEED SURFACE AERATORS

Item	Impeller RPM	Oxygen Transfer Efficiency N_o, lbs O_2/hp-hr
Cone Turbine Impeller [92]	30-60	2.8 - 4.5
Two-Speed, Cone Turbine Impeller [130]	36	2.6 (wire hp)
	48	2.9 (wire hp)
Bladed Conical Shell Turbine Impeller over Draft Tube [10,131]	30	3.1 (shaft hp)
	45	4.2 (shaft hp)
	60	3.6 (shaft hp)

The pumping capacity of the low speed unit is a relatively easily measured quantity, but the mixing that results is not as clear. Depending on the rotational speed and oxygen transfer desired the direct pumping rates of low speed surface aerators are in the range of 2-5 cfs (900-2200 gpm)/shaft hp [20, 91]. Since it is a high volume, low velocity flow the theory given in Section 2.0.0 predicts it will result in better mixing turbulence than a low volume, high velocity flow, but see Section 5.2.4 for literature reports on surface aerators in field performance tests.

5.2.2 High Speed

Description

The gear box maintenance problems and high first cost of the low speed aerators initiated a search for alternate forms of surface aeration. The high speed floating surface aerator was the result. It consists of a vertical waterproof electric motor directly connected to a shrouded pump propeller. This drive/pump assembly is mounted on a floating disc, doughnut, or set of pontoons. Flow through the unit is axial until it is deflected radially over the floating support in a variety of trajectories. High speed surface aerators are applicable to both aerated lagoons and activated sludge.

Operating Characteristics

Oxygen transfer is achieved in a much different way than with the radial flow turbine units. The mechanism consists basically of raising the pumped liquid to a relatively high kinetic energy state and discharging it into the air. This spray is then partially saturated before impinging at a flat angle on the surface. Energy transfer takes place resulting in surface turbulence and induced mixing. Although spraying the liquid into the air brings the solution close to saturation due to high surface areas and surface renewal, the volume of liquid pumped is relatively small in relation to the basin and accounts for no more than 40-60% of the oxygen transferred.

Surface turbulence created by the impinging water creates high surface renewal rates and atmospheric oxygen often entrained in bubbles is able to dissolve into the basin liquid. If the power to unit volume or area is high entrained air bubbles may be carried down to the lower regions of the tank thereby creating still more oxygen transfer. As a result the high speed aerator tends to be much more efficient in high rate treatment systems where a high power density is used than in aerated lagoons.

Although the aerator is simple in design and has only a few moving parts, the motor shaft and extension shaft with propeller assembly, the unit can still have operational problems and limitations. The difficulties center around inadequate maintenance, ingested debris, abrasive and stringy suspended solids, and icing. Because there is no gear box and oil compartment, high speed units are often run without preventative maintenance, but regular maintenance is required to ensure adequate bearing lubrication and to detect corrosion/ abrasion damage. Aerated lagoons are commonly afflicted with floating debris carried by the wind or dislodged material from the basin bottom. This debris can be taken into the pump impeller with serious damage resulting, especially considering that even large dents and nicks can off-balance the propeller.

The high velocities in the propeller area may cause abrasive suspended solids to act like liquid sand paper and result in excessive wear to the propeller and its shroud. Stringy and ropey solids tend to accumulate on discharge supports and internal flow straightening members. Houck and Weis [132] suggest that for problem suspensions composed of ropey solids such as found in digestors, and poorly screened suspensions, low speed turbines or diffused air may be more applicable. Icing can also be a hazard for unprotected high speed aerators just like low speed units. Ice formation on the motor case can cause tilting and sinking. This is likely to happen in cold liquid basins in extreme cold weather. Heater elements have solved most of the problems as these warm the lower surfaces of the motor casing preventing large formations of ice. In other instances the aerators are moored by short cables with slip rings around support piles. Additional cables bracing the motor top ensure that even if ice forms the aerator will not tip over.

Performance

The literature is sadly lacking in the field of performance data for high speed floating aerators. The best data comes from Kormanik [88] as shown in Figure 3.4. This data plus some rather general information is summarized in Table 5.7.

TABLE 5.7

EVALUATION OF HIGH SPEED OXYGEN TRANSFER EFFICIENCIES

Item	Name Plate HP	Power Density HP/MG with 12' S.W.D.*	Oxygen Transfer Efficiency, N_o lbs O_2/hp-hr
Test Data [88]	25	10	1.8 (Nameplate hp)
	25	200	3.3 " "
	50	10	1.9 " "
	50	200	2.5 " "
	75	10	1.6 " "
	75	200	2.0 " "
Published Data According to [88]	50	10	2.5 " "
	50	200	2.8 " "
Test Data [91]	-	133	2.0 (Wire hp)
Surface Aerator [109]	-	-	3.2-3.8 (Type hp - unknown)

* S.W.D. = side wall depth, depth of liquid

The transfer efficiencies are in line with those found in Table 4.2, Section 4.3.0 which is to say that many investigators report similar data; however, on the subject of mixing ability the similarity ends. In terms of direct pumpage high speed aerators move approximately 0.85 - 1.75 cfs (400-750 gpm)/shaft hp [72,88,91] with the minimum value for 50-75 HP units and very small HP aerators producing the large pumping rates. This pumped liquid is discharged almost horizontally and radially onto the water surface at approximately 18 ft/sec. Claims for mixing vary, but usually the literature does not report a substantial advantage in mixing for either low or high speed aerators although fluid mixing theory would show a definite advantage for low speed units. See Section 5.2.4 for literature field performance data.

5.2.3 Bladed Rotors

Description

A bladed rotor consists of tubular metal brush (O.D. = 15-30 in.) which is rotated while partially submerged in a mixed liquor basin. The brush can be almost any length, but generally is not longer than 40 ft and is usually divided into 10 ft sections with a water lubricated journal bearing between each section. These types of aerators generally are rotated relatively fast, at 60-100 rpm, and are driven by a reducing gear box and motor. They are most suited for oval race track oxidation or extended aeration ditches because the discharge is only in one direction. The degree of mixing relative to the oxygen transfer is controlled by submergence, but generally the brush aerators are not used on deep basins as the units do not draw liquid from beneath but from near the surface behind the rotating brush.

Operating Characteristics

Maintenance for the bladed rotor aerator is similar to low speed aerators in that the gear box must receive regular care and in addition there may be some bearing lubrication/inspection requirements. The units are almost always fixed-mounted and with adjustable submergence so that there is control over the oxygen output and mixing. Even though bladed rotors are used in relatively long retention time systems and they spray quite a bit of water icing has not been an operational problem. They are operating in sub-arctic regions without requiring special attention [133].

Extensive use has been made of the rotating brushes in livestock and poultry oxidation ditches. They are unaffected by small floating debris and as long as the ditch is not overly deep or large the aerators are capable of adequate mixing. The normal design for mixing is 13,000-16,000 U.S. gal of ditch volume/ft. of rotor length [133]. Oxygen requirements are met by varying submergence.

Performance

The brushes are very popular in Europe and have been used extensively in oxidation ditches. Literature in North America has not devoted much space to the performance of the bladed rotors. Table 5.8 summarizes the available literature.

TABLE 5.8

EVALUATION OF BLADED ROTOR TRANSFER EFFICIENCIES

Item	Rotor rpm	Submergence	Oxygen Transfer Efficiency, N_o, lbs O_2/hp-hr
1.7 ft dia. Kessner Brush [10,134]	80	4.7 in	2.6 (wire hp)
27.5 in Bladed Rotor [76]	60	3 in	3.6 (shaft hp)
	60	9 in	3.2 " "
	100	3 in	4.1 " "
	100	9 in	4.0 " "
22 in Bladed Rotor [135]	100	4 in	1.9 (wire hp)
27.5 in Bladed Rotor [135]	100	4 in	1.6 (wire hp)

5.2.4 Application to Aerated Lagoons

The aerated lagoon is the dominant form of secondary treatment in the pulp and paper industry today and surface aeration is the most often employed equipment to supply the necessary oxygen. With all the experience gained from the operation of these lagoons "rules-of-thumb" have been developed to aid design engineers and purchasers in the sizing of aeration equipment. The number of variables which enter into the exact amount any particular basin will need depends on a multitude of factors which include; basin depth, basin length: width ratio, BOD_5 loading, expected suspended solids concentration, efficiency of treatment required, and discharge dissolved oxygen concentration. As well, the number of horsepower an aerated lagoon will require depends on the type of aerator used; however, this is a very political topic and many aeration authorities choose to overlook differences among aerators. If one assumes average basin geometry and depth and that there is no difference among surface aerators the following information presented in Table 5.9 shows recent recommendations for aeration power density:

TABLE 5.9

HORSEPOWER REQUIREMENTS FOR VARIOUS BIOLOGICAL TREATMENT SYSTEMS

Reference	Type of Treatment System	Nameplate HP/ Million U.S. Gallons of Basin Volume
Frissora [84]	Complete Mix Activated Sludge (incl. variations)	100 - 130
Bartsch and Randall [136]	Aerobic Aerated Lagoon with solids suspension (Retention time less than 24 hrs.)	100
Frissora [84]	Aerated Lagoon with sludge return (Retention time less than 24 hrs.)	70 - 80
Fleckseder & Malina [137]	Aerobic Lagoon (Retention time approximately 1 day)	30+
Bartsch and Randall [136] Eckenfelder [138]	Facultative Lagoon (Aerobic/Anaerobic) (Retention time between 3-5 days)	15 - 20
Fleckseder & Malina [137]	Aerobic/Anaerobic Lagoon (Retention time 3-5 days)	10 - 20
Houck and Weis [132]	Oxygen dispersion in Aerated Lagoon (Retention time - more than 5 days)	6 - 10

These values are substantiated by numerous operating systems and hydraulic mixing tests. The oxygen dispersion power input is controlled by friction losses both for water and suspended solids. Knop and Kalbskopf [139] found that with mechanical aerators, depending on the shape and size of the tank, 0.5 to 3.0 HP/MG were required to make up for friction and turbulent losses in tap water;

high suspended solids concentrations will increase the amount of required power. They also cite data from Von der Emde (1969) which indicates that a power level of 50 HP/MG is necessary to prevent biological sludge deposits in basins larger than 0.5 MG. Fleckseder and Malina [137] noted that between 10-20 HP/MG solids distribution within an operating basin was not linked to the degree of mixing.

Frissora [84] and Houck and Weis [132] have suggested normal operation depths for high speed surface aerators. For shallower installations anti-erosion assemblies are needed and for greater depths draft tubes are needed. Table 5.10 summarizes this information. While this information is for high speed units, similar depths would be expected for low speed aerators.

TABLE 5.10

RECOMMENDED BASIN DEPTHS VERSUS AERATOR HORSEPOWER

Aerator Nameplate Horsepower	Basin Depth ft	
	Range	Ave.
5	6.0-12	8
7.5	6.0-13	10
10	6.5-14	10
15	6.5-15	12
20	7.5-16	12
25	7.5-17	12
30	8.0-18	14
40	8.0-20	14
50	8.5-23	14
75	8.5-25	16
100	9.0-25	16

One of the most comprehensive field studies on the mixing characteristics of surface aerators in aerated lagoons was presented by McKeown and Buckley [140]. In this study the authors measured treatment parameters, dissolved oxygen profiles, and velocities around individual aerators in thirteen aerated lagoons. Their data do not show one type of aerator as being better than another and their conclusions only mention surface aerator nameplate horsepower.

It is noteworthy to mention that the results of much of the field work was in terms of nameplate horsepower. Where drawn (electrical) horsepower was measured the low speed units consistently drew 10-20 percent less amperage horsepower than nameplate. High speed units usually operated at 90 percent of nameplate or more. If all low speed aerators can be expected to draw much less than nameplate, then it is reasonable to compare the two types of aeration on the basis of nameplate horsepower. However, since level sensitive impellers have been replaced by non-level sensitive designs, low speed units may well draw 90 percent of nameplate horsepower or more; it might therefore be warranted to compare the field data on the basis of drawn horsepower.

McKeown and Buckley [140] presented conclusions reached during their study which include:

1. The degree of mixing in any basin is determined by both the applied horsepower and the basin geometry. Figure 5.1 summarizes the authors findings.

2. The majority of biological suspended solids can be maintained in suspension with a power density of 14 HP/MG in basins having evenly spaced aerator coverage.

3. The optimal system BOD loading was found to be 55 lbs BOD_5 applied/nameplate/HP/day, in terms of oxygen transfer efficiency and BOD removal.

4. The maximum zones of hydraulic influence ranged from 100 ft for 10 HP units to over 300 ft for a 100 HP unit, with an average of 800 ft^2/HP.

