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Aeration may be the most important operation in wastewater treatment. The activated sludge process, currently the most popular method of biological wastewater treatment, requires efficient and reliable aeration systems. Other types of treatment processes, such as lagoons, often require aeration to supplement the naturally occurring oxygen transfer. In-stream aeration, practiced in several European countries to mitigate the effects of oxygen-demanding waste discharged into rivers and lakes, is an extreme example.

A variety of aeration systems are popular with design engineers. Numerous systems have been developed and evaluated over the last 50 years. Many of these systems have been unsuccessful and are rarely found today, although the successful ones have become quite common. Each system has special advantages and disadvantages, and the process of system selection is often a subjective one, based on the experience and confidence of the engineer or user with a particular system. The aeration system is seldom chosen on an entirely rational basis and consequently many modern day designers use obsolete technology in order to comply with a client's request, to match an existing system for component compatibility, or to conform with "tradition."

A decision to upgrade aeration systems should be based on many operational factors as well as on economics.

The spiraling costs of electricity and other energy forms are now causing engineers and their clients to reevaluate the design of aeration systems. The economics of an aeration system, particularly operating costs, are contributing much more heavily to system selection. For this reason, transfer efficiency is increasingly important.

The object of this paper is to evaluate the economics of replacing an older, less efficient aeration system with a new, efficient system such as a fine bubble diffuser system. Current energy savings are put in perspective with the time-value of money (interest rates), operating costs, and future costs projections.

Upgrading the aeration system for a hypothetical 13.1-m^3/min (5-mgd) treatment plant is evaluated with respect to standard efficiencies, process variables, projected operating costs, and process flexibility, using investment costs obtained from seven other upgrading projects.

CONVERSION TO PROCESS RATES

Before an evaluation of aeration system alternatives can be made, field oxygen transfer rates must be determined. Manufacturers usually advertise standard transfer rates determined under standard conditions (in tap water at zero dissolved oxygen (DO) concentration, 20°C, 36% relative humidity, and at barometric pressure corresponding to mean atmospheric pressure). Conversion of the standard oxygen transfer rate to the field rate is done through the use of alpha, beta, and theta factors, and the desired dissolved oxygen concentration as follows:

$$OTR_f = \frac{\alpha(SOTR)\theta^{(T_f-20)}}{\bar{C}^*_{\infty 20}} (\tau_f \beta \omega_f \bar{C}^*_{\infty 20} - \bar{C}) \qquad (1)$$

Where:

OTR_f = transfer rate at field conditions,
α = correction factor for change in mass transfer coefficient for wastewater contaminants,
$SOTR$ = transfer rate at standard conditions,
θ = temperature correction factor,
= 1.024,
T_f = field temperature (°C),
τ_f, ω_f = correction factors for oxygen content in air due to barometric pressure and humidity,
β = correction factor for equilibrium dissolved oxygen concentration,
$\bar{C}^*_{\infty 20}$ = equilibrium dissolved oxygen concentration at 20°C, and
$\bar{C}$ = operating dissolved oxygen concentration.

The American Society of Civil Engineers (ASCE) oxygen transfer subcommittee has formulated a proposed standard procedure[1] for making this conversion and their work should be consulted before using this equation. Additional comment on the use of alpha, beta, and theta factors follows.

Alpha and beta factors were intended to account for changes in oxygen transfer rate with wastewater characteristics; however, it is now well known that the alpha factor for an aeration system is as much a function of the aeration device as wastewater characteristics. Gilbert[2] and Stenstrom and Gilbert[3] and others have noted the effects of aeration device type on alpha factors. Their reviews indicate alpha factors for fine bubble diffusers have frequently been measured in the range of 0.3 to 0.7, and depend very strongly on degree of treatment. Coarse bubble diffusers have higher alpha factors, with the reported range of values for municipal wastewaters averaging about 0.8. Alpha factors for the various types of surface aerators have been reported from 0.6 to 1.2, and depend on energy density, as well as on other factors. Unfortunately, many current texts on treatment plant design still use uniform alpha factors for different aeration devices.

