ANAEROBIC VERSUS AEROBIC TREATMENT IN THE U.S.A.

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ABSTRACT

The economic feasibility of employing anaerobic pretreatment before aerobic polishing treatment was evaluated for high strength industrial wastewaters. The analysis considered a hypothetical, readily biodegradable wastewater with BOD_5 values ranging from 200 to 5,000 mg/l, with a target final effluent value of 20 mg/l soluble BOD_5. The economic analysis included both capital costs and operation and maintenance (O&M) costs, as well as net present value calculations using a 10-yr life and 10 percent interest. The results of the economic modeling indicated that anaerobic pretreatment would be economically feasible at influent wastewater strengths above 1,000 mg/l BOD_5. Treatability evaluations would be required for specific wastewaters, other than most food processing wastewaters, to confirm the technical feasibility of anaerobic pretreatment.

KEYWORDS

Anaerobic pretreatment; anaerobic compared to aerobic treatment; economic comparisons; high strength BOD_5 wastewaters.

INTRODUCTION

National Pollutant Discharge Elimination System (NPDES) permits for industrial wastewater effluents in the United States frequently require discharge levels of 20 mg/l soluble BOD_5 and/or BOD_5 removals of 95 percent or greater. Aerobic biological treatment is the most commonly used process to achieve these effluent requirements. Anaerobic biological treatment alone cannot achieve these performance levels, but it can be cost-effectively employed as pretreatment before aerobic polishing for certain high-strength industrial wastewaters. This paper presents a generalized assessment of when anaerobic pretreatment can be cost-effectively applied, following brief overviews of the contrasts between aerobic and anaerobic biological treatment and of anaerobic treatment alternatives.

ANAEROBIC TREATMENT CONTRASTS WITH AEROBIC TREATMENT

The basic mechanisms and driving forces that allow anaerobic processes to function are the same as those for aerobic systems. The two basic driving forces are as follows:

- Bacteria need energy for growth, support of cell maintenance functions and motility.
- Bacteria require substrate (food) for energy and growth.

The differences between aerobic and anaerobic processes result from the different environmental conditions imposed on the systems. Bacterial cells will, as will all biological reactions, try to achieve maximum cell growth for the least amount of energy expended. Under aerobic conditions free dissolved oxygen is the terminal electron acceptor. This is a highly efficient process. For each unit mass of substrate (i.e. BOD_5) consumed, approximately 70 percent is used for cell growth and 30 percent for energy purposes. Under anoxic conditions, oxygen is obtained from nitrate-nitrogen, which is less efficient because energy must be used to separate the oxygen molecule from the nitrate compound.

Under anaerobic conditions, no molecular oxygen is present and the environment changes from an oxidizing state to a reducing state. This condition can be measured by the oxidation-reduction potential (ORP). ORP values for anaerobic systems will be approximately -490 to -550 mV (Malina, 1962) compared to +50 to +150 mV for aerobic systems. Under anaerobic conditions, alternative electron acceptors must be found. Sulfur can be used if present and will result in the formation of hydrogen sulfide gas. Usually, however, carbon atoms associated with some of the organics will become electron acceptors and be reduced, while other organics will be oxidized to carbon dioxide and volatile acids. This reaction results in end products that still contain large amounts of energy (i.e. the potential to accept electrons) in the form of methane. Therefore, much substrate needs to be processed for the cells to yield enough energy for cell growth and maintenance. Cell reproduction is consequently much lower under anaerobic conditions than aerobic conditions (Pfeffer, et al., 1967).

Some of the specific contrasts between aerobic and anaerobic treatment are briefly reviewed in the following paragraphs.