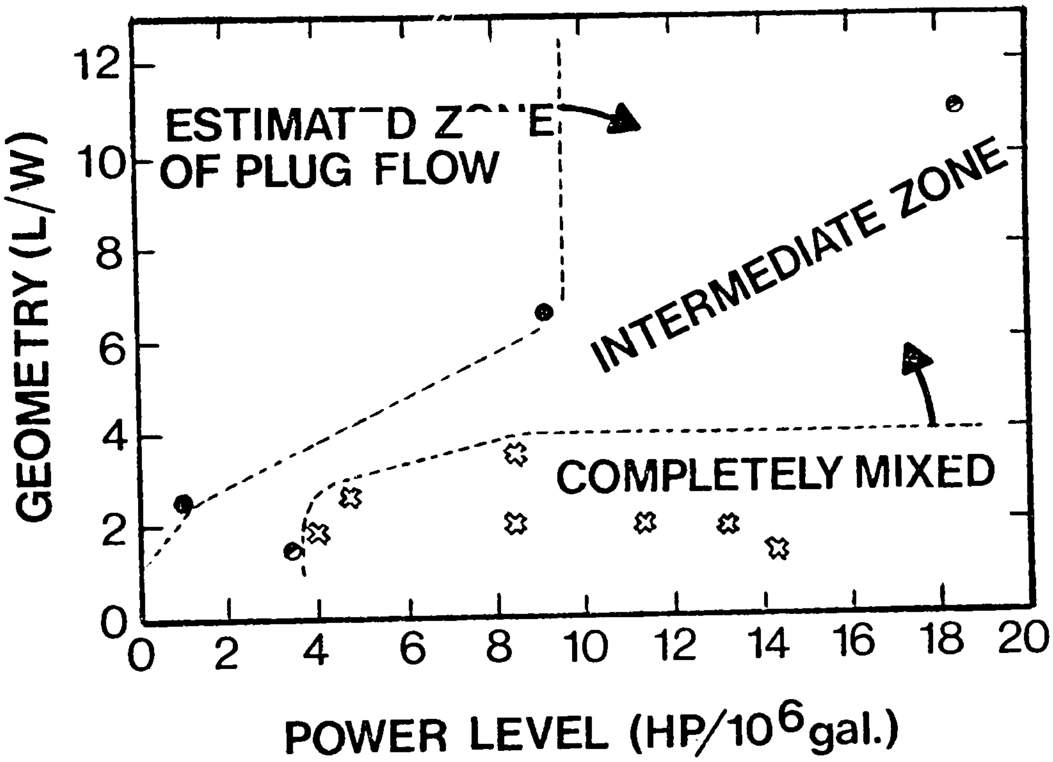
5. Settleable solids production was loading dependent; at 4.5 lbs BOD_5 applied/1000 ft^3 settleable solids were produced, but below this the solids were completely dispersed and non-settleable.

Another study which attempted to show the treatability difference of many small aerators versus fewer large aerators resulted in rather ambivalent conclusions. Amberg, et.al. [141] constructed two equally sized lagoons to treat a sulfite mill effluent. In one they placed six 25 HP high speed aerators and in the other one 75 HP low speed aerator and one 75 HP high speed aerator. The BOD_5 removal efficiency was higher for the two 75 HP units. The authors reluctantly concluded that fewer large units were better than many small ones although this is not in agreement with the fact that smaller units are generally more efficient and pump more liquid per HP than their larger counterparts. Some low speed manufacturers have interpreted this unexpected finding to mean that the low speed aerator was more efficient and made up for the inefficiency in the 75 HP high speed unit to produce a better BOD_5 removal than the six smaller aerators which should have produced the better result.

In spite of the large theoretical advantage for low speed aerators, it appears the difference between them is not clearly evident in the field. The literature does not give the design engineer or purchaser a good deal of assistance in knowing which aerator is best; hopefully accurate non steady-state test procedures and data analysis will.

5.3.0 HYBRID SYSTEMS

Previous sections have discussed mechanical aeration and diffused submerged aeration as being separate alternatives for mixing and oxygen supply. In this section aeration devices which employ both mechanical mixing and submerged air release are covered.



SUMMARY OF FACTORS AFFECTING MIXING REGIONS IN AERATED STABILIZATION BASINS [140]

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	beak	BY BG / DATE 29 MAR 77 / DWG NO A1269-14	FIG 5.1

The reason for combining mechanical agitation and compressed air is simple; in doing so one can obtain system flexibility and efficiency over a wide range that is not obtainable from other methods. It is flexible because mechanical agitation can meet mixing requirements while the air is varied to meet oxygen requirements. It is often very efficient, in that mixing energy can be delivered effectively and oxygen transfer can be accomplished with the benefit of increased driving force and contact time due to submergence.

Three hybrid systems are described in the following sections: submerged turbine, aerated fluid jet, and downfall contactor. Submerged turbines have been widely used in wastewater treatment, but mainly in activated sludge systems as capital costs would be high for long retention time systems. The aerated fluid jet is a relatively new system which is applicable to all mixed liquor systems. Downfall contactors are almost unknown in wastewater treatment but are very useful in deep basin or reservoir aeration.

DATA ANALYSIS

Except for the addition of a mechanical power requirement the analysis of hybrid system aeration is identical to the submerged aeration system analysis shown in Section 5.1.1.

5.3.1 Submerged Turbine

Description

A submerged turbine consists of a motor via reducer gear box driven submerged impeller over a sparger air release device. The mechanically driven turbine impeller pumps water radially, mixing the basin and shearing the sparged air stream. The turbulence created is on both a large scale for solids suspension and a small scale which promotes rapid surface renewal and oxygen dissolution. As well, the intense mixing retains the air bubbles in the liquid longer.

The units are normally installed in activated sludge basins and provide a high oxygenation potential. They are very useful for deep tank basins because of the excellent mixing ability. Submerged turbines are quite flexible in operation in that they can be sized for peak loads, but may be turned down for light loadings while still maintaining solids in suspension.

Operating Characteristics

Submerged turbines generally employ a low speed mixer which turns at 25-80 rpm depending on the mixing requirement. With the low rpm, high torque impellers the submerged turbines are suitable for installation in basins up to 50 ft deep. Although the impeller speed is normally fixed the amount of air may be varied to reduce off-peak horsepower requirements. When the power is equally distributed between the impeller and blower the devices normally deliver the best transfer efficiency and achieve an absorption efficiency of between 15-20 percent. Absorption efficiencies of up to 50 percent are possible if the power to the turbine is increased, but in terms of oxygen transfer efficiency it is best to try for absorption efficiencies in the range of 10-25 percent as horsepower increases on either extreme [20,92].

Operating systems using submerged turbine aeration systems have been highly successful. Laws and Burns [142] report on a conversion from fine and coarse bubble diffusers to submerged turbine aerators at a 20 MGD integrated pulp and bleached board operation activated sludge plant. The submerged turbines not only provided excellent oxygen transfer efficiency and basin mixing but also required much less power and maintenance as they did not suffer from scale plugging problems experienced with the diffused aeration systems. At the Peoria, Illinois municipal activated sludge treatment plant, increases in the influent BOD_5 loading and maintenance with the diffuser plate aeration system accompanied by a reduction in BOD_5 removal suggested more oxygen transfer was required. As Hughes and Meister [143] report submerged turbines were added as a supplementary oxygen source and have upgraded the system significantly without maintenance problems.

Flexibility in the operation of the submerged turbines can be enhanced by oversizing shafts and gear boxes. In this way future loading increases can be accepted by increasing motor horsepower, impeller diameter, and/or the impeller rotational speed. Winter [144] suggests that such initial overdesign will save money and increase overall reliability.

One safety feature which should be incorporated into the submerged turbine is a power cut-off to the impeller motor if the air supply to the impeller ceases for any reason. If not, the effective density of the liquid pumped by the impeller will increase greatly, putting higher loadings on the shaft, gears, and motor. To avoid equipment damage an alternate solution is a special impeller design which does not significantly increase drawn power when the fluid density changes.

Submerged turbine impellers because of their rotational movement tend to create circular horizontal fluid flow. In unbaffled basins this does not create good mixing turbulence. Consequently, it is necessary to install baffles in the tank. The baffles are normally placed at quarter points around the basin perimeter for circular basins and at half points for rectangular basins. The width of the baffles should be about one-twelfth as wide as the tank width or diameter [145].

Maintenance for submerged turbine aeration systems is normally minimal. The air openings being 5/8"-3/4" in diameter are not susceptible to biological slime or mineral scale and do not require air filtration. The motors and gear boxes do require routine preventative maintenance, but are not usually damaged during operation. Since it is a submerged aeration system, icing is not a problem.

Performance

Submerged turbine aerators vary in oxygen transfer efficiency and mixing capability depending on the system design and the power split between the air supply and the impeller. Table 5.11 summarizes some published performance data for the submerged turbine.

TABLE 5.11

EVALUATION OF SUBMERGED TURBINE TRANSFER EFFICIENCIES

Reference	Water Depth, ft	Oxygen Transfer Efficiency, N_o, lbs O_2/hp-hr*
Laws and Burns [142] steady-state oxidation of mixed liquor	15	2.5
Oldshue [145] from pilot activated milk sludge	12	1.5-4.5
Eckenfelder [10]	-	1.6-2.9
Kalinske [92]	-	2.5

* Type of horsepower unknown

Kalinske [20] in addition to deriving an equation for theoretical oxygen transfer from diffused aeration has also presented a method for determining oxygen transfer for submerged turbines. The equation is similar to equation (49) for diffused aeration, but has another term, HP_t, to include impeller power requirements:

$$N_o = \frac{0.96\ E}{0.28\ Y + HP_t} \quad \text{.....................(50)}$$

where N_o = Theoretical oxygen transfer, lbs O_2/hp-hr

E = Absorption efficiency expressed as a fractional decimal

$$Y = \left(\frac{P_2}{P_1}\right)^{.283} - 1$$

P_2 = Absolute outlet pressure, psia.

P_1 = Absolute atmospheric pressure, psia.

HP_t = Impeller horsepower per ft^3 of air, needed to attain absorption efficiency E.

Notes: 1. Equation (50) contains a blower and motor efficiency factor of 70%.

2. Although not confirmed, this equation will probably be optimistic in its predicted N_o value.

5.3.2 Aerated Fluid Jets

Description

An aerated fluid jet is an aerating device that employs hydraulic shear air entrainment by adding air in a turbulent nozzle to a high velocity liquid stream. The nozzle normally contains a converging throat for a high velocity liquid jet that discharges through an air cavity into a slightly diverging discharge section or through a discharge orifice into the basin liquid. The source of the high velocity liquid is normally basin water pumped to the nozzle assembly. The air is normally fed to the air cavity by blowers or under certain circumstances it may be drawn into the low pressure air cavity by aspiration. The nozzles, due to their relatively small size and discharge capacity, are mounted on headers. For aerated stabilization basins the headers are long pipes with a central liquid section and an outer air chamber that discharge in one direction. By contouring the lagoon dikes and using two or more headers per pattern a circulating flow regime may be created. Similarly, the devices have been successfully applied to carousel or racetrack activated sludge or extended aeration channels.

It should be noted that this system should not be confused with a jet aeration system which discharges at or above the liquid surface. These systems are more closely related to surface aeration and would only be applicable to shallow racetrack treatment systems.

Operating Characteristics

Aerated fluid jets have shown themselves to be excellent oxygenation devices. The intense hydraulic shear creates very small bubbles to provide a large interfacial area. The discharge jet together with the rising air/liquid plume provides the mixing. Unfortunately, the devices as they are now designed are relatively new in the marketplace and independent authorities have not substantiated the marketing claims, but a few generalities are possible.

a) The aerated fluid jets employ high hydraulic shear and produce very small bubbles so that the K_La should be high. As well, deeper submergence should produce higher absorption efficiencies.

b) Surface active agents should enhance the oxygen transfer capabilities because of the very high turbulence; therefore it would not be unreasonable for these devices to create alpha factors of one or more (see Section 3.3.3 and Figure 3.1).

c) Due to the high velocity and high level of micro-turbulence, energy losses should be high. Consequently, mixing although it may prove to be adequate for oxygen dispersion will probably be the limiting factor in the design of long retention time aerobic treatment systems. Note that horizontal velocity does not necessarily provide the turbulence necessary for solids suspension. In short retention activated sludge or in long retention aerobic/anaerobic lagoons mixing should not be a problem.

d) Maintenance requirements will depend on types and quantities of debris in the basin and on proper selection of materials. Should a problem develop however, divers and/or emptying of the lagoon will be required.

e) Since the system is submerged, icing is not a problem.

f) Flexibility in the operation of the system is good, as the blowers may be turned down to reduce oxygen transfer during low BOD_5 loads. Mixing will be maintained by the constant fluid pumping.

Even though the aerated fluid jets are relatively new to aerated lagoons there are some operating systems which are meeting or surpassing design expectations. Neubauer [146] reports that a 64 acre, 18 ft deep aerated lagoon with 27 acre quiescent zone is performing satisfactorily for a 38 MGD Newsprint pulp and paper mill discharge. A carousel treatment system using aerated fluid jets was recently installed for the treatment of whole black liquor from both Kraft and neutral sulfite pulp cooks along with effluent from a business paper mill and is performing well, Le Compte [147].

Performance

The oxygen transfer efficiency of the aerated fluid jet as reported in the literature is summarized in Table 5.12. The figures shown in the table are the optimum efficiencies that were obtained during the tests; the variables in the test were normally submergence and air flow rate.

TABLE 5.12

EVALUATION OF AERATED FLUID JET OXYGEN TRANSFER EFFICIENCIES

Reference	Submergence, ft	Oxygen Transfer Efficiency, N_o, lbs O_2/hp-hr
Le Compte [147]	17.5	4.2 (Shaft hp)
West and Paulson [148]	13.7	5.4 (Theoretical hp)
		4.0 (Estimated wire hp)
Huang and Mandt [149]	5	4.4 (Theoretical hp)
	10	4.8 (Theoretical hp)
	15	5.3 (Theoretical hp)
	20	5.7 (Theoretical hp)

5.3.3 Downfall and U-Tube Contractors

Description

Downfall contactors are a group of aerators particularly suited to deep basin or reservoir aeration. The mode of operation is to create a small head either by lifting water to the top of a large diameter pipe or by pumping downward in the pipe to create a downward flow. Air is added near the top of the pipe by air entrainment, aspiration, or blower. The air is caught in the downward liquid flow to the pipe bottom at which point the bubbles rise in a plume. Relatively small heads are required to produce the velocity necessary to carry the air down and the resulting contact time is very long.