Table 1—Hypothetical plant specifications.

Design example retrofit of a fine bubble system	
Plant size	13.1 m^3/min (5.0 mgd)
Operating DO concentration	1.0 mg/L
Average alpha factor (fine)	0.4
Average alpha factor (coarse)	0.8
SOTR (fine)	4.2 Kg O_2/wire-kWh (7.0 lb O_2/wire-hp-hr)
SOTR (coarse)	1.2 Kg O_2/wire-kWh (2.0 lb O_2/wire-hp-hr)

Note.—Number of new fine bubble diffusers = 2715.

It appears that alpha factors are also highly dependent on turbulence and power intensity. It was shown by Stenstrom and Hwang[4] that for identical wastewaters the alpha factor can change by as much as 50% depending on power input level. Alpha factors for surface aerators and turbine aerators frequently increase with increasing power per unit volume. Consequently, design engineers must be cautious and conservative when specifying and measuring alpha factors. If more than one type of aeration device is considered for a proposed design, separate alpha factors should be determined and specified for each device. Extreme care must be exercised when using "bucket" alpha factors for full-scale devices.

It was demonstrated that improper application of alpha factors determined on a small scale can be worse than simply guessing or assuming alpha factors. It is extremely important than the aeration device used for alpha factor testing be as similar as possible to the device to be used in the full-scale installation.

ECONOMICS AND TIME-VALUE OF MONEY

There are a number of alternative ways of expressing the time-value of money—for example, present worth and annual cost. The present worth method is used here because it is particularly suitable when varying payments and benefits are assessed, although identical conclusions would be obtained if the annual cost method were used. The benefit-cost ratio is used to compare alternatives, and represents the ratio of the net present worth of benefits to costs. (Note also, that taxes are neglected in subsequent evaluations.) The methods used here and other methods are described in detail by Grant *et al.*,[5] and by DeGarmo *et al.*[6]

ECONOMICS EXAMPLE PROBLEM

The following hypothetical example illustrates the evaluation of the economic merits of different oxygen transfer rates and systems costs for upgrading an existing plant, using a low efficiency spiral roll system, to a high efficiency fine bubble diffuser system. This alternative system was selected because it is the most commonly used by treatment plant managers. It is usually less capital intensive because existing blowers can normally be reused.

Table 1 shows the basic assumptions for the 13.1 m^3/min (5 mgd) hypothetical treatment plant. An operating DO concentration of 1.0 mg/L is selected as the design basis and SOTRs of 4.2 Kg O_2/wire-kWhr (7.0 lb O_2/wire-hp-hr) for the fine bubble

Table 2—Capital costs for upgrading to fine bubble diffusers.

Location (1)	Project size (mgd) (2)	Year constructed (3)	Number of diffusers (4)	Number of diffusers/ mgd (5)	Original cost[a]		Current cost		Reference (10)
					$/mgd (6)	$/Diffuser (7)	$/mgd (8)	$/Diffuser (9)	
Modgen, UK[b]	126	1961	8050/Tank 18 Tanks	1150	$15,725	$ 13.70	-	-	Houck[7]
Oxford, UK[a]	3.96	1969	990/Tank 8 Tanks	2000	23,700	11.90	29,700	13.50	Houck[7]
Oxford, UK[c]	3.96	1981	1680/Tank 4 Tanks	1670	21,565	12.70	25,000	15.00	Houck[7]
Tallman Island, New York, N.Y.	20	1978	6400/Tank 1 Tank	320	44,000	137.50	60,300	188.00	Houck[7]
Sepulveda, La.	40	1980	3794/Tank 9 Tanks	854	31,000	36.30	36,000	42.30	Birk[8]
Whittier Narrows[d], Los Angeles County	15	1982	2970/Tank 3 Tanks	594	30,000	50.50	31,800	53.50	Yunt[9]
Los Angeles County[e]	123.4	1981	-	-	42,800	-	45,400		Yunt[9]
This study[f]	5	-	2715/Tank 1 Tank	543	-	-	30,000	55.00	

[a] All costs are for wetted tank parts only, and exclude cost of blowers and air headers, except for the 1969 Oxford job which includes cost of blowers, piping and controls, and for Whittier job which includes the cost of an air filter. Variability in cost can occur because of the type of headers used (steel versus stainless), and how much of the main air distribution system, including valves, are replaced.

