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A Computer Program for Optimal Aeration System Design for Activated Sludge Treatment Plants

A thesis submitted in partial satisfaction of the requirements for the degree Master of Science in Civil & Environmental Engineering

by

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ABSTRACT OF THE THESIS

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As operating costs increase, many wastewater treatment aeration systems are replaced with more energy efficient systems, such as fine pore aeration systems. Recent design procedures for fine pore aeration systems do not include an economic analysis of certain design parameters, such as diffuser density and an airflow rate per diffuser, which impact the cost of the replacement. Because of the nonlinear relationship among the parameters, iterative calculations by hand have been necessary to determine the best combination of the parameters. A computer-based methology developed in this thesis uses a constrained optimization procedure written in FORTRAN 77. This methology chooses the optimal process parameters to minimize the total capital and operating costs.

1. Introduction

Aeration is usually the single largest cost in a wastewater treatment system, comprising as much as 50 to 90 percent of the total energy requirements of a secondary wastewater treatment plant (Wesner et al., 1977). Due to the energy crisis in the 1970s and the continuing trend in higher energy costs, increasing aeration efficiency at wastewater treatment plants has been and continues to be a topic of concern for municipalities as well as the U.S. EPA. This trend has accelerated the growth of fine pore submerged aeration systems, which have higher oxygen transfer efficiency than many other aeration systems (U.S. EPA, 1985).

Historical case studies (U.S. EPA, 1989) have shown that fine pore aeration devices can save up to 50 percent of the aeration energy as compared to coarse bubble diffusers. These energy savings have encouraged the conversion of over 1,300 municipal and industrial wastewater treatment facilities from coarse bubble to fine pore aeration systems in the United States and Canada.

Although the U.S. EPA (1989) provided the guidance for designing fine pore aeration systems, plant designers still encounter difficulty when determining design parameters, such as air flow rate, diffuser density and transfer rates under various conditions.

Current design procedure cannot produce a least cost (operating and capital) aeration system design.

It is difficult to perform an optimal design because of the nonlinear relationship among mass transfer variables, such as airflow per diffuser, diffuser spacing (diffuser density), diffuser submergence and mass transfer efficiency. These relationships are sometimes known, but mass transfer variables can only be decided empirically. The optimal design procedure requires many tedious trial and error calculations, and this procedure is usually cost prohibitive.

The objective of this thesis is to provide a methology, by which determines the optimal oxygen transfer variables, diffuser density and air flow rate, at a minimum design cost. The computer-based methology developed in this thesis performs an optimal selection based upon capital cost, interest rates, power cost, and other power and economic parameters. The methology will help engineers design aeration systems with the optimal combination of air flow per diffuser and diffuser density.

2. Literature Review

Aeration is used for transferring oxygen to aqueous wastes in the biological treatment processes to satisfy several types of demands. First, oxygen is involved in the conversion of organic matter to cellular materials and energy, called carbonaceous oxygen demand. Second, oxygen is required for nitrogenous oxygen demand, the result of the oxidation of ammonia nitrogen to nitrate nitrogen. Third, oxygen demand may also occur as the result of oxidizing inorganic materials such as hydrogen sulfide. These three fundamental types of demand must be satisfied for bacteria to utilize organic material and inorganic ions to support growth (U.S. EPA, 1985).

2.1 Mechanism of Aeration

Oxygen can be transferred into the liquid phase of an aeration tank by many different devices. The two most basic methods are diffused aeration and surface or mechanical aeration. The former introduces air or pure oxygen into the wastewater with submerged diffusers, and the latter can be achieved by breaking up the water surface to make contact with the air (Tchobanoglous and Schroeder, 1987). The first type can be considered as gas bubbles in a liquid, while the second type can be considered as liquid drops or "bubbles" in a gas.

When air is introduced into the aeration tank by means of diffused aeration, it is dispersed into small bubbles which rise in the liquid. Thus, air bubbles remain in the liquid for a period of time before they escape at the surface of the tank. During the time the air bubbles rise, there is continuous oxygen transfer from air to liquid (Bewtra and Nichols, 1964). Morgan and Bewtra (1960) showed that about 50% of the total oxygen transfer occurred at the time of bubble formation, indicating the desirability of many fine bubbles. The physical mass transport process of gas-liquid transfer has been described by two film theory by Lewis and Whitman in 1924. Many researchers have proposed improved theories: penetration theory, surface renewal theory, Hatta model, and Kishinevskii theory. Those theories have been well summarized by Bennett (1979). However, the two film theory adequately describes the transfer of a single gas species in wastewater.

2.2 Historical Overview of Aeration

In the early years of wastewater treatment, experiments on wastewater aeration started in England (Martin, 1927). The experiments showed that small bubbles, produced by passing compressed air through porous plates, created a higher oxygen transfer efficiency. In the 1930s and 1940s, porous plates gained popularity for aeration systems in the United States (WPCF/ACSE, 1988).

Before the energy crisis in the 1970s, clogging and fouling had been a major impediment to developing diffused aeration systems in biological wastewater treatment plants in the U.S. (U.S. EPA, 1985). Coarse bubble diffuser systems were more popular because clogging and fouling could be avoided. Despite their poor efficiency and excessive electrical power costs as compared to fine pore diffusers, coarse bubble diffusers were commonly used because of their easy access and low maintenance requirements (WPCF/ASCE, 1988).

Although fine pore diffusers have been associated with some operational difficulties, fine pore aeration systems have been reevaluated due to the increases in energy costs. In spite of operational difficulties, such as diffuser-side clogging, fouling of air distribution system, and the reduction of oxygen transfer efficiency due to surfactants in wastewater (Stenstrom, 1990a), the fine pore diffuser systems are superior to coarse bubble diffuser systems because of their higher oxygen transfer efficiencies (Roe, 1934). An early study (Garber, 1984) showed that conversion from coarse bubble to fine pore diffusers at the Los Angeles Glendale Water Reclamation Plant would result in an energy savings of 35 to 40 % or about $139,000 per year. In addition, fine bubble diffuser systems are more frequently used than mechanical surface aeration systems. Fine pore diffuser systems produce high quality, nitrified effluents and serve a larger population than mechanical surface aeration systems (Thomas et al., 1989).

Fine pore diffuser systems seem to be preferable in areas with cold climates because of the slight heating effect of the compressed air and reducing evaporation rate (Talati, 1988). Operators frequently prefer maintaining two or three blowers than many motors and/or gear boxes mounted remotely on floats or platforms throughout an aeration tank. Therefore, many plants equipped with coarse bubble diffuser systems and mechanical surface aeration systems have been retrofitted with fine pore diffuser systems, resulting in significant power savings (U.S. EPA, 1989).

2.3 Types of Fine Pore Diffusers

The term " fine pore diffuser" used in this paper has been defined in U.S. EPA (1989) as those diffusers, which would produce bubbles of 2 to 5 mm diameter in clean water. The fine bubble diffusers include the following devices:

Porous ceramic plates, discs, domes, and tubes;

Rigid porous plastic plates, discs, and tubes;

Non-rigid porous plastic tubes, and

Perforated membrane tubes and discs.

This section presents information on the various types of fine pore aeration devices currently available. A description of the diffusers that follows includes plates, domes, discs, and tubes. The information is mainly collected from U.S. EPA (1989) and WPCF/ASCE (1988). Their typical shapes are provided in *Appendix 7.1*.

2.3.1 Plate Diffusers

Typical plate diffusers are made of 30 cm (12 in) square and 25-30 mm (1-1.5 in.) thick ceramic plates. The plates are installed in the tank by grouting them into recesses in the tank floor, cementing them into prefabricated holders, or clamping them into metal holders. Since the metal holders are subject to corrosion which may foul the underside of the diffuser, they are less popular.

Although plate diffusers have the advantage of long documented service life, high oxygen transfer efficiency and easy cleaning, their popularity has been declining. Some possible explanations include: problems obtaining uniform air distribution with several plates attached to the same air plenum, the inconvenience of removing plates that are grouted or cemented in place, the difficulty in adding diffusers to meet future increases in plant loading, and lack of active marketing by any equipment supplier or media manufacturer.

2.3.2 Dome Diffusers

Since the 1960s, dome diffusers have been very popular in England and were introduced in the U. S. early 1970s. Many U.S. plants have now installed dome diffusers (Houck, 1988).

The shape of the dome diffuser is a circular disc with a downward-turned edge. The diffuser is approximately 18 cm (7 in.) in diameter and 3.8 cm (1.5 in.) high. The media is usually made of aluminum oxide. The dome diffuser is generally mounted on PVC saddle-type base plate that is solvent welded to the air distribution piping at the factory. For better air distribution and maintainability in the event of a broken dome or hold-down bolt, control orifices are used to create additional head loss and balance the airflow.

Dome diffusers can be operated over a 200 percent change in airflow rate without significant change in head loss. Dome diffusers are usually manufactured to operate at an airflow rate of 0.5-2.5 SCFM/diffuser. Operating above 2.5 SCFM/diffuser is possible, but may result in less transfer oxygen efficiency and increase in pressure head loss.

2.3.3 Disc Diffusers

Disc diffusers have a similar shape to dome diffusers, but are relatively flat without a downward-turned edge. In a similar way to a dome diffuser, the disc is mounted on a plastic or stainless steel saddle-type base plate. To secure the disc to the holder, a screw-on retaining ring with an "O" ring seal is commonly used. A control orifice is placed to have the same effect as dome diffusers. Disc diffusers usually have more positive attachment to the base due to the large retaining ring.

Two methods can be applied to attach disc diffusers to air piping. The first method is to solvent weld the base plate to the PVC header prior to shipment to the job site. The second attachment method is either a bayonet type holder that is forced into a saddle on the pipe, or a wedge section that is placed around the pipe and clamps the holder to the pipe.

There are two types of disc diffusers, based on a material used. One uses a rigid porous media, generally made of ceramics (i.e. aluminum oxide). The other uses a perforated membrane made of thermoplastic or rubber materials, such as polyamide, PVC, EPDM, and polypropylene. Manufacturers often develop interchangeable designs which allow replacement of a ceramic disc with a membrane disc, or vice versa. Ceramic disc diffusers are 18-24 cm (7-9.5 in.) in diameter with a thickness of 1.3-1.9 cm (0.5-0.75 in.) and airflow rate ranges at 0.5-3.0 SCFM/diffuser. Perforated membranes, which are flat without air pressure range from 20-51cm (8-20 in.) in diameter, and have an airflow rate of 1 to 20 SCFM/ diffuser depending on their diameter.

2.3.4 Tube Diffusers

Most of tube diffusers are generally similar in size and shape. The media portion is 50-60 cm (20-24 in.) long and 6.4-7.6 cm (2.5-3.0 in.) outside diameter. The thickness varies based on the type of material used for the membrane.

Tube diffusers consist of two end caps held together by a connecting rod or structure through the center. Most tubes are attached to the air piping system through a threaded nipple. Gaskets are sometimes incorporated to seal the unit to avoid liquid backflow in the event of loss of air pressure.

Tube diffusers are operated at an airflow rates of 1-5 SCFM/diffuser. Less airflow rate may occur toward the exit end of diffuser, resulting in sites for slime growth and other foulant development. Some tube diffusers are installed with control orifice to help create uniform air distribution. Some tube diffusers may have folds in the membrane, which can result in poor air distribution at low airflow rates.

2.4 Factors Affecting Oxygen Transfer Efficiency

The performance of fine bubble diffusers depends on many factors, including water quality. The factors that the designers can directly influence are: 1) submergence, 2)airflow rate per diffuser, 3) diffuser density, and 4) the geometry and placement of the diffusers. These factors will be discussed in this section; water quality impacts will not be discussed, but are discussed by others (Stenstrom and Gilbert, 1981). In an attempt to determine factors affecting fine bubble diffused aeration, Huibregtse et al. (1983) noted that the highest oxygen transfer efficiency for fine pore diffused aeration would be achieved when the highest number of diffusers with the largest diameter were operated at the lowest air flow rate per diffuser at the greatest submergence. Obviously it is not possible to operate in this fashion, but it shows the trend to obtain the highest efficiency.

2.4.1 Diffuser layout

Groves et al. (1992) noted that total floor coverage diffuser layout had higher oxygen transfer efficiency than spiral roll, midwidth, or cross roll diffuser layouts, regardless of the type of diffusers used. The quantitative data comparison for perforated membrane tube diffusers showed that the transfer efficiency was 33 percent higher for the full floor grid layout than for the spiral roll layout. Thus, when design engineers are retrofitting coarse bubble diffusers with fine bubble diffusers, they should consider the additional increase in oxygen transfer that will be obtained with grid layouts that cover the entire tank floor. It is assumed that diffusers are installed in total floor coverage of grid configuration throughout this thesis.

2.4.2 Air flow rate per diffuser

Standard Oxygen Transfer Efficiency (SOTE) for fine pore diffuser systems in a grid placement decreases significantly with increased air flow rate (Morgan and Bewtra 1960; Bewtra and Nicholas, 1964). This response can be explained by a combined effect of the size of the air bubbles and interference from rising bubbles (Ellise and Stanbury, 1980). Bubble size increases with increasing air flow rate, resulting in less specific surface area per unit volume of air which lowers the oxygen transfer efficiency. Transfer efficiency is directly proportional to bubble surface area. Also, fewer and smaller air bubbles formed at low airflow rate may increase transfer efficiency due to the decreasing likelihood of coalescence (Ippen and Carver, 1954). Stenstrom and Gilbert (1981) observed that a reduction in bubble size at low airflow rate would cause a decrease in terminal rise velocity of the bubbles, which would increase the bubble contact time, and these increase the SOTE. An increase in transfer efficiency with reduced air flow rate is the usual response with fine pore diffusers (Huibregtse et al., 1983).

When attempting to create an optimum airflow rate of aeration system, design engineers should carefully consider operational problems at the minimum and maximum airflow rate. At minimum airflow rate, it is necessary to provide adequate mixing to keep biological solids in suspension (Rooney and Huibregtse, 1980), to prevent deposition of suspended solids (Boyle and Redmon, 1983) and to provide uniform air flux across each diffuser's surface area to avoid foulant deposition (U.S. EPA, 1985). Accordingly, these systems will be operated at less than optimum transfer efficiencies, in exchange for reduced diffuser maintenance and improved mixing. Table 1 summarizes recommended minimum mixing air flow. In addition to the criteria of the minimum airflow rate, the maximum airflow rate is also satisfied by the diffusers operating with acceptable pressure-drop.

