OPTIONS FOR THE RATIONAL DESIGN AND OPERATION OF OXIDATION PONDS

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ABSTRACT

Oxidation ponds can degrade wastewaters at low cost and provide a useful biomass if rational design, operation, and sludge removal practices are carried out. Here, the design of a plug flow Algal Bacterial Clay Treatment System (ABCT) is presented on the bases of both incident sunlight and incoming BOD concentration. Results of kinetic experimental studies are presented in order to determine both optimal and limiting operational parameters. From these experiments, it appeared to be critical to limit pH diurnal variations for effective operation of the treatment system. Empirical computer models were developed to predict reactor parameter variations due to diurnal effects. A computer model based on continuous oxidation reduction potential (redox) measurements appeared to be most useful for automated computer control of variations due to diurnal effects. Chemical addition of CaCl₂ facilitated algal biomass flocculation in order to prepare liquid effluents for plant discharge and to prepare biomass for possible beneficial use.

KEY WORDS

Innovative wastewater treatment; energy efficient; low cost treatment; useful microbial biomass

INTRODUCTION

Oxidation ponds have long been used to treat municipal wastewater in rather unsophisticated earthen structures which have required minimal construction and maintenance costs. Historically, these installations have imitated nature in their utilization of the symbiotic or commensalistic relationship of bacteria and algae. These two microbial classes interact, using photosynthetic and respiration mechanisms to generate oxygen and degrade wastewater pollutants. Bacteria respire, thus ultimately degrading BOD in the wastewater to CO₂ and H₂O via Equation 1.[Reynolds, 1982]

\[ C_{6}H_{14}O_{2}N + 3.35 O_{2} \rightarrow 0.12 NH_{4}^{+} + 0.12 OH^{-} + 1.60 CO_{2} + 0.88 C_{5}H_{7}O_{2}N + 3.62 H_{2}O \] (1)

Equation 1 is a respiration reaction which combines the catabolic bacterial breakdown of substrate (C₆H₁₄O₂N) to produce energy and metabolites, and the anabolic production of new cells (C₅H₇O₂N). The metabolically-produced CO₂ is then used by the algae to generate new algal cells according to Equation 2.[Stumm and Morgan, 1981]

\[ 106 CO_{2} + 16 NH_{4}^{+} + HPO_{4}^{2-} + 100 H_{2}O \rightarrow C_{106}H_{263}O_{110}N_{16}P + 103 O_{2} + 2 H^{+} \] (2)

The oxygen produced by the photosynthetic algae support the bacterial respiration. Little aeration is required for the operation of the oxidation pond and, therefore, energy and cost requirements are reduced. Unfortunately, it is very difficult to separate the microbes, especially the visible algae, from the purified wastewater treatment plant effluent in such systems. Little work has been conducted to optimize the algal sludge removal by conventional empirical pond designers and little attention has been directed toward diurnal photosynthetic effects and the resulting deviations from steady state pond operation. Studies were undertaken in our laboratories to examine the factors affecting the rational design resulting from operating a model reactor, the effects of diurnal variations causing deviations from steady state operation, and techniques for carrying out efficient algal sludge removal.
BACKGROUND

Earlier work by Oswald and his co-workers [1957a, 1957b and 1962] led to the development of the Intensive Algal Wastewater Treatment System (IAWTS). Shelef and his co-workers [1968, 1970 and 1973] further refined this system to a High Rate Algal Pond (HRAP). These algal ponds stabilized wastewater without the normal operating costs of intensive mixing and aeration in conventional wastewater treatment processes. The plug flow hydraulic regime required aeration by a low-energy cage aerator at the pond inlet to overcome anaerobic conditions produced in the wastewater collection system. The folding plug flow channels of the HRAP were approximately 0.5 meter in depth to optimize the photosynthetic production of oxygen. Shelef was able to treat high strength wastewater in Israel in a 2-8 day hydraulic detention time and significantly reduce nitrogen and phosphate, as well.

