STUDIES ON A KINETIC MODEL FOR DESIGN AND OPERATION OF AN ACTIVATED SLUDGE PROCESS EMPLOYING CONSTANT CELL FEEDBACK

By

R. SRINIVASARAGHAVAN

Bachelor of Technology
University of Madras
Madras, India
1970

Master of Science
Rose-Hulman Institute of Technology
Terre Haute, Indiana
1972

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
DOCTOR OF PHILOSOPHY
December, 1974

STUDIES ON A KINETIC MODEL FOR DESIGN AND OPERATION OF AN ACTIVATED SLUDGE PROCESS EMPLOYING CONSTANT CELL FEEDBACK

Thesis Approved:

A. F. Gaudy Jr.
Thesis Adviser

Don F Kincannon

Elizabeth T. Gaudy

Richard N. DeSieno

Robert K. Gholson

D. D. Durham
Dean of the Graduate College

To my parents

ACKNOWLEDGEMENTS

The author sincerely appreciates the help rendered by the following individuals:

Dr. Anthony F. Gaudy, Jr., the author's major adviser, for his guidance, understanding, and assistance throughout this course of study. To him I shall always be grateful.

Dr. Elizabeth T. Gaudy, for her friendship and assistance as a committee member.

Dr. Don F. Kincannon, Dr. Joseph H. Sherrard, Dr. Richard N. DeVries, and Dr. Robert K. Gholson, for serving as committee members and for their suggestions.

My mother, Mrs. Kousalya Rengachari, and my father, Mr. Rengachari, for whom I have the greatest respect and love for encouraging me to go on to higher studies.

My brother, R. Vijayaraghavan, to whom I owe so much for helping to support me throughout my graduate studies.

Mr. Crosby Jones, for his assistance during this investigation.

Special thanks to Mrs. Grayce Wynd for her careful typing of this dissertation.

The author wishes to acknowledge the financial support provided by the Oklahoma Water Resources Research Institute, USDI, under research grant A-035 and by the School of Civil Engineering, Oklahoma State University, under an institutional grant.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

LIST OF SYMBOLS

c - Sludge recycle concentration factor, equal to the ratio between the recycle solids concentration, X_R, and the biological solids concentration in the reactor, X

D - Dilution rate. Ratio of the rate of flow, F, and the volume of liquor in the aeration tank, V. It is equal to the reciprocal of the mean hydraulic residence time, $\bar{t}$, in a completely mixed reactor, hr^{-1}

F - Rate of flow of incoming substrate or wastewater, l/hr

F_w - Amount of waste flow

k_d - Maintenance energy coefficient, day^{-1}

K_s - A biological "constant" used in the hyperbolic expression relating specific growth rate to substrate concentration. It is known as the saturation constant. It is numerically equal to the substrate concentration at which specific growth rate is 1/2 the maximum specific growth rate for the system, mg/l

S - Substrate concentration, measured as COD, mg/l

S_i - Concentration of substrate in the inflowing feed in continuous flow operation, measured as COD, mg/l

S_e - Concentration of substrate in the reactor or effluent, filtrate COD, mg/l

$\bar{S}_e$ - Steady state concentration of substrate in the reactor or effluent, filtrate COD, mg/l

S_t - Concentration of COD in the clarifier effluent, supernatant including non-settled biological solids, mg/l

$\bar{S}_t$ - Steady state concentration of COD in the clarifier effluent, supernatant including non-settled biological solids, mg/l

S_R - Filtrate COD in the recycle sludge, mg/l

$\bar{S}_R$ - Steady state filtrate COD in the recycle sludge, mg/l

t - Hydraulic detention time, hrs

U - Specific substrate utilization rate, day^{-1}

X - Biological solids concentration, mg/l

$\bar{X}$ - Steady state biological solids concentration in the reactor, mg/l

X_e - Biological solids concentration in the clarifier effluent, mg/l

$\bar{X}_e$ - Steady state biological solids concentration in the clarifier effluent, mg/l

X_R - Biological solids concentration in the recycle flow to the reactor, mg/l

$\bar{X}_R$ - Steady state biological solids concentration in the recycle flow to the reactor, mg/l

X_w - Excess biological solids (sludge wasted), mg/day

$\bar{X}_w$ - Steady state excess biological solids (sludge wasted), mg/day

Y_B - Mean cell yield obtained during growth at specific growth rate at or near μ_{max} (batch system)

Y_c - Mean cell yield obtained during growth at specific growth rate, μ_c (continuous system without cell recycle)

Y_{c_R} - Mean cell yield obtained during growth at specific growth rate, μ_{c_R} (continuous system with cell recycle)

Y_o - Observed cell yield

Y_t - True cell yield

μ - Specific growth rate in an exponential phase of growth, hr^{-1}

μ_B - Specific growth rate in batch systems, hr^{-1}

μ_{c_R} - Specific growth rate in continuous system with cell feedback, hr^{-1}

μ_c - Specific growth rate in continuous system without cell feedback, hr^{-1}

μ_{max} - The maximum specific growth rate for a system in exponential growth, hr^{-1}

α - Recycle flow ratio

Θ_c - Sludge retention time, days

CHAPTER I

INTRODUCTION

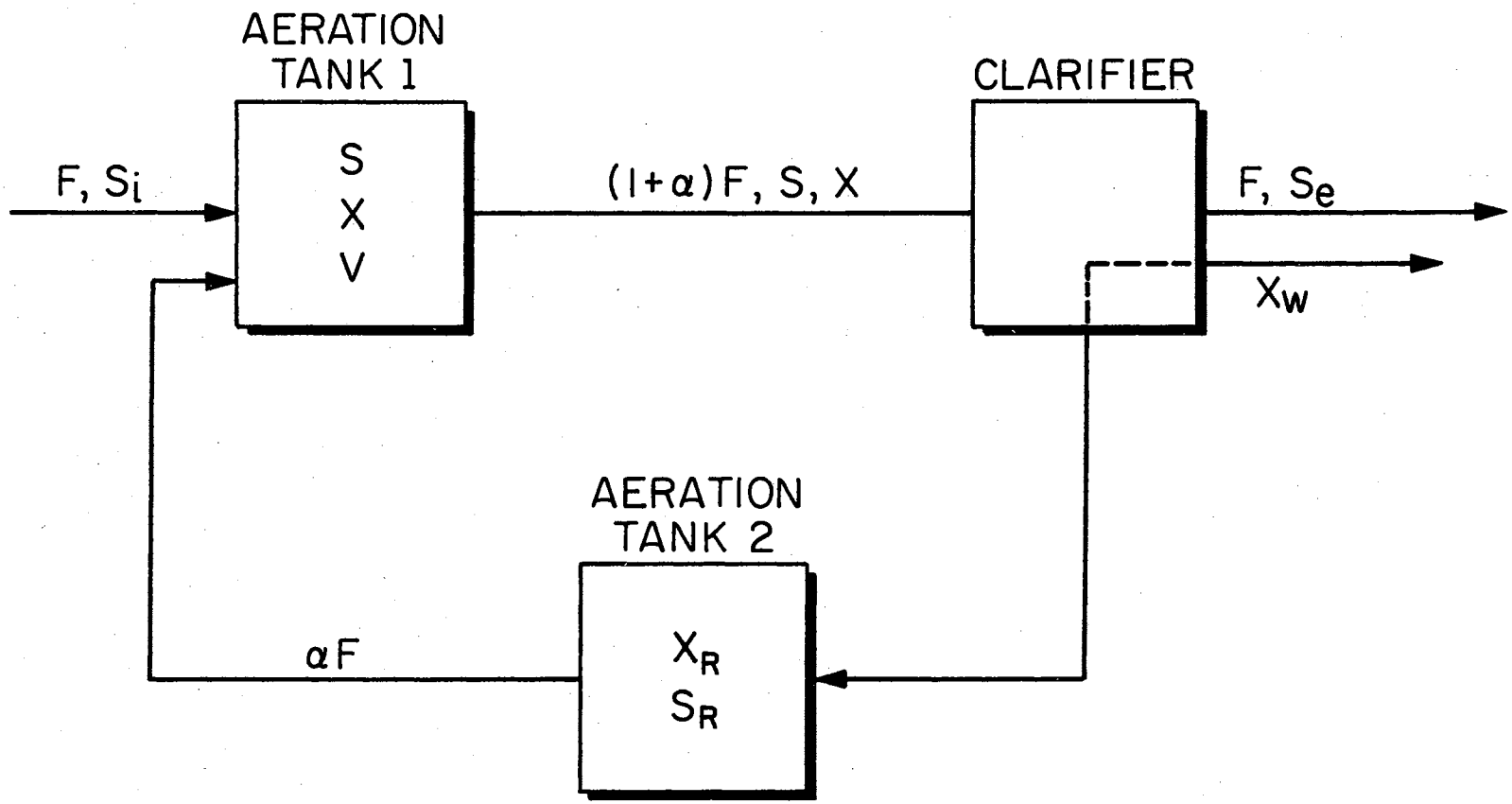
In the thrust to clean up and improve the nation's waters, much time, effort, and money have been expended in the research and development of improved wastewater treatment methods and processes. Several physical-chemical, and biological means of treatment have been developed for the removal of various forms of pollutants contained in wastewater. Each method has its advantages and disadvantages, and the choice among the methods should depend on several basic considerations. However, biological methods have been more frequently employed in the past than have physical-chemical methods of treatment. One of the obvious reasons for such an overwhelming preference of biological processes is the economics of operation.

Of the fluidized and fixed-bed systems within the biological methods of wastewater treatment, the fluidized process, more commonly known as the activated sludge process, has attracted many researchers and practicing engineers because of its versatility and operational control features. There has been continuous effort to develop a reliable design basis for the efficient performance of the activated sludge process. The development of design methods has gone through several phases in the last two decades. Attempts have been made to base the design on strictly empirical "rules of thumb" from past experience. Prior to the development of the biochemical oxygen demand (BOD) to

mixed liquor suspended solids ratio, aeration basin-size determinations were based on selection of a reasonable hydraulic detention time and the mass of BOD applied per 1000 cft of aeration basin value. In recent years, microorganism growth rate is realized as an important parameter which controls the substrate removal rate and sludge production; therefore this is employed as a design tool by some researchers.

It is realized that there should be sound scientific principles behind any design procedure. In some unit operations, a good design may be automatically assumed to give good results, and the operational aspect of the particular unit process may not be as important as the design aspects. However, in the biological unit processes for wastewater treatment the operational aspects are as important as the design of the process, because of the natural variations in the characteristics of biomass employed to accomplish the removal of organic materials from the wastewater and variations in the natural (operational) environment. Successful results are obtainable only where a properly designed process is properly operated, with due regard to the boundary conditions of the design model. Therefore, it will be desirable to have an operational parameter incorporated in the design. This operational parameter should be such that it controls the parameter which determines the performance characteristics of the treatment process. It is known that the bacterial mass is the main factor that controls the treatment. An efficient method of control of the biological solids concentration, X, is to modify the existing system in such a manner as to facilitate direct control of X. Such a modification is shown in Figure 1. The difference between the conventional type of the complete mix activated sludge process and the flow diagram shown in Figure 1 is the

Figure 1. Flow Diagram for Model Employing Constant Recycle Sludge Concentration, X_R


AERATION
TANK 1
S
X
V
F, Si
(1+α)F, S, X
CLARIFIER
F, Se
Xw
AERATION
TANK 2
XR
SR
αF

inclusion of the sludge consistency tank (aeration tank #2) in the recycle line. The sludge consistency tank, as the name implies, is a reactor wherein the concentration of cells is maintained at a constant value, X_R. This serves as a biochemical dosage tank to aerator #1, where the biochemical reactions of substrate removal and bacterial growth take place. The inclusion of such a tank which holds X_R constant makes the other operational parameter, the recycle ratio, α, more effective. Without control of X_R, the recycle ratio would be only partially reliable as a control tool. The constant X_R in conjunction with α is expected to provide an excellent means of effective control and maintenance of "steady state" operational conditions with respect to aerator biological solids concentration, X, as well as effluent substrate concentration, S. Steady state equations were derived under this operational configuration using concepts consistent with the theory of continuous microbial culture, and the behavior of the model was analyzed computationally (1).

The current investigation encompassed an experimental study of the modified activated sludge process with constant cell feedback at the pilot plant level. The overall aims of this research can be stated as follows:

1) to determine the ease of operation of an activated sludge process employing constant X_R at pilot plant level;

2) to observe the steadiness of such a model with respect to X and S under various operational configurations;

3) to compare the experimental results with the values calculated from the equations so as to assess the predictive ability of the model;

4) to check the validity of the assumption made in the original

derivation of steady state equations;

5) to determine values for biological "constants" employed in the model equation from batch growth experiments;

6) to suggest a practical design approach for the activated sludge process employing constant cell feedback.

CHAPTER II

LITERATURE REVIEW

Design Models for the Activated Sludge Process

Treatment of sewage by the activated sludge process was developed in the early 1900s. Since then, several modifications have been proposed and practiced in wastewater treatment. In 1912, aeration in the presence of microorganisms was carried over to England by Dr. G. J. Fowler after his visit to Lawrence Experimental Station in Massachusetts. High purification of sewage was achieved by recovery of flocculant solids and their recycle to the aeration basin. Large-scale experiments were subsequently undertaken, and successful results were reported by several researchers.

In spite of such an early start, it was not until the 1950s that the fundamentals of the activated sludge process were studied in depth. In 1951, Helmers, et al. (2) reported that cell growth was proportional to BOD reduction, if the required amount of nutrients was present. In the same year, Heukelekian, et al. proposed an equation relating the sludge accumulation rate, sludge production due to substrate removal, and the oxidation of solids (3). In 1952, an empirical formula for the composition of activated sludge microorganisms was developed by Hoover and Porges (4). This formula, as well as the metabolic balances provided by these researchers, contributed in considerable measure to

understanding and subsequent modelling of the activated sludge process.

In 1954, Eckenfelder and O'Connor (5) proposed a mathematical model for activated sludge wastewater treatment. Subsequently, in a series of publications, Eckenfelder has advanced mathematical relationships for the process reactions in continuous flow waste treatment (6)(7)(8). Although his initial relationships were based on batch microbial growth kinetics, he has suitably modified these to continuous flow kinetics in later publications. The present method suggested by Eckenfelder is to run laboratory activated sludge units and base the design on the results obtained from them.

From the laboratory studies, values for the following parameters are generated:

$$\frac{S_o - S_e}{X \cdot t}, \quad F/M, \text{ and SVI}$$

where S_o and S_e are influent and effluent substrate concentrations, respectively, X is the biomass concentration in the reactor, t is the hydraulic detention time, F/M is the "food," (i.e., carbon source) to microorganism ratio, and SVI is the sludge volume index. (Symbols shown in this section of the report are used by the proposers of the models.)

Graphical plots of $\frac{S_o - S_e}{X \cdot t}$ vs S_e give a value for the substrate removal rate coefficient, k, which is equal to the slope of this straight line plot. If, however, a residual BOD or COD persists in the effluent, a relationship to account for deviation from theory takes the form of

$$\frac{S_o - S_e}{X \cdot t} = kS_e - Y$$

where Y is an intercept of the above mentioned plot.

A linearized expression to calculate total oxygen requirements is formulated based on the assumption that O_2 is required for (a) biological organic removal, and (b) endogenous respiration. The resulting expression is

$$\frac{R_r}{X} = \frac{a'(S_o - S_e)}{X \cdot t} + b'$$

where R_r is the oxygen utilized per unit reactor volume, a' is the fraction of substrate used for oxidation, b' is the fraction of volatile suspended solids oxidized per day on an oxygen basis. The values of $\frac{R_r}{X}$ are calculated from laboratory data, and a plot is developed between $\frac{R_r}{X}$ and $\frac{S_o - S_e}{X \cdot t}$, the slope of which gives the value for a' and the intercept gives the value for b'. Prediction of sludge production is estimated through the use of a relationship to account for all of the factors that increase and decrease reactor sludge concentration. By rearranging this materials balance, the following equation can be obtained:

$$\frac{\Delta X}{VX} = \frac{a(S_o - S_e)}{X \cdot t} - b$$

where ΔX is the amount of sludge produced, a is the fraction of substrate converted to new microorganisms, and b is the fraction of volatile suspended solids oxidized per day. From the plot of $\frac{\Delta X}{VX}$ vs $\frac{S_o - S_e}{X \cdot t}$, the values for cell yield, a, and the endogenous decay coefficient, b, can be determined.

Thus, from the bench scale pilot plant data, the removal rate coefficient, oxygen required, and sludge production are determined. Aeration basin requirements are based on two criteria: an organic loading dictated by flocculation and settling of sludge in the secondary clarifier, and the effluent quality which meets regulatory authority requirements dictated by removal rate coefficient, k. A suitable F:M ratio that meets these two conditions is chosen from the laboratory data. The hydraulic detention time is calculated for the desired loading and aeration cell concentration. By employing the constants obtained from the laboratory studies and with the knowledge of influent organic concentration and flow rate, the full scale plant design calculations can be made.

In 1962, McKinney proposed a mathematical model for a "complete mixing" activated sludge treatment system (9). This is a model with more constants developed than are used in the materials balance equations, because most of the constants are developed to explain the theoretical concept of the complete mixing activated sludge process. From the materials balance for substrate utilization at steady state, the following equation relating influent substrate concentration, S_o, effluent substrate concentration, S, and hydraulic detention time, t, is obtained:

$$S = \frac{S_o}{1 + k_5 t}$$

where k_5 is equal to the oxygen demand removed divided by the oxygen demand remaining per unit of time.

