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TECHNOLOGY ASSESSMENT
of
FINE BUBBLE AERATORS

by

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DISCLAIMER

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

Increasing power costs and the potential for relatively high oxygen transfer efficiency has generated renewed interest in fine bubble aeration performance. This report evaluates fine bubble aeration technology and discusses its development status.

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ABSTRACT

The technology assessment addresses design and evaluation of fine bubble aeration equipment. It discusses the associated gas transfer theory used as the basis for measuring water and wastewater oxygenation efficiency. Mixing requirements are also discussed.

While bubble aeration is not new technology, increasing power costs and the potential for relatively high oxygen transfer efficiency has generated renewed interest in fine bubble wastewater aeration performance. The many interrelated variables affecting measurement and efficiency of fine bubble aeration systems are identified and discussed. Comparison with other aeration methods is made and an estimate of the national impact fine bubble aeration can have on wastewater treatment energy savings is presented. Research and development efforts which are needed to improve fine bubble aerator performance are identified.

This report evaluates fine bubble aeration technology and discusses its development status. The report is liberally referenced so the reader can obtain details about a particular aeration question if desired.

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ACKNOWLEDGEMENT

The author would like to thank Richard C. Brenner, USEPA, for generously sharing information and insight about fine bubble aerator technology. His assistance has made this assessment a significantly better document.

1. INTRODUCTION AND GENERAL TECHNOLOGY DESCRIPTION

There are two basic methods presently employed in existing wastewater treatment plants for aerating wastewater. The first method is to transfer oxygen into solution from air bubbles produced with submerged porous diffusers or air nozzels. The second method is to agitate the wastewater mechanically to promote solution of oxygen from air in the atmosphere. This technology assessment addresses the transfer of oxygen into wastewater by gas transfer. In particular it concentrates on the specification and evaluation of fine bubble aeration equipment and on the associated gas transfer theory used to explain the introduction of the oxygen in the air into solution.

Fine bubble aerators are defined as those which produce a 2.0-2.5 mm diameter bubble (1). Coarse bubble aerators may produce a bubble up to 25 mm. Aerators are used in wastewater treatment processes where introduction of air into a liquid is required. Examples are preaeration of raw wastewater, aerated grit chambers, activated sludge aeration tanks, aerated lagoons, aerobic digesters and post aeration (2).

Aeration of wastewater performs multiple functions. It supplies oxygen required for the metabolic processes of the living organisms. It provides sufficient mixing of the wastewater so that the organisms can receive adequate dissolved oxygen and come into intimate contact with the dissolved and suspended organic matter. It scrubs out of the water various metabolic waste products such as CO_2. The first and third of these functions are gas transfer processes. The second function is a mechanical energy transfer process. In most activated sludge processes, transfering adequate oxygen into solution is the function which establishes minimum requirements for the input of air or mechanical energy (2) (3). Thus this assessment of fine bubble aerators emphasizes transfer of gas (oxygen) into solution. Mixing requirements are not regarded lightly, however. There must be adequate mixing for the gas transfer model to be valid.

Experiments on aeration of wastewater began in England about 1882 and the activated sludge process was first introduced in 1914 (2). The volume of reference material on wastewater aeration and fine bubble aeration accordingly very large. This technology assessment is based on a limited selection of significant papers representing three broad areas: early pioneering and theoretical work which comes mostly from "classical" or "bench mark" published papers; state-of-the-art information which comes from published papers, text books, WPCF Manual of Practice No. 5, and proceedings from an EPA workshop titled "Workshop Toward an Oxygen Transfer Standard"; and plant scale research efforts and information which come from EPA sponsored project reports or related papers as well as the Workshop proceedings.

Clean water oxygen transfer efficiencies for fine bubble aerators fall into a fairly broad range, depending on water depth and diffuser configuration, with maximum efficiency being about 50%. There is considerable room for improvement. In addition, evaluation of diffuser efficiency itself is not an exact science, especially under activated sludge process conditions with a respiring biological system. There are many factors impacting on aerator design and evaluation. This assessment identifies the major factors, discusses their importance, and lists areas which need further process development or research. It is liberally referenced so the reader can obtain specific details if he desires.

2. DEVELOPMENT STATUS

Summary of Research Findings

A detailed summary of significant research about bubble aeration in general and fine bubble aeration in particular is incorporated as part of the Technology Evaluation (Section 3). This section summarizes present and projected EPA sponsored research.

From November 1977 to March 1979, the Los Angeles County Sanitation Districts (LACSD) supported in part by EPA conducted a series of clean water oxygen transfer tests under closely controlled conditions comparing various generic types of submerged air aeration equipment. Six types of devices were selected which represented typical methods of dispersing various sizes of bubbles:

Fine Bubbles	Medium Bubbles	Coarse Bubbles
Jet Aerator	Static Aerator	Fixed Orifice
Dome Diffuser		Variable Orifice
Tube Diffuser		

All devices were compared using the same test tank and identical test procedures throughout. The test tank was 20 ft x 20 ft x 25 ft maximum variable depth. Clean water dissolved oxygen uptake was carried to equilibrium using water chemically deoxygenated with sodium sulfite and cobalt chloride catalyst. Three runs at four different depths (10, 15, 20, and 25ft) were made. Each run had a different input power level (varying from 0.008-.04 kW/m^3) delivered to the water. Diffuser configurations were selected by aerator manufacturers who were allowed different configurations for different depths but had to maintain a constant configuration over the series of three runs at any given depth. The configuration or geometric pattern selected was one intended to be economically feasible at full scale and over the range of input powers evaluated.

Preliminary findings from this study were presented in a slide summary at the 1980 Water and Wastewater Equipment Manufacturers Association Industrial Pollution Conference [4]. The official report will be issued by EPA's Office of Research and Development in early 1982. In general, the ceramic dome diffuser was found to transfer oxygen most efficiently. Its efficiency was followed by that of the tube diffuser, then the jet aerator. Efficiencies of the static aerator and coarse bubble diffusers were less than the fine bubble diffusers and their results were mixed, depending on test conditions. Table 1 summarizes the general trends found for the testing period November 1977 to March 1979. The reader is urged to review the pending EPA report or Reference [4] for details and qualifications applicable to the general trends summarized.

TABLE 1

PRELIMINARY TRENDS OF SUBMERGED AERATION EQUIPMENT EFFICIENCIES [4]

STANDARD OXYGEN TRANSFER EFFICIENCY (%) VS. DELIVERED POWER DENSITY (hp/1000 ft^3)

- efficiency decreased for the fine bubble diffusers, remained fairly constant for the static aerator, and increased for the coarse bubble diffusers as power density increased

STANDARD WIRE AERATION EFFICIENCY (lbs O_2/wire hp-hr) VS. DELIVERED POWER DENSITY (hp/1000 ft^3)

- efficiency decreased significantly for the fine bubble dome and tube diffusers, decreased slightly for the static mixer or remained fairly constant for the coarse bubble equipment as power density increased
- the jet aerator had a local maximum in the middle of the power density range tested

STANDARD OXYGEN TRANSFER EFFICIENCY (%) VS. DEPTH (ft)

- efficiency increased as depth increased

STANDARD WIRE AERATION EFFICIENCY (lbs O_2/wire hp-hr) VS. DEPTH (ft)

- efficiency increased or remained fairly constant as depth increased

STANDARD OXYGEN SATURATION CONCENTRATION (mg/l) VS. DEPTH (ft)

- oxygen saturation concentration increased as depth increased

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In order to determine the alpha and beta factors associated with some of these devices, the LACSD in conjunction with USEPA is conducting full scale wastewater oxygen transfer tests. A decision was made to test three promising types: 1) porous disc diffusers applied in a total floor coverage configuration; 2) porous tube diffusers applied in a wide band dual aeration configuration; and 3) directional jet aerators arranged along one longitudinal wall and aimed at the opposite longitudinal wall. Tests began in May 1981 and will run until the spring of 1982. In non-specific terms, the proposed scope of work is the following [5]:

1) To concurrently evaluate the oxygen transfer capabilities of the three aeration systems in a municipal wastewater;

2) To concurrently evaluate the clogging potential of the three aeration systems under field operating conditions;

3) To evaluate the process performance of the most cost-effective of the three aeration systems at different aeration times and organic loadings;

4) To run laboratory scale tests (including clean water runs) to evaluate alpha and beta for all three of the aeration systems;

5) To run plant scale tests (including clean water runs) to evaluate alpha and beta for all three aeration systems.

Full Scale Facilities in Use

Houck (3) has made a plant survey of 19 activated sludge wastewater treatment plants using fine bubble diffuser aeration as part of an EPA effort designed to define full scale aeration experience. The list of plants visited is in Table 2. The plants were selected primarily on the basis of long term operating experience with fine bubble diffusers (five years or more). All were basically municipal wastewater treatment plants with varying industrial contributions and all coincidentally used fine bubble dome diffusers. Overall objectives of the survey were to better define full scale plant aeration efficiency (i.e., oxygenation power economy) operation and maintenance requirements, and proper design approaches for fine bubble aeration systems.

TABLE 2

FINE BUBBLE AERATION PLANTS SURVEYED (3)

United Kingdom	Holland	United States
Basingstoke	Holten-Markelo	Glendale, CA
Beckton (New Plant)	Steenwijk	Madison, WI
Beddington		Fort Worth, TX
Dartford		Tallman Island, NYC, NY
Mogden (Batt B)		
Oxford		
Ryemeads (Stage III)		
Coolport		
Coleshill (Stage III)		
Finham (South)		
Hartshill		
Minworth		
Strongford (New)		

Basic conclusions of the Houck study about oxygen transfer performance were that dome/disc fine bubble diffusers can (relatively) efficiently transfer large amounts of dissolved oxygen into the water if they are designed properly and good operation and maintenance procedures are routinely practiced. The principal factors affecting plant performance were found to be, in order of significance: 1) mixed liquor dissolved oxygen (D.O.) concentration (maintenance of high D.O. levels decreased aeration efficiency); 2) the oxygen transfer factor, alpha (which significantly affected the correct specification of aeration equipment for wastewater basins); and 3) basin geometry (which significantly influenced the value of alpha and the D.O. profile for the basin). Aeration efficiency (computed using a BOD and oxidized nitrogen mass balance technique) varied considerably among plants because of differences in design and operation. It averaged 1.5 kg O_2/kWh and ranged from 0.8 to 2.1 kg O_2/kWh. Houck concluded that with enhanced design and operating techniques and with no unusual alpha-depressing wastes present, it would not be unreasonable to expect routine achievement of aeration efficiencies 25 to 75 percent higher than the average value observed for the 19 plants surveyed. Houck's design, energy, and operation and maintenance observations about fine bubble diffusers are discussed in Section 3 under the appropriate subject area.

Equipment/Hardware

Fine bubble aerators have been historically designed as permeable structures formed by bonding near spherical or blocky particles at their contact points which leaves a labyrinth of interconnecting passageways through which air flows. As the air emerges from the surface pores, pore size, surface tension, and flow rate interact to produce the characteristic bubble size which is released at the diffusers' surface. As the bubble rises through the "head" of the liquid, oxygen from the air of the bubble is continuously dissolved (diffused) into the liquid [6].

Ceramic diffuser media best typify the fine bubble diffusers. Most common ceramic diffuser media compositions are: ceramically bonded grains of fused, crystalline aluminum oxide; vitrous-silicate-bonded grains of pure silica; and resin bonded grains of pure silica. Other diffuser media consist of modified acrylonitrile-styrene copolymer and polyethylene plastic, which is reportedly cleanable in soap and water [3].

With regard to shape, manufacturers offer plates, usually 12 x 12 x 1 or 1-1/2 inches thick, and tubes, usually 2-1/2 inches outer diameter x 1-3/4 inches inner diameter x 24 inches long.