[b] Original cost updated to 1979 by Houck[7].

[c] Project under construction at the time of this writing, costs reported originally indexed to 1981.

[d] Includes the cost of an air filter. Also one-third of the diffusers were 9-in. plates that have been converted to domes using a ratio of 0.8.

[e] Projected costs for eight treatment plants.

[f] Projected costs.

Table 3—Cost indices.

Year (1)	ENR[a] construction (2)	ENR[a] building (3)	EPA[b] (4)	CE plant[c] (5)	M & S[d] (6)
1978	2869	1734	145	218	545
1979	3140	1909	158	239	599
1980	3376	2017	169	261	660
1981	3705	2184	180	297	721
1982	3931	2294			746

[a] "Engineering News-record" index for the fourth quarter of each year.

[b] EPA national average index for 5-mgd plants for the fourth quarter of each year.

[c] CE plant cost index, published in *Chem. Eng.*

[d] M & S equipment cost index published in *Chem. Eng.*

diffuser system and 1.2 Kg O_2/wire-kWhr (2.0 lb O_2/wire-hp-hr) for an existing coarse bubble diffuser system are assumed. The SOTR for the fine bubble system is representative of an average case fine bubble diffuser system operating at a low energy density (0.008 to 0.13 kW/m^3 or 0.3 to 0.5 hp/1000 cu ft) with a blower/motor efficiency of 70%. The 2.0 lb O_2/wire-hp-hr SOTR is representative of a well designed and operated spiral roll system. Average alpha factors of 0.4 for the fine bubble and 0.8 for the coarse bubble system are assumed. A beta factor of 0.95 was also assumed. The OTR for the fine bubble system is 1.44 Kg O_2/wire-kWhr (2.38 lb O_2/wire-hp-hr) and the OTR for the coarse bubble system is 0.83Kg O_2/wire-kWhr (1.36 lb O_2/wire-hp-hr).

The capital costs to upgrade several treatment plants are shown in Table 2. These figures were obtained by a survey of plants in the Los Angeles area, and from published data. Estimates were updated to December, 1982 using the "Engineering News-Record" cost estimates shown in Table 3. The other cost indices are provided as comparison. The plant data are included to show the cost variability and range of recent projects. The cost selected for the example problem is slightly higher than the mean cost for the recent projects. This was done in anticipation of the inflation that will occur between the time of this writing (January, 1983), and publication. An informal survey of manufacturers indicates that the lowest cost for purchase and installation of the diffusers and wetted tank parts, if obtained through competitive bidding, is approximately $35 to $40 per diffuser. Actual cost estimates for any installation should be obtained considering the site-specific aspects of each installation. The estimates provided here should only be used for scoping or planning purposes.

Table 4—Annual operating costs.

Summary annual operating costs excluding energy costs

Task (1)	Person hours (2)	Skill factor (3)	Extension (4)
Air filter maintenance (2 hr/1000/month)	33	1.2	40
Air flow and head loss monitoring (2 hr/1000 diffusers/month)	65	1.2	78
Hours subtotal	98		118
Cost at $14/hr			$1650
Replacement air filters (2/1000/yr, at $50/each)			$ 270
Total			$1920

Table 5—Summary of fifth-year cleaning costs.