U-tube contactors are virtually the same device, but instead of discharging to the bulk liquid the downward flow is turned by a 180° elbow and is directed back to the surface in a large diameter pipe. This method is not therefore applicable to partial basin aeration; it is applicable to the oxygenation of entire effluents or entire basins. Effluents could have their dissolved oxygen content increased by using a small amount of head to force the liquid down the U-tube with air being added near the top of the downcomer. Similarly, an entire aeration basin could be in the shape of a U-tube connected at the top and the mixed liquor circulated by downward discharging air. Mavinic and Bewtra [150] have found this type of aeration to be very promising.

Operating Characteristics

By pumping downward the entrained air is subjected to large pressure increases and extended contact time. Both of these factors tend to produce a higher oxygen transfer rate. With large pipes where pipe friction losses are minor deep submergences are possible such that the limiting factor in both oxygen transfer and mixing is the efficiency of the pumping mechanism.

McKeown, et.al. [151] supervised the testing of an experimental 40 ft downfall contactor in a dam reservoir. In comparing it against low speed surface aeration they found that the contactor more effectively mixed lower regions of the basin and provided oxygen transfer rates in excess of the low speed units.

Variations of the downfall contactor and U-tube have been used in reservoir aeration around the world. Their special use in reservoir aeration stems from the fact that deep reservoirs and lakes tend to become stratified into temperature layers due to density differences. The bottom section, the hypolimnion supports life which is dependent on the temperature and on adequate dissolved oxygen. Therefore, devices which provide oxygen transfer without mixing are necessary. The downfall contactor is well suited to this need if both the intake for the downfall pipe and the discharge are in the hypolimnion. Fast and Lorenzen [152] review this area and present a summary of various devices which have been used or proposed. Fast, et.al. [153] reported that based on cost estimates and performance tests deep full air-lift oxygenators were much more cost effective than all other types.

Performance

The downfall and U-tube contactors have been employed because they are energy efficient. Using small heads and long contact times they achieve very good transfer rates. Two investigations looked at oxygen transfer. Mavinic and Bewtra [150] found with relatively shallow U-tubes (maximum depth = 9 ft) that the oxygen transfer efficiency ranged from 2.9-4.5 lbs O_2/Theoretical hp-hr when the head energy was included. McKeown et.al. [151] reported that the downfall contactor transfer efficiency ranged from 1.4-2.0 lbs O_2/wire hp-hr as compared to low speed surface aerators which managed only 0.9 - 1.7 lbs O_2/wire hp-hr in the same reservoir. These transfer efficiencies are for water with initial D.O. values so that clean water efficiencies would be considerably higher.

5.4.0 GRAVITY HEAD SYSTEMS

This section deals with air entrainment and oxygen transfer using gravity head as the source of turbulent energy. Although the gravity head aeration has no application to aerated lagoons or other mixed liquor biological treatment basins it is felt that information on effluent and stream aeration will be useful in determining the impact of discharges on receiving bodies.

5.4.1 Aeration Valves and Jets

Description

This form of aeration makes use of static head available from reservoirs and other storage basins for energy. The objective of this methodology is to eject a high velocity jet of water into the atmosphere allowing it to become partially saturated before it enters the bulk liquid. The higher the ejection velocity of the stream and the more dispersed the jet plume becomes the better the oxygen transfer rate.

Considerations in the use of an aeration valve or ski-jump pipe discharge must include production of undesirable quantities of fine spray, misting, and foam generation. As well, effluents with high amounts of color may be aesthetically objectionable when sprayed into the air. However, if the head is available and the desirability of increasing the dissolved oxygen concentration out-weighs the possible negative effects, then this is a very inexpensive and effective method of aeration.

Performance

Elder, et.al. [154] used a Howell-Bunger valve for aerating reservoir water. Static heads of up to 160 ft and discharge velocities over 30 ft/sec produced aeration efficiencies greater than 0.8. Aeration efficiency is defined by equation (51).

$$E = \frac{(C_s - C) - (C_s - C_d)}{C_s - C} = \frac{C_d - C}{C_s - C} \quad \text{.................(51)}$$

where E = Aeration efficiency

C_s = Surface saturation concentration of dissolved oxygen in the liquid under aeration at the test temperature and pressure ($C_{ss(t,p)}$), mg/l

C = Dissolved oxygen concentration of the liquid entering the aeration device, mg/l

C_d = Dissolved oxygen concentration of the liquid as it enters the bulk liquid, mg/l.

Containment of the spray by shrouds or discharge tunnels did not significantly decrease aeration efficiencies as long as the discharge velocity was at least 30 ft/sec [154].

5.4.2 Aeration by Streams

The ability of a flowing stream to absorb oxygen from the atmosphere is a crucial element in pollution abatement considerations. The natural reaeration capacity controls and limits the stream's ability to receive and assimilate oxygen depleting wastes without becoming seriously degraded. The reaeration capacity of a stream is a function of turbulence and several investigators have reported reaeration constants based on hydraulic properties.

O'Connor and Dobbins [12] developed a predictive empirical equation to correlate K_La to stream depth and velocity.

$$K_La = \frac{(D_LU)^{1/2}}{H^{3/2}} \quad \text{....................(52)}$$

where D_L = Diffusion coefficient

U = Average stream velocity, ft/sec.

H = Average stream depth, ft.

Tsivoglou and Neal [155] have summarized their findings on predicting reaeration capacity of inland streams. Since the change in water surface elevation between two points in a stream is related to the energy expended by the flowing water in turbulence it is possible to correlate the rate of energy expended to the amount of oxygen transferred. The authors present this relation in the empirical equation (53) for water at 20°C:

$$K_La = C\left(\frac{\triangle h}{t_f}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (53)$$

where C = Constant of proportionality, ft^{-1}

h = Water surface elevation change, ft

t_f = Time of flow for elevation change, hr.

The average value for C for moderately polluted rivers with flows between 25 - 3,000 cfs is 0.054. Small streams also moderately polluted with flows between 1 - 25 cfs usually have a value of C = 0.110. With the streams surveyed the value of K_La varied between almost zero for large stagnant rivers to $15hr^{-1}$ for small waterfalls. K_La should be adjusted to other temperatures by the standard correction factor, discussed in Section 3.2.0.

When the time of flow between two points on a river segment is unavailable the reaeration rate coefficient may be estimated by equation (54):

$$K_La = B\left(\frac{\triangle h}{L}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (54)$$

where B = Constant

L = Length of the stream segment, ft.

The value for B depends on the size of the stream, the water quality, and time of travel but may be taken as 0.025. Use standard temperature correction for stream water temperatures of other than 20°C.

Based on the reported studies and radioactive tracer technique of Tsivoglou, Foree [156] developed additional relationships between head and slope and reaeration. His observed data on streams yielded the following empirical equation:

$$K_a = 0.30 + 0.19S^{1.2} \quad \ldots\ldots\ldots\ldots\ldots(55)$$

where K_a = Reaeration coefficient in base e at 25°C, $days^{-1}$

$S = \frac{\Delta h}{L}$ = slope of stream segment, ft/mile with Δh in ft and L in miles.

Note: Adjustments to K_a should be by the following equation:

$$K_{a\ (25°C)} = K_{a(T)}\ (1.022)^{25-T} \quad \ldots\ldots\ldots\ldots\ldots(56)$$

The data accumulated for small waterfalls yielded the following relation:

$$r = e^{0.16H} = \frac{C_s - C_u}{C_s - C_d} \quad \ldots\ldots\ldots\ldots\ldots\ldots(57)$$

where r = Dissolved oxygen deficit ratio

H = Difference in water surface elevation immediately above and below the dams or falls, ft

C_s = Dissolved oxygen saturation concentration of the stream water, mg/l

C_u, C_d = Dissolved oxygen concentrations immediately upstream and downstream, respectively, of the dams or falls.

Finally, if the river has virtually no velocity or surface turbulence, oxygen may only enter the bulk liquid as a result of simple diffusion. Oswald [157] reports that less than 40 lbs O_2/acre-day may be introduced into a quiescent lagoon. The amount of transfer would decrease in the presence of foam or large SAA concentrations and increase with wind generated turbulence.

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FIELD PERFORMANCE REVIEW

7.0.0 SURVEY OF NORTHERN BIOLOGICAL WASTE TREATMENT INSTALLATIONS

7.1.0 Purpose

The literature review portion of this report was intended to be theoretical and detailed. It dwelled heavily on the proper procedures for aerator testing, data analysis, and description of aeration system performance characteristics based on clean water testing. However, aerators do not operate in precisely controlled environments such as clean water. As well maintenance of the systems often consists of running the devices until they cease to function and then repairing them. Consequently, the objective of this section is to give a brief summary of the performance and reliability of operating aeration systems in aerated lagoons in Canada.

In clean water reaeration tests, environmental and fluid conditions are accurately measured. The resulting transfer efficiency is usually reliable and systems can be compared by using an efficiency term of lbs O_2/HP-hr. With aerated lagoons in the field where clean water tests are not feasible and steady-state oxidation of mixed liquor tests are difficult to perform accurately, aeration system performance is commonly expressed in terms of BOD_5 removal efficiency. This approach, because of the multitude of interdependent variables is inexact at best. Some of the variables involved include:

a. Wastewater treatability
b. Retention time
c. Organic loading rate
d. Oxygen supply
e. Mixing
f. Temperature
g. Nutrients
h. Toxic or inhibiting substances.

However, despite the inexactness, for large scale field performance surveys BOD_5 removal is all that there is to compare. Therefore, secondary treatment efficiency has been used in comparing the performance of various aeration systems. The data shown in this section should be used with caution and is presented, not as an absolute measure of the aeration systems' performance capabilities, but as a general indication of field performance characteristics of aeration systems. It follows that conclusions drawn from this cursory review of operating systems are only intended to be general in nature and to provide estimations of aeration system performance characteristics.

A survey population of 25 pulp and paper mills with aerated stabilization basin systems was used in this field performance review. The mills were asked to provide information in the following areas:

a. Description of biological treatment basin and aeration system.

b. Secondary treatment system BOD_5 reduction efficiency.

c. Description of aeration system preventative maintenance programs.

d. Details of aeration system problems.

e. Cost of maintaining aeration system in working order.

Since the absolute performance of any aeration system is best measured under controlled circumstances the biological treatment data was of secondary importance. The prime purpose of the review was to obtain information on operating system reliability and susceptibility to icing. Even though the quantity and quality of this information is somewhat limited it is sufficient to provide some insight into the realm of maintenance requirements and system reliability.

Although this field performance review was intended to compare the operating reliability and resistance to winter operational problems of surface aerators and submerged aeration systems, too few submerged systems for aerated lagoons have been operating for a sufficient time in the northern latitudes to provide this comparison. Because low and high speed surface aerators are the predominate aeration systems in use in aerated stabilization basins all the data is for these aerators. However, enough is known about submerged aeration systems to be able to make general comparisons; these will be discussed later.

7.2.0 SUMMARY OF BIOLOGICAL TREATMENT SYSTEM OPERATION DATA

Biological treatment system operation and design data for 25 pulp and paper mills in Canada and northern U.S. have been summarized in Table 7.1. The data are representative of the averages of the warm weather performance of the individual systems.

The limitations of the data have been discussed previously in Section 7.1.0, but in the absence of better information the data in Table 7.1 are relatively useful. Several plots of the biological treatment information were attempted:

a. Lbs BOD_5 applied/HP-day versus lbs BOD_5 removed/HP-day
b. Lbs BOD_5 applied/1000 ft^3 versus BOD_5 removal efficiency
c. Retention time versus BOD_5 removal efficiency
d. Power density versus BOD_5 removal efficiency.

The first two correlations, Figures 7.1 and 7.2, plotted in a reasonably predictable manner and yield interesting information. The second two were not well correlated, in that changes in retention time or power density did not result in a predictable change in treatment efficiency.

From Figure 7.1 the data plotted reasonably linearly up to approximately 55 lbs BOD_5 applied/nameplate HP-day and then seemed to flatten out immediately at 46 lbs BOD_5 removed/nameplate HP-day. The values of 55 and 46 for applied and removed loadings compare well with the findings of McKeown and Buckley [140], as discussed in Section 5.2.4. As well, if the ratio of lbs O_2 supplied/lbs BOD_5 removed is assumed to be one, then 46 lbs BOD_5 removed/nameplate HP-day is equal to 1.9 lbs O_2/HP-hr. This compares favourably with the results of the sample calculation shown in Section 4.1.5 where the field transfer rate of a low speed surface aerator was expected to be 1.8-2.0 lbs O_2/HP-hr.