A third shape, ceramic "dome" or "bell" has become an accepted standard in England. This report focuses on long term operation and maintenance (O&M) and oxygen transfer performance of fine bubble dome diffusers because the 19 fine bubble aeration plants surveyed by Houck coincidentally all had dome diffusers [3]. Criteria for plant selection was that they be in operation at least five years and they employ well mixed aeration basins to maximize oxygen transfer characteristics. The plants chosen to meet these characteristics were in England, the Netherlands and the United States. Houck and Boon who conducted the survey concluded that the data they evaluated in the study indicated some parity of performance among the ceramic dome and disc diffusers presently marketed in the United States. Disc diffusers are generically similar to domes, but are flat or nearly so without the turned down domw periphery and are not equipped with a center hold down bolt.

Aeration tanks using fine bubble diffusers frequently have a diffuser grid configuration covering the entire aeration tank floor with unplasticized polyvinyl chloride (UPVC) air supply piping and appurtenant hardware. Air is metered to each diffuser disc or dome through a control orifice.

Diffusers are not the only type devices which generate fine bubbles. Jet aeration equipment consists either of radial jet clusters, each with a distribution chamber or directional jet assemblies in which all the jet nozzles are aligned in the same direction. The distribution chamber receives recirculated mixed liquor from submersible pumps and low pressure air from centrifugal blowers through separate submerged manifold piping. Air and mixed liquor are combined within the jet nozzle where vortex mixing results in shearing of the air into small bubbles. The bubbles are discharged horizontally with recirculated mixed liquor as a jet plume at the bottom of the basin. An important advantage of this type of aeration device over diffusers is that mixing action is independent of air flow rate. This permits oxygen supplied to match process conditions without compromising mixing requirements of the basin. Jet aeration devices are particularly desirable for aerated lagoons where mixing and circulation often control aeration design.

Another aeration device that is particularly applicable to aeration situations where mixing and circulation may control design is the motor driven propeller aspirator pump. This device basically consists of a 4-ft hollow tube with an electric motor on one end and a propeller at the other. The propeller end of the tube is equipped with a quide to direct underwater air flow. The pump draws air from the atmosphere at high velocity and injects it underwater where both velocity and propeller action create turbulence and diffuse the air as bubbles into the water. Pumps can be positioned at various angles depending on basin depth, aeration, and mixing/circulation requirements. The pump is portable and can be mounted on booms or floats in lakes and ponds. Degree of mixing, vector (initial bubble direction), and speed of aspiration can be controlled. A new aspirator pump with a disc rather than a propeller at the end to create a finer bubble and disperse bubbles at a 90 degree angle to the shaft has been introduced.

Figures 1 to 5 show examples of typical fine bubble aeration equipment including some mounting arrangements. Table 3 lists names and addresses of aeration equipment manufacturers.

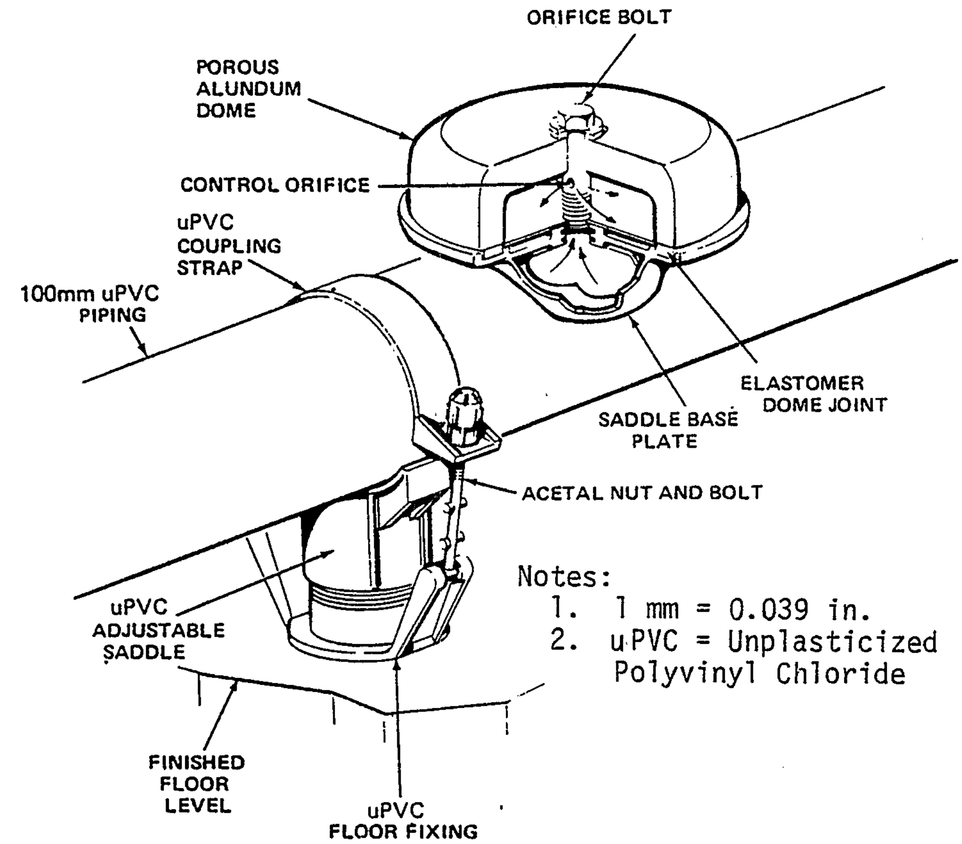
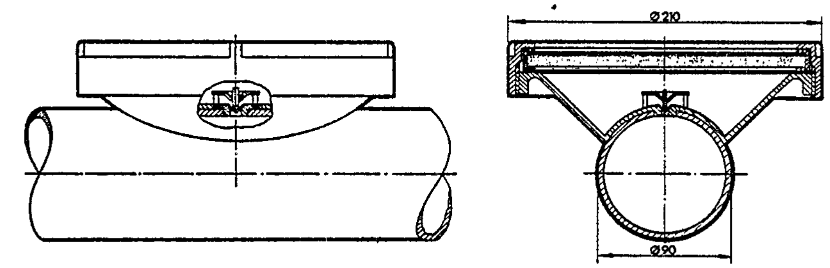


Figure 1. The Norton/Howker-Siddley dome diffuser



HKL 210 or MKL 210 diffuser, side and front

Figure 2. The EPI/Nokia disc diffuser

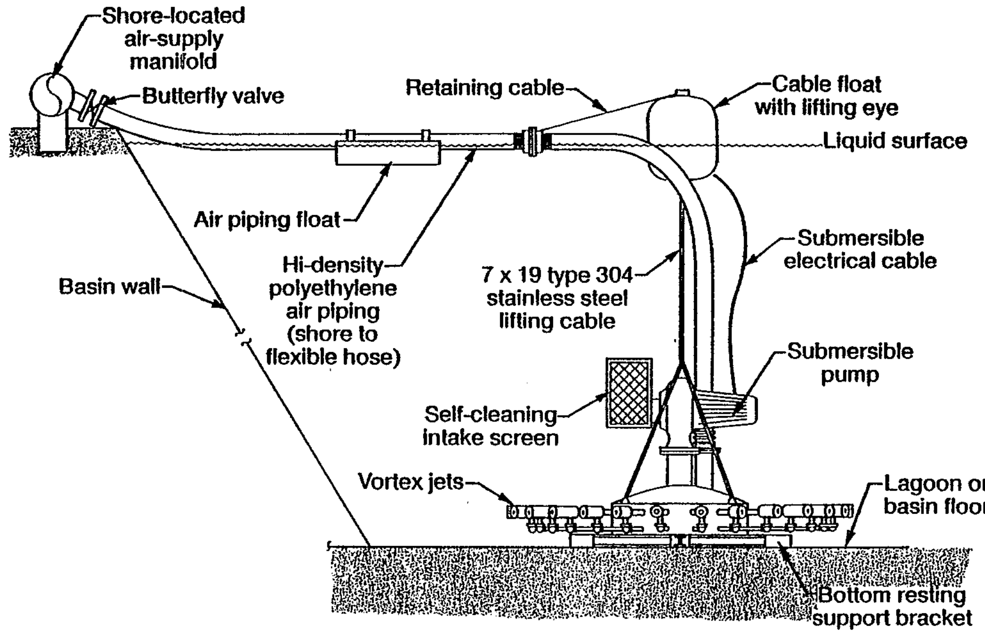


Figure 3. The Clevepak jet aerator

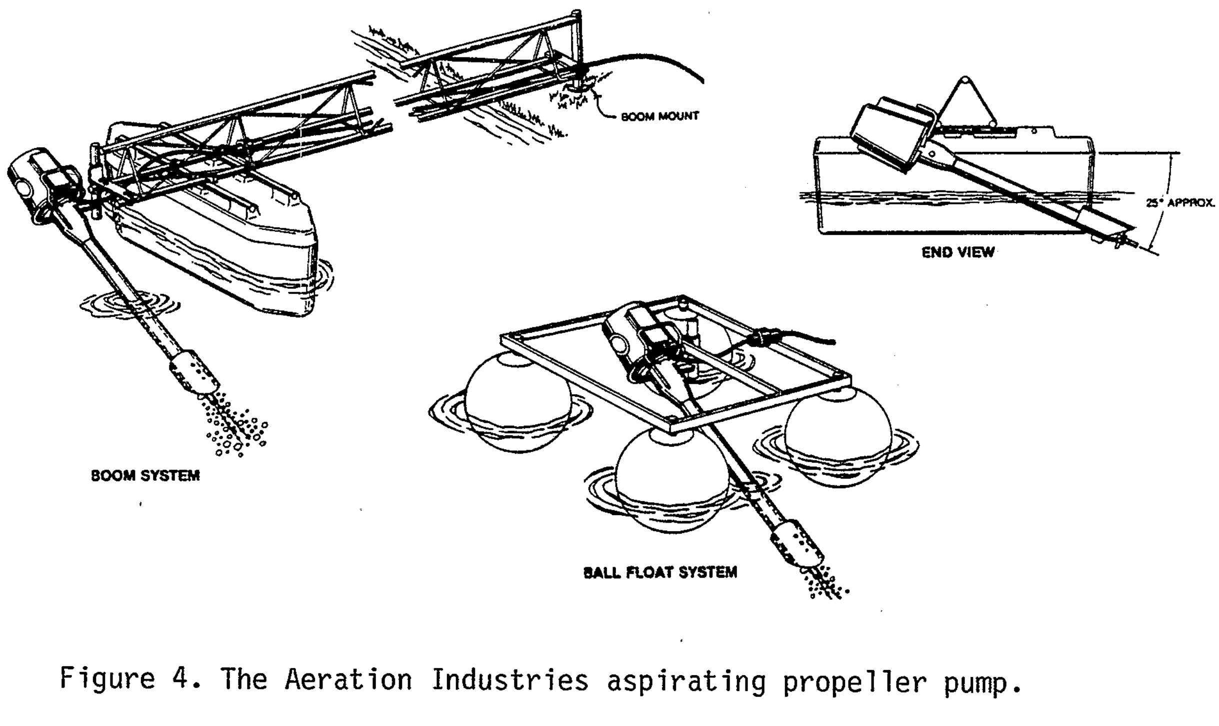


Figure 4. The Aeration Industries aspirating propeller pump.

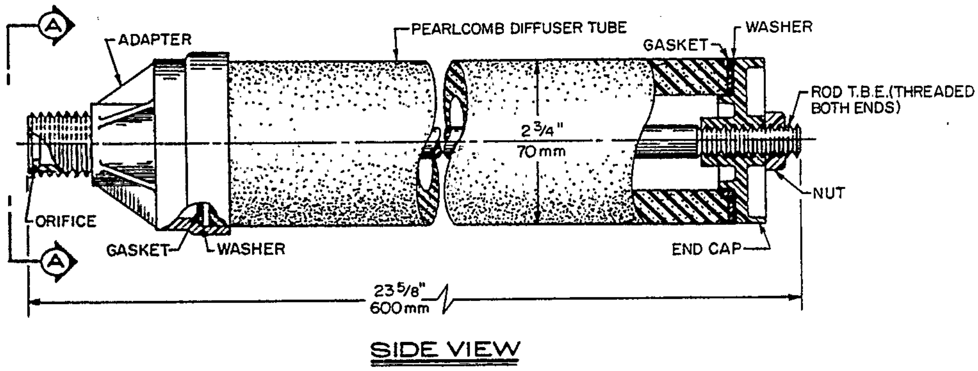


Figure 5. The FMC tube diffuser.