Carberry and her co-workers [1981, 1989, 1991] have modified the HRAP by adding a small concentration of clay to the plug flow reactor inlet. The resulting Algal Bacterial Clay Treatment (ABCT) process would have several advantages due to the addition of clay; any adverse effects due to transient high concentrations of biodegradable or non-biodegradable pollutants on plug flow respiration reactors would be decreased, the resulting slightly attenuated incident sunlight would dampen photosynthetic diurnal effects of oscillating pH and DO concentrations, and both algal flocculation at the terminal end of the reactor and any subsequent aquaculture feeding process of the sludge would be enhanced. [Ali and Pruder, 1982]. This paper presents ABCT pond designs and operational criteria developed from: (1) incident light calculations developed by Shelef; (2) stoichiometric reactions developed by Reynolds and Stumm & Morgan; and (3) kinetic studies conducted in our laboratory.

MATERIALS AND METHODS

(1) FOR POND DESIGN FROM INCIDENT SUNLIGHT, the following equation for algal production was utilized from Shelef, et al. [1977]:

\[
\text{ALGAL PRODUCTION} = \frac{(\text{CONVERSION EFFICIENCY})(\text{SOLAR INCIDENCE})}{(\text{ENERGY OF FORMATION OR COMBUSTION})}
\]

where \( \text{PRODUCTION} = \text{rate in kg algae/(m}^2 \cdot \text{month}) \)

\( \text{SOLAR INCIDENCE} = f \) (latitude, month of year) in units of kcal/(m\(^2 \cdot \) month)

\( \text{ENERGY OF FORMATION OR COMBUSTION} = 0.0055 \text{ kcal/kilogram algae} \)

From Equation 1, the CO\(_2\) produced from the incoming BOD can be calculated by Equation 4, as follows:

\[
\left(\frac{\text{gm CO}_2 \text{ as BOD}_m}{\text{m}^3}\right) \left(\frac{\text{mole O}_2}{32 \text{ gm } \text{O}_2}\right) \left(\frac{1.60 \text{ mole } \text{CO}_2}{3.35 \text{ mole } \text{O}_2}\right) \left(\frac{44 \text{ gm } \text{CO}_2}{\text{mole } \text{CO}_2}\right) = \frac{x \text{ gm } \text{CO}_2}{\text{m}^3}
\]

Simplification yields a CO\(_2\) production factor, as follows:

\[
\frac{0.657 \text{ gm CO}_2 \text{ as incoming BOD}}{\text{m}^3} = \frac{x \text{ gm } \text{CO}_2}{\text{m}^3}
\]

From Equation 2, the CO\(_2\) required for algal production can be calculated as follows:

\[
\left(\frac{106 \text{ mole } \text{CO}_2}{\text{mole algae}}\right) \left(\frac{44 \text{ gm } \text{CO}_2}{\text{mole } \text{CO}_2}\right) \left(\frac{\text{mole algae}}{3542 \text{ gm algae}}\right) = \frac{1.32 \text{ gm } \text{CO}_2 \text{ required}}{\text{gm algae produced}}
\]

or 0.76 gm algae produced per gm CO\(_2\) consumed.

From Equation 2, the CO\(_2\) required for O\(_2\) production can be calculated as follows:

\[
\left(\frac{103 \text{ mole } \text{O}_2}{\text{mole algae}}\right) \left(\frac{\text{mole algae}}{3542 \text{ gm algae}}\right) \left(\frac{32 \text{ gm } \text{O}_2}{\text{mole } \text{O}_2}\right) = \frac{0.93 \text{ gm } \text{O}_2}{\text{gm algae}}
\]

and therefore,

\[
\left(\frac{0.93 \text{ gm } \text{O}_2}{\text{gm algae}}\right) \left(\frac{\text{gm algae}}{1.32 \text{ gm } \text{CO}_2}\right) = \frac{0.7 \text{ gm } \text{O}_2 \text{ produced}}{\text{gm CO}_2 \text{ consumed}}
\]

From Equation 1, the O\(_2\) required for incoming BOD degradation can be calculated as follows:
From Equation 3, the production of algae due to sunlight intensities can be calculated, according to solar incidence provided by Liu and Jordan [1976]. From Equations 4, 5 and 6, the algal production due to BOD input can be calculated. From a dimensional analysis of the two approaches one can see that the required surface area can be calculated by dividing Equation 3 for algal production (in units of kg algae per m² per month) by the algal production from Equations 4, 5 and 6 (in units of kg algae per month). The resulting surface area can be multiplied by the limiting depth, 0.5 meter as specified by Shelef [1970] to obtain the pond volume. The detention time required is then obtained by multiplying by the volumetric flow rate.

