Economic Implications of Fine-Pore Diffuser Aging

Diego Rosso, Michael K. Stenstrom

ABSTRACT: Aerobic biological treatment, such as the activated sludge process, is commonly used for municipal wastewater treatment. Fine-pore diffusers have virtually replaced coarse-bubble diffusers in such operations, but most of the plant's energy expenditure is still consumed by aeration. Therefore, the performance of diffusers will critically affect plant economics. This paper analyzes and quantifies the consequences of aging processes on fine-pore diffusers. Datasets from 94 field measurements were analyzed and showed a clear pattern of performance decline with time in operation. Efficiency declines rapidly during the first 24 months of operation when the rate of decline decreases and efficiency stabilizes at a low value. For example, cost analysis scenarios were performed using the measured rate of decline in diffuser performance. The analyses include loss of transfer efficiency and elevated headloss, which both increase operating cost. Cleaning the diffusers within 12 months of operation is generally economically favorable, restores efficiency, and reduces power overhead. Periodic cleaning prolongs the economically viable lifespan for the aeration system. *Water Environ. Res.,* **78,** 810 (2006).

KEYWORDS: aeration, fine pore, fouling, oxygen transfer, economics.
doi:10.2175/106143006X101683

Introduction

Fine-pore aeration systems are used almost to the exclusion of other aeration systems for municipal wastewater treatment plants in the United States and Europe. Generally, fine-pore diffusers reduce energy cost by 50% when compared to coarse bubble diffusers (Stenstrom et al., 1984). Fine-pore diffusers produce small bubbles by releasing compressed air through small orifices or pores in either punched membranes or porous material, such as ceramic stones or sintered plastic. Because of the chemical nature and morphology of these materials, they experience fouling and scaling depending on process conditions, water quality, diffuser type, and time in operation (U.S. EPA, 1989). As a result, fine-pore diffusers need to be routinely cleaned. The choice of cleaning frequency and method determines the long-term efficiency and benefits of using fine-pore aeration.

Various methods have been used to clean fine-pore diffusers and vary in difficulty and cost. The simplest method is to dewater the aeration tank and wash the diffusers from the tank top. This form of cleaning, called *tank top hosing*, is effective in removing biological slime buildup and generally restores or partially restores efficiency. For cases where inorganic precipitates (silica, calcium carbonate, gypsum, etc.) have caused scaling, acid cleaning may be required. Manually washing with low-strength hydrochloric acid (10 to 15% wt) is popular and acid gas cleaning using hydrochloric acid gas or acetic acid injected to air distribution lines is also possible (Schmit et al., 1989).

Specific results will depend on plant design and provisions for diffuser cleaning (Rieth et al., 1990). For example, it is necessary to have spare capacity or periods of reduced loading or modified operation to dewater aeration tanks for cleaning. This is generally possible at large plants, but may not be possible at small plants. There are also direct cleaning costs, such as the labor associated with cleaning, chemicals, and replacement parts. Therefore, the choice of cleaning methods and frequencies is nontrivial.

This paper analyzes 94 offgas aeration efficiency test results from 21 different facilities, using 9 different diffuser models from 5 manufacturers, and quantifies reductions in efficiency and improvements provided by cleaning. The results are generalized and used in a net-present-worth economic analysis to show the benefits of cleaning. A generalized result, which can be scaled up or down to estimate optimal cleaning frequencies for a specific plant, is provided.

Field Data. Offgas aeration efficiency analysis is now routinely used in evaluating diffuser aeration system efficiency. Under U.S. Environmental Protection Agency (U.S. EPA) (Washington, D.C.) and American Society of Civil Engineers (ASCE) (Reston, Virginia) sponsorship, the current technique was first developed by Redmon et al. (1983). A mass balance between the incoming and outgoing air streams is used to calculate the oxygen transfer efficiency (OTE, %). The OTE may be adjusted to standard conditions (standard oxygen transfer efficiency or SOTE, %) by adjusting for the dissolved oxygen concentration, temperature, salinity, and barometric pressure—except for the effects of contaminants. The effects of contaminants are typically quantified by an alpha (α) factor, which is the ratio of process water to clean water mass transfer coefficients, or K_La_{pw}/K_La_{cw}, as defined in the ASCE standard (ASCE, 1991). To differentiate the effects of fouling, the F factor was introduced, with F ranging from 0 to 1, to quantify the effects of diffuser fouling or aging. The combined effects, quantified by the αF factor, are obtained when measuring the transfer efficiency of fouled aeration systems. The field efficiency may be recorded as αSOTE (%, new diffusers) or αFSOTE (%; aged, fouled diffusers), depending on the condition of the diffusers. The α or αF factors are calculated from field measurements obtained through offgas testing by dividing αSOTE (%) or αFSOTE (%) by the clean water efficiency SOTE (%). Clean water efficiency must be obtained from a clean water test (ASCE, 1991), either in the field or through manufacturer's data. This paper uses both nomenclatures, where the terms including the fouling factor, F, are for aged or old diffusers.