Temperature

Temperature affects both aerobic and anaerobic reactions, but the anaerobic process requires a higher operating temperature than the aerobic process in order to obtain practically applicable reaction rates (Lawrence, 1971). Available data indicate that a 10°C reduction in temperature reduces both aerobic and anaerobic reaction rates by a factor of two. Loss of treatment efficiency in both the aerobic and the anaerobic processes due to temperature reduction may be compensated for by increasing the biomass. The anaerobic process can often cost-effectively use biogas generated by the process to heat the reactor and maintain performance efficiency.

pH and Alkalinity

Aerobic processes operate most effectively over a range of pH 6.5 to pH 8.5. In most instances, a completely mixed activated sludge (CMAS) system is a self-neutralizing process in that caustic alkalinity reacts with CO_2 generated by the biological reaction and yields bicarbonate. Volatile acids biodegrade to CO_2 and H_2O, and the CO_2 is then stripped from the reactor. No external neutralization is typically required as long as the effluent BOD is less than 25 mg/l.

In anaerobic processes, the methanogenic bacteria are pH sensitive and generally have an optimum range of pH 6.5 to pH 7.5 (Clark and Speece, 1971). It is especially important for the methanobacteria to maintain at least pH 6.2 in the system. If moderate levels of sulfates are present, then it is preferable to maintain pH 7 to pH 8 to avoid hydrogen sulfide toxicity problems. It is desirable to have bicarbonate alkalinity in the range of 2,500 to 5,000 mg/l in order to provide a buffer capacity to handle volatile acid increases with a minimal decrease in pH. Alkalinity and pH are often controlled by adding bicarbonate to the reactor.

Excess Sludge Production and Nutrient Requirements

For most wastewaters, the net sludge yield from aerobic activated sludge treatment is in the order of 0.5 kg VSS/kg COD removed. By contrast, the sludge yield from anaerobic treatment is approximately 0.1 kg VSS/kg COD removed. Anaerobic bacteria contain approximately the same cell composition as all other types of bacteria. Hence nutrients are required in the same proportions in anaerobic and aerobic systems to enable good cell growth. The difference is that cell production is less in anaerobic systems and nutrient requirements are therefore proportionately less. Nitrogen and phosphorus quantities added to the system need to be approximately 8 to 12 percent and 1.5 to 2.5 percent, respectively, of the change in total cell mass. As a rule of thumb, anaerobic waste sludge production and nutrient requirements will be about one-fifth those of aerobic processes.

Summary Comparison

From the above discussion, the respective advantages and disadvantages of anaerobic and aerobic systems are summarized in Table 1. Anaerobic treatment lends itself to situations where readily degradable and high strength wastestreams with reasonably consistent influent characteristics require treatment. Carbohydrates with their high oxygen content are easily metabolized. Wastestreams from food and beverage processing industries contain carbohydrates and are typically well suited for anaerobic treatment. Anaerobic treatment is being more frequently applied to the treatment of complex organic chemicals industry wastewaters, however.

TABLE 1 Comparison of Anaerobic and Aerobic Treatment

Parameter	Anaerobic	Aerobic
Energy Requirements	Low	High
Degree of Treatment	Moderate (60 to 90%)	High (95%+)
Sludge Production	Low	High
Process Stability (to toxic compounds & load changes)	Low to moderate	Moderate to high
Startup Time	2 to 4 months	2 to 4 weeks
Nutrient Requirements	Low	High for certain industrial wastes
Odor	Potential odor problems	Less opportunity for odors
Alkalinity Requirements	High for certain industrial wastes	Low
Biogas Production	Yes (net benefit is contingent on the need for reactor heating)	No

ANAEROBIC TREATMENT ALTERNATIVES

The major obstacles to the application of anaerobic systems for the treatment of industrial wastewater containing soluble organics have historically been the separation of biological solids and treated liquor, process susceptibility to toxic compound shocks, and slow startup times. A number of different proprietary systems have been developed which try to overcome one or more of these problems. In addition, designers have attempted to reduce hydraulic residence times (HRT) to minimize reactor volumes and system costs. The selection of the best system for any particular situation will depend on the wastewater characteristics and the degree of treatment required. Three basic types of anaerobic systems have been developed--dispersed growth, fluidized bed and packed bed. A brief discussion of each of these system types follows.