TABLE 7.1

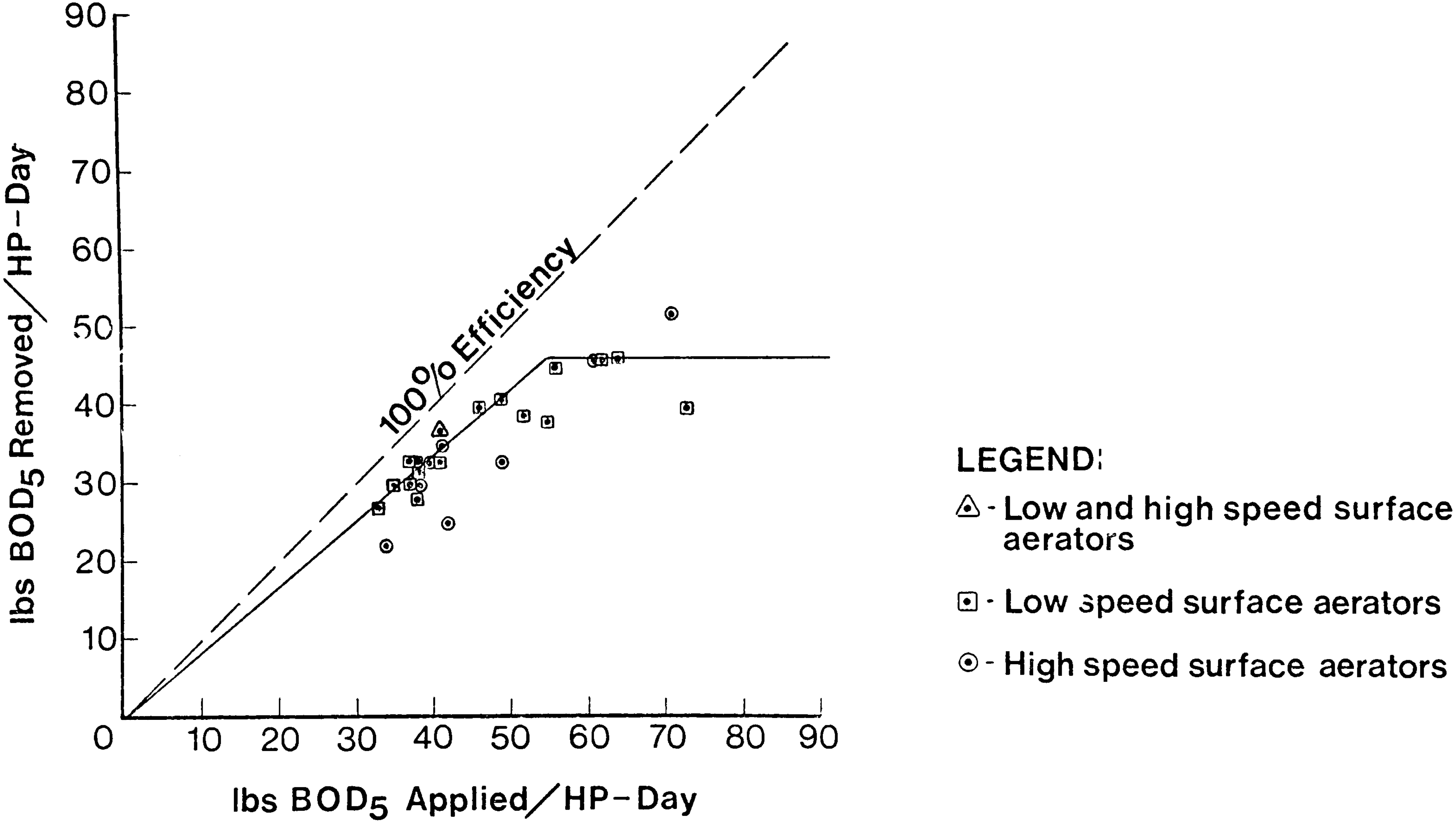
SUMMARY OF BIOLOGICAL TREATMENT SYSTEM OPERATION DATA

Mill	Type of Aerator*	lbs BOD_5 Applied/ 1000 ft^3	lbs BOD_5/HP+-day Applied	lbs BOD_5/HP+-day Removed	%**	Aerator HP+/MG	Retention Time, Days
Mill A	LS	2.5	52	39	75	7	6.5
Mill B	HS	2.6	34	22	65	10	5.3
Mill C	LS	5.2	56	45	80	12	4.7
Mill D	HS	2.8	61	46	75	6	5.1
Mill E	LS	4.4	49	41	84	12	3.5
Mill F	HS+LS	1.8	41	37	90	6	5.5
Mill G	HS	2.7	41	35	85	9	6.8
Mill H	LS	2.3	41	33	80	7	6.0
Mill I	LS	2.4	55	38	69	6	6.4
Mill J	HS	2.5	41	33	80	8	5.3
Mill K	LS	1.5	38	33	87	5	10.7
Mill L	LS	14.5	35	30	86	56	18.0
Mill M	LS	3.7	37	33	89	14	5.7
Mill N	LS	4.8	64	46	72	10	4.5
Mill O	LS	3.9	37	30	81	14	8.0
Mill P	LS	2.1	33	27	82	8	5.5
Mill Q	LS	1.7	38	32	84	6	12.8
Mill R	HS	2.1	71	52	73	4	10.0
Mill S	LS	2.0	46	40	87	6	12.2
Mill T	LS	5.4	62	46	74	12	9.0
Mill U	HS	2.5	38	30	79	9	5.3
Mill V	HS	3.7	49	33	67	10	5.5
Mill W	HS	5.9	42	25	60	19	2.9
Mill X	LS	1.9	38	28	74	7	6.7
Mill Y	LS	2.9	73	40	55	5	5.0

* LS - Low speed surface
HS - High speed surface

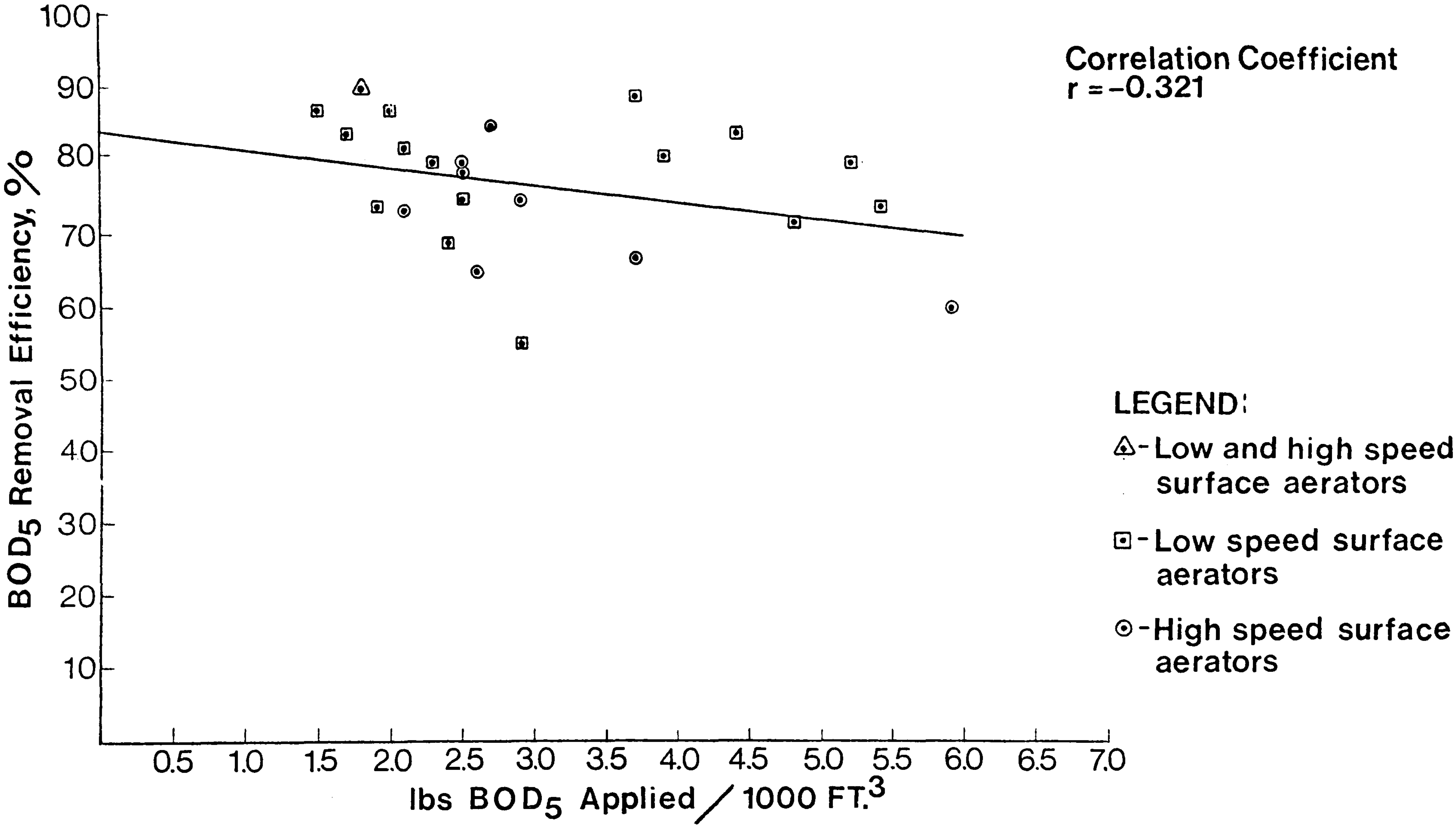
\+ All horsepowers are nameplate

** Warm weather treatment efficiency only



ORGANIC LOADING RATE VERSUS REMOVAL RATE

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	beak	BY BG	DATE: 26 APR 77	FIG. 7.1
		DWG. NO. A1269 - 15		



ORGANIC LOADING RATE VERSUS REMOVAL EFFICIENCY

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	BY BG	DATE: 27 APR 77	FIG. 7.2
	DWG. NO. A1269 - 16		

Figure 7.2 although interesting does not seem to lend itself well to an exact linear interpretation. The correlation coefficient of all the data plotted together is only -0.321. This lack of correlation is to be expected considering the number of variables involved; however, a general interpretation is warranted. The data suggests that the chances of obtaining high BOD_5 removal efficiencies improve as the organic loading is reduced; specifically, an organic loading rate of 2.5 lbs BOD_5 applied/1000 ft^3 or less appears necessary to achieve a removal efficiency of 80 percent or better.

The effect on temperature was not closely investigated in the survey of the field installations as it was not directly in the scope of the work. However, in general, mid-winter removals are 5-15% less than mid-summer removals due to decreases in bioactivity at colder temperatures. This effect is minimal when lagoon temperatures remain above 20°C (68°F) and becomes increasingly more apparent as the lagoon temperature drops below 15°C (59°F). Below 4°C (40°F) bioactivity becomes very lethargic. When projected lagoon temperature losses show temperature drops below optimal bioactivity temperatures the choice of aeration system may be important. All surface aerators, especially those which have high spray patterns, tend to cool the liquid under aeration. This effect is somewhat countered by foam generation, but on non-foamy effluents the temperature loss due to surface aeration can be significant. Submerged aeration systems, on the other hand, do not spray liquid nor create the same surface cooling turbulence. In fact, the heat of air compression provides a slight, but positive heat input.

In some instances, the opposite problem is a determining factor, because temperatures over 40°C (104°F) tend to create treatment problems. In these cases cooling may be a desirable result so that high spray pattern aerators would be favored.

The assumption mentioned earlier concerning a 1:1 ratio between lbs O_2 supplied:lbs BOD_5 removal is generally known to be a variable ratio not fixed.

A system which in the first year of operation is achieving design removal efficiencies with an aerobic discharge may find after 2-3 years a deterioration in treatment efficiency. This deterioration in treatment efficiency may be a result of biosolids which were produced during previous conversion of organic substrate to biocellular mass. These biosolids impose an oxygen demand on the aeration system of between 10-40% of the influent organic load. Therefore, many treatment facilities have found it necessary to purchase additional aeration capacity after the system has been in operation for some time.

Another operating problem in long retention basins which experience low basin temperatures is the spring solids turnover or float. This condition is a result of large quantities of biosolids produced previously which have been held in cold storage over the winter. As the basin warms, anaerobic activity increases digesting the accumulated sludge, but also producing an off-gas. The gas bubbles are enmeshed in the sludge blanket until the bouyancy wins over gravity and then the air bubbles along with globs of sludge rise to the surface. Commonly, before the air bubbles escape from the confines of the sludge, the floating sludge is discharged with the treated effluent. Should the gas bubbles escape from the sludge material first, the sludge will settle harmlessly back to the basin floor, but may also be refloated. This is a significant problem at some lagoons that have low power densities (only enough power for oxygen dispersion) and/or those which have non aerated quiescent zones after the aerated portion of the lagoon.

7.3.0 SUMMARY OF AERATION SYSTEM MAINTENANCE AND OPERATIONAL PROBLEMS

Of the 25 mills surveyed, 15 reported sufficient maintenance procedure and maintenance cost data to be useful for comparison. This is not a large population sample considering the number of variables involved, but it is sufficient to report some general findings. A summary of the maintenance and operational problems of the aeration systems at 15 mills is shown in Table 7.2.

Three major areas were to be covered in the maintenance and operational problem survey: winter icing problems, general electrical and mechanical reliability and total maintenance costs. Icing proved to be a function of the aeration system type, basin temperature, air temperature and wind velocity. Operating reliability and maintenance costs were shown to be inseparably related.

TABLE 7.2

SUMMARY OF AERATION SYSTEM MAINTENANCE AND OPERATIONAL PROBLEMS

Mill	Type of Aerator	Floating (F) or Stationary (S)	Age, Yrs.	Severity of Winter Icing Problem	Emphasis on Preventative Maintenance	Electrical + Mechanical Breakdowns: Life Ave. % units/yr	Electrical + Mechanical Breakdowns: 1976 % units/yr	Maintenance Cost: Life Ave. $/HP/yr	Maintenance Cost: 1976 $/HP/yr
Mill A	LS	25% F 75% S	3 5	Nil	Ave.	25	-	-	16
Mill B	HS	F	5	Nil	B.T.A.	33	-	37	-
Mill C	LS	S	4	Nil	Ave.	17	-	-	5
Mill D	HS	F	Up to 8	Nil	None	50	-	11	-
Mill E	LS	F	Up to 7	Minor	W.T.A.	Nil	Nil	-	4
Mill F	HS+LS	F	Up to 12	Nil	Strong	12	-	-	46
Mill G	HS	F	Up to 10	Nil	None	140	92	-	5
Mill H	LS	S	4	Nil	Ave.	Nil	Nil	-	3
Mill I	LS	F	5	Major	Ave.	25	-	8	23
Mill J	HS	F	5	Nil	Strong	25	Nil	-	5
Mill K	LS	S	5-8	Nil	Ave.	Nil	Nil	4	4
Mill L	LS	S	4	Severe	W.T.A.	20	60	24	37
Mill M	LS	F	Up to 3	Moderate	W.T.A.	10	-	-	13
Mill N	LS	F	7	Moderate	Strong	Nil	Nil	-	54
Mill O	LS	S	3	Minor	W.T.A.	Nil	Nil	-	2

TABLE 7.2 (cont'd)

Explanation of Terms:

LS	=	Low speed surface aerator.
HS	=	High speed surface aerator.
F	=	Floating: aerator supported by pontoons or circular float.
S	=	Stationary: aerator fixed to a platform on piles.
Minor	=	0-25% of aerators have been shut-down due to icing.
Moderate	=	25% or more of aerators have been shut-down due to icing.
Major	=	0-50% of aerators have been damaged by ice.
Severe	=	50% or more of aerators have been damaged by ice.
None	=	No preventative maintenance is performed; the aerators are run till they cease to function and then are repaired.
W.T.A.	=	Worse Than Average: Lubrication checked and changed as recommended by manufacturer.
Ave.	=	Average: Frequent lubrication and electrical power draw checks are made in addition to required lubrication changes.
B.T.A.	=	Better Than Average: In addition to items covered in Ave., 0-20% of the aerators are overhauled each year.
Strong	=	More than 20% of the aerators are overhauled each year in addition to items covered in Ave.

