OXYGEN UPTAKE CALCULATIONS

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Of all the ingredients necessary for the stabilization of wastewater, oxygen is primary. It has a role in almost all chemical and biological reactions in a stabilization pond environment. When accessible to the biology and chemicals requiring it, oxygen will be used at a pace dictated by the speed of the reactions in which it takes part (kinetics). An abundance of oxygen, however, does not, of itself, accelerate these reactions. This paper focuses on the mechanisms of oxygen uptake and how the functions of the Pond Doctor technology, operating under the Controlled Mix Stabilization Process (**CMS™ Process),** influences these principles.

"Oxygen uptake" is the term generally ascribed to the rate at which "users" of oxygen subtract it from the environment in which it may be present. A number of life forms and chemicals existing in a stabilization pond demand oxygen in some form (free oxygen, O_2, or elemental oxygen, O) and at some stage in their progression towards stability. The magnitude of this demand varies in terms of quantity, strength, and time. The measure of each of these variables against all of the possible users of oxygen is very complex, but has been reasonably approximated through experimentation and theoretical calculations.

For example, disregarding phosphorus, sulfur, and trace elements, the use of oxygen by organic matter in sewage in a thoroughly mixed pond has been found experimentally by Oswald, Hee, and Gottaas to follow the reaction:

$$C_{11}H_{29}O_7N + 14O_2 + H^+ \rightarrow 11CO_2 + 13H_2O + NH_4^+ \qquad (1)$$

This is considered a "first stage" reaction since the first demand that must be satisfied is made by the carbonaceous components, sometimes referred to as the *ultimate carbonaceous* BOD (UBOD).

The second stage begins when the carbonaceous BOD ($CBOD_5$) is mostly satisfied and the demand by nitrogen compounds begins, as illustrated in Figure 1. This nitrification demand requires a "habitat" for nitrifying organisms, such as the fixed biofilm that may develop on surfaces in the aerobic zones of a pond. Since the sides and bottom of a typical facultative lagoon are normally anaerobic, there is little chance that these nitrifiers can become established.

In addition to a biofilm habitat, the nitrifiers'' growth and sustenance are dependent upon dissolved oxygen (DO) and soluble BOD_5 concentrations, wastewater temperature, pH and alkalinity, flows, and loading variability. Field data obtained from rotating biological contactor nitrification designs (a device that provides an artificial habitat), indicate that nitrification is typically observed when the soluble BOD_5 declines to 15 mg/l, and maximum nitrification occurs when soluble BOD_5 concentrations drop to 10 mg/l or less.(1) Oswald found that the oxidation of ammonium ion (NH_4^+) to nitrate rarely occurs in stabilization ponds, as it is either lost to the air, assimilated by algae, or precipitated during high periods of pH, before nitrification can be established.(2)

Without consideration for oxygen uptake in nitrification, from equation (1), one can calculate the weight of molecular oxygen required to completely oxidize organic matter. Using molecular weights and a stoichiometric (electron-balanced) equation, the amount of oxygen required is found to be 1.56 times

the weight of the organic matter oxidized. This finding implies that the free oxygen supply (from all sources) must be about 56% greater than the desired $CBOD_5$ reduction.
This calculation only predicts the total weight of oxygen required. The rate at which this quantity is used, or uptake, requires another calculation. Oxygen uptake is influenced by temperature, mixing, and the stage of the life cycle microorganisms may be in.

With regard to the life cycle influence, three oxygen-consuming phases occur. First, a portion of the waste is oxidized to end products that produce energy for cell maintenance and the synthesis of new cell tissue. This is the "Oxidation" phase. Simultaneously, in the second phase, some of the waste is converted into new cell tissue using part of the energy released during oxidation. This is the "Synthesis" phase. In the final phase, when the organic matter is used up, the new cells begin to consume their own cell tissue to obtain energy for cell maintenance. This is referred to as the "Endogenous Respiration" phase.