Table 1. Manufacturer Recommended Minimum Fine Bubble Diffusers Mixing Air flow Rate (Reith, 1991)

Manufacturer and Diffuser Model	Diffuser Type	Recommended Minimum Mixing Airflow Rate
Parkson FineAir	Ceramic dome	10 scfm/1000 cu.ft.
Sanitaire	Ceramic disc	0.12 scfm/sq.ft.
Aeration Industries Nopol	Flexible membrane disc	0.12 scfm/sq.ft.
Envirex Elastox IFU	Flexible membrane disc	0.12 scfm/sq.ft.
Roediger Roeflex	Flexible membrane disc	15 scfm/1000 sq.ft.
Wilfley Weber Duradisk	Flexible membrane disc	10 scfm/1000 sq.ft. (<15 ft SWD)

2.4.3 Diffuser density

Diffuser density is defined as the number of diffusers per unit of horizontal floor surface area. Increasing the diffuser density at a constant total air flow rate increase the SOTE (U.S. EPA, 1989). The diffuser density should be maximized with the restrictions of minimum allowable airflows and capital costs (WPCF/ASCE, 1988). Percent oxygen transfer rates due to diffuser density tends to converge sharply as airflow rate is increased, demonstrating that diffuser density becomes less significant at higher airflow rates than at lower airflow rates. The arrangement of diffusers in a plug flow regime should also be tapered from inlet to outlet to create the desired uniform dissolved oxygen concentration throughout the aeration tank (U.S. EPA, 1985). These tapered-aeration diffuser layouts can be cost effective since the layouts can match the diffuser density (i.e., number of diffusers) to the oxygen transfer rate in the basin (U.S. EPA, 1989).

2.4.4 Diffuser submergence

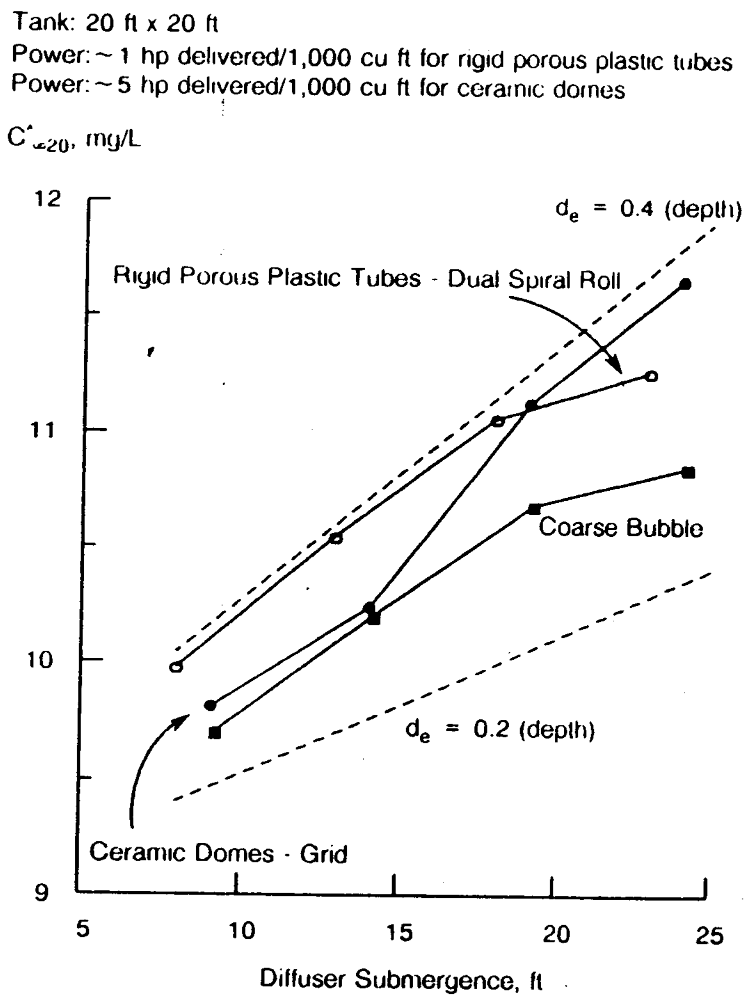
The SOTE for fine pore diffuser systems increases with increasing depth. This results for two reasons: the increased oxygen partial pressure creates a greater driving force, and the greater depth creates contact time in the aeration tank (U.S. EPA, 1985; Mavinic and Bewtra, 1974). The results for a variety of diffuser types at selected diffuser submergence are presented in Figure 1.

When selecting the aeration tank depth, which controls the diffuser submergence, several other factors in addition to SOTE must be considered. These are available area, land costs, soil bearing strength, and the difficulty and cost of construction (WPCF/ASCE, 1988).

2.5 Current Methology

The following section presents a typical method to determine oxygen transfer variables, diffuser density and airflow rate, without using an optimization technique (U.S. EPA, 1989).

Figure 1 Effect of Diffuser Submergence on $C^*_{\infty 20}$ for Three Diffuser Types (U.S. EPA 1989)



Prior to determining the oxygen transfer parameters, there are several steps to be considered. First, the total process oxygen requirement (also called the actual oxygen requirement, or AOR) must be provided by design engineers. Several methods to calculate AOR are well discussed in U.S. EPA (1989). In order to determine rational

AOR, design engineers must take into account BOD loading, ammonia loading, possible nitrification conditions and side stream loading. Further analysis of the oxygen demand loadings and how they occur spatially in time may result in minimum, average and peak values of AOR. Additional summer and winter operating conditions can be also be different. Normal diurnal flow and loading patterns may be altered by factors such as sludge treatment operations occurring in a single 8 hours work shift, and should be factored into the design. Second, it is necessary to convert OTRf (called the field oxygen transfer rate) value to SOTR value to account for the effects of process operating conditions. It is the designer's responsibility to select proper conversion factors translating AOR to SOTR, referred as oxygen transfer rate under standard conditions (20 ^oC, 1 ATM, C=0 mg/L, 36% relative humanity). This conversion is required to calculate the amount of air supplied to meet the biological oxygen demand. The equation for correction formulated by U.S. EPA (1989) is as follows:

$$OTRf = \alpha F(SOTR)\theta^{T-20}(\Omega\tau\beta C^*_{\infty 20} - C)/C^*_{\infty 20} \quad (1)$$

where,

α = process water K_La of a new diffuser divided by clean water K_La of a new diffuser,

F = process water K_La of a diffuser after a given time in service divided by K_La of a new diffuser in the same process water,

θ = temperature correction factor (1.024),

T = process water temperature in °C,

Ω = pressure correction for $C^*_\infty \approx P_b/P_s$,

P_b = field atmospheric pressure in psia,

P_s = standard atmospheric pressure (14.7 psia),

τ = temperature correction for $C^*_\infty = C^*_\infty/C^*_{\infty 20} = C^*_s/C^*_{s20}$,

β = correction factor for equilibrium dissolved oxygen concentration
= process water C^*_∞ divided by clean water C^*_∞,

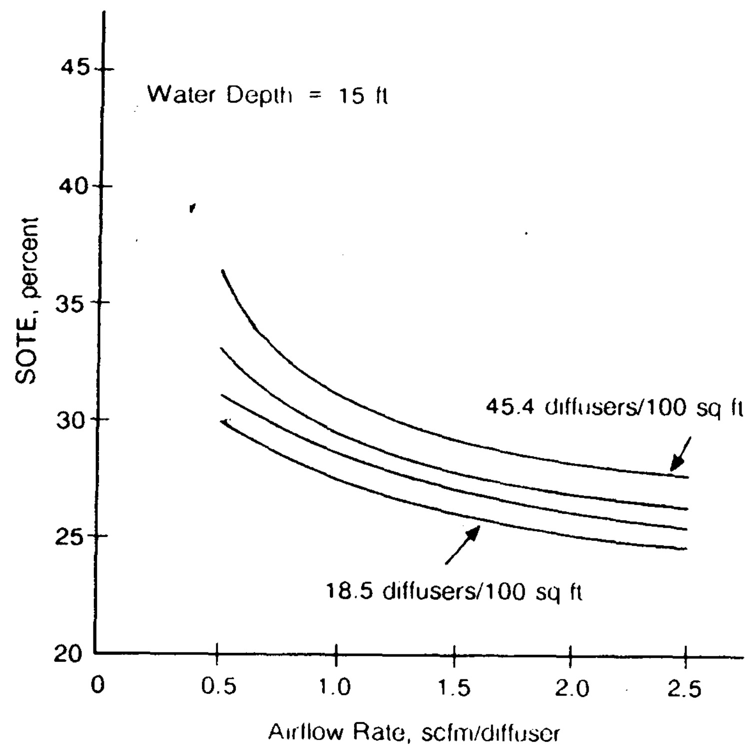
$C^*_{\infty 20}$ = steady- state DO saturation concentration attained infinite time for a given diffuser at 20 °C and 1 ATM in the unit of mg/L, and

C = process water DO concentration in mg/L.

Manufacturers often develop a generalized family of curves for their own diffusers which can provide an initial estimate (this will be an iterative process) for oxygen transfer variables. A typical family of curves as shown in Figure 2 represents the relationship between the SOTE and airflow rate per diffuser for each diffuser density tested at a given water depth. This family of curves allows the design engineer to select a combination of diffuser density and airflow rate per diffuser.

To determine oxygen transfer efficiency and design parameters, several trial guesses and an iterative process are required. After selecting a plausible airflow rate per diffuser (AFD) for a common diffuser density (DENG), the SOTE can be estimated

Figure 2. Generalized Percent Transfer VS. Airflow at Given Diffuser Densities for Ceramic Dome Grid Configuration (Gilbert and Sullivan, 1983).



from Figure 2. The airflow rate (AF) in SCFM and required number of diffuser (NDIFF) can be calculated using an equation that follows:

$$AF = (0.04 \text{ scfm/lb } O_2\text{/day}) \cdot (SOTR)/(SOTE) \quad (2)$$

$$NDIFF = AF/AFD \quad (3)$$

$$DENC = (100) \cdot NDIFF/(\text{basin area}) \quad (4)$$

where,

AF = airflow rate in scfm (standard cu ft. per min),

AFD = airflow rate per diffuser in scfm/diffuser,

DENG = diffuser density guessed in diffuser/100 ft^2,

DENC = diffuser density calculated in diffuser/100 ft^2,

NDIFF = total number of diffuser in basin area,

SOTR = standard oxygen transfer in lb/day,

SOTE = standard oxygen transfer efficiency,

0.04 scfm/lb O_2/day = (100 lb air/23 lb O_2)(ft^3/0.075 lb air)(day/1440 min),

and Basin area in ft^2.

The iterative process continues until the difference between the guessed diffuser density and calculated diffuser density becomes negligible.

3. SOTE Data and Regression

The following section discusses oxygen transfer data for fine pore diffusers. To perform the optimization and work several example problem, it is necessary to collect SOTE data as a function of airflow rate, diffuser density and submergence as shown in Figures 1 and 2.

3.1 Standard Oxygen Transfer Efficiency

The SOTE data were collected from several sources. These sources are compiled from the evaluations of the SOTEs in wastewater plants in technical papers and the estimated SOTE values from manufacture's formulas or graphs. The data in *Appendix 7.2* represent typical efficiencies of fine pore diffusers. The typical fine pore diffusers grouped in *Appendix 7.2* are limited to ceramic discs, ceramic domes, membrane discs and membrane tubes.

The SOTE data obtained in *Appendix 7.2* do not represent all factors affecting oxygen transfer; they are provided in order to illustrate the optimization technique, and should not be extrapolated to a specific location. The diffuser performance data is a function of three factors affecting oxygen transfer: air flow rate per diffuser; diffuser density, and diffuser submergence. Other factors (for example, mean cell retention time, diffuser age, diffuser fouling, loading conditions, wastewater characteristics) are excluded. Therefore, it is required that design engineers and aeration equipment manufacturers prepare their own SOTE data for a given condition before they determine the regression parameters which will be discussed in Section 3.2.

3.2 Regression Parameters

Although many factors affect standard oxygen transfer efficiency in fine bubble diffuser aeration systems (U.S. EPA, 1989), the model used here to represent the SOTE is a function only of air flow rate per diffuser, diffuser density, and diffuser submergence. The model used in this thesis to represent SOTE and SOTR is as follows:

$$SOTE = A(1) + A(2) \cdot AF + A(3) \cdot AF^2 + A(4) \cdot SUBM + A(5) \cdot DENS \quad (5)$$

$$SOTR = \frac{AF \cdot SOTE \cdot (1.036)}{100} \quad (6)$$

where,

SOTE = standard oxygen transfer rate in %,

SOTR = standard oxygen rate in lb^{O_2}/hr,

AF = air flow rate per diffuser in SCFM/diffuser,

Table 2. Summary of Regression Parameters by SAS(1991)

	A(1)	A(2)	A(3)	A(4)	A(5)
Ceramic Disc	11.79/2.932	-2.97/-6.690	0.0/0.0	1.23/4.991	0.16/3.168
Ceramic Dome	13.82/13.716	-4.52/-19.423	0.0/0.0	1.12/21.136	0.18/13.424
Membrane Disc	8.48/1.249	-5.38/-2.791	1.06/2.049	1.72/4.154	-0.023/-0.550
Membrane Tube	7.57/16.807	-2.72/-16.497	0.15/7.460	1.50/108.021	0.16/9.652

code: the entries are written as parameter value/ t statistic. For example, parameters A(1) for a ceramic disc has a value of 11.79 with a t statistic of 2.932. The higher the t statistic represents the greater the significance of the parameter.

SUBM = diffuser submergence in ft,

DENS = diffuser density in diffuser/100 ft^2,

1.036 = weight of air · %O_2 · min/hr, and

A(1), A(2), A(3), A(4), A(5) are regression parameters.