When a new aerated stabilization system is being designed or an existing facility expanded in most areas of Canada and northern U.S., icing is an important consideration. The results of the field survey show icing problems accounting for up to 90% of all mechanical breakdowns in some systems. In others icing is never a problem, not even during the extremely cold winter of 1976-1977. The major icing problems were associated with low speed floating aerators. Of the 15 installations, 6 reported icing problems and of those, 4 had low speed floating aerators. The above water structure of the floating aerators would become ice covered until the weight of the ice caused enough submergence to overload and trip-out the motor. The general procedure for restarting was to go out in a barge or boat and beat the ice off with sledge hammers. Only one mill reported a problem with aerators flipping over, and this was corrected by adding oversized pontoons. The other two systems with icing problems were for stationary or fix mounted low speed aerators. The most severe icing problem developed as a result of cold lagoon water and high platforms, seven feet above the water. Spray and mist froze on the structure, but more importantly on the tops of the blades. With the long impeller shaft the impeller icing caused pendulum like oscillation of the entire unit until the unit broke or was turned off. The sixth system with fix mounted aerators reported that their icing problems were held to an acceptable minimum due to low platforms and warm effluent. See Section 5.2.0 for recommendations on anti-icing techniques for aeration systems.

Those installations which reported icing incidents indicated the following conditions usually initiated the problem:

a. Lagoon temperatures below 4°C (40°F) and air temperatures below 0°C (32°F)

b. Any lagoon temperature, air temperature at -18°C (0°F) and wind

c. Any lagoon temperature, no wind, and air temperatures below -29°C (-20°F).

Of course, there are many installations which operate satisfactorily throughout the winter and experience cold and wind as described above. Obviously, warm basin temperatures and proper aerator mooring decrease icing problems.

Although no submerged systems were included in the maintenance data, Table 7.2, they are known to present few if any winter operating problems. Since all basin structures are below water, the system will function normally unless the entire basin freezes solid. Therefore, at aerated stabilization basin treatment systems located in severe cold areas, submerged aeration systems offer a winter-resistant alternative.

Operating reliability as reported by the surveyed mills was found to be a function of the type of aerator and the amount of preventative maintenance given to the aeration system. The survey, although not necessarily statistically valid, showed that low speed aerators, while not trouble free, were significantly less prone to breakdowns than high speed units. This is exemplified by Table 7.2 which shows that of the 15 mills surveyed five reported no significant breakdowns during the life of the aeration system and all five used low speed aerators.

From the survey one general comment may be warranted; where high rotational speeds and close tolerances exist long term mechanical reliability is low. This may be seen in both the high speed and surprisingly enough, low speed aerators.

The high speed aerator being essentially a vertical lift impeller in a shroud derives its operational problems from its name, high speed. Vibration and/or water intrusion into the bearings accounts for most of the operational difficulties. Vibration eventually destroys the bearings and motor, but may also cause float and motor mount damage. The lack of dynamic balance may be evident at start-up or, more likely, may result from ingested debris. Most manufacturers perform dynamic testing in a test tank prior to delivery and this results in an insignificant level of start-up vibration problems. However, the perfect dynamic balance may soon be lost in the field because of ingested debris problems. Floating debris which have been reported as problematic consist of 2"x4" scrap, broom handles, tumbleweed, and ice chunks. The very least this material does when passing through the aerator is to cause impeller bending and nicks, which again results in a loss of dynamic balance. Inlet screens will prevent the large debris from entering, but have a tendency to clog with leaves, weeds, and wood chips.

Low speed aerators have shown in this survey that on the average they are less prone to breakdowns. When breakdowns do occur it is normally due to reducer gear box problems. The item most frequently mentioned was the high speed bearing; the most frequent cause was insufficient lubrication. Other less significant breakdowns included bolt shearing on impeller blades and icing derived imbalance damage to the gear box.

Unfortunately, operating reliability is only part of the picture. At least as important to a mill operator is the cost of maintaining the system in operating condition. For aeration systems the cost of maintenance can be broken down into two items: the ease of maintenance and the frequency of required maintenance. The survey showed that there is little question that high speed aerators are the easiest surface aerators to maintain. For both minor and major maintenance the high speed unit is disconnected and towed ashore. From there it is lifted out of the water and transported to the shop. Consequently, the time spent on the lagoon is minimized or eliminated (depending on the type of mooring system) and work can be performed speedily and safely in the comfort of the workshop. On the other hand, a low speed aerator, if floating, is normally too big to be brought indoors and, if stationary, is often difficult to move with ease from its platform. Therefore, when maintenance must be performed, it is done from a boat or barge, or on the aerator platform. The size and the weight of the low speed aerator components makes it difficult to perform major rebuilding on the lagoon; catwalks improve accessibility and ease maintenance greatly.

The survey showed that frequency of maintenance tends to be a function of the amount of preventative maintenance given to the aeration system. The information from the survey is obviously somewhat sketchy, but seems to support the following observation. The more emphasis that is placed on preventative maintenance the more reliable the system is, but at the price of a higher cost of maintenance. Conversely, if a system is turned on and repaired as it breaks down, the overall cost of maintenance will be low, but the chances are also low of maintaining a satisfactorily operating biological treatment system.

Submerged aeration systems normally are very reliable, easy to repair, and involve low maintenance costs. They are reliable in that there are only a few moving parts and these are located indoors. As well, most systems are installed with a spare motor and blower which means very little system downtime. The ease of repair is the best of all aeration systems, because all repairable mechanisms are located indoors. In summarv, industrial experience with blowers and motors shows low maintenance requirements and costs. However, if rags, papers, leaves and twigs are permitted in an air-gun submerged aeration system basin, plugging may result. Clogging is essentially mechanically non-damaging, but system performance is impaired. Clearing blocked underwater units is very inconvenient and can involve considerable maintenance costs and system downtime.

To summarize the maintenance and cost information presented in this section, Table 7.3 has been included. The information is general and, for the submerged air-gun installations, based on non-site specific information. The ranking of the aeration systems in an order based on generic types is not necessarily consistent with field data, as some manufacturers have had more problems than others. Consequently, some trade name devices may well be more appropriately rated either higher or lower than is shown here based on their specific reliability and maintenance requirements.

TABLE 7.3

SUMMARY OF AERATION SYSTEM OPERATIONAL CHARACTERISTICS

Type of System	Probability of Icing Problems	Rate of Mechanical Breakdowns with Ave. Preventative Maintenance	Overall Cost of Main. when Strong emphasis on Preventative Maintenance followed
High Speed, floating	1	3	2
Low Speed, floating	4	2	4
Low Speed, stationary	2	1	3
Submerged, air-gun	0	1	1

0 = Nil

1 = Low

2 = Low - Medium

3 = Medium - High

4 = High

DISCUSSION

DISCUSSION AND CONCLUSIONS

The objectives of this report were based on a need by process engineers and purchasers of aeration equipment to have in one volume virtually all information on oxygen transfer and biological treatment system aeration. Current literature written both by manufacturers and independent investigators is contradictory and confusing. Therefore, the construction of the report was aimed at providing a unified concept of aeration.

The report is divided into two basic sections: first a relatively detailed account of aeration theory, testing procedures, data analysis, and aeration device operation; second, a general field review of operating aerated stabilization basins (aerated lagoons). Although many conclusions are a result of a blending of the two sources most are a result of specific information from the literature or the field. Therefore the conclusions will be presented under the two sub-sections of literature review and field review.

MAIN CONCEPTS AND CONCLUSIONS OF THE LITERATURE REVIEW

1. The Whitman two film theory is held to be accurate in its depiction of a gaseous film next to a liquid film. With a slightly soluble gas such as oxygen all resistance to gaseous dissolution lies in the liquid film. Consequently, atmospheric gaseous conditions are negligible.

2. Large, slow moving mechanical impellers are more efficient mixers than either high speed impellers or compressed submerged air. Efficient oxygen transfer depends on small scale, intense turbulence which is not produced by large, slow moving impellers. Therefore, aeration devices are a compromise between mixers and oxygenators.

3. Over a moderate temperature range (10°-25°C) K_La can be accurately corrected by either an exponential or linear equation. The choice of theta factors is large and the correct one may depend on the temperature involved. At low temperatures, the linear correction equation will probably yield the most accurate result.

4. Increases in total dissolved solids concentration decreases oxygen diffusivity and increases solution viscosity. The net effect usually results in a decrease in K_La.

5. The concentration of suspended solids is not well correlated as to its effect on K_La. In general, inorganic non-flocculent solids have negligible effects, while organic flocculent solids may increase K_La due to interfacial conditions.

6. The effect that surface active agents (SAA) creates depends on the intensity of the turbulence. Low turbulence in the presence of SAA decreases oxygen transfer. A high intensity turbulence may actually increase oxygen transfer, while at some intermediary intensity level, there is no effect.

7. The wastewater oxygen transfer efficiency : clean water oxygen transfer efficiency (alpha) correction factor is inherently inaccurate. Differences in turbulence between the full scale basin and the lab alpha test tank as well as extended aeration stripping of volatile organic material accounts for most of the error. If the K_La of the full scale basin and aeration system and the lab tank are close, then a close estimation may be obtained. Alpha may exceed 1.0 when SAA are present with intense turbulence, but for design purposes the lowest observed alpha should be used.

8. The beta correction factor test despite the interference of volatile material stripping is reasonably accurate.

9. The effect of power density (either HP/volume or HP/area) is not well correlated at the present time and requires further research. However, in general high power density with surface aerators can significantly increase oxygen transfer while low levels of turbulence intensity resulting from low power density reduces oxygen transfer. The effect of power density on oxygen transfer rates for submerged aeration is not documented, but should show a similar relationship as for surface aerators. It is important to state or to ask for the power density used in a clean water test relative to the field power density application.

10. The only accurate and recognized standard evaluation procedure for aeration systems is the clean water non steady-state reaeration test. One of the important test assumptions is that the basin is perfectly mixed. Dissolved oxygen gradients (in excess of 0.25 mg/l from the mean) resulting from inadequate mixing invalidate the test results.

11. To ensure adequate mixing in the non steady-state test the aeration system must be capable of raising the dissolved oxygen concentration from 0-90% of saturation in 10-30 minutes. This reaeration rate diminishes dissolved oxygen gradients, but does not account for power density effects.

12. Clean water deoxygenation may be performed in two ways:

    a. Addition of 100 mg/l Na_2SO_3 for water at 20°C after the system is at hydraulic steady-state. Use either 2.0 mg/l or 0.05 mg/l Cobalt Chloride catalyst depending on the method for determining dissolved oxygen (see No.13 below).

    b. Addition of nitrogen gas from submerged aeration system while system is at hydraulic steady-state.

13. Depending on the method employed for deoxygenation the appropriate dissolved oxygen determination methods are:

    a. For Na_2SO_3 and 0.05 mg/l catalyst use the Winkler method or an appropriate variation according to Standard Methods [39].

    b. For Na_2SO_3 and 2.0 mg/l catalyst use the chemical blank method for measuring the positive interference as proposed by Lakin [103] in addition to the Winkler method.

    c. For Na_2SO_3 and any catalyst concentration a fast response polargraphic probe may be used instead of the Winkler determination.

    d. For nitrogen gas either a fast response probe or the Winkler determination may be employed.

14. Regardless of the dissolved oxygen determination method the rise in total solids in the clean water must be controlled; a single batch of water should be used no more than 10 times when deoxygenating with Na_2SO_3.

15. Regardless of the dissolved oxygen determination method the number of sampling points required to obtain a representative dissolved oxygen level is determined by the basin geometry; a minimum of four are required in a well mixed, properly baffled tank and as many as ten may be required in a poorly mixed basin.

16. The dissolved oxygen saturation concentration determination method should be based on a flexible, comparative approach.

Submerged Aeration C_{se} Determination Methods:

a. Mid-depth corrected
b. Log mean driving force
c. Best fit of the data
d. Direct analysis of the data
e. Direct observation by extended aeration

Surface Aeration C_{se} Determination Methods:

a. Standard saturation value $C_{ss(t,p)}$ Tables
b. Best fit of the data
c. Direct analysis of the data
d. Direct observation by extended aeration

The C_{se} values resulting from these determination methods should be compared. If they are in close agreement, then the confidence in the resulting K_La will be high. If the values are divergent, then some models may be invalidated due to compromising of their assumptions. However, if no substantial reason can be found for the divergency, then all values should be used to compute K_La and oxygen transfer efficiency numbers. By reporting all results the credibility of the reported figures will be improved.