Task (1)	Person hours (2)	Skill factor (3)	Extension (4)
Dome transport unloading and loading (4 hr/1000 domes)	10.9	1.0	10.9
Tank dewatering and gross cleaning (12 hr/1000 domes)	32.6	1.0	32.6
Diffuser removal and collection (50 hr/1000 domes)	135.8	1.0	135.8
Dome firing (10 hr/1000 domes)	27.2	1.2	32.6
Reinstallation (75 hr/1000 domes)	203.6	1.2	244.4
Hours subtotal	410.1		456.
Cost at $14/hr			$6388.
Kiln costs			$1000.
Diffuser and gasket replacement costs assuming 7% loss and $10/diffuser stone.			$1900.
Total			$9288.

The annual operating costs except those for energy are shown in Table 4. Items such as blower maintenance were not considered because it was assumed they would be the same for both systems. These costs were estimated based on surveys of the Los Angeles area plants and the data presented by Houck and Boon.[7]

It is also routinely noted that fine bubble aeration efficiency declines over time because of gas-side and liquid-side clogging, and ranges of 5 to 10% decline per year are reported. This clogging problem would make it necessary to clean the diffusers every five years, which would entail shut-down of an aeration basin and cleanup with removal and refiring of all diffusers. The estimated expenses for cleanup shown in Table 5 were also developed from a survey of the Los Angeles area plants and the work of Houck and Boon.[7] They are slightly higher than the "rule of thumb" estimates of $3/diffuser.

Power cost was assumed to be $0.07/kWh, which is typical for power in the Los Angeles area. Benefits due to energy savings were calculated from the difference in horsepower consumption of the two systems.

In developing this example it was assumed that many components of the coarse bubble system, such as blowers, associated electrical controls, and primary air header could be salvaged and need not be upgraded or replaced. Also it was assumed that the interest rate for both principal and for discounting of

Table 6—Comparisons of various alternatives for economic evaluation.

Project life (years) (1)	Aeration assumption (2)	Inflation assumption (3)	Benefit cost-ratio (4)	Net worth (dollars) (5)
20	Constant	None	2.02	179 000
5	Constant	None	1.05	8 700
20	Declining (5%/yr)	None	1.78	136 900
20	Declining (10%/yr)	None	1.54	94 900
20	Declining (10%/yr)	Increasing (5%/yr)	2.05	198 000
5	Declining (10%/yr) + DO control[a]	Increasing (5%/yr)	1.23	41 900
20	Declining (10%/yr) + DO control[a]	Increasing (5%/yr)	2.68	370 000

[a] It is assumed that DO control provides 25% horsepower savings.

future benefits and costs is 12% for all cases, unless otherwise specified.

Table 6 shows the present worth and benefit-cost ratio of seven probable investment alternatives, using different scenarios for power cost, declining aeration system efficiency, and project life. The first row of Table 6 shows the most basic case that assumes constant aeration efficiency and constant power costs with a 20-year project life. The net present worth of upgrading the system with fine bubble diffusers is $179 000. The benefit-cost ratio is 2.02, which is the ratio of present worth of benefits divided by present worth of costs. Positive values of present worth and benefit-cost ratios greater than unity indicate economically favorable projects, for the assumptions stated.

Row 2 in Table 6 is identical to the example in Row 1 except for project life. The benefits decline if the project is required to recover all capital costs in five years. This decline results from higher principal payments. Investment is just recovered in the 5-year period. Row 3 in Table 6 shows the economic benefits if aeration efficiency of the fine bubble diffuser system declines by 5%/yr with 5-year cleanings, which restore efficiency to its original value. Row 4 is identical to Row 3 except that aeration efficiency declines by 10% per year. Declining efficiency affects the net worth, but the project is still quite favorable. Row 5 shows an even more extreme case, which assumes an inflation increase of 5% per year for all costs, including power. If inflation is assumed the retrofit project becomes more economical.

The most economical alternative, presented in the final two rows in Table 6, requires the addition of a DO control system that saves 25% of the power costs. It was assumed in developing this example that capital costs would increase by $10 000 and that annual operating costs would increase by $2000.

