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COLD TEMPERATURE BIO-KINETICS OF AERATED LAGOONS

by

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ABSTRACT

A study of cold temperature aerated lagoon kinetics was performed on the Portage la Prairie aerated lagoon waste treatment system. The results of the study indicated that the overall BOD removal reaction rate, K, of the lagoons after 15 years of continuous operation was adequately described by the van't Hoff-Arrhenius relationship with a Θ value of 1.062 and a $K_{20^\circ C}$ value of 0.586 (days^{-1}).

Dynamic analysis of the aerated lagoon system indicated that the overall BOD removal reaction rate at $19.2^\circ C$ had decreased due to sludge accumulation from 0.72 (days^{-1}) after 1 year to 0.56 (days^{-1}) after 15 years of continuous operation.

Temperature was also found to have a significant effect on suspended solids removal in the aerated lagoon system, with percent removal varying linearly from 83.4% to 96.0% at 0° and $20^\circ C$, respectively.

TABLE OF CONTENTS

TABLE OF CONTENTS, Continued

Page

CHAPTER 5 Experimental Results 58

TABLE OF CONTENTS, Continued

LIST OF FIGURES

LIST OF FIGURES, Continued

Page

LIST OF TABLES

COLD TEMPERATURE BIO-KINETICS OF AERATED LAGOONS

CHAPTER 1

INTRODUCTION

1. Introduction

Organic material in municipal and industrial wastewaters which is discharged into waterways is a primary cause of water pollution. Current techniques for controlling the undesirable effects of wastewater effluents usually utilize biological systems for the removal of organic materials from the carrier stream. The aerated lagoon is an example of one of these biological waste treatment systems. Temperature is of paramount importance in the design and performance of biological waste treatment systems as it has a direct affect on biological, physical and chemical reactions occurring within the system. For facilities constructed in cold climates a complete understanding of the influence of temperature on these reactions is essential in developing sound design criteria.

1.1. Statement of Problem

The present design of aerated lagoons is based upon empirical relationships evolved through trial and error or from scientific concepts developed by Eckenfelder and O'Conner (1) or McKinney (2). Research results of the past contain many conflicts as to the processes involved and the factors affecting the performance of aerated lagoons. This is especially true of temperature effects. Limited research has been done on the performance and characteristics of aerated lagoons operating at low temperatures. Research emphasis to date has been toward the area of greatest need, which is the design of facilities for warm and temperate climatic regions. Adaption of warm climate design criteria to cold temperature climates using empirical parameters has commonly resulted in inadequate design.

Aerated lagoon design must be based upon fundamental concepts of biological waste treatment together with sound hydraulic concepts in order to accurately assess the influence of temperature on the system. There are two basic variations of aerated lagoons; aerobic and aerobic-anaerobic or facultative aerated lagoons. This classification is very important in developing sound design criteria. The contents of an aerobic aerated lagoon are completely mixed, and both the incoming solids and the biological solids produced from waste conversion do not settle out. In the case of the facultative aerated lagoon the contents of the basin are not completely mixed, and a large portion of the incoming solids and the biological solids produced from waste conversion settles to the bottom of the lagoon. The failure to recognize these aerated lagoon modifications has been a serious source of confusion in evaluating and extrapolating warm climate design criteria to cold temperature climates.

1.2. Reason for Study

There is limited research available with respect to aerated lagoon kinetics which is directly applicable to the Western Canadian climatic situation. This study was undertaken to provide a more thorough understanding of the local problems of the aerated lagoon waste treatment process. Traditionally, engineers have used an empirical equation to describe the temperature response of biological phenomena. This equation incorporates the use of a temperature coefficient, theta (Θ), which defines the temperature sensitivity of the phenomenon. Limited and contradictory information is available on the effect of temperature on aerated lagoon performance, with reported theta values varying from 1.000 (3) to 1.131 (4). Small variations in theta are significant because the process response varies exponentially with changes in theta. Many investigators have found that theta remains constant for only a small range of temperatures (4) (5) (6). In aerated lagoons constructed in cold climates seasonal variations in liquid temperature commonly range from 0° to 20°C. As most research on the temperature response of aerated lagoons has been conducted in moderate temperature ranges, it was apparent that further investigation into low temperature operating conditions was warranted.

Biological waste treatment processes, such as aerated lagoons, are composed of numerous interrelated chemical, physical, and biological phenomena. In the past, temperatures corrections have commonly been applied to gross performance characteristics rather than identifying the points of control within the process. In this study, an attempt was made to identify the controlling parameters on which the temperature effect operates. Considering the response in terms of the integrated treatment process was felt to be necessary in order to accurately establish the temperature sensitivity of the aerated lagoon waste treatment process.

CHAPTER 2

PURPOSE AND EXTENT OF INVESTIGATION

2.1. Purpose

The primary objective of this study was to experimentally establish the effect of low temperature operation on the biological treatment efficiency of aerated lagoons. Secondary objectives of this study were to establish dynamic design criteria for facultative aerated lagoons operating under high seasonal temperature variations and to determine the suitability of the standard BOD test for kinetic reaction rate determinations of the waste treatment system.

2.2. Extent of Investigation

The aerated lagoon system studied is located in Portage la Prairie, Manitoba. Sampling was conducted on a weekly basis from November, 1976 through April, 1977. On each sampling date approximately 2 liter grab samples were taken from the lagoon influent, effluent and mixed liquor and the temperature of the lagoon liquid was recorded.

Mixed liquor samples were taken at the middle of the lagoon from the side dykes during periods of open water. Under ice cover conditions samples were obtained nearer the lagoon center using an ice pick and a standard DO and BOD sampler assembly. Influent and effluent samples were taken directly from the influent and effluent pipes housed within the lagoon control structure.

Samples were immediately transported to the University of Manitoba for laboratory analysis. Standard BOD dilutions were performed for influent, effluent and mixed liquor samples. Influent and effluent samples were incubated at both 20°C and at ambient temperature conditions of the lagoon for 5-day BOD test analysis. Mixed liquor samples were also incubated at 20°C and at ambient temperature conditions of the lagoon for BOD progression analysis based upon 1, 2, 3, 4 and 5-day test results. All samples were incubated in duplicate, at different dilutions. In addition, suspended and volatile suspended solids analysis were performed on the weekly mixed liquor samples obtained from March 4, 1977 to April 1, 1977.

The lagoon operator's data was also acquired from February, 1976 through March, 1977. This data included influent and effluent values for standard 5-day BOD, suspended solids, and COD tests as well as average daily sewage flow and daily temperature of the lagoon liquid.

A mathematical model of the Portage la Prairie aerated lagoon system was developed from available laboratory and lagoon operational data. The model was used to simulate the dynamic behaviour of the facultative aerated lagoon system over a 15 year period of continuous operation.

CHAPTER 3

LITERATURE REVIEW

3. Literature Review

Aerated lagoons are a relatively recent development in biological waste treatment systems. This concept was initially developed to supplement oxygen during the period of spring break-up by artificially aerating stabilization ponds. Lagoon aeration technology has been developed to the point where aerated lagoons are now designed for complete waste treatment. Oxygen is artificially supplied to the basin, usually by means of surface aerators or diffused aeration units. The action of the aerators and that of the rising bubbles from the diffusers serves to maintain solids in suspension and to ensure an adequate and evenly dispersed oxygen supply for the effective bio-oxidation of waste. Aerated lagoons represent an intermediate biological process between aerobic systems which depend on a high concentration of microbial mass supported by an aeration system, and the conventional stabilization ponds with a low concentration of microbial mass supported only by natural oxygenation processes.

The term aerated lagoon is a general description applying to a variety of processes. The essential difference between these processes is the degree of artificial mixing and oxidation provided by mechanical or diffused aeration units. Aerated lagoons are generally classified as either aerobic or facultative. An aerobic lagoon is a high rate system where soluble BOD is converted to cellular protoplasm with some stabilization occurring. These high rate lagoons are completely mixed with no solids deposition and must operate at power levels sufficient to maintain all solids in suspension.

In a facultative aerated lagoon the turbulence levels are not sufficient to maintain all of the solids in suspension. A large portion of the incoming solids and the biological solids produced during waste conversion settle to the bottom of the lagoon where they undergo anaerobic decomposition. The anaerobic by-products are in turn oxidized in the upper aerobic layers of the basin.

The facultative aerated lagoon is used as a waste treatment system almost exclusively rather than the aerobic lagoon due to the excessive power input required to maintain complete-mix conditions in a lagoon basin. The subject of this study is a facultative aerated lagoon system located at Portage la Prairie, Manitoba.

The active biological solids mass in the facultative aerated lagoon is low, resulting in BOD removal being primarily a function of detention time, temperature, and the nature of the waste being treated. In order to provide a basis for the evaluation of these conditions and to establish a basis of design, the basic considerations in biochemical oxidation, including a review of current literature on aerated lagoons, are presented herein.

3.1. Bacterial Growth

Environmental control in biological waste treatment is based on an understanding of the basic principles governing the growth of microorganisms. The following discussion is concerned with the growth of bacteria, the microorganisms of primary importance in all forms of biological treatment.

3.1.1. General Growth Patterns

In the growth of a bacterial culture, a succession of phases, characterized by variations of the growth rate, may be distinguished. This is a classical conception, but the different phases have not always been defined in the same way. The general growth pattern of bacteria, as described by Metcalf & Eddy (7), is shown in Figure 3-1.

The growth pattern based on the number of microorganisms has four distinct phases:

(1) The lag phase. The lag phase represents the time required for the organisms to acclimate to their new environment and/or substrate;

(2) The log growth phase. During this phase the bacterial cells divide at a rate only limited by their generation time and their ability to process food (constant percentage growth rate);

(3) The stationary phase. Bacterial population remains constant due to substrate or nutrient limitation. The

growth of new cells is offset by the death of old cells.

(4) The log death phase. During this phase the bacterial death rate exceeds the production of new cells. The rate of dying is usually a function of the viable population.

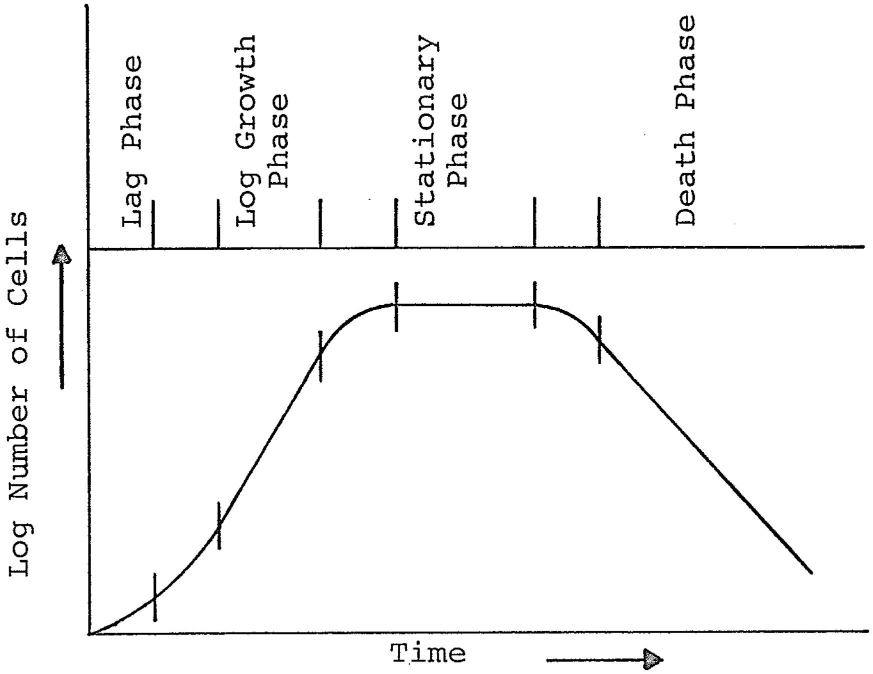

Figure 3-1. Typical Bacterial Growth Curve (7).

Bacterial growth patterns are also discussed in terms of the variation of microorganism mass with time. As is shown in Figure 3-2, this growth pattern consists of three phases.

(1) The log growth phase. There is always an excess amount of food around the microorganisms. The rate of metabolism and growth is limited only by the microorganisms' ability to process the substrate. At the

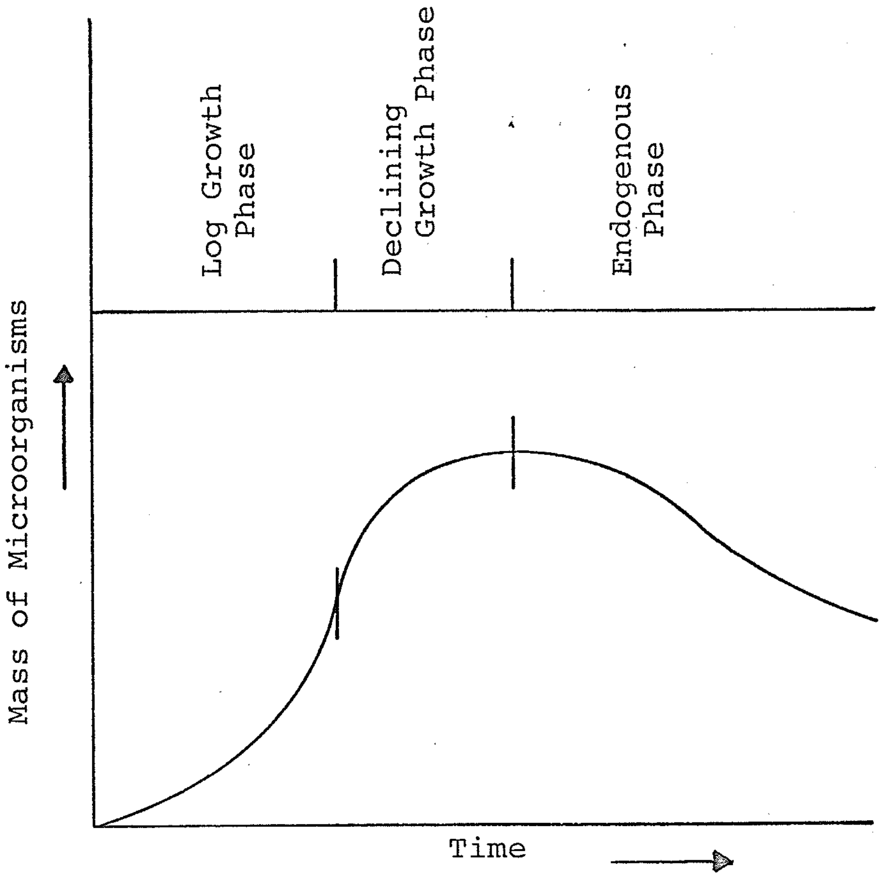

Figure 3-2. Growth Pattern Based on Mass of Microorganisms (8).

end of the log growth phase the microorganisms are growing and removing organic matter from solution at their maximum rate;

(2) Declining growth phase. The limitation of food causes the rate of growth to decrease in the declining growth phase. As the microorganisms lower the food concentration, the rate of growth becomes less and less until eventually reaching zero at the end of the phase;

(3) Endogenous phase. The microorganisms are forced to metabolize their own protoplasm without replacement, since the concentration of available food is at a minimum.

The maximum rate of stabilization or organic matter occurs during the log growth phase. For this reason, it would appear to be advantageous for a biological treatment process to operate in this phase of bacterial growth. However, the use of the log growth phase for stabilizing wastes is limited by the fact that the organic concentration in the liquid surrounding the microorganisms must be high if the log growth phase is to be maintained. This means that it is impossible to produce a stable effluent as long as microorganisms are in log growth. The declining growth phase is most commonly used for the biological stabilization of waste. The lower substrate concentration and lower rate of metabolism in this phase allows the efficient flocculation and settling of bacterial cells, resulting in a more stabilized effluent.

The declining growth phase is of greatest significance to this particular study as aerated lagoons generally operate within this phase. An important point in developing biological kinetics for the declining growth phase is whether or not endogenous metabolism occurs constantly or only when food is insufficient for growth. McKinney (8) states that existing evidence with radiotracers has indicated that endogenous metabolism and respiration occurs continuously but that during growth it is masked by new synthesis. McKinney further states that from a practical point of view the endogenous metabolism reaction has little effect on the mass of protoplasm formed during the log growth phase but becomes significant during the declining growth phase.

3.1.2. Kinetics of Biological Growth

A controlled environment is essential for efficient biological waste treatment. Environmental conditions such as pH, temperature, mixing, and nutrient and oxygen concentration must be controlled to ensure that the microorganisms have a proper medium in which to grow. Another condition which is essential to the growth of microorganisms is that they are allowed to remain in the system long enough to reproduce. This period depends on the microorganisms' growth rate, which is related directly to the rate at which they metabolize or utilize the waste.

Traditionally, microbiologists have used the following expression to describe growth of biological mass, X, during the log growth phase (9);

$$\frac{dX}{dt} = K'X \qquad \text{.....(1)}$$

where dX/dt = net growth rate of microorganisms (mass/volume-time);
K' = specific growth rate (time^{-1});
X = concentration of microorganisms (mass/volume).

As growth proceeds from the log growth phase into the declining growth phase the specific growth rate, K', gradually decreases and the influence of endogenous respiration increases, rendering the expression less applicable.

An empirically developed relationship between biological growth and substrate utilization that is commonly used for biological systems through all phases of the growth curve is (7) (9);

$$\frac{dX}{dt} = Y\frac{dF}{dt} - k_d X \qquad \text{.....(2)}$$

where Y = growth-yield coefficient (mass of microorganisms/mass of substrate utilized);
dF/dt = rate of substrate utilization by microorganisms (mass/volume - time);
k_d = microorganism decay coefficient (time^{-1}).

Equation 2 states that the rate of change in the microorganism mass is equal to the rate of growth minus the rate of decay of active biological mass. This equation, or one with slight modifications, has been used successfully by numerous investigators to describe both aerobic and anaerobic biological waste treatment systems.

The rate of waste utilization, dF/dt, has in turn been related to the waste concentration in contact with the microorganisms by the following equation (7);

$$\frac{dF}{dt} = \frac{kXS}{K'_s+S} = \frac{dS}{dt} \qquad .....(3)$$

where k = maximum rate of waste utilization per unit weight of microorganisms (time^{-1});

K'_s = waste concentration at which rate of waste utilization per unit weight of microorganisms is one-half the maximum rate (mass/volume);

S = concentration of waste surrounding the microorganisms (mass/volume).

A graphical representation of Equation 3 is presented in Figure 3-3.

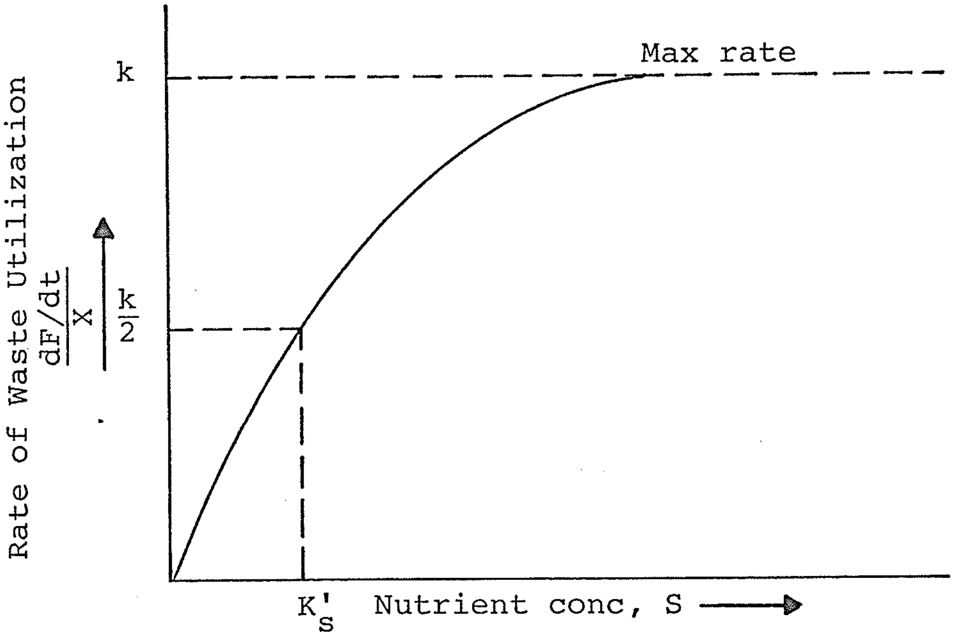

Figure 3-3. Rate of Waste Utilization per Unit Mass of Microorganisms versus Concentration of a Limiting Nutrient (7).

Equation 3 is similar to an expression developed by Monod (10) for describing the relationship between the concentration of a limiting nutrient and the growth rate of microorganisms. The Michaelis-Menten relationship (11) developed to describe enzyme-catalyzed reactions is also of similar form.

In combination, Equations 2 and 3 express the net rate of production of biological mass in terms of the concentration of waste and mass of microorganisms as follows;

$$\frac{dX}{dt} = Y \frac{(kXS)}{K_s'+S} - k_d X \qquad .....(4)$$

Equation 4 is basic to the understanding of biological treatment kinetics, and is theoretically applicable to all types of process design, including batch flow, plug flow, and complete-mix systems. Theoretical models of aerated lagoons are commonly based upon continuous flow, complete-mix assumptions. In such a system the concentration of the waste is uniform throughout the reactor thus facilitating the development of a simple mathematical model which can easily be used for design purposes.

3.1.3. The Complete Mix-No Recycle Model

The complete mix-no recycle reactor scheme, shown in Figure 3-4, is commonly considered characteristic of typical aerated lagoon operation.

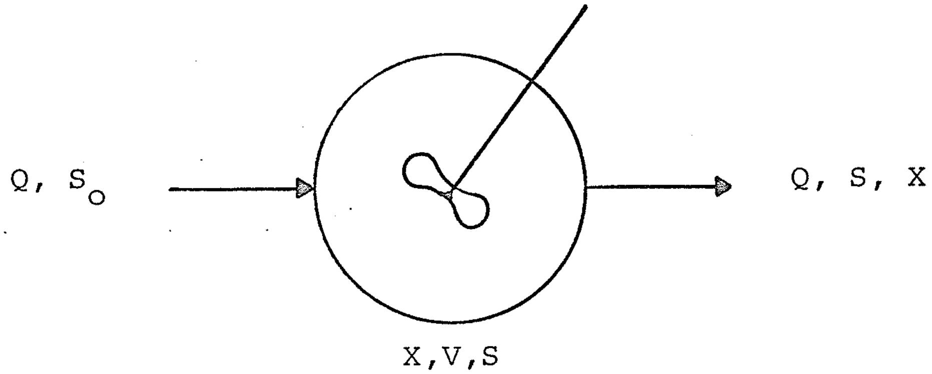

Figure 3-4. Schematic of a Complete-Mix Reactor without Recycle (7).

The reactor unit is assumed to be completely mixed with no organisms in the influent. The hydraulic or liquid retention time, Θ, is;

$$\Theta = V/Q \qquad .....(5)$$

where V = reactor volume;

Q = volumetric flow rate.

The mean cell residence time, Θ_c, is defined as;

$$\Theta_c = VX/QX \qquad .....(6)$$

where X = mass concentration of microorganisms in the reactor.

By equating Equations 5 and 6, it can be seen that;

$$\Theta_c = \Theta \qquad .....(7)$$

Equation 7 states that the average retention time of the cells in the system is the same as that of the liquid.

Utilizing Equation 2, a mass balance for the mass of microorganisms in the reactor system can be written as:

$$V\left(\frac{dX}{dt}\right) = \left(Y\frac{dF}{dt} - k_d X\right)V - QX \qquad .....(8)$$

Equation 8 states that the rate of change of organism concentration in the reactor is equal to the net rate of organism growth in the reactor minus the rate of organism outflow from the reactor. At steady-state, dX/dt equals 0, and Equation 8 may be rewritten as;

$$\frac{Q}{V} = Y\,\frac{dF/dt}{X} - k_d = \frac{1}{\Theta_c} \qquad .....(9)$$

The term, (dF/dt)/X, in Equation 9 is commonly known as the food-to-microorganism ratio, and referred to as U. Therefore, Equation 9 may be rewritten as;

$$\frac{1}{\Theta_c} = Y\,U - k_d \qquad \text{....(10)}$$

It can be seen from Equation 10 that the hydraulic retention time, Θ, which is equal to the mean cell residence time, Θ_c, is directly related to the food-to-microorganism ratio U.

The relationship of Θ_c and U, and therefore Θ, to the efficiency of waste stabilization in the reactor can be demonstrated as follows:

$$E = 100\,\frac{(S_o - S)}{S_o} \qquad \text{....(11)}$$

where E = efficiency of waste stabilization expressed as a percent;

S_o = mass concentration of influent waste;

S = mass concentration of effluent waste.