Dispersed Growth Systems

In dispersed growth anaerobic systems, the biomass is suspended in the reactor by mechanical and/or biogas mixing. These systems are also known as anaerobic contact processes. Most of these systems employ a completely mixed reactor followed by a clarifier with sludge recycle. A vacuum degasifier is typically installed after the reactor to minimize floating sludge in the clarifier. One proprietary dispersed growth system is distinguished by using separate reactors for acid-forming bacteria and methane-forming bacteria.

Dispersed growth systems are the only type which may be economically designed for low organic loading rate operation. Low rate, dispersed growth anaerobic systems operate at loadings of 1 to 2 kg COD/cu m-day and are claimed to be less susceptible to toxic shocks than high rate systems. Low rate systems are typically operated as plug flow anaerobic lagoons with little or no mechanical mixing and no separate clarifiers. The space requirements for low rate systems are considerably greater than those for high rate systems.

Fluidized Bed Systems

In fluidized bed anaerobic systems, the biomass grows on granular media (typically sand) which is expanded (fluidized) by high effluent recycle rates. Uniform hydraulic flow must be maintained across the reactor diameter to avoid short circuiting. Vendors have reported biomass concentrations greater than 40,000 mg/l, attributable to the large surface area provided by the media.

A hybrid of the fluidized bed and dispersed growth systems is the upflow anaerobic sludge blanket (UASB) system, originally developed by CSM-Suiker in the Netherlands. In this system, the anaerobic bacteria themselves form granular media which create a dense (80 to 100 g/l) sludge blanket through which the upflow wastewater passes. The sludge density diminishes towards the top of the reactor where a solids/gas/liquid separation device is installed. Effluent recycle is required to suspend the granular sludge.

Packed Bed Systems

In packed bed systems, the biomass grows on engineered synthetic media similar to those used in aerobic trickling filters. The media may either be randomly packed, in which case the upflow hydraulic regime is typically used, or rigidly constructed, in which case the downflow hydraulic regime may be used.

GENERALIZED COST COMPARISONS

Anaerobic pretreatment is most effectively applied to wastewaters with high concentrations of readily degradable organic constituents. The cost-effectiveness of anaerobic pretreatment is specific to each wastewater and associated parameters (e.g. ability to use biogas, power costs, sludge disposal costs). In this section, however, we have attempted to provide a generalized cost/benefit analysis of when anaerobic pretreatment should be considered.

The general concept is based on achieving effluent discharge limits of 20 mg/l soluble BOD_5 and 30 mg/l TSS. These limits may be achieved either by all-aerobic treatment or by anaerobic/aerobic treatment (Figure 1). The scenarios considered do not include indirect discharge of the effluent through an existing municipal wastewater treatment plant where economies of scale and pre-existing capacity would lower the aerobic treatment cost estimates (both for all-aerobic treatment and for aerobic polishing of an anaerobic system effluent).