(2) FOR POND DESIGN USING STOICHIOMETRY, one must know the CO₂ uptake rate by algae. According to Pruder [1981] algae can use 10 gm carbon per m² per 14 hours of sunlight. This value for carbon uptake can be converted to CO₂ uptake by Equation 10.

\[
\text{UPTAKE} = \left( \frac{10 \text{ gm carbon}}{m^2 \cdot 14 \text{ hr sunlight}} \right) \left( \frac{44 \text{ gm}}{\text{mole CO}_2} \right) \left( \frac{\text{mole carbon}}{12 \text{ gm}} \right)
\]

or,

\[
\text{UPTAKE} = \frac{2.62 \text{ gm CO}_2}{m^2 \cdot \text{hr}'}
\]

where hr' = hours of sunlight.

From Equations 4 and 5, the CO₂ produced from incoming BOD can be calculated per unit volume. By limiting the pond depth to 0.5 meter and multiplying the CO₂ produced by that factor of 0.657, the pond surface area can be calculated. If the calculated surface area is divided by the CO₂ uptake rate of 2.62 gm CO₂ per m² per hour of sunlight from Equation 11, then the required number of sunlight hours can be determined. The total hydraulic detention time can be calculated by dividing the number of required sunlight hours by the number of sunlight hours available per day.

(3) FOR POND DESIGN USING EXPERIMENTALLY-DETERMINED KINETIC RATE CONSTANTS, various batch experiments were conducted to simulate a plug flow reactor. Optimal conditions for wastewater biodegradation were determined according to Carberry and Henshaw [1989]. In early experiments, the effects of diurnal variations were controlled by automatic acid/base additions to the electronic biostat 5-liter reactor. Michaelis-Menten kinetics were used to calculate the maximum degradation rate constant, \( k_o \), and the half velocity constant, \( K_S \), according to Equation 12.

\[
\frac{-r_s}{S} = \frac{k_o S}{K_S + S}
\]

where \( r_s \) = observed specific substrate uptake rate

\( S = \) BOD concentration

\( K_S = \) half velocity constant for substrate uptake

The Monod Equation was used to determine bacterial growth according to Equations 13 and 14.

\[
\mu = \frac{\mu_{\text{max}} S}{K_M + S}
\]

where \( \mu_{\text{max}} \) = maximum specific bacterial growth rate

\( \mu = \) observed specific bacterial growth rate,

\( K_M = \) half velocity constant for growth, and,

\[
\mu_{\text{max}} = k_o Y
\]

where \( Y = \) bacterial yield

Equations 4, 5, and 6 were used to predict algal production, and the experimental results were compared to the predicted results. These batch experiments determined optimal conditions for pond design.

The reactor was operated during later experiments first in a continuous flow, pH-controlled mode and then in an uncontrolled mode with no automatic additions of acid or base to overcome pH deviations caused by photosynthetic diurnal variations. These latter experiments were conducted according to Carberry and Brunner [1991], in which probe
output voltages were channeled from the biostat reactor for pH, O₂, and CO₂, and from the Beckman redox meter through the Keithley Data Acquisition System (KDAS) to an IBM PC AT personal computer. Four different extended experiments were conducted using 12-hour photoperiods as previously, but the pH was not controlled. After about a week of running in the batch mode on the initial glucose input, daily inputs of glucose began. The glucose was dissolved in 250 ml of synthetic waste or water and added to the reactor in a fed batch mode. Comparable sample volumes were removed from the reactor with a wide-mouth pipette for analysis and for maintenance of constant reactor volume. Results from these latter experiments were used to develop empirical equations used in two computer models to predict CO₂, O₂ and pH changes over time. From plots of CO₂, O₂ and pH, clearly linear trends were evident. For example, pH linearly increased or decreased as CO₂ decreased or increased, respectively. For each test then, the slopes of the various linear portions of each CO₂, O₂, and pH curve were calculated, averaged, and classified for empirical computer model development. COD also linearly declined until the final COD was reached, and an average slope value was defined for COD changes as well.