TABLE 3

MAJOR SUBMEREGED AERATION EQUIPMENT MANUFACTURERS

Norton Co.
Control·Industrial Ceramics Division
1 New Bond Street
Worcester, MA 01606
617-853-1000

FMC Corporation
Environmental Equipment Division
1800 FMC Dr. West
Itasca. IL 60143

Kenics Corporation
Kenics Park
North Andover, MA 01845
617-687-0101

Ajax International Corporation
P.O. Box 26607
San Diego, CA 92126
805-966-1796

Aeration Industries, Inc.
Hazeltine Gates
Chaska, MN 55318
612-448-6789

Sanitaire-Water Pollution Control Corp.
P.O. Box 744
Milwaukee, WI 53201

Envirex Inc.
1901 S. Prairie Ave.
Waukesha, WI 53186
414-547-0141

Infilco Degremont Inc.
Box K7
Richmond, VA 23288
804-285-9961

Enviroquip, Inc.
P.O. Box 9069
Austin, TX 78766
512-836-1614

Aeracleve Deivision of
Clevepak
1075 Airport Road
Fall River, MA 02720
617-676-8571

3. TECHNOLOGY EVALUATION

Process Theory

Gas Transfer in Water

All solutes tend to diffuse through solutions until there is a stable and homogenous state of uniform concentration throughout (equilibrium). According to Fick's first law of diffusion, the rate of such molecular diffusion of a gas through a liquid depends on characteristics of the gas and liquid (diffusivity), the cross sectional area through which diffusion occurs, temperature, and most importantly, magnitude of change of concentration with distance (concentration gradient) of the gas being diffused.

One theory advanced to explain the gas transfer process is the two film theory of gas transfer proposed by Lewis and Whitman (7). The film theory has no physical basis and no film has been observed, however it has practical value in that two fictitious films at the interface are widely used for the correlation and interpretation of mass transfer data. Lewis and Whitman addressed gas absorption into a liquid not saturated with the gas (supersaturation is considered negative absorption). The rate of absorption or transfer of the gas from the gas phase (gas bubble) to the liquid phase (water) is considered limited by two thin layers each side of a gas-liquid interface which are essentially free of turbulent mixing. These layers, or films, always persist regardless of turbulence in the liquid or gas bulk although turbulence may reduce film thickness. The films, one gas and one liquid, are assumed to offer all resistance to gas transfer into the liquid bulk. The gas-liquid interface itself is considered to offer no resistance and the two phases are considered at equilibrium at that point even though there may be rapid diffusion (high concentration gradients) on each side of the interface. All gas diffusion proceeds through both films in series. Figure 6 is a schematic of the gas transfer mechanism according to the two film theory of gas transfer.

Considering that the amount of gas transfer is proportional to the interfacial area and that gas diffuses through the gas and liquid films in series, the amount of gas absorbed per unit time and unit interfacial area is:

$$\frac{dW}{dt}\frac{1}{A} = k_g\,(P_g - P_i) = k_L\,(C_i - C_L) \qquad [1]$$

where W = weight of gas, grams
t = time, hours
A = interfacial area through which transfer takes place, cm^2
P = pressure of gas in gas phase, atmospheres
C = concentration of gas in liquid phase, gm/ml
subscript g applies to conditions in the bulk gas phase
subscript i applies to conditions at gas-liquid interface
subscript L applies to conditions in the bulk liquid phase

k_g = transfer coefficient through gas film, gm/hr-cm^2-atm
k_L = transfer coefficient through liquid film, cm/hr

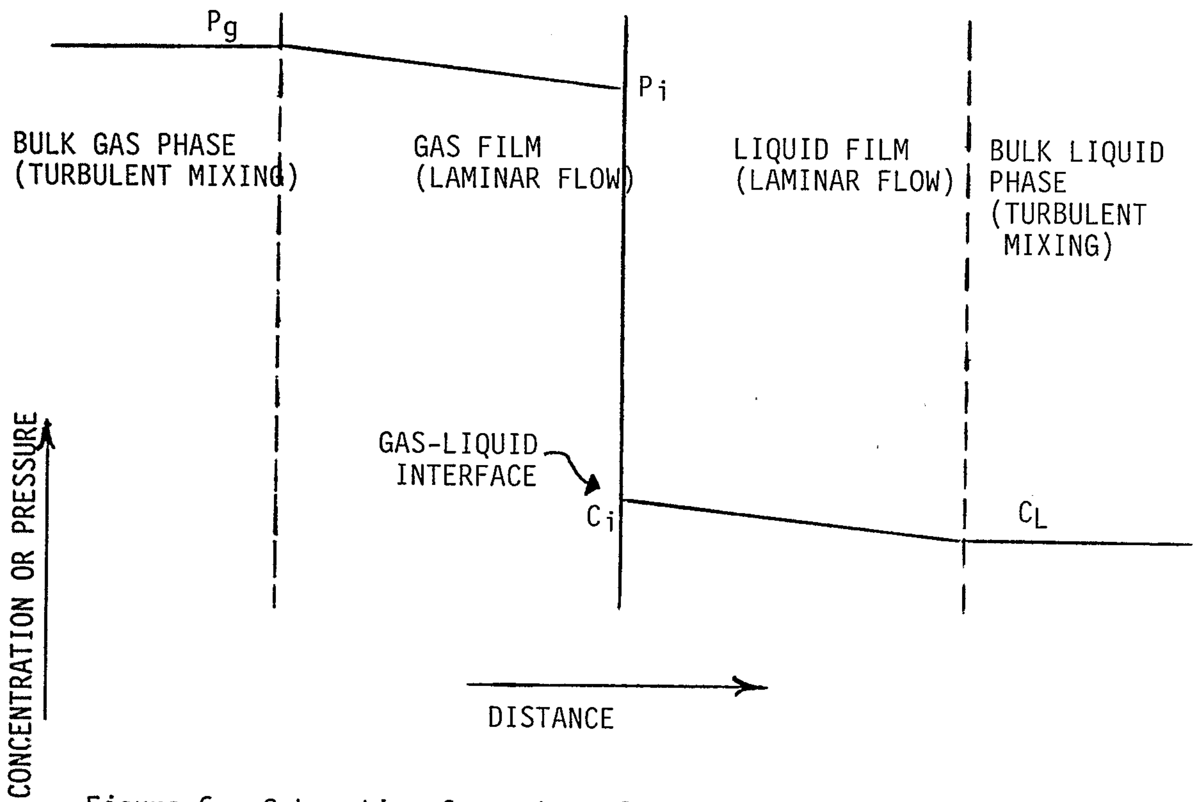


Figure 6. Schematic of gas transfer mechanism showing pressure/concentration gradients for gases of low solubility(7)

Equation [1] is the fundamental gas absorption equation given by Lewis and Whitman and serves as the basic model applicable to the addition of oxygen to water. It applies to gas transfer under constant temperature conditions, when the liquid bulk is not saturated with the gas, and in the absence of appreciable chemical or biochemical oxygen demand.

Oxygen is a slightly soluble gas in water. As a result, it will diffuse slowly through the liquid film which will offer the most resistance and limit the rate of transfer. Because diffusion is slow, only a small pressure difference is needed across the gas film to transfer it to the liquid phase. This difference in gas film partial pressures is considered negligible so that $P_g \sim P_i$. Furthermore, at the interface, P_i is in equilibrium with C_i and in proportion according to Henry's Law. For these special conditions where the interfacial conditions are practically the same as those existing in the main body of the gas, the value of Ci is essentially the same as that of a liquid saturated with oxygen at Pg and may be expressed as C_s. When the concentration gradient is taken as a straight line as in Figure 6, the rate of gas transfer into solution can be written as an ordinary differential equation in time:

$$\frac{dW}{dt}\frac{1}{V} = \frac{dC}{dt} = K_L a\ (C_s - C_L) \qquad [2]$$

where V = volume of liquid phase, cm^3 or ml

$a = A/V$

C_s = equilibrium concentration of the gas in the liquid phase corresponding to its pressure in the gas phase (saturation concentration, constant for given temperature), mg/l

$K_L a$ = overall gas transfer coefficient (assumed constant), hr^{-1}

This simpler concept of gas transfer modeled by equation [2] is sometimes termed the stationary liquid film theory. Equation [2] is the basic aeration equation employed in aeration equipment evaluation. The overall (both films) gas transfer coefficient $K_L a$ can be considered as an overall conductance: when the resistance to gas transfer is large, $K_L a$ will be small, and vice-versa.

As the liquid bulk approaches saturation with respect to the gas being transferred into it, the rate of gas transfer (dC/dt) is not constant because C_L is changing with time and, therefore, concentration deficit (C_s-C_L) is changing. For this non-steady state case, a transfer rate expression can be derived by integrating equation [2] between the limits of time equal to t_1, and t_2. This has been done below after some rearranging:

$$K_L a = \frac{\ln\ [(C_s-C_1)/(Cs-C_2)]}{(t_2-t_1)} \qquad [3] \qquad \text{or}$$

$$K_L a = \frac{2.3\ \log\ [(C_s-C_1)/(C_s-C_2)]}{(t_2-t_1)} \qquad [4]$$

where C_1 and C_2 = concentration of solute in liquid phase at time t_1 and t_2 respectively, mg/l

Equations [3] and [4] imply that a semilog plot of $(C_s-C_1)/(C_s-C_2)$ versus (t_2-t_1) will give a linear trace with slope equal to $K_L a/2.3$ enabling the overall gas transfer coefficient to be evaluated for different aeration systems. This mathematical approach for non-steady state evaluation of aeration systems represented a real contribution to understanding aeraton systems and is generally attributed to Haney [8].

Haney's detailed evaluation of the principles of aeration and the characteristics of liquids and gases resulted in a cogent description of fundamental and theoretical advantages and disadvantages about the aeration of water. His main points are summarized briefly below. Haney's original paper should be read for proper appreciation of his conclusions:

1. The rate of gas transfer at any instant is proportional to the concentration deficit at that time.

2. The rate of gas transfer is proportional to the area/volume ratio, a.

3. The rate of gas transfer is porportional to the gas transfer coefficient which in turn is a function of diffusivity and film resistance.

4. Changes in temperature are important. An increase in temperature makes the gas less soluble in the liquid, but increases its rate of absorption into the liquid.

5. Agitation and mixing decrease film resistance and minimize the concentration gradients in the liquid bulk.

6. Film "thickness" may be considered an overall measure of resistance to gas transfer. (Haney is referring to the liquid film. The gas film may be thicker but offers negligible resistance which is ignored as discussed in the derivation of equation [2]).

7. Gas partial pressure influences the saturation value of the gas and therefore gas absorption.

8. Depth of the basin affects gas pressure and bubble area/ volume ratio and therefore gas absorption.

Haney also evaluated in detail the reciprocal relationship of A/V and time with respect to gas transfer efficiency. He noted that for a given bubble volume, surface area increases as bubbles get smaller and emphasized the importance of obtaining as much uniformity in (small) bubble size as possible. Haney's evaluation of bubble aeration effectively outlined the basic controlling parameters for subsurface aeration design. They are 1) bubble size; 2) relative velocity; and 3) residence time.

Gas Transfer in Wastewater

Strictly speaking, mathematical models for gas transfer into wastewater are not theoretically derived as was the case for pure water because of wastewater's varying composition and biological activity. Instead, the approach has been to take these differences into account and modify gas transfer equations obtained for pure water accordingly.