The results confirm the earlier observations of Kessner and Ribbius (1935), who observed different α factors for different aeration methods (i.e., coarse-bubble, fine-pore, and surface). The values for different aeration methods have been discussed by Stenstrom and Gilbert (1981), but a recent study (Rosso, Iranpour, and Stenstrom, 2005) found no evidence of different α factors for different makes and models of fine-pore diffusers. The reasons for

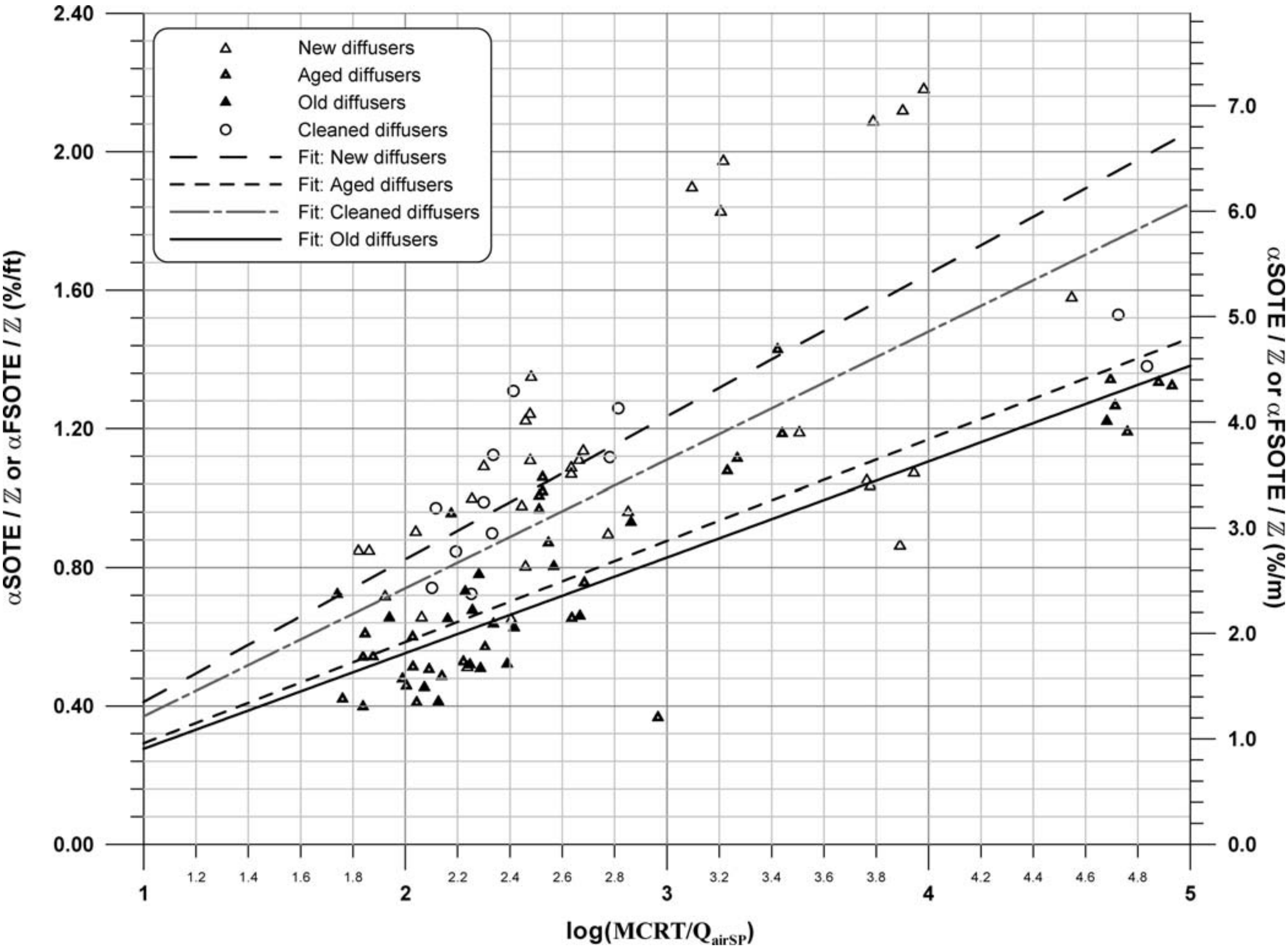

Figure 1—Standard oxygen transfer efficiency per unit depth versus plant operative parameters (Q_{airSP} = airflow rate/ total diffuser active area).

the differences in α factors for different methods of aeration have been discussed by Rosso, Huo, and Stenstrom (2005). Different α factors were observed for different mean cell retention times (MCRT) and for varying periods of operation.

The operative parameters included in this analysis were MCRT; airflow rate; diffuser geometry (depth, active surface area [i.e., bubbling], and number of units in operation); and efficiency parameters (αSOTE and α). To better show the results, MCRT, airflow rate, and geometry were grouped together as the plant characteristic number, χ, as follows:

$$\chi = \mathrm{MCRT}/\mathrm{Q_{airSP}} \quad (1)$$

Where Q_{airSP} (with dimensions of time, squared) is defined as follows:

$$\mathrm{Q_{airSP}} = \frac{\text{airflow rate}}{\text{number of diffusers} \cdot \text{submergence} \cdot \text{diffuser active area}} \quad (2)$$