One computer model based on COD, Model I, and the second model based on redox potential, Model II, were developed. For fed batch periods of the experiments, all parameter data were separated into 24 hour periods. The last value for each 24-hour period was used as the initial value for the subsequent 24 hour period. Measured values for each experimental variation were compared to predicted values for both Model I, based on COD, and for Model II, based on redox potential.

RESULTS

Design calculations using considerations of incident sunlight, stoichiometry and degradation kinetics follow:

1. **Incident sunlight:** Monthly incident sunlight intensities were obtained from Liu and Jordan [1979] for a latitude of 39° 30’ comparable to Delaware. Calculations were conducted for a hypothetical wastewater with a 1 MGD flow rate (3800 m³/day) and an incoming BOD concentration of 300 mg/l. Results for monthly calculations are presented in Table 1.

<table>
<thead>
<tr>
<th>MONTH</th>
<th>Intensity from Eq. 3 (\text{m}^2 \cdot \text{month} \times 10^4)</th>
<th>Production from Eq. 2 (\text{kg} \cdot \text{m}^2 \cdot \text{month})</th>
<th>Production (\text{kg} \cdot \text{mo} \times 10^3)</th>
<th>(\theta) Hydraulic</th>
<th>Surface Area (\text{hectare})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>4.8</td>
<td>0.260</td>
<td>17.7</td>
<td>8.9</td>
<td>6.76</td>
</tr>
<tr>
<td>Feb</td>
<td>7.0</td>
<td>0.379</td>
<td>15.4</td>
<td>5.3</td>
<td>4.03</td>
</tr>
<tr>
<td>Mar</td>
<td>9.7</td>
<td>0.526</td>
<td>17.7</td>
<td>4.4</td>
<td>3.34</td>
</tr>
<tr>
<td>Apr</td>
<td>12.4</td>
<td>0.672</td>
<td>17.1</td>
<td>3.3</td>
<td>2.51</td>
</tr>
<tr>
<td>May</td>
<td>14.7</td>
<td>0.796</td>
<td>17.7</td>
<td>2.9</td>
<td>2.20</td>
</tr>
<tr>
<td>Jun</td>
<td>16.0</td>
<td>0.867</td>
<td>17.1</td>
<td>2.6</td>
<td>1.98</td>
</tr>
<tr>
<td>Jul</td>
<td>15.9</td>
<td>0.861</td>
<td>17.1</td>
<td>2.6</td>
<td>1.98</td>
</tr>
<tr>
<td>Aug</td>
<td>14.0</td>
<td>0.758</td>
<td>17.7</td>
<td>3.1</td>
<td>2.33</td>
</tr>
<tr>
<td>Sep</td>
<td>11.8</td>
<td>0.639</td>
<td>17.1</td>
<td>3.5</td>
<td>2.66</td>
</tr>
<tr>
<td>Oct</td>
<td>8.7</td>
<td>0.471</td>
<td>17.7</td>
<td>4.9</td>
<td>3.72</td>
</tr>
<tr>
<td>Nov</td>
<td>5.9</td>
<td>0.320</td>
<td>17.7</td>
<td>7.3</td>
<td>5.55</td>
</tr>
<tr>
<td>Dec</td>
<td>4.3</td>
<td>0.233</td>
<td>17.7</td>
<td>9.9</td>
<td>7.52</td>
</tr>
</tbody>
</table>

Results presented in Table 1 indicate that for the months of November, December and January, the pond surface area required is greater than 5 hectares. A recommended design for such a system would depend on discharge levels permitted by the responsible regulatory agency. In the summer, which presents the greatest public health danger to untreated wastewater discharges, the pond system would work most efficiently. If higher levels of BOD discharge would be permitted in the winter, then a series of three 2-hectare ponds would be effective for all but two winter months. During the winter months, the three 2-hectare ponds would still significantly reduce the discharged BOD, and in the summer when all three ponds would not be needed, one or more ponds could be by-passed for maintenance.