17. All clean water tests should be run to an asymptotic C_{se} value. The observed C_{se} value will be of use in comparing other C_{se} determination methods and there is no valid experimental reason for truncating the test and test data at 70-90% of the saturation concentration.

18. However, initial reaeration test data is not important, so the first 10-20% of the reaeration data may be neglected.

19. Overall, the accuracy of a properly performed clean water reaeration test is approximately ± 5%. Since the interferences and correction factors for extrapolating test data to the field are even less accurate the ability to estimate the expected performance of an aeration device in the field is limited. This is not to say that precise testing methods and data analysis procedures are not warranted, but that when the standard oxygen transfer rate is extrapolated to the field, a high degree of confidence in the result is not possible and a conservative approach is necessary.

20. The steady-state oxidation of mixed liquor aeration test is not recommended as a standard test, but is useful in the field when a clean water reaeration test is impractical. Lack of precision and accuracy in determining alpha, beta, oxygen uptake, and dissolved oxygen gradients compromise the test results.

21. Sulfite oxidation aeration testing is recognized as a poor standard test and its results have a low correlation to what can be expected in the field. The simultaneous chemical reaction occurring with the oxygen diffusion results in oxygen transfer efficiencies as much as 50% higher than the clean water reaeration tests.

22. The references to horsepower in the literature and in manufacturers' bulletins have varied meanings. The most relevant terms for the purchaser are wire, electrical, line, or gross horsepower as these refer to how much electrical energy the device will consume. Often shaft or delivered horsepower figures are quoted. These terms account for actual power input to the shaft of an aerator. They do not include efficiency losses in the electrical motor or gear box. Adiabatic horsepower is a theoretical power term used for submerged aeration devices. It only specifies how much horsepower is required to compress air to a specific pressure; motor, blower, air delivery line, and exit losses must be included to reach wire horsepower. The final term found in general literature including this

report is nameplate horsepower. Although it is often the only measure of power available from field surveys it is a useless number because the power actually delivered or drawn can be either less than, equal to, or more than what is written on the motor nameplate. For performance data aeration systems should be compared on the basis of wire horsepower.

23. Measurement of mixing performance is very difficult. Power densities are not meaningful because different aeration systems do not all have the same fluid mixing ability for the same horsepower input. Pumping rates are also relatively useless in that direct volume/time does not account for kinetic energy advantages in higher velocities. Induced pumpage figures are almost impossible to verify. What does provide meaningful mixing data is uniformity of dissolved oxygen in aerated lagoons and mixed liquor suspended solids in high rate treatment systems. Within individual aerator "areas-of-influence" both D.O. and MLSS should vary no more than $\pm$ 10% from the mean. When entire basins are considered the tolerance should be enlarged to $\pm$ 20%.

24. Although clean water reaeration tests are useful in determining maximum oxygenation capacity, this capacity may never be achieved in the field as the devices are controlled to a great extent by the biological reaction rate. In the field aerators operate, practically speaking, at steady-state conditions. The operating D.O. level dictates the driving force and therefore controls the rate of oxygen transfer. Since the biological reaction rates normally experienced in the field fall within the range of the oxygen supply rates of most aeration systems, the net effect is to have comparable BOD_5 removal produced by low and high efficiency systems but to have higher D.O.'s in basins with more efficient aeration systems. This is to say that although one system may be much more efficient as compared to another on the basis of the clean water non steady-state test there may be little difference in the BOD_5 removal efficiencies of the two treatment systems. The advantage of the higher efficiency system will be evident when the system is loaded beyond design as a result of increased production or spills.

MAIN CONCEPTS AND CONCLUSIONS OF THE FIELD SURVEY

1. The review of the literature and operational histories of field installations fail to show one type of aeration system as being the most cost effective in all instances. Instead what can be said is that many aeration systems when properly applied will yield a feasible and economic source of dissolved oxygen and mixing.

2. Surface aeration continues to be an attractive method of aeration for shallow and medium depth lagoons (less than 20 feet deep). Despite the clean water reaeration test oxygen transfer efficiency advantage of the low speed aerators, they do not provide obvious and significant increases in BOD_5 removal over that of high speed aerators.

3. Submerged aeration, particularly static air-gun tubes, can be competitive in medium depth basin applications and are superior in deep basin lagoons (more than 25 feet deep) by virtue of the fact that their oxygen transfer rate is enhanced and their mixing is not greatly deteriorated by greater submergence. Surface aerators are unable to adequately mix deep basins even with draft tubes.

4. Winter icing problems may be minimized by observing the following guidelines:

   a. Maintain the aeration basin liquid temperature as high as possible by using shorter retention, higher rate treatment systems.
   b. Unless special precautions are taken, as noted in the report, low speed floating surface aerators should be avoided in applications where severe winter cold and winds are experienced.
   c. Low speed stationary surface aerators should be mounted on low rather than high platforms. The structural members should be made of smooth surfaced materials and without projecting ledges, nuts, and bolts.
   d. Icing has not been a severe problem with high speed floating aerators, but if extreme winter conditions are expected winter tie-downs, mooring with slip rings and short cables, and motor heaters may be useful.

5. The cost effectiveness of any aeration system is influenced by four variables. The following table summarizes in a general comparison the trade-offs of surface and submerged aeration systems for aerated stabilization basins.

Item	Low Speed Surface Floating	Low Speed Surface Stationary	High Speed Surface	Submerged Air-gun
Capital Cost	3	4	1	5
Operating Cost	3	3	3	1-5*
Maintenance Cost**	4	3	2	1
Equipment Life	3	4	2	5

* depth dependent

** with strong emphasis on preventative maintenance

1 = low

2 = lower than average

3 = average

4 = higher than average

5 = high

Unfortunately, a general comparison such as the above table can only serve as an indication of what can be expected. Actual prices and costs are required for a good comparison of alternative aeration systems.

a. Capital cost is heavily dependent on local market conditions. Sometimes manufacturers reduce profit margins to establish treatment systems with their product.

b. Operating cost can be calculated from the estimated electrical horsepower drawn by the devices.

c. Maintenance costs appear to be directly related to the level of preventative maintenance. A strong preventative maintenance program has a significant cost associated with it, but high operating reliability. If little preventative maintenance is performed the overall cost of maintenance will be low, but mechanical reliability will also be low.

d. The life of an aeration system is dependent on the level of preventative maintenance and the type of system. Mechanical surface aerators have a useful life expectancy of 5-10 years with high speed units with no preventative maintenance on the low end and low speed stationary aerators with a high level of preventative maintenance in the upper portion of the range. Submerged systems whose only moving parts are motors and blowers have a much longer life expectancy of up to 20 years.

6. When considering mixing requirements in an aerated stabilization basin (aerated lagoon) treatment system the following power density guidelines should be applied:

1 day retention time - 30 nameplate HP/MG or more
3-5 days retention time - 10-20 nameplate HP/MG
5 days retention time or longer - 6-10 nameplate HP/MG.

These guidelines apply only to solids suspension and oxygen dispersion. Operating efficiencies will vary depending on availability of oxygen and nutrients, high temperature related inhibition, and wastewater treatability. BOD_5 reduction during cold weather will depend on the basin temperature with significant reductions commencing below 15°C (59°F).

Although the recommendations and conclusions contained in this section tend to be general, this was in part due to the constraint of not using trade names and the limited time available to assemble this report. Nonetheless, it is hoped that the information presented will prove both enlightening and interesting.

APPENDICES

APPENDIX 1

EXAMPLE PROBLEM SHOWING EFFECT OF C_{se} ON $K_L a$

The following example is taken from Campbell et.al. [98] to show the results of constant C_{se} estimations and their effect on K_La. The reaeration test data was collected in a large circular test tank using tap water. The important test parameters are as follows:

Test Basin

Tank diameter = 90 ft

Tank depth = 24 ft

Tank volume (nominal) = 1.1×10^6 U.S. gals.

Aeration System

Submerged Static Tubes = 184 units on approximately 6 ft centers

Air flow = 32 SCFM/unit

Submergence = 23 ft.

Water and Environmental Conditions

Water Quality - "Clean"

Number of prior tests on same water - UNKNOWN

Cobalt Catalyst concentration - UNKNOWN

Temperature = 28°C (results corrected to 20°C by equation (24) with $\theta = 1.024$)

Atmospheric pressure = UNKNOWN - assumed 14.7 psia

Power density = 265 HP/MG (assumed blower and motor efficiency = 65%)

Procedural

D.O. determination method - UNKNOWN

Oxygen transfer efficiency from air bubbles to liquid = UNKNOWN

The reported reaeration test data is shown in Table A.1. Although this example is intended to only show the effect of C_{se} or K_La, the artificial truncation of data at a D.O. of 7.80 mg/l, which corresponds to approximately 80% of saturation, is also a possible source of error as discussed in Section 4.1.1.

TABLE A.1

DISSOLVED OXYGEN DATA FOR NON STEADY-STATE
CLEAN WATER REAERATION TEST

Time (min)	D.O. (mg/l)
0.0	0.00
0.5	1.15
1.0	2.10
1.5	3.00
2.0	3.70
2.5	4.35
3.0	4.90
3.5	5.45
4.0	5.85
4.5	6.25
5.0	6.55
5.5	6.85
6.0	7.10
6.5	7.30
7.0	7.50
7.5	7.65
8.0	7.80

Some very common C_{se} estimation procedures were used to obtain the values of C_{se}; the equations and a brief description of each model follows:

a. Surface Saturation Model

This model assumes the source of oxygen to be air at atmospheric pressure. Although this model seems rather irrational for submerged aeration it has been used on some occasions. C_{se} is determined from the Standard Methods [39] or ASCE [105] tables at the correct temperature and adjusted for the local atmospheric pressure, $C_{ss(t,p)}$.

b. Mid-Depth Model

The mid-depth model was the first model used in the analysis of submerged aeration equipment and assumes that the C_{se} occurs at the mid-depth of the liquid because of the pressure of submergence. The mid-depth is measured as 1/2 the distance from the surface to the air outlet. Equation (A1) is the common definition of the mid-depth model,

$$C_{se} = C_{sm(t,p)} = C_{ss(t)} \left(\frac{P + 0.433\ (H/2)}{14.7} \right) \text{.........(A1)}$$

where P = Site barometric pressure, psia

H = Depth of liquid above air outlet, ft.

Note: The water vapor pressure, p, has been neglected. To be more correct both the numerator and denominator should have an additional term of, p, the water vapor pressure in psia (Table 3.1), subtracted from them before dividing the fraction.

c. Mid-Depth Corrected Model

This model is similar to the mid-depth model but corrects for the diminishing oxygen content in the rising air bubble.

$$C_{se} = C_{sm(t,p)} = C_{ss(t)} \left[\frac{P + 0.433\ H}{29.4} + \frac{P\ (O_r)}{(14.7)(42)} \right] \text{.........(A2)}$$

where O_r = Oxygen content of the air leaving the liquid

$$= \frac{21(1-E)100}{79+21(1-E)} \text{ (expressed as a \%)}$$

E = Decimal fraction of oxygen in air bubbles transferred to the basin liquid.

Note: The water vapor pressure, p, has been neglected.

d. Log-Mean Saturation Value Model

This model assumes that the log-mean of the oxygen saturation at the tank bottom and the oxygen saturation at the surface corrected for decreased oxygen partial pressure yields a closer approximation of the C_{se}. Equation (A3) defines the C_{se} for this model:

$$\ln C_{se} = \frac{\ln\left[C_{ss(t)}\left(\frac{P+0.433H}{14.7}\right)\right] + \ln\left[C_{ss(t)}\left(\frac{O_r}{21}\right)\right]}{2} \quad \text{(A3)}$$

Note: The water vapor pressure, p, has been neglected.

e. Bottom Saturation Model

This C_{se} model assumes that all oxygen transfer takes place at the point of air release which is clearly inaccurate, but has been included to show the ultra-conservative K_La number which results. For this model C_{se} is determined by equation (A4).

$$C_{se} = C_{sb(t,p)} = C_{ss(t)}\left(\frac{P+0.433H}{14.7}\right) \quad \text{(A4)}$$

Note: The water vapor pressure, p, has been neglected.

f. Best-Fit Model

All of the above models assume that the C_{se} value may be calculated from various combinations of the physical test facility dimensions, water temperature, and atmospheric pressure, but the best-fit model acknowledges that all attempts to calculate a fixed C_{se} based on geometry can only result in a rough approximation. The proponents of this model further assert that the most correct constant C_{se} value can only be determined by the data i.e. whatever makes the data plot straight is the correct value. With the data truncation shown in this example, however, there are many values which would seem equally good. Therefore, the C_{se} shown in Table A.2 for the best-fit model is also only an approximation and other investigators could determine additional best-fit C_{se} values that would be statistically valid, but in variance with the example.