The transfer efficiency varies inversely with Q_{airSP}, with lower efficiency occurring at higher air flux.

The 21 tested facilities included conventional, nitrifying-only, and nitrifying–denitrifying process layouts. Sludge ages (MCRT) ranged from 1.6 to 7.5 days for conventional processes, 5.6 to 21 days for nitrifying-only, and 9.6 to 22 days for nitrifying–denitrifying layouts. The following five fine-pore diffuser technologies were tested: ceramic discs (two types), ceramic domes (two types), membrane discs (two types), membrane tubes (two types), and membrane panels (one manufacturer, four generations). Each diffuser technology was tested in at least two locations. All data were divided into the following four categories according to the diffuser time in operation: new (less than 1 month in operation), aged (up to 2 years in operation), old (more than 2 years in operation), and cleaned diffusers (cleaned within one month of testing). The cleaned diffuser category includes both ceramic and membrane diffusers. All cleaning methods were grouped together because the effects of the different methods, at least within the present dataset, were too small to quantify.

Results and Discussion

The plant characteristic number MCRT/Q_{airSP} was plotted versus the efficiency parameter αSOTE normalized per unit depth (Figure 1). A log-linear plot shows the proportionality of efficiency versus MCRT and diffuser submergence and the inverse proportionality with airflow rate per unit of diffuser active area (Q_{airSP}).