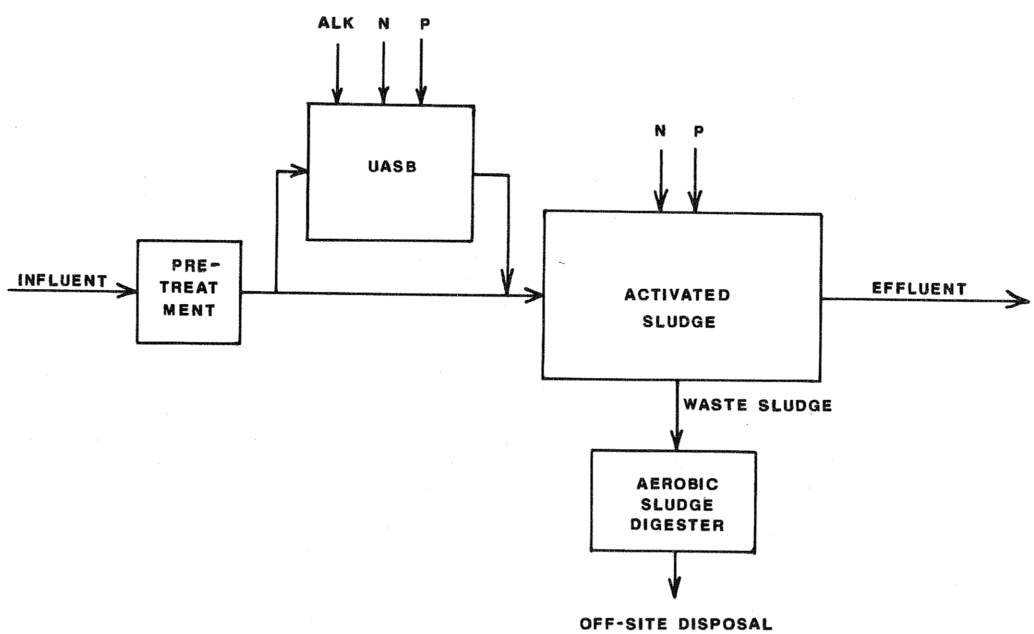

Fig. 1. Generalized flow diagram for process alternatives

General assumptions used in preparing the estimates for the subsequent cost comparisons are listed below:

- Required effluent soluble BOD_5 = 20 mg/l.
- Required effluent TSS = 30 mg/l.
- Influent wastewater requirements for equalization, neutralization and primary clarification are the same for both aerobic and anaerobic treatment alternatives and are hence not included in the analysis.
- Costs of land are excluded.
- Waste biological sludge is non-hazardous and is disposed at a cost of $17/1,000 gal ($4.40/cu m) or $200/ton ($220/1,000 kg) of dry solids assuming solids concentration of 2 percent.
- Labor cost = $20/hr.
- Electricity cost = $75/1,000-kWh.
- Steam cost (150 psi) = $6/1,000 lb ($13.20/1,000 kg).
- Methane value = $4/$10^6$ BTU.
- Influent wastewater contains no N, P, or alkalinity.
- Nitrogen requirements supplied by anhydrous ammonia at $0.20/lb ($0.44/kg).
- Phosphorus requirements supplied by 35 percent phosphoric acid at $0.13/lb H_3PO_4 ($0.29/kg H_3PO_4).
- Alkalinity requirements supplied by caustic soda at $0.10/lb ($0.22/kg).

Costs of the aerobic and anaerobic treatment alternatives were evaluated for readily biodegradable wastewaters, such as those from the food processing industry. It was assumed that no macro-nutrients were present in the wastewater, and that the stream required the addition of stoichiometric quantities of alkalinity (i. e. no alkalinity present in the wastewater). The design and subsequent cost estimation was performed for wastewater strengths ranging from 200 to 5,000 mg/l BOD_5 for the all-aerobic treatment alternative and from 500 to 5,000 mg/l for the anaerobic/aerobic alternative.

The aerobic treatment design was based on the following assumptions:

- Flow = 1 MGD.
- COD:BOD_5 = 1.5:1.
- Reaction rate = 15 day^{-1}.
- F/M = 0.3 g BOD_5/g VSS-day.
- Aeration basin MLVSS = 3,000 mg/l.
- Coarse bubble aeration.
- The aeration basins were designed either as a plug flow configuration or with the use of a selector to suppress filamentous bulking.
- No nitrification.
- No primary treatment.
- Secondary clarifiers solids loading of 400 lb/ft^2-day (1,960 kg/m^2-day).
- Waste activated sludge (1 percent TSS) is aerobically digested (50 percent VSS reduction) and then disposed of off-site.

Major parameters of the resulting aerobic treatment are summarized in Table 2. Turn-key capital costs and some elements of operating and maintenance (O&M) costs were provided by Walker Process Corporation, Aurora, Illinois.