A similar type of materials balance for microbial growth leads to

the relationship

$$X_a = \frac{k_6 S}{\frac{1}{t}(x - xw + sw) + k_7}$$

where X_a is the active mass in the aeration tank, k_6 is the synthesis constant, k_7 is the decay constant, μ is the ratio of effluent solids to the aeration tank solids, S is the compaction coefficient to relate recycle and aeration basin solids concentration, and w is the fraction of influent flow wasted per day. To calculate the total oxygen demand of the effluent, an account for the concentration of microorganisms in the effluent is included. This gives the following equation:

$$\text{effluent COD} = S + xk_{10}X_a$$

where k_{10} is a constant to account for carbonaceous and/or nitrogenous metabolism. In designing a treatment facility, values for μ, S, k_6, k_7, and k_{10} are assumed. For the desired detention time, which is chosen by the designer, S, X_2, and w are calculated using the above equations.

In the early 1960s, Busch developed a model for activated sludge wastewater treatment design which was based on some mathematical as well as empirical relationship (10). Busch's approach was to run a laboratory bench scale pilot plant unit to obtain design data. The acclimated batch-grown cells were used to run a continuous unit without intentional sludge wastage. Data were collected daily during the non-steady state period of microbial solids accumulation. By monitoring the substrate and solids concentrations in the unit, graphical relationships were obtained between various parameters which formed the basis for the design. Three main curves were developed from the

laboratory data for the design of the activated sludge process. They are:

1) loading, lbs BOD/day/lbs mixed liquor suspended solids (F:M ratio) vs substrate removal, lbs BOD removed/day/lb of MLSS. The slope relates to the plant efficiency. This curve is of little use in formulation of process design criteria.

2) effluent BOD, mg/l, vs loading, lbs BOD/day/lbs MLSS (F:M ratio). This relationship is very useful in that the intercept of the curve shows the minimum attainable effluent BOD.

3) observed yield vs sludge age. This is another important curve for the design of sludge handling facilities. During the period of solids accumulation in the continuous flow unit, it is necessary to perform a batch microbial growth experiment using microorganisms from the continuous flow treatment unit to obtain a relationship between BOD removal rate, $\frac{dS}{Xdt}$, vs BOD concentration, S_t. After obtaining these design curves, the design procedure is as follows:

Fix the effluent BOD and calculate the BOD removed/day/lb MLSS from the batch rate concentration plot. The MLSS required is then found by dividing substrate removed by loading. From influent BOD and MLSS, deduce the F:M ratio. At this F:M ratio, check with the plot of F:M vs effluent BOD obtained from continuous flow laboratory pilot plant study to determine if the effluent criteria can be met. The selection of hydraulic detention time in Busch's method is governed solely by the optimum combination of MLSS concentration and economic tank volume. Excess sludge production is calculated by determining the cell age at which the system to be operated will meet the required effluent quality. Once this cell age is obtained from the plot of cell

age vs effluent BOD, excess sludge produced can be obtained from the plot of observed yield (or sludge produced, lbs/lbs BOD removed) vs cell age.

Regarding the batch studies suggested by Busch, it is agreed that there is an advantage in using activated sludge from continuous flow units as initial inoculum for batch studies. Also, it can be conceived that cells from such units do remain fairly constant in their metabolic activity measured by endogenous oxygen uptake. Such a parameter may facilitate comparison of characteristics of cells at various times during an investigation. Another point of discussion of this model is the concept of cell age. In a system where there was no intentional sludge wastage, it is rather difficult to conceive of the idea of cell age although it was assumed in his method that the cell was as old as the system so long as the solids concentration in the effluent was negligible. It was found recently in an investigation of this method (11) that under non-steady state conditions, activated sludge showed markedly different characteristics than under steady state conditions.

In 1963, Grieves, Milbury, and Pipes (12) put forth a mixing model for the activated sludge process. The mixing conventions were mainly those of Cholette and Cloutier (13). The equations of hydraulic regime were integrated with steady state equations of continuous microbial culture. The growth equation employed was one that depicted two-phase growth, in which a linear relationship between growth rate and substrate concentration would be predicted at growth-limiting concentrations of substrate. Their approach did not gain much support among design engineers.

In 1964, another mathematical model was published by Schulze (14).

In this paper, a series of mathematical equations was developed, defining the steady state substrate and cell concentration for once-through and feedback systems. The relationship assumed between the specific growth rate, μ, and substrate concentration, S, was different from that of Monod. This was a linear equation proposed by Teissier. The equations of Monod and Teissier and relationships proposed by other researchers were tested by Gaudy, et al. (15). The results obtained by Gaudy, et al. offer support for the practical application, rather than proof of, the Monod equation in reactors employing heterogeneous populations.

With regard to the choice between the two-phase or single-phase kinetic model, if an investigator bases his conclusions or selection of one type over the other on the basis of best fit of the data, it must be realized that there are situations where either concept would seem justified. If the system has a low "saturation constant," K_S, the selection of either the Monod type expression or the linear two-phase expression would appear to make little practical difference in defining the relationship between μ and S. However, for systems with larger K_S values, the numerical difference between the two predictions is increased. Concerning the use of either relation between μ and S, it is also important to note that in the lower ranges of S (e.g., 25-75 mg/l), the curves predicted by the Monod expression at various K_S values could be plotted as a straight line without serious error. Since wastewater treatment plants to be effective must yield effluent of at least this quality, preferably better, a linear relation could, for practical reasons, be assumed, and the two-phase concept was originally proposed on this basis (16). In general, the results presented by Gaudy, et al.

(15) indicate that experimental data pertinent to the relationship between μ and S support the use of the Monod equation. Therefore, even though at the lower substrate ranges and at low K_S values a linear relationship could be used, it cannot be recommended, since it does not fit the entire range of μ and S levels for any particular values of μ_{max} and K_S, and fits only approximately in special cases. It surely cannot be argued that a heterogeneous population is such a special case. The final conclusion of Gaudy, et al. was that refinement of the Monod equation does not seem warranted from the standpoint of practical application.

A design method for the continuous flow activated sludge process utilizing batch growth and substrate removal rates in conjunction with mixing theory has been developed by Bhatla, et al. (17). An acclimated microbial population is developed by fill-and-draw technique. Batch experiments are conducted using these acclimated cultures at various loadings to obtain design data. These batch experiments are used to establish BOD transfer kinetics of the laboratory biological oxidation system. From the laboratory batch data design formulations are obtained in the following sequence:

1) An arithmetic plot of BOD vs time of sampling is made for each batch test. Two linear regions are located. An empirical average rate constant is found at each loading from the initial linear region of the plotted data by the relationship

$$r = \frac{S_o - S}{t(S)}$$

where S_o is the initial BOD, S is the BOD at time t.

2) A relationship between fraction of BOD removed, D, and r is then

calculated by the expression

$$D = 1 - (1 - r)^t$$

and plotted against treatment time for each batch run.

The batch kinetics are integrated with mixing theory to predict the performance of a continuous process. A curve for complete mixing kinetics in a single basin is obtained by plotting $\frac{t}{t_b}$ vs Y, fraction of flow held for time t or longer, where t is the treatment time and t_b is the average retention time in the basin.

3) For design predictions, an average hydraulic retention time in the aeration basin, t, is selected, and 1 - r is plotted against D. The percent of the total graph area which lies under this curve is a prediction of the performance of a continuous system which has the specified detention period. Once basic data are obtained from batch experiments, a mathematical trial-and-error procedure is followed to find a suitable design. Although a procedure undoubtedly exists to relate information obtained to final design consideration, the aeration basin solids concentration, X, and sludge production to be expected--this information has, to the author's knowledge, not been divulged by Bhatla, et al. (17).

One of the recent models is one by Lawrence and McCarty (18). The basic difference between this model and others is the equation employed to relate the rate of substrate utilization, concentration of microorganisms, and substrate remaining. Monod's equation is modified for substrate utilization rate, and assumes the form

$$\frac{dF}{dt} = \frac{kSX}{K_s + S}$$

where $\frac{dF}{dt}$ is the rate of microbial substrate utilization per unit volume, k is the maximum rate of substrate utilization per unit weight of microorganisms, K_s is the saturation constant, and S is the substrate concentration surrounding the microorganisms.

The basic operational parameter of this model is the mean cell retention time, or biological solids retention time, and is defined as

$$\Theta_c = \frac{X_T}{\left(\frac{\Delta X}{\Delta t}\right)_T}$$

where X_T = total active microbial mass in the system, and $\left(\frac{\Delta X}{\Delta t}\right)_T$ is the total quantity of active microbial mass withdrawn daily, including those solids purposely wasted as well as those lost in the effluent. By writing a mass balance for microbial growth, it is shown that

$$\Theta_c = \frac{VX}{Q_w X_w + Q_{eff} X_{eff}}$$

At the steady state condition it is shown that

$$\frac{1}{\Theta_c} = \frac{Y\ dF/dt}{X} - k_d$$

By employing these equations in the materials balance for substrate removal and microbial growth, steady state equations for X and S are obtained. In this model, a constant yield and decay coefficient are used to account for the variability of cell yield at various cell ages. The parameters for which values are to be assigned (or determined) are Y, k_d, k, and K_s. Once the desired treatment efficiency is stated, a Θ_c can be chosen to obtain the desired effluent BOD or COD

for a given set of conditions. For each value of Θ_c, there is a unique value of efficiency, $\bar{S}$, and X. Within the limits of technical and process feasibility, the final choice of a design volume would be based upon an economic analysis of the factors determining the cost associated with a given volume such as capital cost, recycle pumping costs, and aeration or mixing costs.

In a series of publications (19)(20)(21), Sherrard and Schroeder have developed a mathematical model that can be used to describe biochemical reactions in a continuous flow, completely mixed biological wastewater treatment system. The basis for development of the model was to utilize a variable microorganism yield coefficient in conjunction with microbial continuous culture theory. The observed or variable yield coefficient is dependent on the value of the specific growth rate, μ, or its reciprocal sludge retention time, SRT, or sludge age, Θ_c, and this principle was used to relate the growth rate and substrate utilization rate. They have also shown that the observed cell yield is maximum at high μ and minimum at low μ values. The primary reasons attributed to the variation in yield by these authors were predation activities of higher life forms and increased microorganism maintenance energy requirements at lower μ. The main difference between this model and that of Lawrence and McCarty is the way in which the variation in yield with cell age is incorporated in mathematical equations. The design approach proposed by Sherrard is to select a suitable Θ_c that would produce an effluent of required quality and from the yield value at that cell age, calculate the amount of sludge production for the substrate removed by using the formula

$$P_x = QY_{obs} (S_o - S)$$

This is the amount to be wasted to operate the system at the desired Θ_c. The steady state substrate and aeration tank solids are calculated at that particular Θ_c from equations derived from these two parameters drawing a materials balance for the system.

From the review of literature, it is found that two main approaches to design of the activated sludge process are 1) the so-called F:M ratio approach, and 2) the sludge residence time approach. In recent publications by Goodman and Englande (22), and Stensel and Shell (23), these approaches are compared critically. The F:M and SRT design models are useful in predicting effluent substrate concentration. It can be shown by a materials balance equation that for a given F:M ratio, a specific SRT exists.

The success of a treatment plant depends not only on proper design of unit processes, but also on the effective operation of the plant to produce a desired quality of effluent. While the F:M technique emphasizes maintaining a constant MLSS, the SRT method emphasizes the amount of sludge wasted per day as the operational control. The operation and the control of any process by any method is feasible only if the parameters involved are measurable with ease in a relatively short time and with reasonable accuracy. In the F:M technique, the important parameter is the measurement of solids concentration which can be done without very involved procedures. But the problem with this method is the variation in aeration solids concentration which can occur due to fluctuations in substrate concentration and cell or sludge yield values. Also, changes in suspended solids concentration in the inflowing

waste can result in a different F:M ratio. A similar situation would arise if the proportion of active mass in the total suspended solids present in the system changes. If the original design ratio was low, a decrease in active mass may not cause serious disruption in biochemical efficiency, although it can cause inefficient clarification due to changes in settling characteristics (23). Conversely, if the ratio were to go to the other side, i.e., to decrease below the design ratio due to an increase in active mass, this will result in increased amount of oxygen uptake. The measurement of the other parameter, the "food" concentration in the influent, is limited if the BOD test is used. However, the ΔCOD test (24), which appears to be a better method for this purpose, could be employed. Thus, control of the F:M ratio is dependent on the fluctuation in the biomass concentration and measuring techniques employed to determine the substrate concentration in the feed. This approach requires active control of solids concentration in the aeration basin, but the models that propose this approach do not have an operational parameter that would easily facilitate such a control. The control of X would call for immense operational effort in the absence of a direct method. Thus, control of F:M ratio requires involved procedures which make it a difficult approach.

The SRT technique requires the control of solids domain in the system to vary the growth rate. This is accomplished by wastage rate which requires measurement of suspended solids concentration. An increase in organics would mean a higher wastage rate to maintain the same SRT. In the hydraulic method of SRT control proposed by Walker (25), solids concentration in the recycle was assumed constant. In this type of control, the clarifier performance is very important.

The compacted sludge concentration depends on the characteristics of the particular sludge and the blanket level. This may vary if the wastage rate is varied. Thus, an increase in the volume of sludge wasted will not ensure a proportional increase in total wastage.

Energy of Maintenance

The decrease in yield with decreasing growth rate has been a phenomenon which is reported and discussed by researchers in microbiology and sanitary engineering fields. Several attempts have been made by microbiologists to provide theoretical explanations for this phenomenon. A review of literature on the maintenance energy requirement of bacteria is presented in this section for two reasons: 1) it was of interest to the author to determine if the model studied experimentally in this research investigation could be improved by the inclusion of a maintenance energy coefficient in the steady state equations employed to predict the performance characteristics; 2) a very interesting and important observation regarding the cell yield values in batch and continuous systems was made during the course of this investigation which raised questions about the validity of the possible theoretical basis for the maintenance energy concept.

Duclaux (1898) was probably the earliest microbiologist to distinguish between energy required for growth and energy of maintenance of cells. He calculated that for yeast, the energy of maintenance was 0.25 gm of sugar/gm yeast/hr. Pirt (26) discounts this as a possible error due to inadequate data. According to most theoretical opinion, existence of an energy of maintenance ought to be universal and has been widely assumed, though not always so designated or considered as

discrete from growth processes.

The following two paragraphs are the summary of literature on the energy of maintenance reported by Mallette (27), McGrew and Mallette (28), and Dawes and Ribbons (29)(pages 523, 844, and 135, respectively):

> Rahn (30) ascribed to the energy of maintenance the role of overcoming the effects of "chemical wear and tear" resulting from hydrolysis and decomposition. Sugita stressed internal inefficiencies and the need for a balanced entrophy in organisms. Lockhart (31) commented that continuity of growth of bacteria is a function of per cell concentration of limiting nutrients. Lamanna and Mallette (32) and McGrew and Mallette (28) summarized the findings and problems involved in demonstrating an energy of maintenance in bacteria. Although energy of maintenance has been established for higher animals, suggested for higher plants, and might be expected to be carried over to microorganisms, experimental demonstration has been difficult in the last instance. Kandler (33) in 1955 demonstrated at least the possibility of energy of maintenance in plant tissues where he showed that not all of the exogenous materials go to growth. Windisch and Nordheim (34) emphasized that starvation depletes cells of reserves, preventing their growth unless supplemented. This idea suggests the energy of maintenance.
>
> If energy is utilized specifically for maintenance, one would predict that at sufficiently low feed rates, exogenous materials could not produce cell growth. Hence, plots of dry weight, or some related property, against amount of energy source supplied ought not extrapolate to the origin. A positive value for the energy source at zero growth would correspond to energy of maintenance. Using this approach, Maze (35) plotted yield of fungus against invert sugar or methanol consumed, and extrapolated the line through the origin, thus concluding that energy of maintenance was undetectable. The results actually do not appear to be clearcut, possibly because the experimental points were not presented. Later, Rottier (36) obtained a similar linear relationship between total growth of Polytoma uvella and the amount of peptone in the medium. In one case, the data extrapolated to a negative intercept on the substrate axis. With somewhat more sensitive methods, Monod and Teissier (37) found that the total population of Glaucoma piriformis increased linearly with food supply over the range studied. They concluded that a given amount of food was necessary per new cell, regardless of the exogenous energy level. Later, Monod (38) re-studied the problem more extensively using Escherichia coli and Bacillus subtilis, and again concluded that energy of maintenance was zero. In another series of experiments, Monod varied

> the temperature and found a decrease in total population at higher temperature. This rather generally observed phenomenon might be anticipated on the basis of increased energy requirements needed to offset the more rapid degradation of cellular components. On the other hand, such an effect could be offset partly or completely by the increase in time required to reach the maximal population at lower temperatures. Monod concluded that there were not sufficient data to resolve the problem of the effect of temperature on the maximal population with a limited energy supply. Dagley, et al. (39) studied A. aerogenes and recorded linear growth of cultures as a function of glucose. The curves were drawn through the origin as usual, though it must be borne in mind that such experiments ordinarily are not concerned with the presence or absence of small intercepts. In 1958, Herbert (40), from studies of continuous culture, postulated an endogenous metabolism in growing bacteria to account for yield variation with growth rates. The endogenous metabolism is equivalent to maintenance energy requirement, and he suggested a modification to the growth rate law.
>
> Battley (41) and Bauchop and Elsden (42) reported similar observation. Thus, the existence of an energy of maintenance for growing bacteria has been problematical.

Marr, Nilson and Clark (43) have adopted Herbert's formulation but modified the terms used as a rate constant by Herbert to specific maintenance rate. Schulze and Lipe (44) have provided a further analysis of the maintenance energy requirement. They formulated the maintenance energy according to the older expression used by Monod; that is, in terms of energy substrate consumed per unit mass of organisms per unit time. In 1965, Pirt (26) made further studies and compared the two expressions proposed by Marr and Schulze for maintenance energy in growing cultures. He plotted the data of Herbert (40) and Hobson (45). While the data of Herbert did not indicate any evidence of maintenance energy requirement, Hobson's data strongly suggested the existence of such a requirement. From his own studies, Pirt concluded that maintenance energy is a significant factor in determining the amount of total growth at low growth rates.