2. **Stoichiometric considerations:** From Equation 11, a factor was calculated for 2.62 gm CO₂ used per m² per hour of sunlight by algae. For a wastewater of 300 mg/l and from Equation 5 which indicated that 0.657 gm CO₂ were produced per gram of BOD, the resulting calculation follows:
Design and operation of oxidation ponds

\[
\Theta' = \left( \frac{300 \text{ gm BOD}}{\text{m}^3} \right) \left( \frac{0.657 \text{ gm CO}_2}{\text{gm BOD}} \right) (0.5 \text{ m depth})
\]

\[= 98.7 \frac{\text{gm CO}_2}{\text{m}^2}\]

(15)

where \(\Theta'\) = sunlit hydraulic detention time

\[
\Theta' = \frac{\text{CO}_2 \text{ production/m}^2}{\text{CO}_2 \text{ uptake per m}^2 \text{ per hr'}}
\]

\[
\Theta' = \frac{98.7 \text{ gm CO}_2/\text{m}^2}{2.62 \text{ gm CO}_2/\text{m}^2 - \text{ hr'}}
\]

(16)

where \(hr'\) = hours of sunlight

\[
\Theta' = 37.7 \text{ hr'}
\]

(17)

\[
\Theta_{Hydraulic} = \frac{\Theta'}{\text{hrs sunlight per day}}
\]

(18)

Since the hours of sunlight per day vary by the month, Table 2 presents required hydraulic detention times and resulting pond surface area for each month from Equations 17 and 18.

### Table 2: POND DESIGNS FROM STOICHIOMETRIC CONSIDERATIONS

<table>
<thead>
<tr>
<th>MONTH</th>
<th>hrs sunlight per day</th>
<th>(\Theta_{Hydraulic}) days</th>
<th>Surface Area Hectare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>8.5</td>
<td>4.4</td>
<td>3.34</td>
</tr>
<tr>
<td>Feb</td>
<td>9</td>
<td>4.2</td>
<td>3.19</td>
</tr>
<tr>
<td>Mar</td>
<td>10</td>
<td>3.8</td>
<td>2.89</td>
</tr>
<tr>
<td>Apr</td>
<td>11</td>
<td>3.4</td>
<td>2.58</td>
</tr>
<tr>
<td>May</td>
<td>12</td>
<td>3.1</td>
<td>2.36</td>
</tr>
<tr>
<td>Jun</td>
<td>13</td>
<td>2.9</td>
<td>2.20</td>
</tr>
<tr>
<td>Jul</td>
<td>12</td>
<td>3.1</td>
<td>2.36</td>
</tr>
<tr>
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<td>11</td>
<td>3.4</td>
<td>2.58</td>
</tr>
<tr>
<td>Sep</td>
<td>10</td>
<td>3.8</td>
<td>2.89</td>
</tr>
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</tr>
<tr>
<td>Nov</td>
<td>8.5</td>
<td>4.4</td>
<td>3.34</td>
</tr>
<tr>
<td>Dec</td>
<td>8.0</td>
<td>4.7</td>
<td>3.57</td>
</tr>
</tbody>
</table>

These results indicate that sunlight intensity is not a variable in these stoichiometric calculations. Instead, the stoichiometric design approach considers the sunlight factor to be only a binary off/on system, regardless of the angle of incidence or intensity. If one compares the stoichiometric design results from Table 2 with the previous results in Table 1 which considered sunlight intensity, one can see the apparent inadequacy of the stoichiometric design approach. None of the stoichiometric monthly hydraulic detention times in Table 2 exceed 4 days, while the November, December, and January hydraulic detention times all exceed 5 days when sunlight intensity is considered in the Table 1 calculations. Comparison of these two approaches indicates that when sunlight intensity is not a limiting factor, stoichiometric calculations provide an adequate design approach for oxidation ponds. Conversely, at northerly latitudes where sunlight intensity becomes limiting, stoichiometric design calculations are inadequate.