Using the term *COHNS* (which represents the elements of carbon, oxygen, hydrogen, nitrogen, and sulfur) to represent the organic waste, and the term $C_5H_7NO_2$ to represent cell tissue, the three phases can be defined by the following generalized chemical reactions:

Oxidation:

$$COHNS + O_2 + \text{bacteria} \rightarrow CO_2 + H_2O + NH_3 + \text{other end products} + \text{energy}$$

Synthesis:

$$COHNS + O_2 + \text{bacteria} + \text{energy} \rightarrow C_5H_7NO_2$$

Endogenous respiration:

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + NH_3 + 2H_2O$$

Taking these phases into account, the general equation for oxygen uptake rate during the first stage or the oxidation of carbonaceous BOD ($CBOD_5$), can be written as follows:

$$R = a' \frac{(S_o - S_e)}{t} + b'X , \qquad (2)$$

in which, R = oxygen uptake rate (lbs./day),

$\frac{S_o - S_e}{t}$ = $CBOD_5$ removal rate (lbs./day),

X = mass of mixed volume of suspended solids (lbs. of MLSS),

a' = oxygen required for synthesis of $CBOD_5$ removed (lbs. O_2/lbs. $CBOD_5$), and

b' = oxygen required for endogenous respiration (lbs. O_2/lbs. MLSS-day).

Typical values of *a'* and *b*' for municipal wastewater are a' = 0.53 (0.40 to 0.65) and b' = 0.15 per day. The value for *b'* is affected markedly by temperature. The value presented is typical of summer conditions and is widely used. The mixed liquor suspended solids (MLSS) volume is an indirect measure of the volume of matter that consists of living cells (suspended) that have begun to consume their own cell tissue (endogenous respiration). In a facultative lagoon, this volume is difficult to measure. However, it is likely that the slurry zone of sludge, when mixed would roughly approximate the MLSS volume in a facultative pond.

In a heavily loaded facultative pond, the concentration of the slurry (MLSS) may reach 1,000 mg/L; a level approaching the empirical loading design parameters for an activated sludge process. When the Pond Doctor technology is used for mixing and reaeration, and the depth of the intake dish is set such that the slurry zone is circulated, this concentration is diluted. This is simply due to the fact that the un-circulated slurry zone, which normally lies in a variable stratum just above the weight bearing sludge layer, is redistributed throughout the volume of the pond from the surface to the depth of the intake dish.

Equation (2) represents the daily oxygen requirements for the biodegradation of organic material ($CBOD_5$); however, at low organic loading rates and long detention times, nitrification can be expected, provided the biofilm habitat and adequate oxygen exist.[3] Nitrification is normally not a factor in heavily loaded facultative ponds in which Pond Doctor technology is working. This is primarily because the surface area (pond bottom) required by nitrifiers is likely anaerobic in a heavily loaded pond and will not support this life form. Secondarily, the oxygen supply mechanism of a Pond Doctor, which is based upon continually exposing oxygen depleted water to the surface for reaeration from the atmosphere, does not supply the "excess" oxygen required by nitrification reactions.

However, if conditions for nitrification do exist, typically the oxygen demand due to nitrification will occur from 5 to 8 days after the start of a conventional BOD_5 test as shown in Figure 1. The oxygen requirements for nitrification, known as nitrogenous oxygen demand (NOD), may be expressed as a stoichiometric relationship:

$$2NH_4^+ + 4O_2 \rightarrow 2NO_3^- + H_2O + 4H^+ \qquad (3)$$

This reaction indicates that approximately 4.6 pounds of oxygen are required to convert one mole of ammonia-nitrogen to nitrated nitrogen. The oxygen per pound of nitrogen converted can be calculated as; 64/14 = 4.57.[4] The rate of oxygen uptake for nitrification can be expressed as:

$$RN = 4.60 \frac{\Delta NH_3}{t}, \qquad (4)$$

in which, RN = oxygen uptake rate for nitrification (lbs./day),
ΔNH_3 = ammonia nitrogen removed (lbs.), and
t = aeration time (days).