Palumbo and Witter (46), in studying the influence of temperature on glucose utilization, found that yield and specific maintenance decreased with decreasing temperature. However, the amount of glucose consumed per generation for maintenance increased with decreasing temperature. This increased glucose consumption for maintenance may provide a partial explanation for the decrease in yield at low temperature. Mannett and Nakayama (47) have studied the dependence of yield and maintenance requirement on temperature. They concluded that the results obtained indicate that the specific maintenance rate decreases with decreasing temperature. In 1973, abbott and Clamen (48) analyzed the dependence of Y on μ and m. Their analysis disclosed that maintenance requirement caused two- to threefold variation in the yield coefficients as μ was increased from 10 percent to 100 percent of μ_{max}, and found that the value of m had a significant effect on Y values even at high μ values.

CHAPTER III

THEORETICAL DEVELOPMENT OF THE MODEL

Extensive investigation was done by Gaudy and co-workers to gain insight on growth characteristics of heterogeneous microbial populations cultivated continuously in completely mixed reactors of the once-through and with-cell-feedback type operations (15)(49). These studies had direct applicability to understanding of activated sludge processes for treatment of wastewaters, and they were undertaken for the purpose of assessing the applicability of various models relating values of kinetic growth parameters to concentrations of limiting nutrients (in this case, concentration of carbon source, S), and for the purpose of determining whether steady state operation with respect to biological solids concentration, X, and substrate concentration, S, could be approached for heterogeneous populations. It was found that a hyperbolic function, the Monod equation, relating the logarithmic growth rate constant, μ, to the substrate concentration, S, was applicable.

$$\mu = \mu_{max}(S)/K_s + S)$$

Due to heterogeneity of the population, some variation in the maximum logarithmic growth rate constant, μ_{max} and saturation constant, K_s, was to be expected and was found even under constant operational conditions. It was also found that the value of cell yield, Y, could be expected to vary. It was concluded that these growth "constants" for

natural populations were understandably variable. The kinetic concepts could be employed, but a useable range of values rather than a precise numberical value should be employed. Concerning the attainment of a steady state with respect to S and X, it was found that a steady state could be approached only rather closely for S and less closely for X.

One such model that has an inherent operational control parameter is that of Herbert (50). The steady state equation for S and X, according to this model, is shown in Table I. There are three biological "constants," μ_{max}, K_s, and Y, and two hydraulic parameters, α and c. These five parameters control S and X at any selected dilution rate, D. The operational system constant is the ratio of recycle solids concentration to the aeration tank solids concentration ($X_R/X = c$). The requirement of this model is that c should be held constant. The growth rate in the system can be controlled by selection of c for a particular α and D. Since $\mu = D\left(1 + \alpha - \alpha\frac{X_R}{X}\right)$, it is seen that a relationship between μ and c can be developed for various combinations of α and D. Thus, the system can be run at desired growth rates or cell ages by proper choice of α, D, and c. Once this theoretical possibility is established, the practical feasibility of such a theoretical mode of operation needed to be tested. Here the model failed insofar as its use with heterogeneous populations is concerned. It is realized from the equation for growth rate, that μ is very sensitive to the value of c. Thus, it is essential that c be maintained constant at the desired value. In order to keep c constant, X_R should be adjusted for every change in X. The trouble involved in such an operation can be visualized by anyone who has experience in operating a laboratory pilot plant employing heterogeneous populations. Even under controlled laboratory

TABLE I

COMPARISON OF STEADY STATE EQUATIONS ACCORDING TO MODELS OF HERBERT AND OF RAMANATHAN AND GAUDY

Herbert Constant $c\left(c = \frac{X_R}{\bar{X}}\right)$		Ramanathan & Gaudy Constant X_R	
$\bar{X} = \frac{Y}{1+\alpha-\alpha c}\left(S_i-\bar{S}\right)$	(1a)	$\bar{X} = \frac{Y\left[S_i-(1+\alpha)\bar{S}\right]+\alpha X_R}{1+\alpha}$	(1)
$\bar{S} = \frac{K_s D(1+\alpha-\alpha c)}{\mu_{max}-D(1+\alpha-\alpha c)}$	(2a)	$S = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$ $a = \mu_{max}-(1+\alpha)D$ $b = D\left[S_i-(1+\alpha)K_s\right]-\frac{\mu_{max}}{1+\alpha}\left[S_i+\frac{\alpha X_R}{Y}\right]$ $c = K_s D S_i$	(2)
$\mu = D(1+\alpha-\alpha c)$	(3a)	$\mu = D\left(1+\alpha-\alpha\frac{X_R}{\bar{X}}\right)$	(3)

conditions, the value of X fluctuates within practical limits. Any alteration in X_R to maintain constant c will disrupt the system. This was observed experimentally by Ramanathan and Gaudy (49). When X_R was increased for an increase in X to keep c constant, X was increased further and pushed the system further away from steady state, acting directly against the purpose of the control procedure. Therefore, it was reasoned that operation at a constant recycle sludge concentration, X_R, rather than a constant value for c would be more easily facilitated and might exert a steadying influence on the steady state concentration of biological solids.

Writing materials balances for $\bar{X}$ and $\bar{S}$ in the steady state, holding X_R constant and assuming that the concentration of S in the recycle solids was negligible, led to the equations shown in Table I. These equations are those evolved as a consequence of an operational decision to employ X_R rather than c as a constant in the kinetic model. This operational decision and the assumption that S in the recycle flow was very low in comparison to S_i and therefore was negligible were the only changes from the simple model which was developed in Herbert's theoretical analysis of continuous culture systems of the completely mixed type in the steady state. Herbert's purpose was to develop a simple model which could depict the behavior of X and $\bar{S}$ as D was varied. The equations of Herbert represent generally applicable expressions for continuous growths of pure cultures. The model developed herein represents one intended to apply over a range of dilution rates one might reasonably consider for activated sludge processes. In such processes, one is not interested in operating at dilution rates yielding high substrate leakage. Thus, the theoretical discrepancy inherent in the

assumption of constant X_R and negligible substrate concentrations in cell recycle are of less consequence than for general equations of continuous culture. From a theoretical standpoint, as a consequence of assuming zero substrate concentration in the recycle rather than $\bar{S}$, the value of $\bar{S}$ cannot approach S_i as D approaches very high values. Instead, it approaches the value $S_i \left[1/(1 + \alpha)\right]$. It is realized that this is an unrealistic assumption at the extreme upper boundary of D values. However, it can also be seen that these boundary values are outside a range of practical utilization in activated sludge processes. Concerning the assumption of constant X_R at very high dilution rates, the value of $\bar{X}$ would approach $X_R\left[\alpha/(1 + \alpha)\right]$, there would be no new growth, and the only cells in the aeration tank would be those due to recycle flow. Thus, at extremely high dilution rates, the assumption of constant X_R is unrealistic. However, in the near and intermediate future, the major challenge in the area of aerobic biological treatment of organic wastewaters does not lie in finding ways to increase to unrealistically high values the dilution rates at which activated sludge processes can be operated, but in gaining better operational and kinetic understanding of the process in order to increase the reliability of biological efficiency for secondary treatment and increase the organic loadings which can be successfully handled. High dilution rates would result in inefficient clarification due to lack of flocculation as well as low biochemical efficiency at higher loading (S_i) conditions. Such high dilution rates would also make the system very unstable even under mild shock load situations, either quantitative or hydraulic. Thus, operation at very high dilution rates is of little practical significance and the theoretical weakness at high values of D of the kinetic model herein studied

does not militate against the applicability of this operational model for activated sludge processes.

A computational program was set up to determine the behavior of the kinetic equations for $\bar{S}$ and $\bar{X}$ of this model as the biological parameters, maximum specific growth rate, μ_{max}, saturation constant, K_s, and cell or sludge yield, Y, as well as the engineering constants, hydraulic recycle rate, α, and recycle solids concentration, X_R, were varied. These results have been reported and the kinetic consequences and ramifications of the equation discussed (1).

The variation in yield values has been of concern to the proposers of this new operational model. It has been reported by engineers as well as by microbiologists that growth rate is one of the factors which affect the cell yield value. Analytical equations have been suggested for correlating the growth rate, μ, cell yield, Y, and the maintenance or decay coefficient, k_d. In order to account for the variability in cell yield in the past, two methods have been adopted by various investigators. Either a constant yield and a decay coefficient are included in materials balance equations, or yield is considered as a variable of the system, depending on the operational conditions. In the viewpoint of the author, the former method offers a more practical approach as well as one more closely associated with the theory of continuous culture. It allows one to retain the "true cell yield," Y, as a property of the biomass rather than a joint property of the biomass and the operation conditions.

It was of interest to see the effect of an additional biological constant, i.e., the maintenance energy coefficient, on the steady state equations for $\bar{X}$ and $\bar{S}$ on the model employing constant X_R. Thus,

derivation of new steady state equations including k_d was undertaken. The boundary conditions and assumptions made in deriving the equations were precisely the same as before, except for the inclusion of k_d. When a term for decay was included in the materials balance for solids, the following equation was obtained.

$$\frac{dX}{dt} = DX_R + \bar{X} - D(1 + \alpha)\bar{X} - k_d\bar{X} \tag{4}$$

Rate of change in X = recycle + growth - outflow - decay.

Assuming the rate of change in solids concentration at steady state as zero, $\frac{dX}{dt} = 0$, equation (4) reduces to

$$\mu = D\left[1 + \alpha - \alpha\frac{X_R}{\bar{X}}\right] + k_d \tag{5}$$

From Monod's equation, it follows

$$\bar{S} = \frac{K_s\mu}{\mu_{max} - \mu} \tag{6}$$

Substituting equation (5) for μ in equation (6), equation (7) is obtained:

$$\bar{S} = \frac{K_s\left[D\left(1 + \alpha - \alpha\frac{X_R}{\bar{X}}\right) + k_d\right]}{\mu_{max} - D\left[1 + \frac{\alpha X_R}{\bar{X}}\right] + k_d} \tag{7}$$

A materials balance for substrate yields

$$\frac{dS}{dt} = DS_i - \mu X/Y - D(1 + \alpha)\bar{S} \tag{8}$$

Rate of change in S = inflow - utilization - outflow

Again, by assuming $\frac{dS}{dt} = 0$ at steady state

$$\bar{X} = \frac{XD}{\mu}\left[S_i - (1 + \alpha)\bar{S}\right] \tag{9}$$

Substituting equation (5) for μ in equation (9), equation (10) is obtained:

$$\bar{X} = \frac{YD\left[S_i - (1 + \alpha)\bar{S}\right] + \alpha X_R D}{D(1 + \alpha) + k_d} = \frac{Y\left[S_i - (1 + \alpha)\bar{S}\right] + \alpha X_R}{1 + \alpha + (k_d/D)} \tag{10}$$

Substituting equation (10) for $\bar{X}$ in equation (7) leads to a quadratic expression for $\bar{S}$ in terms of α, X_R, μ_{max}, Y, D, and k_d, of the form

$$aS^2 + b\bar{S} + c = 0 \tag{11}$$

where

$$a = \mu_{max} - (1 + \alpha)D + k_d$$

$$b = D\left[S_i - (1 + \alpha)K_s\right] - \frac{\mu_{max}}{1 + \alpha}\left[S_i + \frac{\alpha X_R}{Y}\right] - k_d\left[\frac{S_i}{1 + \alpha} + K_s\right]$$

$$c = K_s D\, S_i + \frac{k_d}{1 + \alpha} K_s\, S_i$$

From equation (11) it can be seen

$$S = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{12}$$

An equation to predict the amount of excess sludge produced was derived by writing a mass balance around the clarifier (Figure 1):

$$(1 + \alpha)D\alpha\bar{X} = DX_R + \frac{F_w}{V} X_R + DXe \qquad (13)$$

If the settling tank performs efficiently, the solids in the effluent can be considered as negligible compared to solids in the system. By this assumption it is seen that equation (13) reduces to

$$(1 + \alpha)D\bar{X} = D\alpha X_R + \frac{X_w}{V} \qquad (14)$$

where $X_w = F_x X_R$. By rearranging the terms of equation (14), equation (15) can be obtained:

$$X_w = V\bar{X}D\left(1 + \alpha - \alpha\frac{X_R}{\bar{X}}\right) \qquad (15)$$

Substituting μ for $D\left(1 + \alpha - \alpha\frac{X_R}{\bar{X}}\right)$ in equation (15)

$$X_w = V\bar{X}\mu \qquad (16)$$

Equation (16) predicts excess sludge produced per day. However, it will be of more practical use if it is divided by flow to get the sludge produced per unit flow. This results in equation (17):

$$X_w = \frac{\mu X}{D} \qquad (17)$$

From equation (17) it is seen that the specific growth rate, μ, is the total amount of cells wasted or produced per unit volume divided by the cell concentration per unit volume in the aeration basin. It is pointed out that the reciprocal of this expression is defined as the cell age or mean cell residence time, Θ_c.

$$\Theta_c = \frac{1}{\mu} = \frac{\bar{X}}{X_w D} \qquad (18)$$

The modified model equations employing constant X_R are shown in Table II.

The method of approach for design and operation of the activated sludge process outlined in this section offers many advantages over the other methods reviewed in Chapter II. The main advantage of the model proposed herein is that an operational parameter for the control of the process is inherent in design. The operating engineer stands little chance of operating the system steadily and reliably unless the means for exerting control over selectable variables are provided for by the design engineer. Conversely, if they are provided in the design, they are of little avail unless used by the operating engineer. Unlike the parameters of control mentioned in other models (e.g., F/M or Θ_c, discussed in the literature review section), the controlling parameter X_R in this model was felt to be easily measured or estimated in a short time. Also, it was felt that the automatic control of X_R might be possible without employing sophisticated instrumentation. The importance of controlling recycle solids concentration in order to achieve and maintain a steady state has been realized by some workers, but its control has been neglected or X_R has been assumed as constant. From field experience in treatment plants, it is known that this assumption is not valid unless X_R is made a constant. One of the methods suggested for controlling or holding X_R constant is to control the sludge blanket level in the final clarifier. It is well known that the sludge blanket level is a function of the amount of solids in the system, settling characteristics of the microorganisms, which are subject to fluctuations at frequent

TABLE II

STEADY STATE EQUATIONS INCLUDING MAINTENANCE ENERGY COEFFICIENT FOR THE MODEL EMPLOYING CONSTANT X_R

$$\bar{X} = \frac{Y\left[S_i - (1+\alpha)\bar{S}\right] + \alpha X_R}{(1+\alpha) + k_d/D} \tag{10}$$

$$\bar{S} = \frac{-b \pm \sqrt{b^2-4ac}}{2a}$$

$$a = \mu_{max} - (1+\alpha)D + k_d \tag{12}$$

$$b = D\left[S_i - (1+\alpha)K_s\right] - \frac{\mu_{max}}{1+\alpha}\left[S_i + \frac{\alpha X_R}{Y}\right] - k_d\left[\frac{S_i}{1+\alpha} + K_s\right]$$

$$c = K_s D S_i + \frac{k_d}{1+\alpha} K_s \cdot S_i$$

$$X_w = V\bar{x}\mu \text{ mg/day} \tag{16}$$

$$= \mu\bar{x}/D \text{ mg/l (to convert to mg/day multiply Eq. 17 by F)} \tag{17}$$

$$\mu = X_w/V\bar{x} = \frac{1}{\text{sludge age}} = \frac{1}{\theta_c} \text{ (where } X_w \text{ is given in mg/day)} \tag{19}$$

$$= \frac{X_w D}{\bar{X}} = \frac{1}{\text{sludge age}} \text{ (where } X_w \text{ is given in mg/l)} \tag{20}$$

intervals, and rate of withdrawal of sludge from the bottom of the clarifier which, in turn, depends on α. The independent control of α without control of X_R is ineffective. An increase or decrease of pumping rate of sludge will not ensure a proportional change in the total amount of cells being returned to the aeration basin. Thus, when X_R is maintained constant in a sludge consistency tank, there are three independent hydraulic parameters available for control: α, X_R, and D (see Figure 1). The other models do not have such a possibility, although it is assumed they do. Various combinations of α, X_R, and D, within practical limits, can be chosen to achieve the desired results. This provides the designer with an opportunity to consider the economic and operational aspects without having to sacrifice the efficiency of treatment. The approach taken in proposing this model considers all of the biochemical aspects, μ_{max}, K_s, Y, and k_d, and all of the hydraulic aspects, α, X_R, D, and S_i. This is an engineering adaptation of the continuous culture theory and is closer to it than other models. It remained, however, to be seen if this model could be easily "operated," and if the performance could be predicted using the biological and operations parameters which the steady state equations indicate control X and S; thus, the experimental program described in the next chapter was undertaken. Before presenting the materials and methods employed, it is appropriate to delineate another feature of the proposed design and operational approach.

This model can be employed to accommodate other modes of control proposed. The F/M ratio can be easily controlled by adjusting X_R or α, which brings about an increase or decrease in X which, in turn, controls F/M. The constant X_R method has direct control on X as opposed

to the sludge wastage control (Θ_c method), which is an indirect method of arriving at a steady state value for aeration tank solids concentration.