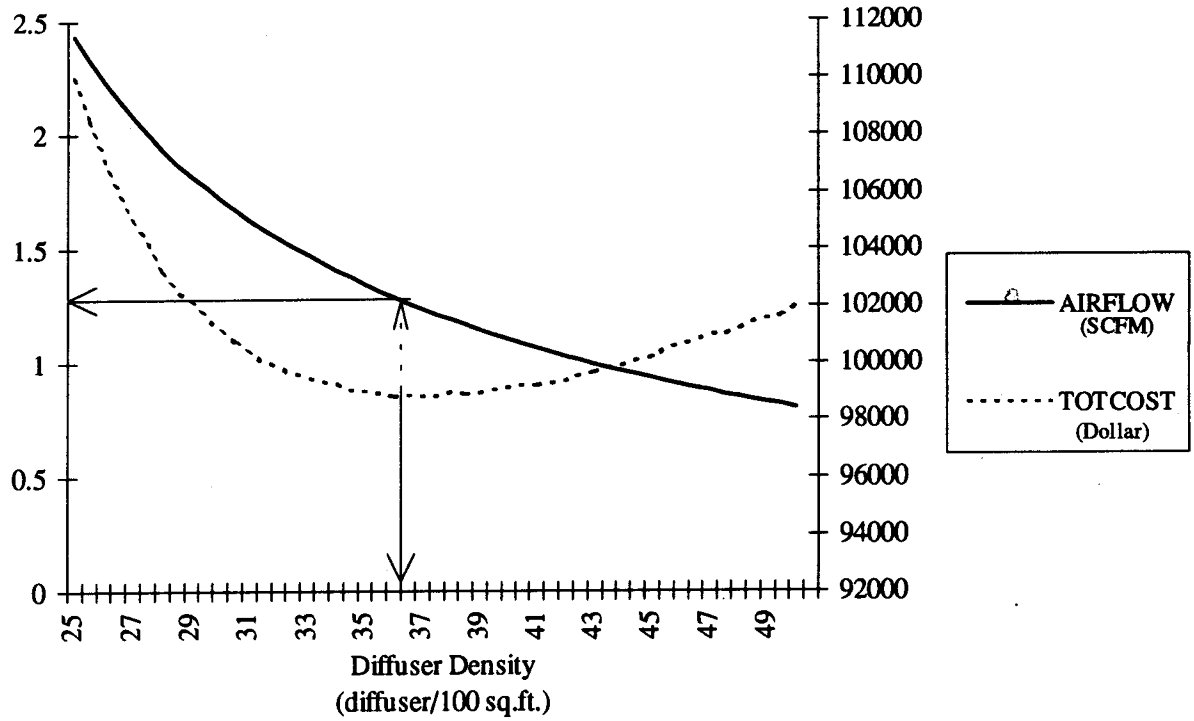
To determine the regression parameters from SOTE data in Table 2, a statistical software package, SAS (1991), was used for each type of diffuser. The results are provided in the *Appendix 7.3* and the summary of regression parameters for each types of diffusers are shown in Table 2.

4. Optimization

There exists a trade-off between operating cost and capital cost. Energy saving in the aeration process requires additional capital costs. The benefit can be only be judged by an economic evaluation, taking into account any differences in capital and operating costs. The operating cost is usually associated with the electrical power cost of operating blowers, while the capital cost is associated with the installation costs of the fine bubble diffuser system. When air flow rate per diffuser decreases, higher diffuser density is required because the SOTR must be satisfied for all conditions. Therefore, if operating cost decreases the capital cost must increase. Consideration of the two criteria, air flow rate and diffuser density, generally result in iterative design procedure. The optimization technique used here, however, makes it possible to select the optimal air flow rate per diffuser and diffuser density to provide the least total cost of the project, for given economic parameters, such as interest rate and electrical energy cost.

A graphical method can be used to show the optimal combination of diffuser density and airflow rate to provide the least project cost. Figure 3 shows the minimum project cost for a specific condition occurred at an airflow rate of 1.30 SCFM/diffuser and

Figure 3. A Relationship between Airflow Rate vs. Cost for Given Diffuser Densities



36.4 diffuser/100 ft². This combination of oxygen transfer variables will be compared with the results from an optimization procedure described later.

4.1 Optimization Technique

There are many optimization procedure which are suitable for the type of optimization required to obtain the minimum cost. The problem is nonlinear, since the SOTE functions cannot be simply expressed as a linear combination of airflow rate and diffuser density. The optimization technique must be constrained, since there exist minimum and maximum airflow rates and diffuser densities. The Complex Method, developed by Box (1965), was selected for this application, and was implemented in FORTRAN.

The complex procedure for one independent variable begins by generating three initial feasible points randomly in the domain. Conceptually the simplest way of generating feasible starting points is to randomly select points between the upper and lower constraints. This procedure can be expressed as:

$$X_i = X^{(L)} + R_i \cdot (X^{(U)} - X^{(L)}) \quad i = 1, \ldots, m \tag{7}$$

where,

X_i = denotes the ith feasible starting point,

$X^{(U)}$ = upper constraint of the variable,

$X^{(L)}$ = lower constraint of the variable,

R_i = denotes the ith random number distributed on the interval (0,1),

i = as subscript, denotes the ith starting point, and

m = number of feasible points.

After selecting the initial set of points, the objective function is evaluated at each point. The point with the largest value of the objective function, becomes the rejected point. A new point can be found by projecting from the rejected point through the centroid of the remaining points. Because the optimal points can be located outside the space contained within the remaining two points, the projection should extend beyond the centroid. A projection factor, called psi (Ψ), is selected as 1.3 times the distance from the rejected point to the centroid. Mathematically, this new trial point is represented as:

$$X^N = \overline{X} + \Psi \cdot (\overline{X} - X^R) \tag{8}$$

where,

X^N = new trial point,

$\overline{X}$ = centroid of the remaining points (does not include the rejected point),

X^R = rejected point, and

Ψ = reflection factor (1.3 is recommended by Box).

If the error for the new trial point is greater than that of the rejected point, another new point is selected using the value of Ψ divided by 2. This procedure is repeated until the error for the new point is less than that for the rejected point, then the new point replaces the rejected point. If the resulting new point is infeasible, which means that the resulting new point violates one or more constraints, the value of Ψ is halved again until a feasible point is obtained. The Complex Method is guaranteed to locate the optimal value for a convex objective function. This process is continued until the pattern of points has shrunk so that the points are sufficiently close together and/or when the differences between the function values at the points becomes small enough. It is recommended that the termination criteria include the use of maximum number of iterations as well as an error improvement criterion.

4.2 Economic analysis

The method used here to calculate operating costs is the present worth (PW) method (DeGarmo et al. 1989). The present worth method is suitable for selecting diffusers and evaluating the cost analysis (U.S. EPA 1989). The PW method is based on the concept of equivalent worth of all cash flows relative to the beginning point in time. That means all cash flows are converted to a single sum equivalent at time zero using an interest rate before tax equal to the minimum attractive rate of return (MARR).

Prior to calculating a total operating cost , power requirements must be calculated. The easiest way to do this is to use the adiabatic compression formula and a combined blower and motor efficiency (Yunt, 1979; U.S. EPA, 1989). The adiabatic compression formula is:

$$WP = [3.19\times10^{-4}\cdot AF\cdot T_a/E][(P_d/P_b)^{0.283}-1] \quad (9)$$

where,

WP = wire power consumption in kW,

AF = air flow rate in scfm,

T_a = blower inlet air temperature in °R,

E = combined blower and motor efficiency(0.7 is recommended),

P_d = blower discharge pressure in psia,

P_b = field atmospheric pressure in psia, and

3.19×10^{-4} is in units of kW-min/ft^3-°R.

The expression to calculate a total operating cost using present worth method is (U.S. EPA 1989):

$$OCST = WP\cdot UPC\cdot(24\text{ hr/day})\cdot(365\text{ day/yr}) \quad (10)$$

$$POCST = OCST\cdot USPWF \quad (11)$$

where,

OCST = annual operating power cost in dollar,

POCST = total operating cost using present worth method for n years,

USPWF = uniform series present worth factor

$= [(1+I)^n-1]/[I(1+I)^n]$,

UPC = unit electrical power cost in \$/kWh,

n = number of interest periods in years, and

I = interest rate per interest period.

5. Results

The entire optimization procedure was implemented in FORTRAN 77. To illustrate the technique, a ceramic dome diffusers system is selected. The hypothetical aeration tank is divided into three zones as shown in *Appendix 7.4*. The optimization is performed for each zone.

Prior to execution of the program, a specific input data file must be prepared. When executing the program for each zone, some values must vary depending upon design engineer's judgment. The first zone, for instance, will require a higher field oxygen demand (OTR_f) and will usually have lower αF values than the other zones.

The input data and output results for second zone as follows:

TYPE OF DIFFUSER: CERAMIC DOME
NUMBER OF ZONE DESIGNED: ZONE 2

****
THE INPUT DATA ARE AS FOLLOWS:
****

ALPHA*F	= .300	THETA	= 1.024
TEMPERATURE	= 25.00 (C)	OMEGA	= .970
TAU	= .910	BETA	= .980
MAX ITERATION	= 200	INTEREST RATE	= .100
BLWR EFFICIENCY	= .700	NO OF YEAR	= 3 (years)
C-STAR at 20	= 10.50 (mg/L)	C-process	= 1.00 (mg/L)
OTR-field	= 900.0 (lb/day)	AIR DENSITY	= .075 (lb/cu.ft)
BASIN LENGTH	= 43.30 (ft)	BASIN WIDTH	= 23.00 (ft)
SUBMERGENCE	= 14.00 (ft)	SYSTEM HEAD	= 20.00 (ft)
ATMO PRESSURE	= 14.30 (psia)	# OF DIFF/LAT	= 15 (#diff/lateral)
LOWER AIRFLOW	= .500 (scfm/diff)	UPPER AIRFLOW	= 2.500 (scfm/diff)
LOWER DIFF DENS	= 15.0 (diff/100sq.ft)	UPPER DIFF DENS	= 50.0 (diff/100sq.ft)

OPERATING COST = .1200 ($/KWh)		FIXED COST	= 1000.00 ($)
DIFFUSER COST = 80.0 ($/diffuser)		LATERAL COST	= 100.0 ($/lateral)

MINIMUM MIXING AIRFLOW RATE = .100 (scfm/sq.ft.)

REGRESSION PARAMETERS:INTERCEPT	=	13.8200
AIRFLOW	=	-4.5200
AIRFLOW**2	=	.0000
SUBMERGENCE	=	1.1200
DIFF DENSITY	=	.1800

SOTR required = 3461.298000(lb/day)

MAXIMUM SOTR available = 8410.974000(lb/day)
MINIMUM SOTR available = 555.495300(lb/day)

****
THE RESULTS ARE AS FOLLOWS:
****

TOTAL AIR FLOW RATE	=	461.145 (SCFM)
AIR FLOW RATE	=	1.281 (SCFM/DIFFUSER)
DIFFUSER DENSITY	=	36.148 (DIFFUSER/100 SQ FT)
NO OF DIFFUSER	=	360 (DIFFUSER)
NO OF LATERAL	=	24 (LATERAL)
OPTIMAL TOTAL COST	=	98809.340 ($)
OPTIMAL CAPITAL COST	=	32200.000 ($)
OPTIMAL OPERATING COST	=	66609.340 ($)

The graphical results from Figure 3 agree well with the results using the optimization technique. The curves in Figure 3 were generated under the same operating conditions of zone 2 design. Their agreement with results, shown in Table 3, verify the results from the optimization technique.

The comparisons of costs between two methods indicate that the optimization technique can prove cost-savings. To show how much savings can be obtained, four

Table 3 . Comparisons of Design Variables

	Diffuser Density	Airflow Rate
	(diffuser/100 sq.ft)	(SCFM/Diffuser)
Graphical Method	36.40	1.29
Complex Method	36.15	1.28

Table 4 Total Cost and Cost Savings for Four Cases.
(cost in thousands of dollars)

	Case 1	Case 2	Case 3	Case 4
Cost at maximum density	77.5	102.0	38.5	65.9
Cost at optimal density	77.5	99.8	37.7	55.8
Cost at minimum density	100.8	110.3	41.8	56.7
Maximum possible savings	23.3	10.5	4.1	10.1

extreme cases of unit cost of electrical power($/kWh) and the cost of diffuser are considered. The costs listed below are calculated only for zone 2. Four cases in Table 4 are at:

1. high unit cost of electrical power($0.12/kWh) and low diffuser cost($25/diff),
2. high unit cost of electrical power($0.12/kWh) and high diffuser cost($80/diff),
3. low unit cost of electrical power($0.04/kWh) and low diffuser cost($25/diff),
4. low unit cost of electrical power($0.04/kWh) and high diffuser cost($80/diff).

Table 4 shows the maximum saving of the optimal design. If the design engineer was to select the boundary values (e.g., lowest or highest airflow rate per diffuser, or lowest or greatest diffuser density) the savings shown in the table could be realized. It is likely that less than this saving will be realized, since it is unlikely that the design engineers would pick the worst case.

6. Conclusions

This thesis provides design engineers with a useful methology for designing fine pore diffuser aeration systems. The best combination (e.g. minimum cost) of oxygen transfer design variables, airflow rate and diffuser density, can be obtained using the procedure and optimization technique developed in this study.

There is a trade-off between airflow rate and diffuser density when designing fine pore diffuser aeration systems in wastewater treatment plants: when a lower airflow rate is required, a higher diffuser density must be provided to satisfy the SOTR at any given conditions. The SOTR, as a mass transfer variable, has a nonlinear relationship with these design variables (airflow rate and diffuser density). Due to the nonlinearity, engineers usually perform iterative calculations to determine better combinations of the design variables. They seldom select the optimum combination.

The methology presented here consists of several steps to avoid many trial and error calculations. The collection of SOTE data is the initial step to represent the SOTE and SOTR as functions of the design variables, as shown in equations (5) and (6). Most of the SOTE data are determined from clean water tests in wastewater plant construction, and from diffuser manufacturers' test curves. To obtain the coefficients in equation

(5), a statistical software package, such as SAS(1991), is used to execute multiple linear regression of SOTE data for each variable. Total cost is the sum of operating and capital cost. To determine the operating cost, power requirements must be calculated. The adiabatic compression formula is practiced to do this, and the present worth method is accepted to calculate the annual operating cost. When calculating the capital cost, a diffuser cost and a lateral cost are primarily considered. The optimization technique, called Complex Method, is next used in computer programming to select the best combination of the design variables. The Complex Method is known to be successful for searching the optimal value if an objective function is convex and can accommodate implicit and explicit constraints.