To obtain an expression for the effluent waste concentration, S, Equation 9 can be rewritten, utilizing Equation 3, to yield;

$$\frac{1}{\Theta_c} = Y\left(\frac{kS}{K_s' + S}\right) - k_d \qquad \text{....(12)}$$

Solving Equation 12 for S yields;

$$S = \frac{K_s'(1 + k_d\Theta_c)}{\Theta_c(Yk - k_d) - 1} \qquad \text{....(13)}$$

For a specified waste, a biological community, and a particular set of environmental conditions, the kinetic coefficients Y, k, K_s' and k_d can be defined as constants and obtained through a detailed laboratory analysis. Consequently, the effluent waste concentration which is equal to the substrate concentration, S, in a complete-mix system, is a direct function of Θ_c. Thus, for a complete mix-no recycle system that is growth specified (specified values of S_o, Y, K_s', k, and k_d), fixing the mean cell residence time, Θ_c, establishes the microorganism concentration in the reactor.

The most significant result of this development is that the effluent concentration, S, and thus the treatment efficiency, E, are related directly to Θ_c, which is equal to the hydraulic retention time Θ. In the complete mix-no recycle system there is no separate control of the microorganisms, because the mean microorganism retention time, Θ_c, and the liquid retention time, Θ, are the same. The only parameter of control for treatment efficiency in the system is the hydraulic retention time, Θ. To obtain a high treatment efficiency the hydraulic retention time, Θ, must be long.

The major difficulty in applying this complete mix-no recycle kinetic model to aerated lagoons operating in the field is that it ignores the effect of settling. Aerated lagoons are generally not a complete-mix system and settling plays a significant role in the overall BOD removal efficiency of the process. O'Connor and Eckenfelder (1) report sludge accumulation has been found to vary from 0.1 to 0.2 lbs/lb of BOD removed in aerated lagoons. Two distinctly different biological processes are occurring and interacting simultaneously in the system; anaerobic decomposition in the settled solids and aerobic decomposition of the soluble substrate and suspended solids. The complete mix-no recycle kinetic model only attempts to describe the aerobic substrate utilization process occurring in aerated lagoons.

A further limitation of this model is the difficulty involved in accurately establishing the growth and substrate utilization parameters, k, K_s', Y and k_d. Limited data is available with respect to these parameters or with respect to their variation with environmental conditions within the reactor.

3.2. Kinetic Theory of Aerated Lagoons

The facultative aerated lagoon is a complex combination of physical, chemical, and biological processes operating and interacting simultaneously. Due to the difficulty in analyzing each individual component functioning within the system, aerated lagoon kinetic theory has in past been generally based upon overall BOD removal characteristics.

3.2.1. BOD Removal Characteristics of Aerated Lagoons

The rate of biological oxidation of waste after Monod (10) and Michaelis-Menten (11), as previously described in Section 3.1.2., is as follows;

$$\frac{dS}{dt} = \frac{kXS}{K_s' + S} \qquad \text{.....(3)}$$

Equation 3 varies from a zero order reaction to a first order reaction at limiting conditions. When $S >> K_s'$ Equation 3 reduces to:

$$\frac{dS}{dt} = \frac{kXS}{S} = kX \qquad \text{....(14)}$$

Equation 14 represents a zero order reaction as the rate of change of substrate concentration with respect to time is independent of the substrate concentration in the reactor. The rate of waste utilization is at its' maximum due to unlimited substrate and is only dependent upon the available microorganism mass. This represents a biological system operating in the log growth phase.

Most biological waste treatment systems, including aerated lagoons, operate in the declining growth phase. In this phase of bacterial growth substrate concentration is limiting the rate of waste utilization and the limiting condition were $K_s' >> S$ is approached. Equation 3 then reduces to:

$$\frac{dS}{dt} = \frac{kXS}{K_s'} \qquad \text{....(15)}$$

Under steady-state conditions the microorganism concentration, X, and the half-rate velocity coefficient, K_s', can be assumed constants and can be incorporated into the reaction rate constant, k. This results in a new reaction rate coefficient K^1 where:

$$\frac{dS}{dt} = K^1 S \qquad \text{....(16)}$$

Equation 16 states that the rate of waste utilization is directly proportional to the concentration of organic matter present at any time and thus represents a first-order reaction. The coefficient K^1 is a measure of this rate. The constant K^1 is expressed in Equation 16 to the base e; however, values are commonly reported to the base 10, and the coefficient identified as K (where $K^1 = 2.3K$). The fundamental validity of Equation 16 is questionnable since biological wastewater-treatment systems are affected by factors other than substrate concentration, such as the concentration of active solids in suspension, intensity of fluid turbulence, and dissolved oxygen concentration. As the concentration of active biological solids in aerated lagoons is low and dissolved oxygen concentration seldom limiting, the first-order reaction has been found to adequately describe aerated lagoon performance by numerous investigators (1)(12)(13).

Assuming complete-mix conditions, the concentration of BOD in the lagoon effluent is essentially equal to the concentration of BOD in the lagoon itself, S. To evaluate basin efficiency under these conditions and the conditions imposed by Equation 16, a mass balance may be formulated to represent the BOD removal expected in the aerated lagoon as follows:

lbs BOD influent - lb BOD effluent = lbs BOD removed

or $$S_oQ - SQ = \frac{dSV}{dt} \qquad \text{....(17)}$$

where S_o = influent BOD_5 (mg/l);

S = effluent and lagoon BOD_5 (mg/l);

Q = sewage flow (lbs x 10^{-6}/day);

V = lagoon volume (lbs x 10^{-6});

dS/dt = rate of change of lagoon BOD_5 per unit of time (mg/l/day).

Substituting Equation 16 into Equation 17:

$$S_oQ - SQ = K^1SV \qquad \text{....(18)}$$

As the lagoon detention time, t = V/Q, it follows that:

$$S_o - S = K^1ST \qquad \text{....(19)}$$

or $$S = \frac{S_o}{1 + K^1t} = \frac{S_o}{1 + 2.3Kt} \qquad \text{....(20)}$$

Equation 20 may also be expressed in terms of percent BOD removal efficiency, E, as follows:

$$E = \frac{100\ K^1t}{1 + K^1t} = \frac{230\ Kt}{1 + 2.3Kt} \qquad \text{....(21)}$$

and in terms of detention time, t, as:

$$t = \frac{E}{K^1(100-E)} = \frac{E}{2.3K(100-E)} \qquad \text{....(22)}$$

Using the above equations in the design of an aerated lagoon, the value of the influent BOD, S_o, is assumed to be known. The required effluent BOD, S, is generally dictated by government authorities or other regulatory bodies, establishing the desired BOD removal efficiency, E, for the aerated lagoon. If the values of the reaction constant K^1 or K is known, the required detention time, t, or the lagoon capacity may then be calculated. This reaction constant can be determined experimentally using a pilot plant or laboratory plant operating under several conditions of loading and detention time. In order for a pilot plant to accurately simulate the operation of an aerated lagoon it must be operating under steady-state conditions and at the same turbulence levels as would be expected in a full scale installation. Factors such as temperature, sewage characteristics, BOD loading, sewage flow rate, and sludge solids accumulation will cycle on a yearly basis in a full scale aerated lagoon installation. The cyclic variation of these factors has a very significant effect on the overall BOD removal performance of an aerated lagoon, and thus should be incorporated into pilot plant operation in order to accurately determine the reaction constant K^1. Such detailed laboratory experiments are generally beyond the scope of activities of most consulting engineers and must be undertaken by institutions equipped for laboratory and research studies. Metcalf & Eddy (7) report overall K^1 values at $20^{\circ}C$ vary from 0.25 to greater than 1.0, for aerated lagoons treating domestic wastes.

In the absence of kinetic data, the Minnesota Pollution Control Agency (14) suggests aerated lagoon design be based upon a K^1 value of 0.46/day at 20°C or 0.18 at 0°C for the complete treatment of normal domestic sewage.

Equation 22 is based upon steady-state conditions, therefore, the use of this equation to evaluate lagoon performance before steady-state conditions are reached would result in error. Several years of operation are required for a facultative aerated lagoon to reach steady-state with respect to sludge solids accumulation. Until steady-state conditions are reached, BOD removal rates will be enhanced due to the sedimentation of solids and biomass in the system. As the anaerobic decomposition of these settled solids is a relatively slow process in relation to the aerobic decomposition of waste, a net increase in settled solids occurs until an equilibrium is reached. At steady-state, the resuspension and decomposition of settled solids is equal to the rate of solids sedimentation. After initial acclimation of the lagoons' limited biomass, the BOD removal rate will decrease steadily until a steady-state condition is reached with respect to solids deposition. The wide range of K^1 values reported in the literature could, in part, result from the evaluation of BOD removal rates before a steady-state condition is reached. This problem becomes more significant in colder climates as steady-state conditions take longer to establish if indeed they are ever established.

3.2.2. Dynamic Behaviour of Aerated Lagoons

Equilibrium is actually never established in an aerated lagoon operating under cyclic changing temperature and loading conditions. The system is dynamic in nature and its behaviour can at best only be approximated by steady-state analysis after a number of years of operation. Dynamic analysis of aerated lagoons not only eliminates the technically invalid assumption of steady-state operation but will predict the time period required before the application of this simplifying assumption can be made to aerated lagoon kinetics.

In a facultative aerated lagoon mixing energy is insufficient to keep settleable solids in suspension resulting in a sludge layer building up in the bottom of the lagoon. Pilot plant studies by Black (15) indicate that approximately 40% of the BOD load settles out in an aeration pond, and becomes available for utilization by the aerobic organisms only at rates dependent upon conditions affecting anaerobic decomposition. Anaerobic fermentation develops in this sludge layer, which releases nutrients to the supernatant, gas to the atmosphere and heat energy. The gas, a mixture of principally CO_2 and CH_4, still contains bound chemical energy and its loss, therefore, relieves the supernatant of this fraction of the influent load energy. The effect of sludge is significant in a facultative aerated lagoon, and can be readily incorporated into the degradation rate equations if the following assumptions are made:

(1) Sludge fermentation, as with the aerobic oxidation of waste, is a first order reaction;

(2) All BOD's are ultimate first stage;

(3) A fraction, $i\rho$, of influent BOD, is dispersed within the body of the lagoon, the remaining fraction $(1 - i\rho)$, settles as sludge;

(4) Complete and instanteous mixing in the lagoon liquid and no liquid loss;

(5) A fraction, $s\rho$, of BOD lost in the sludge fermentation enters into the lagoon liquid, the remaining fraction leaves the system as heat energy and fermentation gas.

Based upon the above assumptions, the rate of change of sludge mass in an aerated lagoon is as follows:

$$\frac{dL_t}{dt} = (1-i\rho)S_oQG.10^{-6} - K_LL_t \qquad \text{....(23)}$$

where L_t = total sludge mass in terms of kg or lbs of ultimate BOD;

$i\rho$ = the fraction of ultimate influent BOD dispersed within the body of the lagoon;

S_o = influent ultimate BOD (mg/l);

Q = sewage flow (m^3/day or ft^3/day)

G = mass density of water (kg/m^3 or lbs/ft^3);

K_L = sludge fermentation reaction rate ($days^{-1}$).

The rate of change of BOD in the lagoon liquid can, therefore, be written as:

$$\frac{dS}{dt} = \frac{i\rho S_o}{R} - K_s S - \frac{S}{R} + \frac{s\rho K_L L_t . 10^6}{VG} \qquad ....(24)$$

where S = lagoon liquid ultimate BOD (mg/l);

R = lagoon retention time (days);

K_s = aerobic degradation rate (days^{-1});

$s\rho$ = fraction of BOD entering lagoon liquid after sludge fermentation;

V = lagoon volume (m^3 or A^3).

If K_L is assumed constant, Equation 23, at equilibrium ($dL_t/dt = 0$) reduces to:

$$L_t = (1 - i\rho) S_o QG . 10^{-1} / K_L \qquad ....(25)$$

Substituting Equation 25 into Equation 24, and assuming equilibrium conditions ($dS/dt = 0$), Equation 24 reduces to:

$$S = \frac{S_o(s\rho(1-i\rho) + i\rho)}{(K_s R + 1)} \qquad ....(26)$$

Equation 26 can be further reduced by eliminating the influence of settling; (ie $i\rho = 1$);

$$S = \frac{S_o}{(K_s R + 1)} \qquad ....(27)$$

Equation 27 is commonly used to describe BOD removal characteristics of aerated lagoons and has been derived from complete-mix assumptions by both O'Connor and Eckenfelder (1) and McKinney (16). Although $i\rho$ and $s\rho$ are assumed constants, the relative effects of the fermentation products and the nonsettleable influent BOD on the lagoon BOD change significantly over the yearly temperature cycle. The reasons for this are that equilibrium is never established under cyclic changing temperature conditions due to the effect of temperature on the values of K_s and K_L and the fact that the two reaction rate values are not temperature dependent to the same degree. Due to the temperature effect on K_s and K_L during cyclic temperature changes and the definite influence of settling on aerated lagoon kinetics, there is little merit in considering the equilibrium and complete-mix conditions assumed in Equation 27.

If $i\rho$, $s\rho$, K_s and K_L are known, the dynamic behaviour of an aerated lagoon over the yearly temperature, sewage flow and BOD loading cycle can be simulated by simultaneously solving Equations 23 and 24. Unfortunately, information on these parameters is meagre.

The fraction of influent BOD load remaining in suspension in an aerated lagoon, $i\rho$, is directly dependent on the mixing energy input to the pond, and to some degree on the type of waste being treated. The fraction, $i\rho$, can be as high as one at high energy input levels such as in completely aerobic lagoons and is probably near 0.4 (17) at no energy imput as in conventional oxidation ponds. Marais and Capri (18) found an $i\rho$ value of 0.6 to result in the best overall fit for two simulations of aerated lagoon behaviour, using various combinations of constants. A recent study by Black (15) indicated that approximately 40% of the BOD load settled out in the aeration basin of an aerated lagoon located in Brampton, Ontario. This supports

Marais and Capri's findings of an iρ value of 0.6 for conventional aerated lagoons.

Considering sρ, the fraction of sludge fermentation products entering the lagoon liquid, nothing of a quantitative nature is known. After many trial runs of oxidation pond simulations on a computer, Marais (17) found the best fit to experimental pond BOD data was obtained with an sρ value of 0.4. In the same study, Marais also obtained reaction rate constants for the sludge layer by monitoring gas evolution of oxidation pond sludge at different temperatures. The experimental relationship between the logarithm of the ratios of the rates of gas evolution and the temperature were found to be approximately linear. This indicated that the sludge reaction rate, K_L, varied with temperature according to the van't Hoff-Arrhenius relationship as is shown in Equation 28 (17):

$$K_L = 0.002\ (1.35)^{(T-20)} \qquad \ldots.(28)$$

where T = temperature in °C.

Sludge settling tests in an aerated lagoon in Alaska by Reid (19) demonstrated that settled solids did not undergo significant decomposition in the winter but did in the summer. Biological decomposition of the sludge was also found to follow the van't Hoff-Arrhenius relationship between 0.5° and 20°C. Gloyna (20) reports Oswald found that at temperatures between 15° and 23°C the gas produced from sludge deposits in a facultative pond followed a simple linear relationship with temperature variation. Pfeffer

(21), in summarizing recent work by McCarty on the influence of temperature on the rate of anaerobic waste stabilization in lagoons, indicates that the Θ value of the Streeter-Phelps temperature formulation increases with decreasing temperature. The study covered a temperature range of 5° to $35^{\circ}C$ but due to limited low temperature data positive conclusions could not be drawn.

Another significant effect of sludge accumulation on the operating performance of an aerated lagoon is that anaerobic gas production will tend to resuspend bottom sludges as it vents to the lagoon surface. A study by Clark et al (22) on sludge core samples of the Northway, Alaska aerated lagoon indicated partial digestion and significant methane production was occurring in the bottom sludge during the summer of 1967. Further tests between August 1967 and May 1968 indicated that the maximum depth of bottom sludge did not increase between the sampling dates but shifted in location. This shifting seems to indicate that gas production resuspends bottom sludge and thus increases lagoon loading rates during summer months when active anaerobic digestion is occurring.

The aerobic waste utilization reaction rate of aerated lagoons, K_s, and its variation with temperature is a subject of extensive research and will be discussed in detail in following sections of this paper.

3.3. The Effect of Temperature on Bio-Oxidation Reactions

One of the most important factors affecting microbial growth, and thus biological waste treatment processes, is temperature. It has been observed that bacteria grow quite slowly at low temperatures but increase their rate of reaction as temperature increases. "It has been generally stated that the rate of microbial growth doubles with every $10^{o}C$ increase in temperature up to the limiting temperature." (8) For convenience, bacteria have been catalogued into groups - psycrophiles, mesophiles and thermophiles - according to their temperature-growth range. The mesophilic and psychrophilic microorganism groups are of primary interest in this study. They grow in the moderate and low temperature ranges respectively, which is characteristic of the normal operation of aerated lagoons.

3.3.1. Temperature-Reaction Rate Relationships

Two basic equations relating temperature to the reaction rate of biological systems are currently in widespread usage. These two equations are the Streeter-Phelps formulation and the van't Hoff-Arrhenius expression. The Streeter-Phelps equation is an empirical formulation incorporating a temperature coefficient, theta (θ). This coefficient defines the temperature sensitivity of the biological phenomenon and is considered to be a unique parameter associated with a given biological system. The van't Hoff expression is a fundamental relationship which can be interpreted in terms of the chemical kinetics associated with the enzyme reactions of biological phenomena.

The van't Hoff-Arrhenius expression is (23):

$$K_{T2}/K_{T1} = \exp\left((\mu/T_1T_2)(T_2 - T_1)\right) \qquad ....(29)$$

where T = the absolute temperature;

K_{T1}, K_{T2} = the reaction rate constants at temperatures T_1 and T_2 respectively (day^{-1}) and;

μ = the temperature characteristic, a constant for a given set of conditions (^{o}K).

Equation 29 may be rewritten as follows:

$$\ln (K_{T2}/K_{T1}) = \frac{\mu}{T_1T_2}(T_2 - T_1) \qquad ....(30)$$

or

$$\ln K_{T2} - \ln K_{T1} = -\mu\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \qquad ....(31)$$

Equation 31 is the equation of a straight line in the following form:

$$y_2 - y_1 = m(x_2 - x_1) \qquad ....(32)$$

where

y_2, y_1 = $\ln K_{T_2}$ and $\ln K_{T_1}$ respectively;

x_2, x_1 = $\frac{1}{T_2}$ and $\frac{1}{T_1}$, respectively and;

$m = -\mu$.

Thus a plot of inverse absolute temperature (T^{-1}) versus the natural logarithm of the reaction rate constant ($\ln K_T$) yields a straight line with a slope equal to μ. "Different biological systems yield different slopes, thus, μ is a characteristic of a given biological system." (23)

For well defined biological reactions such as particular enzyme reactions, the temperature characteristic, μ, of the van't Hoff equation can be interpreted in terms of the activation energy for the reaction, as follows:

$$\mu = Ea/R. \qquad \ldots.(33)$$

where Ea = the activation energy for the reaction, (cal/mole) and;

R = the universal gas constant, (cal/mole/$^{\circ}$K).

When the van't Hoff equation is applied to gross measures of biological activity such as growth or respiration, the reactions associated with these activities usually are ill-defined. For this reason Equation 29 employing the temperature characteristic μ, is more applicable to most engineering situations than the more fundamental interpretation associated with the energy of activation.

The Streeter-Phelps equation is generally accepted as an adequate approximation of the van't Hoff expression, and is presently used, almost exclusively, to predict the temperature response of biological oxidation systems. The Streeter-Phelps equation is (23):

$$K_{T2}/K_{T1} = \Theta^{(T_2 - T_1)} \qquad \ldots.(34)$$

where Θ = the temperature coefficient, an empirical constant (dimensionless).

Like the van't Hoff equation, Equation 34 can be written in a straight line form as follows:

$$\ln (K_{T2}/K_{T1}) = \ln (\Theta^{(T_2-T_1)}) = (\ln\Theta)(T_2-T_1). (35)$$

or $$\ln K_{T2} - \ln K_{T1} = (\ln\Theta)\ (T_2-T_1) \quad ....(36)$$

which is of the same linear form as Equation 34, where,

$x_2, x_1 = T_2$ and T_1, respectively, and;

$m = \ln\Theta$.

Equation 36 yields a straight line on a plot of absolute temperature, T, versus the natural logarithm of the reaction rate constant, $\ln K_T$.

From the preceeding development it can be seen that the temperature coefficient, Θ, is a measure of the slope of the Streeter-Phelps plot and is, therefore, analogous to the temperature characteristic, μ, of the van't Hoff expression. Again, theta is considered to be a characteristic parameter of a given biological system where increasing values of theta indicate increasing sensitivity to changes in temperature.

The van't Hoff expression is the fundamental equation relating reaction rates of biological systems to changes in temperature and the applicability of the empirical Streeter-Phelps equation should be examined in relation to it. A comparison of Equations 30 and 35 show that the van't Hoff and Streeter-Phelps formulations are related by the following equation:

$$\ln\Theta = \mu/T_1T_2 \qquad ....(37)$$

or

$$\Theta = \exp\ (\mu/T_1T_2) \qquad ....(38)$$

For the Streeter-Phelps equation to be a valid representation of the temperature effect over the temperature range T_1 to T_2, it follows that theta must be a constant. However, from Equation 38 it can be seen that theta is actually a function of temperature, and the power of the exponent, μ/T_1T_2 is not dimensionless. This anomaly is due to the empiricism of the Streeter-Phelps equation. "Calculations based upon the van't Hoff expression indicate that theta is not a constant but rather is a function of temperature and decreases as temperature increases (24)." The magnitude of the error introduced by the Streeter-Phelps approximation is dependent upon several factors, including the magnitude of the temperature characteristic of the reaction, μ, and the temperature range over which the extrapolation was made.

The greater the temperature range over which a value of theta is assumed, the greater the error in relation to the fundamental van't Hoff expression. This factor could be significant in considering aerated lagoons in northern climates as operation temperatures commonly cycle from $0^{\circ}C$ to $20^{\circ}C$ on a yearly basis. The application of a constant theta value for cold temperature aerated lagoon operation is more questionnable when the magnitude of the temperature characteristic, μ, is considered. Calculations performed by

Benedict (23) over a temperature range of $1^{\circ}C$ to $35^{\circ}C$ indicate an error of 23 percent for $\mu = 4000^{\circ}K$ and 33 percent for $\mu = 9000^{\circ}K$ using the Streeter-Phelps equation. At low temperatures, characteristic of the winter operation of aerated lagoons, the energy of activation becomes high and can increase to as much as 20,000 cal near $0^{\circ}C$ (25) for the BOD reaction.

Establishing a relationship between reaction rate values for various temperatures using a single thermal constant, θ, indicates that the overall average energy of activation for all the organisms functioning in the culture at each temperature results in a straight line plot. This is an obvious over simplification in considering a complex biological waste treatment system, and a number of alternate relationships to the Streeter-Phelps equation have been proposed. Some of the more prominent are listed below (26):

$$\text{Log } \frac{K_2}{K_1} = 0.0368(T_1 - T_2) \qquad \text{Eckenfelder (1961)}$$

$$0.0315 = \frac{\text{Log } K_1 - \text{Log } K_2}{T_1 - T_2} \qquad \text{Wuhrman}$$

$$\frac{K_T}{K_{25^{\circ}C}} \times 100 = 0.71T^{1.54} \qquad \text{Sawyer \& Rohlich}$$

where K_1 and K_2 are reaction rate values at temperatures 1 and 2 respectively.

Studies by Sawyer (27) (1966) indicated that the variation in BOD removal characteristics over a temperature range of $10^{\circ}C$ - $30^{\circ}C$ in aerated lagoons could be adequately described by the Streeter-Phelps equation. The temperature coefficient Θ, from this data was determined to be 1.035.

Carpenter et al (5) conducted an extensive study of aerated lagoons treating pulp and paper mill wastes and calculated an average Θ of 1.035 for five different wastes over a temperature range of $2^{o}C - 30^{o}C$. A trend was observed in this study for each waste indicating an increase in Θ with a decrease in temperature range. Values of Θ equal to 1.026 and 1.058 for temperature ranges of $10^{o}C - 30^{o}C$ and $2^{o}C-10^{o}C$ respectively were obtained.

Sawyer (27) and Carpenter et al (5) both concluded that aerated lagoons with short detention times will be extremely sensitive to temperature change and that this effect is dampened by retention periods in excess of five days.

Most investigators have found that Θ remains constant for a relatively small range of temperatures. Moore (6) in 1941 conducted a major study of the effect of temperature on bio-chemical oxygen demand at low temperatures. He used the dilution bottle technique to determine reaction rate values, K, for settled domestic sewage in both bicarbonate and phosphate dilution waters and also undiluted samples from two streams which contained a moderate amount of pollution from a remote origin. He noted the reaction rate value can vary widely for the same sewage. He concluded that the slope of the line drawn through the K values was constant for the interval between 5^{o} and $20^{o}C$ and was described by a value of Θ of 1.065. He found a break at 5°C with a larger Θ value of 1.145 for the interval between 0.5 and 5°C.