CHAPTER IV

MATERIALS AND METHODS

A laboratory pilot plant was operated to study the behavior of the mathematical model. The experimental setup of the continuous flow pilot plant is shown in Figure 2. The volume of aeration tank #1 was two liters, and the volume of the settling tank was five liters. A sludge consistency tank (aeration tank #2) of one-liter capacity was used in the recycle line. Cells were grown in batch reactors using the primary effluent from the municipal waste treatment plant at Stillwater, Oklahoma, as initial inoculum. After growing sufficient cells, continuous flow operation was started. The composition of feeds employed in this study is shown in Tables III, IV, and V. The synthetic waste was pumped to aeration tank #1 by a dual positive displacement pump (Minipump, Milton Roy Model MM1-B-96R) at a predetermined rate to give the desired mean hydraulic retention time, $\bar{t}$ ($\bar{t} = V/F$). Alternately, each of the feed lines was cleaned by pumping a one-percent solution of Clorox in distilled water. Thus, one of the lines was disinfected while the other was being used. This procedure adequately prevented growth in the feed line. The air supply was adjusted to provide adequate mixing of the reactor contents and maintain a dissolved oxygen concentration level of above 90 percent of saturation value at the laboratory temperature. The system was checked for complete mixing, using procedures described by Komolrit and Gaudy (51). The mixed liquor from

Figure 2. Activated Sludge Pilot Plant for Operation With Constant X_R

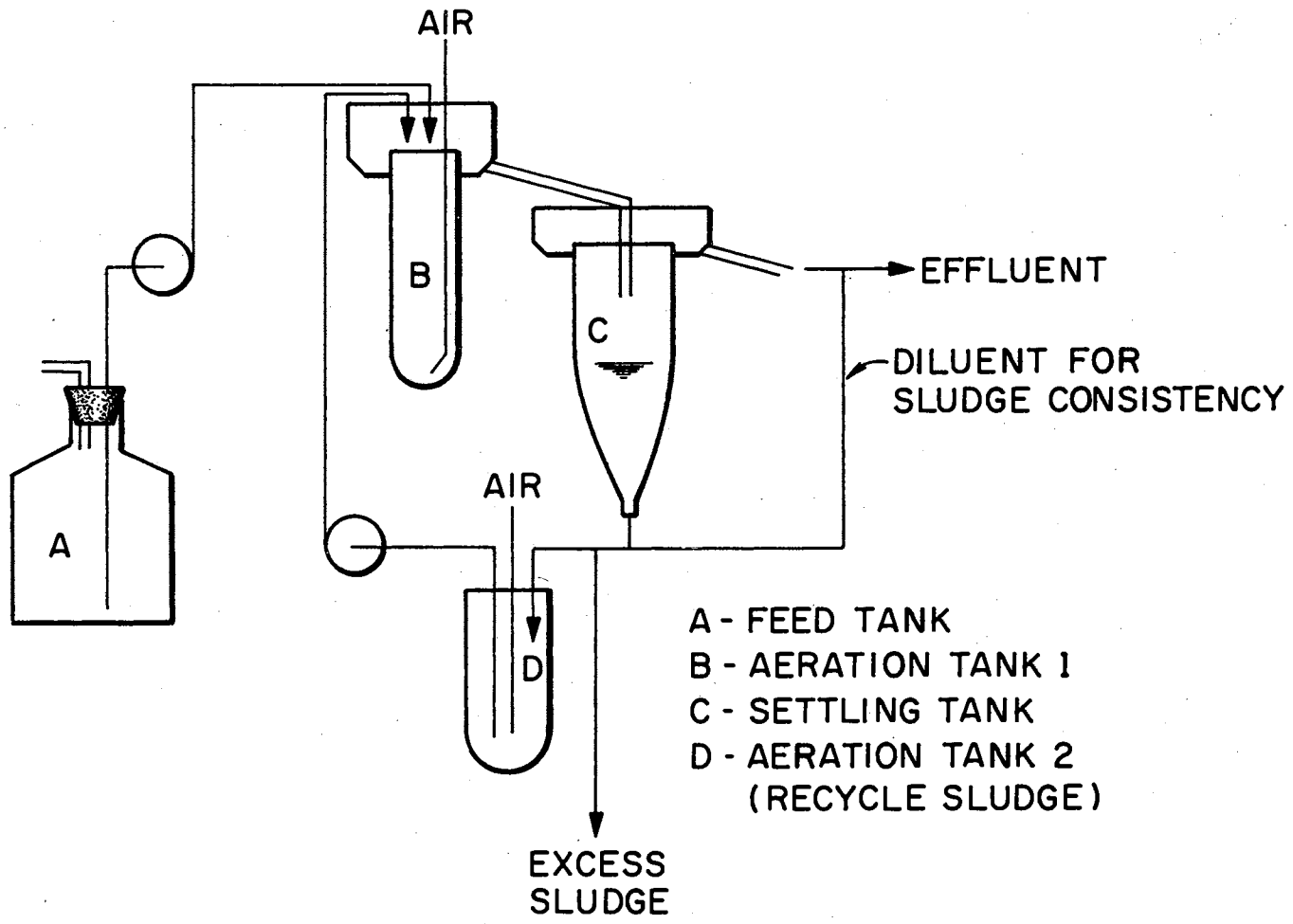

AIR
B
C
EFFLUENT
DILUENT FOR
SLUDGE CONSISTENCY
A
AIR
D
A - FEED TANK
B - AERATION TANK 1
C - SETTLING TANK
D - AERATION TANK 2
(RECYCLE SLUDGE)
EXCESS
SLUDGE

TABLE III

COMPOSITION OF GROWTH MEDIUM PER 500 mg/l GLUCOSE

Constituents	Amount
Glucose	500 mg/l
Ammonium sulfate $(NH_4)_2SO_4$	250 mg/l
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	50 mg/l
Ferric chloride, $FeCl_3 \cdot 6H_2O$	0.25 mg/l
Manganous sulfate, $MnSO_4 \cdot H_2O$	5.0 mg/l
Calcium chloride, $CaCl_2$	3.75 mg/l
1 M phosphate buffer solution, pH 7.0	5 ml/l
Tap water	50 ml/l

TABLE IV

COMPOSITION OF GROWTH MEDIUM PER 1000 mg/l GLUCOSE

Constituents	Amount
Glucose	1000 mg/l
Ammonium sulfate $(NH_4)_2SO_4$	500 mg/l
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	100 mg/l
Ferric chloride, $FeCl_3 \cdot 6H_2O$	0.5 mg/l
Manganous sulfate, $MnSO_4 \cdot H_2O$	10.0 mg/l
Calcium chloride, $CaCl_2$	7.5 mg/l
1 M phosphate buffer solution, pH 7.0	10 ml/l
Tap water	100 ml/l

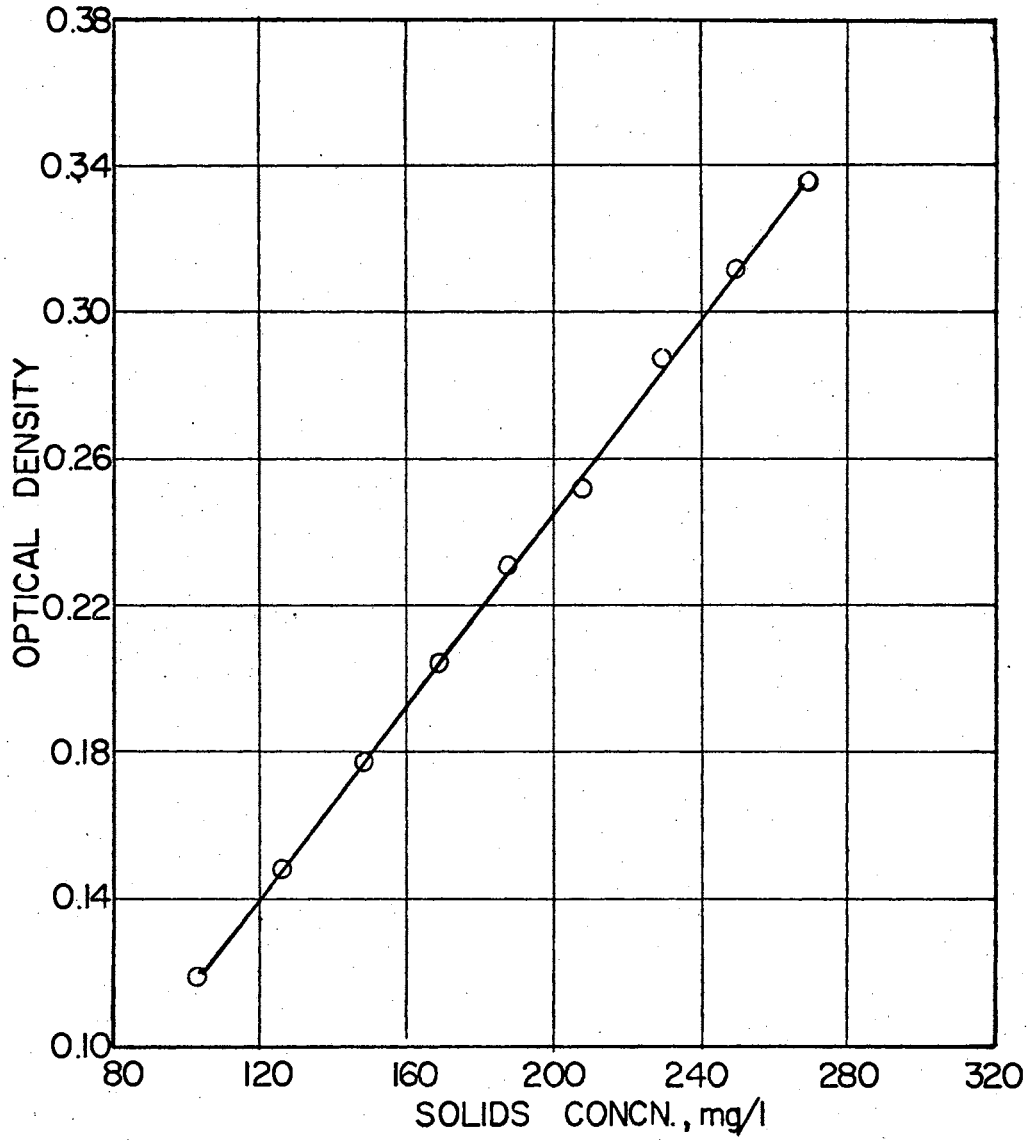
TABLE V

COMPOSITION OF GROWTH MEDIUM PER 2000 mg/l GLUCOSE

Constituents	Amount
Glucose	2000 mg/l
Ammonium sulfate $(NH_4)_2SO_4$	1000 mg/l
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	200 mg/l
Ferric chloride, $FeCl_3 \cdot 6H_2O$	1.0 mg/l
Manganous sulfate, $MnSO_4 \cdot H_2O$	20.0 mg/l
Calcium chloride, $CaCl_2$	15.0 mg/l
1 M phosphate buffer solution, pH 7.0	20.0 ml/l
Tap water	200 ml/l

the reactor overflowed into the settling tank where the detention time was 16 hours. The quiescent conditions in the settling tank facilitated solid-liquid separation by gravity. Every 12 hours, the settled sludge was withdrawn from the bottom of the clarifier. A concentrated sample of sludge was diluted to a range in which optical density was directly proportional to concentration in mg/l, and the OD values were compared to the previously prepared standard curve. This curve was obtained by taking samples of various solids concentrations and measuring the optical density in a spectrophotometer. These samples were analyzed for solids concentration by membrane filter technique (52). The optical density was plotted against the suspended solids concentration in mg/l. A typical plot of this type is shown in Figure 3. As can be seen from this figure, the spectrophotometer reading is linear and most reliable between 120 and 250 mg/l suspended solids concentration. This curve was checked for its reliability at frequent intervals by repeating the above mentioned procedure. From the OD reading of the diluted sample, the approximate suspended solids concentration of the thickened sludge was calculated. The sludge was then further diluted to obtain the desired X_R concentration. A required volume of this sludge was placed in the sludge consistency tank, from where it was pumped to aeration tank #1 by a Sigmamotor "finger" pump, Model T-8. The contents of the sludge consistency tank were aerated to keep them aerobic and mixed. The ratio of the recycle flow to the feed flow, α, was 0.25. The sludge that was left after placing required amounts in the recycle tank, was the excess sludge produced as a result of substrate removal. The parameters monitored during the steady state period are the following:

Figure 3. Relationship Between Optical Density and Solids Concentration


0.38
0.34
0.30
0.26
0.22
0.18
0.14
0.10
OPTICAL DENSITY
80
120
160
200
240
280
320
SOLIDS CONCN., mg/l

1. Feed
   a) COD (daily)
   b) NH_3-N (periodically)
2. Effluent
   a) Filtrate
      1) COD (daily)
      2) NH_3-N (periodically)
      3) NO_3-N (periodically)
      4) NO_2-N (periodically)
      5) Glucostat (periodically)
   b) Supernatant
      1) COD (daily)
      2) Suspended solids (daily)
      3) BOD (periodically)
3. Aeration tank mixed liquor
   a) Biological solids (daily)
   b) Dissolved oxygen (daily)
   c) pH (daily)
4. Sludge Consistency Tank
   a) Suspended solids (daily)
   b) Filtrate COD (daily)
   c) Protein (periodically)
   d) Carbohydrate (periodically)
   e) Oxygen uptake (periodically)

During each steady state, continuous run, cells from aeration tank #1 were employed as initial inoculum for batch experiments to determine

μ_{max}, K_s, and Y_B, using methodologies described previously (15)(24)(53). The medium used for batch growth experiments was the same as that employed in continuous flow studies. The cells were grown in 250-ml Erlenmeyer flasks with glucose concentrations ranging from 100 to 1000 mg/l as the limiting nutrient. All of the flasks received the same amount of initial inoculum from the continuous flow unit to bring the optical density to approximately 0.046 (percent transmission = 90 per cent). The total volume of sample per flask in these experiments was 40 ml. These flasks were placed on an oscillating shaker (Eberbach), which was adjusted to give 100-110 oscillations/min. The growth curve was obtained by measuring OD at frequent intervals. The initial and final suspended solids and substrate concentration were measured (52), which allowed determination of the batch cell yield, Y_B. The μ_{max} and K_s were calculated by plotting the data obtained from batch growth experiments. The plotting and calculation technique will be given in the results section.

At the end of the steady state data collecting period on each run, the recycle was stopped and the system was run as a once-through chemostat to obtain the yield, Y_c. During this time, the solids and substrate concentration in the reactor were monitored twice a day, when the new steady state was reached.

At the end of two of the nine steady state runs, the system was subjected to a three-fold increase in influent feed concentration--from 500 to 1500, and from 1000 to 3000 mg/l--to observe the response of the model to shock loads. The shock load was applied for 36 hours; then the units were shut off. During this period, samples were taken at frequent intervals at key stations in the pilot plant to follow the

response of the system. The parameters monitored were the solids concentration in the aerator, effluent solids, COD, and carbohydrate (anthrone) COD. The procedures adopted for these tests are referenced in the analytical procedures section of this chapter.

For the studies employing pure cultures, a culture of Escherichia intermedia was isolated from municipal sewage. This culture was identified by extensive microbiological tests (54). A once-through chemostat was employed for this investigation, since recycling of cells would not be feasible without possible contamination if simple laboratory procedures were used. The experimental setup was as shown in Figure 4. The volume of the chemostat was one liter. The termperature of the chemostat contents was kept at 30°C by a constant waterbath. The composition of the medium used for growing cells is given in Table VI. Glucose was the limiting carbon and energy source. As can be noted, the composition shown in Table VI is essentially the same as that in Table IV, except for the yeast extract. Each component of the medium was dissolved in a portion of water and autoclaved separately. The solutions were mixed aseptically after cooling.

The culture isolated from sewage was grown in a shaker in a flask containing the growth medium. The resulting suspension was then transferred to the chemostat filled with the same medium, and aerated over night. The unit was turned to continuous flow operation after some growth was observed. Experiments were conducted at dilution rates of 0.17 hr^{-1} and 0.042 hr^{-1} (detention times six and 24 hours). Samples of the effluent from the chemostat were analyzed for cell concentration and substrate in the filtrate (52). The cell yield was calculated from these data. During operation at each dilution rate, small amounts of

Figure 4. Once-through Chemostat Employed in Pure Culture Studies

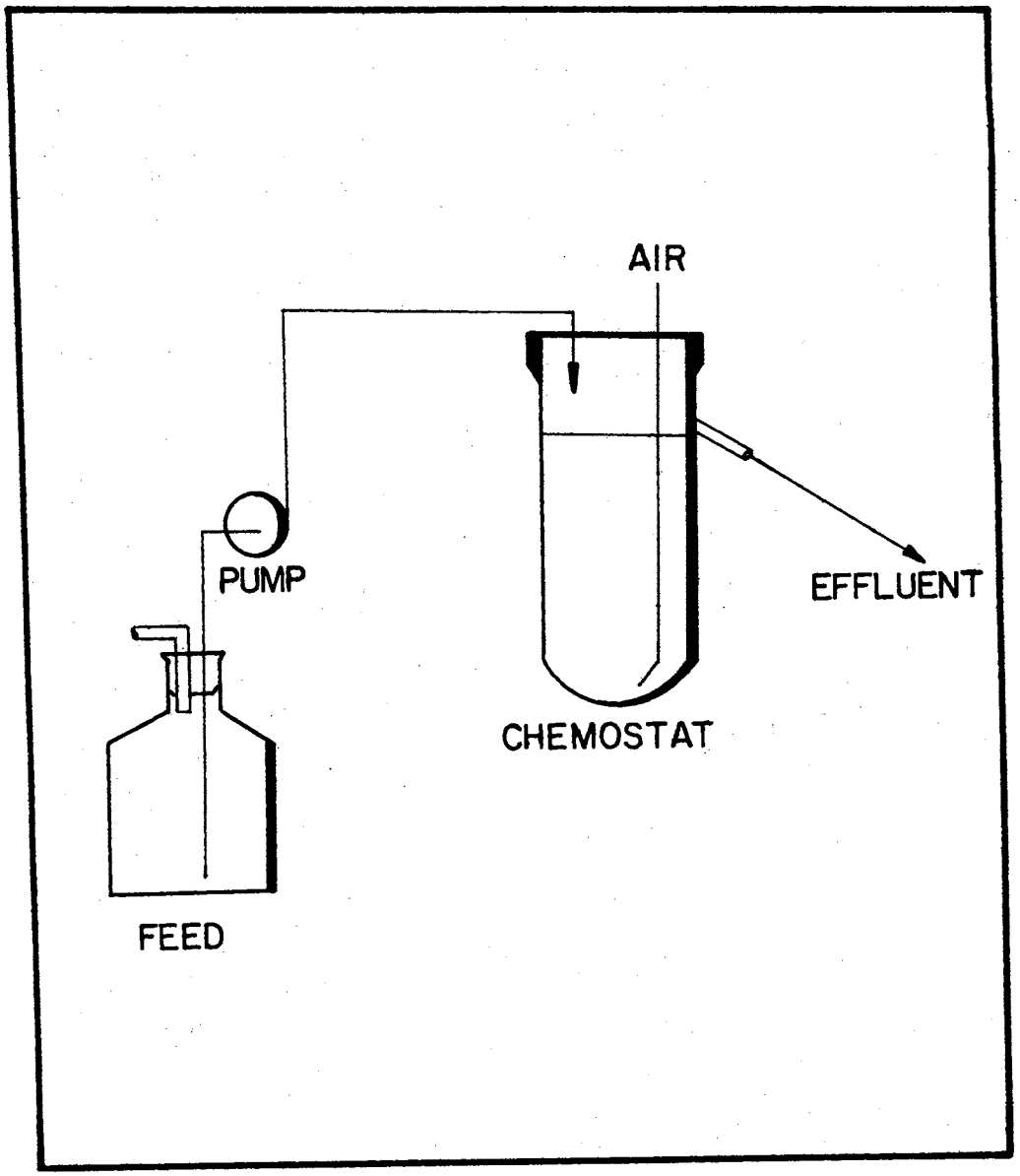

AIR
PUMP
EFFLUENT
CHEMOSTAT
FEED

TABLE VI

COMPOSITION OF GROWTH MEDIUM PER 1000 mg/l GLUCOSE EMPLOYED IN PURE CULTURE STUDIES

Constituents	Amount
Glucose	1000 mg/l
Ammonium sulfate $(NH_4)_2SO_4$	500 mg/l
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	100 mg/l
Ferric chloride, $FeCl_3 \cdot 6H_2O$	0.5 mg/l
Manganous sulfate, $MnSO_4 \cdot H_2O$	10.0 mg/l
Calcium chloride, $CaCl_2$	7.5 mg/l
1 M phosphate buffer, pH 7.0	10 ml/l
Tap water	100 ml/l
Yeast extract	1 mg/l

chemostat effluent were employed as inocula for batch growth studies. Contamination of the chemostat content was checked by frequent microscopic examination of wet mounts and plating the culture on EMB and nutrient agar. When contamination occurred, the unit was shut down, cleaned, sterilized, and re-inoculated with pure stock culture.