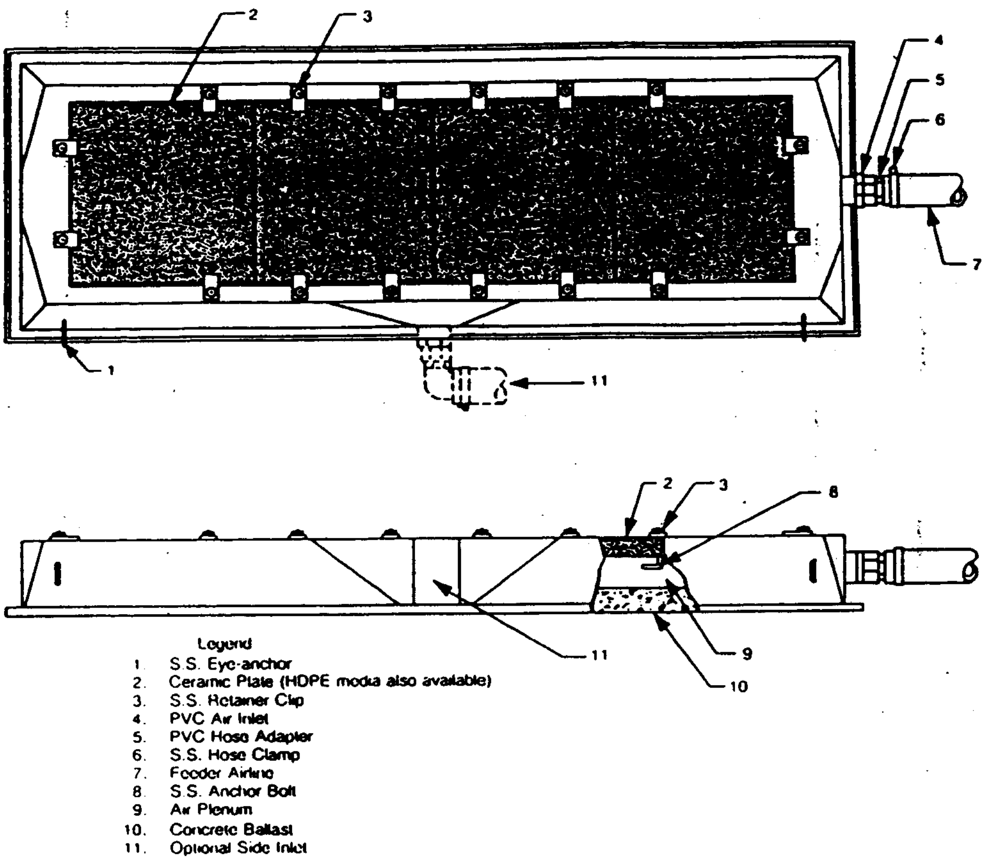
The methology not only obtains the design variables which satisfy the SOTR requirement, but it also guarantees the minimum cost of the installation of fine pore diffuser aeration systems. The comparisons in Table 3 indicate the reliability of this method. As shown in Table 4, it is possible to achieve savings ranging from 5 to 25% of cost of each aeration system or subsystem. If there are four tanks with three zones per a tank as shown in a hypothetical activated sludge system in *Appendix 7.4*, the savings become much higher.

Further work can be accomplished to enhance the procedure developed in this thesis. Additional data could be obtained for different diffuser types and over rich performance ranges. More precise cost data would also be useful. Finally, a more powerful optimization technique which would allow the use of integer variables would facilitate more accurate design and cost estimating procedure.

7. Appendix

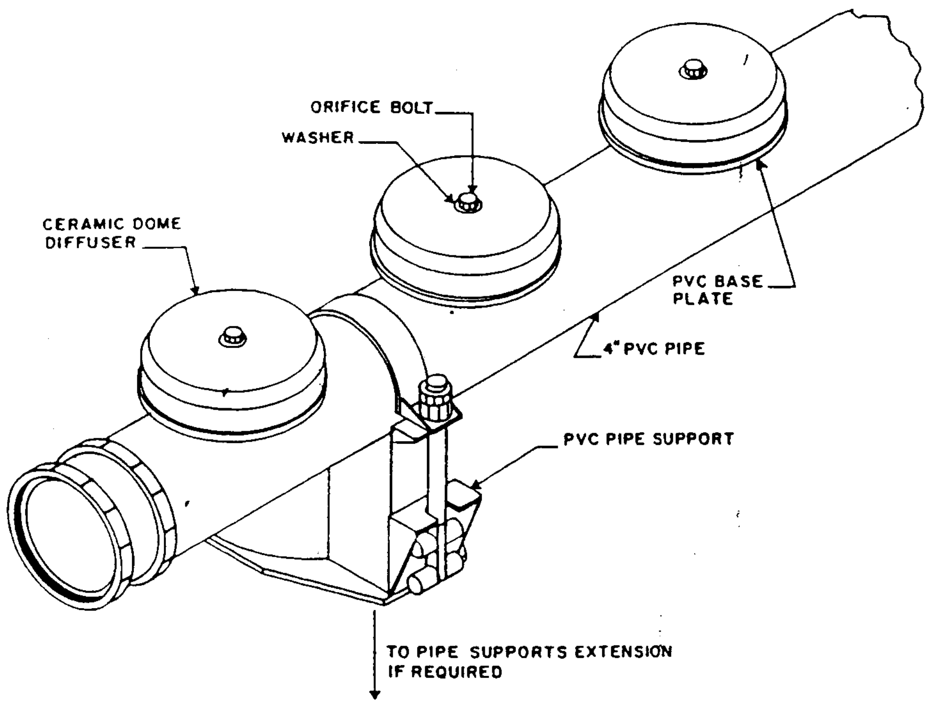
7.1 Shapes of Typical Diffusers

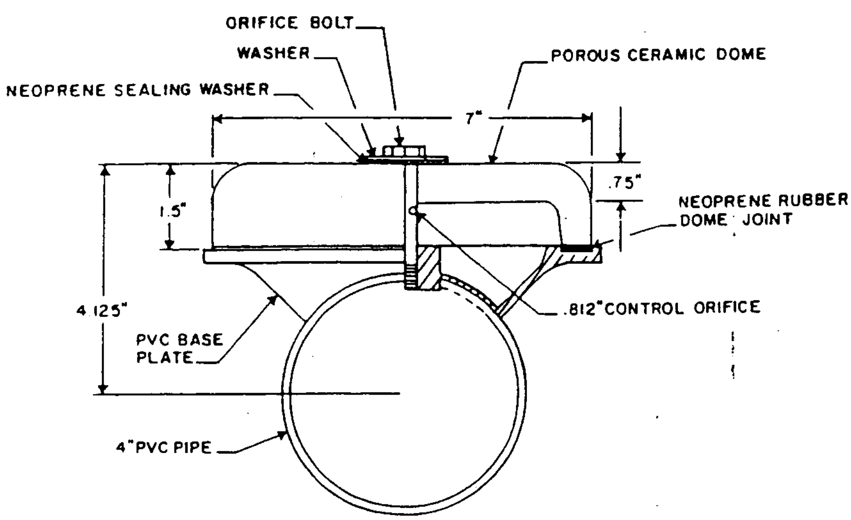
7.1.1 Plate Diffuser



Environmental Dynamics Ceramic Plate Diffusers
(Drawing Courtesy of Environmental Dynamics Inc.)

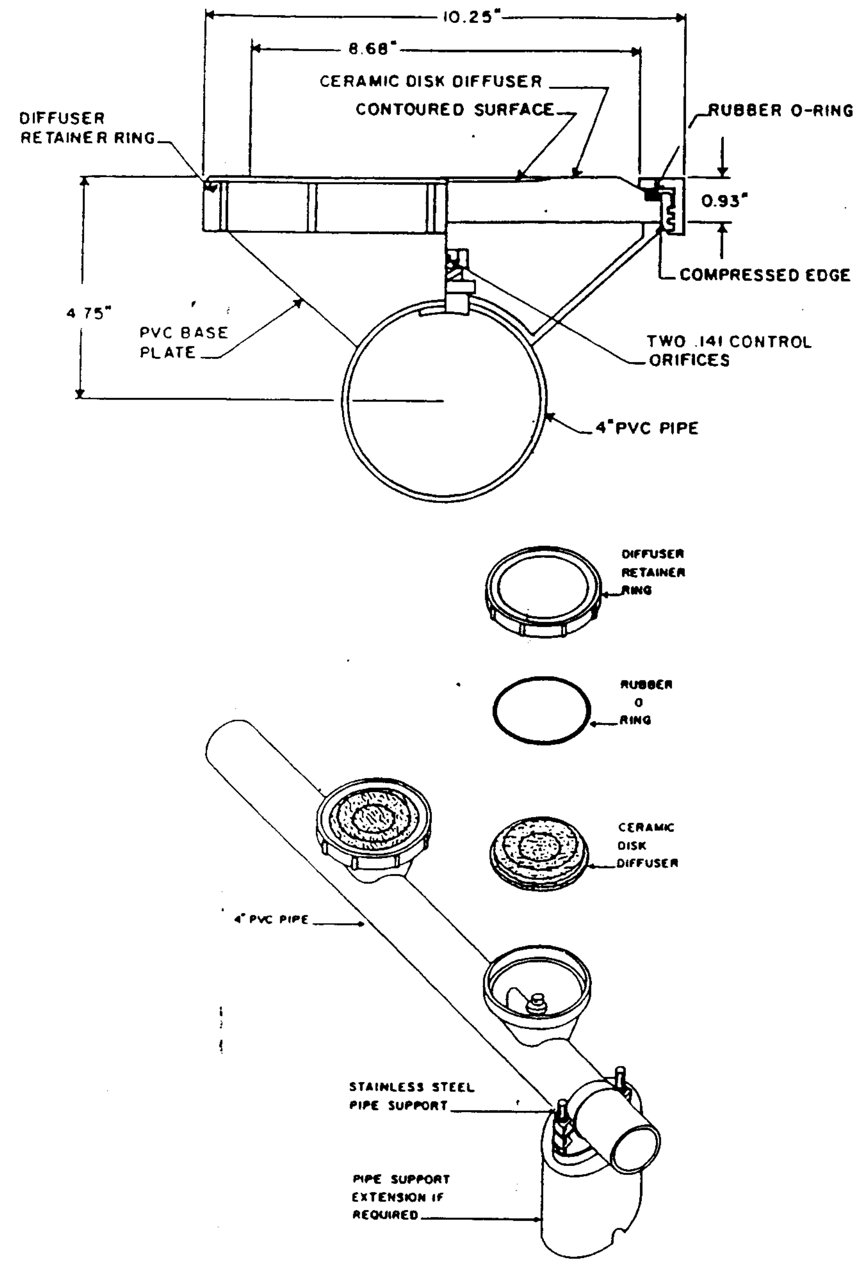
7.1.2 Dome Diffuser





Norton Dome Diffuser (Drawing courtesy of LACSD)

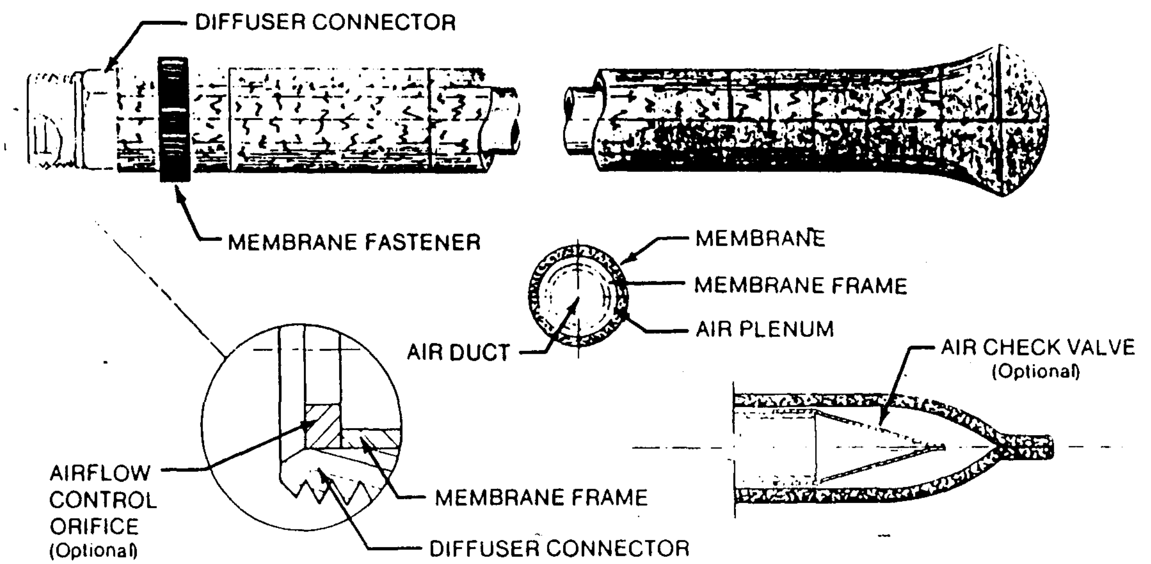
7.1.3 Disk Diffuser



Sanitaire Disk Diffuser (Drawing courtesy of LACSD)

AERSYSTEMS
ENGINEERED PRODUCTS BY
AERATION TECHNOLOGIES, INC.

AERMAX TPD DIFFUSER — S and P SERIES



MODEL NO.	NOM. LGTH.	NOM. DIA.	WT.	QTY.
-124	27 in.	1.25 in.	1.50 lbs.	
-130	33 in.	1.25 in.	1.75 lbs.	
-136	39 in.	1.25 in.	2.00 lbs.	
-	in.	1.25 in.	lbs.	

	STANDARD	OPTIONS
DIFFUSER CONNECTOR	☐ 304SS	☐ PVC
MEMBRANE FASTENER	☐ ACETAL	☐ OTHER*
MEMBRANE FRAME	☐ 304SS	☐ OTHER*
MEMBRANE	☐ HE	☐ UHE
CONTROL ORIFICE	☐ NO	☐ YES
CHECK VALVE	☐ NO	☐ YES

* material to be specified

AERMAX Diffuser (Drawing courtesy of AERTEC)

