Biological Process Design for Wastewater Treatment

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Preface

The authors have observed during their years of experience that the majority of the biological wastewater treatment processes actually put into operation are not designed using fundamental biological treatment principles, even though such principles have been available for many years. The result is that many of the installations do not operate properly and considerable time and expense must be spent diagnosing design problems and correcting them before satisfactory operation can be achieved. We believe that much of the problem exists because the design engineers do not have available to them a thorough yet relatively concise compilation of the fundamental and design aspects of biological waste treatment, presented so that the underlying principles are truly learned. Such learning is required if the engineer is to become a process design decision maker rather than a user of formulas. This book is our attempt to fill this perceived gap in available information.

Even though biological processes are essential components of most wastewater treatment systems, no text is available which covers in detail both the theoretical and design aspects of such components. Our objective in this book is to integrate both of these aspects into a single text which can be used by both the student and the practicing engineer. To achieve this objective, the book is developed in the following format: (a) process fundamentals are presented; (b) wherever possible, these fundamentals are used to develop design relationships for a particular process; (c) a design procedure using these relationships is illustrated using example problems which typify the calculations required in each process application; (d) finally, essential reference material is included at the end of each chapter. Throughout the text, it is emphasized that process design criteria should be obtained from laboratory investigations. However, in many instances practicing consultants do not have the time or resources for laboratory studies. In this regard, design information for specific treatment situations is presented which can be particularly valuable when comparing process alternatives for facility planning purposes.

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1

Fundamentals of Process Kinetics

All biological wastewater treatment processes take place in a volume defined by specific boundaries. Such a volume is commonly termed a *reactor*. Changes in the composition and concentration of materials that occur while the wastewater is retained in the reactor are important factors in wastewater treatment. These changes are caused by hydraulic transport of materials into and out of the reactor as well as by reactions that occur within the reactor. To fully define a reactor system and design similar ones it is necessary to know the rate at which the changes occur and the extent of the changes.

The engineer who is designing a biological process is generally interested in the rates at which various components (such as organic material) are removed from the wastewater and the rate at which biomass is produced in the reactor. Such rates of change are important because they directly affect the size of the reactor required for a specific degree of treatment.

1-1
Reaction Rates

Chemical reactions may be classified in one of the following ways:

1/ On the basis of the number of molecules that must react to form the reaction product.
2/ On a kinetic basis by reaction order.

It is the latter classification that is useful in describing the kinetics of most biological processes.

When reactions are classified on a kinetic basis, different reaction orders may occur for variations in organisms, substrates, or environmental conditions.

The relationship among rate of reaction, concentration of reactant, and reaction order, n, is given by the expression

$$\text{rate} = (\text{conc})^n \tag{1-1}$$

or by taking the log of both sides of the equation,

$$\log \text{rate} = n \log (\text{conc}) \tag{1-2}$$

By applying equation 1-2, experimental results may be interpreted to establish a reaction order and rate. For any constant-order reaction, if the log of the instantaneous rate of change of reactant concentration at any time is plotted as a function of the log of the reactant concentration at that instant, a straight line will result and the slope of the line will be the order of the reaction (see Figure 1-1). The zero-order reaction results in a horizontal line, and the rate of reaction is concentration-independent or the same at any reactant concentration. For the first-order reaction the rate of reaction is directly propor-

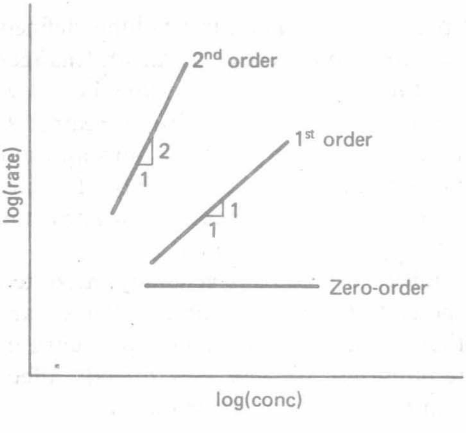

Figure 1-1. Determining Reaction Order by Log Plotting.

tional to the reactant concentration, and with second-order equations the rate is proportional to the concentration squared. Fractional reaction orders are possible, especially in mixed biological cultures, but for the solution of many rate problems, an integer value for the reaction order is determined or assumed. With this condition, a more detailed evaluation of integer-order rate equations can be made as a function of reaction elapsed time.

Zero-Order Reactions

Zero-order reactions are those reactions that proceed at a rate independent of the concentration of any reactant. As an example, consider the conversion of a single reactant to a single product:

$$\underset{\text{reactant}}{\mathrm{A}} \longrightarrow \underset{\text{product}}{\mathrm{P}}$$

If such a conversion follows zero-order kinetics, the rate of disappearance of A is described by the rate equation

$$-\frac{d[\mathrm{A}]}{dt} = K[\mathrm{A}]^0 = K$$

where $-\frac{d[\mathrm{A}]}{dt}$ = rate of disappearance of A

K = reaction-rate constant

If C represents the concentration of A at any time, t, then the rate equation can be expressed as

$$-\frac{dC}{dt} = K \tag{1-3}$$

where $-\frac{dC}{dt}$ = rate of change in concentration of A with time, mass volume^{-1} time^{-1} (the negative sign indicates that the concentration of A decreases with time; if a positive sign were given, this would indicate an increase in concentration with time)

K = reaction-rate constant, mass volume^{-1} time^{-1}

Integrating equation 1-3 gives the formulation

$$C = -Kt + \text{constant of integration} \tag{1-4}$$

The constant of integration is evaluated by letting $C = C_0$ at $t = 0$. This implies that

$$C_0 = \text{constant of integration}$$

and shows that the integrated rate law has the form

$$C - C_0 = -Kt \tag{1-5}$$

A plot of concentration versus time for a zero-order reaction is illustrated in Figure 1-2. Note that the response is linear when the plot is made on arithmetic paper.