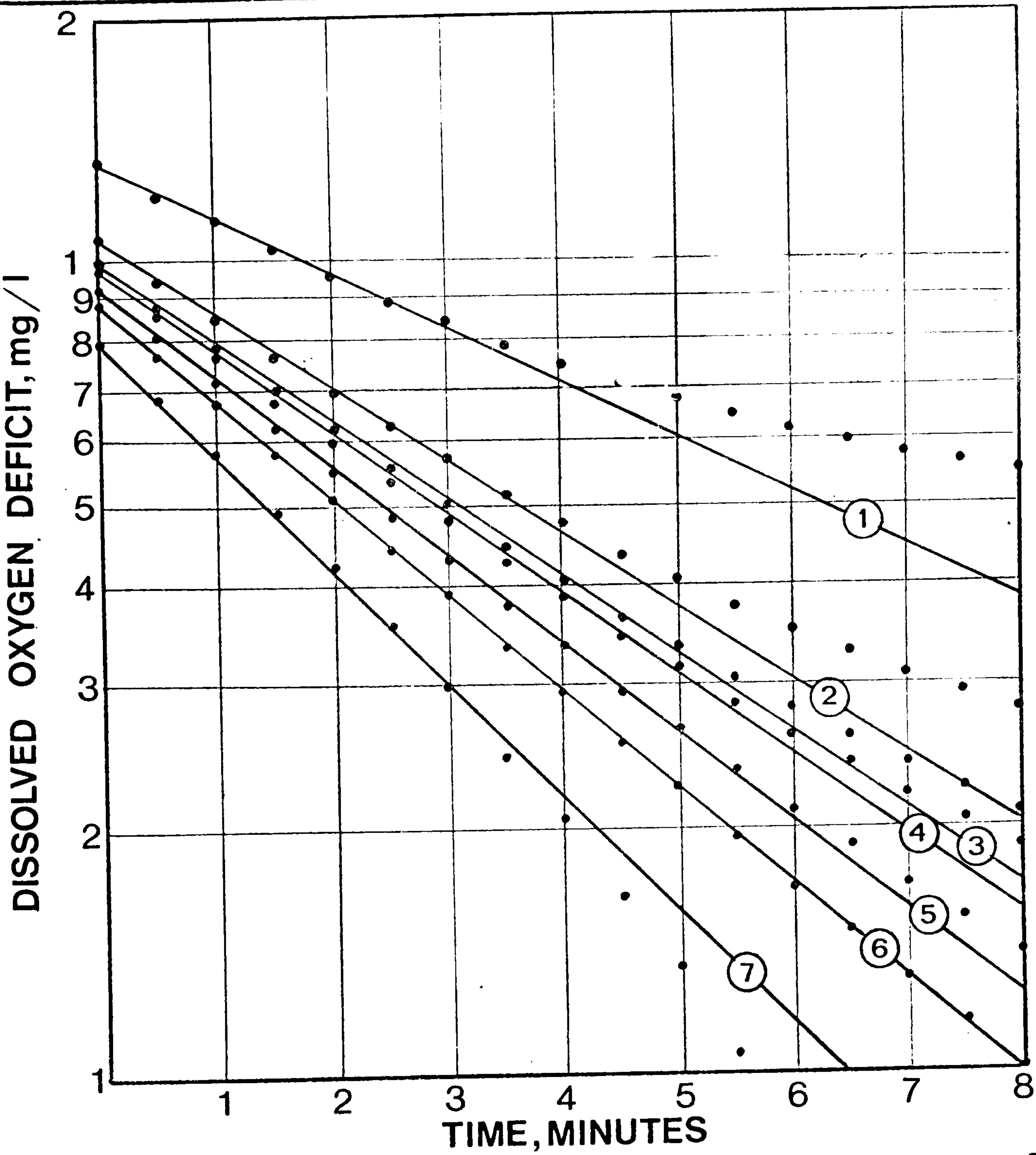
g. 0.25 Submergence Model

This model is based on test experience of extended aeration C_{se} determination that has shown C_{se} to be equivalent to 0.22-0.33 of submergence. Even though the model is not based on an equation one may be written for it to make it more clear,

$$C_{se} = C_{ss(t)} \left(\frac{P+0.433\ (.25H)}{14.7}\right) \qquad \text{(A5)}$$

These models have been used to obtain a C_{se} for the K_La semi-log graph, Figure A.1, and are shown along with the resulting oxygen transfer figures in Table A.2. Figure A.2 shows a graphical comparison of the oxygen transfer resulting from the selection of C_{se}.

Note that the use of this example of test data for static tube aerators in no way shows an endorsement of the product. Nor does it confirm the oxygen transfer ability of the devices, because too many of the test parameters are unknown. The sole purpose is to show the importance of correct data analysis if a valid oxygen transfer rate is to be obtained.



MODEL	$K_La(28^o)$	$C_{se}(28^oC)$
1. Bottom Saturation	9.3 hr^{-1}	13.3 mg/l
2. Mid-Depth	12.3 "	10.6 "
3. Mid-Depth Corrected	13.2 "	9.9 "
4. Log Mean	13.8 "	9.7 "
5. 0.25 Submergence	15.0 "	9.2 "
6. Best Fit	16.3 "	8.8 "
7. Suface Saturation	19.1 hr^{-1}	7.9 mg/l

K_La PLOTS FOR VARIOUS C_{se} MODELS

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	beak	BY BG DATE 30 MAR 77 DWG NO A1269-13	FIG. A.1

TABLE A.2

RESULTS OF C_{se} MODEL EVALUATION FOR CALCULATION OF OXYGEN TRANSFER RATE

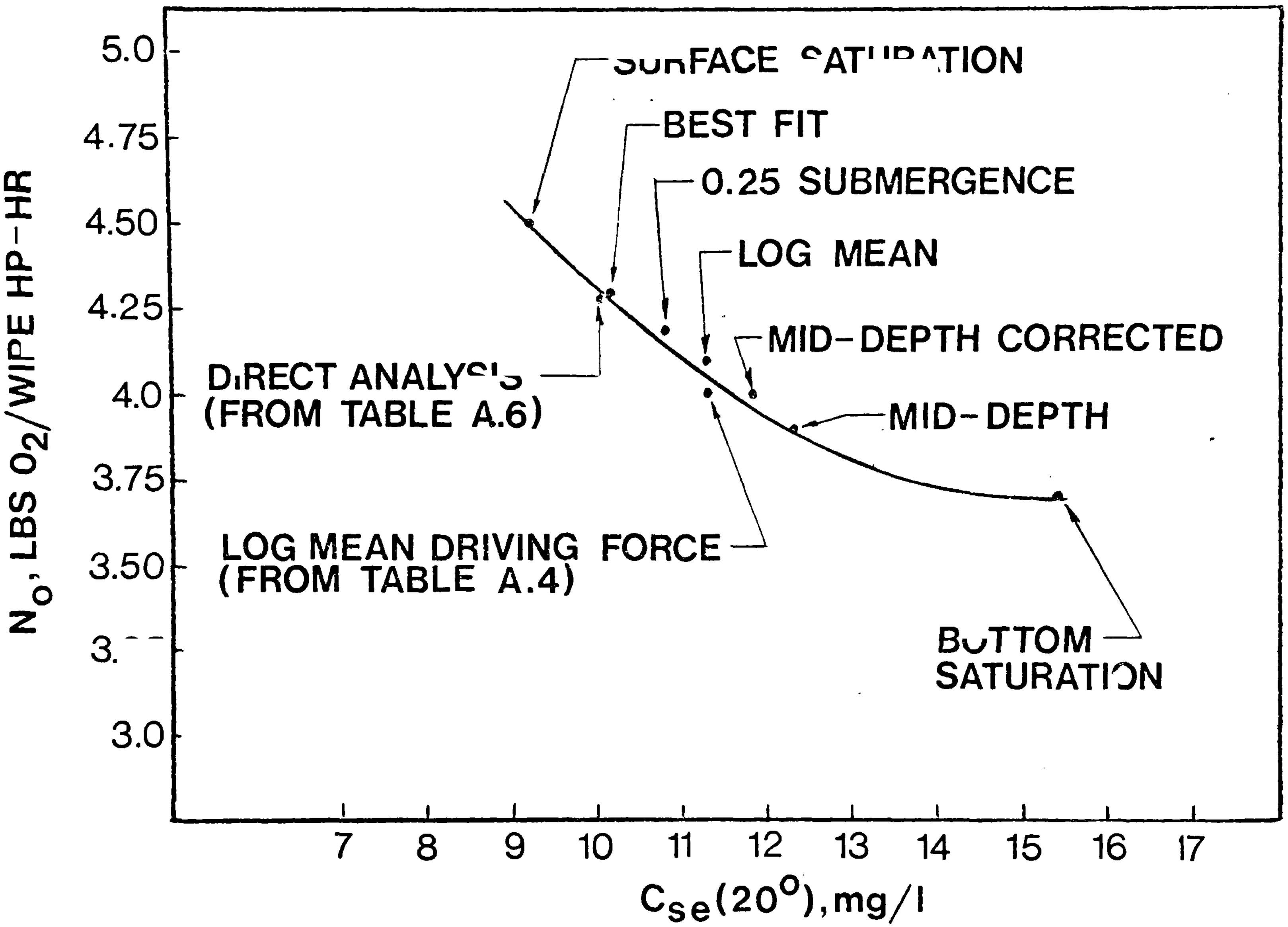
C_{se} Model	C_{se}(28°C) mg/l	Effective Depth ft	Effective Depth % Submergence	From Fig. A.1 K_La(28°C) hrs^{-1}	K_La(20°C) hrs^{-1}	C_{se} (20°C) mg/l	R lbs O_2/hr/unit	N_o lbs O_2/hp-hr[c]	Error[d] Of C_{se} Model
Surface Saturation	7.9	0	0	19.1	15.8	9.2	7.5	4.5	+13
Best fit	8.8	3.9	17	16.3	13.5	10.2	7.1	4.3	+8
.25 Submergence	9.2	5.6	25	15.0	12.4	10.8	6.9	4.2	+5
Log-Mean	9.7	7.7	34	13.8	11.4	11.3	6.7	4.1	+3
Mid-depth Corrected	9.9	8.6	37	13.2	10.9	11.8	6.6	4.0	0
Mid-depth	10.6	11.5	50	12.3	10.2	12.3	6.5	3.9	-3
Bottom Saturation	13.3	23	100	9.3	7.7	15.4	6.1	3.7	-8

a. $C_{ss(20°C \text{ and } 28°C)}$ from Standard Methods [39]

b. Assumed absorption efficiency (E) = 13% [112]

c. Assumed efficiency of motor, blower, and delivery lines = 65%

d. Assuming Mid-depth corrected model transfer efficiency as correct



STANDARD OXYGEN TRANSFER RATES FOR VARIOUS C_{se} MODELS

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542	BY BG	DATE: 29 MAR 77	FIG. A.2
	DWG. NO.	A1269-12	

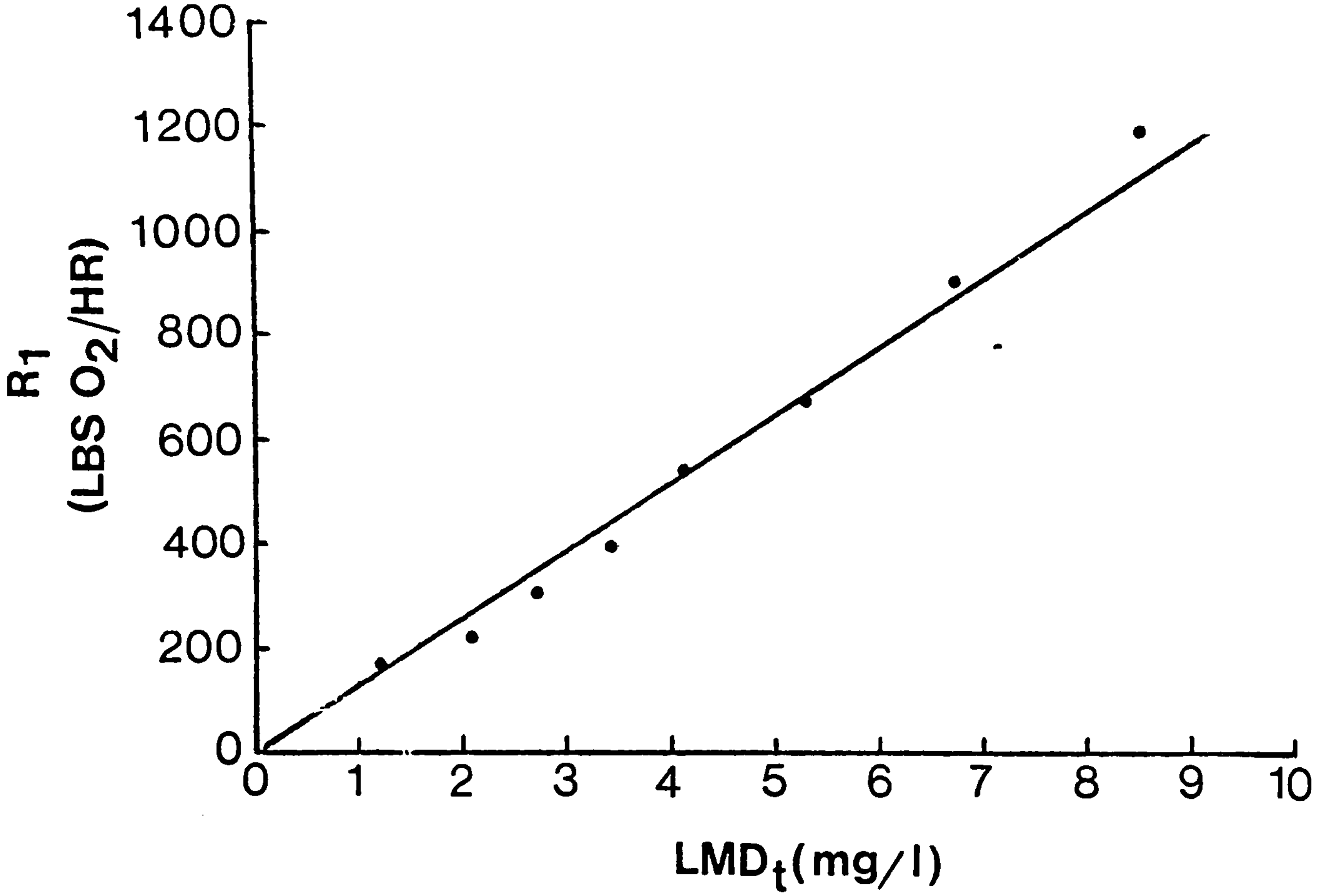
From Figure A.2 it is obvious that the oxygen transfer rate of a submerged aeration device or a surface aerator is vitally dependent on the C_{se} value. Since it is conceivable that any of a number of oxygenation devices both submerged and surface could have generated the reaeration test data shown in Table A.1, it is all important to define the C_{se} appropriate to each device so that the systems may be compared on an equal basis. Eckenfelder [8,9,10,13,109], Shell et.al. [91,112], and Berk et.al. [95] to mention a few, have supported the use of the mid-depth corrected model for C_{se} determination, but without much correlation to the extended aeration (directly observed) C_{se} values. The key question becomes, what is the correct value of C_{se}? Before attempting to answer this knotty question it might be worthwhile to examine other C_{se} determination methods. The other methods that might be used include direct observation of C_{se} during the test, calculation of C_{se} at various times during the test (log mean driving force), and direct data analysis as proposed by Stukenberg and McKinney [85]. Direct observation, since it was not done during the test, is not possible in this example problem, but has been suggested as a very useful method for determining C_{se} and gaining insight into the dynamics of the operating system [102,104].