Analytical Procedures

1. Chemical Oxygen Demand

The COD test was performed to measure the total organic concentration in various samples. The procedure adopted was as described in Standard Methods (52). Silver sulfate and mercuric sulfate were used for all COD determinations.

2. Suspended Solids Concentration

This test was performed to measure the cell concentration in various samples. The pore size of the filters was 0.45 μm (Millipore Filter Corp., Bedford, Mass.). Samples with high cell concentration were first centrifuged and then filtered for more rapid determinations. The general procedure was as given in Standard Methods (52).

3. Nitrogen

Ammonia nitrogen, NH_3-N, concentration in the influent and effluent was determined by a method developed by Niss and described by Ecker and Lockhart (55). Nitrite and nitrate-nitrogen determinations were in accordance with Standard Methods (52).

4. Biochemical Oxygen Demand

The azide modification of the Winkler Method (52) was employed for periodic determination of BOD of the effluent supernatant from the pilot plant.

5. Protein and Carbohydrate

Periodic analyses of sludge for protein and carbohydrate content were performed, as outlined by Gaudy (56).

6. Glucostat

Spot checks for glucose concentration in the effluent filtrate were made using reagents manufactured by Worthington Biochemical Corporation, adopting the procedures described by Ramanathan, Gaudy, and Cook (57).

7. Oxygen Uptake

The oxygen uptake rate of the sludge from the recycle tank was measured at regular intervals during continuous runs using the Warburg apparatus by employing the method outlined in "Manometric Techniques" by Umbreit, et al. (58).

In addition to the above mentioned analyses, regular microscopic examinations of the reactor mixed liquor and effluent were performed to follow changes in predominance and morphological form of microbes. Dissolved oxygen concentration was measured using a Weston & Stack oxygen analyzer; the pH was measured by a Beckman Expandomatic SS-2 pH meter.

CHAPTER V

RESULTS

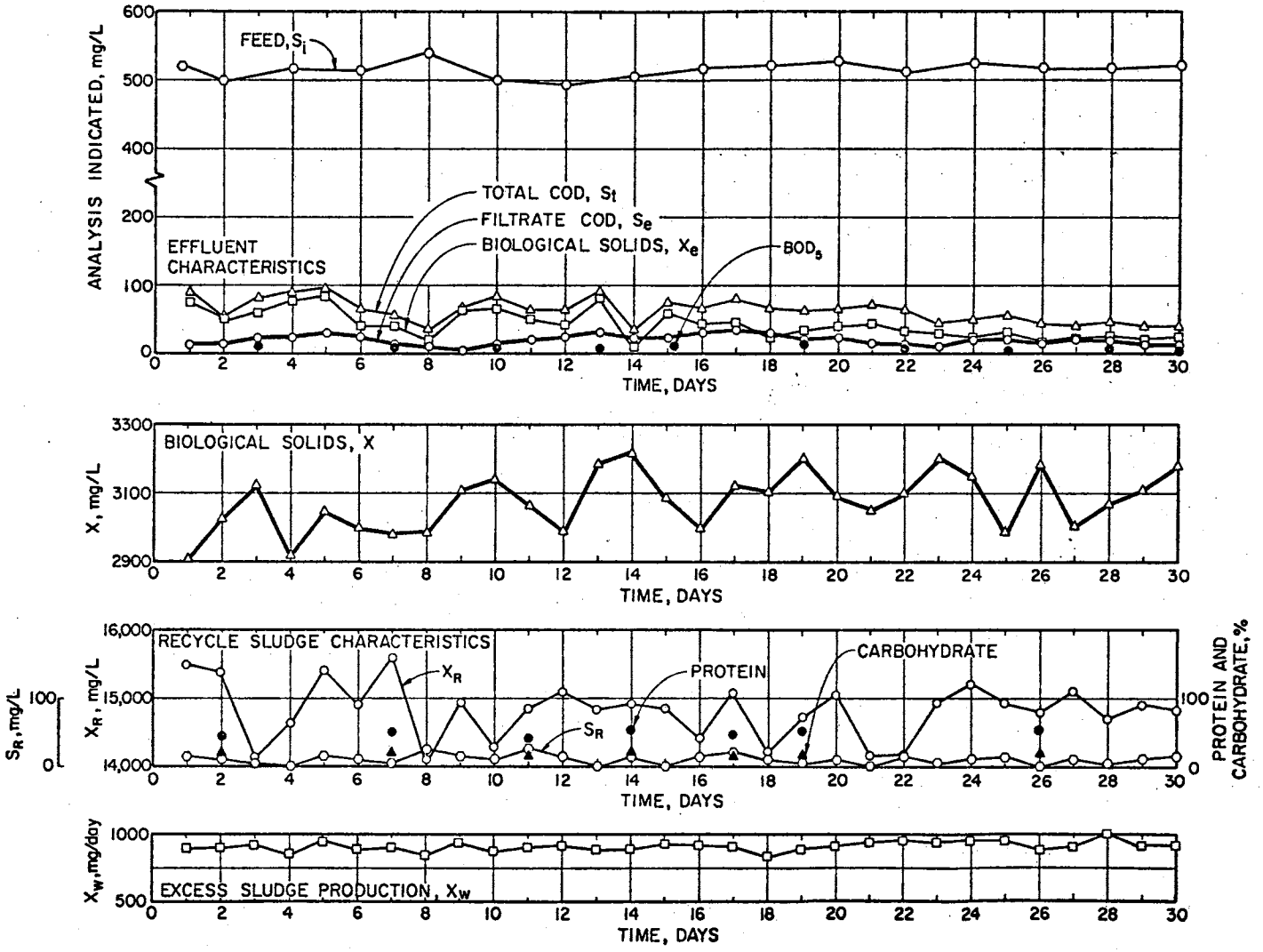
In order to evaluate the operational stability of the model, the pilot plant was operated with different influent substrate loadings, S_i, at various recycle solids concentrations, X_R. The S_i loadings employed were 500, 1000, and 2000 mg/l of glucose, and the values of X_R employed were 5000, 10,000, and 15,000 mg/l. The steady state data obtained during the continuous flow run with 500 mg/l glucose as feed and 15,000 mg/l X_R are given in Table VII. The main parameters indicating the performance characteristics are plotted in Figure 5 for this run. Also shown are the relatively few determinations of BOD_5 on clarifier supernatant, and protein and carbohydrate content of the sludge. The COD of the influent ranged from 490 to 540 mg/l with an average of 520 mg/l. The effluent characteristics as measured by filtrate COD, S_e, was excellent; the mean S_e was 20 mg/l providing 96 percent removal of the substrate. The suspended solids concentration in the effluent in this steady state run was higher than for other runs, and this resulted in lower process efficiency on the basis of total COD in the effluent. However, the BOD_5 of the effluent, i.e., the parameter used most often by sanitary engineers to express the effluent quality, was low--8.0 mg/l. The range of values for filtrate COD, S_e, was 5 mg/l to 30 mg/l, While X_e varied between 10 and 80 mg/l. In general, the system provided very satisfactory treatment and delivered effluent of high

TABLE VII

STEADY STATE DATA AT S_i = 500 mg/l GLUCOSE, X_R = 15,000 mg/l

Days	X mg/l	X_R mg/l	X_e mg/l	X_w mg/day	S_e mg/l	S_t mg/l	S_R mg/l	BOD_5 mg/l	Glucostat mg/l	Protein %	Carbo. %	Endog. O_2 Uptake mg/gm	NH_3-N Feed mg/l	NH_3-N Eff. mg/l
1	2910	15510	73	890	15	90	15							
2	3036	15370	48	915	15	50	10			45	20	7	55	40
3	3134	14140	60.0	920	25	80	5	10	3					
4	2920	14580	78	870	25	90	0							
5	3052	15380	82	940	30	95	15							
6	3004	14960	40	900	25	65	10			50	19	8	53	40
7	2984	15600	40	915	15	55	5	5	1					
8	2902	14080	20	855	10	35	25							
9	3112	14970	62	940	5	65	15			40	18	6	50	35
10	3140	14260	67	890	15	80	10	7	0					
11	3082	14800	44	910	20	65	25							
12	2988	15080	40	920	25	65	15							
13	3188	14760	80	910	30	90	0	9	1	52	21	5	54	41
14	3216	14860	10	900	25	35	15							
15	3095	14850	65	920	25	75	0							
16	2996	45	910	30	65	15		10	2	45	17	4	55	44
17	3124	15070	45	900	35	80	20							
18	3100	14200	25	840	30	65	10							
19	3215	14700	35	890	20	60	5	15	3					
20	3090	15050	40	920	25	65	10			48	19	6	58	46
21	3045	14170	45	940	15	70	0							
22	3105	14200	32	950	15	65	15	7	2					
23	3205	14950	30	940	10	45	5							
24	3150	15200	25	950	20	50	10							
25	3060	14950	28	950	20	55	15	5	5					
26	3180	14800	15	890	15	45	0			51	21	5	55	40
27	2990	15100	18	915	20	40	10							
28	3070	14700	22	990	20	45	5	10						
29	3110	14890	20	920	15	40	10							
30	3180	14800	25	915	15	40	15	5						

Figure 5. Operational Characteristics of an Activated Sludge Process With Constant X_R of 15,000 mg/l at an S_i of 500 mg/l


ANALYSIS INDICATED, mg/L
FEED, S_i
TOTAL COD, S_t
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X_e
BOD_5
EFFLUENT CHARACTERISTICS
TIME, DAYS
BIOLOGICAL SOLIDS, X
X, mg/L
RECYCLE SLUDGE CHARACTERISTICS
X_R
PROTEIN
CARBOHYDRATE
S_R
S_R, mg/L
X_R, mg/L
PROTEIN AND CARBOHYDRATE, %
EXCESS SLUDGE PRODUCTION, X_w
X_w, mg/day

quality. The biological solids concentration in the aerator varied between 2900 and 3200 mg/l, with a mean of 3082 mg/l. However, from Figure 5 it can be seen that the system was rather steady with respect to X. The X_R values ranged from 14,080 to 15,600 mg/l, and the average was 14,810 mg/l. The COD values for recycle sludge filtrate, S_R, indicate very little substrate was being returned to the aerator with recycle sludge, justifying the basic assumption made in the derivation of steady state equations. Determination for protein and carbohydrate content of the sludge indicated values in the expected range, i.e., protein, 47 percent, and carbohydrate, 20 percent. The bottom graph in Figure 5 shows the daily production of excess sludge. The values varied between 870 and 990 mg/day; it is seen that it remained relatively steady.

The growth curves obtained from batch experiments conducted during this continuous flow run are shown in Figures 6, 7, and 8. The plots shown at the top of these figures are the semilogarithmic plot of the optical density vs time during the growth period. For clarity sake, in all of the batch growth plots, the experimental points are shown as dots. In most of the growth experiments, more frequent optical density readings than those shown in the figure were taken. The initial substrate concentration, S_o, of each flask is shown on the curves. It can be clearly seen that exponential growth existed even at S_o as low as 125 mg/l of glucose.

In the bottom portion of the figure, the points shown are the experimentally observed values of μ at various S_o values. The curve drawn is a plot calculated using the equation

$$\mu = \frac{\mu_{max} S_o}{K_s + S_o}$$

Figure 6. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 15,000 mg/l. Experiment No. 1

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.35 hr^{-1} and 150 mg/l, respectively

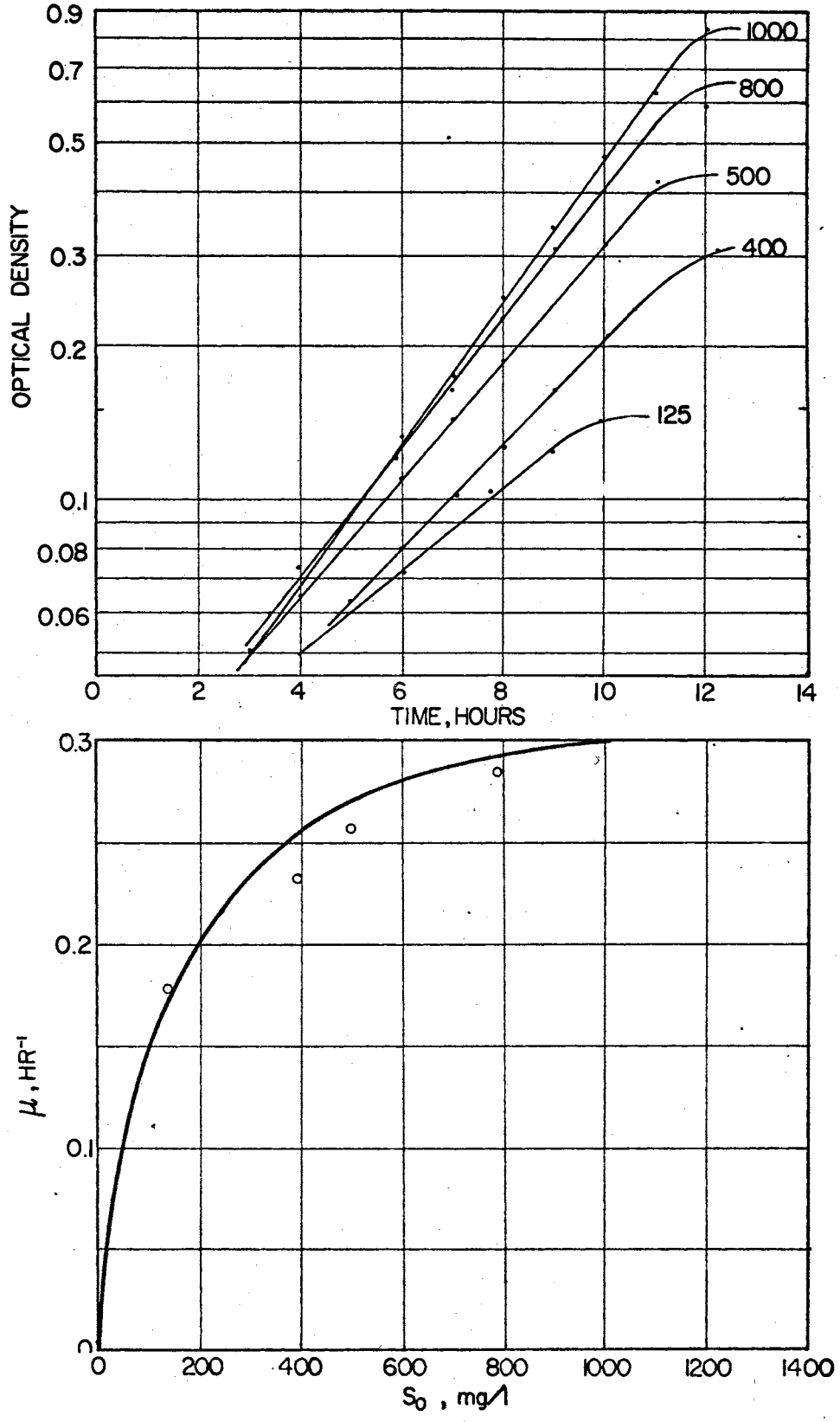
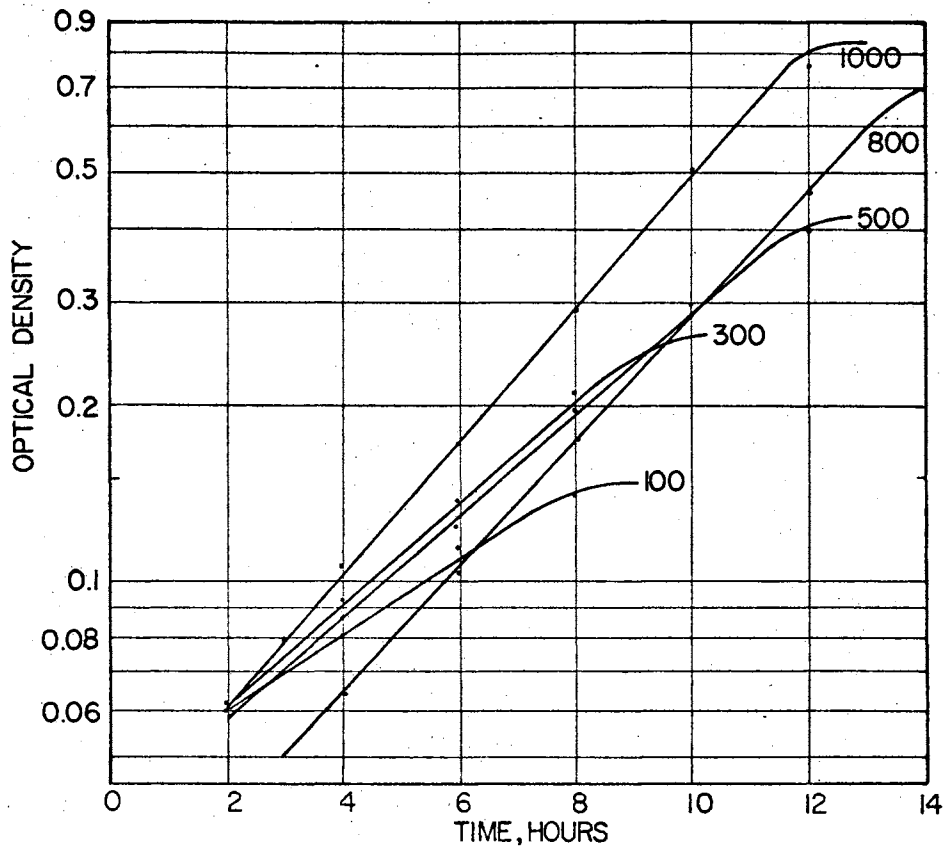

OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
500
400
125
0
2
4
6
8
10
12
14
TIME, HOURS
μ, HR⁻¹
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
S₀ , mg/l

Figure 7. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 15,000 mg/l. Experiment No. 2

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.31 hr^{-1} and 155 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
500
300
100
0
2
4
6
8
10
12
14
TIME, HOURS

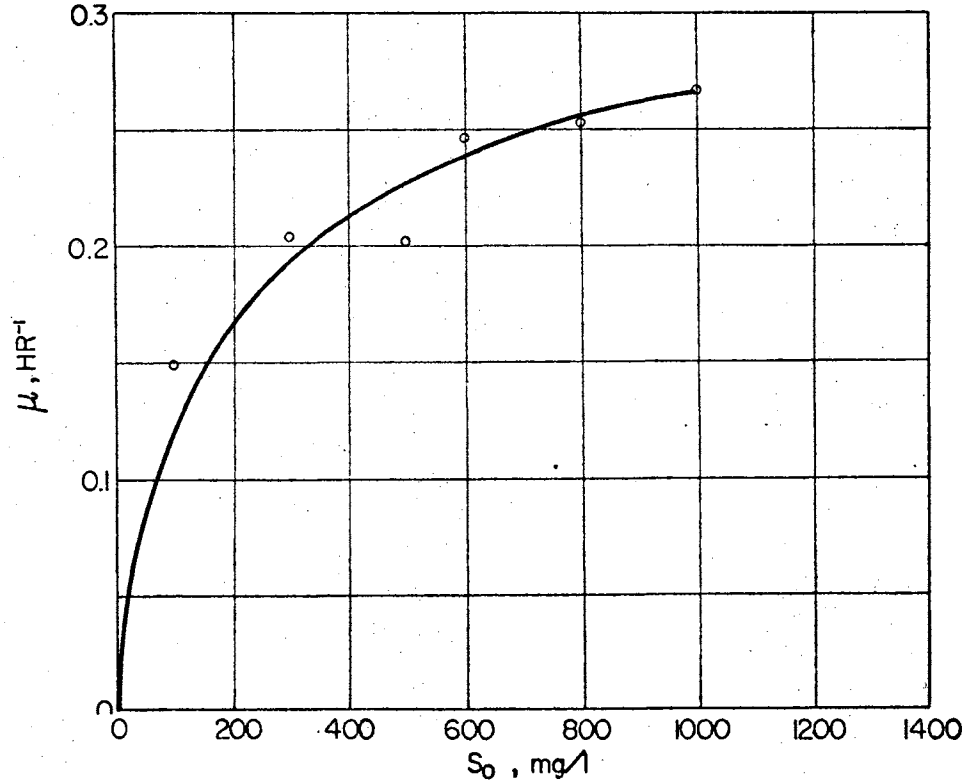
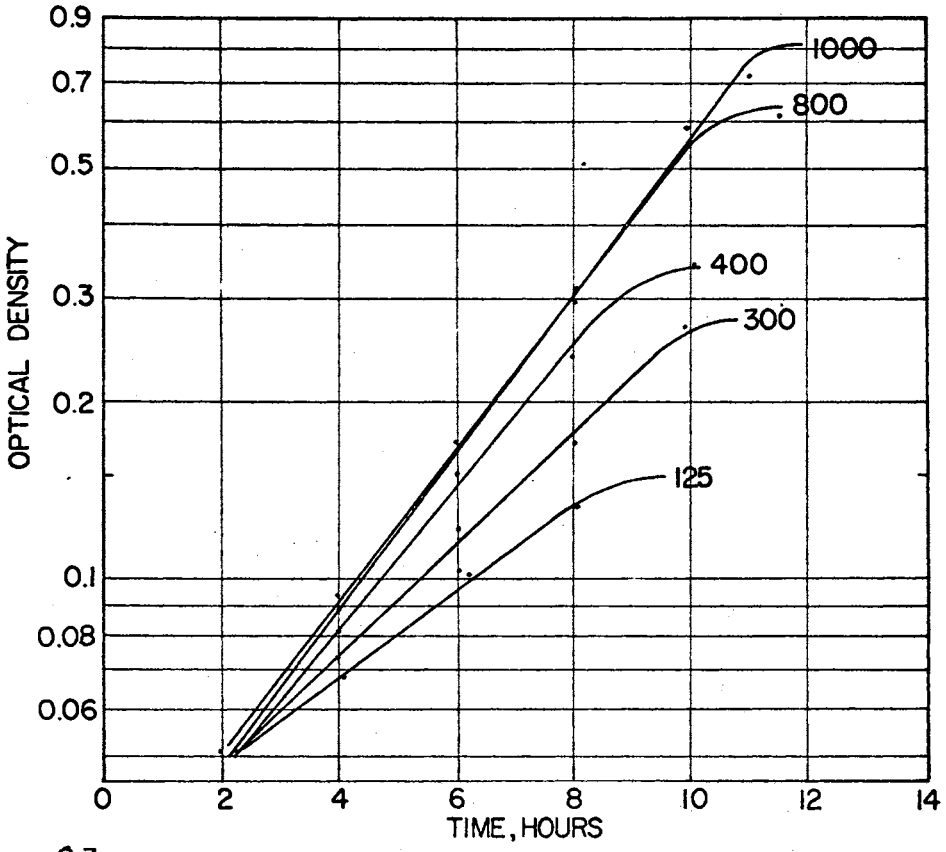
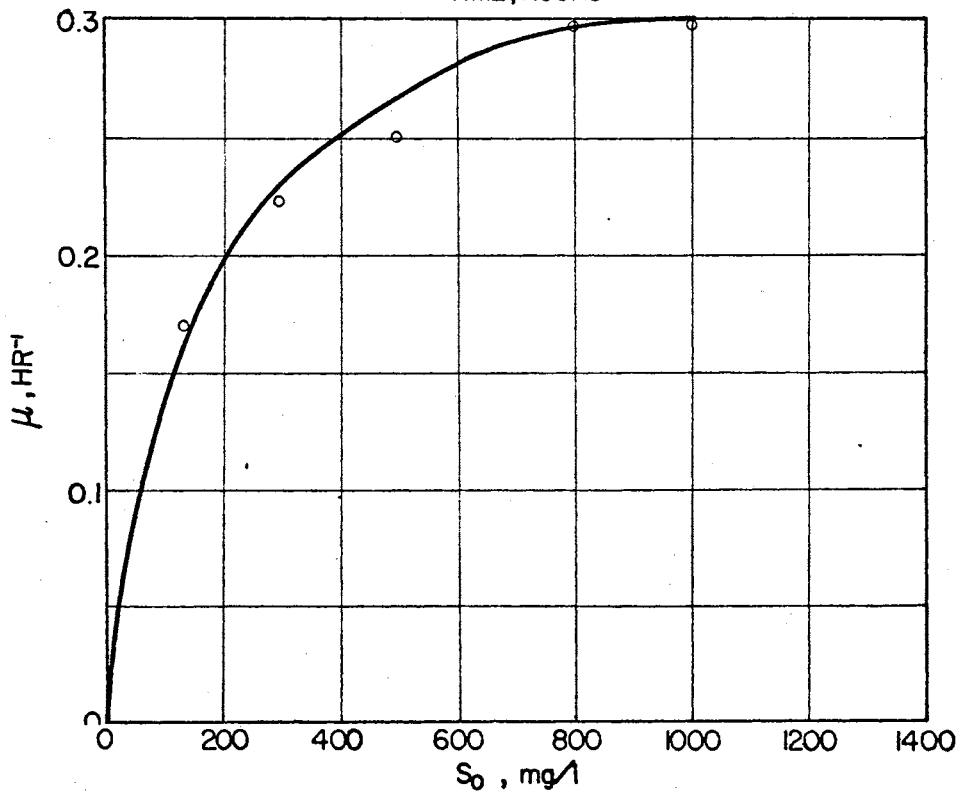

μ, HR⁻¹
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
S₀, mg/l

Figure 8. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 15,000 mg/l. Experiment No. 3

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.34 hr^{-1} and 140 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
400
300
125
0
2
4
6
8
10
12
14
TIME, HOURS


μ, HR⁻¹
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
S₀, mg/l

with values for μ_{max} and K_s obtained from the double reciprocal plot of $1/S_o$ vs $1/\mu$ as shown in Figure 9. It is seen that the observed values compare favorably with calculated values of μ by employing S_o in the Monod equation. The values of μ_{max} and K_s were determined by plotting $1/S_o$ vs $1/\mu$, and employing the equation

$$1/\mu = \frac{K_s}{\mu_{max}} \frac{1}{S_o} + \frac{1}{\mu_{max}}$$

An example plot is shown in Figure 9. The maximum specific growth rate, μ_{max}, observed in these experiments ranged between 0.31 and 0.35 hr^{-1}, and K_s varied between 110 and 150 mg/l.

The data obtained by operating the unit as a once-through system subsequent to stopping the recycle of sludge are shown in Figure 10. The dotted line portion of the solids curve indicates the transient state when solids were being diluted out of the aerator. After this period, a new steady state in biological solids concentrations was reached at approximately 150 mg/l. In order to determine a cell yield value during this period of operation as a once-through process, the substrate concentration, S_e, was also measured; it is shown at the bottom portion of Figure 10. An important observation on cell yield values from batch and continuous flow experiments will be discussed in a later section of this report. It is seen after about 70 hours of operation, the solids concentration in the aerator started increasing and reached a higher level and remained steady at that level for about 40 hours, when the experiment was terminated.

Another S_i loading employed at the same X_R (15,000 mg/l) as the previous run was 1000 mg/l of glucose in the feed. The data obtained

Figure 9. Reciprocal Plot of μ versus S_o to Determine μ_{max} and K_s From Batch Growth Curves

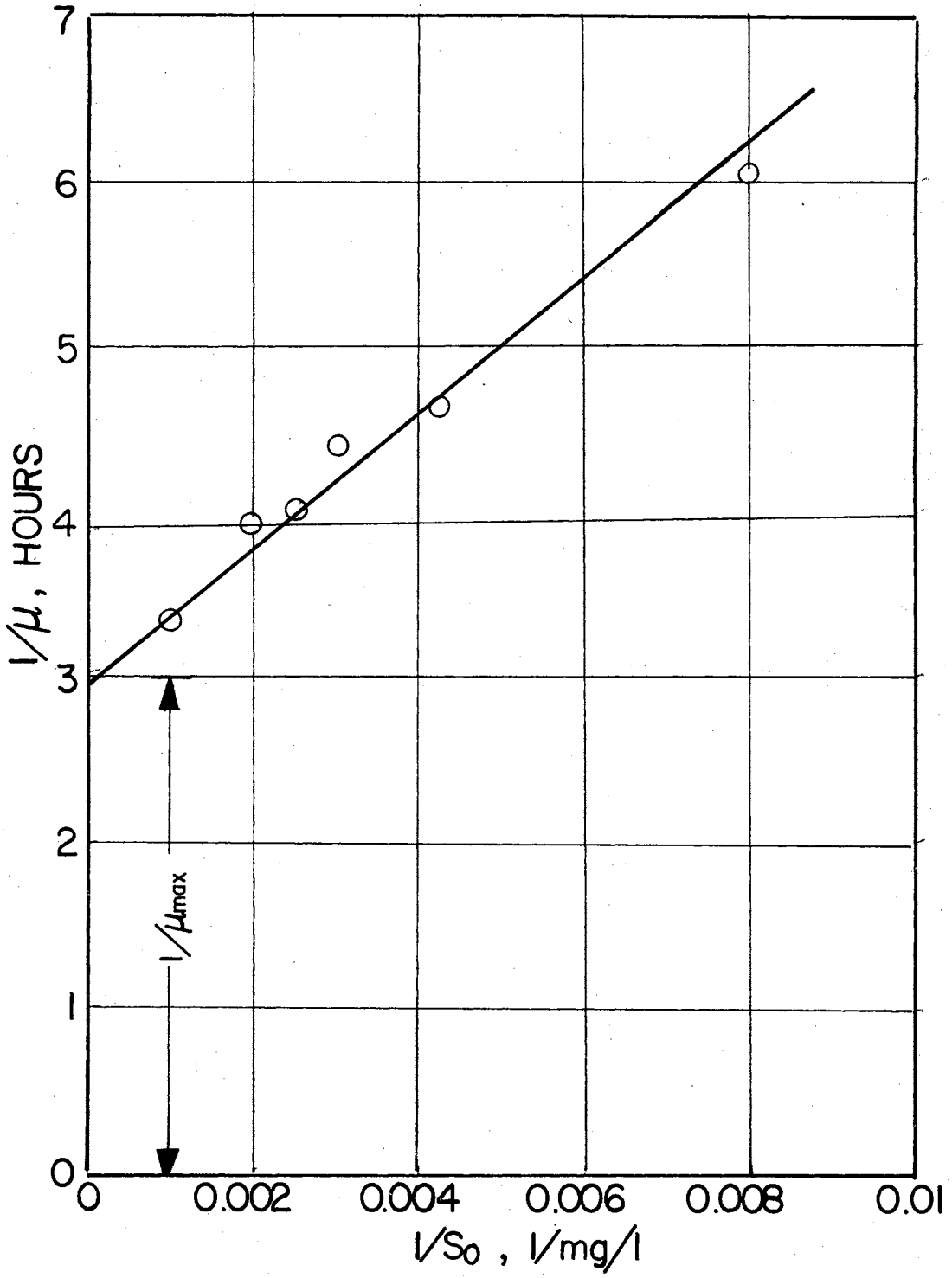
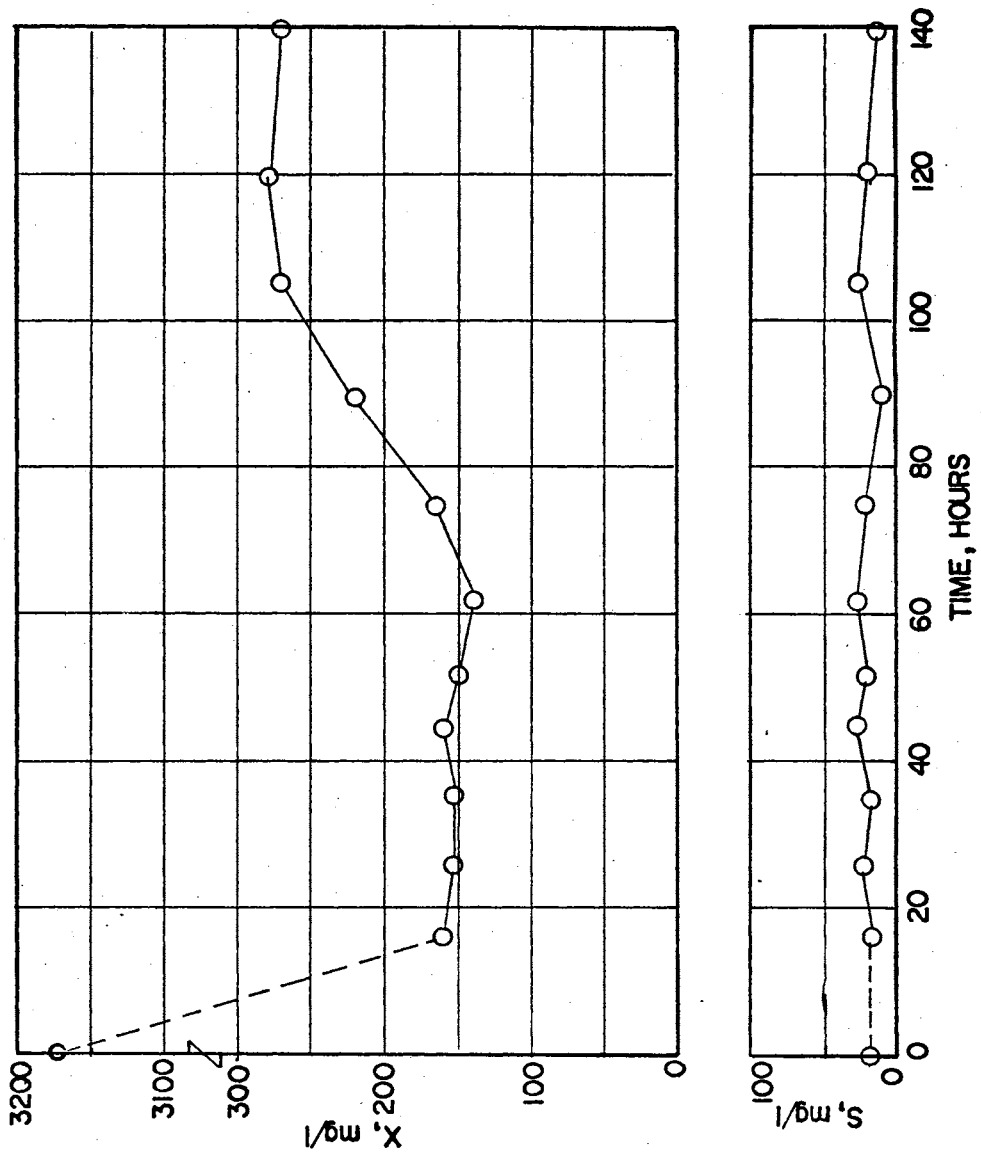

