BOD REMOVAL: FIRST-ORDER REACTION RATE

CALCULATION OF BOD5 REMOVAL: FIRST-ORDER REACTION RATE

Testing the BOD5 removal in dozens of wastewater stabilization ponds in which the Sunflo2 unit was operating, has demonstrated that reliable predictions of the performance can be calculated. The theoretical approach used for this calculation has been successfully applied, under similar conditions, for more than 25 years. It is based on a "first-order" reaction rate. The following discussion describes the mathematical and physical principles involved in the calculations.

The term used to describe the change (decrease or increase) in the number of moles of a reactive substance per unit of time per volume (for homogeneous reactions), or per unit of surface area or mass (for heterogeneous reactions), is the "rate of reaction" (Denbigh and Turner, 1984). The rate at which a reaction proceeds is an important consideration in wastewater treatment. For example, treatment processes may be designed on the basis of the rate at which the reaction proceeds rather than the equilibrium position of the reaction, because the reaction takes too long to go to completion. Moreover, in most treatment systems, it is not necessary for the reaction to go to completion, i.e., achieve 100% BOD5 removal.

The rate at which a reaction is observed to occur, can be expressed mathematically in terms of a coefficient (constant for a given reactant and temperature) when such rate is dependent upon the initial concentration of the reactant. For example, if in an experiment the reaction rate was found to be:

$$r = KX,$$

where r = rate of reaction,

K = coefficient of reaction in moles/time/volume, moles/area, or moles/mass, and

X = concentration of reactant in mass/volume,

the reaction is said to be "first-order" since the reaction is directly proportional to the first power of the concentration (X^1). By definition, a first-order reaction is one in which the rate of completion is observed to be directly proportional to the first power of the concentration of the reactant. In some reactions, the rate of change is proportional to the square of the concentration of the reactants (X^2). In the latter instance, the term "second-order" would apply.

Because this concept is based on the assumption that the reactants are in sufficiently close proximity to react continuously over a period of time (contact time), both mixing and adequate time for the reaction to take place are important factors. The time required for optimum biological, physical, and chemical reactions to occur in a stabilization pond is critical. While the hydraulic detention time is used in most design methods, short-circuiting, temperature stratification, sludge displacement, and other factors may effectively reduce the available contact time for adequate reactions to occur (BOD5 reduction)

A more accurate measure of the contact time is "mean cell residence" time. Metcalf and Eddy (1972) define mean cell residence time as the average time that the mass concentration of the microorganisms remain in the pond, expressed mathematically as:

$$q_C = \frac{VX_P}{QX_F},$$

where q_C = mean cell residence time (days),

V = volume of pond (million gal.),

Q = inflow rate of wastewater (mgd)

X_P = mass concentration of microorganisms in the pond (mg/l), and

X_F = mass concentration of microorganisms in the influent flow (mg/l).

Simplified, one can see that the mean cell residence time (q_C) = detention time (V/Q), when the mass concentration of the living organisms contained in the volume of the pond is equal to the mass concentration of the living organisms contained in the flow rate. Put another way, this means that the average detention time of the organisms in the system is the same as that of the liquid. This is a very important concept that requires thorough mixing of the pond.

Unfortunately, very little research has been done in determining factors influencing actual mean cell residence time. In evaluating common wastewater stabilization pond designs, Finney and Middlebrooks (1978), found that consistent predictions of pond performance by any design method without accurate projections of mean cell residence time is impossible.

Metcalf and Eddy outlined a basis for design that involves the selection of a mean cell residence time that will ensure: (1) that the suspended microorganisms will bio flocculate for easy removal by sedimentation, and (2) that an adequate factor of safety is provided when compared to the mean cell residence time of washout.

This design concept demonstrates, empirically, that the mean cell residence time of a complete-mix-no-recycle system or an aerated stabilized pond approaches its designed detention time. As such, a first-order reaction calculation adequately predicts the expected BOD5 removal rate for these designs.

If, however, mixing is confined to some volume less than that of the entire pond, the mean cell residence time is equal to the volume of the mixed portion divided by the flow, expressed as:

$$q_c = \frac{V_m}{Q},$$

where V_m = mixed volume (million gal.), and

Q = inflow rate of wastewater (mgd).

Like an aerated stabilization pond, the controlled mixing and reaeration action by the Sunflo[2] unit, increases the mean cell residence time by increasing the mixing and volume of the aerated zone over that of a quiescent pond. The volume of circulation achieved by the Sunflo[2] technology is a function of the depth of the intake and the number of units for a given surface area.