7.2 Diffuser Performance Data

Type of	Density Density	Submergence	Airflow Rate	SOTE	References
Diffuser	(diff/100ft2)	(ft)	(scfm/diff)	%	cited
cdisc	23.4	15	0.72	30.8	5
cdisc	23.4	15	0.96	28.4	5
cdisc	23.4	15	1.48	26	5
cdisc	23.4	15	1.92	24.2	5
cdisc	19.2	15.8	0.85	32.2	1
cdisc	19.2	15.8	0.86	32.6	1
cdisc	27	18.7	1.65	35.8	1
cdisc	23.3	14.4	2.88	25.3	1
cdisc	23.3	14.4	2.11	27.1	1
cdisc	25	14.8	0.76	30.9	1
cdisc	25	14.8	0.79	30.4	1
cdisc	25	14.8	0.72	31	1
cdisc	25	14.8	0.91	30.2	1
cdisc	25	17	0.91	36.3	1
cdisc	31.2	14	0.65	31.8	3
cdisc	31.2	14	1.29	29.3	3
cdisc	31.2	14	2.58	26	3
cdisc	31.2	14	2.99	25.3	3
cdisc	37.4	13.75	1.4	30	6
cdisc	37.4	13.75	1.36	30.1	6
cdisc	37.4	13.75	1.56	29.7	6
cdisc	37.4	13.75	1.42	30	6
cdisc	30	13.75	1.53	30.4	6
cdisc	30	13.75	1.49	30.4	6
cdisc	30	13.75	1.5	30.4	6
cdisc	30	13.75	1.43	30.4	6
cdisc	24	13.75	1.42	30	6
cdisc	24	13.75	1.35	30.1	6
cdisc	24	13.75	1.32	30.2	6
cdisc	24	13.75	1.3	30.2	6

cdisc	20	13.75	1.22	27.7	6
cdisc	20	13.75	1.21	27.7	6
cdisc	20	13.75	0.53	30.8	6
cdisc	20	13.75	0.47	31.2	6
cdisc	20	13.75	0.38	31.8	6
cdome	18.5	14	0.5	30	2
cdome	18.5	14	0.63	29.4	2
cdome	18.5	14	0.75	28.7	2
cdome	18.5	14	0.88	28.1	2
cdome	18.5	14	1	27.6	2
cdome	18.5	14	1.13	27.3	2
cdome	18.5	14	1.25	26.8	2
cdome	18.5	14	1.38	26.4	2
cdome	18.5	14	1.5	26	2
cdome	18.5	14	1.63	25.5	2
cdome	18.5	14	1.75	25.3	2
cdome	18.5	14	1.88	25.2	2
cdome	18.5	14	2	25.1	2
cdome	18.5	14	2.13	25	2
cdome	18.5	14	2.25	24.9	2
cdome	18.5	14	2.38	24.8	2
cdome	18.5	14	2.5	24.7	2
cdome	22.7	14	0.5	31.2	2
cdome	22.7	14	0.63	30.3	2
cdome	22.7	14	0.75	29.7	2
cdome	22.7	14	0.88	28.6	2
cdome	22.7	14	1	28.2	2
cdome	22.7	14	1.13	27.8	2
cdome	22.7	14	1.25	27.3	2
cdome	22.7	14	1.38	27.1	2
cdome	22.7	14	1.5	26.8	2
cdome	22.7	14	1.63	26.5	2
cdome	22.7	14	1.75	26.2	2
cdome	22.7	14	1.88	26	2
cdome	22.7	14	2	25.8	2

cdome	22.7	14	2.13	25.7	2
cdome	22.7	14	2.25	25.6	2
cdome	22.7	14	2.38	25.5	2
cdome	22.7	14	2.5	25.4	2
cdome	31.25	14	0.5	33.3	2
cdome	31.25	14	0.63	31.9	2
cdome	31.25	14	0.75	31	2
cdome	31.25	14	0.88	30.1	2
cdome	31.25	14	1	29.5	2
cdome	31.25	14	1.13	29	2
cdome	31.25	14	1.25	28.6	2
cdome	31.25	14	1.38	28.1	2
cdome	31.25	14	1.5	27.8	2
cdome	31.25	14	1.63	27.5	2
cdome	31.25	14	1.75	27.4	2
cdome	31.25	14	1.88	27.3	2
cdome	31.25	14	2	27.2	2
cdome	31.25	14	2.13	27	2
cdome	31.25	14	2.25	26.9	2
cdome	31.25	14	2.38	26.8	2
cdome	31.25	14	2.5	26.7	2
cdome	45.5	14	0.5	36.4	2
cdome	45.5	14	0.63	34.3	2
cdome	45.5	14	0.75	32.9	2
cdome	45.5	14	0.88	31.9	2
cdome	45.5	14	1	31.2	2
cdome	45.5	14	1.13	30.5	2
cdome	45.5	14	1.25	30	2
cdome	45.5	14	1.38	29.7	2
cdome	45.5	14	1.5	29.3	2
cdome	45.5	14	1.63	28.9	2
cdome	45.5	14	1.75	28.8	2
cdome	45.5	14	1.88	28.6	2
cdome	45.5	14	2	28.5	2
cdome	45.5	14	2.13	28.4	2

cdome	45.5	14	2.25	28.3	2
cdome	45.5	14	2.38	28.2	2
cdome	45.5	14	2.5	28.1	2
cdome	18.5	19	0.5	35	2
cdome	18.5	19	0.6	34.1	2
cdome	18.5	19	0.7	33.1	2
cdome	18.5	19	0.8	32.3	2
cdome	18.5	19	0.9	31.7	2
cdome	18.5	19	1	31.3	2
cdome	18.5	19	1.1	30.9	2
cdome	18.5	19	1.2	30.6	2
cdome	18.5	19	1.3	30.2	2
cdome	18.5	19	1.4	30	2
cdome	18.5	19	1.5	29.8	2
cdome	18.5	19	1.6	29.6	2
cdome	18.5	19	1.7	29.4	2
cdome	18.5	19	1.8	29.3	2
cdome	18.5	19	1.9	29.1	2
cdome	18.5	19	2	29	2
cdome	18.5	19	2.1	28.8	2
cdome	18.5	19	2.2	28.6	2
cdome	18.5	19	2.3	28.5	2
cdome	22.7	19	0.4	43	2
cdome	22.7	19	0.5	41.1	2
cdome	22.7	19	0.6	39.4	2
cdome	22.7	19	0.7	37.8	2
cdome	22.7	19	0.8	36.6	2
cdome	22.7	19	0.9	35.3	2
cdome	22.7	19	1	34.7	2
cdome	22.7	19	1.1	34	2
cdome	22.7	19	1.2	33.3	2
cdome	22.7	19	1.3	32.8	2
cdome	22.7	19	1.4	32.2	2
cdome	22.7	19	1.5	31.8	2
cdome	22.7	19	1.6	31.4	2

cdome	22.7	19	1.7	31	2
cdome	22.7	19	1.8	30.7	2
cdome	22.7	19	1.9	30.2	2
cdome	22.7	19	2	29.9	2
cdome	22.7	19	2.1	29.6	2
cdome	22.7	19	2.2	29.3	2
cdome	22.7	19	2.3	29	2
cdome	31.25	19	0.4	45.7	2
cdome	31.25	19	0.5	43.5	2
cdome	31.25	19	0.6	41.6	2
cdome	31.25	19	0.7	39.9	2
cdome	31.25	19	0.8	38.6	2
cdome	31.25	19	0.9	37.2	2
cdome	31.25	19	1	36.3	2
cdome	31.25	19	1.1	35.6	2
cdome	31.25	19	1.2	35.1	2
cdome	31.25	19	1.3	34.6	2
cdome	31.25	19	1.4	33.9	2
cdome	31.25	19	1.5	33.4	2
cdome	31.25	19	1.6	33	2
cdome	31.25	19	1.7	32.5	2
cdome	31.25	19	1.8	32	2
cdome	31.25	19	1.9	31.5	2
cdome	31.25	19	2	31	2
cdome	31.25	19	2.1	30.5	2
cdome	31.25	19	2.2	29.9	2
cdome	31.25	19	2.3	29.5	2
cdome	45.5	19	0.6	46.6	2
cdome	45.5	19	0.7	44	2
cdome	45.5	19	0.8	42.2	2
cdome	45.5	19	0.9	41.5	2
cdome	45.5	19	1	39.3	2
cdome	45.5	19	1.1	38.2	2
cdome	45.5	19	1.2	37.3	2
cdome	45.5	19	1.3	36.5	2

cdome	45.5	19	1.4	35.7	2
cdome	45.5	19	1.5	35	2
cdome	45.5	19	1.6	34.4	2
cdome	45.5	19	1.7	33.8	2
cdome	45.5	19	1.8	33.2	2
cdome	45.5	19	1.9	32.5	2
cdome	45.5	19	2	31.9	2
cdome	45.5	19	2.1	31.3	2
cdome	45.5	19	2.2	30.7	2
cdome	45.5	19	2.3	30.4	2
cdome	24	13.75	1.26	26.5	6
cdome	24	13.75	1.31	26.5	6
cdome	24	13.75	1.43	26.2	6
cdome	24	13.75	1.51	26	6
cdome	24	13.75	1.67	25.7	6
cdome	24	13.75	1.69	25.7	6
cdome	24	13.75	1.09	27	6
cdome	24	13.75	1.27	26.5	6
cdome	24	13.75	1.43	26.2	6
cdome	24	13.75	1.25	26.5	6
cdome	24	13.75	1.2	26.7	6
cdome	24	13.75	1.14	26.9	6
cdome	24	13.75	1.6	25.8	6
cdome	24	13.75	1.16	26.8	6
cdome	24	13.75	1.35	26.4	6
cdome	48	13.75	0.89	35.6	6
cdome	48	13.75	0.91	35.6	6
cdome	48	13.75	0.99	34.8	6
cdome	22.7	11.5	1.6	23.1	1
cdome	21.7	14	1.67	25	1
cdome	21.7	14	1.34	24.4	1
cdome	21.7	14	1.56	23.2	1
cdome	21.7	14	1.15	26.8	1
cdome	21.7	14	2.49	22.7	1
cdome	21.7	14	1.47	25.2	1

cdome	11.5	14	1.23	26.7	1
cdome	11.5	14	1.17	26.4	1
cdome	11.5	14	1.14	26.9	1
cdome	24.4	15	1.94	29.5	1
cdome	25.6	15	1.62	27.6	1
cdome	25.6	15	2.39	24.6	1
cdome	25.6	15	2.34	25.4	1
cdome	25.6	15	2.15	25.8	1
cdome	25.6	15	1.82	26.4	1
cdome	25.6	15	2.59	24.5	1
cdome	25.6	15	1.21	29.2	1
cdome	41	15	0.54	35.4	4
cdome	41	15	1.05	28.8	4
cdome	41	15	1.7	25	4
mdisc	19.2	15.8	0.86	32.2	1
mdisc	13.2	13.7	2.53	26.5	1
mdisc	30.2	15.2	1.42	28.3	7
mdisc	28.1	15.2	1.37	28.3	7
mdisc	32.7	15.2	1.48	28.3	7
mdisc	35.3	15.2	1.69	27.7	7
mdisc	15.8	15.2	1.13	28.6	7
mdisc	17.5	15.2	1.08	29	7
mdisc	20	15.2	1.16	29	7
mdisc	26	15.2	1.32	28.5	7
mdisc	20.9	15.2	1.18	29	7
mdisc	20.5	15.2	1.17	29	7
mdisc	28.7	16.33	0.5	34.1	9
mdisc	28.7	16.33	1	32.5	9
mdisc	28.7	16.33	1.5	31.1	9
mdisc	28.7	16.33	2	30	9
mdisc	28.7	16.33	3	28.3	9
mtube	11.1	17.5	2	30	1
mtube	11.1	17.5	3.05	29.1	1

mtube	11.1	17.5	2.87	28.7	1
mtube	11.1	17.5	3.11	28.7	1
mtube	7.1	13.5	3.28	11.9	1
mtube	17.5	13	3.22	23.2	1
mtube	21.3	12.8	1.36	24.5	1
mtube	21.3	12.8	1.76	22.3	1
mtube	22.7	19	1.24	32.8	1
mtube	22.6	19	1	33	8
mtube	22.6	19	1.5	32.6	8
mtube	22.6	19	2	32.2	8
mtube	22.6	19	2.5	31.6	8
mtube	22.6	19	3	31.1	8
mtube	22.6	19	3.5	30.7	8
mtube	22.6	19	4	30.1	8
mtube	22.6	19	4.5	29.7	8
mtube	22.6	19	5	29.1	8
mtube	22.6	19	5.5	28.7	8
mtube	22.6	19	6	28.2	8
mtube	22.6	19	6.5	27.8	8
mtube	22.6	19	7	27.2	8
mtube	22.6	19	7.5	26.9	8
mtube	22.6	19	8	26.3	8
mtube	22.6	19	8.5	25.9	8
mtube	22.6	19	9	25.3	8
mtube	22.6	14	1	25.7	8
mtube	22.6	14	1.5	25.2	8
mtube	22.6	14	2	24.8	8
mtube	22.6	14	2.5	24.2	8
mtube	22.6	14	3	23.7	8
mtube	22.6	14	3.5	23.2	8
mtube	22.6	14	4	22.7	8
mtube	22.6	14	4.5	22.2	8
mtube	22.6	14	5	21.7	8
mtube	22.6	14	5.5	21.2	8
mtube	22.6	14	6	20.6	8

mtube	22.6	14	6.5	20.1	8
mtube	22.6	14	7	19.5	8
mtube	22.6	14	7.5	19	8
mtube	22.6	14	8	18.4	8
mtube	22.6	14	8.5	17.9	8
mtube	22.6	14	9	17.3	8
mtube	22.6	9	1	17.4	8
mtube	22.6	9	1.5	17	8
mtube	22.6	9	2	16.7	8
mtube	22.6	9	2.5	16.3	8
mtube	22.6	9	3	15.9	8
mtube	22.6	9	3.5	15.4	8
mtube	22.6	9	4	15.1	8
mtube	22.6	9	4.5	14.7	8
mtube	22.6	9	5	14.3	8
mtube	22.6	9	5.5	13.9	8
mtube	22.6	9	6	13.5	8
mtube	22.6	9	6.5	13.1	8
mtube	22.6	9	7	12.8	8
mtube	22.6	9	7.5	12.3	8
mtube	22.6	9	8	12	8
mtube	22.6	9	8.5	11.6	8
mtube	22.6	9	9	11.1	8
mtube	18.9	25	0.5	50.7	10
mtube	18.9	25	0.75	49.1	10
mtube	18.9	25	1	47.6	10
mtube	18.9	25	1.25	46.4	10
mtube	18.9	25	1.5	45.2	10
mtube	18.9	25	1.75	44.2	10
mtube	18.9	25	2	43.2	10
mtube	18.9	25	2.25	42.4	10
mtube	18.9	25	2.5	41.8	10
mtube	18.9	25	2.75	41	10
mtube	18.9	25	3	40.6	10
mtube	18.9	25	3.25	40.2	10

mtube	18.9	25	3.5	39.8	10
mtube	18.9	25	3.75	39.4	10
mtube	18.9	25	4	39.1	10
mtube	18.9	25	4.25	38.8	10
mtube	18.9	25	4.5	38.6	10
mtube	18.9	25	4.75	38.3	10
mtube	18.9	25	5	38	10
mtube	18.9	25	5.25	37.9	10
mtube	18.9	25	5.5	37.8	10
mtube	18.9	25	5.75	37.7	10
mtube	18.9	25	6	37.6	10
mtube	8.4	25	0.5	47.9	10
mtube	8.4	25	0.75	46.2	10
mtube	8.4	25	1	44.8	10
mtube	8.4	25	1.25	43.3	10
mtube	8.4	25	1.5	42.1	10
mtube	8.4	25	1.75	41.1	10
mtube	8.4	25	2	40	10
mtube	8.4	25	2.25	39.4	10
mtube	8.4	25	2.5	38.7	10
mtube	8.4	25	2.75	38	10
mtube	8.4	25	3	37.5	10
mtube	8.4	25	3.25	37	10
mtube	8.4	25	3.5	36.6	10
mtube	8.4	25	3.75	36.2	10
mtube	8.4	25	4	35.9	10
mtube	8.4	25	4.25	35.6	10
mtube	8.4	25	4.5	35.2	10
mtube	8.4	25	4.75	35	10
mtube	8.4	25	5	34.8	10
mtube	8.4	25	5.25	34.7	10
mtube	8.4	25	5.5	34.5	10
mtube	8.4	25	5.75	34.3	10
mtube	8.4	25	6	35.2	10
mtube	18.9	20	0.5	43.9	10