7
6
5
4
3
2
1
0
0
0.002
0.004
0.006
0.008
0.01
1/μ, HOURS
1/Sₒ , 1/mg/l
1/μmax

Figure 10. Performance of Once-through System at an S_i of 500 mg/l Subsequent to Cessation of Recycle of Sludge of 15,000 mg/l X_R


3200
3100
300
200
100
0
X, mg/l
100
0
S, mg/l
0
20
40
60
80
100
120
140
TIME, HOURS

during this run are shown in Table VIII. The performance characteristics during the steady state period are plotted in Figure 11. Effluent characteristics were monitored in terms of clarifier effluent COD, S_t, filtrate COD, S_e, and supernatant solids concentration, X_e. Also, spot checks were made for 5-day BOD on the effluent of the clarifier supernatant, S_t, and amount of glucose (glucostat determination) left untreated in the filtered effluent. The biochemical efficiency based on the average feed COD of 1060 mg/l and effluent filtrate COD of 48 mg/l was 95 percent. The BOD_5 of the clarifier overflow ranged between 15 and 35 mg/l. However, the glucostat test indicated very little of the original substrate, glucose, was left in the effluent; the maximum amount of glucose found was 10 mg/l with an average of 5.5 mg/l. The biological solids concentration in the aerator was higher than the previous run, since S_i was doubled. The average biological solids concentration was 3362 mg/l for this loading compared to 3082 for the previous run. The system exhibited a high degree of steadiness with respect to aerator solids concentration as well as effluent characteristics. The recycle solids concentration, X_R, was controlled within 1000 mg/l of the desired 15,000 mg/l. It is interesting to note that the COD of recycle sludge filtrate was only 11 mg/l compared to the effluent filtrate COD of 48 mg/l. This result provides evidence that the residual COD in the effluent was further removed in the sludge consistency tank. The excess sludge production during this run was more than twice that of the previous run. The average amount of excess sludge produced was 2284 mg/day compared to 914 mg/day in the previous run. The reason for this result will be discussed later.

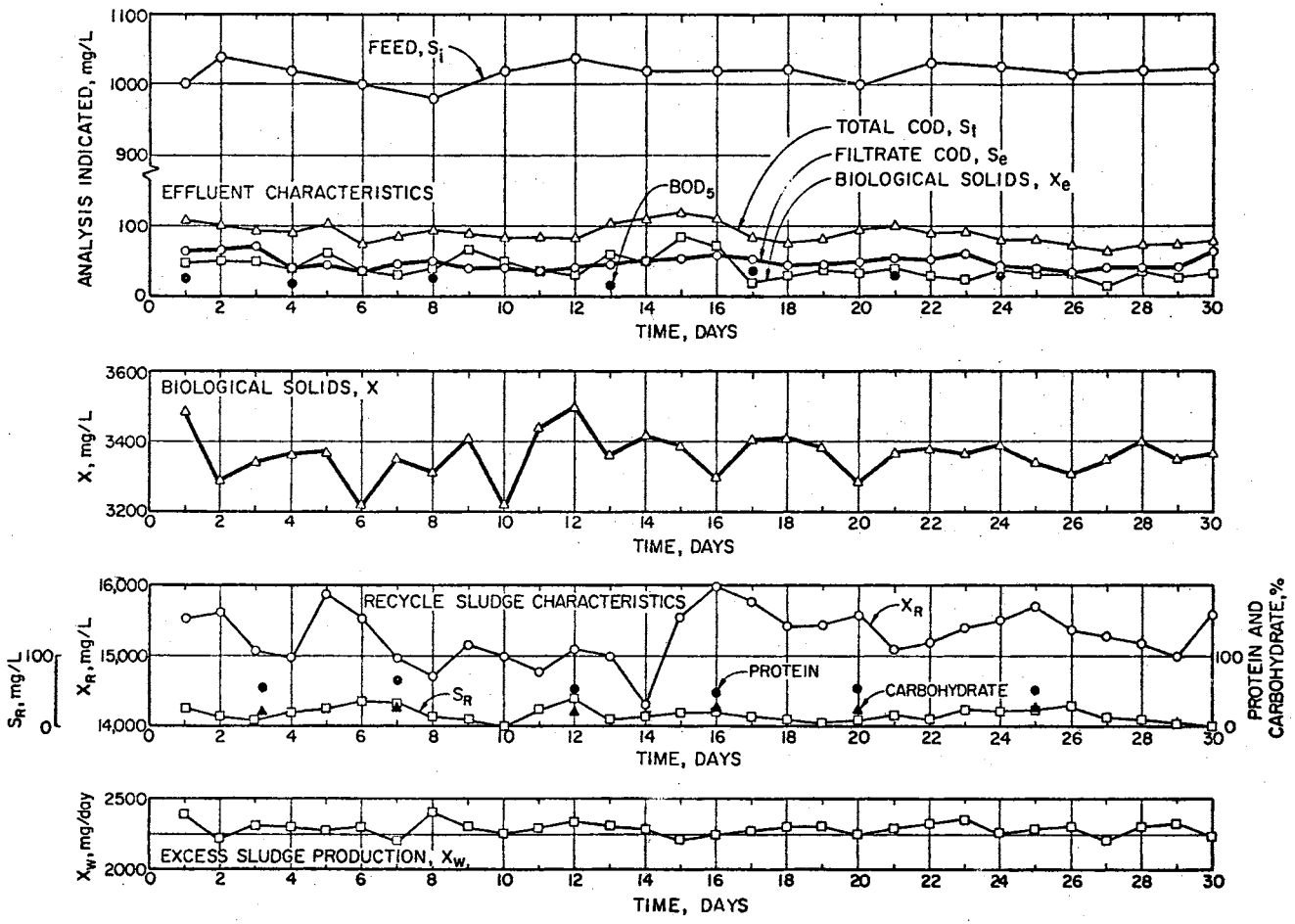
The batch growth curves and the hypervolic plot, μ vs S_o, are

TABLE VIII

STEADY STATE DATA AT S_i = 1000 mg/l GLUCOSE, X_R = 15,000 mg/l

Days	X mg/l	X_R mg/l	X_e mg/l	X_w mg/day	S_e mg/l	S_t mg/l	S_R mg/l	BOD_5 mg/l	Glucostat mg/l	Protein %	Carbo. %	Endog. O_2 Uptake mg/gm	NH_3-N Feed mg/l	NH_3-N Eff. mg/l
1	3480	15550	47.5	2380	65	110	25	25	3					
2	3288	16000	52.5	2220	65	100	15			55	20	10	104	74
3	3340	15130	47.5	2310	70	95	10							
4	3356	14950	40.0	2300	40	90	20	20	5					
5	3368	15860	62.5	2270	45	110	25							
6	3220	15530	35.0	2280	35	75	35						110	75
7	3352	14960	30.0	2200	45	85	30			65	30	12		
8	3316	14680	37.5	2400	50	95	15	25						
9	3408	15170	65.0	2280	40	90	10							
10	3220	14990	50.0	2250	40	85	0							
11	3438	14740	35.0	2290	35	85	25		5				107	75
12	3490	15100	30.0	2320	40	85	40			52	22	9		
13	3360	15010	62.5	2300	45	110	10	15						
14	3420	14300	50.0	2280	50	110	15							
15	3390	15560	85.0	2210	55	120	20		10				105	80
16	3300	16000	60.0	2240	60	110	20			48	27	15		
17	3410	15770	22.5	2270	55	85	15	35						
18	3410	15360	27.5	2280	45	75	10							
19	3390	15400	35.0	2290	45	80	5						102	71
20	3290	15600	35.0	2250	50	95	10							
21	3370	15100	40.0	22.80	55	100	15	30	5	55	25	12		
22	3380	15200	30.0	2320	55	95	10							
23	3365	15400	25.0	2340	60	95	25						99	70
24	3390	15500	35.0	2270	45	80	20							
25	3340	15700	27.0	2280	40	80	25	30	5	50	25	13		
26	3310	15400	30.0	2295	35	75	30							
27	3345	15300	15.0	2210	40	65	15							
28	3400	15200	35.0	2310	40	75	10						105	75
29	3350	15000	25.0	2320	40	75	5							
30	3365	15600	27.5	2270	64	80	0							

Figure 11. Operational Characteristics for an Activated Sludge Process With Constant X_R of 15,000 mg/l at an S_i of 1000 mg/l


ANALYSIS INDICATED, mg/L
FEED, S_i
TOTAL COD, S_t
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X_e
EFFLUENT CHARACTERISTICS
BOD_5
TIME, DAYS
BIOLOGICAL SOLIDS, X
X, mg/L
TIME, DAYS
RECYCLE SLUDGE CHARACTERISTICS
X_R
PROTEIN
CARBOHYDRATE
S_R
S_R, mg/L
X_R, mg/L
PROTEIN AND CARBOHYDRATE, %
TIME, DAYS
X_w, mg/day
EXCESS SLUDGE PRODUCTION, X_w,
TIME, DAYS

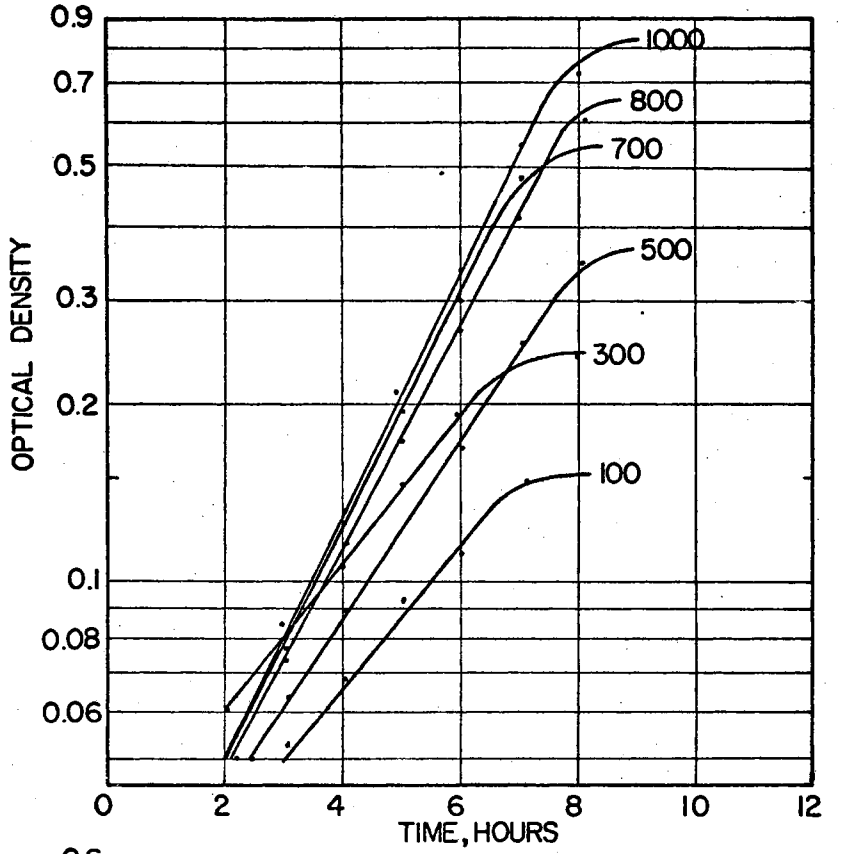
shown in Figures 12, 13, and 14. The μ_{max} values obtained from three individual growth studies were essentially the same, i.e., 0.51, 0.50, and 0.49 hr^{-1}, and the K_s values were 110, 95, and 140 mg/l. While K_s was in the same range as the last run, μ_{max} was higher than the mean μ_{max} previously observed.

The once-through chemostat data are shown in Figure 15, where aerator solids and filtrate COD are plotted after the transient stage following cessation of cell recycle. Again, it is noted that there was, after attainment of an apparent steady state, a gradual increase in solids concentration after approximately 90 hours. The system appeared to attain a new steady state at a higher level of biological solids. A similar observation was made in the last run.

Another recycle solids concentration, X_R, at which the steadiness of the model was tested during this investigation, was 10,000 mg/l, which is close to the values observed in the field. In Table IX, the performance characteristics of the pilot plant with an S_i loading which ranged from 960 to 1040 mg/l of COD with an average recycle solids concentration of 9655 mg/l are shown. The steadiness of the operational model is exhibited by the effluent characteristics, as well as by the biological solids concentration, X, as shown in Figure 16. The effluent filtrate COD varied from 5 to 50 mg/l, while the 5-day BOD samples indicate lower values. The extremely low values of S_R, in addition to substantiating the justification for assuming $S_R = 0$ in the equation, attest to the fact that the residual COD in the effluent is subject to further removal by the biomass. The average X value for this steady state run was 2275 mg/l. Thus, the effect of X_R on X can be readily seen by comparing the steady state values of the aerator solids

Figure 12. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 15,000 mg/l. Experiment No. 1

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.51 hr^{-1} and 110 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
700
500
300
100
0
2
4
6
8
10
12
TIME, HOURS

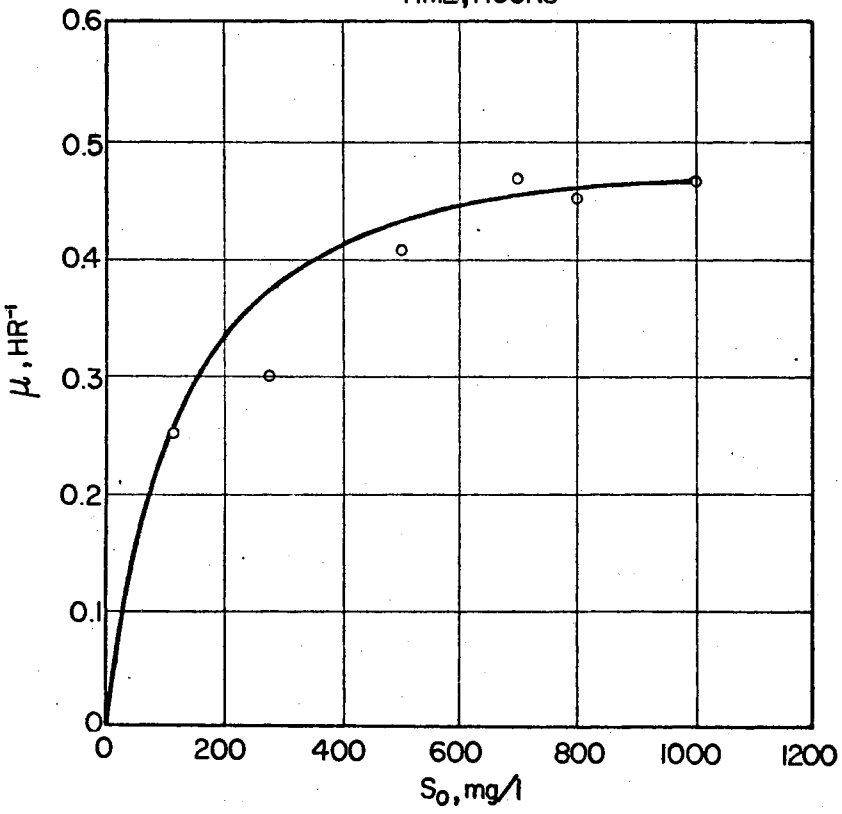
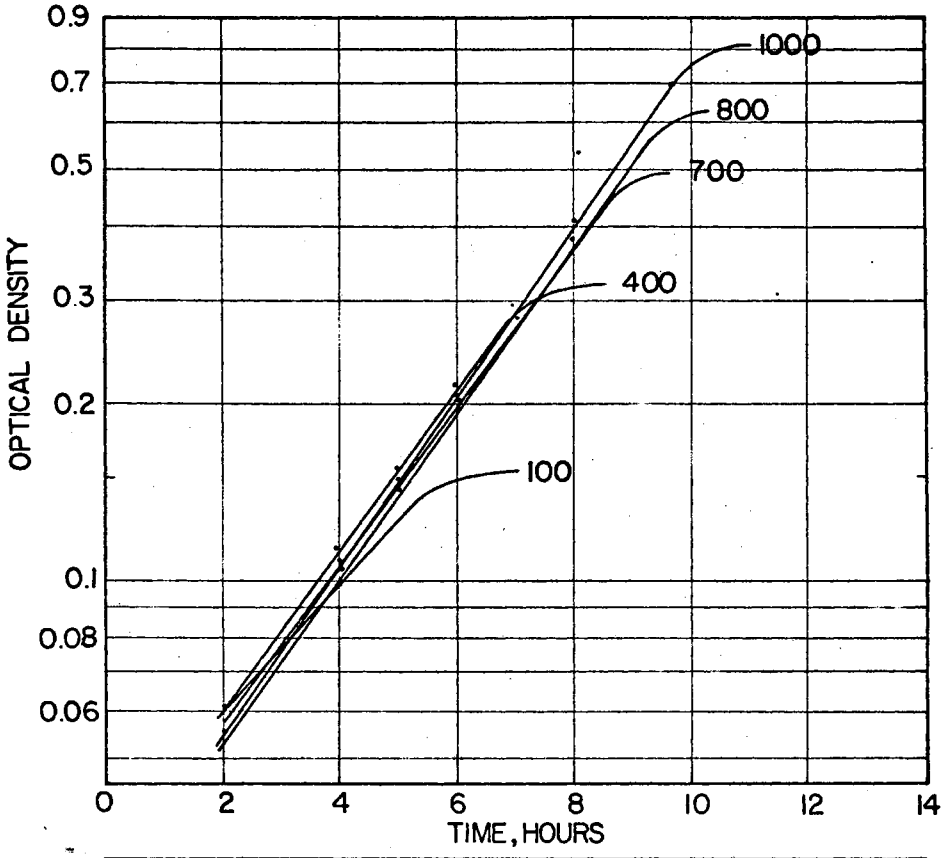