In wastewater the value of K_La is usually less for wastewater than for tap water. This is because of the presence of soluble organic compounds, particularly surface active materials. The surface active materials, such as short chain fatty acids and alcohols, create a concentration of molecules or additional "film" at the air/water interface which retards molecular diffusion and decreases K_La. The effect of waste constituents on oxygen transfer was studied in detail by Barnhart [9]. He hypothesized that the film's effect depended on the type of surface active agent, the number of carbon atoms, molecular configuration, and the time necessary to reach adsorption equilibrium. Barnhart defined a coefficient, alpha (α) to relate the oxygen transfer rate in waste to the transfer rate in water.

$$\alpha = \frac{K_L a \text{ of wastewater}}{K_L a \text{ of tap water}} \qquad [5]$$

The saturation concentration of oxygen in water depends on the concentration of dissolved salts, temperature, and partial pressure of the oxygen in contact with the water. The dissolved salts may be organic or inorganic and reduce the solubility of oxygen in the water. To compensate for this, a beta (β) correction factor is normally used to compensate for oxygen saturation differences in water and wastewater:

$$\beta = \frac{\text{oxygen saturation concentration in wastewater}}{\text{oxygen saturation concentration of tap water}} \qquad [6]$$

In an activated sludge system, dissolved oxygen in the waste diffuses into the microbial cell for reaction in the terminal enzyme system to allow completion of biochemical oxidation of the organic matter. The rate of metabolism sets the rate of oxygen demand, and maintaining the minimum dissolved oxygen concentration that the microorganisms can effectively utilize becomes the controlling factor for the aeration system. Thus, the oxygen transfer reaction occurs in two steps. The first step is transfer from the gaseous phase to the liquid phase. The second step is transfer from the liquid outside the microbial cells to the liquid inside the microbial cells [10]. The rate at which aeration equipment is required to transfer oxygen into the wastewater is determined from a modification of equation [2] which incorporates the considerations just discussed:

$$\frac{dC}{dt} = \alpha \langle K_L a \,(C_s - C_L) \; - \; dO/dt \qquad [7]$$

where dO/dt = rate of oxygen uptake by the activated sludge, mg/l-hr

Assuming a steady state condition in activated sludge where dissolved oxygen concentration in the mixed liquor does not change with time ($dC/dt = 0$) and matches requirements of the bio-oxidation system, equation [7] becomes:

$$K_L a = \frac{dO/dt}{\alpha \, (\beta C_s - C_L)} \qquad [8]$$

The oxygen transfer coefficient for activated sludge may be calculated using equation [8].

Capabilities and Limitations

General

Molecular diffusion theory indicates that gas transfer capability is limited by the magnitude of the driving force (saturation deficit) pushing it into solution and the diffusion potential of the gas entering the liquid (Fick's Law). The simplicity is deceiving. Identifying, quantifying, and minimizing the many factors which contribute to these limitations have resulted in a large volume of work from many different approaches which is beyond the scope of this assessment. The intent of this section is to outline in a convenient form the major topics which should be addressed when considering bubble aeration systems and to provide some key references for more detailed study if desired.

Clean Water Considerations

The work of Bewtra and Nicholas using tap water and a full scale aeration tank expanded on Haney's earlier fundamental observations about bubble size, residence time, and bubble velocity (11). They noted that for fine bubble diffusers most oxygen transfer occurs during bubble formation when the interfacial area exposed to the liquid is constantly being renewed. Remaining diffusion occurs during the bubble's ascent to the surface and at the water surface itself (the least). They explored the relationship between air flow rate and bubble formation and release. They investigated the relative velocity of the rising bubble to that of the surrounding water and its effect on liquid film thickness. They experimented with different diffuser arrangements, submergences, and differing tank geometries, bubble sizes and air flow rates. Numerous conclusions about the behavior of variables affecting: 1) the rate of oxygen transfer into solution as predicted by their oxygen transfer equation (a special version of equation [2]; 2) the effect of diffuser submergence on oxygenation; and 3) the effect of aeration tank width on oxygenation added further insight to diffuser design considerations. The reader is urged to review the detailed conclusions in the paper.

Bubble size and aeration capacity was studied in detail by Barnhart(9). He evaluated data from his and other studies to show that despite theoretical considerations about increasing interfacial area per unit volume with decreasing bubble size, the overall gas transfer coefficient, K_La, increased as the bubble diameter approached 0.22 cm then decreased as the diameter got smaller. He explained this by considering the forces acting on the bubble surface and obtaining a coefficient of drag which he correlated with the rate of bubble surface renewal and the liquid film coefficient.

The influence of water temperature on aerator testing is quite significant. If, for example, temperature increases from 10 to 20°C, the gas transfer coefficient can increase by more than 50 percent and the dissolved oxygen saturation concentration will decrease about 20 percent (12). Equation [2] gives the relationship of these parameters on the rate of gas transfer into solution (dC/dt). Present practice is to evaluate the overall gas transfer coefficient at standard temperature conditions (20°C) or convert it to standard conditions using the following empirical relationship:

$$(K_La)_T = (K_La)_{20}\,\theta^{(T-20)} \quad (9)$$

where T = actual temperature, ^oC
θ = temperature correction factor

The temperature correction factor has been reported to vary from less than 1.01 to more than 1.05 (13). A common value used is 1.024[14].

Oxygen saturation values also vary with pressure, and the depth of the aerator must be taken into account. Because most aeration units use oxygen from air under pressure, generally the average of saturation at the surface and saturation value for diffused aeration is more nearly found at the one-third depth point (14). The Process Equipment Manufacturers Association recommends the following formula:

$$C_s = \underline{C_s'}\left(\frac{Pb}{59.84} + \frac{0_t}{42}\right) \quad [10]$$

where C_s' = oxygen saturation at the surface, mg/l
Pb = air pressure at release for the bubble aerator, inches of mercury
0_t = percentage of oxygen in the gas leaving the tank surface

Wastewater Considerations

All the parameters which effect oxygen transfer in water affect them in wastewater. Wastewater composition adds an additional complicating factor to attempts to consistently measure wastewater aeration efficiency. Alpha and beta determinations are intended to minimize water and wastewater test differences and have been defined earlier. It is reasonable to state that there is a lack of consensus among researchers regarding the influence and significance of these parameters [13]. Conversely, most investigators agree it is difficult to obtain true values of beta and especially alpha that are representative of process conditions [10][13][14].

In general, the important variables in alpha determination are mixing, air flow rate, temperature, wastewater composition and aeration device type and geometry. The effect of these variables is minimized by following certain techniques. Stukenberg [14] recommends adjusting the air flow rate so that the K_La in the test unit is the same as that expected in the full-scale aeration tank. This procedure is intended to minimize the differences in mixing between the bench scale aeration tank used to determine alpha and the full-scale unit itself. Barnhart [9] notes that bubble size differences between bench- and full-scale units significantly affect alpha values, and cautions that the bench-scale diffuser should produce the same size bubbles as in the actual aeration tank. Temperature effects can be minimized by running all tests at standard 20^{o}C or at the expected waste temperature (preferred). Surfactants in wastewater are generally acknowledged to be the wastewater components that have most effect on oxygen transfer (9) (14) (15). Surfactants may increase or decrease alpha depending on the aeration system. In a mechanical surface aeration system, for example, the large number of small bubbles formed (due to the decreased surface tension) have surfaces which are continually renewed with respect to the bulk liquid and aeration efficiency is reportedly increased. In fine bubble diffusion these surfaces are not renewed and the detergent forms a stationary film or boundry layer, decreasing oxygen transfer despite increased surface area. High suspended solids concentrations may also have an effect on alpha values, but this is still being debated (14) (15) (16). Experiments with a fine bubble aeration system operating in an essentially plug flow aeration tank have shown variations in alpha from 0.3 at the start of treatment (when the wastewater first comes into contact with recycled sludge) to 0.8 at completion of treatment (when a fully nitrified effluent is produced (15). Thus alpha can vary throughout the length of a plug flow tank. For such cases (compared to completely mixed conditions) wastewater samples must be taken at several points throughout the length of the tank for alpha determination.

Beta is commonly referred to as a salinity correction factor because dissolved salts reduce oxygen solubility in wastewater. Dissolved organics and gases also reduce oxygen solubility and, unfortunately, can affect dissolved oxygen measurements as well (13). Like alpha, well designed and standardized tests can minimize beta errors. Conducting measurements at equal barametric pressure and at field design temperatures will reduce variations to those caused by wastewater constituents alone. Again, wastewater samples should be taken at several points throughout the tank for plug systems to minimize differences in wastewater composition.

Biological oxygen uptake measurements (dO/dt) must be made with care because the waste sample being analyzed is changing as it is stablized. Fresh wastes do not enter the sample during this test and the rate of oxygen uptake decreases to the point where endogenous respiration is the sole cause of oxygen use. One method proposed to reduce the error in trying to measure a changing uptake rate is to stop fresh wastewater flow to the aeration basin at least 60 minutes (longer if nitrification is occuring) prior to testing and run the aeration tests under endogenous respiration conditions. Oxygen uptake rates will be low (F 60 mg/l-hr is desired) and their rate of change will be at a minimum resulting in less chance for error in the oxygen uptake test (14). Other investigators feel such externally determined values are artifical and not representative of what is actually going on in the aeration basin. Indirect dO/dt calculation methods have been proposed to get a "true" oxygen uptake rate without having to directly measure it from samples taken from the basin (17).

Knowledge of dissolved oxygen (D.O.) concentrations throughout the aeration basin is important for several reasons. The fundmental gas absorption equation (equation [1]) shows that the rate of transfer of oxygen into the wastewater will decrease as the saturation deficit decreases. The important D.O. measurement point in this case is in the liquid approaching the aerator since that value determines the driving force accross the aerator. There must also be a minimum dissolved oxygen concentration throughout the tank so that D.O. transfer from the liquid to the microbes will not be limiting. It is important to recognize that it is possible to have a residual D.O. in the mixed liquor and still be deficient in oxygen. This minimum concentration is usually considered to be about 2 mg/l [15], however, this is an area which needs additional research [14]. Finally, determining a dissolved oxygen profile around the aeration tank will also aid in understanding tank fluid flow patterns and aid determining if the fliud is short circuiting.

Mixing and Tank Geometry

Mixing is defined as the circulation which conveys the oxygen enriched fluid throughout the basin and provides the degree of agitation necessary to maintain solids suspension [18]. A precise process model would seperate gas transfer effects and fluid convection effects, but a simplified first order differential equation which varies with time only (and not distance) is generally used to describe the overall process (equation [2]). Thus, mixing effects are intrinsic to the gas transfer model (adequate mixing is assumed) and the gas transfer coefficient is indicative of both mixing and gas transfer interactions.

Practically speaking, there must be adequate mixing to keep the microorganisms in suspension in uniform contact with the dissolved oxygen and oxidizable waste. Bottom velocities (magnitude and direction) are good indicators of solids suspension capabilities and are often specified in a velocity profile diagram for a given aerator under certain conditions [18] [19]. WPCF Manual of Practice (MOP) No. 5 recommends a minimum velocity of 0.5 fps across the bottom of the aeration tank to keep solids in suspension [2]. The MOP summarizes the effect of diffuser placement on mixing velocities for a full scale sprial flow tank as follows:

1. Increasing tank width decreases surface and bottom velocities.

2. Increasing diffuser band width adjacent to the side of a tank decreases surface and bottom velocities.

3. Moving the air diffusion band toward the center of a tank (within the outer third of the tank width) decreases surface and bottom velocities.