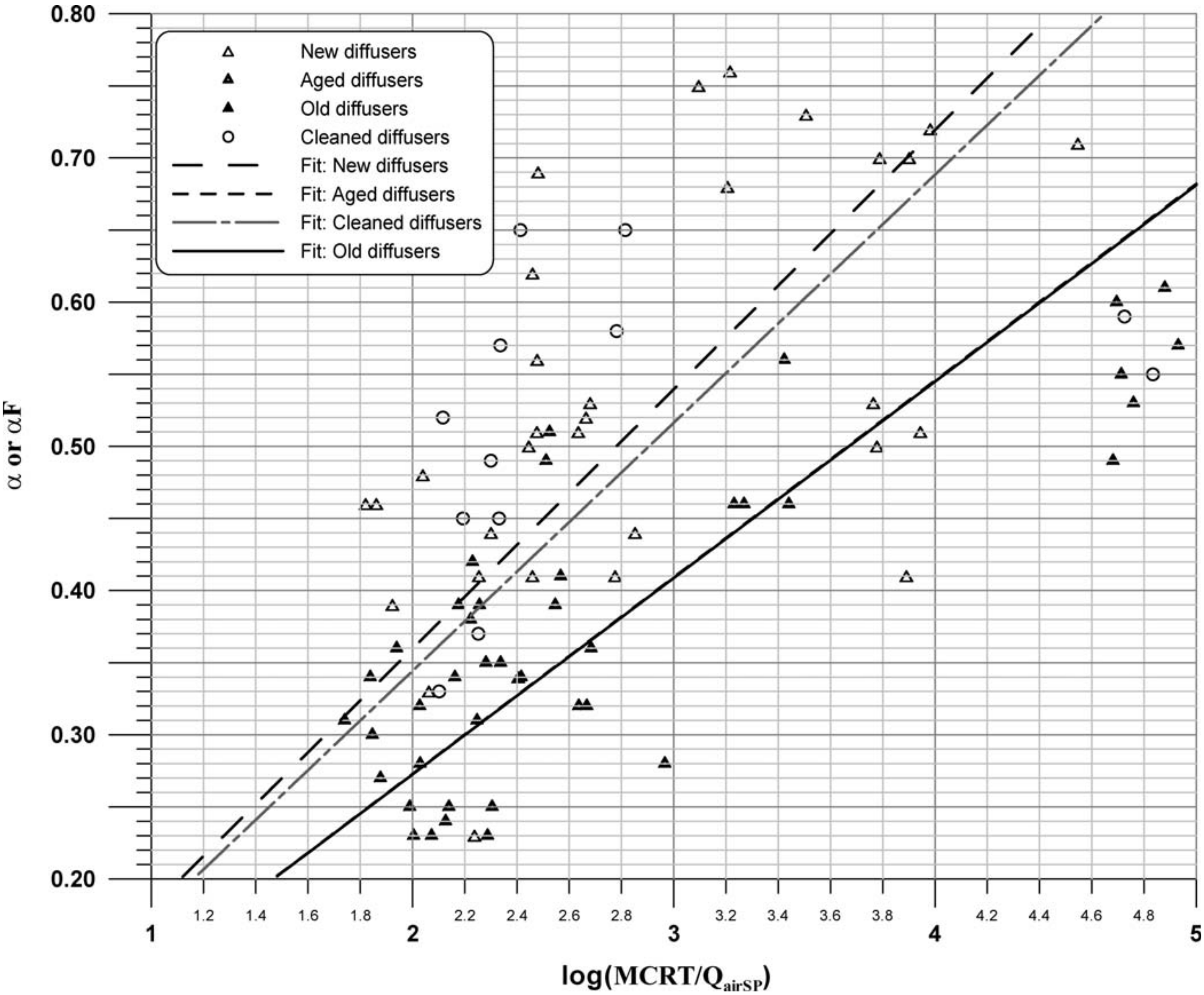

Figure 2—Water quality parameter a versus plant operative parameters (Q_{airSP} = airflow rate/total diffuser active area).

An analogous behavior is shown in Figure 2 for the water quality parameter α. Each diffuser group (new, aged, old, and cleaned) was analyzed separately with linear regression. The best-fit linear regressions shown in Figures 1 and 2 are statistically significant ($P < 0.001$). These fits show a dramatic efficiency decrease over time with higher rates of decline in the first 24 months of operation and lower rates of decline after 24 months. Diffuser cleaning restores efficiency and, for both α and αSOTE, the recovery is high, although not complete. This is because certain fouling, scaling, and especially material aging processes are irreversible.

Figure 3 shows the efficiency decline comparing the average and variations of efficiency for diffusers without cleaning. The α or αSOTE refers to the left most bar (new) and α*F* and α*F*SOTE refer to the middle and left most columns (aged and old). As expected, the new diffusers are routinely higher in efficiency than aged or old diffusers. The decline in efficiency with age occurs because of larger bubble formation or bubble coalescence as a result of the biofilm coating the diffuser surface. Fouling may plug a portion of the orifices or pores, and larger bubbles are a direct consequence of higher air flow for each orifice or pore. This figure does not show the effect of MCRT on performance, but higher MCRT systems are clustered at the top of the bars.