The log mean driving force model as proposed by Stanton and Bradley [93] is applicable here and should not be confused with the log mean saturation model which assumes a constant value. The log mean driving force (LMD) model divides the test into equal time intervals and calculates the LMD_t during each time interval. Using the data in Table A.1, Table A.3 has been completed. Plotting the oxygen transfer rate versus the LMD_t yields a straight line through the origin, the slope of which is K_La W as shown in Figure A.3.

TABLE A.3

COMPUTATION OF LOG MEAN DRIVING FORCE

Time Interval (Min)	Average Time (Min)	Change in D.O. During 1 Min (mg/1)	Mid Point D.O. (mg/1)	Rate of O_2 Transfer (lbs/hr) R_1	% Absorption Efficiency	% Oxygen in Off-Gas	Cse at Surface (mg/1)	Driving Force Surface (mg/1) - Dst	Cse at Bottom (mg/1)	Driving Force Bottom (mg/1) - D_{bt}	Log Mean Driving Force (mg/1) - LMD_t
0-1	0.5	2.10	1.05	1198	21.5	17.5	6.6	5.55	13.3	12.25	8.46
1-2	1.5	1.60	2.90	913	16.4	18.4	6.9	4.0	13.3	10.4	6.70
2-3	2.5	1.20	4.3	685	12.3	19.0	7.1	2.8	13.3	9.0	5.31
3-4	3.5	0.95	5.38	542	9.7	19.5	7.3	1.9	13.3	7.9	4.21
4-5	4.5	0.70	6.2	399	7.2	19.9	7.5	1.3	13.3	7.1	3.42
5-6	5.5	0.55	6.83	314	5.6	20.2	7.6	0.77	13.3	6.5	2.69
6-7	6.5	0.40	7.30	228	4.1	20.4	7.7	0.40	13.3	6.0	2.07
7-8	7.5	0.30	7.65	171	3.1	20.5	7.7	0.05	13.3	5.65	1.18



OXYGEN TRANSFER RATE VERSUS DRIVING FORCE

COOPERATIVE POLLUTION ABATEMENT RESEARCH
CPAR PROJECT NO. 542

BY B G | DATE: 25 MAR 77
DWG. NO. A1269-10
FIG. A.3

Table A.4 summarizes the results of the log mean driving force model.

TABLE A.4

EVALUATION OF LOG MEAN DRIVING FORCE MODEL FOR K_La DETERMINATION

Item	Value
K_La (28°C)	13.7 hr^{-1}
K_La (20°C)	11.3 hr^{-1}
Equivalent average C_{se} (28°C)	9.7 mg/l
Equivalent average C_{se} (20°C)	11.3 mg/l
Equivalent effective depth	7.7 ft
Mass transfer rate, R	6.6 lbs O_2/hr/unit
Oxygenation efficiency, N_o	4.0 lbs O_2/hp-hr (shown on Figure A.2)

The log mean driving force for this example correlates well with the mid-depth corrected model for N_o and the log mean constant value for C_{se}. As can be seen from Figure A.1 the mid-depth corrected model shows a definite curve upwards indicating that the C_{se} determined is high, the log mean shows less upward curvature but still is not linear.

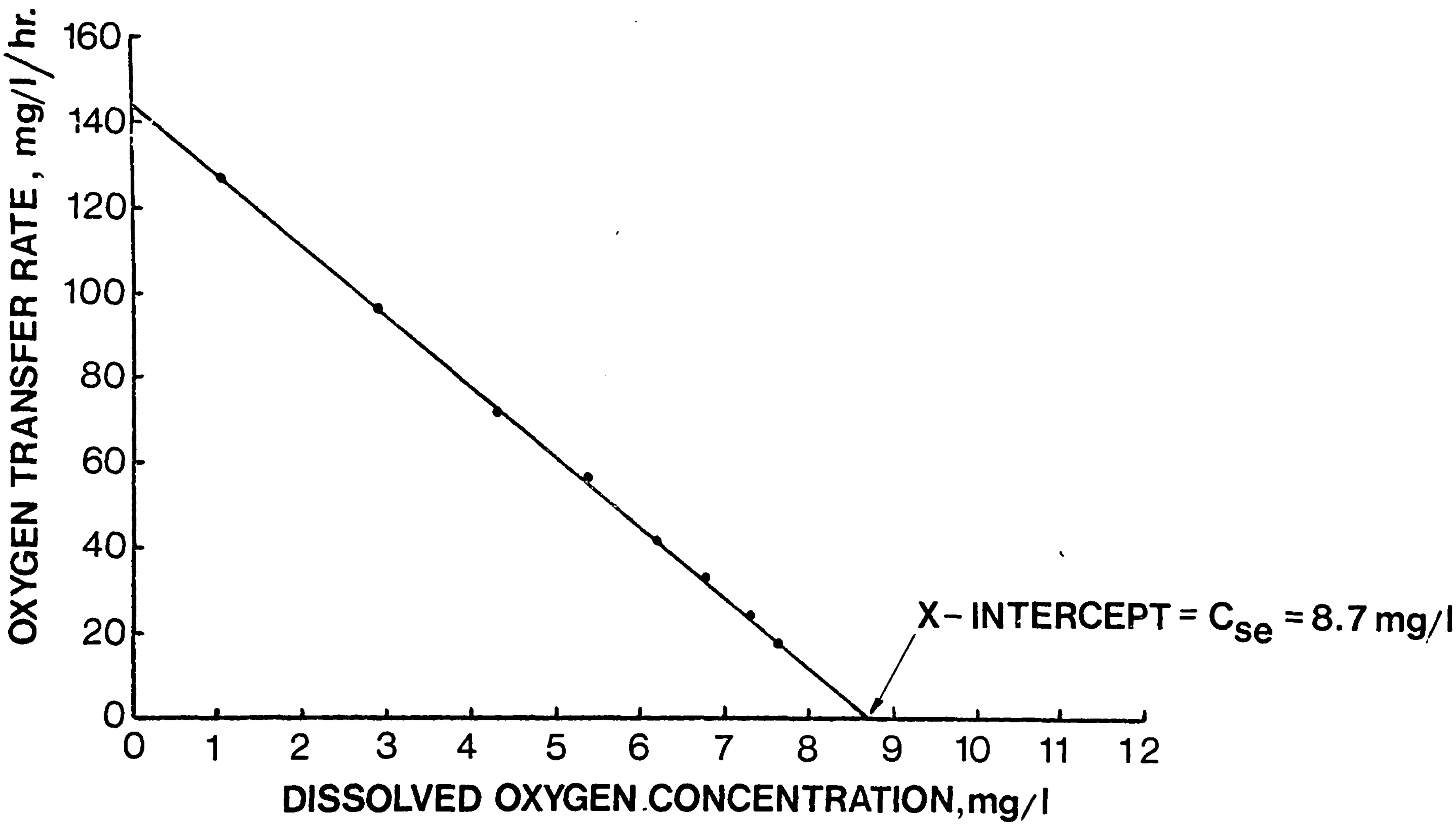
The direct data analysis method as proposed by Stukenberg and McKinney [85] involves plotting the average dissolved oxygen concentration (abscissa) during a time period versus the oxygen supplied to the water during that period (ordinate) and drawing a best fit line through the data. The x-intercept is C_{se}. Table A.5 summarizes the data preparation.

TABLE A.5

DATA SUMMARY FOR DIRECT ANALYSIS DETERMINATION OF C_{se}

Time Interval, min	Change in D.O., mg/l	Mid-Interval Time, min	Mid-Interval D.O., (X), mg/l	Rate of Transfer, (Y), mg/l/hr
0-1	2.10	0.5	1.05	126
1-2	1.60	1.5	2.90	96
2-3	1.20	2.5	4.30	72
3-4	0.95	3.5	5.38	57
4-5	0.70	4.5	6.20	42
5-6	0.55	5.5	6.83	33
6-7	0.40	6.5	7.30	24
7-8	0.30	7.5	7.65	18

Figure A.4 shows the plot of the rate of transfer versus the mid-interval D.O. and the connecting line intercepts at C_{se} = 8.7. This corresponds very well to the best fit model. The derived C_{se} value has been used to compute the oxygenation efficiency according to this method, the results of which are presented in Table A.6 and Figure A.2.



DIRECT ANALYSIS DETERMINATION OF C_{se}

COOPERATIVE POLLUTION ABATEMENT RESEARCH CPAR PROJECT NO. 542		BY BG	DATE : 25 MAR 77	FIG. A.4
		DWG. NO. A1269 - 11		

TABLE A.6

EVALUATION OF DIRECT ANALYSIS METHOD FOR C_{se} DETERMINATION

Item	Value
C_{se} (28°C)	8.7 mg/l
C_{se} (20°C)	10.1 mg/l
Effective Depth	3.4 ft
K_La (28°C)	16.5 hr^{-1}
K_La (20°C)	13.6 hr^{-1}
Mass transfer rate, R	7.1 lbs O_2/hr/unit
Oxygen transfer efficiency, N_o	4.3 lbs O_2/hp-hr (shown on Figure A.2)

In this example problem a total 9 different C_{se} determination methods and models have been examined. The range of performance varies from 3.7 - 4.5 lbs O_2/hp-hr at standard conditions for the same test data. Answering the question of which one is correct, is not easy in this case because of the variance in the values.

However, it would seem that three values could be eliminated without further consideration: surface saturation, mid-depth, and bottom saturation. The reasons for eliminating these are obvious and as well, the models have no substantial support in the literature. The remaining six methods range between 4.0 and 4.3 and all have varied amounts of support in the literature. It is unfortunate that the test was not run to an asymptotic saturation so that the C_{se} could be observed directly as this would be of great help in giving further insight into which one is the best approximation. Three of the models assume a constant value based on the physical geometry. Two of the remaining models determine a constant C_{se}, but the data is allowed to determine it.

The final model uses the data, but computes a C_{se} during each time interval, a method which should yield the best approximation. Since all models make "reasonable" assumptions and give very nearly the same result to say that one model is the best estimation of the oxygen transfer efficiency would be rather arbitrary and without experimental support. A compromise solution is to include all six models and their results and let the designer or customer use the one he feels most comfortable with when he makes his comparison of tenders; of course, the more conservative figure of 4.0 lbs O_2/hp-hr should be used in design. The reader is reminded that the reported accuracy of the reaeration test is $\pm$5% even when done exactly as described in the report. Therefore, the oxygen transfer efficiency could easily be reported as an average of 4.15 $\pm$0.2 lbs O_2/hp-hr and include all six values within that single number.

In summary what can be said is that with the given data the oxygen transfer efficiency for the tested submerged system is somewhere between 4.0 and 4.3 lbs O_2/hp-hr and has an average value of 4.15 lbs O_2/hp-hr with a probable error of $\pm$0.2 lbs O_2/hp-hr.

Whether the transfer efficiency is actually representative of the submerged equipment that was tested is dependent on the test and dissolved oxygen determination procedures. Since the test conditions and procedures are not sufficiently reported and actual efficiency of the blower and motor are unknown no comment is possible.

APPENDIX 2

METRIC CONVERSIONS

METRIC CONVERSIONS

To Convert	Multiply By	To Obtain
Acres	4.047×10^{3}	sq. meters
Atmosphere	7.60×10^{2}	mm mercury
Cubic feet	2.832×10^{-2}	cu. meters
Cubic feet	7.481	U.S. gallons
Cubic feet/sec	1.699×10^{3}	litres/minute
Cubic meters	1×10^{3}	litres
Feet	3.048×10^{-1}	meters
Feet/sec	3.048×10^{1}	cm/sec
Gallons U.S.	8.3267×10^{-1}	gallons Imp.
Gallons U.S.	3.785×10^{-3}	cu. meters
Gallons U.S.	3.785	litres
Gallons U.S./min	2.228×10^{-3}	cu. feet/sec
Gallons U.S./min	6.308×10^{-2}	litres/sec
Horsepower	7.457×10^{-1}	kilowatts
Horsepower-hours	7.457×10^{-1}	kilowatt-hours
Inches	2.540	centimeters
Inches of mercury	3.453×10^{-2}	Kgs./sq. cm
Million U.S. gallons/day	3.786×10^{3}	cu. Meters/day
Pounds	4.536×10^{-1}	kilograms
Pounds/sq. in.	7.03×10^{-2}	kgs/sq. cm
Revolutions/min	1.047×10^{-1}	radians/sec
Square feet	9.29×10^{-2}	sq. meters
Square inches	6.452	sq. centimeters
Temperature °F	(T-32)/1.8	temperature °C
Temperature °C	1.8T + 32	temperature °F