Dissolved oxygen gradients are to be expected in a well mixed basin and all other conditions being equal, will be "typical" or characteristic of well mixed conditions. Dissolved oxygen uptake rates and/or suspended solids concentrations should be uniform throughout the basin and should be used in conjunction with D.O. gradient information to ascertain if a basin is well mixed [14] [18]. For tests such as these, at least four to six sample points in the aeration basin must be analyzed. Desirable sample locations have been recommended for diffused aeration systems [14] [20]. Indirect indicators of mixing such as aerated wastewater turnover time, pumping capacity, and power per unit volume do not alone assure adequate solids suspension. They must be used in conjunction with other measurements for a given tank geometry.

Basin geometry affects the mixing regime established by a specific aeration device and, therefore, the oxygen transfer rate. This is the principal reason mixed results have been obtained using manufacturers shop test tanks to specify field aerator performance, even though the shop tests are closely controlled. Substitution of shop tests for field tests have not been without problems (14) (21).

There are inconclusive data about the relationship between velocity of circulation and aeration efficiency (2). Higher velocities improve mixing but may decrease time of bubble contact ("hang time"). One study evaluating coarse bubble diffusers in tap water concluded that tank geometry and diffuser placement configurations were most significant to oxygen transfer efficiencies at depths over 15 feet (21). Another study evaluating fine bubble diffusers in tap water with 5 mg/l anionic detergent found that basin geometry and diffuser placement influences were most significant at depths of 10 feet and less (15). Although specific conclusions vary, it is generally agreed that changes in tank geomerty and diffuser placement result in changes in mixing patterns and hence the relative velocities of bubbles and water, all of which affect oxygen transfer. It is important to note, however, that for any given aeration device, the influence of basin geometry is a definable parameter (22).

Houck discusses how dome diffuser operating characteristics are influenced by mixing and tank geometry (3). As discussed earlier, alpha in plug flow systems can approximately double (Houck reported ranges from 0.4 to 0.8) as wastewater is progressively oxidized from inlet to outlet. The situation encourages biological fouling (sliming) tendencies which primarily occur in regions of high organic loading and low dissolved oxygen. Plug flow further exacerbates such tendencies because of the localized high organic loadings experienced in the first pass. In situations where there are long narrow tanks in multiple pass series, oxygen demand is lowered to the point where it is virtually impossible to decrease diffuser density adequately to prevent overaeration and still maintain sufficient mixing. Houck's data suggested a correlation between length to width ratio (L/W) and aeration efficiency. The three most efficient plants visited all had L/W less than 12:1.

In addition to poor matching of air flow capability with oxygen requirements, lack of control to adequately adjust the air flow capacity available and basin geometry poorly suited to the operating characteristics of the diffuser equipment were noted as other factors contributing to low aeration efficiency. Houck concluded that aeration tank design and operation is easier in a system where alpha is averaged and localized high volumetric organic loadings which can occur in the influent zone of the first pass of multiple pass plug flow tanks are avoided. High localized loadings can lead to low D.O. and biological fouling of dome exteriors followed by the onset of coarse bubbling and reduced oxygen transfer efficiency. He recommended consideration of completely mixed tanks (as opposed to plug flow) whenever possible and noted that such completely mixed systems could probably be operated at volumetric and sludge loadings in excess of those currently used. Where plug flow geometry is utilized, Houck recommended the design of single-pass tanks with L/W limited to 12:1.

A better understanding of optional design and operating parameters is required. Current, largely empirical knowledge is inadequate according to observations from Houck's survey. EPA has recently co-sponsored a project with the United Kingdom and Canada at Rye Meads Wastewater Treatment Plant near London, England to investigate and/or document optimal and limiting aeration tank geometry, particularly tank L/W, aeration taper, diffuser density, and air flow per diffuser for two activated sludge process varations (23). Several operating strategies will be explored. Process performance efficiency and economics will be documented. Field evaluation is scheduled to run until July 1982 or longer, depending on the severity of the 1981/82 winter.

Sampling and Measurement Considerations

Sampling and measurement techniques following quality assurance guidelines serve little purpose if the samples taken are not representative or the measurements made are erroneous. Considerable work has been done to take into account outside effects on aerator test procedures. Detailed discussions about representative sampling and the effects of interferences on key measurements used to determine aeration equipment capacity and efficiency are found in the references listed in Table 4 below.

TABLE 4
REFERENCES DICUSSING SAMPLING AND MEASUREMENT CONSIDERATIONS FOR VARIOUS WASTEWATER PARAMETERS

Parameter	Reference Number
sampling	24
oxygen	25
temperature	12
pH, Fe, Mn	26
gas flow and power	27
general test procedures	20

Design Considerations

Characteristics of Fine Bubble Aerators that Affect Design (2) (3)

Major design factors affecting fine bubble aerator performance efficiency are air flow range, aerator density and configuration, depth and tank geometry.

Use of a wider air flow range for peak load periods will allow specification of fewer aerators for the aeration basin. Rarely will oxygen demand require more than three to four times the minimum air flow rate in a municipal wastewater treatment plant. For example, a range of 0.5-2 cfm/dome for the

Norton Hawker-Siddeley dome was found to be desirable in Houck's study. A suggested design procedure is to determine the number of domes for 0.5 cfm air flow per dome to meet the minimum oxygen demand and then check the air flows for maximum demand. Minimum air flow rates are controlled by the headloss across the control orifice. Maximum rates are controlled by their relationship with oxygen transfer efficiency which decreases with increasing air flows. Hawker-Siddeley currently recommends that their diffusers be designed for a 5:1 maximum:minimum air flow ratio.

Aerator density should be maximized within the constraints of minimum air flows and economic costs. Denisity should also be tapered in plug flow tanks concomittant with decreasing oxygen demand to avoid potentially extreme overaeration and reduction of power economy in the middle and latter sections of aeration tanks. There appears to be a definite correllation between dome or disc diameter (horizontal surface) and specific oxygen transfer per diffuser. Data from clean water tests suggests that fewer of the larger diameter disc units may be required to transfer equivalent ammounts of oxygen at the same oxygen transfer efficiency as the smaller diameter dome units.

The nearly linear correlation between increased oxygen transfer and aerator depth to at least 20 ft overcomes increased hydrostatic pressure power requirements. The net result is a decrease in blower brake horsepower with depth for a given oxygen demand. Tapering off of oxygen transfer efficiency at higher depths (20 ft) is caused by oxygen depletion in the bubble. Within limits imposed by the treatment plant site and economic considerations, maximization of aeration tank depth up to 30 ft is recommended. (This assumes well mixed conditions exist in the basin and that oxygen transfer, not mixing controls diffuser placement. Other researchers suggest that a diffuser depth between 8 and 16 ft usually gives the optimum balance between mixing and oxygen transfer rate [1]).

Reference 2 summarizes aeration practices in wastewater treatment as of 1971. It is an important background reference which discusses in detail the design considerations affecting aeration equipment selection and addresses most of the itmes discussed in this Technology Evaluation Section. Reference 3 contains the results of a 1979 full size activated sludge plant survey designed to review, document, and evaluate power requirements, design practices and operating and maintenance characteristics for 19 fine bubble dome diffuser aeration systems. The information documented in Reference 3 should be of particular interest to design engineers and municipal officials who are considering utilizing fine bubble aeration equipment in new activated sludge plants or switching to such equipment in existing plants.

Specifying and Evaluating Wastewater Aeration Equipment [2] [14] [28]

Two major areas require specification: Mechanical aspects and equipment performance. This discussion concentrates primarily on performance requirements.

Very generally, the aeration system must maintain microbial solids in suspension so they can come into contact with dissolved oxygen in the wastewater, and it must transfer enough oxygen to the wastewater to satisfy microbial metabolism requirements. Mixing requirements are normally specified by minimum wastewater horizontal flow velocities which must be maintained in the basin. Oxygen transfer requirements are specified by an oxygen transfer coefficient K_La. Activated sludge systems are designed to be food limiting so that metabolism rather than a limiting oxygen concentration sets the rate of oxygen demand. In doing so, the transfer of oxygen through the films to the bulk liquid to maintain the dissolved oxygen concentration desired becomes the controlling factor for the aeration system design.

It is important that mixing power requirements be checked for each application. In the design of activated sludge basins, adequate mixing usually occurs if metabolic oxygen demands are met. In the design of aerated lagoons for the treatment of domestic wastes, the mixing power requirement will most often be the controlling factor. Typical air requirements for diffused air systems to insure good mixing vary from 20 to 30 cfm/1000 ft^3 of tank volume (29). Mixing by jet aerators is independent of air flow since they recirculate the wastewater as well as aerate.

Designing aeration systems based on oxygen transfer requirements makes it possible in theory to use either steady or non-steady state tests to determine aeration equipment characteristics. Some practical difficulties with this approach are discussed in the section below. In any case, manufacturers' commonly used criteria for aeration performance are aeration capacity (weight of oxygen absorbed into solution per unit time) and aeration efficiency (aeration capacity per unit of energy supplied). Results are normally given for clean water using the non-steady state test at standard conditions (20°C, 1 atmosphere pressure, and 0 mg/l initial dissolved oxygen). Table 5 gives estimated ranges of comparative clean water oxygen transfer and aeration efficiencies for several generic devices. It is an update of original compilations by Brenner [(30)].

Aeration requirements for the bio-oxidation process under consideration are a function of the measured or design uptake rate (dO/dt) of that process. In addition, the expected oxygen deficit (C_S - C_L) as well as alpha and beta must be estimated or determined. Once this is done, the value of K_La can be calculated (equation [8]), oxygen requirements determined, and aeration equipment selected from manufacturers aeration capacity and efficiency information discussed earlier.

In practice, selection of aeration equipment involves more than oxygen requirement considerations. Selection of aeration systems also involves consideration of climate; mixing flexibility; diurnal flow variations; mechanical complexity and reliability; capital, operating and maintenance costs; aesthetics; and perferences of the owner. Table 6 outlines considerations which must be addressed to select any type of aeration equipment. Fisette provides additional insight into the many tangible and intangible considerations which must be taken into account [(31)].

TABLE 5

COMPARATIVE CLEAN WATER OXYGEN TRANSFER INFORMATION FOR AIR AERATION SYSTEMS UNDER STANDARD CONDITIONS[44] (a)

Type of Aeration Device	Range of Clean Water O_2 Transfer (%)	Range of Clean Water Efficiencies kg O_2/kwh (lb O_2/hp-hr)	Energy Requirement kwh/kg O_2 (kwh/lb O_2)
Mechanical Aerator			
Low speed surface	-	1.5-2.2	0.46-0.66
	-	(2.5-3.5)	(0.21-0.30)
High speed surface	-	1.2-1.8	0.55-0.82
		(2.0-3.0)	(0.25-0.37)
Turbine sparger (b)	14-18	1.2-1.8	0.55-0.82
		(2.0-3.0)	(0.25-0.37)
Fine Bubble Aerators (c)			
Fine Bubble Diffuser			
Total floor coverage	20-32	3.0-4.6	0.22-0.33
		(5.0-7.5)	(0.10-0.15)
Side wall mounted	15-20	1.8-3.3	0.31-0.55
		(3.0-5.5)	(0.14-0.25)
Jet Aerator (b)	15-26	1.6-2.3	0.44-0.62
		(2.7-3.8)	(0.20-0.28)
Coarse Bubble Diffuser (c)			
Static aerator	10-16	1.4-1.9	0.51-0.71
		(2.3-3.2)	(0.23-0.32)
Coarse bubble dual aeration	10-13	1.4-1.6	0.62-0.71
		(2.3-2.7)	(0.28-0.32)
Coarse bubble single side aeration	8-10	1.2-1.5	0.60-0.71
		(2.0-2.5)	(0.30-0.32)

(a) Compiled using a combination of manufacturers' company bulletins, technical reports, and historically accepted data ranges.
(b) Includes energy requirements for two prime movers.
(c) Based on clean water test at 15 ft. water depth; submergence varies depending on device.