The costs of diffuser fouling and the economic benefits of cleaning are quantified with a net-present-value calculation tool. The tool consists of an iterative algorithm that calculates the net-present values of power cost, power overhead resulting from decreased oxygen transfer efficiency and increased diffuser pressure drop, and cleaning frequency. The cleaning frequency is based on the cleaning cost and cumulative power overhead. When the wasted power exceeds the cleaning cost, cleaning is recommended and, if performed, the power cost is reset to the initial (new) value. For the purpose of this analysis, the difference between the power cost for new and cleaned diffusers was neglected. This is justified by comparing this difference with the magnitude of the power increase between new (or cleaned) and old diffusers. The algorithm calculates costs in local currency; however, to make results independent of plant size, aerator model, other plant characteristics, and currency effects (exchange rates, etc.), the results are reported in a generalized form.

All results were normalized to two dimensionless cost ratios, actual power/initial power, and power waste/cleaning cost. In this

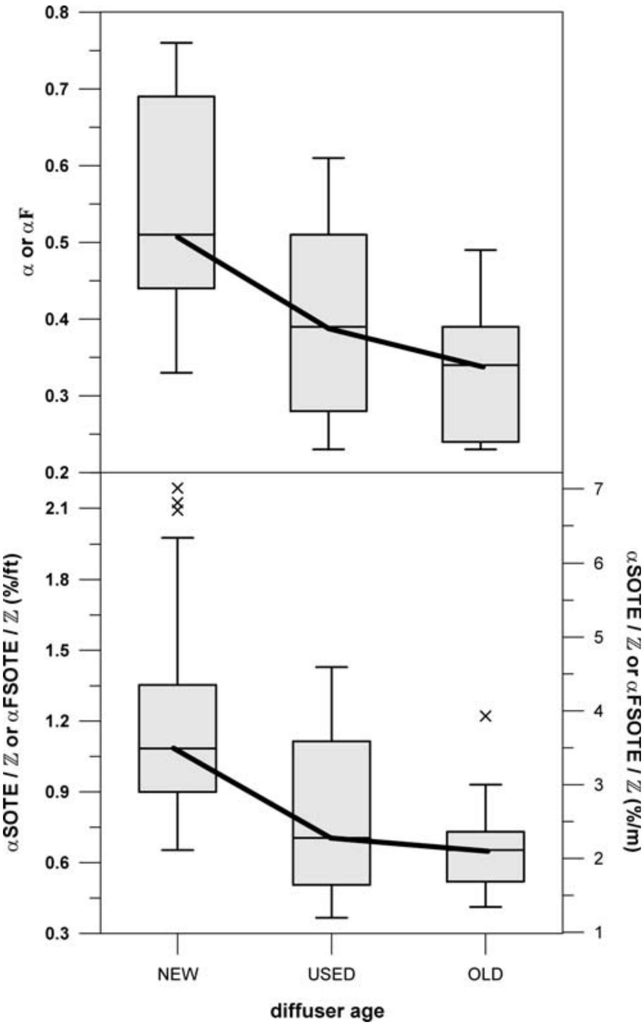

Figure 3—Efficiency decrease versus time in operation: α(*F*) factor on the top, and on the bottom α(*F*)SOTE/Z. "X" symbols represent outliers.

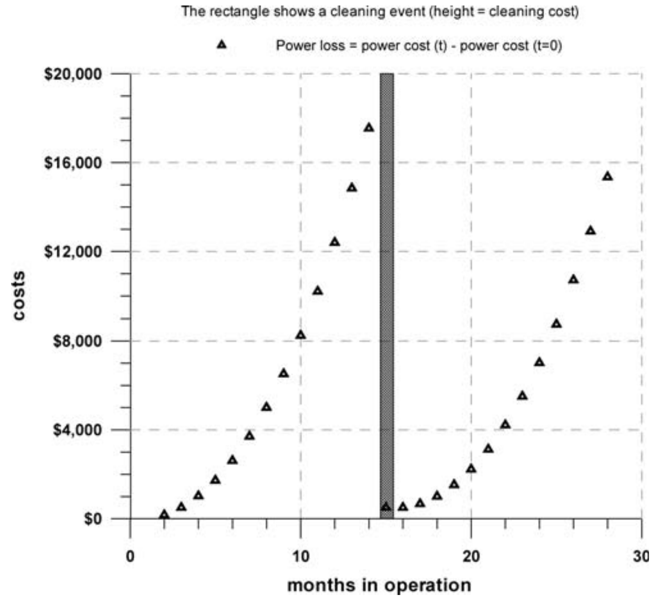

Figure 4—Power waste and cleaning cost versus time in operation for an example scenario. Assumed values are as follows: cleaning cost = \$20,000; airflow rate = 0.472 m³/s (1000 SCFM); initial αSOTE = 30%; power cost = \$0.065/kWh; and annual interest rate = 4.00%. Shaded rectangle represents a cleaning event (height = cleaning cost); power loss = power cost (t) − power cost (t = 0).