Table 7 shows the economics of the retrofit project for three economic/process assumptions: 5%/yr inflation and constant efficiency, 10%/yr declining efficiency and no inflation, and 10%/yr declining efficiency with 5%/yr inflation, for project periods from 2 to 10 years. The payback period for the 5%/yr inflation, zero-decline assumption is less than 4 years. Payback periods range from 5 to 7 years depending on the economic assumptions.

Table 8 shows the present worth of energy savings, neglecting all costs for the three process/economic assumptions. These

Table 7—Economic comparisons of varying project life with different inflation and clogging assumptions.

	Inflation and efficiency assumptions[a]					
	Constant efficiency and 5%/yr inflation		Declining efficiency and zero inflation		Declining efficiency and 5%/yr inflation	
Project life (years) (1)	Benefit-cost ratio (2)	Net worth (dollars) (3)	Benefit-cost ratio (4)	Net worth (dollars) (5)	Benefit-cost ratio (6)	Net worth (dollars) (7)
2	0.56	−67 400	0.49	−78 200	0.53	−73 000
3	0.81	−29 900	0.65	−54 800	0.70	−45 900
4	1.03	5 200	0.76	−38 000	0.84	−25 400
5	1.19	31 500	0.80	−31 800	0.89	−17 500
6	1.38	62 300	0.95	−8 700	1.08	13 300
7	1.55	91 300	1.05	8 900	1.23	38 300
10	1.93	163 000	1.21	35 300	1.45	78 400

[a] Where efficiency declines, a rate of 10%/yr is assumed.

Table 8—Present worth of energy savings from increased transfer efficiency.

Investment period (years) (1)	Net present worth (dollars)[a] Const. E/5% Inf. net worth (dollars) (2)	Declining E/0% Inf. net worth (dollars) (3)	Declining E/5% Inf. net worth (dollars) (4)
3	125 000	99 800	109 000
4	162 000	118 000	131 000
5	196 000	130 000	147 000
8	287 000	187 000	226 000
10	338 000	204 000	254 000
15	441 000	246 000	331 000
20	516 000	270 000	387 000

[a] Where efficiency declines 10%/yr is assumed.

savings were included to show the present worth of potential savings that can be used to predict the economically justified investment for each project life and assumption. Other operating costs, including cleaning cost, were neglected. The net present worth can be directly compared to the present investment cost of an alternative. This table is included so that comparisons may be made to investment costs which are different from those assumed.

Table 9 presents an analysis of cleaning frequency. Houck and Boon[7] reported that diffusers are most frequently cleaned at 6- or 7-year intervals. A 5-year period was assumed for the previous analyses. Table 7 shows the benefit-cost ratios for varying cleaning frequency from 2 to 15 years. Three years is the most economical period. A decline of 10%/yr in transfer efficiency is sufficiently large to warrant further developments in cleaning. An *in-situ* technique to clean the outside of the diffusers as well as internal stone fouling, would be very economical if it could be performed at little cost.

Figures 1, 2, 3, and 4 further illustrate the economics of upgrading the aeration system for different process and economic conditions. Figure 1 shows the benefit-cost ratio for power cost varying from $0.03 to $0.13/kWh while varying the fine bubble diffuser alpha factor from 0.3 to 0.7. Project life of 20 years and 10%/yr declining aeration efficiency with 5-year cleaning frequency were used in all 4 figures. Unless otherwise noted, the assumptions presented in Table 1 were also used for Figures 1 through 4.

Table 9—Cleaning frequency analysis.

Cleaning frequency (years) (1)	No inflation (2)	5% Inflation (3)
2	1.68	2.19
3	1.68	2.24
4	1.62	2.16
5	1.54	2.05
6	1.47	1.97
10	1.10	1.36
15	0.80	0.89

Note—Assuming 10%/yr decline in efficiency with 100% restoration after cleaning.