mtube	18.9	20	0.75	42.2	10
mtube	18.9	20	1	40.7	10
mtube	18.9	20	1.25	39.4	10
mtube	18.9	20	1.5	38.2	10
mtube	18.9	20	1.75	37.1	10
mtube	18.9	20	2	36.2	10
mtube	18.9	20	2.25	35.4	10
mtube	18.9	20	2.5	34.9	10
mtube	18.9	20	2.75	34.3	10
mtube	18.9	20	3	34	10
mtube	18.9	20	3.25	33.7	10
mtube	18.9	20	3.5	33.3	10
mtube	18.9	20	3.75	33	10
mtube	18.9	20	4	32.7	10
mtube	18.9	20	4.25	32.4	10
mtube	18.9	20	4.5	32.1	10
mtube	18.9	20	4.75	31.9	10
mtube	18.9	20	5	31.7	10
mtube	18.9	20	5.25	31.6	10
mtube	18.9	20	5.5	31.5	10
mtube	18.9	20	5.75	31.4	10
mtube	18.9	20	6	31.2	10
mtube	8.4	20	0.5	41	10
mtube	8.4	20	0.75	39.6	10
mtube	8.4	20	1	38	10
mtube	8.4	20	1.25	36.8	10
mtube	8.4	20	1.5	35.5	10
mtube	8.4	20	1.75	34.7	10
mtube	8.4	20	2	33.8	10
mtube	8.4	20	2.25	33	10
mtube	8.4	20	2.5	32.3	10
mtube	8.4	20	2.75	31.8	10
mtube	8.4	20	3	31.2	10
mtube	8.4	20	3.25	30.9	10
mtube	8.4	20	3.5	30.4	10

mtube	8.4	20	3.75	30.1	10
mtube	8.4	20	4	29.8	10
mtube	8.4	20	4.25	29.4	10
mtube	8.4	20	4.5	29	10
mtube	8.4	20	4.75	28.8	10
mtube	8.4	20	5	28.6	10
mtube	8.4	20	5.25	28.5	10
mtube	8.4	20	5.5	28.3	10
mtube	8.4	20	5.75	28.2	10
mtube	8.4	20	6	28.1	10
mtube	18.9	15	0.5	35	10
mtube	18.9	15	0.75	33.6	10
mtube	18.9	15	1	32.5	10
mtube	18.9	15	1.25	31.4	10
mtube	18.9	15	1.5	30.7	10
mtube	18.9	15	1.75	29.8	10
mtube	18.9	15	2	29	10
mtube	18.9	15	2.25	28.4	10
mtube	18.9	15	2.5	27.9	10
mtube	18.9	15	2.75	27.5	10
mtube	18.9	15	3	27.1	10
mtube	18.9	15	3.25	26.8	10
mtube	18.9	15	3.5	26.4	10
mtube	18.9	15	3.75	26	10
mtube	18.9	15	4	25.8	10
mtube	18.9	15	4.25	25.4	10
mtube	18.9	15	4.5	25.2	10
mtube	18.9	15	4.75	25	10
mtube	18.9	15	5	24.9	10
mtube	18.9	15	5.25	24.8	10
mtube	18.9	15	5.5	24.7	10
mtube	18.9	15	5.75	24.6	10
mtube	18.9	15	6	24.6	10
mtube	8.4	15	0.5	32.4	10
mtube	8.4	15	0.75	31	10

mtube	8.4	15	1	29.9	10
mtube	8.4	15	1.25	28.8	10
mtube	8.4	15	1.5	28	10
mtube	8.4	15	1.75	27	10
mtube	8.4	15	2	26.3	10
mtube	8.4	15	2.25	25.8	10
mtube	8.4	15	2.5	25.2	10
mtube	8.4	15	2.75	24.8	10
mtube	8.4	15	3	24.3	10
mtube	8.4	15	3.25	23.9	10
mtube	8.4	15	3.5	23.4	10
mtube	8.4	15	3.75	23	10
mtube	8.4	15	4	22.8	10
mtube	8.4	15	4.25	22.4	10
mtube	8.4	15	4.5	22.2	10
mtube	8.4	15	4.75	22	10
mtube	8.4	15	5	21.8	10
mtube	8.4	15	5.25	21.7	10
mtube	8.4	15	5.5	21.5	10
mtube	8.4	15	5.75	21.3	10
mtube	8.4	15	6	21.2	10
mtube	18.9	10	0.5	25	10
mtube	18.9	10	0.75	24.2	10
mtube	18.9	10	1	23.4	10
mtube	18.9	10	1.25	22.8	10
mtube	18.9	10	1.5	22.1	10
mtube	18.9	10	1.75	21.5	10
mtube	18.9	10	2	21	10
mtube	18.9	10	2.25	20.5	10
mtube	18.9	10	2.5	20.2	10
mtube	18.9	10	2.75	19.8	10
mtube	18.9	10	3	19.5	10
mtube	18.9	10	3.25	19.2	10
mtube	18.9	10	3.5	18.8	10
mtube	18.9	10	3.75	18.6	10

mtube	18.9	10	4	18.4	10
mtube	18.9	10	4.25	18.1	10
mtube	18.9	10	4.5	18	10
mtube	18.9	10	4.75	17.8	10
mtube	18.9	10	5	17.7	10
mtube	18.9	10	5.25	17.6	10
mtube	18.9	10	5.5	17.5	10
mtube	18.9	10	5.75	17.4	10
mtube	18.9	10	6	17.3	10
mtube	8.4	10	0.5	22.8	10
mtube	8.4	10	0.75	21.9	10
mtube	8.4	10	1	21.2	10
mtube	8.4	10	1.25	20.3	10
mtube	8.4	10	1.5	19.8	10
mtube	8.4	10	1.75	19.2	10
mtube	8.4	10	2	18.7	10
mtube	8.4	10	2.25	18.1	10
mtube	8.4	10	2.5	17.7	10
mtube	8.4	10	2.75	17.2	10
mtube	8.4	10	3	16.9	10
mtube	8.4	10	3.25	16.6	10
mtube	8.4	10	3.5	16.2	10
mtube	8.4	10	3.75	16	10
mtube	8.4	10	4	15.8	10
mtube	8.4	10	4.25	15.5	10
mtube	8.4	10	4.5	15.3	10
mtube	8.4	10	4.75	15.1	10
mtube	8.4	10	5	15	10
mtube	8.4	10	5.25	14.9	10
mtube	8.4	10	5.5	14.8	10
mtube	8.4	10	5.75	14.7	10
mtube	8.4	10	6	14.6	10
mtube	18.9	5	0.5	15.9	10
mtube	18.9	5	0.75	15	10
mtube	18.9	5	1	14.4	10

mtube	18.9	5	1.25	13.7	10
mtube	18.9	5	1.5	13.1	10
mtube	18.9	5	1.75	12.6	10
mtube	18.9	5	2	12.1	10
mtube	18.9	5	2.25	11.8	10
mtube	18.9	5	2.5	11.4	10
mtube	18.9	5	2.75	11	10
mtube	18.9	5	3	10.8	10
mtube	18.9	5	3.25	10.5	10
mtube	18.9	5	3.5	10.2	10
mtube	18.9	5	3.75	10.1	10
mtube	18.9	5	4	10	10
mtube	18.9	5	4.25	9.8	10
mtube	18.9	5	4.5	9.7	10
mtube	18.9	5	4.75	9.6	10
mtube	18.9	5	5	9.5	10
mtube	18.9	5	5.25	9.5	10
mtube	18.9	5	5.5	9.4	10
mtube	18.9	5	5.75	9.4	10
mtube	18.9	5	6	9.4	10
mtube	8.4	5	0.5	13.9	10
mtube	8.4	5	0.75	13	10
mtube	8.4	5	1	12.4	10
mtube	8.4	5	1.25	11.7	10
mtube	8.4	5	1.5	11.1	10
mtube	8.4	5	1.75	10.5	10
mtube	8.4	5	2	10.1	10
mtube	8.4	5	2.25	9.7	10
mtube	8.4	5	2.5	9.3	10
mtube	8.4	5	2.75	8.9	10
mtube	8.4	5	3	8.7	10
mtube	8.4	5	3.25	8.3	10
mtube	8.4	5	3.5	8.1	10
mtube	8.4	5	3.75	7.9	10
mtube	8.4	5	4	7.8	10

mtube	8.4	5	4.25	7.6	10
mtube	8.4	5	4.5	7.4	10
mtube	8.4	5	4.75	7.3	10
mtube	8.4	5	5	7.2	10
mtube	8.4	5	5.25	7.2	10
mtube	8.4	5	5.5	7.1	10
mtube	8.4	5	5.75	7	10
mtube	8.4	5	6	6.9	10

Key to Reference Numbers - See 8. References

1. Groves et al.(1992)
2. Gilbert and Sullivan (1983)
3. Stenstrom (1991)
4. Stenstrom (1990b)
5. Stenstrom (1992)
6. Ewing Engineering Co. (1986)
7. Egan-Benck et al. (1992)
8. Stenstrom (1993)
9. Sanitaire (1993)
10. Environmental Dynamics Inc. (1993)

7.3 Results of Regression Parameters

7.3.1 Ceramic Disk Diffuser

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------------------------------- GROUP=cdisc --------------------------------

Model: MODEL1
Dependent Variable: SOTE

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	159.46458	53.15486	23.284	0.0001
Error	32	73.05098	2.28284		
C Total	35	232.51556			

Root MSE	1.51091	R-square	0.6858
Dep Mean	29.78889	Adj R-sq	0.6564
C.V.	5.07205		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	11.793009	4.02230618	2.932	0.0062
AIRFLOW	1	-2.973277	0.44445681	-6.690	0.0001
DEPTH	1	1.229950	0.24644657	4.991	0.0001
DENSITY	1	0.159408	0.05031774	3.168	0.0034

7.3.2 Ceramic Dome Diffuser

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----------------------------- GROUP=cdome -----------------------------

Model: MODEL1
Dependent Variable: SOTE

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	3	3490.91874	1163.63958	372.877	0.0001
Error	180	561.72735	3.12071		
C Total	183	4052.64609			

Root MSE	1.76655	R-square	0.8614
Dep Mean	30.34130	Adj R-sq	0.8591
C.V.	5.82227		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	13.818740	1.00752342	13.716	0.0001
AIRFLOW	1	-4.523419	0.23289147	-19.423	0.0001
DEPTH	1	1.120051	0.05299270	21.136	0.0001
DENSITY	1	0.175101	0.01304413	13.424	0.0001

7.3.3 Membrane Disk Diffuser

------------------------------- GROUP=mdisc -------------------------------

Model: MODEL1
Dependent Variable: SOTE

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	4	52.74616	13.18654	19.174	0.0001
Error	12	8.25267	0.68772		
C Total	16	60.99882			

Root MSE	0.82929	R-square	0.8647
Dep Mean	29.43529	Adj R-sq	0.8196
C.V.	2.81733		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	8.478401	6.78661949	1.249	0.2354
AIRFLOW	1	-5.384852	1.92955643	-2.791	0.0163
AIRFLOW2	1	1.057844	0.51623484	2.049	0.0630
DEPTH	1	1.726093	0.41557018	4.154	0.0013
DENSITY	1	-0.023303	0.04234732	-0.550	0.5922

7.3.4 Membrane Tube Diffuser

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------------------------------- GROUP=mtube -------------------------------

Model: MODEL1
Dependent Variable: SOTE

Analysis of Variance

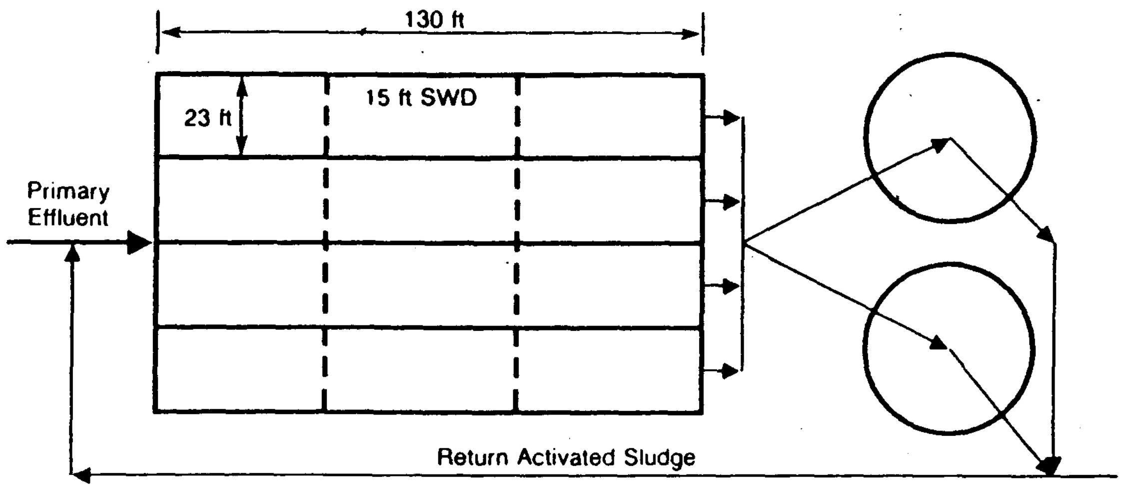
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	4	30717.06783	7679.26696	3215.653	0.0001
Error	285	680.60541	2.38809		
C Total	289	31397.67324			

Root MSE	1.54534	R-square	0.9783
Dep Mean	24.99517	Adj R-sq	0.9780
C.V.	6.18257		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	7.574466	0.45067594	16.807	0.0001
AIRFLOW	1	-2.723224	0.16507276	-16.497	0.0001
AIRFLOW2	1	0.150413	0.02016324	7.460	0.0001
DEPTH	1	1.497303	0.01386116	108.021	0.0001
DENSITY	1	0.155525	0.01611349	9.652	0.0001