paper, "power waste" is defined as the difference between the actual power cost (at any time after startup or cleaning) and the initial power cost (i.e., actual power cost minus initial power cost). The ratio of actual to initial power is always equal to or greater than 1, where the lower limit (1) occurs when the diffusers are new or cleaned (i.e., the actual power cost equals the initial value and the power waste equals zero). The power waste/cleaning cost ratio compares the power waste (i.e., actual minus initial power cost) with the cleaning cost for the specific case and ranges from 0 to 1. When the power waste approaches the cleaning cost, cleaning is performed, because having a power waste higher than the cleaning cost is not an economically viable operation. Using site-specific values, the cleaning cost must be estimated by plant management from labor and material cost and the expected time for cleaning. For example, cleaning cost was estimated for one of the plants in this study, as reported in Table 1.

Table 1—Cleaning cost calculation.

Tank dimensions	39.6 × 20 × 5.30 m (130 × 65 × 17.4 ft) (L × W × D)
Number of diffusers	2430/tank
Tank dewatering and hosing labor	8 hours/tank-year
Diffuser membrane life	3 years
Membrane cost	$12/diffuser
Membrane replacement labor	1 hour/10 membranes

For a specific location, diffuser cleaning costs may be generally estimated using these factors. The costs over time in operation were calculated for one example location, requiring an initial airflow rate of 0.472 m^3/s (1000 standard ft^3/min [SCFM]). The facility considered had an initial αSOTE of 30% and a αSOTE value of 18.7% after 15 months of operation. At $t = 0$, the power waste equaled zero, as the power cost equaled the initial value. The algorithm scheduled a cleaning event at $t = 15$ months, because, after that, the power waste is greater than the assumed cleaning cost of \$20,000. The power cost assumed is \$0.065/kWh, and the annual interest rate was 4.00%. Figure 4 plots the evolution of the power waste over time, and the shaded rectangle shows a cleaning event.

The dimensionless cost ratios have wide application and can easily be converted to absolute costs when local unit costs are known. For example, they may be applied to locations with relatively inexpensive labor and expensive power cost (i.e., most developing countries), with expensive labor and inexpensive power cost (i.e., Canada), or with expensive labor and expensive power cost (i.e., Italy).

A dimensionless plot of the power waste to cleaning cost is plotted in Figure 5. The family of curves in Figure 5 is parametric in the percentage of annual efficiency decline, defined as follows:

$$\Delta \mathrm{eff}_{\mathrm{annual}} = \frac{\alpha \mathrm{SOTE}_{\mathrm{initial}} - \alpha \mathrm{SOTE}}{\alpha \mathrm{SOTE}_{\mathrm{initial}}} / \text{time in operation} \quad (3)$$

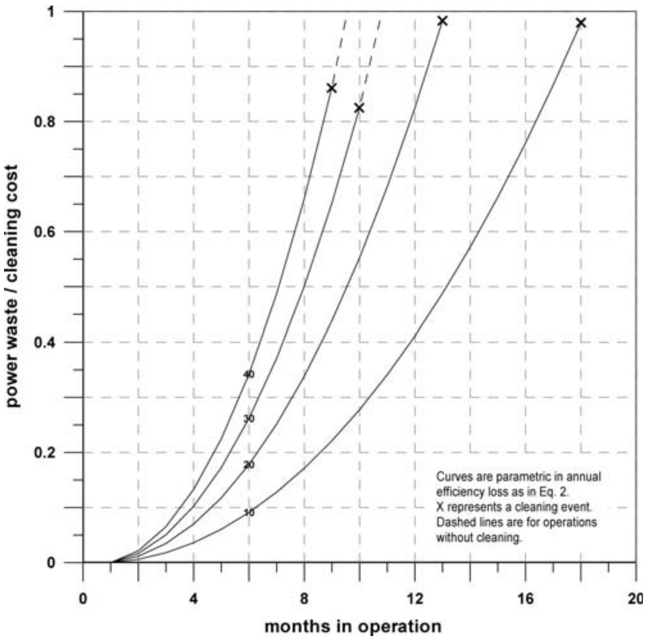

Figure 5—Power waste to cleaning cost ratio versus time in operation. Curves are parametric in annual efficiency loss as in eq 2. "X" represents a cleaning event. Dashed 2rations without cleaning.