Gotaas (4) showed that the maximum reaction rate is reached at about 30°C, and decreases at higher temperatures. He also found that the value of the constant, Θ, is higher at lower temperatures. Gotaas found that the variation of reaction rate with temperature could be accurately described by the Streeter-Phelps equation with three temperature ranges. He proposed a Θ value of 1.109 in the range of 5° to 15°C, 1.042 in the range of 15° to 30°C, and 0.967 in the 30° to 40°C range. For the range 5° to 30°C, the average value of Θ was 1.071.

Belehradek (28) suggested that the reacting rate varied with the temperature raised to some power, which was also confirmed by Gotaas, with the value of the exponent equal to 0.932 for the range of 5° to 30°C.

A recent study by Cox (29) on the effect of temperature on metabolic rates in aerobic systems indicated a constantly decreasing Θ value with increasing temperature in the 0° to 35°C range.

Townshend et al (30) studied fourteen aerated lagoons in Ontario and noted that Θ tended to increase with decreasing temperature and decreasing suspended solids. They concluded that the Streeter-Phelps equation should not be used to correct rate constants from one temperature to another unless Θ has been determined experimentally for a particular waste treatment system over the temperature ranges involved.

Stoltenberg and Sobel (31) hypothesized an empirical quadratic relationship between reaction rate and temperature, and found that it was statistically significant when compared with a linear relationship. Their relationship shows a greater change in reaction rate per degree at high temperatures (up to 30°C) than at lower temperatures, which seems to contradict the findings of Gotaas. Stoltenberg and Sobel however, made few tests at lower temperature ranges.

Recent reports by Reid (32) and Grube et al (3) both indicate a relatively small temperature effect on aerated lagoons treating domestic sewage in Arctic climates. Two factors must be considered in interpreting such data. First, the major portion of the BOD in domestic sewage is present in the suspended and colloidal form and a primary removal mechanism is adsorption and flocculation (33). These mechanisms are relatively insensitive to change in temperature. Secondly, the retention periods for aerated lagoons operated in the Arctic are long, and changes in removal due to temperature become insignificant.

It should not be expected that the data of different workers on this subject will agree. The rate of oxidation will vary with the type of waste and the type of biological population which grows in response and oxidizes the waste. Under different conditions and in different biological treatment systems, different biological populations will vary in their susceptibility so that temperature coefficients and the temperatures of maximum reaction rates will also vary.

A general conclusion which is verified by a great deal of recent research and supported by the fundamental van't Hoff-Arrhenius expression, is that the value of θ increases with decreasing temperatures.

3.3.2. The Effect of Substrate Concentration on Temperature Response

Temperature correction factors are commonly used in analyzing biological waste treatment processes to modify microorganism growth rates or substrate utilization rates for temperature variations. As has been previously discussed, the most commonly applied temperature correction for biological waste treatment processes is the Streeter-Phelps modification of the Arrhenius equation. This type of temperature growth rate correction has been thought to only apply over a limited temperature region, the breadth of which depends on the substrate and the type of organisms involved in the metabolism of the substrate. Previous investigators have found that the temperature response, θ, of a biological system depends on many parameters, among which are the temperature range, substrate concentration, food:microorganism ratio, number of test temperatures used, type of substrate, and method of chemical analysis (33) (34).

Of the above mentioned factors, the substrate concentrations or food:microorganism ratio seem to be the most significant. Pohl (26) concluded that θ was dependent on the mixed liquor suspended solids concentration (MLSS), ranging from $\theta = 1.038$ at low MLSS to $\theta = 1.00$ at high MLSS.

Benedict (24) conducted studies in the temperature range of 4° to $32^{\circ}C$, and concluded that Θ was independent of organic loading when the loading rate did not exceed 0.53 lb biochemical oxygen demand (BOD)/day/lb MLSS, but Θ increased when loadings above 0.53 were imposed. Eckenfelder (35) suggested that Θ, based upon overall treatment efficiencies, was a function of organic loading and reported Θ values for activated sludge of 1.00 at low loadings and 1.02 at high loadings. Novak (36) reports that for aerobic systems, Θ increases from a value at or near 1.00 at low substrate levels to values varying from 1.02 to 1.18 at high substrate concentrations, depending on the substrate being metabolized.

Steady-state kinetic equations presented by Lawrence and McCarty (37) for complete-mix biological process design indicate that variation of treatment efficiency with temperature is dependent upon the mean cell residence time Θ_c or the average time an organism is retained in a reactor. The equations developed by Lawrence and McCarty show that the expected loss of treatment efficiency associated with low temperature process operation may be minimized by operation at high values of Θ_c. Since activated sludge processes normally operate at Θ_c values between 6 and 30 days (9)(35) little variation in the effluent substrate concentration would be expected at varying operational temperatures. The insensitivity of the activated sludge process to temperature fluctuations has been noted by many investigators (33)(38) (39). Aerobic processes that operate at low cell residence times due to the absence of sludge recycle, such as aerated lagoons, lose efficiency rapidly as temperatures fall (2)(33).

Eckenfelder and Englande (33) state that the most responsive factor relating temperature effect to process performance is the food microorganism ratio (F/M).

> "At high F/M values the biomass may be filamentous or dispersed and Θ will be high indicating a direct temperature effect on each organism. By contrast, at lower F/M ratios the biomass is flocculated and diffusional mechanisms into the floc become significant. More of the floc is aerobic at lower temperatures so that a greater aerobic biomass at lower temperatures is capable of stabilizing almost the same quantity of organic matter as a smaller more active biomass at higher temperatures." (33)

Eckenfelder (33) states that it is because of this phenomenon that the activated sludge process at conventional loading rates (F/M = 0.6) and trickling filters yield a much lower temperature coefficient, Θ, than those processes using primarily dispersed growths such as aerated lagoons.

In general, it seems that the Θ value determined for a particular biological treatment system depends on either the substrate concentration or the food:microorganism ratio and the temperature range used. Low cell systems like aerated lagoons are more temperature sensitive than processes where high organism levels are maintained, although a workable model for predicting Θ values has not been developed.

3.3.3. Temperature Acclimation

When an organism is subjected to a temperature change within the biologically active range, the response of the organism at the new temperature depends on its ability to adapt or acclimate to the new environment. The exact processes by which temperature acclimation occurs are not well established for pure culture systems, and even less is known about this phenomenon for mixed culture systems. The temperature acclimation of mixed cultures, as would be found in a wastewater community, is complicated by the fact that gross culture adaption may depend on shifts in population as well as the adaption of specific bacteria within the culture.

An example of the significance of population interactions in mixed culture systems has been presented by Beyers (24) who found that within the range of 14° to $32^{\circ}C$ the effect of temperature changes on the gross metabolic activity of a balanced, laboratory ecosystem was less than the effect on either a wastewater community or the single organism, Daphnia, in that order. This suggests that the effects of temperature variations are reduced as a mixed system approaches an ecological balance.

Although temperature acclimation is generally considered significant in determining the temperature response of mixed culture systems, the length of time required for adaptation is not well established. Ludzack et al (40) concluded from their study that at least two weeks are required for population adjustment after a significant temperature change has occurred and this time period has also been chosen arbitrarily by other researchers. Benedict et al (41) conducted studies on mixed cultures in continuous-flow pilot plants and concluded that acclimation following a shock temperature change from 19°C to 4°C was essentially complete within 2 weeks.

Most investigators have concluded that temperature acclimation is not important in determining treatment efficiency of completely mixed activated sludge systems. In systems operating at or near ambient temperature conditions such as aerated lagoons, temperature changes are gradual thus enhancing the acclimation process. Studies by Sawyer (42) found effective BOD removal at all temperatures between 10° and 25°C during six weeks of batch culture experiments, suggesting that acclimation is not important. In addition, Adamse (41) found that there was no significant difference in the bacterial compositions of two mixed cultures maintained at 8° to 12°C and 15° to 20°C respectively, suggesting that shifts in bacterial population with changes in temperature within this range may not affect the temperature adaption phenomenon.

Although the temperature acclimation of mixed cultures may not have a significant effect on the treatment efficiency of complete-mix systems it may have a significant effect on the laboratory analysis of the treatment system. The standard 5-day biochemical oxygen demand (BOD) test performed at 20°C could represent a shock temperature change of approximately 20°C in samples obtained for the analysis of winter operation of aerated lagoons. In light of recent literature, approximately 2 weeks would be required for the complete acclimation of a mixed culture system to this magnitude of temperature shock. For this reason kinetic data obtained from the BOD test is of questionable significance unless samples have been incubated at or near ambient temperature conditions.

3.4. The Effect of Temperature on Physical-Chemical Reactions

The temperature dependence of the biological reaction-rate constant used in assessing the overall efficiency of a biological treatment process is dependent upon both biological and physical-chemical reactions occurring within the system. Temperature not only influences the metabolic activities of the microbiological population, but also has a profound effect on such factors as gas transfer rates, settling characteristics and adsorption. As settling and possibly bio-adsorption play an integral role in the overall BOD removal efficiency of aerated lagoons, the temperature dependence of these processes must be considered in analysing the temperature dependence of the waste treatment system.

3.4.1. The Effect of Temperature on Settling Rate

Settling plays a very significant role in the overall BOD removal efficiency of aerated lagoons as up to 40% of the influent BOD load settles out and undergoes anaerobic decomposition (15)(18). Sedimentation theory is only partially understood and the design parameters for settling of domestic sewage are based upon empirical relationships.

The law for frictional drag, which determines the settling velocity of a discrete particle, represents the only sedimentation theory based upon classical mechanics. The law was first proposed by Sir Isaac Newton and is usually written as (43):

$$F_\Delta = C_\Delta A \frac{\rho V^2}{2} \qquad \text{....(39)}$$

where F_Δ = drag force;

C_Δ = drag coefficient (dimensionless);

A = projected area of the body in the direction of motion;

V = the relative velocity between the body and the fluid;

$\frac{\rho V^2}{2}$ = the dynamic pressure;

ρ = the mass density of the fluid.

Although this equation is not directly applicable to sedimentation in wastewater it shows that the settling velocity of a specific particle is a function of the viscosity of the liquid which is in turn a function of temperature. This phenomenon can logically be expected to affect not only the settling of descrete particles but all types of settling.

Keefer (38) reports Hasen to have shown that fine particles will settle twice as fast at 23°C as at 0°C. Howland (44) states that it can be shown that raising the temperature from 21° to 27°C increases percentage removal by about 13%. He quotes Schroepfer as demonstrating that the removal in sewage settling tanks actually improved in this temperature range by this amount.

Reed and Murphy (45) conducted an investigation on settling characteristics of activated sludge at temperatures ranging from 1.1° to 23.4°C and found that the influences of temperature on settling velocity decreased as the concentration increased. As the concentration of biological solids in an aerated lagoon are very low the influence of temperature on settling characteristics would be expected to be more severe than those found in conventional activated sludge systems. In a study by Black (15) variations in temperature were noted to affect effluent suspended solids concentration in an aerated lagoon in Brampton, Ontario. An increase in effluent suspended solids was noted with a decrease in temperature.

Operation of an exposed waste treatment facility during winter months, such as an aerated lagoon, could result in a secondary effect on settling. During the winter the temperatures at the surface of the lagoon, and consequently liquid temperatures at the surface, could be appreciably lower than the bulk of the liquid. The resulting changes in liquid density could cause thermal currents which would hinder settling and may cause short circuiting. The significance of this effect would depend upon the process involved. An activated sludge clarifier designed for a marginal overflow rate, would be affected much more by these conditions than an aerated lagoon.

3.4.2. The Effect of Temperature on Adsorption

A well conditioned activated sludge has the ability to physically adsorb colloidal and suspended materials in the media. This property was recognized many years ago and was first exploited by Ulrich and Smith (46)(47) in Austin, Texas, in 1951. The process was commonly referred to as the Biosorption Process but is now more commonly called Contact Stabilization. The adsorption phenomenon is reasonably well understood by physical chemists. It is based on the fact that the adsorption properties of a system can be materially affected by the structure and the nature of the interface between two phases of the system. The free energy of a surface, G, is equal to the work required to produce the surface (the surface area times the surface tension). This is usually expressed as $G = \alpha A$. The efficient system, then, is where G is a minimum. Any material will attempt to make G a minimum by reducing the surface area or surface tension or both. A pure liquid (water, for example) cannot reduce α but will attempt to make A a minimum by assuming the most efficient shape, a sphere. If a material is introduced to a liquid which will reduce the surface tension, that material will concentrate at the surface in order to make G a minimum. If the solute will increase surface tension, it will migrate away from the surface. When the concentration of a solute is different at the surface than in the rest of the solution, the condition is called adsorption. The amount of adsorption at a surface depends upon the amount by which surface tension changes with increased concentration of the adsorbed material. The relationship is described by the Gibbs equation (26).

The Gibbs equation states that the rate of adsorption is inversely proportional to the temperature and is therefore more rapid at low temperatures than at high temperatures. Howland (44) suggests the possibility that adsorption plays an important part in bioflocculation and thus could also affect settling rates in secondary clarifiers. The significance of the bioadsorption phenomena in the overall BOD removal efficiency of aerated lagoons is questionable due to the low level of biological solids in the system. Under cold temperature operating conditions the effect may become more pronounced but as yet little or no research has been done on dilute biological systems.

3.5. The Effect of Turbulence and Mixing on Reaction Rate

The values for the reaction rate constant, K, obtained in a laboratory are frequently used in predicting the rate of biological stabilization of waste in numerous types of biological waste treatment systems. An important factor influencing the oxidation rate in a waste treatment system is turbulence or mixing, which does not occur in standard determinations of K in the laboratory.

Tordi and Heukelekian (48) using wastewater filtered through glass wool, noted an increase in the rate constant with mixing. Swilley and Bryan (49) carried out a BOD progression study on glutamic acid to compare uptake rates in stirred and quiescent BOD bottles. The stirred environments caused higher reaction rates than quiescent conditions. More recently Gannon (50) determined the influence of mixing on the BOD rate constant for river water. The BOD rate constant under continuous mixing was more than 10 times the rate constant obtained under quiescent conditions. Pohl (26) reports that a study by Jezeski showed that the generation time at various temperatures was different for stationary cultures than for shake cultures. Jezeski's work was done using a pure culture of pseudomonas fluorescens which is a psychrophilic organism. The study was performed over a temperature range of 4° to 32°C and not only confirmed a decrease in generation time with turbulence but an increase in the magnitude of this effect with a decrease in temperature. Using a glucose substrate a 33% decrease in generation time was noted in the shake culture at 4°C while only a 4% decrease was noted in the 25°C shake culture.

A comprehensive study by Hamdy and Bewtra (51) indicated that not only the reaction rate constant but 5-day BOD values also increased in wastewater being stirred in relation to samples maintained under quiescent condtions. An average increase of 17 percent in 5-day BOD values was obtained when test samples were stirred at speeds ranging from 120 to 1300 rpm. Hamdy et al found that the variation in rate constant (in days^{-1}) with change in stirrer speed (in rpm) was described by the following equation (51);

$$K_{STIRRED} = K_{QUIESCENT} + 0.000033 \text{ X SPEED} \quad ....(40)$$

A possible explanation for differences observed in BOD rate constant values between stirred and quiescent conditions is the increased rate of bacterial activity and multiplication with an increase in turbulence. The turbulence around the bacterial cell increases the rate of material transport into the cell and the rate of removal of by-products accummulating in the cell membrane. Turbulence also increases contact between the bacterial cells and the substrate, increasing the rate of assimilation.

These observations suggest that BOD and rate constant values obtained by the standard method (quiescent conditions) should be interpreted cautiously, particularly when applying them to turbulent or mixing conditions such as in aerated lagoons. More realistic BOD values and rate constants could possibly be obtained by tests with continuous stirring of BOD bottle contents at a rate which approximates the degree of mixing occurring in the waste treatment facility been studied. Velocity gradients in aerated lagoons have been measured by O'Connor and Eckenfelder (1) and range from 0.1 to 4.0 feet per second, which is of the same order as those found in natural streams.

CHAPTER 4

EXPERIMENTAL PROCEDURE

4. Experimental Procedure

The experimental procedures used for this study are discussed in the following sections as:

(1) Sampling Methods; and,

(2) Tests and Analytical Procedures.

4.1. Sampling Methods

Sampling of the aerated lagoons located in Portage la Prairie, Manitoba, was performed on a weekly basis from November, 1976 through April, 1977. Two liter grab samples were taken from the lagoon mixed liquor, influent and effluent on Fridays at approximately 10:00 a.m. throughout this sampling period. The lagoon mixed liquor temperature was also recorded on each sampling date.

Mixed liquor samples were obtained at the middle of the lagoon from the side dykes using a bucket and rope during ice-free operating conditions. During periods of ice cover samples were obtained near the center of the lagoon using a standard DO and BOD sampling assembly. Holes were made in the ice with an ice pick. These samples were taken at a depth of approximately 2 feet in order to prevent ice chips from entering the sample. Influent and effluent samples were obtained directly from taps located on the influent and effluent lines housed within the lagoon control structure. All effluent samples were taken prior to chlorination.

Samples were collected in clean, small mouth, 2 liter screwcap polyethylene bottles. These bottles were filled and immediately returned, by automobile, to the University of Manitoba for laboratory analysis without further field treatment.

Two aerated lagoons are in operation at Portage La Prairie, both having the same volume and aeration capacity. Sewage loading is alternated between these two lagoons in order to maintain a minimum dissolved oxygen concentration of 2 mg/l in the system. During the sampling period of this study, each lagoon was loaded continuously for a period of 4 to 7 days before sewage flow was diverted to the alternate lagoon. Samples were taken from the lagoon that was being loaded at the time of sampling.

4.2. Tests and Analytical Procedures

All analytical tests performed for this study were carried out in accordance to the procedures outlined in Standard Methods for the Examination of Water and Waste-Water (52) hereafter referred to as Standard Methods.

Biochemical oxygen demand tests were performed on a weekly basis throughout the sampling period in accordance to Section 507 of Standard Methods (52). Biochemical oxygen demand samples of lagoon influent and effluent were incubated, in duplicate, at both 20°C and at the ambient lagoon operating temperature.

Biochemical oxygen demand tests on lagoon mixed liquor samples were performed for 1, 2, 3, 4 and 5 day incubation periods. Samples were again incubated, in duplicate, at both 20°C and at ambient lagoon operating temperature.

Dissolved oxygen tests performed for the determination of biochemical oxygen demand employed the azide modification of the idometric method as described in Section 422B. of Standard Methods (52).

Total suspended solids and total volatile suspended solids determinations were made on lagoon mixed liquor samples obtained from March 4, 1977 through April 1, 1977. Suspended and volatile suspended solids tests were performed in accordance to procedures outlined in Sections 208D. and 208E. of Standard Methods (52), respectively.

In addition to laboratory tests performed for this study, the results of laboratory tests performed by the lagoon operator from February, 1976 through March, 1977, were obtained. This data included influent and effluent, biochemical oxygen demand, chemical oxygen demand, and suspended solids test results. A daily record of sewage flow rates and lagoon mixed liquor temperatures was also obtained for this time period.

CHAPTER 5

EXPERIMENTAL RESULTS

The experimental results obtained from this study will be presented as:

(1) Lagoon Operational Data;
(2) Analytical Test Results;
(3) Temperature Effect on Aerated Lagoon Kinetics; and
(4) Dynamic Model Test Results.

5.1. Lagoon Operational Data

The lagoon operational data includes sewage flow rates, lagoon retention time and lagoon operating temperature from February, 1976 through March, 1977. Daily sewage flow rate estimates were obtained by applying a previously determined calibration factor to the monthly power consumption of pumping facilities. Average monthly lagoon operating temperatures were based upon daily readings of three thermalcouples located at varied depths within the lagoon liquid. The lagoon retention time (V/Q) was calculated from average monthly flow rates and the effective lagoon volume. The calculations of effective lagoon volume are presented in Appendix 1. The flow rates, retention time and operating temperature of the lagoon are presented in Table 5-1.

TABLE 5-1. Lagoon Operational Data

Date (Month)	Av. Flow (Imp. Gal/Day)	Av. Temp (°C)	Retention* (Days)
Feb/76	2.09×10^6	2.2	6.86
March	1.94×10^6	2.2	7.39
April	2.00×10^6	10.2	7.18
May	2.62×10^6	14.7	5.48
June	2.56×10^6	21.1	5.61
July	1.70×10^6	**	8.46
August	1.90×10^6	17.5	7.57
September	1.73×10^6	17.2	8.31
October	1.61×10^6	12.7	8.89
November	1.48×10^6	4.1	9.69
December	1.50×10^6	1.7	9.59
Jan/77	1.45×10^6	2.2	9.93
February	1.50×10^6	2.2	9.54
March	1.86×10^6	3.3	7.71

* Based upon 14.35×10^6 Imp. Gal. lagoon vol. (see Appendix 1)

** Data not available

5.2. Analytical Test Results

5.2.1. Biochemical Oxygen Demand Tests

Biochemical oxygen demand tests were performed on lagoon mixed liquor samples using 1, 2, 3, 4 and 5 day incubation periods. The biochemical oxygen demand reaction rates were then determined by both the Thomas Method (53) and the Method of Moments (54). The Thomas Method analysis resulted in the most consistent data and was therefore adopted for this study.

Values of $(t/y)^{1/3}$ were calculated, were t = time (days) and y = BOD (mg/l) at time t. A "best fit" straight line was then determined for a plot of $(t/y)^{1/3}$ vs time by linear regression analysis on a Hewlett Packard, Model 9100A, calculator. The values of "A" (y - intercept), "B" (slope of straight line), and "R" (correlation coefficient (55)) were obtained from this linear regression analysis. Using the values of "A" and "B", the biochemical oxygen demand reaction rate, K, was determined as follows (53):

$$K = (2.61)\ B/A \qquad .....(41)$$

An example of typical biochemical oxygen demand test results at both ambient lagoon temperature and at 20°C are shown in Figure 5-1. Calculated reaction rate constants for lagoon mixed liquor samples incubated at 20°C and at ambient lagoon temperatures are shown in Table 5-2. Only data resulting in a linear regression correlation coefficient, R, of greater than 0.85 are shown in this table.

Biochemical oxygen demand test results for a five-day incubation period at 20°C on lagoon influent and effluent samples were also obtained. The average monthly BOD_5 values shown in Table 5-3 are based upon 12 influent and effluent test values per month. The overall BOD_5 removal reaction rate, K, of the lagoon was calculated from influent and effluent BOD_5 values as follows:

$$K = (S_o/S - 1)/R \qquad ....(42)$$

where K = overall BOD_5 removal reaction rate (days^{-1})

S_o = influent BOD_5 (mg/l)

S = effluent BOD_5 (mg/l)

R = retention time (days)

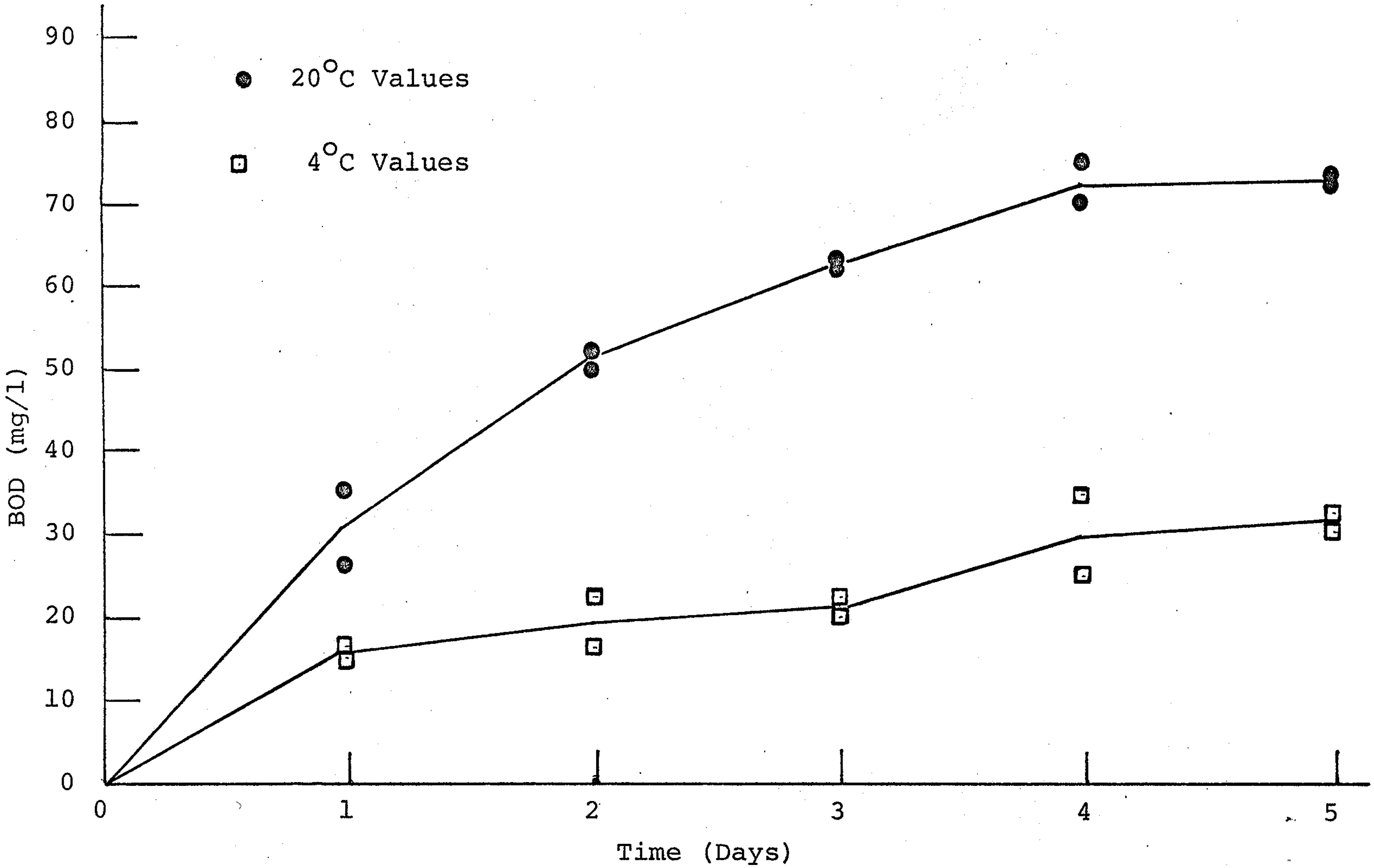

Figure 5-1. BOD Test Results of Lagoon Mixed-Liquor. November 19, 1976.