In this case, the observed BOD5 removal (either overall including soluble and suspended solids concentration or soluble only) can be described in terms of a first-order removal function. The equation for a single pond, assisted by an adequate number of Sunflo[2] units with prescribed intake depths, and that are properly positioned is:

$$S/S_o = \frac{l}{l + K\,(V_m/Q)},$$

where S = effluent BOD_5 concentration (mg/l),

S_o = influent BOD_5 concentration (mg/l),

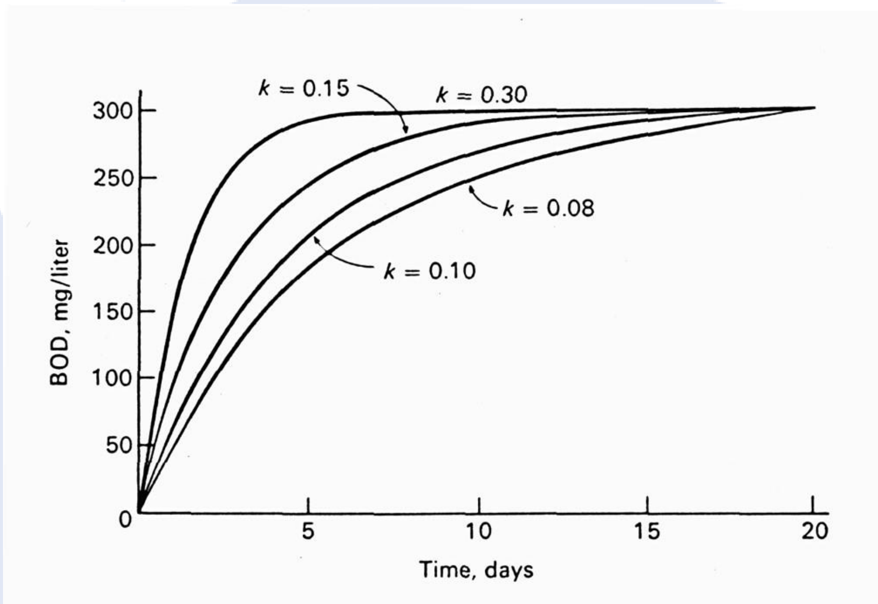
K = overall first-order BOD_5 removal rate constant (days $^{-1}$),

V_m = mixed volume (million gal.), and

Q = flow rate (mgd)

The removal rate constant, *K*, is a function of temperature and the consistency of the wastewater. Reported overall *K* values vary from 0.25 to 1.0. The average value of *K* for domestic sewage is 0.39 at 20C. Removal rates for soluble BOD5 are somewhat higher. For a given consistency of BOD, the oxygen uptake (BOD5 reduction) will vary with time and with different *K* values. The effect of lower rate *K* values is shown in Figure 1.

FIGURE 1. EFFECT OF THE RATE CONSTANT, K, ON ULTIMATE FIRST-STAGE BOD (*SO*)



The temperature at which the BOD5 of a wastewater sample is determined is usually 20C. It is possible, however, to determine the removal rate constant, *K*, at a temperature other than 20C (K_T). The following approximate equation may be used:

$$K_T = K_{20}\, C_T^{(T-20°)}$$

where K_T = the BOD_5 removal rate constant, adjusted for temperature,

K_{20} = standard BOD_5 removal rate at 20°C for a given BOD_5 consistency,

C_T = temperature coefficient, and

T = temperature of wastewater

Research has found that the value of C_T varies from 1.056 in the temperature range between 20C and 30C to 1.135 in the temperature range between 4C and 20C.

From a practical point of view, the above relationships indicate that under certain conditions, greater than 90% BOD5 removal can be expected when the Sunflo2 unit is providing enhanced reaeration and mixing. Those conditions include municipal wastewater of average consistency at 20C; properly designed wastewater stabilization pond; and Mean Cell Residence Time (MCRT)*, of at least 15 days. The significant difference between the Sunflo^2 assisted pond and an unassisted design, being the ability to improve the MCRT.

Before the number of units and their placement on the pond is recommended, Sunflo^2 engineers conduct a thorough analysis of the pond design with existing and expected flows, influent concentrations, and desired BOD5 removal rates. This analysis is based on the concepts presented herein as verified by over 200 installations in wastewater treatment environs. The analysis predicts, with high confidence, the expected BOD5 reduction for a given system, assuming a specific number of Sunflo^2 units, with specific placements on the pond, and with specific depth settings of the intake dish.

*One of the siting criteria for a Sunflo^2 units 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).