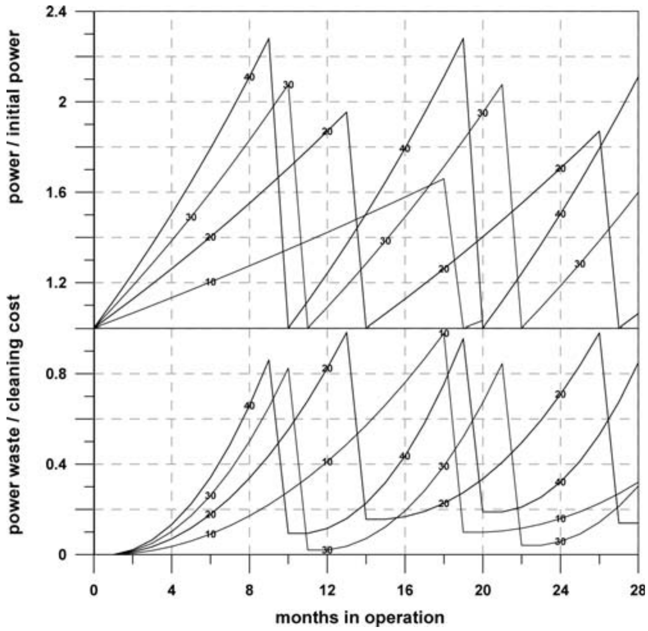

Figure 6—Dimensionless cost ratios versus time in operation.

Equation 3 ranges from 10 to 40%, and each curve is labeled accordingly (Figure 5). The "x" symbols in Figure 5 represent a cleaning event scheduled by the net-present-value algorithm; however, because of the discrete compounding on a monthly basis, these symbols do not correspond to the same ordinate for all curves. Operations above the symbols (dashed lines) will result in economically unfavorable scenarios, because the monthly compounding cycle following each symbol would end with a power waste to cleaning cost ratio greater than 1. It is also evident that the cost analysis is very sensitive to variations in efficiency, and lower efficiency declines will result in longer periods between cleaning events.

Figure 6 shows the generalized results of the economic analyses for a longer range of time in operation. The saw tooth curves represent facilities with new (at 0 months), aged (within 24 months), old (after 24 months), and cleaned diffusers. Each curve is labeled according to eq 3. The upper half of the graph shows the evolution over time of the ratio of actual power to initial power (i.e., the dimensionless power waste). The bottom half plots the power waste to cleaning cost ratio versus time in operation. The characteristic saw tooth shape describes the evolution of costs over time. As the time in operation increases, the power waste to cleaning cost ratio grows, and, when it approaches 1, the algorithm sets a cleaning event with a steep decline in cost. The maxima represent the cumulative power overhead over the period in operation.

Applications. To apply the results, the following three different example scenarios are proposed and analyzed:

(1) Estimating power waste from known time in operation, known cleaning cost, and known annual efficiency loss;
(2) Estimating expected time in operation from known cleaning cost, known power waste, and known annual efficiency loss;
(3) Estimating annual efficiency loss from known cleaning cost, known power waste, and known expected time in operation.

Scenario 1 is often the case for a large treatment plant or for a plant where the energy expenditure is recorded by a different entity than the operations management. If the initial and current field efficiencies were measured with offgas testing, the annual efficiency loss may be calculated as in eq 3. This uniquely identifies one point on each half of the graph by moving along a vertical line correspondent to the time in operation since last cleaning (or startup). The two points will result in the ratio between the actual power and the initial power (upper half) and in the ratio between power waste and cleaning cost (lower half). Given the cleaning cost, it is possible to calculate the power waste.

Scenario 2 may be encountered, for example, in a treatment plant at startup or directly after cleaning. The cleaning cost and power waste are known, and the annual field efficiency decline is measured through offgas testing. It is possible to determine the time for cleaning by moving along a horizontal line on the lower half of Figure 6. The point at the abscissa is the expected time in operation for the next cleaning event.

Scenario 3 provides the operator a way to assess annual efficiency loss without performing an offgas test. By locating, on Figure 6, the time in operation on the horizontal axis and the cleaning to power ratio on the vertical axis, the expected annual field efficiency decline is identified.