TABLE 6

INFORMATION REQUIRED TO SELECT AND VERIFY
AERATION EQUIPMENT PERFORMANCE

Treatment Process Description

- design flow
- tank geometry and configuration to give
  - aeration basin volume
  - hydraulic detention time
- operating conditions
  - flow rate
  - mean cell residence time for activated sludge processes
  - environmental parameters (temperature, pH, altitude)
  - mixing requirements
  - dissolved oxygen concentration at steady state

Wastewater Characterization

- expected influent and required effluent BOD
- oxidation and nitrification metabolic requirements
- dissolved oxygen saturation concentration
- oxygen uptake rate in the aeration system
- suspended solid concentrations in the aeration system

Oxygen Transfer Coefficient K_La Determination

- alpha
- beta

Aerator Performance and Design Requirements

- equipment operating flexibility
- allowable power variations and limitations
- aerator placement and configuration
- mixing capacity - basin horzontal liquid velocities
- aeration capacity
- oxygen transfer efficiency

Method of Aeration Equipment Testing

- steady state
- non-steady state
- power measurement

Data Analysis Method

Health and Welfare Aspects

- spray
- mist
- noise

The aeration system selected should be field tested to determine if it meets expectations. Each application of aeration equipment is sufficiently site specific such that the field performance of the aeration equipment cannot be predicted with confidence. The compexity of the interrelated variables affecting aeration performance and its measurements is the subject of this assessment. Testing aeration equipment, even though adding considerably to the cost of the installation is necessary and justified (14).

Basin Geometry and Mixing Considerations (3)

Recognizing the process advantages of plug flow systems and considering the wastewater characteristics which contribute to sliming, Houck recommended in his 19 plant study that new dome or disc diffuser systems should be used in a plug flow aeration tank having the lowest practicable L/W. Tapered aeration was also recommended; however it was noted that it is only a partial solution, limited by the aeration/mixing requirements of the lightly loaded back end of the plug flow system. It was reconized that step feeding helps distribute oxygen demand and alpha depression more equally; however its use is limited in single-stage nitrification systems. It was also reported that some plants have had good experience with feeding raw sewage down stream of the mixed liquor feed, effectively creating a zone of sludge reaeration in the first section of the aeration tank. In any case it was emphasized that the oxygen demand for each distinct segment of the plug flow aeration process should be calculated and the aeration system sized appropriately, taking into account the variation of alpha from inlet to outlet. Dissolved oxygen monitoring and provision for independent air flow control should be provided for each aeration grid and/or pass in a multiple channel tank.

The rationale behind minimum allowable air flow requirements has been discussed previously. Houck found that for the plants he surveyed, the practice of adhering to minimum specific air flow rates promoted good maintenance history but contributed to mediocre energy efficiency at many of the plants because oxygen demand requirements were exceeded. Better matching of process and aeration tank design to diffuser system design constraints was considered the most effective solution to the problem of overaeration.

Clean water studies show a nearly linear correllation between oxygen transfer efficiency and depth up to at least 20 ft. Furthermore, increases in blower efficiency can be expected up to about 30 ft using a blower equation comparing blower power required versus depth to transfer into solution an equivalent amount of oxygen. Beyond this, oxygen depletion in the bubble clouds the analysis. Thus, overall aeration efficiency should improve with increasing tank depth. Significantly, however, Houcks data showed no clear correlation between mixed liquor depth and oxygenation efficiency at depths greater than 12 ft. Plants that had shallow aeration tanks, 12 ft or less, had lowered oxygen transfer efficiency. It is likely that the relatively modest improvement in efficiency with depth is overshadowed by other factors in the aeration system when tanks are 12 ft of deeper.

Depending on the age of the plant, Houck found that some aeration basins were constructed with ridge and furrow floor design. This configuration was originally developed as an aid in mixing and tank circulation. Houck reports that the concensus in England is that the ridge and furrow configuration is costly to construct and adds little to performance; consequently, it was not seen in the newer plants in his survey.

Specifying Air Supply Equipment

The type of blower used for a particular situation depends primarily on economics, space and air flow. Generally speaking, both positive displacement and centrifugal blowers are normally considered for air volumes to 15,000 cubic feet per minute (CFM) of air. Overall economy favors centrifugal blowers for units larger than 15,000 CFM. The Axial compressor, ideally suited for large flows, should be considered for volumes over 100,000 CFM. Szczensy discusses the many types of compressors used in sewage aeration applications [32]. The trend seems to be toward single-stage centrufugal compressors with their lower first cost and efficiency comparable to multistage centrifugal compressors. Table 7 gives a summary of general application information on types of units and their volume range of application [32].

There are three basic types of air cleaning systems: viscous impingment, dry barrier, and electrostatic precipitation. In a viscous inpingment system, filtrate particles strike an oil-coated surface of a filter and become trapped until the filter is cleaned. A large portion of low specific gravity particles, however, can pass trough. This type of air cleaning system is most suitable for primary filtering. In a dry carrier system, the filter material if generally quite fine. Bag house dry barrier systems are most commonly used. Their efficient is greater after they are partially dirty or precoated because retained particles increase effectiveness of the straining mediun. Bag house collector size, expense and precoat requirements have diminished their selection in many newer plants. Replaceable filter assemblies are an easy method to filter the air but can be costly. The electrostatic precipitator gives particles and electric charge so that they are subsequently removed by attraction to elements of opposite polarity. Electrostatic precipitators can remove small particles at a constant high efficiency. Ashe discusses wastewater treatment plant air filter design considerations in some detail [33].

Cleaning efficiency is the primary filter design characteristic and is determined by the equipment it is designed to protect. For fine bubble diffusers, the common standard recommended for effluent air quality is 0.1 milligrams or less of dirt per thousand cubic feet of air.

In addition to particulates in the air, diffusers can be clogged externally by fine sand in the tank liquor, excessive calcium carbonate hardness in the water supply, and reduced iron salts in the incoming waste. When retrofitting fine bubble diffusers into existing plants, the air piping should be carefully checked for rusting or scaling. Consideration should be given to cleaning or coating existing piping to avoid particle

TABLE 7. BLOWER APPLICATION CHART (32)

Volume Range	Blower Types Available	Remarks
To 15,000 CFM	Lobe-Positive Displacement Modularized Vertically-Split Multi-Stage Centrifugal	Low First Cost
15,000 CFM to 47,000 CFM	Integral-Gear, Single-Stage	Lowest cost, minimum space
	Pedestal-Type, Single-Stage Centrifugal	Intermediate cost, more space.
	Multi-Stage, Horizontally-Split Centrifugal	Traditional approach, more costly (need extra stages to go direct drive).
47,000 CFM to 100,000 CFM	Pedestal-Type Single-Stage Centrifugal	Lowest first cost at comparable efficiency.
	Multi-Stage, Horizontally-Split Centrifugal-Single or Double Inlet	Traditional approach, more costly.
100,000 CFM to 150,000 CFM	Pedestal-Type, Single-Stage Centrifugal	Lowest first cost.
100,000 CFM to 200,000 CFM +	Axial	Highest cost-highest efficiency. Evaluates best over long operation period.

shedding from its walls where it can cause fouling. Morgan discusses plant experience and proposes corrective measures for causes of diffuser fouling other than dirty air [34]. It is important to keep in mind however that a properly filtered air supply is the most important single consideration for minimizing diffuser fouling.

Methods of Aeration Equipment Testing

There are two general methods for determining the oxygen transfer capicity of aeration equipment selected. The non-steady state or clean water test measures oxygen transfer capacity from the gas to the liquid phase (tap water) and does not address the effect of wastewater constituents. In this test, the concentration of the dissolved oxygen in the water is constantly changing over time (dC/dt is not constant) as the liquid approaches saturation. The steady state test is conducted under process conditions, which for an activated sludge treatment plant means after the plant is in operation and microbial suspension has developed to the design value. In this case, the concentration of oxygen in the wastewater is constant over time (dC/dt=0).

The general mathematical models which have been adopted to describe the transfer of oxygen to a liquid have been developed earlier for both the non-steady state and steady state tests (equations [3] and [8], respectively). There are two basic assumptions common to the use of both these models. First, it is assumed that oxygen uptake and transfer are occuring in an adequately (homogeneously) mixed fluid. Secondly, it is assumed that Henry's Law applies and the ratio k_L/k_g remains constant throughout the contacting device [7]. In practice, this ratio may not remain constant (and K_La will vary) when aeration capacity is inadequate to satisfy BOD and dissolved oxygen concentrations in the bulk liquid do not follow Henry's Law predictions. From a practical standpoint, correlation between steady state wastewater tests and non-steady state clean water tests are difficult because of these and other inherent problems discussed earlier. The need to accurately correlate clean water and wastewater test results to minimize costs of field modifications of aeration equipment has been recognized by EPA as an important area of research [30].

Considerable literature is available describing various approaches used to conduct steady state and non-steady state tests. There is no commonly accepted procedure, and engineering apecifications outlining test methods vary. Paulson [20] has summarized the non-steady and steady state procedures cited in the literature as well as those currently in use by owners, consultants, and manufacturers. He discusses significant differences among them. Other more recent procedures for field evaluation of both fine and coarse bubble aeration devices are discussed in references 35 and 36.

Neither the steady state nor non-steady state aeration equipment test is free of problems. However the problems are not insurmountable and the tests are valid. Major problems in the steady state test are determination of the correct values of dO/dt, alpha, C_s, and C_L to be used. Major problems in the non-steady state test are determination of the correct value of C_s to be used and possible interferences in the dissolved oxygen analysis. Measures to minimize these problems have been discussed or referenced elsewhere in this paper. From a theoretical standpoint the steady state test is the preferred method of aeration equipment evaluation because it takes into account wastewater composition. However, practically speaking, the non-steady state method is more commonly used because it has less interferences and possibilities for error and in many design situations field testing with biomass is not feasible. The value of clean water testing is enhanced when it is conducted in the actual aeration tank with continuous dissolved oxygen measurement and recording.

Data Analysis

The basic mathematical model describing the rate of gas transfer into solution is defined in equation (2). The model allows estimation of the gas transfer coefficient K_La by analysis of data obtained from experimental measurement of dissolved oxygen concentration with time. The K_La is characteristic of the aeration equipment and process conditions producing it and allows equipment efficiencies to be calculated. Three forms of this basic mathematical model are commonly used for estimation of K_La. Equation [2] is called the differential or general form and is repeated below:

$$\frac{dC}{dt} = K_La\ (C_s-C_L) \qquad [2]\ \text{DIFFERENTIAL FORM}$$

By specifying the initial condition that $C_L=C_o$ at $t_1=0$ and $C_L=C$ at $t_2=t$, equation [2] can be integrated and rearranged to become a more specific equation [3] which is termed the integrated of log deficit form:

$$\ln\ (C_s-C) = \ln(C_s-C_o) - K_Lat \qquad [11]\ \text{LOG DEFICIT FORM}$$

Finally, transforming the logarithmic form to base 10 numbers allows equation [11] to be expressed in terms of dissolved oxygen concentration:

$$C=C_s - (C_s-C_o)e\ {-K_Lat} \qquad [12]\ \text{EXPONENTIAL FORM}$$

where e=2.71828

A variety of graphical and numerical procedures have been proposed to to analyze oxygen transfer data. Most procedures deal with the non-steady state test. The conventional approach graphs semi-log plots of oxygen saturation deficits versus time according to Haney (8) using the log deficit form of the equation. The slope of the line is the negative of the gas transfer coefficient K_La. C_s, the oxygen saturation value, may be assumed to be the value at the surface, corrected for depth, or experimentally measured. A newer data evaluation procedure has been proposed by Stukenberg (14) which uses the differential form of the basic equation and plots oxygen transfer rate versus oxygen concentration directly. This method of analysis may be used on results from steady state tests (where the oxygen saturation concentration is βC_s) or used for non-steady state tests. Still another procedure fits the exponential form of the basic equation to the experimental data. In this analysis, values of dissolved oxygen concentration are used directly and equation [12] is fit to the data using non-linear least squares procedures. Brown has discussed these and other oxygen transfer parameter estimation methods in detail (37).