TABLE 5-2. BOD Reaction Rates-Thomas Method (53) Lagoon Mixed Liquor

Sampling Date	Incubation Temp. (°C)	Reaction Rate K(Days^{-1})	Correlation Coeff. R
Nov.19/76	4.0°	0.222	0.9135
Nov.19	4.0°	0.265	0.8960
Nov.26	2.0°	0.131	0.9656
Nov.26	2.0°	0.118	0.9529
Jan.21/77	0.5°	0.074	0.9646
Jan.21	0.5°	0.131	0.9348
Feb.11	1.5°	0.097	0.8740
Feb.11	1.5°	0.103	0.9401
Feb.18	0.5°	0.083	0.9725
Feb.18	0.5°	0.079	0.8839
March 4	1.0°	0.069	0.9626
March 25	2.5°	0.072	0.9622
Nov. 5/76	20°	0.157	0.9880
Nov. 5	20°	0.171	0.9812
Nov. 12	20°	0.159	0.9790
Nov. 12	20°	0.169	0.9839
Nov. 19	20°	0.244	0.9958
Nov. 19	20°	0.163	0.9807
Nov. 26	20°	0.219	0.9733
Nov. 26	20°	0.160	0.9783
Jan. 2/77	20°	0.087	0.9790
Feb. 11	20°	0.203	0.9441
Feb. 11	20°	0.268	0.9532
Feb. 18	20°	0.260	0.9701
March 18	20°	0.048	0.8805
April 1	20°	0.205	0.9937
April 1	20°	0.116	0.9384

Results of these reaction rate calculations are shown in Table 5-3. Average monthly lagoon temperature and retention time, obtained from Table 5-1, are also presented in Table 5-3.

TABLE 5-3. Lagoon BOD_5 Removal Reaction Rates

Date (Month)	Av. BOD_5 Inf. (mg/l)	Av. BOD_5 Eff. (mg/l)	Retention (Days)	Reaction Rate (Day^{-1})	Temp. (^oC)
Feb./76	390	161	6.86	0.207	2.2
March	288	116	7.39	0.200	2.2
April	259	85	7.18	0.285	10.2
May	216	61	5.48	0.464	14.7
June	347	72	5.61	0.680	21.1
July	203	55	8.46	0.318	*
August	278	62	7.57	0.460	17.5
September	299	63	8.31	0.451	17.2
October	320	66	8.89	0.433	12.7
November	336	71	9.69	0.385	4.1
December	412	72	9.59	0.497	1.7
Jan./77	352	72	9.93	0.392	2.2
February	357	89	9.54	0.316	2.2
March	301	81	7.71	0.352	3.3

*Data not Available

5.2.2. Chemical Oxygen Demand Tests

Chemical oxygen demand (COD) test results of lagoon influent and effluent are shown in Table 5-4. Average monthly COD values are based upon 4 to 5 individual test values per month. The overall COD removal reaction rate, K_c, of the lagoon was calculated from influent and effluent COD values as follows:

$$K_c = (C_o/C - 1)\ /R \qquad \text{....(43)}$$

where K_c = overall COD removal reaction rate (days^{-1});

C_o = influent COD (mg/l);

C = effluent COD (mg/l).

Results of these reaction rate calculations are shown in Table 5-4 with average monthly lagoon retention time and temperature values.

TABLE 5-4. COD Test Results

Date (Month)	Av. COD Inf. (mg/l)	Av. COD Eff. (mg/l)	Retention (Days)	Reaction Rate (Days^{-1})	Temp. (^{o}C)
Feb./76	609	199	6.86	0.300	2.2
March	556	201	7.39	0.239	2.2
April	406	102	7.18	0.415	10.2
May	586	145	5.48	0.555	14.7
June	672	128	5.61	0.757	21.1
July	431	97	8.46	0.407	*
August	601	93	7.57	0.722	17.5
September	640	90	8.31	0.736	17.2
October	860	137	8.89	0.593	12.7
November	877	141	9.69	0.539	4.1
December	760	184	9.59	0.326	1.7
Jan./77	741	234	9.93	0.158	2.2
February	741	195	9.54	0.293	2.2
March	780	194	7.71	0.392	3.3

* Data not available.

5.2.3. Suspended Solids Tests

Suspended solids (SS) test results of lagoon influent and effluent are shown in Table 5-5. Average monthly suspended solids values are based upon daily test results on both lagoon influent and effluent samples. Percent suspended solids removal and lagoon temperature are also presented in Table 5-5.

TABLE 5-5. Suspended Solids Test Results

Date (Month)	SS - Inf. (mg/l)	SS - Eff. (mg/l)	Removal (%)	Temp. (°C)
Feb./76	279	66	76	2.2
March	329	60	82	2.2
April	371	39	89	10.2
May	349	31	91	14.7
June	261	33	87	21.1
July	210	29	86	*
August	330	18	94	17.5
September	373	23	94	17.2
October	522	39	93	12.7
November	291	43	85	4.1
December	488	44	91	1.7
Jan./77	336	31	91	2.2
February	364	51	86	2.2
March	427	55	87	3.3

* Data not available.

5.3. Temperature Effect on Aerated Lagoon Kinetics

5.3.1. Temperature Effects on BOD Reaction Rates

The BOD reaction rates of lagoon mixed liquor samples incubated at ambient lagoon operating temperatures are shown in Table 5-2. The variation of reaction rate with temperature is illustrated graphically in Figure 5-2. The reaction rate to temperature relationships was found to be best approximated as follows:

$$K_{T_1} = K_{T_2} \times \theta^{(T_1 - T_2)} \qquad \ldots .(44)$$

where T_1, T_2 = two temperatures within temperature response range;

K_{T_1}, K_{T_2} = reaction rate coefficients at temperatures T_1 and T_2, respectively;

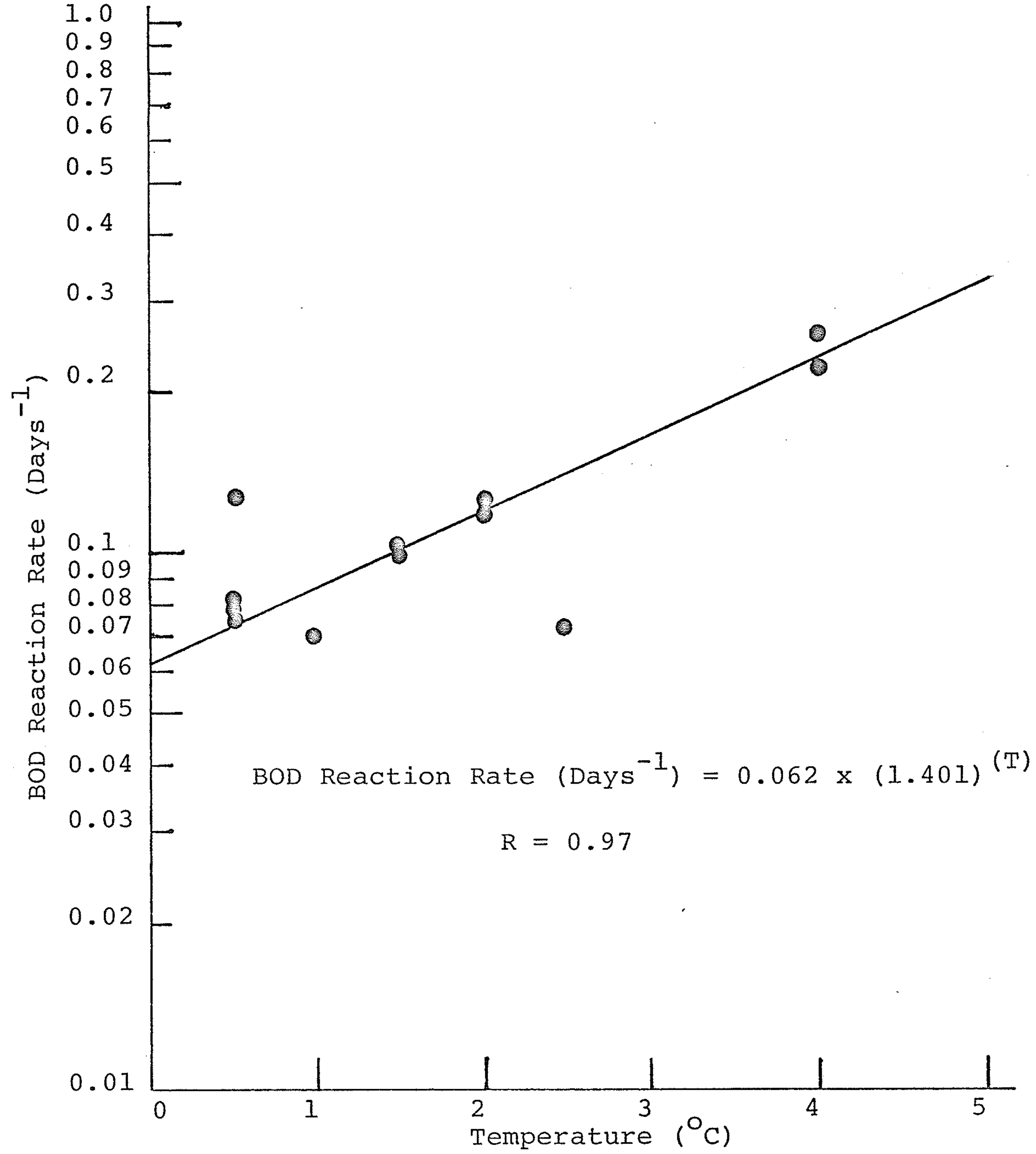

Figure 5-2. BOD Reaction Rate versus Temperature.

Θ = temperature sensitivity coefficient ($\log^{-1}$ of slope of log K vs. T plot).

The "best fit" slope, and thus the Θ value, of the log K vs T relationship shown in Figure 5-2 was obtained by linear regression analysis on a Hewlett Packard, Model 9100 A calculator.

5.3.2. Temperature Effects on Aerated Lagoon BOD Removal

The effect of temperature variation on the overall BOD removal rate of the aerated lagoon is shown in Figure 5-3. The overall BOD removal reaction rates are based upon data from February, 1976 through October, 1976, presented in Table 5-3. Equation 44 was found to best approximate the overall BOD removal rate to temperature relationship. The "best fit" slope, and thus the Θ value, of the log K vs. T relationship shown in Figure 5-3 was obtained by least squares exponential fit analysis (55) on a Hewlett Packard, Model 9100 A, calculator.

5.3.3. Temperature Effects on Aerated Lagoon COD Removal

The effect of temperature variation on the overall COD removal rate of the aerated lagoon is shown in Figure 5-4. The overall COD removal reaction rates of the lagoon are based upon data presented in Table 5-4. Equation 44 was found to best approximate the overall COD removal rate to temperature relationship. The "best fit" slope, and

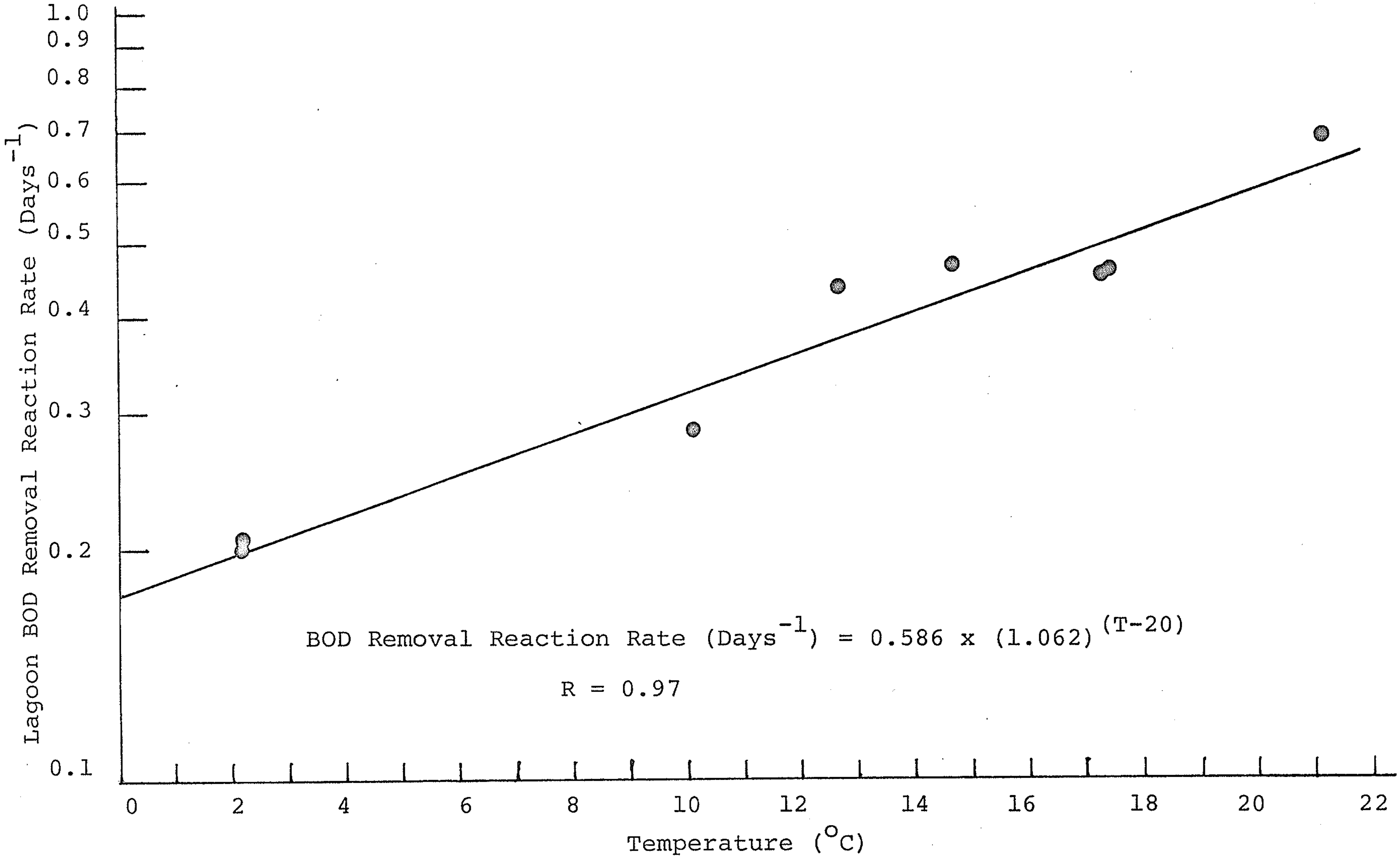

Figure 5-3. Lagoon BOD Removal Reaction Rate versus Temperature.

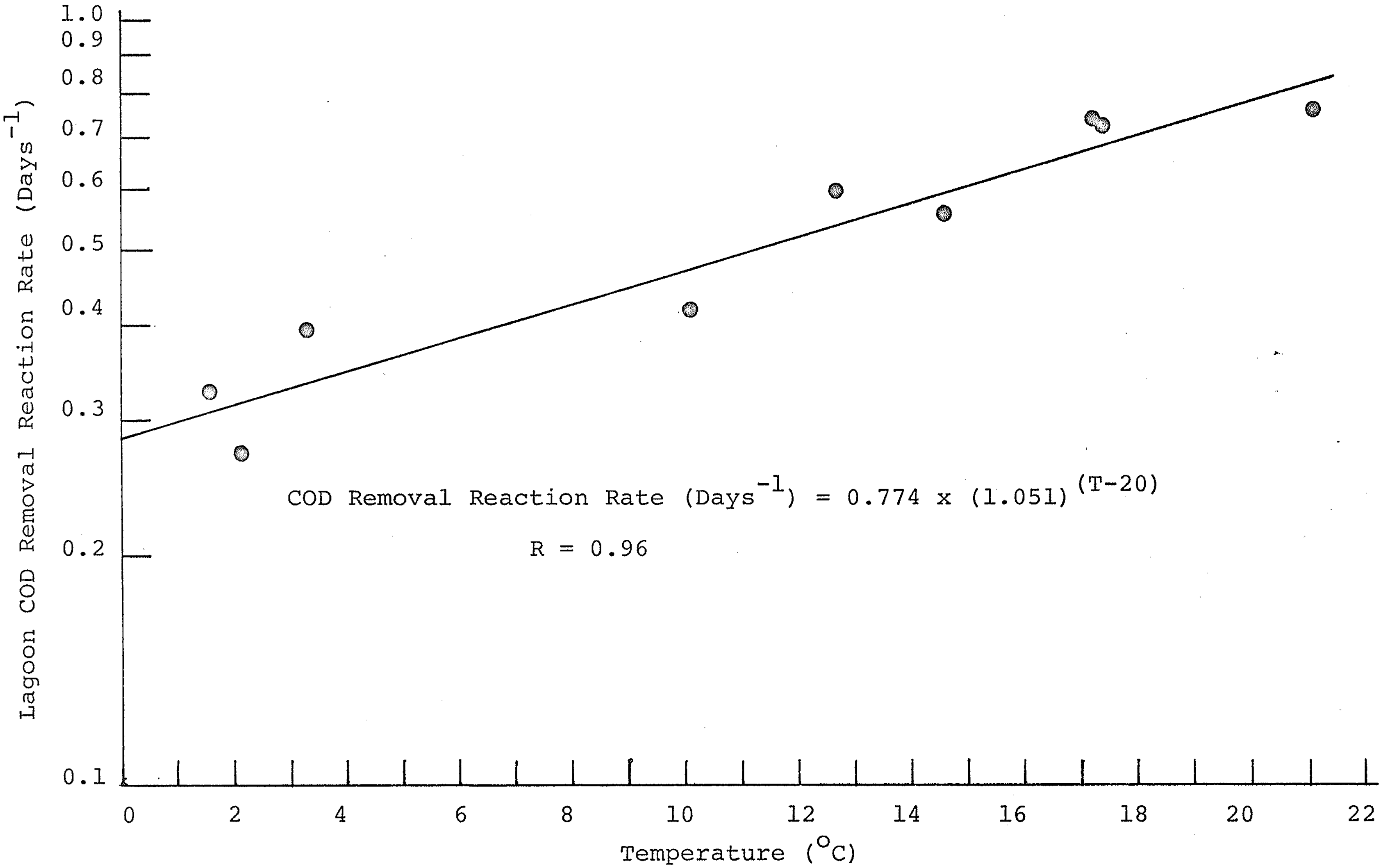

Figure 5-4. Lagoon COD Removal Reaction Rate versus Temperature.

thus Θ value, of the log K vs. T relationship shown in Figure 5-4 was obtained by least squares exponential fit analysis (55) on a Hewlett Packard, Model 9100 A, calculator.

5.3.4. Temperature Effects on Aerated Lagoon Suspended Solids Removal

The effect of temperature variation on the suspended solids (SS) removal rate of the aerated lagoon is shown in Figure 5-5. The percentage suspended solids removal rates are based upon data presented in Table 5-5. The best approximation of suspended solids removal vs. temperature was obtained with a linear relationship. The equation of the "best fit" straight line shown in Figure 5-5 was obtained by linear regression analysis (55) on a Hewlett Packard, Model 9100A, calculator.

5.4. Dynamic Model Test Results

5.4.1. Temperature, Sewage Flow, and BOD Loading Simulations

In order to develop a dynamic model of the Portage la Prairie aerated lagoons, the yearly cyclic variations of temperature, sewage flow rates and BOD loading rates were estimated. The lagoon operational data presented in Table 5-1 and the lagoon BOD loading data presented in Table 5-3 were assumed representative of average yearly cyclic variations of these parameters within the lagoon. Sinusoidal approximations of these yearly cyclic variations

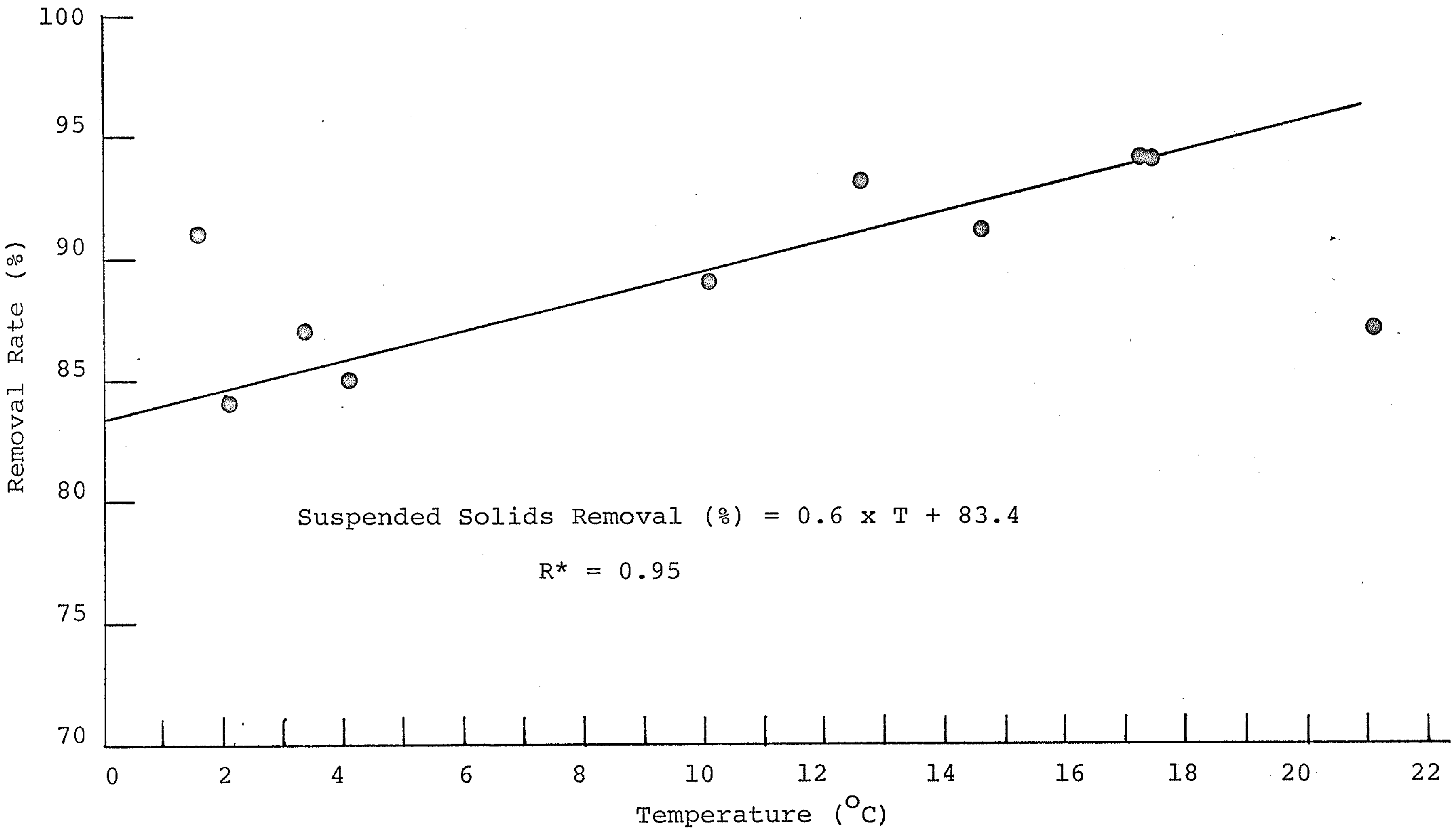

Figure 5-5. Suspended Solids Removal versus Temperature.