Figure 2 shows similar contours for identical conditions except for varying power costs and interest rates. Again the project is highly favorable except at very low power costs and very high interest rates.

Figures 3 and 4 show similar contours with 12% interest rates, $0.07/kWh power costs, and changing alpha factors for both aeration systems. These figures show the effects of inflation. Figure 4 includes 5%/yr inflation while Figure 3 does not. Inflation always makes the aeration upgrading project more favorable, because energy cost is the primary operating cost.

CONCLUSIONS

The preceding example and discussion shows the economic results of upgrading a low-efficiency coarse bubble system to a

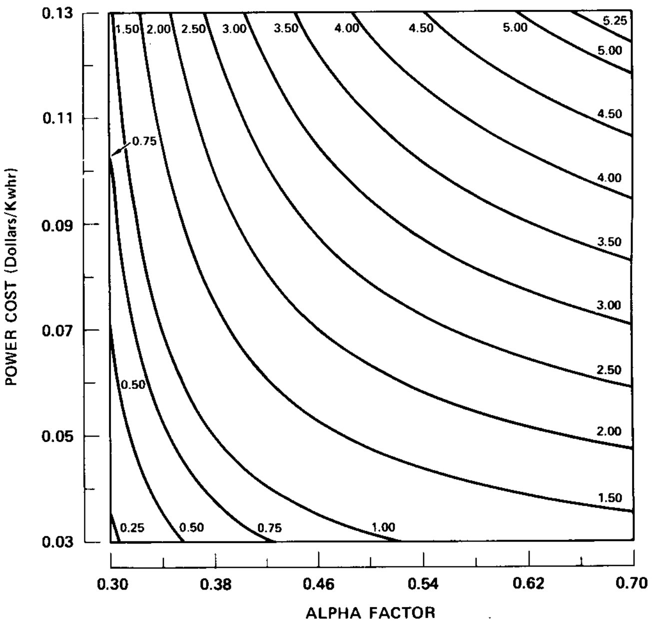

Figure 1—Benefit-cost ratio for varying power cost and fine bubble alpha factor.

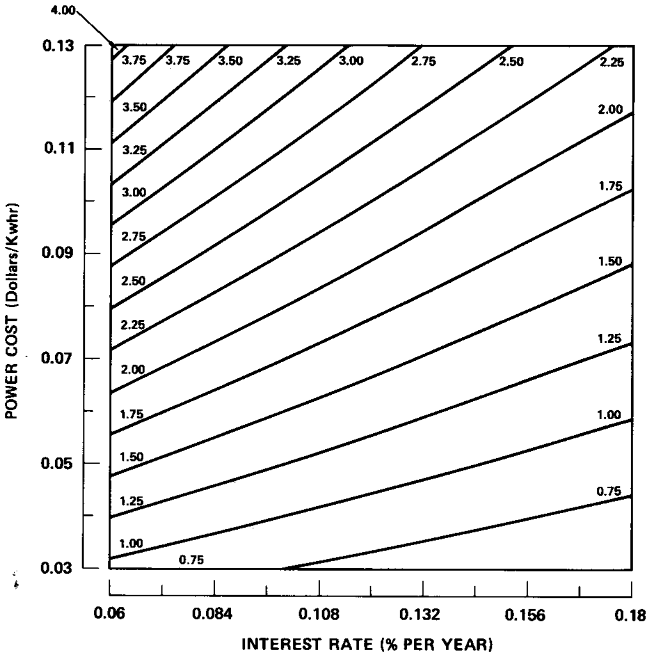

Figure 2—Benefit-cost ratio for varying power cost and interest rate.

high-efficiency fine bubble system. The example is typical because it included a well designed diffuser system and gas flow regime and the assumed cost of the upgrade was average to moderately high. This example is not intended to be typical of any particular aeration system, but to the best of the authors' knowledge, is accurate and representative of a real project. The economics of the proposed project vary from favorable to very favorable, and illustrate the advantages of upgrading low-efficiency aeration systems.