TABLE 2 Aerobic Treatment Parameters

Parameter	Influent Strength, mg/l BOD_5				
	200	500	1,000	2,500	5,000
Aeration Basin Volume, mil gal	0.22	0.56	1.1	2.8	5.6
Aeration Capacity, hp	40	100	200	500	1,000
Aerobic Sludge Digester Volume, mil gal	0.15	0.42	0.88	2.2	4.5
Digester Aeration, hp	15	35	70	175	350

The anaerobic/aerobic treatment alternative consists of a high-rate, upflow anaerobic sludge blanket reactor, followed by an aerobic polishing system. The BOD_5 removal efficiency of the anaerobic reactor was assumed to be 85 percent. The design and cost estimate of the anaerobic reactor were provided by the Biothane Corporation, Camden, New Jersey. The capital and O&M costs for the aerobic polishing system were extrapolated from the data developed for the all-aerobic alternative.

Tables 3 and 4 present the relative capital and O&M costs of the aerobic and anaerobic treatments, respectively. Aerobic polishing costs are not included in Table 4. The costs shown in Tables 3 and 4 are relative to the cost of treating the wastewater with the lowest strength evaluated for each alternative (200 mg/l BOD_5 for aerobic treatment and 500 mg/l BOD_5 for anaerobic treatment).

TABLE 3 Relative Costs For Aerobic Treatment[a]

Item	Wastewater Strength, mg BOD_5/l				
	200	500	1,000	2,500	5,000
Capital Cost	100	159	227	354	555
Operating and Maintenance Costs					
Electricity	100	195	358	800	1,560
Sludge disposal[b]	100	250	500	1,500	2,500
Maintenance[b,c]	100	144	195	284	441
N	100	250	500	1,250	2,500
P	100	250	500	1,250	2,500
Alkalinity	100	105	107	110	110
Labor[b,d]	100	100	100	100	100
O & M Total	100	144	215	411	742
Net Present Value[e]	100	150	220	383	661

[a]Based on information obtained from Walker Process Corporation, Aurora, Illinois, except as noted otherwise.

[b]Estimated by authors.

[c]Assumed to be 2 percent of capital costs for the 200 mg/l BOD_5 plant. For the remaining options, maintenance cost was assumed to be equal to the 200 mg/l option plus 1.5 percent of the capital cost difference between 200 mg/l option and the respective option.

[d]Estimated to be 12 hr of operator time per day.

[e]Calculated for 10 yr, 10 percent interest rate.

TABLE 4 Relative Costs For Anaerobic Treatment (Excluding Aerobic Polishing)[a]

Item	Wastewater Strength, mg BOD_5/l			
	500	1,000	2,500	5,000
Capital Cost[b]	100	127	173	218
Operating and Maintenance Costs				
Electricity	100	100	100	100
Sludge Disposal[c]	100	228	600	1,200
Maintenance[c]	100	127	172	218
N	100	200	500	1,000
P	100	200	500	1,000
Alkalinity[d]	100	144	277	496
Labor[e]	100	100	100	100
Heating[f]	100	100	100	100
Biogas credit	100	226	583	1,190
O & M Total	100	103	111	121
Net Present Value[g]	100	113	136	160

[a] Based on information obtained from Biothane® Corporation, Camden, New Jersey, except as noted otherwise.

[b] To the capital cost provided by the vendor, 10 percent was added for the cost of odor control and gas handling equipment (scrubbers).

[c] Estimated by authors.

[d] Includes cost of caustic soda for gas scrubber (assuming 100 mg H_2S removal per liter of wastewater).

[e] Estimated to be 6 hr of operator time per day.

[f] At influent temperature of 20°C.

[g] Calculated for 10 yr, 10 percent interest rate.