* 21.1^{O}C Data Point Omitted in Regression Analysis.

were obtained from a Fourier series analysis performed by computer. The computer program illustrated in Appendix 2 was used to determine the "best fit" Fourier series approximations for the available data. The sinusoidal approximations developed to simulate yearly cyclic variations in temperature, sewage flow and BOD loading are illustrated graphically in Figures 5-6, 5-7, and 5-8, respectively.

5.4.2. Predicted Sludge Accumulation and Effluent BOD Quality

The dynamic facultative aerated lagoon model developed for this study is illustrated in Appendix 3. This model employs the Continuous Systems Modelling Program (CSMP) - IBM computer package. Sinusoidal approximations of temperature, sewage flow, and BOD loading shown in Figures 5-6, 5-7, and 5-8 and BOD reaction rate data shown in Figure 5-2 were incorporated into the model. Other information, K_L and $s\rho$, necessary for the operation of the simulation model was obtained from studies performed by previous investigators (4)(17)(18). The sludge accumulation predicted by the dynamic aerated lagoon model is shown in Figure 5-9 through 5-12. The effluent BOD_5 quality predicted by the dynamic aerated lagoon model is shown in Figures 5-13 through 5-16.

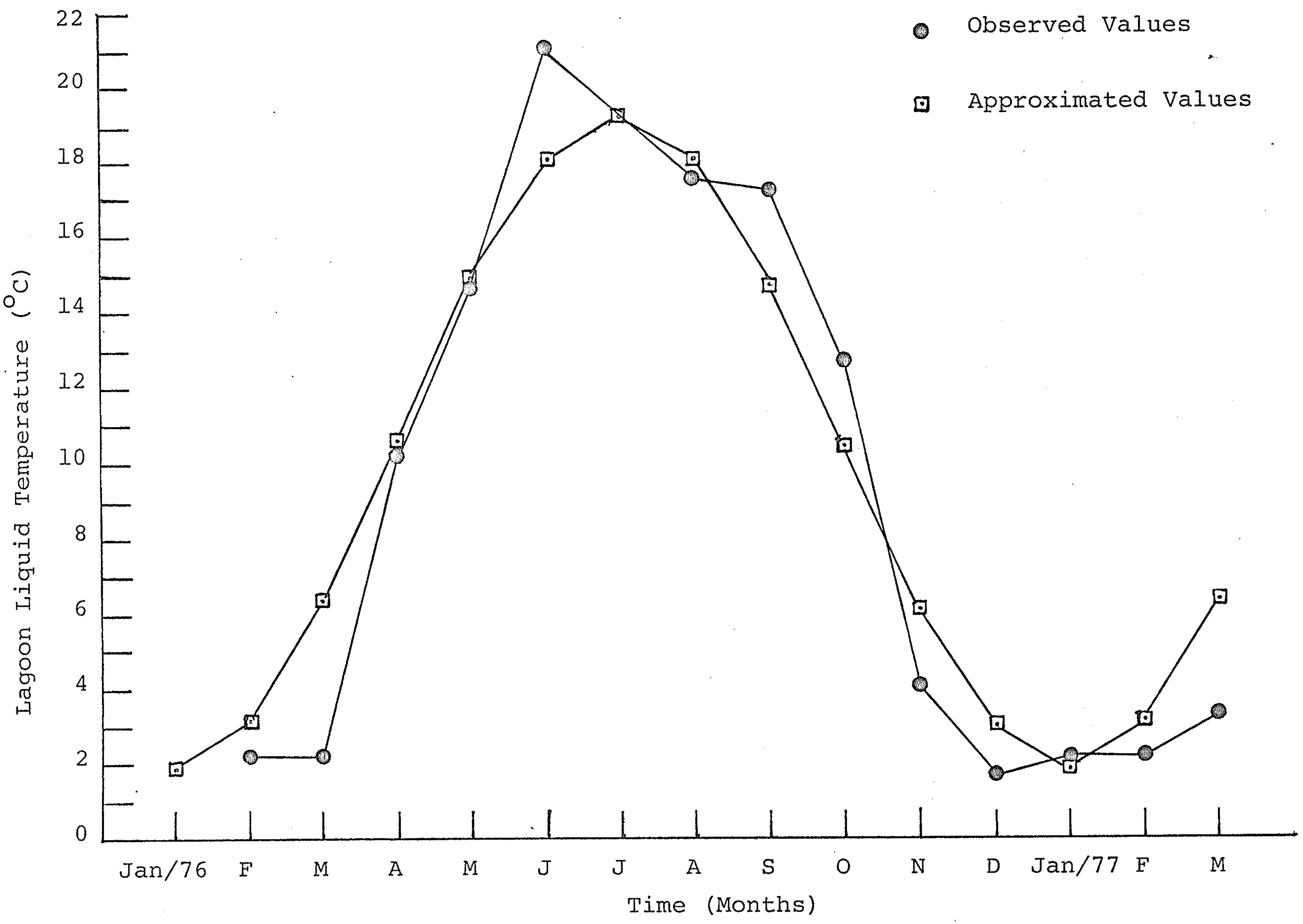

Figure 5-6. Sinusoidal Approximation of Lagoon Liquid Temperature.

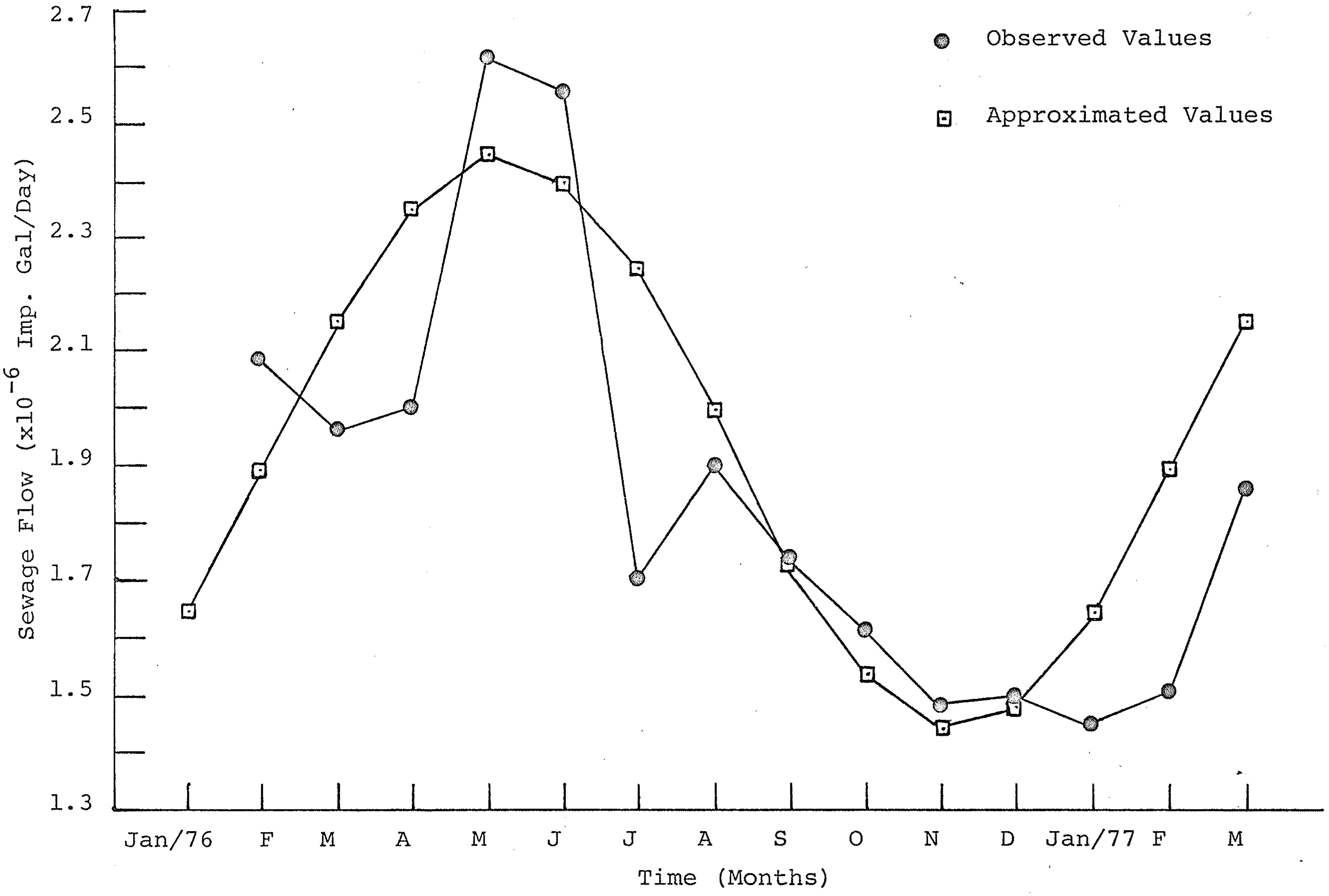

Figure 5-7. Sinusoidal Approximation of Sewage Flow Rate.

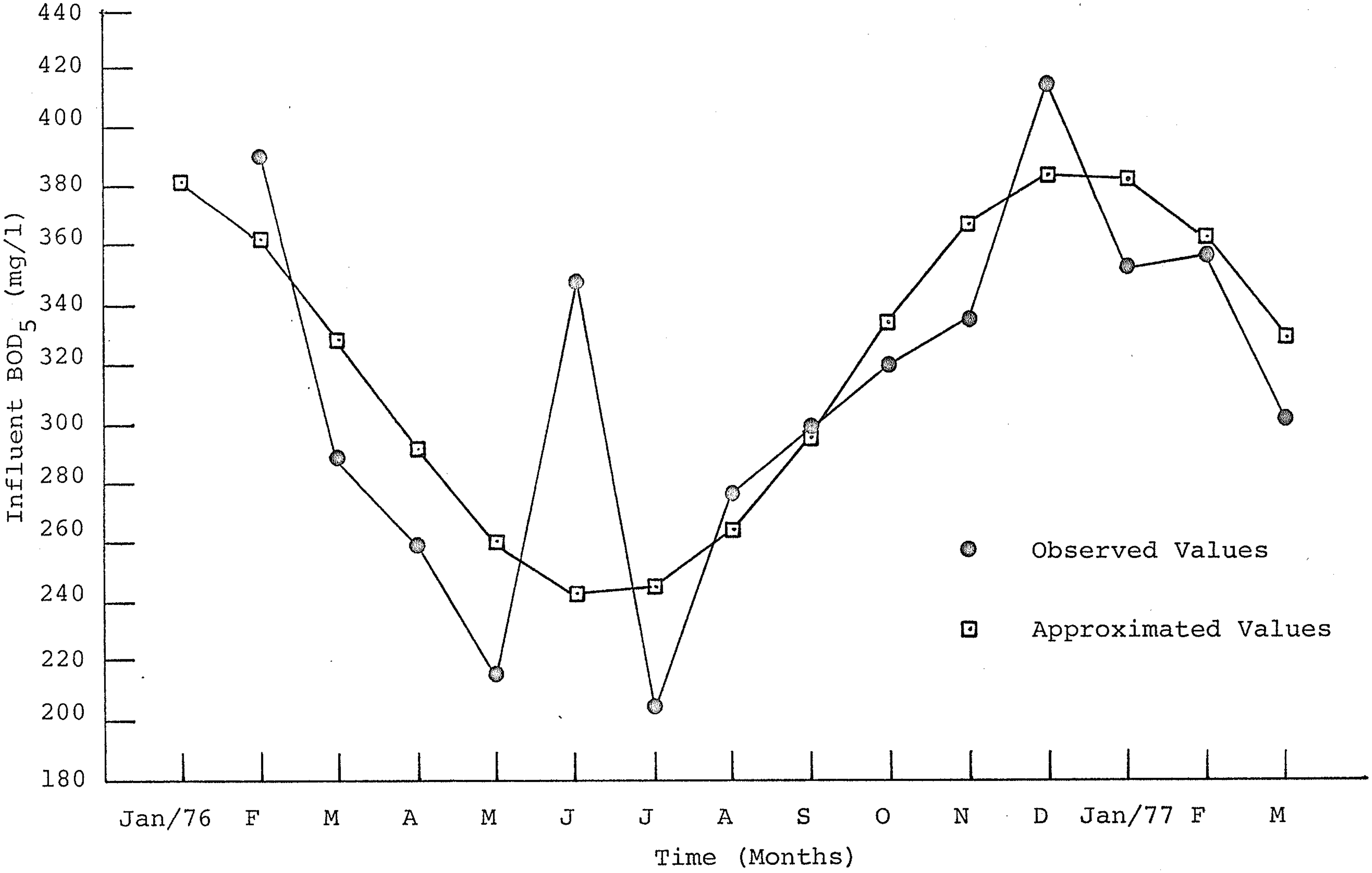

Figure 5-8. Sinusoidal Approximation of BOD_5 Loading Rate.

```
 TIME(Months)      S(Lbs-BOD)      I
0.0               1.0000E+01      +
1.0000E+00        8.8207E+04      +
2.0000E+00        1.8187E+05      -+
3.0000E+00        2.7525E+05      --+
4.0000E+00        3.6161E+05      ---+
5.0000E+00        4.3393E+05      ---+
6.0000E+00        4.8948E+05      ----+
7.0000E+00        5.3942E+05      ----+
8.0000E+00        5.9656E+05      ----+
9.0000E+00        6.6076E+05      -----+
1.0000E+01        7.2874E+05      ------+
1.1000E+01        8.0126E+05      ------+
1.2000E+01        8.8102E+05      -------+
1.3000E+01        9.6895E+05      --------+
1.4000E+01        1.0621E+06      --------+
1.5000E+01        1.1537E+06      ---------+
1.6000E+01        1.2334E+06      ----------+
1.7000E+01        1.2858E+06      ----------+
1.8000E+01        1.3055E+06      ----------+
1.9000E+01        1.3214E+06      ----------+
2.0000E+01        1.3613E+06      -----------+
2.1000E+01        1.4200E+06      -----------+
2.2000E+01        1.4865E+06      ------------+
2.3000E+01        1.5585E+06      ------------+
2.4000E+01        1.6381E+06      -------------+
2.5000E+01        1.7258E+06      --------------+
2.6000E+01        1.8184E+06      ---------------+
2.7000E+01        1.9085E+06      ---------------+
2.8000E+01        1.9825E+06      ----------------+
2.9000E+01        2.0179E+06      ----------------+
3.0000E+01        2.0067E+06      ----------------+
3.1000E+01        1.9935E+06      ----------------+
3.2000E+01        2.0185E+06      ----------------+
3.3000E+01        2.0724E+06      -----------------+
3.4000E+01        2.1376E+06      -----------------+
3.5000E+01        2.2093E+06      ------------------+
3.6000E+01        2.2887E+06      -------------------+
3.7000E+01        2.3762E+06      -------------------+
3.8000E+01        2.4684E+06      --------------------+
3.9000E+01        2.5572E+06      ---------------------+
4.0000E+01        2.6263E+06      ---------------------+
4.1000E+01        2.6470E+06      ----------------------+
4.2000E+01        2.6093E+06      ---------------------+
4.3000E+01        2.5710E+06      ---------------------+
4.4000E+01        2.5832E+06      ---------------------+
4.5000E+01        2.6331E+06      ---------------------+
4.6000E+01        2.6972E+06      ----------------------+
4.7000E+01        2.7686E+06      -----------------------+
4.8000E+01        2.8478E+06      -----------------------+
4.9000E+01        2.9351E+06      ------------------------+
5.0000E+01        3.0270E+06      -------------------------+
```

Fig. 5-9. Variation of Lagoon Model Sludge Mass with Time (0 to 50 months).

```
 TIME(Months)     S (Lbs-BOD)    I
5.1000E+01      3.1147E+06    ------------------------+
5.2000E+01      3.1796E+06    -------------------------+
5.3000E+01      3.1876E+06    -------------------------+
5.4000E+01      3.1272E+06    -------------------------+
5.5000E+01      3.0673E+06    ------------------------+
5.6000E+01      3.0686E+06    ------------------------+
5.7000E+01      3.1149E+06    ------------------------+
5.8000E+01      3.1782E+06    -------------------------+
5.9000E+01      3.2492E+06    --------------------------+
6.0000E+01      3.3283E+06    --------------------------+
6.1000E+01      3.4155E+06    ---------------------------+
6.2000E+01      3.5071E+06    ----------------------------+
6.3000E+01      3.5938E+06    ----------------------------+
6.4000E+01      3.6551E+06    -----------------------------+
6.5000E+01      3.6522E+06    -----------------------------+
6.6000E+01      3.5723E+06    ----------------------------+
6.7000E+01      3.4938E+06    ----------------------------+
6.8000E+01      3.4857E+06    ---------------------------+
6.9000E+01      3.5290E+06    ----------------------------+
7.0000E+01      3.5915E+06    ----------------------------+
7.1000E+01      3.6623E+06    -----------------------------+
7.2000E+01      3.7412E+06    ------------------------------+
7.3000E+01      3.8283E+06    ------------------------------+
7.4000E+01      3.9196E+06    -------------------------------+
7.5000E+01      4.0055E+06    --------------------------------+
7.6000E+01      4.0637E+06    --------------------------------+
7.7000E+01      4.0515E+06    --------------------------------+
7.8000E+01      3.9547E+06    -------------------------------+
7.9000E+01      3.8604E+06    -------------------------------+
8.0000E+01      3.8441E+06    ------------------------------+
8.1000E+01      3.8848E+06    -------------------------------+
8.2000E+01      3.9466E+06    -------------------------------+
8.3000E+01      4.0172E+06    --------------------------------+
8.4000E+01      4.0960E+06    ---------------------------------+
8.5000E+01      4.1830E+06    ---------------------------------+
8.6000E+01      4.2741E+06    ----------------------------------+
8.7000E+01      4.3593E+06    -----------------------------------+
8.8000E+01      4.4148E+06    -----------------------------------+
8.9000E+01      4.3946E+06    -----------------------------------+
9.0000E+01      4.2834E+06    ----------------------------------+
9.1000E+01      4.1754E+06    ---------------------------------+
9.2000E+01      4.1521E+06    ---------------------------------+
9.3000E+01      4.1906E+06    ---------------------------------+
9.4000E+01      4.2518E+06    ----------------------------------+
9.5000E+01      4.3223E+06    ----------------------------------+
9.6000E+01      4.4010E+06    -----------------------------------+
9.7000E+01      4.4879E+06    ------------------------------------+
9.8000E+01      4.5788E+06    -------------------------------------+
9.9000E+01      4.6634E+06    -------------------------------------+
1.0000E+02      4.7166E+06    --------------------------------------+
1.0100E+02      4.6895E+06    --------------------------------------+
```

Fig. 5-10. Variation of Lagoon Model Sludge Mass with Time (51 to 101 months)

```
 TIME (Months)  S (Lbs-BOD)  I
1.0200E+02    4.5659E+06    ---------------------------------------+
1.0300E+02    4.4461E+06    --------------------------------------+
1.0400E+02    4.4168E+06    --------------------------------------+
1.0500E+02    4.4534E+06    ---------------------------------------+
1.0600E+02    4.5141E+06    ---------------------------------------+
1.0700E+02    4.5844E+06    ----------------------------------------+
1.0800E+02    4.6631E+06    ----------------------------------------+
1.0900E+02    4.7498E+06    -----------------------------------------+
1.1000E+02    4.8407E+06    ------------------------------------------+
1.1100E+02    4.9247E+06    ------------------------------------------+
1.1200E+02    4.9759E+06    -------------------------------------------+
1.1300E+02    4.9430E+06    -------------------------------------------+
1.1400E+02    4.8086E+06    -----------------------------------------+
1.1500E+02    4.6787E+06    ----------------------------------------+
1.1600E+02    4.6443E+06    ----------------------------------------+
1.1700E+02    4.6793E+06    ----------------------------------------+
1.1800E+02    4.7396E+06    -----------------------------------------+
1.1900E+02    4.8097E+06    -----------------------------------------+
1.2000E+02    4.8883E+06    ------------------------------------------+
1.2100E+02    4.9750E+06    -------------------------------------------+
1.2200E+02    5.0657E+06    --------------------------------------------+
1.2300E+02    5.1493E+06    --------------------------------------------+
1.2400E+02    5.1988E+06    ---------------------------------------------+
1.2500E+02    5.1607E+06    --------------------------------------------+
1.2600E+02    5.0172E+06    -------------------------------------------+
1.2700E+02    4.8787E+06    ------------------------------------------+
1.2800E+02    4.8399E+06    ------------------------------------------+
1.2900E+02    4.8734E+06    ------------------------------------------+
1.3000E+02    4.9333E+06    -------------------------------------------+
1.3100E+02    5.0033E+06    -------------------------------------------+
1.3200E+02    5.0818E+06    --------------------------------------------+
1.3300E+02    5.1685E+06    --------------------------------------------+
1.3400E+02    5.2590E+06    ---------------------------------------------+
1.3500E+02    5.3422E+06    ----------------------------------------------+
1.3600E+02    5.3903E+06    ----------------------------------------------+
1.3700E+02    5.3479E+06    ----------------------------------------------+
1.3800E+02    5.1965E+06    ---------------------------------------------+
1.3900E+02    5.0505E+06    --------------------------------------------+
1.4000E+02    5.0079E+06    -------------------------------------------+
1.4100E+02    5.0402E+06    -------------------------------------------+
1.4200E+02    5.0998E+06    --------------------------------------------+
1.4300E+02    5.1697E+06    --------------------------------------------+
1.4400E+02    5.2481E+06    ---------------------------------------------+
1.4500E+02    5.3348E+06    ----------------------------------------------+
1.4600E+02    5.4252E+06    -----------------------------------------------+
1.4700E+02    5.5081E+06    -----------------------------------------------+
1.4800E+02    5.5549E+06    ------------------------------------------------+
1.4900E+02    5.5087E+06    -----------------------------------------------+
1.5000E+02    5.3506E+06    ----------------------------------------------+
1.5100E+02    5.1981E+06    ---------------------------------------------+
1.5200E+02    5.1522E+06    --------------------------------------------+
```

Fig. 5-11. Variation of Lagoon Model Sludge Mass with Time (102 to 152 months)

```
TIME(Months)     S (Lbs-BOD)
1.5300E+02       5.1835E+06
1.5400E+02       5.2428E+06
1.5500E+02       5.3127E+06
1.5600E+02       5.3911E+06
1.5700E+02       5.4777E+06
1.5800E+02       5.5680E+06
1.5900E+02       5.6506E+06
1.6000E+02       5.6963E+06
1.6100E+02       5.6470E+06
1.6200E+02       5.4830E+06
1.6300E+02       5.3250E+06
1.6400E+02       5.2763E+06
1.6500E+02       5.3067E+06
1.6600E+02       5.3658E+06
1.6700E+02       5.4355E+06
1.6800E+02       5.5139E+06
1.6900E+02       5.6005E+06
1.7000E+02       5.6908E+06
1.7100E+02       5.7731E+06
1.7200E+02       5.8179E+06
1.7300E+02       5.7657E+06
1.7400E+02       5.5968E+06
1.7500E+02       5.4340E+06
1.7600E+02       5.3830E+06
1.7700E+02       5.4126E+06
1.7800E+02       5.4714E+06
1.7900E+02       5.5411E+06
1.8000E+02       5.6195E+06
1.8100E+02       5.7060E+06
1.8200E+02       5.7962E+06
1.8300E+02       5.8783E+06
1.8400E+02       5.9224E+06
1.8500E+02       5.8678E+06
1.8600E+02       5.6946E+06
1.8700E+02       5.5278E+06
1.8800E+02       5.4746E+06
1.8900E+02       5.5035E+06
1.9000E+02       5.5622E+06
1.9100E+02       5.6319E+06
1.9200E+02       5.7102E+06
1.9300E+02       5.7967E+06
1.9400E+02       5.8869E+06
1.9500E+02       5.9688E+06
1.9600E+02       6.0121E+06
1.9700E+02       5.9555E+06
1.9800E+02       5.7786E+06
1.9900E+02       5.6083E+06
2.0000E+02       5.5533E+06
```