In aerated treatment plants that have a low organic load, and where, presumably, there are adequate oxygen supplies, partial nitrification can be expected. Consequently, if nitrification is not included in calculations of oxygen required, higher values of the coefficient, a', must be used in equation (2). The total oxygen required, including nitrification, can be expressed by combining equations (2) and (4) as follows:

$$R_{tot} = a' \left(\frac{S_o - S_e}{t}\right) + b'X + 4.60 \frac{\Delta NH_3}{t} \qquad (5)$$

Figure 1 illustrates the first and second stage rate of BOD removal over time, at three different temperatures. One can see by these curves that increased temperature greatly increases the stabilization rate. The organic makeup of the waste to be treated is also an important factor. This graph depicts the natural treatment process of pollutants discharged into a river as observed and measured by Imhoff and Fair.

As explained earlier, under typical circumstances in which the Pond Doctor SS Model (solar powered) is expected to operate, only the carbonaceous (first-stage) oxygen demand is exerted. In this case, equation (2) may be used to estimate the rate of uptake. This amount will provide an estimate of the total amount of oxygen to be supplied by the Pond Doctor unit(s) per day for a given $CBOD_5$ removal rate, assuming there are no other sources of free oxygen.

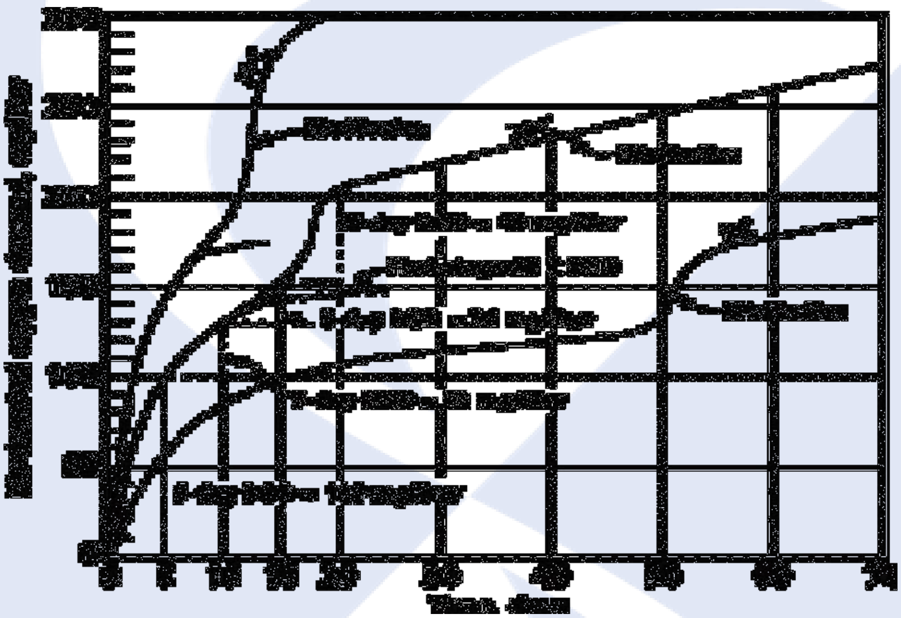

Figure 1. Progress of biochemical oxygen demand at 9, 20, and 30ºC (after Theriault).

Generally, the rate of oxygen uptake is governed by the natural kinetics of the biological and chemical reactions which require oxygen. Excess oxygen, by itself, does not accelerate the reactions, except to stimulate nitrification when other requirements are met. However, if the oxygen supply is less than the demand, the biological and chemical reactions will be incomplete.

Measuring a residual concentration of DO is an indication that the oxygen supply is more than enough to meet the natural kinetics and uptake rate. On the other hand, measuring no residual DO does not necessarily mean that the oxygen supply is inadequate. The demand and supply might be in balance, that is, the natural kinetics and O_2 uptake are equal to the oxygen supply. In this case an observer might measure substantial BOD_5 reduction in the absence of residual DO.

It is also interesting to note that when the oxygen supply is just enough to satisfy the first stage demands, but not sufficient to support nitrification, there is a substantial "savings" in precious oxygen resources. In this case however, any desired nitrogen removal will depend on other mechanisms such as gassing off, assimilation by algae, etc.