For each of the above scenarios, the upper half of Figure 6 shows the cumulative power waste resulting in operating the facility for a specific duration. The inevitable decline resulting from fouling will cause operation to diverge from the upper horizontal axis directly after startup (or cleaning), which results in power waste. The family of segmented graphs shows clearly that higher efficiency declines produce higher power wastes. This decline is purely a function of environmental conditions (i.e., wastewater and aerator characteristics) and will only increase in magnitude, as shown in Figure 3.

Conclusions

The oxygen transfer efficiency and pressure drop of fine-pore diffusers inevitably decreases over time. Both effects contribute in lowering the overall process efficiency and create power wastage. Cleaning the diffusers restores process efficiency and reduces power costs. Different cleaning techniques are available and all appear to effectively restore aeration efficiency.

Observation using 94 field tests shows that efficiency decreases with time and the greatest rate of decrease occurs in the first 24 months of operation. Efficiency declines were quantified and included in the cost analyses and the net-present worth of dimensionless cost ratios. An advanced analysis compares the cumulative wasted power to cleaning costs and calculates optimal cleaning frequency. The cleaning frequency is always higher for higher fouling rates. Three different scenarios demonstrated these results.

Acknowledgments

Credits. The authors are grateful to the agencies whose treatment plant was included in this study. The California Energy Commission (Sacramento, California) and Southern California Edison (Rosemead, California) provided partial support for this work.

Authors. At the time of this study, Diego Rosso was a graduate research engineer and Ph.D. candidate in the Civil and Environmental Engineering Department at the University of California, Los Angeles (UCLA). Michael K. Stenstrom is a professor in the Civil and Environmental Engineering Department at UCLA. Correspondence should be addressed to Prof. M.K. Stenstrom, UCLA, 5714 Boelter Hall, Los Angeles, CA, 90095-1593; e-mail: stenstro@seas.ucla.edu.

Submitted for publication March 2, 2005; revised manuscript submitted June 17, 2005; accepted for publication July 14, 2005.

The deadline to submit Discussions of this paper is November 15, 2006.

References

American Society of Civil Engineers (1991) Measurement of Oxygen Transfer in Clean Water, ASCE 2-91; American Society of Civil Engineers: Reston, Virginia.

Kessner, H. J.; Ribbius, F. J. (1935) Practical Activated Sludge Research. *J. Proc. Inst. Sew. Purification*, 50–56.

Redmon, D. T.; Boyle, W. C.; Ewing, L. (1983) Oxygen Transfer Efficiency Measurements in Mixed Liquor Using Off-Gas Techniques. *J. Water Pollut. Control Fed.,* **55,** 1338–1347.

Rieth, M. G.; Boyle, W. C.; Ewing, L. (1990) Effects of Selected Design Parameters on the Fouling Characteristics of Ceramic Diffusers. *Res. J. Water Pollut. Control Fed.,* **62** (7), 877–886.

Rosso, D.; Iranpour, R.; Stenstrom, M. K. (2005) Fifteen Years of Off-Gas Transfer Efficiency Measurements on Fine Pore Aerators: Key Role of Sludge Age and Normalized Air Flux. *Water Environ. Res.,* **77** (3), 266–273.

Rosso, D.; Huo, D. L.; Stenstrom, M. K. (2005b) Gas Transfer Depression by Interfacial Surfactant Contamination at Bubble Interfaces. *Chem. Eng. Sci.,* (submitted).

Schmit, F. L.; Redmond, D. T.; Ewing, L. (1989) In-Place Gas Cleaning of Diffusion Elements. U.S. Patent 4,889,620, December 26.

Stenstrom, M. K.; Gilbert, R. G. (1981) Effects of Alpha, Beta and Theta Factors in Design, Specification and Operations of Aeration Systems. *Water Res.,* **15,** 643–654.

Stenstrom, M. K.; Vazirinejad, H. O.; Ng, A. (1984) Economic Evaluation of Upgrading Aeration Systems. *J. Water Pollut. Control Fed.,* **56** (1), 20–26.

U.S. Environmental Protection Agency (1989) *Fine Pore (Fine Bubble) Aeration Systems*, EPA/625/1-89/023; U.S. Environmental Protection Agency: Cincinnati, Ohio.