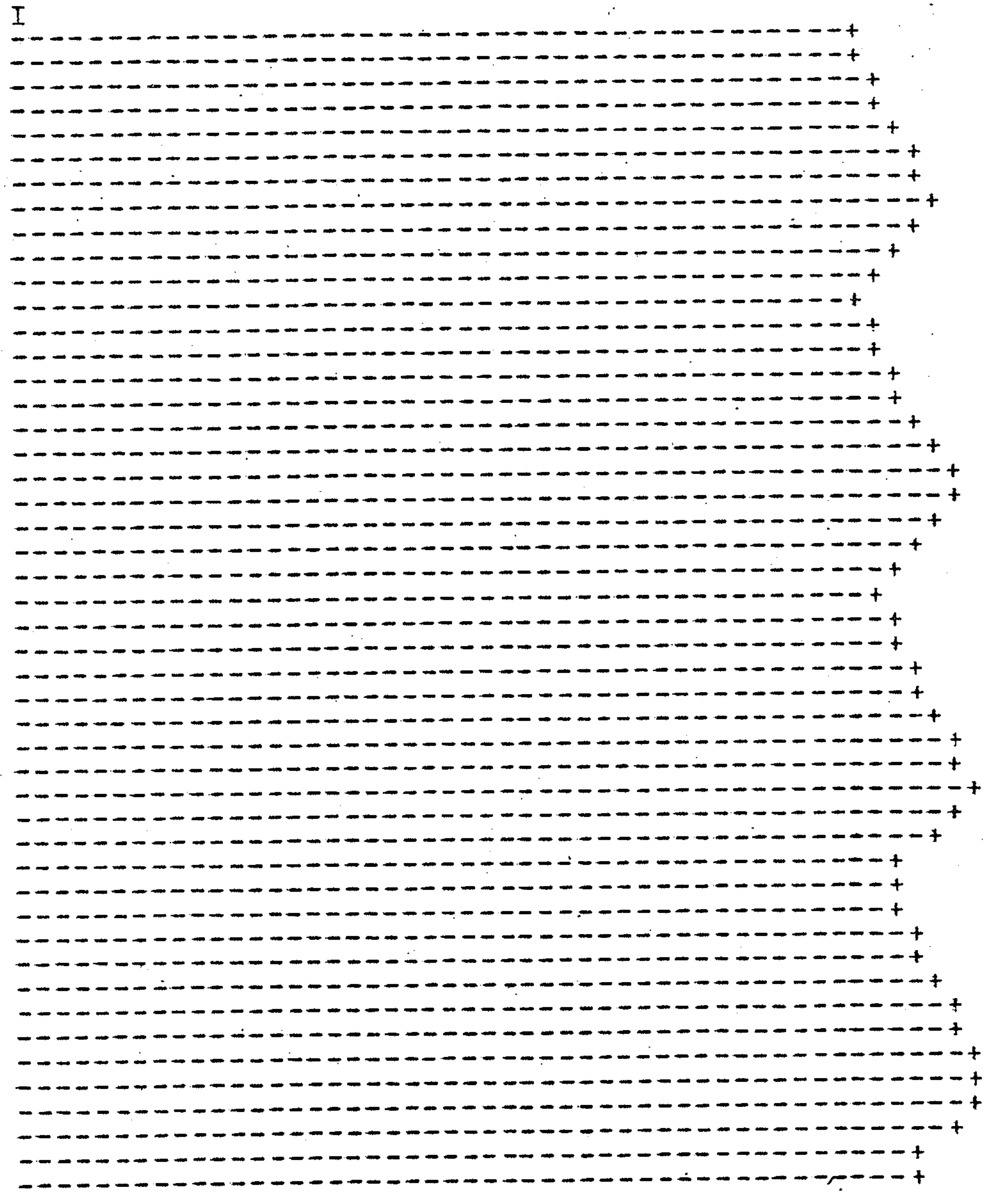

Fig. 5-12. Variation of Lagoon Model Sludge Mass with Time (153 to 200 months).

```
 TIME (Months)      BOD(Mg/L)
0.0               6.8027E+00    +
1.0000E+00        1.5257E+02    ------------------------------------------+
2.0000E+00        1.0680E+02    ----------------------------+
3.0000E+00        7.2496E+01    ------------------+
4.0000E+00        5.2454E+01    -------------+
5.0000E+00        4.2232E+01    ----------+
6.0000E+00        3.8617E+01    ---------+
7.0000E+00        3.9660E+01    ---------+
8.0000E+00        4.5619E+01    -----------+
9.0000E+00        5.9261E+01    ---------------+
1.0000E+01        8.6541E+01    ----------------------+
1.1000E+01        1.3221E+02    -------------------------------------+
1.2000E+01        1.7167E+02    ------------------------------------------------+
1.3000E+01        1.5447E+02    -------------------------------------------+
1.4000E+01        1.0797E+02    -----------------------------+
1.5000E+01        7.3608E+01    -------------------+
1.6000E+01        5.3762E+01    -------------+
1.7000E+01        4.4142E+01    ----------+
1.8000E+01        4.0914E+01    ---------+
1.9000E+01        4.1509E+01    ---------+
2.0000E+01        4.6839E+01    -----------+
2.1000E+01        6.0251E+01    ---------------+
2.2000E+01        8.7635E+01    -----------------------+
2.3000E+01        1.3347E+02    -------------------------------------+
2.4000E+01        1.7283E+02    ------------------------------------------------+
2.5000E+01        1.5549E+02    -------------------------------------------+
2.6000E+01        1.0900E+02    -----------------------------+
2.7000E+01        7.4586E+01    -------------------+
2.8000E+01        5.4915E+01    -------------+
2.9000E+01        4.5829E+01    -----------+
3.0000E+01        4.2942E+01    ----------+
3.1000E+01        4.3141E+01    ----------+
3.2000E+01        4.7913E+01    -----------+
3.3000E+01        6.1122E+01    ---------------+
3.4000E+01        8.8595E+01    -----------------------+
3.5000E+01        1.3457E+02    -------------------------------------+
3.6000E+01        1.7383E+02    -------------------------------------------------+
3.7000E+01        1.5639E+02    --------------------------------------------+
3.8000E+01        1.0990E+02    -----------------------------+
3.9000E+01        7.5445E+01    -------------------+
4.0000E+01        5.5930E+01    --------------+
4.1000E+01        4.7313E+01    -----------+
4.2000E+01        4.4726E+01    ----------+
4.3000E+01        4.4574E+01    ----------+
4.4000E+01        4.8857E+01    ------------+
4.5000E+01        6.1886E+01    ---------------+
4.6000E+01        8.9436E+01    -----------------------+
4.7000E+01        1.3553E+02    --------------------------------------+
4.8000E+01        1.7470E+02    -------------------------------------------------+
4.9000E+01        1.5717E+02    --------------------------------------------+
5.0000E+01        1.1068E+02    ------------------------------+
```

Fig. 5-13. Variation of Lagoon Model Effluent BOD$_5$ with Time (0 to 50 Months).

```
 TIME (Months)  BOD(Mg/L)
5.1000E+01     7.6197E+01     -------------------+
5.2000E+01     5.6819E+01     --------------+
5.3000E+01     4.8615E+01     ------------+
5.4000E+01     4.6291E+01     -----------+
5.5000E+01     4.5830E+01     -----------+
5.6000E+01     4.9684E+01     ------------+
5.7000E+01     6.2554E+01     ----------------+
5.8000E+01     9.0170E+01     -----------------------+
5.9000E+01     1.3637E+02     -------------------------------------+
6.0000E+01     1.7545E+02     -----------------------------------------------+
6.1000E+01     1.5785E+02     ------------------------------------------+
6.2000E+01     1.1136E+02     ------------------------------+
6.3000E+01     7.6853E+01     --------------------+
6.4000E+01     5.7596E+01     --------------+
6.5000E+01     4.9755E+01     ------------+
6.6000E+01     4.7659E+01     -----------+
6.7000E+01     4.6930E+01     -----------+
6.8000E+01     5.0406E+01     ------------+
6.9000E+01     6.3138E+01     ----------------+
7.0000E+01     9.0810E+01     ------------------------+
7.1000E+01     1.3709E+02     -------------------------------------+
7.2000E+01     1.7610E+02     -----------------------------------------------+
7.3000E+01     1.5844E+02     ------------------------------------------+
7.4000E+01     1.1195E+02     ------------------------------+
7.5000E+01     7.7424E+01     --------------------+
7.6000E+01     5.8274E+01     --------------+
7.7000E+01     5.0748E+01     ------------+
7.8000E+01     4.8852E+01     ------------+
7.9000E+01     4.7887E+01     -----------+
8.0000E+01     5.1037E+01     ------------+
8.1000E+01     6.3646E+01     ----------------+
8.2000E+01     9.1366E+01     ------------------------+
8.3000E+01     1.3772E+02     -------------------------------------+
8.4000E+01     1.7666E+02     -----------------------------------------------+
8.5000E+01     1.5894E+02     ------------------------------------------+
8.6000E+01     1.1247E+02     ------------------------------+
8.7000E+01     7.7920E+01     --------------------+
8.8000E+01     5.8865E+01     --------------+
8.9000E+01     5.1615E+01     ------------+
9.0000E+01     4.9891E+01     ------------+
9.1000E+01     4.8721E+01     ------------+
9.2000E+01     5.1583E+01     ------------+
9.3000E+01     6.4088E+01     ----------------+
9.4000E+01     9.1849E+01     ------------------------+
9.5000E+01     1.3827E+02     -------------------------------------+
9.6000E+01     1.7714E+02     ------------------------------------------------+
9.7000E+01     1.5938E+02     ------------------------------------------+
9.8000E+01     1.1291E+02     ------------------------------+
9.9000E+01     7.8353E+01     --------------------+
1.0000E+02     5.9379E+01     ---------------+
1.0100E+02     5.2368E+01     -------------+
```

Fig. 5-14. Variation of Lagoon Model Effluent BOD$_5$ with Time (51 to 101 months).

```
 TIME (Months)    BOD (Mg/L)
1.0200E+02      5.0796E+01      -------------+
1.0300E+02      4.9445E+01      -------------+
1.0400E+02      5.2059E+01      --------------+
1.0500E+02      6.4472E+01      -----------------+
1.0600E+02      9.2267E+01      -------------------------+
1.0700E+02      1.3874E+02      --------------------------------------+
1.0800E+02      1.7756E+02      ---------------------------------------------------+
1.0900E+02      1.5976E+02      ----------------------------------------------+
1.1000E+02      1.1330E+02      -------------------------------+
1.1100E+02      7.8726E+01      ---------------------+
1.1200E+02      5.9824E+01      ----------------+
1.1300E+02      5.3021E+01      --------------+
1.1400E+02      5.1580E+01      -------------+
1.1500E+02      5.0073E+01      -------------+
1.1600E+02      5.2473E+01      --------------+
1.1700E+02      6.4806E+01      -----------------+
1.1800E+02      9.2629E+01      -------------------------+
1.1900E+02      1.3915E+02      ---------------------------------------+
1.2000E+02      1.7793E+02      ---------------------------------------------------+
1.2100E+02      1.6008E+02      ----------------------------------------------+
1.2200E+02      1.1363E+02      -------------------------------+
1.2300E+02      7.9051E+01      ---------------------+
1.2400E+02      6.0209E+01      ----------------+
1.2500E+02      5.3588E+01      --------------+
1.2600E+02      5.2260E+01      --------------+
1.2700E+02      5.0618E+01      -------------+
1.2800E+02      5.2829E+01      --------------+
1.2900E+02      6.5092E+01      -----------------+
1.3000E+02      9.2943E+01      -------------------------+
1.3100E+02      1.3950E+02      ---------------------------------------+
1.3200E+02      1.7824E+02      ---------------------------------------------------+
1.3300E+02      1.6037E+02      ----------------------------------------------+
1.3400E+02      1.1392E+02      -------------------------------+
1.3500E+02      7.9330E+01      ---------------------+
1.3600E+02      6.0546E+01      ----------------+
1.3700E+02      5.4079E+01      --------------+
1.3800E+02      5.2849E+01      --------------+
1.3900E+02      5.1089E+01      -------------+
1.4000E+02      5.3138E+01      --------------+
1.4100E+02      6.5342E+01      -----------------+
1.4200E+02      9.3215E+01      -------------------------+
1.4300E+02      1.3981E+02      ---------------------------------------+
1.4400E+02      1.7851E+02      ---------------------------------------------------+
1.4500E+02      1.6061E+02      ----------------------------------------------+
1.4600E+02      1.1417E+02      -------------------------------+
1.4700E+02      7.9572E+01      ---------------------+
1.4800E+02      6.0833E+01      ----------------+
1.4900E+02      5.4503E+01      --------------+
1.5000E+02      5.3358E+01      --------------+
1.5100E+02      5.1497E+01      -------------+
1.5200E+02      5.3405E+01      --------------+
```

Fig. 5-15. Variation of Lagoon Model Effluent BOD_5 with Time (102 to 152 Months).

```
TIME (Months)     BOD (Mg/L)
1.5300E+02        6.5556E+01
1.5400E+02        9.3448E+01
1.5500E+02        1.4007E+02
1.5600E+02        1.7873E+02
1.5700E+02        1.6082E+02
1.5800E+02        1.1438E+02
1.5900E+02        7.9782E+01
1.6000E+02        6.1083E+01
1.6100E+02        5.4870E+01
1.6200E+02        5.3797E+01
1.6300E+02        5.1849E+01
1.6400E+02        5.3636E+01
1.6500E+02        6.5742E+01
1.6600E+02        9.3650E+01
1.6700E+02        1.4029E+02
1.6800E+02        1.7894E+02
1.6900E+02        1.6100E+02
1.7000E+02        1.1457E+02
1.7100E+02        7.9961E+01
1.7200E+02        6.1299E+01
1.7300E+02        5.5186E+01
1.7400E+02        5.4177E+01
1.7500E+02        5.2152E+01
1.7600E+02        5.3835E+01
1.7700E+02        6.5902E+01
1.7800E+02        9.3823E+01
1.7900E+02        1.4049E+02
1.8000E+02        1.7910E+02
1.8100E+02        1.6116E+02
1.8200E+02        1.1473E+02
1.8300E+02        8.0117E+01
1.8400E+02        6.1485E+01
1.8500E+02        5.5459E+01
1.8600E+02        5.4505E+01
1.8700E+02        5.2415E+01
1.8800E+02        5.4007E+01
1.8900E+02        6.6040E+01
1.9000E+02        9.3974E+01
1.9100E+02        1.4066E+02
1.9200E+02        1.7925E+02
1.9300E+02        1.6129E+02
1.9400E+02        1.1487E+02
1.9500E+02        8.0251E+01
1.9600E+02        6.1645E+01
1.9700E+02        5.5695E+01
1.9800E+02        5.4787E+01
1.9900E+02        5.2642E+01
2.0000E+02        5.4156E+01
```

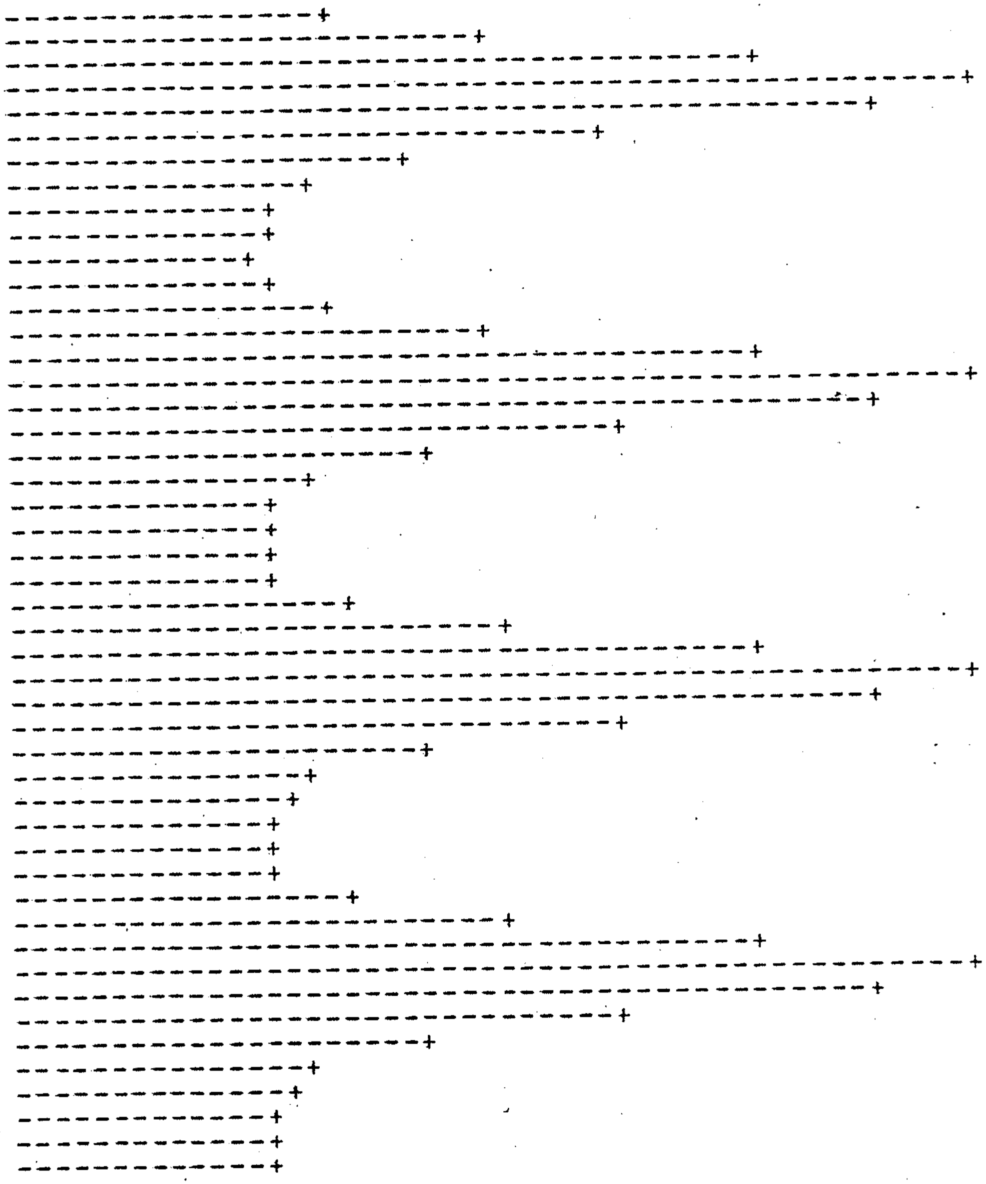

Fig. 5-16. Variation of Lagoon Model Effluent BOD_5 with Time (153 to 200 Months)

5.4.3. Predicted Variation of Aerated Lagoon BOD Removal Rate with Time

The overall BOD removal reaction rate, K, of the aerated lagoon model was calculated as described in Equation 42. Influent and effluent BOD and lagoon retention time were based upon average monthly values predicted by the model. The variation of the overall BOD removal over a 24 year period of continuous operation is shown in Figure 5-17. The reaction rates plotted in Figure 5-17 were obtained from the 6th month of each yearly cycle of the lagoon model where the average lagoon temperature was constantly 19.2°C (see Figure 5-6). The variation of the overall BOD removal reaction rate, K, of the lagoon model over a yearly cycle where lagoon temperature ranges from 1.9° to 19.2°C, is shown in Figure 5-18. Data plotted in Figure 5-18 represents the 15th year of continuous lagoon operation.

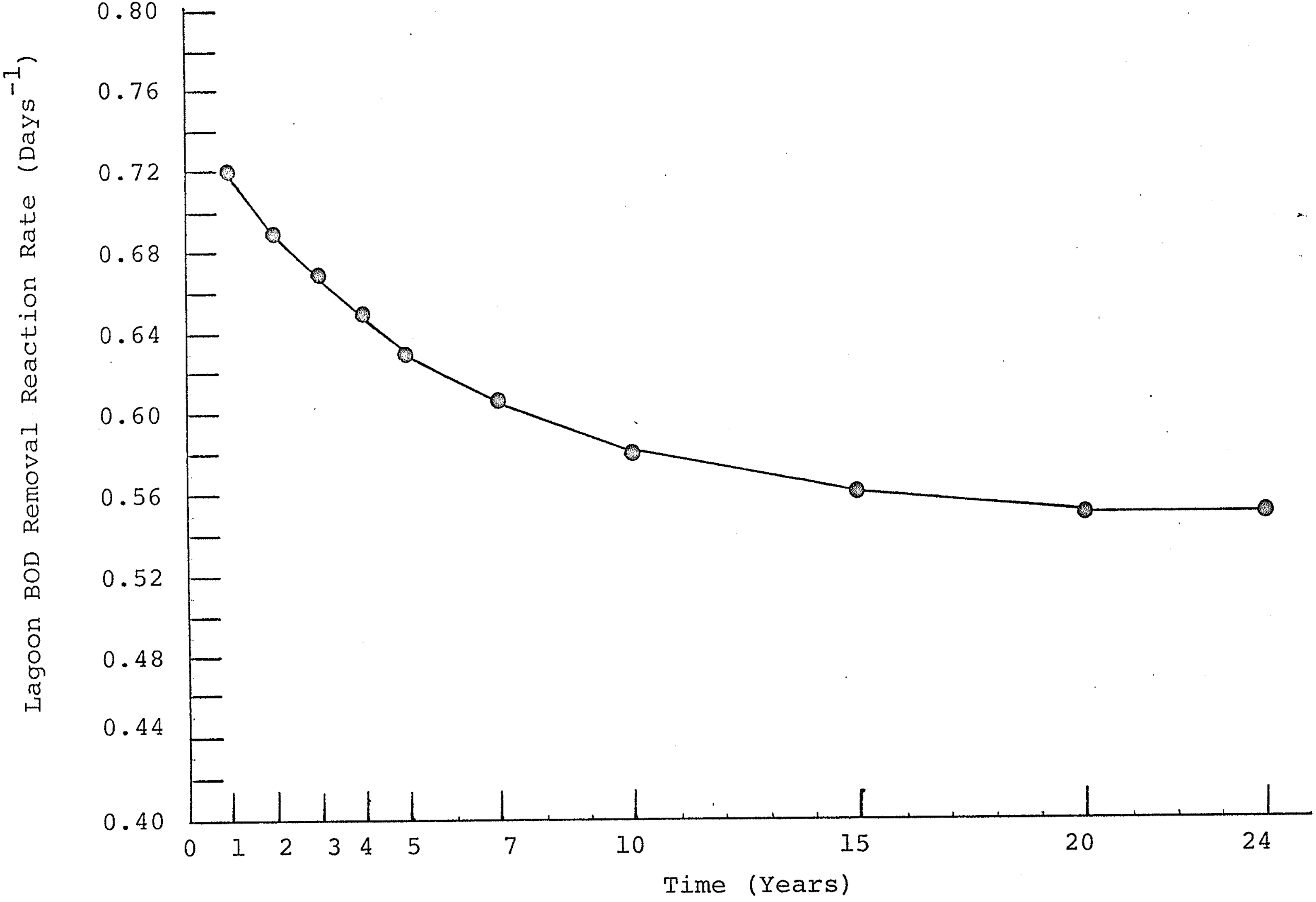

Figure 5-17. Variation of Lagoon Model BOD Removal Reaction Rate at 19.2°C with Time.

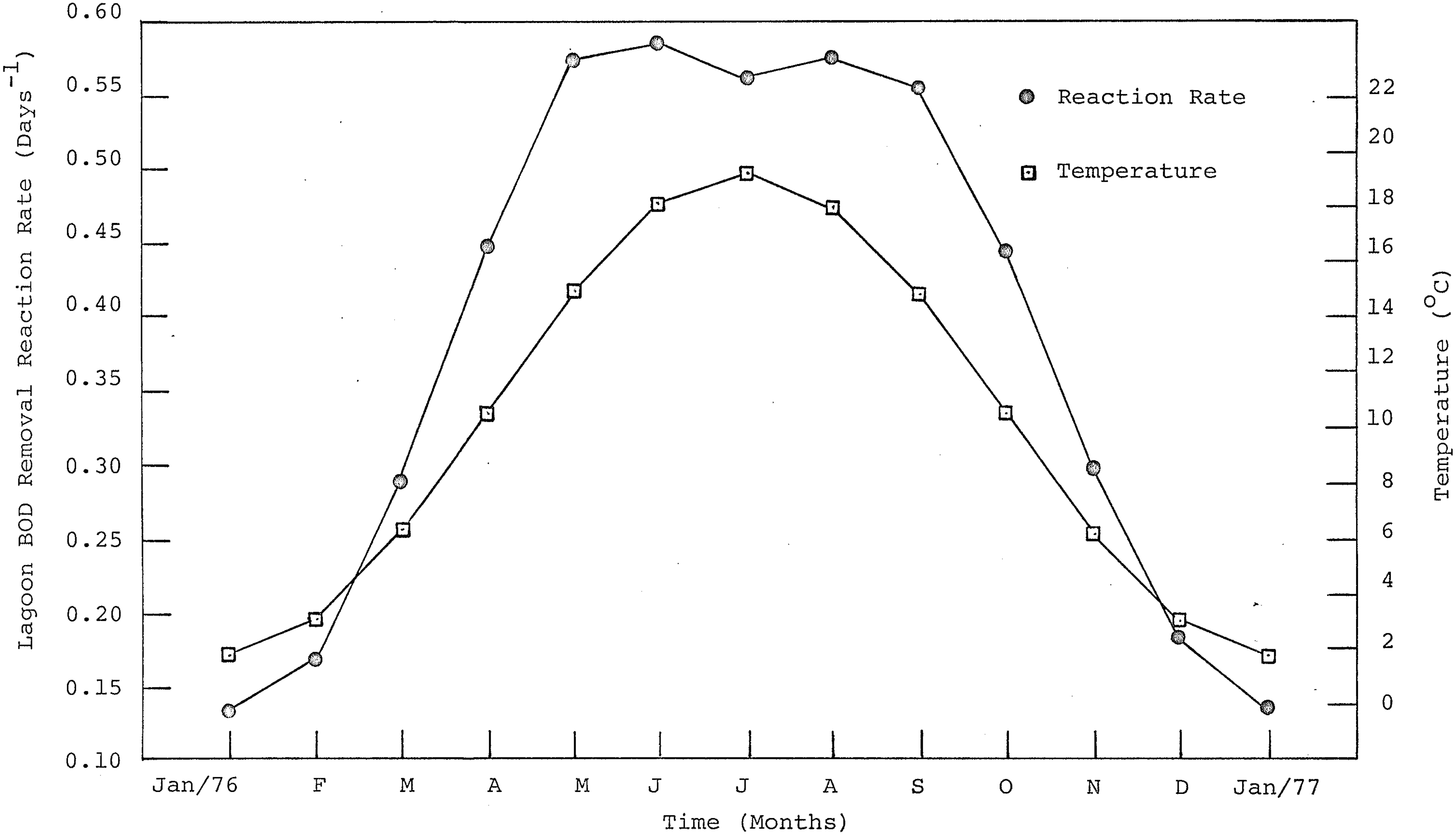

Figure 5-18. Variation of Lagoon Model BOD Removal Reaction Rate over a Yearly Temperature Cycle.