7.4 Hypothetical Activated Sludge System for an Example



7.5 Source Program

```
c***********************************************************************
c -DESCRIPTION-
c    THIS PROGRAM DETERMINES THE OPTIMAL AERATION SYSTEM
c    DESIGN FOR ACTIVATED SLUDGE TREATMENT PLANTS USING
c    COMPLEX OPTIMIZATION METHOD.
c
c -EXECUTION-
c
c    TO EXECUTE THE PROGRAM, INPUT DATA SET MUST BE SUPPLIED.
c    THE PROGRAM IS SET UP TO READ THE DATA FROM UNIT 7. IF
c    ANOTHER UNIT NUMBER IS USED, IT MUST REPLACE '7' IN 'OPEN'
c    STATEMENT AND WHERE THE DATA IS READ IN.
c
c    THE PROGRAM ALSO WRITES TO AN OUTPUT FILE. UNIT 9 USED FOR
c    THE RESULTS AND ANY MESSAGE GIVEN BY THE PROGRAM TO THE USER.
c    TO USE ANOTHER UNIT NUMBER, REPLACE '9' BY THE NUMBER IN THE
c    'OPEN' STATEMENT AND ALL WRITE(9,*) STATEMENTS.
c
c -NOMENCLATURE-
c    TYPE        : TYPE OF DIFFUSER
c    ALPHAF      :(PROCESS WATER KLa OF A DIFFUSER AFTER A GIVEN TIME
c                  IN SERVICE)/(CLEAN WATER KLa OF A NEW DIFFUSER)
c    THETA       : 1.024
c    TEMP        : PROCESS WATER TEMPERATURE, C
c    TEMPIN      : BLOWER INLET AIR TEMPERATURE, R
c    OMEGA       : PRESSURE CORRECTION
c    TAU         : TEMPERATURE CORRECTION
c    BETA        : (PROCESS WATER C-STAR INF)/(CLEAN WATER C-STAR INF)
c    C-STAR20    : STEADY STATE DO SATURATION CONCENTRATION ATTAINED AT
c                  INFINITE TIME FOR A GIVEN DIFFUSER AT 20 oC AND 1 ATM,  mg/L
c    Cp          : PROCESS WATER DO CONCENTRATION, mg/L
c    OTRf        : OXYGEN TRANSFER RATE UNDER PROCESS CONDITIONS, lb/day
c    SOTR        : OXYGEN TRANSFER RATE UNDER STANDARD CONDITION
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c                (20 deg C, 1 atm, C=0.0 mg/L), lb/day
c   SOTRD       : SOTR PER DIFFUSER, lb/day/diffuser
c   AIRDEN      : AIR DENSITY AT GIVEN TEMPERATURE, lb/cu ft
c   LENGTH      : LENGTH OF BASIN, ft
c   WIDTH       : WIDTH OF BASIN, ft
c   SUBM        : SUBMERGENCE OF DIFFUSER, ft
c   ITERMAX     : MAXIMUM NUMBER OF ITERATION
c   INTRST      : EFFECTIVE INTEREST RATE PER COMPOUNDING PERIOD
c   YEARS       : NUMBER OF COMPOUNDING PERIODS IN THE PLANNING HORIZON
c   BLOWEFF     : BLOWER EFFICIENCY
c   DEPTH       : DEPTH OF PROCESS WATER, ft
c   STHEAD      : STATIC HEAD, ft
c   SYSHEAD     : SYSTEM HEAD INCLUDING STATIC HEAD,DIFFUSER HEADLOSS,
c                 PIPING HEADLOSS,INLET VALVE AND FILTER HEAD, ft
c   PATMO       : FIELD ATMOSPHERIC PRESSURE, psia
c   THDLOSS     : TOTAL DISCHARGE PRESSURE, SUM OF SYSHEAD AND PATMO,psia
c   Qs          : AIR FLOW RATE, scfm
c   4.28E-4     : CONVERSION FACTOR, hp-min/cu ft-R
c   WP          : WIRE POWER CONSUMPTION, hp
c   PKWATT      : WIRE POWER CONSUMPTION, Kwatt
c   AOPCOST     : ANNUAL OPERATING COST, $
c   USPWF       : UNIFORM SERIES PRESENT WORTH FACTOR
c   PWOPCOST    : PRESENT WORTH OF OPERATING COST, $
c   CAPCOST     : CAPITAL COST, $
c   TOTAL       : TOTAL COST OF THE PROJECT OVER COMPOUNDING YEARS
c   NDPLAT      : NUMBER OF DIFFUSER PER LATERAL
c   NLAT        : NUMBER OF LATERAL
c   AF,AFG      : AIR FLOW RATE, scfm/diffuser
c   AFCON       : LOWER AND UPPER LIMITS OF AIR FLOW RATE, scfm/diffuser
c   NDIFF       : NUMBER OF DIFFUSER
c   DENS        : DIFFUSER DENSITY, diffuser/100 sq ft
c   DENSCON     : LOWER AND UPPER LIMITS OF DIFFUSER DENSITY,diffuser/100 sq ft
c   C            C(1)=UNIT PRICE OF POWER CONSUMPTION, $/KWh
c                C(2)=FIXED COST FOR DIFFUSER INSTALLATION, $
c                C(3)=UNIT PRICE OF DIFFUSER, $/diffuser
```

```
c                    C(4)=UNIT PRICE OF LATERAL, $/lateral
c   A               : REGRESSION PARAMETERS
c                    A(1)=INTERCEPT
c                    A(2)=COEFFICIENT OF AIRFLOW RATE(AF)
c                    A(3)=COEFFICIENT OF AIRFLOW RATE(AF)**2
c                    A(4)=COEFFICIENT OF SUBMERGENCE(SUBM)
c                    A(5)=COEFFICIENT OF DIFFUSER DENSITY(DENS)
c*****************************************************************
      CHARACTER*80 TITLE,INDATA,OUTDATA
      REAL LENGTH,DENSCON(2),NDIFF(4),NDIFF1,NDIFF4,INTRST,
     +   MXNDIFF,MNNDIFF,MXSOTR,MNSOTR,MIXAF,MINAF,MIXREQ
      INTEGER YEARS,TYPE,TOTNDIFF,TOTNLAT,ZONE
      DIMENSION AFCON(2),A(5),C(4),DENS(4),SOTRD(4),AF(4),XCOST(4),
     +        CAPCOST(4),PWOPCOST(4)
      DATA EPS/1.0E-3/
c
c.........NAME INPUT AND OUTPUT DATA FILE.
c
      WRITE(5,10)
 10   FORMAT(/' NAME OF INPUT DATA FILE:  ')
      READ(5,20) INDATA
 20   FORMAT(A80)
      WRITE(5,30)
 30   FORMAT(/' NAME OF OUTPUT DATA FILE:  ')
      READ(5,20) OUTDATA
c
c..........WRITE TITLES.
c
      OPEN(UNIT = 7,FILE=INDATA)
      OPEN(UNIT = 9,FILE=OUTDATA)
c
c.........READ TITLE.
      READ(7,20) TITLE
      WRITE(6,50) TITLE
 50   FORMAT(/' OPTIMAL DESIGN OF AERATION SYSTEM: ',A80,/)
```

```
c
c..........READ INPUT PARAMETERS.
c
      READ(7,*) ALPHA,F,THETA,TEMP,OMEGA,TAU,BETA,CSTAR20,Cp,OTRf,
     +    AIRDEN,LENGTH,WIDTH,SUBM,ITERMAX,INTRST,YEARS,BLOWEFF,
     +    SYSHEAD,PATMO,NDPLAT,AFCON,DENSCON,C,MIXAF,A,TYPE,ERC,
     +    XTERMIN,XTERSTEP,ITERNUM,ZONE
c
      ALPHAF=ALPHA*F
      AREA=LENGTH*WIDTH
c
c...........CHOOSE THE TYPE OF DIFFUSER and ZONE
c
      IF(TYPE.EQ.1) THEN
      WRITE(9,*) 'TYPE OF DIFFUSER: CERAMIC DISC'
      ELSE IF(TYPE.EQ.2) THEN
      WRITE(9,*) 'TYPE OF DIFFUSER: CERAMIC DOME'
      ELSE IF(TYPE.EQ.3) THEN
      WRITE(9,*) 'TYPE OF DIFFUSER: CERAMIC TUBE'
      ELSE IF(TYPE.EQ.4) THEN
      WRITE(9,*) 'TYPE OF DIFFUSER: MEMBRANE TUBE'
      ELSE
      WRITE(9,*) 'TYPE OF DIFFUSER: MEMBRANE DISC'
      END IF
      WRITE(9,53) ZONE
 53   FORMAT(' NUMBER OF ZONE DESIGNED: ZONE',I2,/,)
c
c.............WRITE INPUT DATA.
c
      WRITE(9,*)'*********************************************************
     +*********************'
      WRITE(9,55)
 55   FORMAT(' THE INPUT DATA ARE FOLLOWINGS:')
      WRITE(9,*)'*********************************************************
     +*********************'
```

```
      WRITE(9,60) ALPHAF,THETA,TEMP,OMEGA,TAU,BETA,ITERMAX,INTRST,
     +         BLOWEFF,YEARS,CSTAR20,Cp,OTRf,AIRDEN,LENGTH,WIDTH,
     +         SUBM,SYSHEAD,PATMO,NDPLAT,AFCON,DENSCON,C,MIXAF
60   FORMAT(/,' ALPHA*F       =',F8.3,15x,
     +    ' THETA         =',F10.3,/,
     +    ' TEMPERATURE   =',F8.2,' (C)',11x,
     +    ' OMEGA         =',F8.3,/,
     +    ' TAU           =',F8.3,15x,
     +    ' BETA          =',F8.3,/,
     +    ' MAX ITERATION =',I7,16X,
     +    ' INTEREST RATE =',F8.3,/,
     +    ' BLWR EFFICIENCY=',F8.3,15X,
     +    ' NO OF YEAR    =',I8,' (years)',/,
     +    ' C-STAR at 20  =',F9.2,' (mg/L)',7x,
     +    ' C-process     =',F9.2,' (mg/L)',/,
     +    ' OTR-field     =',F10.1,' (lb/day)',4x,
     +    ' AIR DENSITY   =',F8.3,' (lb/cu.ft)',/,
     +    ' BASIN LENGTH  =',F8.2,' (ft)',10x,
     +    ' BASIN WIDTH   =',F8.2,' (ft)',/,
     +    ' SUBMERGENCE   =',F8.2,' (ft)',10x,
     +    ' SYSTEM HEAD   =',F8.2,' (ft)',/,
     +    ' ATMO PRESSURE =',F8.2,' (psia)',8X,
     +    ' # OF DIFF/LAT =',I5,  ' (#diff/lateral)',/,
     +    ' LOWER AIRFLOW =',F8.3,' (scfm/diff)',3x,
     +    ' UPPER AIRFLOW =',F8.3,' (scfm/diff)',/,
     +    ' LOWER DIFF DENS=',F6.1,' (diff/100sq.ft)',1x,
     +    ' UPPER DIFF DENS=',F6.1,' (diff/100sq.ft)',/,
     +    ' OPERATING COST =',F8.4,' ($/KWh)',7X,
     +    ' FIXED COST    =',F9.2,' ($)',/,
     +    ' DIFFUSER COST =',F6.1,' ($/diffuser)',4x,
     +    ' LATERAL COST  =',F8.1,' ($/lateral)',/,
     +    ' MINIMUM MIXING AIRFLOW RATE = ',F7.3,' (scfm/sq.ft.)'/)
      WRITE(9,64) A
64   FORMAT(' REGRESSION PARAMETERS:INTERCEPT   = ',F10.4,/,
     + 22X,              ' AIRFLOW     = ',F10.4,/,
```

```
     + 22X,              ' AIRFLOW**2  = ',F10.4,/,
     + 22X,              ' SUBMERGENCE = ',F10.4,/,
     + 22X,              ' DIFF DENSITY = ',F10.4,//)

c
c..........CALCULATE SOTR.
c
 100 SOTR=(OTRf*CSTAR20)/(ALPHAF*(THETA**(TEMP-20.0))*
     +  (OMEGA*TAU*BETA*CSTAR20-Cp))
c
     WRITE(9,101) SOTR
 101 FORMAT(/,' SOTR required =',f14.6,'(lb/day)')
c
c........CALCULATE MAXIMUM AND MINIMUM SOTR's AVAILABLE.
     AFCON2=AFCON(2)
     AFCON1=AFCON(1)
     DENSCON2=DENSCON(2)
     DENSCON1=DENSCON(1)
     MXNDIFF=DENSCON2*(AREA/100.)
     MNNDIFF=DENSCON1*(AREA/100.)
     MXSOTR=SOTRF1(AFCON2,AIRDEN,A,DENSCON2,SUBM,SOTES)*MXNDIFF
     MNSOTR=SOTRF1(AFCON1,AIRDEN,A,DENSCON1,SUBM,SOTES)*MNNDIFF
c
     WRITE(9,150) MXSOTR,MNSOTR
 150 FORMAT(/,' MAXIMUM SOTR available =',f14.6,'(lb/day)',/,
    1     ' MINIMUM SOTR available =',f14.6,'(lb/day)',//)
c
c.......CHECK THE IMPLICIT CONSTRAINTS.
c
     IF(SOTR.GT.MXSOTR) THEN
 1770 WRITE(5,1800)
 1800 FORMAT(//,' The calculation is terminated because ',
     + ' SOTR required never be satisfied        ',
     + ' with SOTR available. Other types of',
     + ' diffuser are recommended.')
```

```
      GOTO 4444
      END IF
      IF(SOTR.LT.MNSOTR) THEN
 1790 WRITE(5,1850)
 1850 FORMAT(//,' The calculation is terminated because ',
     + ' Minimum SOTR available is too large to satisfy with ',
     + ' SOTR required. Other types of',
     + ' diffuser are recommended.')
      GOTO 4444
      END IF
c
c..........SET THE ITERATION COUNTER TO ZERO.
c
      ITER=0
      ITER1=0
c
c..........SET THE NUMBER OF VERTEX
c
      NP=3
      NP1=NP-1
c
c..........NOW GUESS THREE # OF DIFFUSER/100 SQ FT.
c
      DENS(1)=DENSCON(1)+(DENSCON(2)-DENSCON(1))*0.1
      DENS(2)=DENSCON(1)+(DENSCON(2)-DENSCON(1))*0.3
      DENS(3)=DENSCON(1)+(DENSCON(2)-DENSCON(1))*0.9
c
c........CALCULATE THREE AF's and THREE COST's......
c
      DO 460 I=1,NP
 7777 IF(DENS(I).LT.DENSCON(1).OR.DENS(I).GT.DENSCON(2)) THEN
c 1780 WRITE(5,1800)
c 1800 FORMAT(//,'The calculation is terminated because SOTR available