Data analysis methods are influenced by the form of the fundamental mass transfer equation they follow and by how they attempt to account for limitations in the experimental data. As a result there is a relatively large number of them. Differences among then result from the use of a variety of values for C_s: some calculated and some determined from experimental data. Linear models commonly use the least squares method to fit the equations to the expermental data. Non-linear models use other iterative regression analysis techniques. Data truncation (below 20 and above 80 percent of saturation) is often required because of dissolved oxygen measurement limitations, especially as dissolved oxygen saturation is reached. Brown and Yunt have summarized and presented a general review of data analysis techniques along with information about each (37) (38). The five common methods noted above are presented in Table 8.

Energy Utilization

The costliest item in the activated sludge process is the aeration system because of its high energy consumption during operation. Aeration equipment power consumption for secondary activated sludge normally accounts for 60-80% of total power demand (3) (39).

Electrical power consumption can be estimated for diffused air equipment which consumes most of the power in the activated sludge process (39):

$$\text{kWh/lb } O_2 = (0.39 + 0.318\ GP)/OTE \qquad [13]$$

where: GP = compressor exit pressure, psig
OTE = oxygen transfer efficiency in percent =

$$\frac{\text{mass air dissolved in aeration basin}}{\text{mass air supplied to diffusers}} \times 100$$

It can be seen that electrical power consumption per unit weight of oxygen required is inversely proportional to oxygen transfer efficiency and directly proportional to compressor exit pressure.

Clean water aeration energy requirements can be estimated using Table 5. For example, the average estimated energy requirement for fine bubble aerators is 0.41 kwh/kg O_2 from the data in Table 5. For an oxygen requirement of 1000 lbs/yr, electrical energy required is 67,868 kWh/yr. Table 9 summarizes the average energy requirements from the ranges given in Table 5 for the three major aeration devices in clean water. It then estimates these requirements for wastewater. Assumptions are given in the table.

TABLE 8. SUMMARY OF COMMON DATA ANALYSIS METHODS

DATA ANALYSIS METHOD	FORM OF BASIC EQUATION	D.O. SATURATION DETERMINATION	TYPE OF REGRESSION ANALYSIS	ERROR STRUCTURE	USUAL DATA TRUNCATION	REMARKS
conventional method (surface saturation)	log deficit	calculated	least squares	biased	low and high	inadequate for subsurface aeration
conventional method (corrected saturation)	log deficit	calculated	least squares	OK, except as $C \rightarrow C_s$	low and high as $C \rightarrow C_s$	K_La sensitive to assumed C_s
conventional method (measured saturation)	log deficit	measured	least squares	OK, except as $C \rightarrow C_s$	low and high	C_s and K_La determined from data
direct method	differential form	derived from data analysis	least squares	errors increase as dC/dt increases	low and high if data noisy	magnifies scatter in data
exponential method	exponential form	derived from data analysis	non-linear	errors decrease as C increases	low only	C_o, K_La, and C_s determined from data

Note that the estimation of aeration efficiency is very important when calculating energy requirements. In Houck's survey, aeration efficiency was estimated for 16 operating activated sludge systems using dome diffuser fine bubble aeration (3). The highest and lowest yearly average aeration efficiencies observed were 3.5 lb O_2/wire hp-hr and 1.3 lb O_2/wire hp-hr. For the three plants with a reasonably sufficient comparative data base, fine bubble dome diffuser systems were approximately 1.7 times higher than for side-by-side coarse bubble diffuser systems (2.56 vs 1.56 lb O_2/wire hp-hr). It was the opinion of the authors that with enhanced design and operating techniques, aeration efficiencies of dome diffuser plants with no unusual alpha depressing wastes present could be increased 25-75 percent over the average value of 2.43 lb O_2/wire hp-hr estimated from the survey.

Energy utilization is only one parameter of aerator performance. Mixing capability, reliability and flexibility of operation should also be considered in conjunction with operational and capital costs when selecting the aerator type.

O&M Requirements (3)

Historically, fine bubble aeration equipment was widely used in the United States prior to 1950. Because of fairly intensive maintenance requirements it was gradually replaced with low maintenance coarse bubble equipment. The increase in power costs since 1974 has resulted in renewed interest in fine bubble aeration operation because of its more efficient oxygen transfer potential.

The plants surveyed by Houck exhibited few maintenance problems with the dome diffuser aeration systems. The Norton/Hawker-Siddeley dome diffuser was in use in all of the plants surveyed in this study. The dome diffuser was developed in 1954, and its clean water aeration efficiency normally runs 7.4-8.2 lb/wire hp-hr at 13-15 ft water depths. Houck concluded that the good mainteance experience was directly attributable to two principal factors:

- Concientious (though not labor intensive) attention to aeration system operation, particularly as related to air cleaning and repair of infrequent equipment failures. Minimizing interruption of air flow and maintaining an air flow per dome of 0.5 cfm also contributed substantially to the low incidence of maintenance problems.

- Steady improvement of dome diffuser air piping and air cleaning equipment over the course of its history.

A major operational problem encountered was formation of biological slime on the external surface of the diffuser. Diffuser sliming is apparently produced by conditions of high F/M loading and/or low dissolved oxygen and manifests itself as coarse bubling at the aeration tank surface. One possible explanation for the coarse bubbling is that slime causes the bubbles to coalesce during formation. Another theory proposed

TABLE 9

AERATION ENERGY REQUIREMENTS

Aeration Device	In Clean Water kWh/kg O_2*	In Wastewater kWh/kg O_2**	kWh/10^6 gal***
Mechanical aerator	0.64	1.02	546
Fine bubble aerator	0.41	0.65	348
Coarse bubble aerator	0.64	1.02	546

* From Table 7

** Assume wastewater energy requirements = (Clean water energy requirements)/($\alpha x \beta$) where $\alpha = 0.7$, $\beta = 0.9$

*** Assume Δ soluble BOD = (136-20) mg/l, ΔNH_4-N = (20-17) mg/l and unit oxygen requirements per unit of BOD and NH_4-N are 1.1 and 4.6 respectively resulting in 535 kg O_2 needed per million gallons wastewater (1180 lb O_2/mgd) for oxidation is that the slime gradually blocks off air flow through the cermic media, forcing air to take the path of least resistance up through the dome orifice that surrounds the center hold-down bolt and finally out through the poor-sealing bolt gasket. If this latter explanation proves to be valid, the recently developed disc diffuser would probably remedy the situation as it has no other potential avenue for the air to escape other than through the media. The coarse bubble phenomenon deserves increased investigation. Regardless of the cause(s), coarse bubbling is undesirable because larger bubbles result in less oxygen transfer efficiency. Sliming was observed to occur most frequently at tank locations where organic loading was highest and dissolved oxygen the lowest. It was found that mild sliming could be reversed by greatly increasing the air flow and reducing raw sewage flow to the affected tank area for 24-48 hours. Routine tank cleaning (for example, yearly) and in-place dome brushing manually or with high pressure air was found desirable for long term control of sliming at some plants.

Calcium carbonate scaling was not a major problem at the plants surveyed by Houck, with one exception. For that case, domes had to be removed and cleaned every 5 years. Cleaning consisted of scrubbing, acid soak in 10 percent hyrochloric acid for 24 hours, and steam cleaning. The domes were not refired, although the manufacturer recommended refiring after every other cleaning. In general, intervals between major cleaning efforts (removal and refiring or equivalent) for all plants varied from 4 to over 9 years. Table 10 summarizes maintenance experience found by Houck.

Monitoring and maintaining a desired mixed liquor dissolved oxygen concentration is necessary to optimize plant aeration efficiency. If hydraulic and/or organic loading rates decrease and air flow rates do not respond accordingly, the dissolved oxygen deficit in the activated sludge basin decreases, resulting in less than optimum oxygen transfer performance. Houck found a number of plants were overaerating their mixed liquor and had taken no steps to monitor dissolved oxygen concentrations and reduce air flows to more efficent operating levels.

All of the plants reported low maintenance requirements for their air cleaning equipment no matter which type was used. Bag filters required least attention with one or two cleaning cycles per year. Electrostatic units required three to four cleanings per year, but each cleaning operation was simple and took less than half a man-hour. Every 2 years the electrostatic units required more thorough maintenance, consuming half a man-day. Disposable filters were simplest of all, but replacement filters are costly.

Significant industrial waste fractions in municipal wastewaters may substantially lower dome diffuser oxygen transfer efficiency via a reduction in the alpha factor. This is especially true in the first segment of long, plug flow aeration tanks. Houck reported alpha values as low as 0.3-0.4 at the head of such tanks where detergents and other

TABLE 10

MAINTENANCE DATA SUMMARY*

Plant Name/Location	Started Up	Startup Experience	Cleaned	Operating Experience
United Kingdom				
Basingstoke	1964-71	Some problems with plastic tank bottom mounts	Every 5 yr	Fair, scale problems (see discussion)
Beckton				
New Plant	1970	Problems with plastic holddowns	Every 8 yr	Good after initial problems
Old Plant	1959	No significant problems	Twice in 15 yr	Gradual plugging due to rust in cast iron pipes
Beddington (New Tanks)	1969	No significant problems	Every 4 yr**	Poor but improving major slime problem
Long Reach	1978	No significant problems	Not yet	Good, new plant
Mogden (Battery B)	1961	No significant problems	Every 6 yr	Plastic retrofit in Battery B (1968) has not yet required cleaning
Oxford	1969	Some problems with plastic tank bottom mounts	Not yet	Good, no apparent loss of effluent quality after 10 yr
Ryemeads	1956-70	Some problems with retrofitted plastic piping	Every 6 yr	Fair, plugging due to rust in older lines. Plastic system good
Coalport	1970	No significant problems	Not yet	Good
Coleshill (Stage III)	1968	No significant problems	Not yet	Good, tanks cleaned once/year and domes brushed
Finham (South)	1974	No significant problems	Not yet	Good, only have had to repair several small line leaks
Hartshill	1973	No significant problems	Not yet	Fair, some slime growth
Minworth	1971	No significant problems	Not yet	Good, tanks cleaned once/year and domes brushed
Strongford (New Plant)	1972	No significant problems	Not yet	Good
The Netherlands				
Holten-Markelo	1978	No significant problems	Not yet	Good
Steenwijk	1977	No significant problems	Not yet	Good
United States				
Glendale, Calif.	1978	Several blowoff lines failed	Not yet	Good, small evidence of slime
Madison, Wisc.	1977	No significant problems	Not yet	Substantial sliming problem in mid-1980 after 3 yr of operation
Fort Worth, Tex.	1978	Some problems with blowoffs	Not yet	Some line breaks and problems evident, but overall performance stable
Tallman Island, N.Y.	1979	No significant problems	Not yet	Good

* From Reference 3.

** Initially. Cleaning has not been required for the last 6 yr.

surfactants haven't had sufficient contact time to be biodegraded. Alpha increased to values of 0.8 or higher at the effluent end of the tank.

Diffuser cleaning is a labor intensive and costly process that can usually be forstalled by careful O&M. MOP No. 5 discusses common methods used for diffuser cleaning (2). Houck found diffuser cleaning frequencies to vary from 4 to over 9 years in the plants surveyed (see Table 10). It is prudent practice to have provisions for diffuser cleaning at any plant. Methods of cleaning porous ceramic diffusers include kiln burning (refiring), acid cleaning (diffusers removed or in place), and alkaline cleaning. Ultrasound is a new alternative to conventional methods of cleaning which needs further development. In the Sanitaire system, a cleaning agent can be added along with process air. The cleaning agent presently chosen in HCL gas, and gas consumption of 0.25 lb/diffuser per cleaning cycle is reportedly typical (40). The Vortex Jet Aerator manufactured by the Aerocleve Division of Clevepak Corporation contains an automatic pneumatic backflush system which claims to virtually eliminate all below the water maintenance and clogging problems (41).