3. Experimental kinetic design parameters: Carberry and Henshaw [1989] determined that minimal mixing was imperative for effective algal \(\text{CO}_2\) uptake. They also showed that a 25 mg/l clay addition had no effect on substrate removal or bacterial growth and only slightly impeded algal growth. The comparison of experimental results with and
without clay are illustrated in Figure 1. Temperature variations indicated that bacterial respiration rate increased at higher temperature while algal growth rate decreased. Conversely, at lower temperature, the bacterial respiration rate was suppressed while algal growth was increased. These results are shown in Figure 2. These results are important because they indicate that seasonal operational fluctuations will be dampened. For example, in summer months, when sunlight intensity and ambient temperatures are high, bacterial degradation rates will be fast if enough DO can remain in the water to support accelerated respiration rates. Probably, in the summer when ambient temperatures and water temperatures are elevated, the resulting decreased capacity for water to contain DO is not critical, because the respiring bacteria will utilize any photosynthetically-produced DO immediately. During the winter months when temperatures are lowered and sunlight duration and intensity are less, the algae can produce less oxygen. Under extended dark conditions, the algae can in fact respire, thus consuming oxygen. Our work did not determine whether a DO deficit produced by such conditions would lower the biodegradation rate, because these experiments used alternating 12-hour light/dark periods continuously. In the field operation of a pond, however, which would experience effects of seasonal variation in length of alternating light and dark periods, auxiliary aeration might be required during winter months when photosynthetic oxygen production is diminished and both bacteria and algae could be respiring.

![Figure 1. Degradation and Growth Results with and without Clay.](image1)

![Figure 2. Degradation and Growth with Clay at 16 °C and 30 °C.](image2)

For multiple experiments of comparable substrate concentration, the maximum specific substrate degradation rate constant was an average of 0.41 hr⁻¹, for alternating light-dark periods of 12 hours. The average half velocity constant, $K_s$, for the same experiments was 319 mg/l, a comparable value to the 300 mg/l incoming BOD value used in the previous calculations for hypothetical wastewater. By definition, at $K_s$ the degradation rate is 1/2 the maximum velocity. Since the hypothetical wastewater used for previous calculations contains a BOD of 300 mg/l which is comparable to the measured $K_s$ of 319 mg/l, the biodegradation rate constant should be half the maximum rate for this hypothetical wastewater, and the degradation rate can be modeled by a first order reaction. Since a plug flow reactor can be simulated by a batch reactor expression, Equation 19 was used to calculate the BOD concentration at any time $t$.

$$BOD_{out} = (BOD_{in})e^{-kt} \quad (19)$$

Use of this equation to determine reaction time required to reduce the BOD assumes that BOD, not oxygen, is the limiting reactant. Figures 1 and 2 indicate that the BOD used in these experiments is reduced to very low values in less than a day's time. Calculations of BOD reduction using Equation 19 are presented in Table 3 and indicate comparable BOD biodegradation rates to those illustrated in Figures 1 and 2.

<table>
<thead>
<tr>
<th>Table 3: BOD BIODEGRADATION IN PLUG FLOW REACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>time, hours</td>
</tr>
<tr>
<td>BOD, mg/l</td>
</tr>
</tbody>
</table>

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These calculations from experimental results indicated that BOD reduction rates would not be limiting unless oxygen were the limiting reactant. This consideration is most important for the oxidation pond, since only minimal aeration is provided in order to reduce costs. Here, the principal source of oxygen must be from algal photosynthesis. Algal photosynthetic production of oxygen probably controls the rate of BOD degradation, although our experiments do not explicitly examine this possibility. It was imperative, therefore, to measure the effects of photosynthetic algal oxygen production under extended, non-batch conditions. Since the DO production would take place only during light periods, it was critical to measure the diurnal variations of DO and CO₂, as well as the resulting pH fluctuations. These tests were carried out in the electronically monitored biostat for several days, at first, under continuous flow, pH-controlled conditions. Results under pH-controlled, continuous flow conditions are illustrated in Figure 3 for DO and CO₂. In this figure, one can see the fluctuating concentrations of DO and CO₂ with alternating 12-hour photo periods of light and darkness. One can also see that during the first day, the lag in algal growth and photosynthetic oxygen production provides little oxygen for bacterial respiration. However, substrate is removed by the bacteria and CO₂ is produced. It is not until the second day of operation that much measurable DO is produced by photosynthesis. By then the substrate is completely reduced from the first day and the newly photosynthetically produced oxygen can be used to degrade the second day of feed.

Subsequent days' results followed predictably, since the algae were growing and photosynthesizing adequately. Under these conditions, the pH was automatically controlled between 6.2 and 8.8 by dispensing acid or base to the reactor when these pre-set levels were breached. Resulting pH fluctuations are presented in Figure 4.