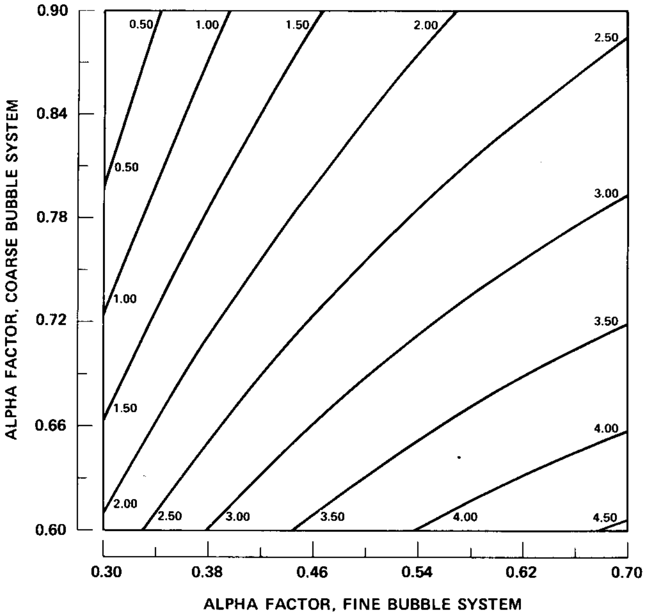

Figure 3—Benefit-cost ratio for varying coarse bubble and fine bubble alpha factors without inflation.

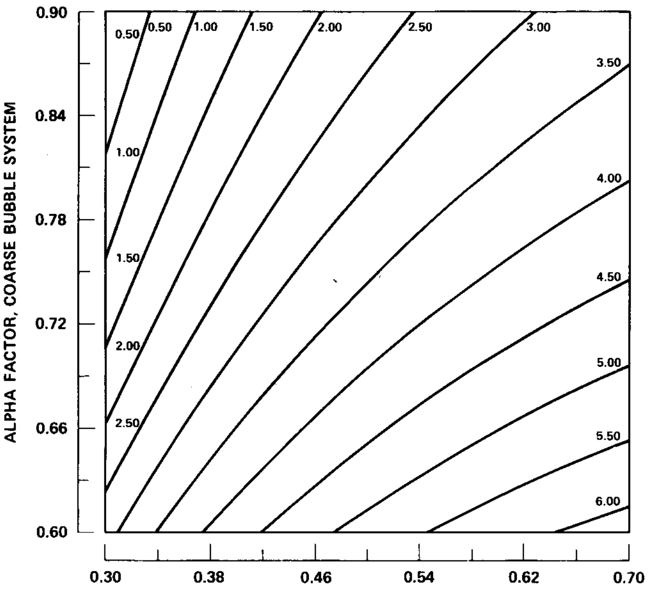

Figure 4—Benefit-cost ratio for varying coarse bubble and fine bubble alpha factors with 5%/yr inflation.

The upgrading project is very favorable when compared to most public works projects.[10] Declining interest rates, or use of tax free bonds to obtain lower interest rates, make the project even more favorable.

The decision to upgrade should not be made solely on an economic basis, but must include operational factors as well. Flexibility is particularly important. The ability to control and maintain the desired DO concentration can be just as important as the efficiency of the aeration system. The analyses show that cleaning, required for economical operation, should be done every 3 years.

The most dramatic result is the automatic DO control. Control would require a small capital investment when compared to an entire retrofit, and savings from this step alone amount to nearly 70% of the energy savings of the entire retrofit.

This example is not intended to promote the use of fine bubble aeration systems, but to promote the use of higher efficiency systems in general. In many applications, low-speed mechanical aerators can provide energy savings similar to those for fine bubble aeration systems and should also be evaluated. If adequate cleaning and maintenance of fine bubble diffusers cannot be provided, the alternative higher efficiency alternatives should be used because inadequate maintenance of the fine-bubble system will nullify most of the energy savings.

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