c    +never satisfies SOTR required. Other diffusers are recommended.')
                    goto 4444
```

```
      END IF
          NDIFF(I)=DENS(I)*(AREA/100.)
          NDIFF1=NDIFF(I)
          SOTRD(I)=SOTR/NDIFF1
          SOTRD1=SOTRD(I)
          DENS1=DENS(I)
          CALL AIRFLOW(DENS1,SOTRD1,AIRDEN,A,SUBM,AFCON,AFGB,
     +        ITERX,PSIX,AVGERR)
c
c..........ADJUST THE DIFFUSER DENSITY IF IT IS INFEASIBLE WHEN
c       CONSTRAINTS OF AIR FLOW CAUSE UNACCEPTABLE OBJECTIVE
c       FUNCTION.
c
          IF((ITERX.GT.ITERMAX).OR.(PSIX.LE.0.001)) THEN
           IF((AVGERR.GT.0.001).AND.(ABS(AFGB-AFCON(1)).LE.ERC)) THEN
              DENS(I)=DENS(I)-(DENS(I)-DENSCON(1))/2.
              GOTO 7777
           ENDIF
           IF((AVGERR.GT.0.001).AND.(ABS(AFGB-AFCON(2)).LE.ERC)) THEN
              DENS(I)=DENS(I)+(DENSCON(2)-DENS(I))/2.
               GOTO 7777
           ENDIF
          ENDIF
c
          CALL ECON(NDIFF1,AFGB,C,COST,INTRST,BLOWEFF,TEMP,SUBM,
     +     SYSHEAD,PATMO,NDPLAT,YEARS,CAPCOST1,PWOPCOST1)
          AF(I)=AFGB
          CAPCOST(I)=CAPCOST1
          PWOPCOST(I)=PWOPCOST1
 460    XCOST(I)=COST
c
c.........IF THE COMPLEX HAS COLLAPSED, THEN TERMINATE.
c
 480  PSI=1.3
      SUMSEC=0.0
```

```
      SUMCON=0.0
      VART=0.0
      DO 490 I=1,NP
            SUMSEC=SUMSEC+XCOST(I)**2
            SUMCON=SUMCON+XCOST(I)
            VAR=(SUMSEC-(SUMCON**2)/NP)/NP1
 490        VART=VART+VAR
      IF(VART.LE.EPS) GOTO 780
c
c............SELECT THE WORST POINT.
c
 500  IWORST=1
      DO 520 N=NP1,NP
 520        IF(XCOST(N).GT.XCOST(IWORST)) IWORST=N
c
c..........CALCULATE THE CENTROID OF REMAINING POINTS NEGLECTING
c           THE WORST POINT.
c
      SUMDENS=0.0
      DO 560 I=1,NP
 560        SUMDENS=SUMDENS+DENS(I)
      DENSCENT=(SUMDENS-DENS(IWORST))/2.
 580  ITER=ITER+1
 590  ITER1=ITER1+1
      IF(PSI.LE.0.00001) GOTO 740
      IF(ITER.GE.ITERMAX) GOTO 760
      DENS(4)=PSI*(DENSCENT-DENS(IWORST))+DENSCENT
c
c......CHECK TO MAKE SURE THE NEW POINT SATISFIES ALL THE CONSTRAINTS.
c
      IF(DENS(4).LE.DENSCON(1).OR.DENS(4).GE.DENSCON(2)) THEN
            PSI=PSI/2.
            GOTO 590
      END IF
c
```

```
c..........CALCULATE A NEW AIR FLOW RATE(AF(4)) AND COST(XCOST(4).
c
8888 NDIFF(4)=DENS(4)*AREA/100.
     SOTRD(4)=SOTR/NDIFF(4)
     DENS4=DENS(4)
     SOTRD4=SOTRD(4)
     NDIFF4=NDIFF(4)
     CALL AIRFLOW(DENS4,SOTRD4,AIRDEN,A,SUBM,AFCON,AFGB,
    +        ITERX,PSIX,AVGERR)
c
c..........ADJUST THE DIFFUSER DENSITY IF IT IS INFEASIBLE WHEN
c      CONSTRAINTS OF AIR FLOW CAUSE UNACCEPTABLE OBJECTIVE
c      FUNCTION.
c
          IF((ITERX.GT.ITERMAX).OR.(PSIX.LE.0.001)) THEN
           IF((AVGERR.GT.0.001).AND.(ABS(AFGB-AFCON(1)).LE.ERC)) THEN
                  PSI=PSI/2.
                  goto 590
           ENDIF
           IF((AVGERR.GT.0.001).AND.(ABS(AFGB-AFCON(2)).LE.ERC)) THEN
                  PSI=PSI/2.
                  goto 590
           ENDIF
          ENDIF
cc
     CALL ECON(NDIFF4,AFGB,C,COST,INTRST,BLOWEFF,TEMP,SUBM,
    +   SYSHEAD,PATMO,NDPLAT,YEARS,CAPCOST4,PWOPCOST4)
          AF(4)=AFGB
          CAPCOST(4)=CAPCOST4
          PWOPCOST(4)=PWOPCOST4
          XCOST(4)=COST
c
c.........CHECK THE COST TO SEE IF THE NEW SET OF PARAMETERS
c        IMPROVES THE OBJECTIVE FUNCTION VALUE.
c
```

```
      IF(XCOST(4).GT.XCOST(IWORST)) THEN
            PSI=PSI/2.
            GOTO 590
      END IF
c
c.............THERE IS IMPROVEMENT. SAVE THE RESULTS.
c
      AF(IWORST)=AF(4)
      DENS(IWORST)=DENS(4)
      CAPCOST(IWORST)=CAPCOST(4)
      PWOPCOST(IWORST)=PWOPCOST(4)
      XCOST(IWORST)=XCOST(4)
      GOTO 480
c
c............TERMINATE CALCULATION DUE TO LOW PSI.
c
 740  WRITE(5,1220) PSI
 1220 FORMAT(/,' PATTERN SEARCH ENDS DUE TO LOW PSI(=',F17.9,')')
          GOTO 780
c
c............TERMINATE CALCULATION DUE TO EXCESSIVE ITERATION.
c
 760  WRITE(5,1230) ITER
 1230 FORMAT(/,' PATTERN SEARCH ENDS DUE TO EXCESSIVE ITERATION(='
     +      ,I4,')')
c
c.............SELECT THE BEST SET OF PARAMETERS.
c
 780  IBEST=1
      DO 800 N=2,NP
 800      IF(XCOST(N).LT.XCOST(IBEST)) IBEST=N
cc
      OPTMAF=AF(IBEST)
      OPTMDENS=DENS(IBEST)
      OPTMCAP=CAPCOST(IBEST)
```

```
      OPTMOP=PWOPCOST(IBEST)
      OPTMCOST=XCOST(IBEST)
      RTNDIFF=OPTMDENS*AREA/100.
      TOTAF=OPTMAF*RTNDIFF
      RTNLAT=RTNDIFF*(1./NDPLAT)
cc
      TOTNDIFF=INT(RTNDIFF)+1
      TOTNLAT=INT(RTNLAT)+1
c
c............WRITING STATEMENT.
c
      WRITE(9,*)'******************************************************'
      WRITE(9,1180)
 1180 FORMAT(' THE RESULTS ARE FOLLOWINGS: ')
      WRITE(9,*)'******************************************************'
      WRITE(9,1200) TOTAF,OPTMAF,OPTMDENS,TOTNDIFF,TOTNLAT,OPTMCOST,
     1          OPTMCAP,OPTMOP
 1200 FORMAT(//,' TOTAL AIR FLOW RATE      =',F15.3,2X,'(SCFM)',/,
     1 ' AIR FLOW RATE            =',F15.3,2X,'(SCFM/DIFFUSER)',/,
     1 ' DIFFUSER DENSITY         =',F15.3,2X,'(DIFFUSER/100 SQ FT)',/,
     1 ' NO OF DIFFUSER           =',6X,I5,6X,'(DIFFUSER)',/,
     1 ' NO OF LATERAL            =',6X,I5,6X,'(LATERAL)',/,
     1 ' OPTIMAL TOTAL COST       =',F15.3,2X,'($)',/,
     1 ' OPTIMAL CAPITAL COST     =',F15.3,2X,'($)',/,
     1 ' OPTIMAL OPERATING COST   =',F15.3,2X,'($)')
c
c..........CHECK MIXING AIRFLOW RATE REQUIREMENTS.
c
      MIXREQ=MIXAF*AREA
      MINAF=TOTNDIFF*AFCON(1)
      IF(MINAF.LT.MIXREQ) THEN
          WRITE(9,1255) MIXREQ,MINAF
 1255  FORMAT(//,' WARNING !! Mixing requirement is violated.',//,
     +  ' MINIMUM MIXING AIRFLOW REQUIRED =',F8.3,' (scfm/zone)',/,
     +  ' MINIMUM AIRFLOW RATE AVAILABLE  =',F8.3,' (scfm/zone)',//,
```

```
     + ' Please provide other options to meet mixing requirements.')
      END IF
 4444 STOP
      END
c
c
c*******************************************************************
c    SUBROUTINE AIRFLOW CALCULATES AIR FLOW RATE(SCFM)
c    USING COMPLEX METHOD.
c*******************************************************************
c
      SUBROUTINE AIRFLOW(DENS1,SOTRD1,AIRDEN,A,SUBM,AFCON,
     +            AFGB,ITERA,PSI,AVGERROR)
      DIMENSION A(5),AFG(4),ERROR(4),AFCON(2)
c
      ITERMX=200
  200 ITERA=0
      EPS=0.0001
c     WRITE(9,11) SOTRD1
c 11  FORMAT( ' SOTRD= ' ,F14.6,'(lb/day/diffuser)')
c
c.........GUESS THREE ADDITIONAL AIR FLOW RATES PER DIFFUSER.
c
      AFG(1)=AFCON(1)+(AFCON(2)-AFCON(1))*0.1
      AFG(2)=AFCON(1)+(AFCON(2)-AFCON(1))*0.4
      AFG(3)=AFCON(1)+(AFCON(2)-AFCON(1))*0.9
c
c.........CALCULATE ERRORS.
c
      DO 205 I=1,3
            AFG1=AFG(I)
  205     ERROR(I)=ABS(SOTRD1-SOTRF1(AFG1,AIRDEN,A,DENS1,SUBM,SOTES))
c
c........CHOOSE THE WORST OR A REJECTED POINT.
c
```

```
 210 IRJ=1
    IF(ERROR(2).GT.ERROR(IRJ)) IRJ=2
    IF(ERROR(3).GT.ERROR(IRJ)) IRJ=3
c
c.........CALCULATE A NEW AFG(4) INSTEAD OF AFG(IRJ).
c
    AFCENT=(AFG(1)+AFG(2)+AFG(3)-AFG(IRJ))/2.
    PSI=1.3
 220 ITERA=ITERA+1
    IF(PSI.LE.0.00001) GOTO 390
    IF(ITERA.GT.ITERMX) GOTO 390
    AFG(4)=PSI*(AFCENT-AFG(IRJ))+AFCENT
c
c.........CHECK TO MAKE SURE THE NEW POINT SATISFIES ALL CONSTRAINTS.
c
    IF(AFG(4).GE.AFCON(2).OR.AFG(4).LE.AFCON(1)) THEN
                PSI=PSI/2.
                GO TO 220
    END IF
c
c.........CALCULATE ERROR(4)...
c
    AFG4=AFG(4)
    SOTRFT=SOTRF1(AFG4,AIRDEN,A,DENS1,SUBM,SOTES)
    ERROR(4)=ABS(SOTRD1-SOTRFT)
c
c.........CHECK TO SEE IF THE NEW SET IMPROVES THE OBJECTIVE FUNCTION
c      VALUE.
c
    IF(ERROR(4).GE.ERROR(IRJ)) THEN
                PSI=PSI/2.
                GO TO 220
    END IF
c
c.........THERE IS IMPROVEMENT. SAVE THE RESULTS.
```

```
c
      AFG(IRJ)=AFG(4)
      ERROR(IRJ)=ERROR(4)
c
c..........CHECK TERMINATION.
c
      AVGERROR=(ERROR(1)+ERROR(2)+ERROR(3))/3.
      IF(AVGERROR.GT.EPS) goto 210
c
c..........AVERAGE THE AIR FLOW RATES PER DIFFUSER.
c
  390 AFGB=(AFG(3)+AFG(2)+AFG(1))/3.
c
      RETURN
      END
c
c*****************************************************************
c     THIS SUBROUTINE(ECON) DETERMINES A TOTAL COST OVER THE
c     NUMBER OF COMPOUNDING YEARS USING THE PRESENT WORTH METHOD
c*****************************************************************
c
      SUBROUTINE ECON(NDIFFS,AFGB,C,COST,INTRST,BLOWEFF,TEMP,
     +  SUBM,SYSHEAD,PATMO,NDPLAT,YR,CAPCOSTt,PWOPCOSTt)
      REAL INTRST,NDIFFS,NLAT
      INTEGER YR,RXNDIFFS,RXNLAT
      DIMENSION C(4)
c
c.........CALCULATE THE POWER(KW) REQUIREMENT.
c
      TEMPIN=((9./5.)*TEMP+32.)+460.
      DEPTH=SUBM+1.
      STHEAD=(DEPTH+SYSHEAD)*0.43
      THDLOSS=STHEAD+PATMO
      PRSSFAC=(((THDLOSS/PATMO)**0.283)-1.)
      Qs=AFGB*NDIFFS
```

```
      WP=(0.000428*Qs*TEMPIN/BLOWEFF)*PRSSFAC
      PKWATT=WP/1.341
c
c.........CALCULATE AN OPERATING POWER COST FOR N YEARS
c         USING THE PRESENT WORTH METHOD.
c
      AOCOST=C(1)*PKWATT*(24.*365.)
      USPWF=(((1.+INTRST)**YR)-1.)/(INTRST*((1.+INTRST)**YR))
      PWOPCOSTt=AOCOST*USPWF
c
c..........CALCULATE THE CAPITAL COST.
c
      NLAT=(1./NDPLAT)*NDIFFS
      RXNDIFFS=INT(NDIFFS)+1
      RXNLAT=INT(NLAT)+1
      CAPCOSTt=C(2)+C(3)*RXNDIFFS+C(4)*RXNLAT
c
c..........CALCULATE TOTAL COST.
c
      TOTAL=PWOPCOSTt+CAPCOSTt
      COST=TOTAL
c
      RETURN
      END
c
c******************************************************************
c     THIS FUNCTION CALCULATES SOTRFs WITH GIVEN REGRESSION
c     PARAMETERS,GUESSED AIR FLOW RATES,DIFFUSER DENSITY,AND
c     SUBMERGENCE.
c******************************************************************
c
      FUNCTION SOTRF1(AFGG,AIRDEN,A,DENSS,SUBM,SOTE)
      DIMENSION A(5)
c
c.........SOTE in % and SOTRF1 in (lb/day/diffuser).
```

```
c
      SOTE = A(1)+A(2)*AFGG+A(3)*(AFGG**2)+A(4)*SUBM+A(5)*DENSS
      SOTRF1 =(0.01)*AFGG*SOTE*AIRDEN*(23./100.)*(60.*24.)
c
      RETURN
      END
```

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