This figure illustrates that very wide fluctuations in pH occurred due to diurnal variation in DO and CO₂. Comparable experiments were conducted, therefore, without pH control of the biostat reactor, using 12-hour light and dark photo periods as before. Each of the latter four experiments was divided into two time periods: a one-week period of batch operation, but with no pH control, and a one-week period of fed batch operation with concentrated daily additions of small volumes of feed and comparable mixed liquor removal while the reactor pH was not controlled. For the period of batch operation, results from four tests were quite similar, regardless of whether synthetic waste or distilled, de-ionized water served as the liquid medium, regardless of the reactant ratios, and regardless of whether pH was controlled or not. Figures 5 and 6 present typical results for Test 3, in which synthetic waste was used as the liquid medium and pH was not controlled. As expected, the results indicated that CO₂ and O₂ were in opposition, and that CO₂ concentration initially increased and peaked about mid-day of the second day, when the algal lag period ceased. Once the initial glucose concentration was metabolized by the bacteria and the resulting metabolically-produced CO₂ metabolized by the algae, the CO₂ never rose significantly again, the pH rose and varied only due to diurnal fluctuations during light and dark periods. The dissolved oxygen initially decreased rapidly due to the bacterial metabolism of the glucose during the algal lag period. Once the algae began to grow and photosynthesize, the dissolved oxygen concentration stabilized with diurnal fluctuations centering at a mid-point concentration about 6 mg/l. It is very interesting to note that for a one-day period, the system was devoid of oxygen near the beginning of the experiment. This condition occurred in all experiments, as noted above, and apparently caused no detrimental effects. The measured redox potential was directly affected by the dissolved oxygen concentration, as shown in Figure 6, and provided a very sensitive measure of the dissolved oxygen. Results from these batch operations for the algae, bacteria and glucose are not shown for simplicity,
but they resembled results from earlier experiments shown in Figures 1 and 2. Biomass results were typical for these latter experiments, with the bacteria exhibiting no lag period, the algae underwent a lag period of approximately one-day, and the glucose degradation took place in a first-order, exponentially decreasing manner.

FIGURE 5. Inverse Relationship of Diurnal Variation in CO₂ and pH.

FIGURE 6. Direct Relationship of O₂ and Redox Potential.

For the experimental period in which daily inputs of glucose were added on a fed batch basis, typical results are shown in Figures 7 and 8. These results illustrate the impact of daily substrate input on the diurnal fluctuations shown previously. Results from these experimental periods are much different than those from pH-controlled batch or continuous flow experiments and from the uncontrolled pH periods of batch operation. Figures 7 and 8 illustrate the previously-noted correlations in DO and redox potential, as well as the inverse correlation between CO₂ and pH. In addition, these figures should be compared to Figures 9 and 10. Figure 9 presents the chlorophyll a data, which indicated that algal viability began to deteriorate around 9 days (13,000 minutes), and the resulting lack of photosynthetic activity and concomitant oxygen production prevented the pH from returning to a near-neutral value. The reduced pH inactivated the algae, but the bacteria continued to degrade the glucose, as shown in Figure 10. As the pH continued to decline, the system could not recover, however, and the fed batch experiment was terminated.

FIGURE 7. Diurnal CO₂ Variation and Uncontrolled pH.

FIGURE 8. Diurnal O₂ Variation and Corresponding Redox Potential.
It should be noted that these fed batch experiments with uncontrolled pH were conducted in this manner in order to simulate, as closely as possible, full-scale prototype operation experiencing daily BOD peaks in a plug flow tank. In a continuous flow prototype operation, however, back mixing would occur and would dampen the fluctuations measured in the laboratory reactor. In addition, the detention time in a full-scale plant would normally not exceed 4 or 5 days, so the late deterioration of the laboratory reactor would be prevented. These experiments, conducted partially on a batch basis and partly on a fed batch basis, were illustrative, in that 1) the first phase defined mean operating conditions and 2) the latter phase defined the acceptable limits of deviation from the mean conditions under a worst case scenario. The critical parameter appeared to be the pH, which could easily be controlled in a full-scale plant by the addition of lime.