Relative capital costs, O&M costs and net present values (10-yr life and 10 percent interest rate) for the all-aerobic treatment, anaerobic pretreatment and anaerobic/aerobic treatment alternatives are presented in Figures 2 through 4. In these figures, unity (relative value of 1.0) is defined as the point where the costs of the all-aerobic alternative and the anaerobic/aerobic alternative are the same.

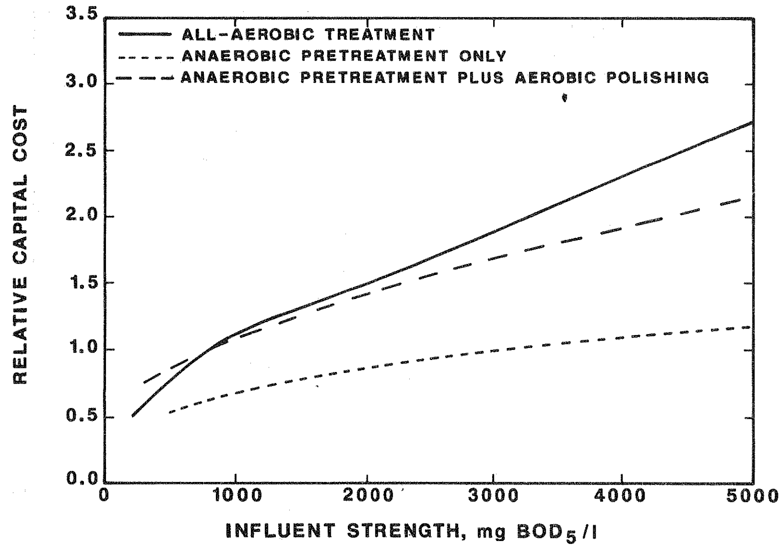

Fig. 2. Comparison of capital costs

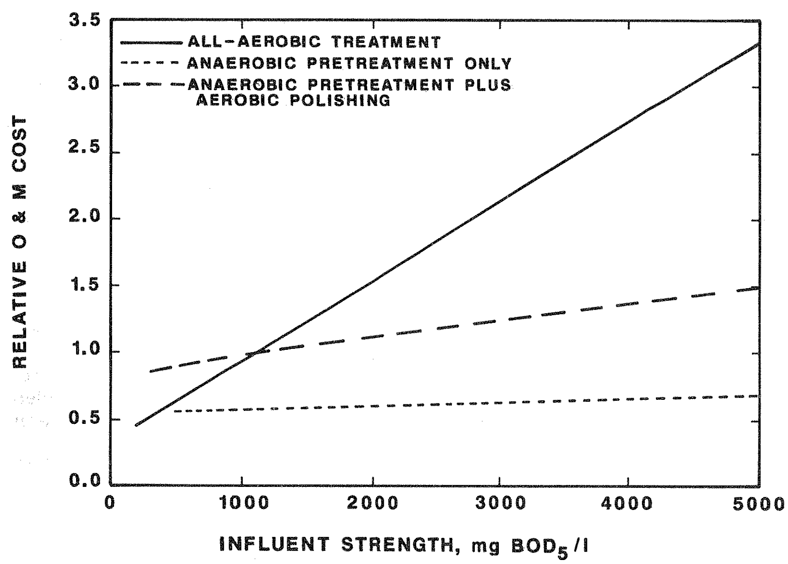

Fig. 3. Comparison of O&M costs

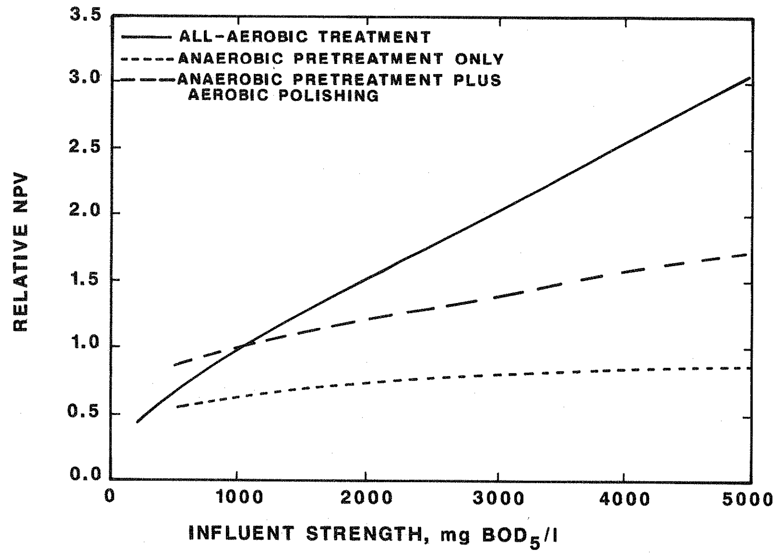

Fig. 4. Comparison of net present values

DISCUSSION AND CONCLUSIONS

The relative impacts of wastewater strength on the individual cost components were presented in Tables 3 and 4. Capital costs of the aerobic system are more sensitive to increasing wastewater strength than those for the anaerobic system (Figure 2). This is a result of proportionately increasing aeration volume required for aerobic treatment at the same F/M. For anaerobic systems, the reactor volume for relatively weak wastewater is controlled by hydraulic considerations, particularly for the upflow anaerobic sludge blanket reactor considered in this comparison.

For the O&M cost components, off-site sludge disposal costs and macro-nutrients costs are linear functions of the wastewater strength for both treatment methods; however, absolute costs for the aerobic option are much higher. The energy requirement for aerobic treatment increases rapidly with wastewater strength, since aeration comprises most of the energy needs. For anaerobic systems, the electricity consumption is much lower and virtually constant for the influent strength range, since only pumping costs are incurred. Maintenance costs for both systems are considered a function of capital costs in this analysis. Alkalinity requirements for anaerobic treatment are higher than for aerobic treatment and increase proportionately with influent strength. This is a consequence of the sensitvity of anaerobic processes to low pH upsets and the necessity to buffer volatile acids generated during the initial reaction step. Labor requirements for both treatment options are not a function of wastewater strength for the plant sizes considered. Heating is specific