Costs

It is the responsibility of the designer to choose an adequate aeration system that will supply the mixing and oxygen requirements for the process at minimum annual cost. Determining the requirements of an adequate system is not simple and was discussed earlier under the Design Considerations Section. Once they are determined, various fine bubble aeration systems made up of a specific number, type, and equipment configuration can be specified and costs for comparison among systems can be estimated.

Major construction cost items are air piping and headers as appropriate, the aeration devices and their supports, air cleaning equipment, blowers, and buildings to house the latter items. Operating and maintenance costs are principally operational power costs, aerator cleaning and replacement costs, and air cleaning costs.

Operational power costs not suprisingly depend on oxygen transfer efficiency of the fine bubble aeration system chosen and influent wastewater characteristics. Aerator cleaning costs depend upon the type of aerator, its flexibility with respect to cleaning (removal) or repalcement, O&M practices at the plant, and influent wastewater characteristics. MOP no. 5 discusses in some depth how cleaning and replacement costs vary with air-passed-betweencleanings and pressure loss from clogging (2). Air cleaning equipment costs represent only a small percentage of total aerator system O&M costs; however, properly filtered air is an important part of aeration system operation. Section 4 which compares equivalent technologies gives some "typical" cost comparisons and references other cost studies.

There are other factors besides cost which may preclude selection of a certain type aeration system. Major ones are climate (winter) considerations affecting operation, controlability of the aeration system, noise levels, and compatability with other aeration systems already on site. The capability to increase aeration capacity in response to potential future increases to oxygen demand or mixing should also be considered.

4. COMPARISON WITH EQUIVALENT CONVENTIONAL TECHNOLIGIES

Current methods used to transfer oxygen in aerobic biological wastewater treatment processes include: 1) jet aeration, 2) compressed air diffusion, 3) submerged turbine aeration, 4) static tube aeration, and 5) mechanical surface aeration. Stukenberg [14] has suggested that compressed air diffusers "of the conventional design" should not be used when oxygen demand exceeds 40 mg/l-hr. Surface aerators are recommerded to meet oxygen demands up to 80 mg/l-hr. Compressed air diffusers and submerged aerators are more suitable for areas experiencing long periods of freezing weather. (Surface aeration is an effective heat disipation process which may significantly lower the temperature of the liquid.) Submereged turbine aerators involve more mechanical equipment but have the most flexibility with respect to turndown.

Stukenberg's suggestions are a guide to system selection. The specific selection will depend on a careful review of many factors which were discussed in the Technology Evaluation Section. In general, any comparision of specific aerators involves defining the performance aspects the aerator must meet (see Table 6), identifying the capabilities and limitations of the equipment being considered (from manufactureers brochures, published literature, and testing), and satisfying the preferences of the owner (including personal, pragmatic, and economic considerations).

Langford made a detailed study of costs of several types of activated sludge aeration systems in general use in the United States in 1972. His purpose was not to make an unequivocable determination about the cost effectiveness of any type aeration system, but rather to present a comparative cost analysis within the framework of assumptions and approximations adopted [42]. A wastewater composition with influent BOD of 180 mg/l was assumed and design prodecures outlined by Eckenfelder were followed to compute needed detention times. Three types of fine bubble diffused air sytems, one coarsebubble system and two mechanical aeration system designs were evaluated. A complete listing of the prices for various sizes of components was developed. These prices plus the cost of the construction needed to put these materials together (basin structures, blowers and piping, air filters, etc.) were then used to develop a range of construction cost estimates for plant sizes from 0.1 to 100 MGD. Operation and maintenance costs for each of these systems were also developed. A summary of the reported costs is presented in Table 11.

Even for the low power costs in effect at the time of this study (<2¢/kWh), the ceramic plate diffusers turned out to be the most economical system at 10 and 100 MGD, and the second most cost effective of the six systems studied at 1 MGD. The study shows that fine bubble diffuser systems are potentially cost effective over a wide range of activated sludge plant sizes. References 35, 43, 44, and 45 contain other cost and energy comparisons of different kinds of aerators for the activated sludge process.

TABLE 11.

COST EFFECTIVENESS COMPARISON FOR SEVERAL ACTIVATED SLUDGE AERATION SYSTEMS (42)

Aerator Types	Q, MGD	Construction Costs, $/year	Maintenance Costs, $/year	Operating Costs, $/year	Total Costs, $/year
Mechanical Low Speed	0.1	924	597	2,136	3,660
	1	2,941	921	5,710	9,570
	10	18,700	4,475	20,100	43,300
	100	130,800	28,952	126,400	286,000
Mechanical High Speed	0.1	654	344	2,124	3,120
	1	2,470	597	5,670	8,740
	10	15,050	3,335	20,000	38,400
	100	116,200	19,412	125,400	261,000
Saran Tubes	0.1	1,133	113	2,512	3,760
	1	3,560	508	6,420	10,500
	10	17,585	3,280	23,200	44,100
	100	136,465	27,100	137,000	301,000
Ceramic Tubes	0.1	1,134	97	2,512	3,740
	1	3,566	353	6,420	10,300
	10	17,640	1,730	23,200	42,600
	100	136,300	11,500	137,000	285,000
Spargers	0.1	1,010	91	2,608	3,710
	1	3,367	385	7,400	11,200
	10	16,715	1,320	27,500	45,500
	100	136,440	6,470	179,000	322,000
Ceramic Plates	0.1	892	95	2,428	3,420
	1	3,020	261	5,630	8,910
	10	16,250	1,440	19,550	37,200
	100	125,290	8,380	103,200	237,000

NOTE: Costs are 1972 dollars.

5. ASSESSMENT OF NATIONAL IMPACT

Of the three major aerobic wastewater treatment processes (activated sludge, trickling filter, aerobic stabilization ponds), activated sludge is by far the most prevalent, both in number of plants and by volume of flow [46]. Houck reports only a "handful" of U.S. activated sludge facilities using fine bubble aeration although he notes that the fine bubbles dome aerators are in use at several hunderd other treatment plants around the world [3]. More importantly, he and others have noted the fact that rapid escalation of power costs and replacement of iron air distrubution networks with plastic piping have made fine bubble diffuser O&M costs more competitive with other aeration equipment. The 1978 Needs Survey compiled a large amount of cost and technical data about present and future municipal wastewater treatment needs [46]. Table 12 summarizes estimated activated sludge unit process requirements to meet needs for the year 2000. It estimates the number of plants and wastewater flow (to be) treated for plants now in use, under construction, or required but not funded.

The large numbers of activated sludge plants where fine bubble diffusers can potentially be used increase their potential impact on treatment costs. Average energy required for activated sludge plants in the United States is $1.07X10^6$ kWh/yr for each plant [43]. From Table 12 the average air activated sludge plant size is 3.5 mgd resulting in a total plant energy requirement of about 306,000 kWh/yr per mgd size plant. Mechanical and coarse bubble aerator requirements are about 199,000 kWh/yr per mgd or 65 percent of total energy requirements according to Table 9 estimates (546 kWh.million gallons). Fine bubble aerators use an average of 127,000 kWh/yr per mgd (at 348 kwh/million gallons), saving approximately 72,000 kWh per mgd yearly when used. This is a potential energy savings of 24 percent of the total plant energy requirements because of increased aeration efficiency.

If aeration efficiency were the only consideration in aeration device selection, or if it were always the limiting design factor then fine bubble aerators would be the simple choice. However, other considerations, especially mixing requirements, total life cycle costs, aeration capacity, and equipment flexibility must also be addressed (see Table 6) so that fine bubble aerators will be chosen only part of the time. In any case, their high aeration efficiency is a definite advantage. Table 13 summarizes this advantage expressed as national potential energy savings when fine bubble aerators are used 20, 40 or 60 percent of the time. These savings are one element of the total cost effectiveness analysis.

TABLE 12.

SUMMARY OF WASTEWATER TREATMENT PLANTS AND FLOWS USING AIR ACTIVATED SLUDGE TREATMENT PROCESSES NATIONWIDE[46]

Activated Sludge Treatment Process	Now in Use Plants (number)	Now in Use Flow (mgd)	Under Construction Plants (number)	Under Construction Flow (mgd)	Required, Not Funded* Plants (number)	Required, Not Funded* Flow (mgd)
Conventional	3816	19,085	378	1723	3178	6199
High rate	34	771	8	221	19	127
Contact stabilization	873	2,257	75	102	249	508
Extended aeration	1902	1,197	176	173	3177	1157
Σ	6625	23,310 } averages 3.5 mgd/plant now in use				

* Required by the year 2000

TABLE 13.

POTENTIAL NATIONAL ENERGY SAVINGS USING FINE BUBBLE AERATORS IN AIR ACTIVATED SLUDGE TREATMENT PROCESSES*

Activated Sludge Treatment Process	(kwh/yr)X10^6 Percent of Time Used in Plants Under Construction 20%	40%	60%	Percent of Time Used in Plants Required, Not Funded** 20%	40%	60%
Conventional	24.9	49.8	74.7	89.6	179.2	268.8
High rate	3.2	6.4	9.6	1.8	3.7	5.5
Contact stabilization	1.5	3.0	4.4	7.3	14.7	22.0
Extended aeration	2.5	5.1	7.6	16.7	33.4	50.2
National Potential Energy Savings Σ	32.1	64.3	96.3	115.4	231.0	346.5

* Using net energy savings of (546-348) = 198 kwh/million gallons wastewater treated and flow information in Table 12.

** Required by the year 2000

6. RECOMMENDATIONS

Research and Development Requirements

Research and developemnt requirements identified by most researchers are those which address in some manner the more significant factors affecting successful aerator performance. There are many approaches depending on the point of view and scope of interest. From a historical perspective, the major factors affecting overall aerator efficiency have been summarized by Eckenfelder [47]. Houck and Brenner have outlined research needs from a more pragmatic viewpoint [3] [30]. From whichever perspective, significant research and development efforts which need to be continued are summarized below. They are not necessarily independent of each other.

1. Efforts to develop a standard method to measure oxygen transfer and evaluate aeration equipment efficiency in wastewater.

2. Efforts to correlate manufacturer aeration efficiency clean water shop test results with wastewater field test results.

3. Efforts to define alpha sensitivity for various types of aerators and especially with respect to basin geometry, degree of mixing, and concentration of surfactants.

4. Efforts to define the minimum dissolved oxygen concentration in the aeration basin required to provide adequate oxygen transfer to the wastewater biota including:

    - the minimum air flow needed to attain it

    - the minimum degree of mixing needed to uniformly disperse it

5. Efforts to define the relationship between the rate of oxygen transfer into solution and the rate of biological oxygen uptake. This involves an investigation into the relationship between the oxygen transfer coefficient and minimum dissolved oxygen for biological oxygen uptake.

6. Efforts to compare different types of aerators side-by-side

    - oxygen transfer performance comparisons under identical conditions

    - O&M comparison over the long term

7. Efforts to evaluate different methods and techniques of diffuser cleaning.

8. Efforts to identify the cause(s) and solutions(s) to the fine bubble diffuser coarse bubble phenomenon due to biological fouling.

Process/Technology Improvements

The maximum aeration capicity currently achieved in practice by full-scale aeration systems is about 0.1 kg O_2/M^3 hr [15]. This can limit the maximum rate of biological treatment for high biomass concentrations. Brenner has noted that the key to efficient high rate-activated sludge treatment is operation with high biomass concentrations allowing low reactor detention times at high organic loadings [30]. Development of high-rate air systems which can efficiently transfer increased amounts of oxygen into solution and stand up to the repeated scrutiny of a testing procedure is a necessary prerequisite for more efficient high-rate activated sludge treatment. In summary, improvements in aeration capacity, in aeration efficiency, and in the ability to reliably measure, reproduce, and predict field wastewater aeration results are the most desirable process/technology improvements.

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