Two data-fitting models were developed from results of these experiments as described in Carberry and Brunner [1991]. Model I was based on COD, while Model II used redox potentials to predict CO₂ and O₂ variation. Results indicated that when the redox value reached a minimum, the CO₂ would peak and start to decrease. The redox values then increased to a plateau value and leveled off. At this point, O₂ levels increased from zero, and afterward, the light conditions and COD levels controlled CO₂ and O₂. Typical results are presented in Figures 11, 12, 13 and 14 for plots of the measured parameters CO₂, O₂, pH and redox potential, respectively, superimposed on predicted values from Models I and II. These results are from the second day of the fill and draw period of Test 3, which utilized synthetic waste and had no pH control. Results indicated that if COD were greater than the final COD, whether during a light or dark period, then CO₂ would continue to rise, pH decreased and O₂ increased at the previously-determined rates for the given COD and light conditions. If conditions were dark, however, CO₂ would increase, pH decreased and O₂ also now decreased due to respiration of both algae and bacteria. For the models, limits were set at minimums of 0.01 mg/l for CO₂ and O₂ to prevent division by zero, and at a maximum value of 8.24 mg/l for DO saturation at 25 °C. The redox values also followed a linear pattern of rapid decrease to a minimum, followed by a rapid increase to an average of 152 mV above the minimum, and then leveled off to a fairly flat slope for the remainder of the 24 hours. Again, using the average minimum value and average slopes, redox potentials were calculated and used to predict CO₂ and O₂. The shapes of the curves for all parameters were well predicted when compared to the shape of the actual data, as can be seen by visual inspection of the graphs. Percent deviation of model predictions from the measured values varied for any given parameter, but visual inspection of these plots indicated that deviations often were due to a time lag between the predicted and measured parameter values. For Test 3, Model I was a better predictor of CO₂ by about a factor of two over Model II. For other experiments though, neither model was consistently better than the other. But because redox potential is a sensitive indicator of the state of the aqueous environment (incorporating dissolved gas concentrations, pH, etc.), Model II could more easily be implemented at a treatment site for an automatic system of sensing and computer control.

The final operational consideration of algal biomass flocculation and removal was examined experimentally at the end of several experiments which were not terminated due to operational failure. Algal flocculation was initiated by the chemical addition of CaCl₂ at a concentration of 100 mg/l at pH of 8.5. This procedure followed recommendations by Sukenik and Shelef [1984]. The chemical was added until the biomass flocculated; then mixing was stopped and the biomass quickly settled. Measurements of the mixed liquor prior to flocculation and of the clear supernatant after
flocculation indicated that 99.9% of the solids were removed consistently. The Sludge Volume Index, unfortunately, was not determined, but the flocculated sludge was nicely concentrated and would be suitable for dewatering. The sludge could possibly be used as a feed supplement for cattle, for aquaculture feed, or for soil amendment, providing that heavy metals and viruses were not present at toxic levels.

**CONCLUSIONS**

A comprehensive approach to the design and operation of oxidation ponds must consider whether incoming wastewater BOD concentration or the prevailing incident sunlight would be limiting to the treatment system. For the hypothetical case considered here, the incident sunlight at a northern latitude of approximately 40° is limiting during winter months. The pond design option based on limiting sunlight would therefore control the design.

Experiments conducted under conditions when incident sunlight was not limiting were able to determine optimum and deviant operating conditions. These experiments indicated that bacterial respiration reactions could quickly reduce the incoming BOD concentrations. Consistently, the algal photosynthetic activity produced sufficient oxygen to support bacterial respiration once the algal growth lag in the batch reactor was overcome. Operational variables were examined
in continuous flow and in fed batch reactor modes. These latter results clearly demonstrated diurnal effects and the limits of pH fluctuations which could not be exceeded. The addition of calcium to the spent reactor contents successfully initiated algal biomass flocculation and sedimentation.

Presumably, at geographical latitudes where sunlight intensity is not limiting, the stoichiometric design approach to pond design would be appropriate. In this case, the same operational considerations determined from laboratory results cited above would be applicable, since these experiments were conducted under conditions when sunlight was not limiting.

On the basis of these conclusions, calculations for annual operation of the 6-hectare pond design are summarized in Figure 15. One can see that there is a deficit of oxygen production which will need to be overcome by operating the cage aerator.

![Diagram](https://iwaponline.com/wst/article-pdf/24/5/21/102025/21.pdf)

**FIGURE 15. Operational Input and Output of 6-Hectare ABCT Pond on Annual Basis.**

**REFERENCES**