CHAPTER 6

DISCUSSION OF RESULTS

6. Discussion of Results

6.1. Temperature Effect on Aerated Lagoon Kinetics

6.1.1. BOD Reaction Rates

The results of laboratory BOD reaction rate determinations on lagoon mixed liquor samples are shown in Table 5-2, and illustrated graphically in Figure 5-2. Data for samples incubated at ambient lagoon temperatures indicated that the BOD reaction rate varied with temperature according to the Streeter-Phelps equation between 0° and $5^{\circ}C$, as follows:

$$K_T = 0.062\ (1.401)^{(T)} \qquad \ldots.(45)$$

where T = temperature ($^{\circ}C$);

K_T = BOD reaction rate ($days^{-1}$)-base 10, at temperature T.

Reaction rate determinations on mixed liquor samples at $20^{\circ}C$ resulted in an average value of 0.175 while reaction rate determinations at $4^{\circ}C$ resulted in an average value of 0.240. This indicates that the $20^{\circ}C$ reaction rate determinations were affected by the ability of the lagoon microorganisms to adapt to the imposed temperature change. As the average lagoon liquid temperature throughout the period of sampling was approximately $2.7^{\circ}C$, a predominance of psycrophilic microorganisms would be expected in the lagoon mixed liquor. At an incubation temperature of $20^{\circ}C$ a shift in bacterial population from psycrophilic to mesophylic microorganism predominance would be required for the most efficient oxidation of substrate. Benedict et al., (41) conducted studies on mixed cultures in continuous flow pilot plants and concluded that acclimation following a shock temperature change from 4°C to 19°C was essentially complete within 2 weeks. As BOD reaction rate determinations were only performed over a 5-day test period, complete acclimation of the lagoon microorganisms was likely incomplete. A shift in bacterial population and possibly the reduced activity of psycrophilic microorganisms caused a lag period in bacterial growth resulting in lower than representative reaction rate values at 20°C.

Reaction rate determinations on mixed liquor samples incubated at ambient lagoon temperature conditions were not subject to a temperature acclimation phase. The relationship indicated by these results is shown in Equation 45. The Streeter-Phelps temperature sensitivity coefficient, theta, of Equation 45 is equal to 1.401. This indicates a highly temperature sensitive BOD reaction rate in the 0° to 5°C temperature range. Moore (6) conducted a major study on the effect of temperature on biochemical oxygen demand and obtained a theta value of 1.145 for the 0.5° to 5°C temperature range. Few other investigators have studied BOD reaction rates in this low temperature range.

Most investigators have found theta remains constant for a relatively small temperature range and tends to increase with decreasing temperature (4)(5)(6)(28)(29). An extensive study by Gotaas (4) indicated that the variation of reaction rate with temperature could be accurately described by theta values of 1.109 in the 5° to 15°C range, and 1.042 in the 15° to 30°C range. The theta values obtained by Gotaas for the 5° to 30°C range in combination with the theta value obtained from this study for the 0° to 5°C range are illustrated graphically in Figure 6-1. As no reliable laboratory kinetic data was obtained from this study in the 5° to 30°C temperature range the theta values determined by Gotaas were assumed representative of the soluble and suspended BOD reaction rate of the Portage la Prairie aerated lagoon system.

A linear regression analysis was performed with a Hewlett Packard, Model 9100A calculator on data points obtained from the reaction rate vs. temperature relationship shown in Figure 6-1. This analysis yielded a correlation coefficient, R, of 0.990 for the following relationship in the 0° to 30°C temperature range;

$$K = 0.057 \times T + 0.016 \qquad \text{....(46)}$$

where K = BOD reaction rate (days^{-1})-base 10;

T = temperature (°C).

The BOD reaction rate relationship described by Equation 46 is of questionable significance in terms of its application to aerated lagoon kinetics. Many studies have indicated that BOD reaction rate values obtained by standard laboratory methods (quiescent conditions) are not

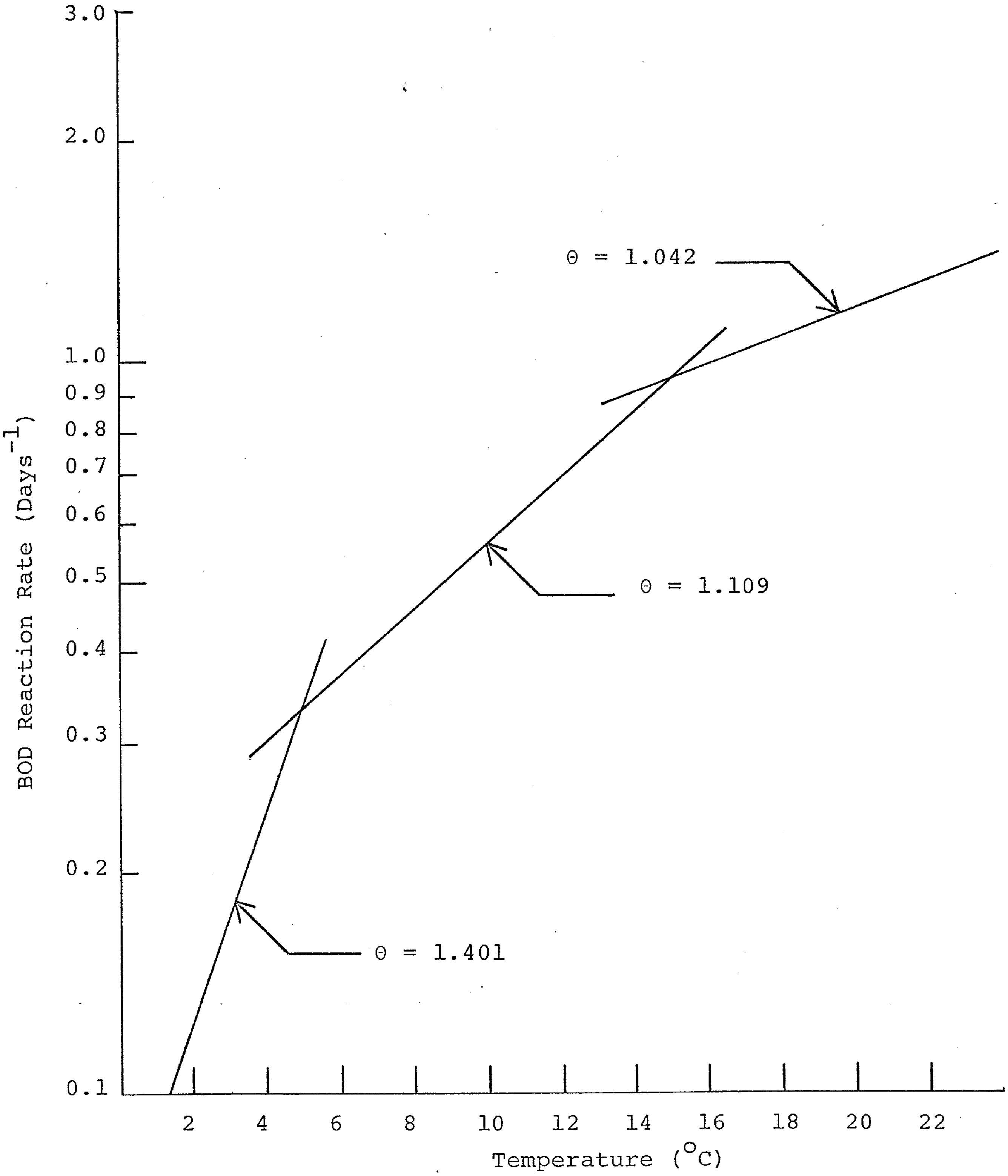

Figure 6-1. Variation of BOD Reaction Rate with Temperature.

representative when applying them to turbulent conditions such as would be found in aerated lagoons (48)(49)(50)(51). The change in substrate concentration from the lagoon basin to the laboratory BOD bottle also makes the application of laboratory reaction rate determinations to lagoon kinetics questionable.

6.1.2. Aerated Lagoon BOD Removal

The results of overall lagoon BOD removal reaction rate determinations based upon influent and effluent BOD_5 values are shown in Table 5-3, and illustrated graphically in Figure 5-3. The overall BOD removal reaction rate for the aerated lagoon was found to vary with temperature according to the Streeter-Phelps equation, between 0° and $21^{\circ}C$, as follows:

$$K = 0.586 \times (1.062)^{(T-20)} \qquad \ldots.(47)$$

where K = overall BOD removal reaction rate (days^{-1});

T = temperature ($^{\circ}C$).

The Streeter-Phelps temperature sensitivity coefficient, theta, of Equation 47 is equal to 1.062. This theta value is within reasonable agreement of values obtained by other investigators. Carpenter et al., (5) conducted a study of aerated lagoon waste treatment and calculated an average theta value of 1.035 for five different wastes over a temperature range of 2° to $30^{\circ}C$. Thimsen (13) reports a theta value of 1.072 is representative of aerated lagoons treating domestic waste. Eckenfelder (33) has reported values of theta ranging from 1.026 to 1.090 for aerated lagoon overall BOD removal reaction rates.

The overall BOD removal reaction rate at 20°C obtained for the Portage la Prairie aerated lagoon system was 0.586. Metcalf and Eddy (7) report overall reaction rate values at 20°C vary from 0.25 to 1.0 for aerated lagoons, thus supporting the findings of this study. Eckenfelder (33) states that average 20°C reaction rate values reported for aerated lagoons are approximately 0.40.

6.1.3. Aerated Lagoon COD Removal

The results of overall lagoon COD removal reaction rate determinations based upon influent and effluent COD values are shown in Table 5-4, and illustrated graphically in Figure 5-4. The overall COD removal reaction rate for the aerated lagoon was found to vary with temperature according to the Streeter-Phelps equation, between 0° and $21^{\circ}C$, as follows;

$$K_C = 0.774 \times (1.051)^{(T-20)} \qquad \text{....(48)}$$

where K_C = overall COD removal reaction rate (days^{-1});

T = temperature ($^{\circ}C$).

The Streeter-Phelps temperature sensitivity coefficient, theta, of Equation 48 is equal to 1.051. The overall BOD removal reaction rate of the lagoon, having a theta value of 1.062, indicates a higher temperature sensitivity than the COD removal reaction rate. This result can be rationalized by the fact that COD determinations oxidize both biodegradable and non-biodegradable matter in a wastewater sample. The oxidation of the constant portion of non-biodegradable matter in both the influent and effluent COD samples results in a reduced temperature sensitivity for the COD removal reaction rate of the lagoon.

The COD removal reaction rate of the lagoon was consistently higher than the BOD removal reaction rate due to the fact that more compounds can be chemically oxidized than can be biologically oxidized. The BOD/COD removal reaction rate ratio obtained at $20^{\circ}C$ was 0.76. Due to the different temperature sensitivities of the two removal rates, this ratio reduced to 0.61 at $0^{\circ}C$. It is therefore apparent that COD removal reaction rate determinations cannot be directly correlated or interpreted in terms of BOD removal reaction rates in a waste treatment system that operates with high seasonal temperature variations.

6.1.4. Aerated Lagoon Suspended Solids Removal

The results of lagoon suspended solids removal based upon influent and effluent suspended solids determinations are shown in Table 5-5, and illustrated graphically in Figure 5-5. The suspended solids removal of the aerated lagoon was found to vary with temperature according to a linear relationship, between 0° and $21^{\circ}C$, as follows;

$$R = 0.6 \times T + 83.4 \qquad \text{....(49)}$$

where R = suspended solids removal rate (%);

T = temperature ($^{\circ}$C).

Equation 49 indicates suspended solids removal rates of 83.4% and 90.6% for lagoon operating temperatures of 0° and 20°C, respectively. An increase in suspended solids removal with temperature increase was also observed by Black (15) in a study of an aerated lagoon located in Brampton, Ontario.

The variation of suspended solids removal rates over the 0° to 21°C temperature range observed in this study can be rationalized as follows. The settling velocity of a particle is a function of the viscosity of the liquid which is in turn a function of temperature. Although a relationship has not yet been developed between the settling rate of domestic sewage and fluid viscosity it is reasonable to assume that as fluid viscosity increases (decreasing temperature) settling is hindered. A secondary effect on settling could be the result of thermal currents and short-circuiting developed during the winter operation of aerated lagoons. During winter conditions thermal currents and short-circuiting are caused by temperature differentials between the liquid surface and the bulk of the liquid in the lagoon. This could result in a significant decrease in sewage settling rates.

Statistical analysis was also performed in an attempt to establish a relationship between suspended solids removal rates shown in Table 5-5, and lagoon retention time shown in Table 5-2. The results of linear regression, exponential least squares, and power curve least squares analysis on this data, using a Hewlett Packard, Model 9100A calculator indicated that no statistically valid relationship could be established.

The suspended solids removal rate determined at the 21.1°C lagoon liquid temperature was 87%, as is shown in Figure 5-5. This value represents a significantly lower removal rate than would be predicted by Equation 49. The resuspension of bottom sludges due to anaerobic gas production, being stimulated by the high operating temperature, was possibly the cause of this data point. Previous investigators (56)(57) have concluded that the resuspension of settled solids due to anaerobic gas production represents a major problem in aerated lagoon waste treatment during summer operating conditions.

6.2. Dynamic Model Test Results

6.2.1. Model Development

The dynamic CSMP-360 model developed for this study is illustrated in Appendix 3. The model is based upon two differential equations representing mass balances of lagoon liquid BOD and sludge BOD in a facultative aerated lagoon system. These equations assume that first-order reactions are representative of both aerobic and anaerobic waste utilization rates in the aerated lagoon. The rate of change of sludge mass in the dynamic aerated lagoon model is described by the following equation;

$$\frac{dL_t}{dt} = (1 - i\rho)\ S_oQG.10^{-6} - K_LL_t \qquad \text{....(23)}$$

where L_t = total sludge mass (lbs - BOD_{ULT});

$i\rho$ = fraction of influent BOD_{ULT} remaining in suspension within the lagoon liquid;

S_o = influent BOD_{ULT} (mg/l);

Q = sewage flow rate (ft^3/day);

G = mass density of water (lbs/ft^3);

K_L = sludge fermentation reaction rate ($days^{-1}$)-base e.

The rate of change of BOD in the lagoon liquid is described in the dynamic aerated lagoon model as:

$$\frac{dS}{dt} = \frac{i\rho S_o}{R} - K_sS - \frac{S}{R} + \frac{s\rho K_LL_t.10^6}{VG} \qquad \text{....(24)}$$

where S = lagoon liquid BOD_{ULT} (mg/l);

R = lagoon retention time (days);

K_s = aerobic degradation rate ($days^{-1}$)-base e;

$s\rho$ = fraction of BOD entering lagoon liquid after sludge fermentation;

V = lagoon volume (ft^3).

Very little information is available with respect to the sludge layer kinetic constants, K_L and s_ρ, for aerated lagoon waste treatment systems. As no studies have been performed to determine the sludge characteristics of the Portage la Prairie aerated lagoon system, the values adopted for the dynamic aerated lagoon model were those determined by Marais (17) in his oxidation pond simulations. These values are as follows:

$$K_L = 0.002\ (1.35)^{(T-20)} \qquad .....(28)$$

where T = temperature (°C)

and $s_\rho = 0.4$ .....(50)

The temperature sensitivity of the aerobic degradation rate, K_s, of the dynamic aerated lagoon model was assumed to vary according to the relationship illustrated in Figure 6-1. The magnitude of the K_s value was varied to obtain the "best-fit" of experimentally determined lagoon BOD effluent values to those predicted by the model. The aerobic degradation reaction rate, K_s, of the lagoon model was found to vary with temperature (°C) as follows:

$$K_s = 0.026 \times T + 0.007 \qquad ....(51)$$

The fraction, $i\rho$, of influent BOD remaining in suspension within the lagoon liquid is a characteristic of the particular waste and waste treatment system to which it is applied. This fraction is dependent upon waste characteristics, type of aeration equipment, power input to lagoon volume ration, and lagoon dimensions. As no information was available with respect to the value of $i\rho$ in the Portage la Prairie aerated lagoon system, this value was also assumed a variable in the dynamic lagoon model. The "best-fit" of experimentally determined lagoon BOD effluent values to those predicted by the lagoon model was obtained with an $i\rho$ value of 0.7. It was possible to manipulate both the magnitude of K_s and the value of iρ in the model to obtain "best-fit" results as each parameter affected predicted BOD effluent values differently. The value of the fraction, iρ, tended to only control the relative range of predicted effluent values over a yearly temperature cycle while the magnitude of K_s controlled the concentration of the predicted effluent values.

The influent BOD loading, S_o, sewage flow, Q, and lagoon temperature, T, exhibit wide fluctuations and seasonal trends in the Portage la Prairie aerated lagoon system. Sinusoidal approximations of this yearly cyclic variations shown in Figures 5-6, 5-7, and 5-8, were incorporated into the dynamic aerated lagoon model. The form of the sinusoidal curve best approximately each parameter was obtained from a Fourier series analysis performed by computer on available lagoon operational data.

The lagoon volume, V, in the aerated lagoon model was based upon effective lagoon volume calculations shown in Appendix 1. The effect of sludge accumulation on the lagoon volume was felt to be significant in the Portage la Prairie aerated lagoon system, and was therefore incorporated into the dynamic aerated lagoon model. An estimation of sludge volume in the Portage La Prairie aerated lagoons was obtained from results of a sludge study performed by a consulting engineering firm in 1973. The estimated sludge volume in 1973, being 3.67 x 10^6 (Imp. gal), represented 11 years of sludge accumulation in the aerated lagoon system

(58). As is shown in Figures 5-11, predicted sludge accumulation after 11 years (132 months) of model simulation is approximately 5.0 x 10^6 (lbs - BOD). The predicted sludge accumulation of the model (lbs - BOD) was therefore related to the estimated sludge volume (Imp. gal) as follows;

$$SE = \frac{3.67 \times 10^6}{5.00 \times 10^6} \times S = 0.7 \times S \qquad ....(52$$

where SE = sludge volume (Imp. gal);

S = predicted sludge accumulation (lbs - BOD).

The effective lagoon volume, V, and its variation with time due to sludge accumulation, was then incorporated into the aerated lagoon model as follows;

$$V = V_o - SE \qquad ....(53)$$

where V = effective lagoon volume (Imp. gal);

V_o = initial lagoon volume (Imp. gal).

Lagoon retention time, R, in the aerated lagoon model was calculated as follows;

$$R = V/Q \qquad ....(54)$$

where R = lagoon model retention time (days);

V = effective lagoon volume (Imp. gal);

Q = approximated sewage flow rate (Imp. gal/day).

6.2.2. Experimental Verification of Model Results

Experimentally determined effluent BOD values for the Portage la Prairie aerated lagoons and those predicted by computer model from February 1976 through October 1976 are shown in Figure 6-2. Experimental values were obtained from Table 5-3 while model predictions were obtained from Figure 5-16 for months 181 through 189 as these values represent the same time period from which experimental values were obtained. Correlation between the calculated and experimentally determined effluent BOD values is generally good with the exception of some values near the end of the period. The poor correlation of the June, 1976, effluent BOD values is due to a sudden peak in BOD loading on the Portage la Prairie lagoons during this period. The BOD loading rate of the lagoon model was based upon the "best-fit" sinusoidal approximation of available data, shown in Figure 5-8. As can be seen from Figure 5-8, the BOD loading rate used in the lagoon model for the month of June, 1976, was considerably lower than the rate actually occurring in the Portage la Prairie lagoons. The inability of the "best-fit" sinusoidal function to approximate the June, 1976, BOD loading rate therefore resulted in a higher effluent BOD than was predicted by the lagoon model.

In order for the lagoon model to predict the Portage la Prairie aerated lagoon BOD removal characteristics over a 15 year period, sludge accumulation must be accurately simulated. The total sludge mass accumulation predicted by the aerated lagoon model after 11 years of simulated operation is approximately 5×10^6 (lbs - BOD), as is shown in Figure 5-11. Calculations of a total sludge

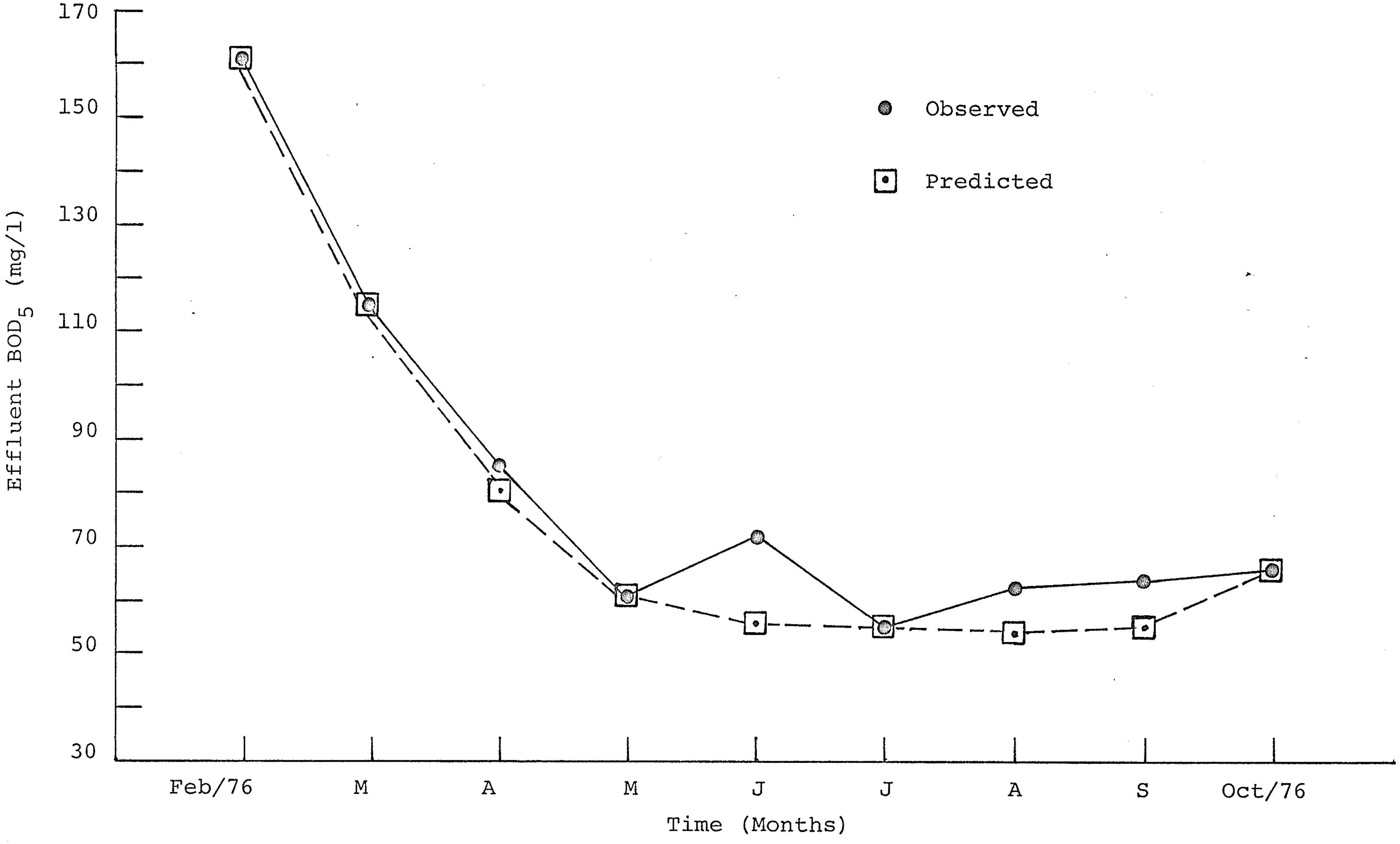

Figure 6-2. Observed and Model Prediction Lagoon Effluent BOD_5.

volume estimate after 11 years of Portage la Prairie lagoon operation shown in Appendix 1 indicate a sludge accumulation of approximately 5.4 x 10^5 (ft^3). Sludge tests from the Eielson Air Force Base aerated lagoon performed by Reid (19) indicated that solids would concentrate to 9.1% with 87% volatile solids and that oxygen demand was 1.49 times the BOD removed. Based upon the values obtained by Reid and assumptions that only volatile solids exert an oxygen demand and a sludge density of 68 (lbs/ft^3), an approximation of expected sludge accumulation (lbs - BOD) in the Portage la Prairie lagoons can be calculated from the sludge volume estimate. The results of this calculation indicate an expected sludge mass of 4.3 x 10^6 (lbs - BOD) after 11 years of lagoon operation. Correlation with the predicted lagoon model sludge accumulation of 5 x 10^6 (lbs - BOD) appears to be significant in terms of the numerous assumptions upon which this calculation was based. Although this calculation does not constitute a definite experimental verification of lagoon model results, it does indicate that some degree of confidence can be placed on model results.