for anaerobic treatment only. Since heating is mostly a function of the wastewater flow (reactor volume), it does not increase with wastewater strength in the range considered. O&M costs of the anaerobic plant are credited with the biogas generated during the treatment, and the credits are proportional to the mass of organic matter removed (wastewater strength).

When all O&M items for aerobic treatment are considered together, they increase steeply with wastewater strength (Figure 3). Whereas, for anaerobic treatment, O&M costs are virtually constant in the wastewater strength range considered. For even higher wastewater strengths, the biogas credit could potentially totally offset other O&M costs.

The relative net present values (NPV), which combine capital and O&M costs, reflect the much higher sensitivity of aerobic treatment costs to influent strength as compared to anaerobic treatment (Tables 3 and 4, Figure 4). The relative values of the cost items for aerobic treatment, anaerobic pretreatment alone and anaerobic/aerobic treatment were compared in Figures 2, 3, and 4. Both capital and O&M costs and, consequently, NPV curves indicate that, for an influent strength of about 1,000 mg/l BOD_5, the treatment costs for both alternatives are equivalent.

The example used in this paper employed the UASB process and a modified activated sludge process treating a hypothetical, readily degradable wastewater. Depending on such factors as land availability and final effluent requirements, the economics could shift in either direction. The assumption of no available nutrients and alkalinity would modify the operating costs, depending on the availability of these chemicals in the wastewater. Other waste- or site-specific factors which could influence the economics include whether the waste aerobic sludge were digested in the anaerobic system (low-rate systems only); the relative aerobic and anaerobic reaction rates; and the ability to recover and use the biogas.

In summary, due to progress in anaerobic treatment technology and the resulting increasing reliability of this process, anaerobic treatment is considered to be an attractive alternative for a growing number of wastewater treatment applications in the U.S.A.

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