One might also observe a difference (gradient) in DO at various depths of a stabilization pond. This is an indication that a greater rate of uptake may be occurring in the lower DO region or there is inadequate mixing of the pond contents. Typically, higher DO concentrations will be observed in the upper strata of an unassisted pond. This is likely due to the presence of photosynthetic plants near the surface, and the concentration of DO at the surface due to the slower function of diffusion.

The Pond Doctor technology, through its ability to control the mixed volume while facilitating reaeration, influences the oxygen uptake rate, *R*, from equation (2), and therefore the rate of decomposition over that of an unassisted pond by the following affects:

1) The volume of biomass zone that is mixed is controllable. It is defined as the depth (ft.) at which the intake dish is set, times the surface area ($ft.^2$) of the pond in which a unit is placed (up to a maximum of 3×10^5 $ft.^2$ for a single unit) x 7.48 gal/$ft.^2$ (up to a maximum of 800,000 gal/day). The mass of the volatile components, X (in equation 2.), can be determined by multiplying the concentration of the MLSS (mg/L) times the volume of the mixed zone (MG), as determined above, times 8.34 lbs./gal.
2) Oxygen supply (reaeration rate) is driven by the demand, i.e., the greater the rate of depletion (oxygen uptake), the greater the mass transfer coefficient. Assuming adequate surface area, and thorough distribution through mixing, reaeration via the one Pond Doctor SS Model unit will supply oxygen at a rate equal to demand, provided the surface area of the pond is greater than one acre but less than six acres.*
3) Like the volume of mixed biomass zones, the volume of the aerobic zone is somewhat controllable by the depth setting of the intake dish of the Pond Doctor. However, the depth of the aerobic zone will be further limited by the total daily supply of oxygen via reaeration and photosynthesis in relation to the demand expected on a daily basis by the ultimate biochemical oxygen demand (UBOD). The depth of the intake dish is adjusted to balance the oxygen supply, providing a residual DO in the upper strata.
4) Gentle mixing of aerobic zone allows the natural kinetics to proceed at optimum pace under any given environmental conditions.
5) $CBOD_5$ removal rate, $S_o - S_e$ /t (lbs. BOD_5/day), can be expected to be 90% or higher in a properly designed facultative wastewater treatment pond having a Mean Cell Residence Time** of 15 days or more.

*Multiple units may be prescribed in a pond when areal loading, detention time, or other factors dictate the need for greater reaeration and/or mixing.

**One of the siting criteria for a Pond Doctor SS Model is based on the Mean Cell Residence Time (MCRT), as defined by the formula: MCRT = V_m/Q , where V_m, is the volume of the mixable contents and is calculated by multiplying the depth of the intake dish (ft.), times the surface area (ft^2), times 7.48 gal/(ft^3), and *Q,* is the actual average daily flow rate (gal/day).

REFERENCES

1. Brenner, R.C., et al. *Design Information on Rotating Biological Contactors.* EPA - 600/2 - 84- 106, U.S. EPA, Cincinnati, OH, 1984.

2. Oswald, W.J., *Fundamental Factors in Oxidation Pond Design*, Conference on Biological Waste Treatment, Manhattan College, April 20, 1960, Paper No. 44.

3. *Nitrogen Removal in Wastewater Stabilization Ponds*, "White Paper", Ponds Rx Us, Inc., 2001.

4. Crites, R. and Tchobanoglous, G., *Small and Decentralized Wastewater Management Systems*, The McGraw-Hill Companies, Inc., 1998.

5. *Oxygen Transfer Via Enhanced Reareation and Mixing,* "White Paper", Pond Doctor, Inc., 2001.

This "white paper" was researched and prepared by Pond Doctor, Inc., 3500 East Divide Ave., Bismarck, ND, 58502. Content consists mainly of excerpts from well respected, published, "pond scientists." Its purpose is to present the known physical, biological and chemical principles of wastewater stabilization pond treatment and to point out the influence that the **CMS™ Process** technology is known to have on these principles. Since some of the original authors' work has been edited and original research by Pond Doctor, Inc., added, Pond Doctor, Inc. assumes full responsibility for the accuracy of the contents of this document. Revised 03/09/04.