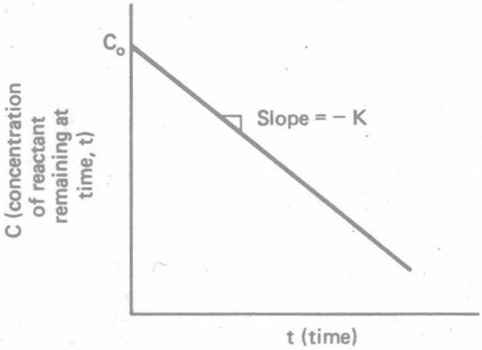

Figure 1-2. Arithmetic Plot of the Course of a Zero-Order Reaction.

First-Order Reactions

First-order reactions are those reactions that proceed at a rate directly proportional to the concentration of one reactant. Since the rate of the reaction depends on the concentration of the reactant and since the concentration of the reactant changes with time, an arithmetic plot of the variation in the concentration of the reactant with time will not give a linear response as it did for a zero-order reaction. Such a graph is presented in Figure 1-3.

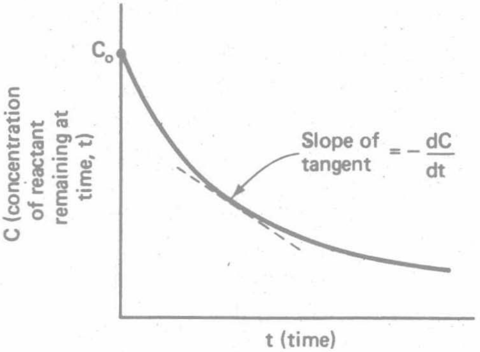

Figure 1-3. Arithmetic Plot of the Course of a First-Order Reaction.

Again consider the conversion of a single reactant to a single product,

$$\underset{\text{reactant}}{A} \longrightarrow \underset{\text{product}}{P}$$

If first-order kinetics are followed, the rate of disappearance of A is described by the rate equation

$$-\frac{dC}{dt} = K(C)^{-1} = KC \qquad (1\text{-}6)$$

where $-\frac{dC}{dt}$ = rate of change in the concentration of A with time, mass volume^{-1} time^{-1}

C = concentration of A at any time, t, mass volume^{-1}

K = reaction-rate constant, time^{-1}

Integrating equation 1-6 and letting $C = C_0$ at $t = 0$ gives an integrated rate law of the form

$$\ell n\left(\frac{C_0}{C}\right) = Kt \qquad (1\text{-}7)$$

or, in the more familiar form,

$$\log\left(\frac{C_0}{C}\right) = \frac{Kt}{2.3} \qquad (1\text{-}8)$$

Equation 1-8 suggests that a plot of log C versus time for a first-order reaction will give a linear trace, as shown in Figure 1-4.

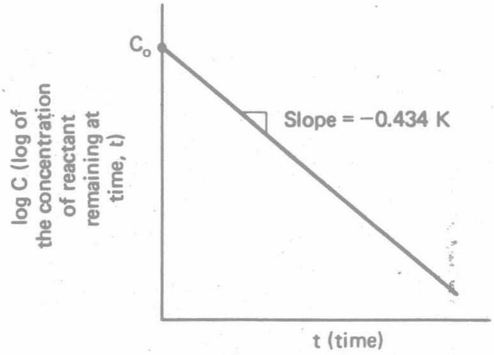

Figure 1-4. Semilog Plot of the Course of a First-Order Reaction.

Second-Order Reactions

Second-order reactions are those reactions that proceed at a rate proportional to the second power of a single reactant. For the reaction describing the conversion of a single reactant to a single product,

$$\underset{\text{reactant}}{2\text{A}} \longrightarrow \underset{\text{product}}{\text{P}}$$

The rate of disappearance of A, for a second-order reaction, is described by the rate equation

$$-\frac{dC}{dt} = K(C)^2 \qquad (1\text{-}9)$$

where K = reaction-rate constant, mass^{-1} volume time^{-1}

The integrated rate law for a second-order reaction has the form

$$\frac{1}{C} - \frac{1}{C_0} = Kt \tag{1-10}$$

Figure 1-5 indicates that an arithmetic plot of $1/C$ versus time will give a linear trace, the slope of which yields the value of K.

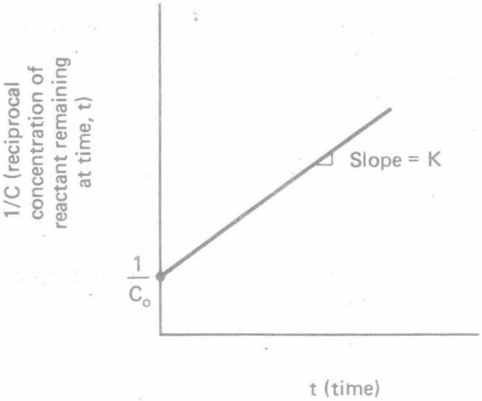

Figure 1-5. Plot of the Course of a Second-Order Reaction.

For a given set of experimental values of C and t, equations 1-5, 1-8, and 1-10 can be used to test for a particular reaction order. This is accomplished by making the appropriate concentration versus time plot and noting any deviation from linearity.

Example 1-1

Glucose was added to a batch culture of microorganisms and removal was measured over time. The following data were obtained:

Glucose concentration measured as COD (mg/ℓ)	*Time (min)*
180	0
155	5
95	12
68	22
42	31
26	40

Determine the reaction order of the removal process by curve fitting.

solution

Make the appropriate concentration versus time plots and note any deviation from linearity.