A more conclusive experimental verification of lagoon model results is indicated by comparisons of lagoon overall BOD removal reaction rate values for the period of February, 1976, through October, 1976. The results of experimentally determined overall BOD removal reaction rates for this period are illustrated in Figure 5-3. These results represent the 15th year of continuous operation of the Portage la Prairie aerated lagoon system. The overall BOD removal reaction rate at 19.2°C during this time period was found to be 0.56 (days^{-1}). As can be seen from Figure 5-17, the overall BOD removal rate at 19.2°C predicted by the lagoon model after 15 years of lagoon operation is 0.56 (days^{-1}). Although this represents a perfect correlation for the period studied the verification of model overall BOD removal reaction rate variation with time could only be definitely established with complete experimental data on all 15 years of lagoon operation.

6.2.3. Effect of Sludge Accumulation on Effluent BOD Quality

The variation of lagoon model sludge mass with time over a 100 month simulation period is shown in Figures 5-9 through 5-12. As can be seen from these figures, lagoon sludge mass does not reach steady-state during the simulation period although, based upon a yearly cycle, this condition is closely approximated after 13 to 15 years. On a monthly basis, sludge mass cycles dynamically with the mass increasing during low temperature and decreasing during high temperature operating conditions.

The accumulation and cyclic variation of sludge mass in an aerated lagoon system has two direct effects upon the effluent BOD quality. As sludge accumulates the effective lagoon volume decreases, thus reducing retention time of the system. Retention time is directly related to effluent BOD concentration in an aerated lagoon, thus, a reduction in retention time results in an increase in effluent BOD concentration. This effect has limited significance with respect to the Portage la Prairie aerated lagoons as sludge accumulation after 15 years of operation only represents approximately 10% of the total lagoon volumes.

The most significant effect of sludge accumulation on aerated lagoon effluent BOD quality is the result of products of fermentation diffusing into the lagoon liquid during periods of active sludge digestion. The effect of these fermentation products on lagoon model effluent BOD for the 15th year of simulation is illustrated graphically in Figure 6-3. As is shown in Figure 6-3, fermentation products cause an increase in summer effluent BOD values by as much as 15 (mg/l) in the lagoon model. The effect of sludge digestion only becomes significant between the period of April to October were the lagoon model operating temperature exceeds 10^{o}C. This is due to the high temperature sensitivity of the anaerobic sludge digestion process.

Over a number of years of operation, sludge accumulation in an aerated lagoon will cause a constant increase in summer BOD effluent values until a steady-state sludge mass is reached. This effect, combined with the effect of sludge volume on lagoon retention time, results in a decreasing overall BOD removal reaction rate of an aerated lagoon system during the period of sludge accumulation.

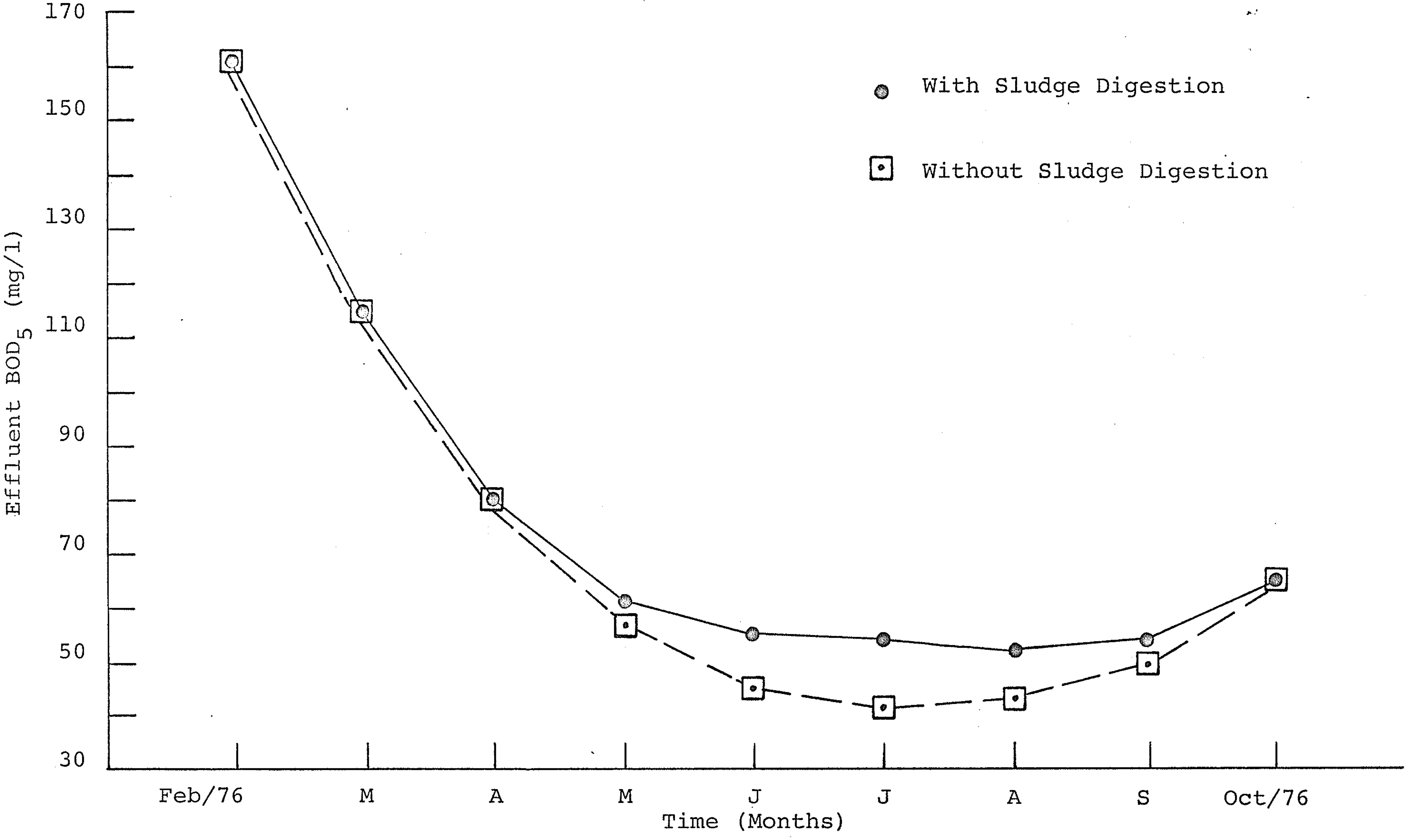

Figure 6-3. Effect of Sludge Digestion on Lagoon Model Effluent BOD_5.

Figure 5-17 illustrates the decreasing overall BOD removal reaction rate of the aerated lagoon model until a steady-state sludge mass is approximated after 13 to 15 years of simulation.

Sludge accumulation would also be expected to cause the temperature sensitivity coefficient, theta, of the overall BOD removal reaction rate to increase as the magnitude of the reaction rate decreases. This is due to the fact that anaerobic decomposition reaction rates are more temperature sensitive than aerobic reaction rates. The relative effect of fermentation products become more significant as sludge accumulates resulting in an increasing value of theta until a steady-state sludge mass is reached.

6.2.4. Variation of Aerated Lagoon Removal Rate With Time

The variation of lagoon model overall BOD removal rate due to sludge accumulation over a 24 year simulation period is illustrated graphically in Figure 5-17. The overall BOD reaction rate at $19.2^{\circ}C$ of the lagoon model after 1 year and 15 years of operation were found to be 0.72 ($days^{-1}$) and 0.56 ($days^{-1}$), respectively. Based upon complete-mix assumptions, the inverse of retention time is directly proportional to aerated lagoon overall BOD removal. Therefore, a decrease in reaction rate from 0.72 ($days^{-1}$) to 0.56 ($days^{-1}$) represents a required 29% lagoon volume increase in order to maintain the same BOD effluent quality. As most aerated lagoons are not complete-mix systems, retention time is not linearly related to BOD removal. Settling is a significant BOD removal mechanism in aerated lagoons which is not directly affected by increased retention. A decrease in overall BOD removal reaction rate would require a greater increase in lagoon retention to obtain equivalent BOD effluent quality than would be indicated by equations based upon complete-mix assumptions. Reduced BOD removal reaction rates due to sludge accumulation therefore have a significant effect on the economics of design for aerated lagoon waste treatment systems.

Metcalf and Eddy (7) report overall BOD removal reaction rates to have been found to vary from 0.25 (days^{-1}) to greater than 1.0 (days^{-1}), for aerated lagoons treating domestic waste. The wide range of overall BOD removal reaction rates reported in the literature is, in part, due to the evaluation of BOD removal rates before a steady-state sludge mass is reached in the aerated lagoon system. Aerated lagoon BOD removal rates are also affected by sewage characteristics, loading rates, and environmental conditions within which the aerated lagoon operates. These factors further contribute to the variability of reported BOD removal rates.

The variation of lagoon model overall BOD removal reaction rate on a yearly temperature cycle is shown in Figure 5-18. Winter sludge storage results in a reduction in overall BOD removal rate during high temperature operating conditions when active sludge digestion is occuring. As is shown in Figure 5-18, lagoon BOD removal rate predicted for May, 1976, with an average lagoon temperature of 15°C, is 0.65 (days^{-1}), while lagoon BOD removal rate predicted for July, 1976, with an average lagoon temperature of 19°C, is 0.52 (days^{-1}). This monthly variability of lagoon BOD removal rates would also be expected to contribute to the inconsistency of reported aerated lagoon BOD removal rates. In order to establish meaningful design criteria for the aerated lagoon waste treatment system overall BOD removal rates, being based upon complete-mix and steady-state assumptions, must be interpreted in terms of dynamic lagoon behaviour.

6.2.5. Model Limitations

The dynamic aerated lagoon model was used in this study for the sole purpose of developing a fundamental understanding of parameters affecting aerated lagoon behaviour in cold climates. Although the model reasonably describes the observed behaviour of the Portage la Prairie aerated lagoons over the period studied, it can only be considered as a framework for future experimental and theoretical investigations due to the numerous assumptions upon which the model was based.

Sewage flow and BOD loading rates incorporated into the model were obtained from lagoon operational data for the period of January, 1976, through March, 1977. The assumption that these values were representative of the past 15 years of operation of the Portage la Prairie lagoons is obviously questionable. Population and industrial activity has substantially increased in Portage la Prairie over the past 15 years, therefore, sewage loading rates on the aerated lagoon system would also be expected to have increased over this period.

Further limitations of the lagoon model are due to the limited information available with respect to the magnitudes of the kinetic constants upon which the model was based. Future detailed investigation into sludge layer reaction rates, soluble and suspended BOD reaction rates, and the fraction of influent BOD remaining in suspension within the lagoon liquid could render this model an effective design tool for aerated lagoon waste treatment systems.

CHAPTER 7

CONCLUSIONS

7. Conclusions

The following conclusions can be drawn from the results of this study:

(1) The BOD reaction rate determinations of Portage la Prairie aerated lagoon mixed liquor samples incubated at ambient lagoon temperature followed the van't Hoff-Arrhenius relationship between 0° and 5°C with a Θ value of 1.401 and a $K_{5^{\circ}C}$ value of 0.33 (days^{-1});

(2) The BOD reaction rate determinations of Portage la Prairie aerated lagoon mixed liquor samples incubated at 20°C were unrepresentative due to inhibition caused by temperature acclimation;

(3) The variation of BOD reaction rate with temperature can be accurately described by the van't Hoff-Arrhenius relationship using three temperature ranges with Θ values of 1.401 in the 0° to 5°C range, 1.109 in the 5° to 15°C range, and 1.042 in the 15° to 30°C range;

(4) The overall BOD removal reaction rate of the Portage la Prairie aerated lagoons varied with temperature according to the van't Hoff-Arrhenius relationship between 0° and 21°C with a Θ value of 1.062 and a $K_{20^{\circ}C}$ value of 0.586 (days^{-1});

(5) The overall COD removal reaction rate of the Portage la Prairie aerated lagoons varied with temperature according to the van't Hoff-Arrhenius relationships between 0^o and 21^oC with a Θ value of 1.051 and a K_{20^oC} value of 0.774 ($days^{-1}$);

(6) The suspended solids removal rate of the Portage la Prairie aerated lagoons varied with temperature according to a linear relationship between 0^o and 21^oC with 83.4% and 96.0% removal at 0^o and 21^oC, respectively;

(7) Sludge accumulation has a significant effect on aerated lagoon BOD removal performance in systems operating in climates with high seasonal temperature variations. The overall BOD removal rate at 19.2^oC at the Portage la Prairie aerated lagoon system predicted by a dynamic aerated lagoon model varied from 0.72 ($days^{-1}$) to 0.56 ($days^{-1}$) after 1 year and 15 years of sludge accumulation, respectively;

(8) The Portage la Prairie aerated lagoon system approximates a steady-state condition with respect to sludge accumulation after 13 to 15 years of continuous operation;

(9) Dynamic analysis of aerated lagoons operating in northern climates indicates potential benefits in partial solids separation by primary pretreatment.

CHAPTER 8

FUTURE STUDY

8. Future Study

As a result of this study future work is suggested in the following areas:

(1) A study should be made to determine the influence of mixing and temperature on aerated lagoon aerobic substrate utilization rates at varied energy input levels;

(2) The effect of substrate concentration on substrate utilization rates at varied temperature and turbulence levels should be established in order to examine first-order reaction rate assumptions at low temperatures in aerated lagoons;

(3) Additional tests should be conducted to establish the concentration of active cell mass in aerated lagoon mixed liquor and its variation with temperature, retention time, and substrate concentration;

(4) A study should be conducted to establish a relationship between the fraction of influent BOD remaining in suspension in an aerated lagoon and the turbulence level of the basin;

(5) A study should be conducted to determine the fraction of BOD consumed in sludge fermentation which re-enters the lagoon liquid and the portion of which represents resuspension of sludge solids by gas production;

(6) Sludge layer kinetic constants and their variation with temperature should be studied in order to assess potential benefits of primary pretreatment or sludge removal for aerated lagoons operating in cold climates;

(7) The effect of sludge accumulation on the temperature sensitivity of the overall BOD removal reaction rate for aerated lagoons should be further investigated.

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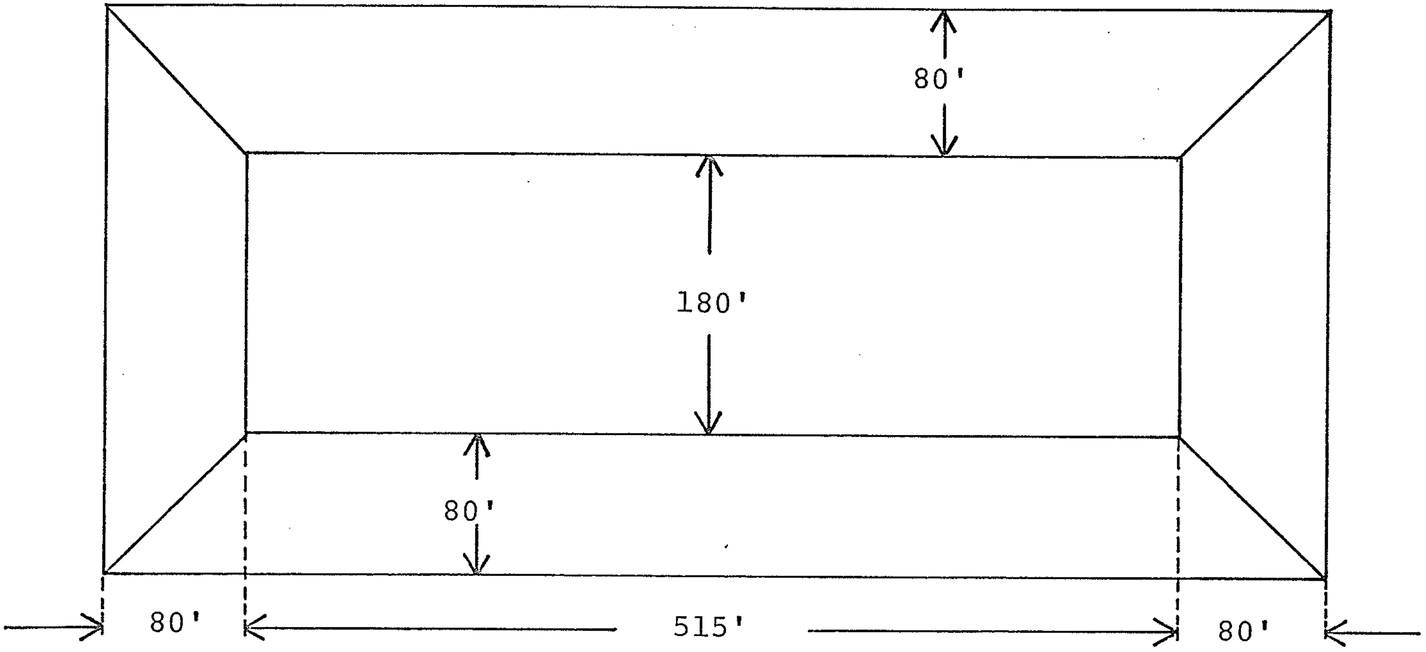
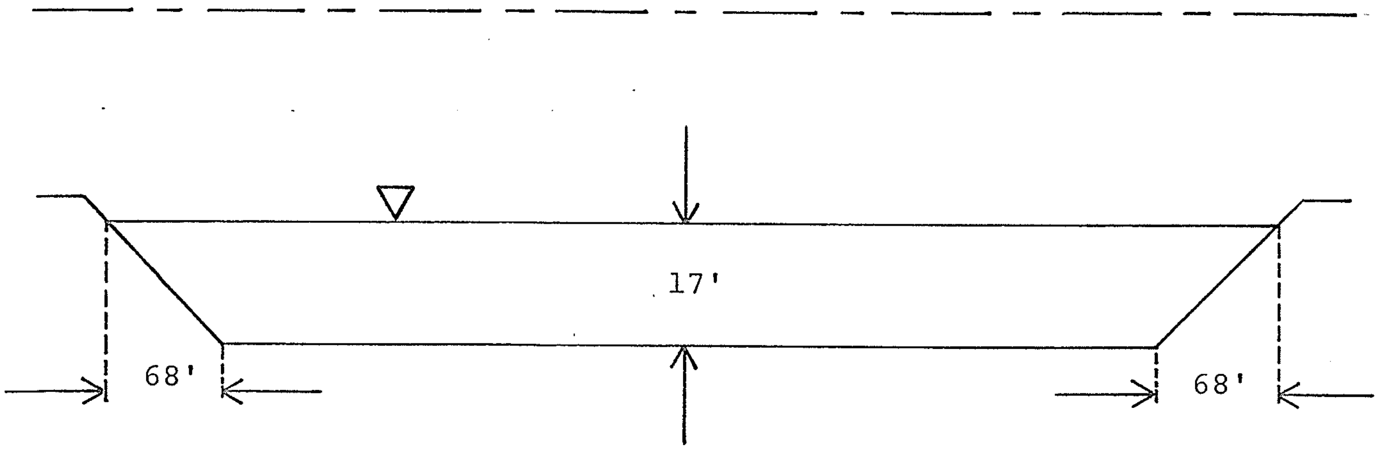
APPENDICES

APPENDIX 1

EFFECTIVE LAGOON VOLUME CALCULATIONS

A. Initial Lagoon Volume





Base volume = 17 x 180 x 515 = $1.60 \times 10^6 ft^3$

Side slope volume = 17 x 68 x (515 + 316) = $9.60 \times 10^5 ft^3$

Therefore, total lagoon volume

$$= 1.60 \times 10^6 + 9.60 \times 10^5 = 2.56 \times 10^6 ft^3$$

B. Sludge Volume

Sludge volume estimated after 11 years of continuous lagoon operation = $2.70 \times 10^5 ft^3$ per lagoon (58)

C. Effective Lagoon Volume

Estimated effective lagoon volume

$$= 2.56 \times 10^6 - 2.70 \times 10^5 = 2.30 \times 10^6 ft^3$$

$$= 14.35 \times 10^6 \text{ Imp. gal.}$$

APPENDIX 2

COMPUTER PROGRAM TO CALCULATE "BEST-FIT" SINUSOIDAL FUNCTION

This program utilizates the subroutine HARMAN to produce 6 sets of coefficients for the combination of sin and cos functions which "best-fit" input data. The resulting function has a period of 2pi/12 in order that monthly input data values will be approximated by a yearly cyclic function.

```
$ JOB  WATFIV  BEMISTER
       DIMENSION (A(14), Y(12)
       NDA = 14
       M = 6
       K = 12
       N = 2
       READ (5,900) (Y(I), I = 1, 12)
  900  FORMAT (1X, 12F5.0)
       CALL HARMAN (K, Y, M, A, N, NDA)
       PRINT, A
       STOP
       END
```

APPENDIX 3

DYNAMIC AERATED LAGOON MODEL PROGRAM

```
INITIAL
    PARAMETER G=10,PI=3.14159
*MASS DENISITY (LBS./IMP. GAL.)
DYNAMIC
    X=(2*PI*TIME)/12
    Y=(2*PI*(TIME-2))/12
    T=10.53-10.18*COS(X)+0.32*COS(X)+1.22*COS(X)+0.86*COS(X)...
    -0.17*COS(X)-0.71*COS(X)-0.73*SIN(X)-0.35*SIN(X)+1.13*SIN(X)...
    -0.55*SIN(X)+0.58*SIN(X)
*TEMPERATURE ( C) VARIATION WITH TIME (MONTHS)
    P=459+100*COS(X)+42*COS(X)+22*COS(X)-24*COS(X)+25*COS(X)...
    -64*COS(X)-37*SIN(X)-12*SIN(X)+26*SIN(X)-27*SIN(X)+19*SIN(X)
* INF. BOD-ULT (MG/L)
    Q=1940000-128000*COS(Y)+63333*COS(Y)+230000*COS(Y)...
    -75000*COS(Y)+123000*COS(Y)-6666*COS(Y)+364022*SIN(Y)...
    -72169*SIN(Y)+143333*SIN(Y)+51962*SIN(Y)-25689*SIN(Y)
* FLOW VARIATION WITH TIME (IMP. GAL/DAY)
    KS=0.002*(1.35**(T-20))
* SLUDGE REACTION RATE (DAY-1)
    VO=15828000
* TOTAL LAGOON VOLUME(IMP. GAL.)
    SE=S*0.70
* SLUDGE VOLUME(IMP. GAL.) -ESTIMATED
    V=VO-(SE/2)
* EFFECTIVE LAGOON VOLUME (IMP. GAL.)
    R=V/(Q*30.5)
* RETENTION TIME (MONTHS)
    S=INTGRL(10,ST)
* TOTAL SLUDGE MASS(LBS. BOD)
    I=0.3
* FRACTION OF INF. BOD ULT. SETTLING
    ST=I*P*30.5*Q*G/1000000-30.5*KS*S
*RATE OF CHANGE OF SLUDGE MASS (LBS./MONTH)
    IP=1.0-I
*FRACTION OF INF. BOD-ULT REMAINING IN SUSPENSION
    K=0.026*T+0.007
*SOLUABLE SUBSTRATE REACTION RATE (DAY-1)
    PE=INTGRL(10,PU)
*EFFLUENT BOD-ULT.(MG/L)
    PU=(IP*P)/R-(30.5*K+1/R)*PE+((SP*30.5*KS*S/2)/(V*G))*1000000
*RATE OF CHANGE OF LAGOON LIQUID BOD-ULT.(MG/L PER MONTH)
    BOD=PE/1.47
*EFFLUENT BOD-5
CONSTANT SP=0.4
* FRACTION CF BOD ENTERING LAGOON LIQUID AFTER SLUDGE FERMENTATION
PRTPLT BOD
TIMER OUTDEL=1.0,FINTIM=200
TIMER PRDEL=1.0
END
```

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