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 13. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 15,000 mg/l. Experiment No. 2

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.50 hr^{-1} and 95 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
700
400
100
0
2
4
6
8
10
12
14
TIME, HOURS

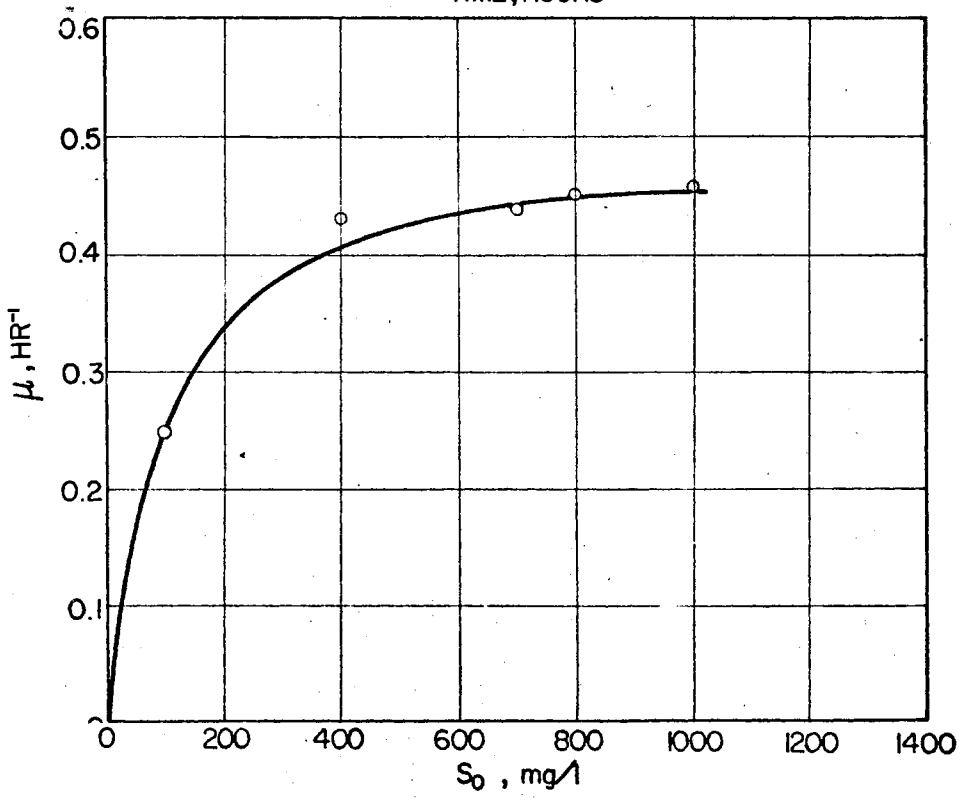
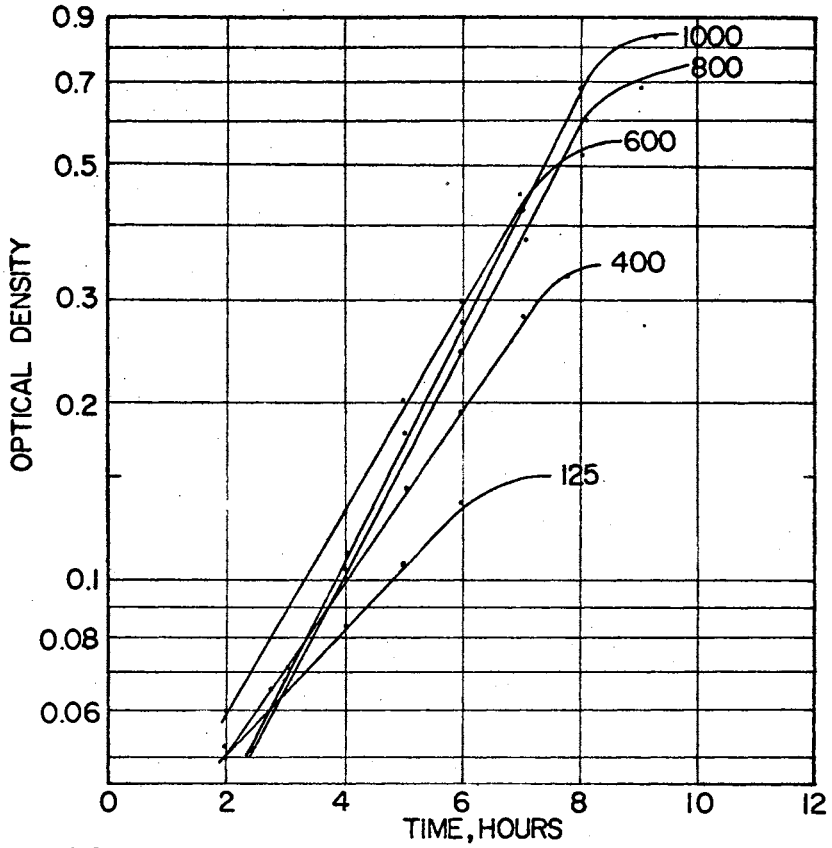

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
200
400
600
800
1000
1200
1400
S₀, mg/l

Figure 14. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 15,000 mg/l. Experiment No. 3

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.49 hr^{-1} and 140 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
600
400
125
0
2
4
6
8
10
12
TIME, HOURS

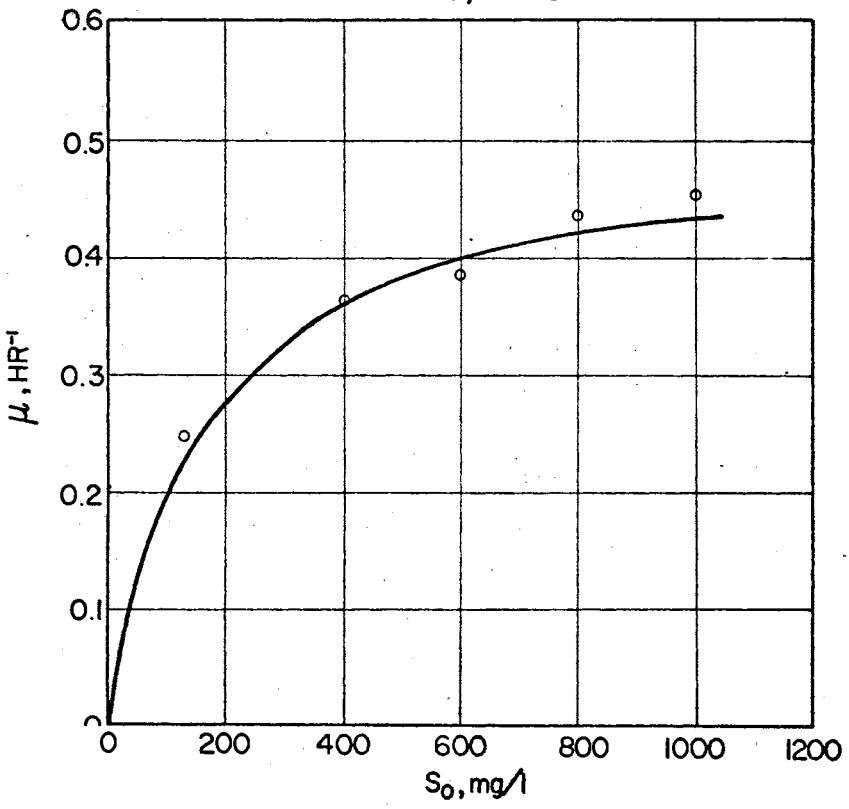

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 15. Performance of Once-through Systems at an S_i of 1000 mg/l Subsequent to Cessation of Recycle of Sludge of 15,000 mg/l X_R

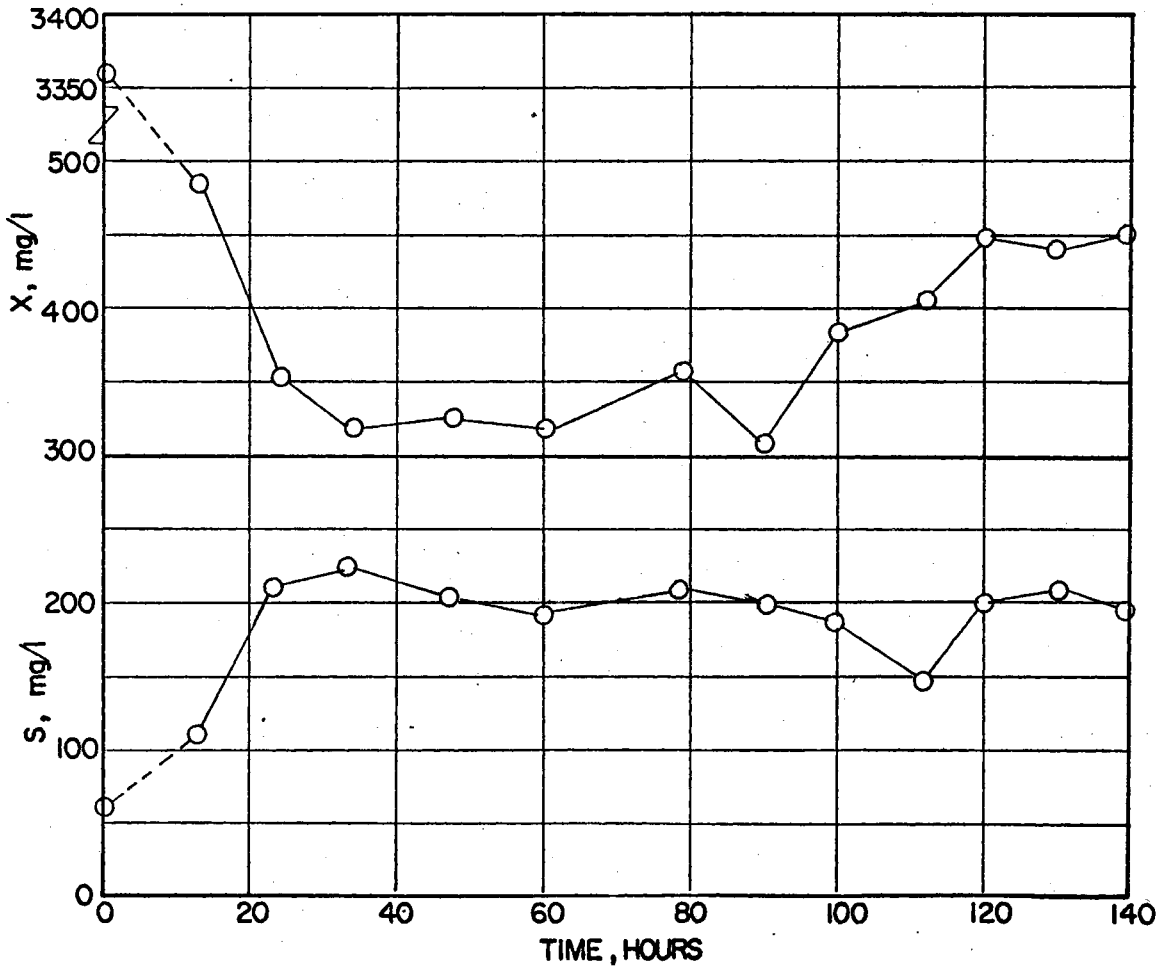
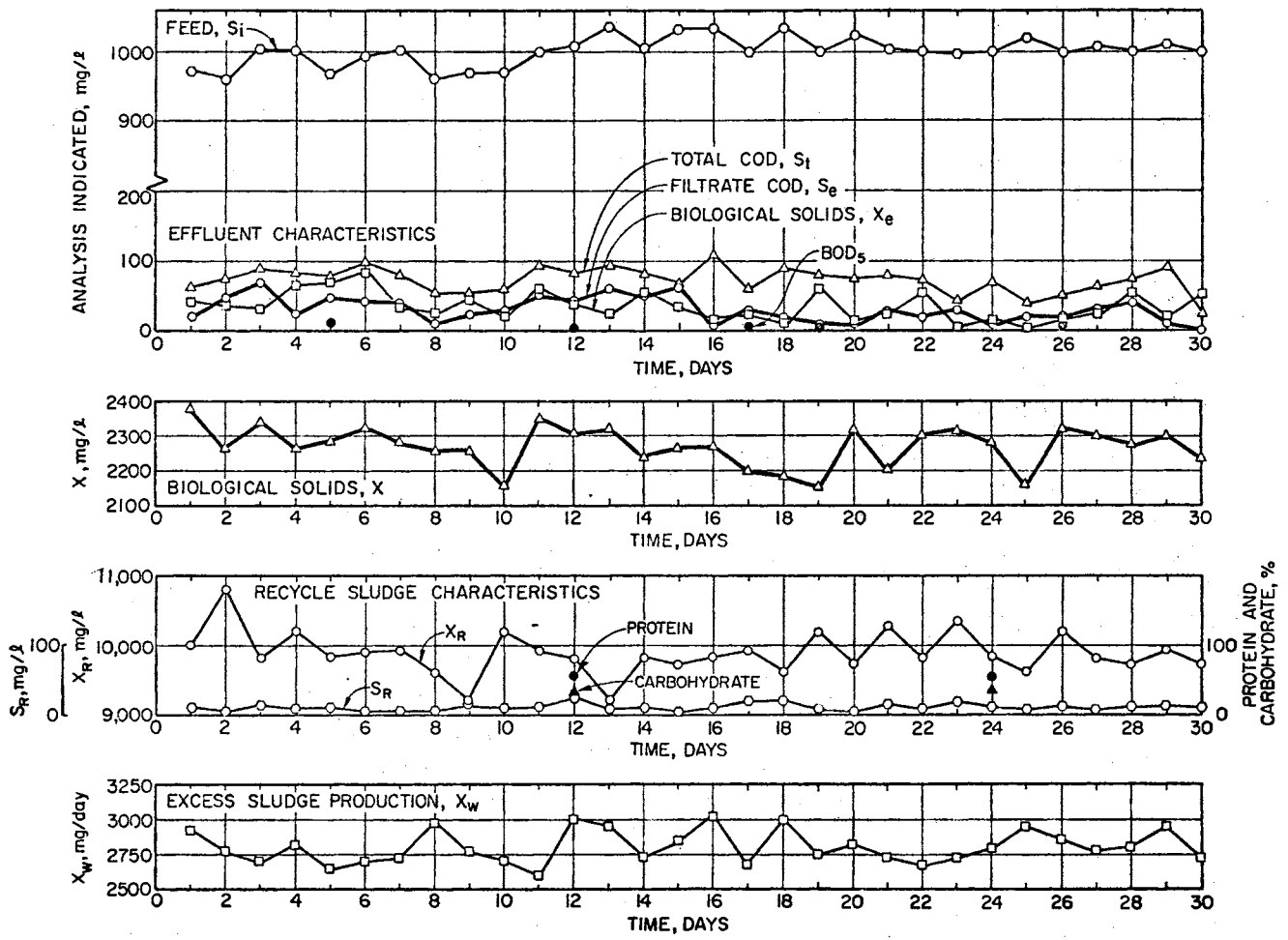

3400
3350
500
400
300
200
100
0
X, mg/l
S, mg/l
0
20
40
60
80
100
120
140
TIME, HOURS

TABLE IX

STEADY STATE DATA AT S_i = 1000 mg/l GLUCOSE, X_R = 10,000 mg/l

Days	X mg/l	X_R mg/l	X_e mg/l	X_w mg/d	S_e mg/l	S_t mg/l	S_R mg/l	Protein %	Carbo. %	BOD_5 mg/l	NH_3-N Feed mg/l	NH_3-N Eff. mg/l
1	2380	10000	40	2840	20	60	10					
2	2280	10900	35	2550	50	75	5					
3	2320	9800	27	2400	70	90	15					
4	2260	10200	65	2650	25	80	8					
5	2280	9840	70	2300	50	78	10			11		
6	2300	9960	83	2400	45	95	12					
7	2280	9900	33	2450	40	80	5					
8	2260	9500	25	2950	10	55	5					
9	2265	9200	40	2550	25	55	6					
10	2150	10300	20	2400	30	60	15					
11	2350	9900	61	2200	50	95	8			6	110	70
12	2310	9850	37	3000	45	80	12	55	38			
13	2320	9200	23	2900	60	90	2					
14	2250	9800	53	2450	50	80	10					
15	2270	9700	32	2700	60	70	10					
16	2280	9800	75	3050	10	110	5				116	80
17	2210	9900	33	2350	30	60	10			6		
18	2200	9500	10	3000	20	90	20					
19	2140	10200	60	2500	10	80	20			6		
20	2300	9150	15	2650	10	75	10					
21	2200	10300	25	2470	25	80	5					
22	2310	9800	55	2350	20	75	15					
23	2320	10320	50	2450	30	45	7				102	60
24	2275	9800	15	2600	10	72	18					
25	2140	9700	5	2900	20	40	8	52	39			
26	2320	10200	15	7700	15	50	5			9		
27	2310	9800	25	2550	30	65	10					
28	2260	9600	55	2600	40	75	3					
29	2280	9900	20	2900	10	90	10					
30	2240	9700	50	2450	5	25	12					

Figure 16. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 1000 mg/l

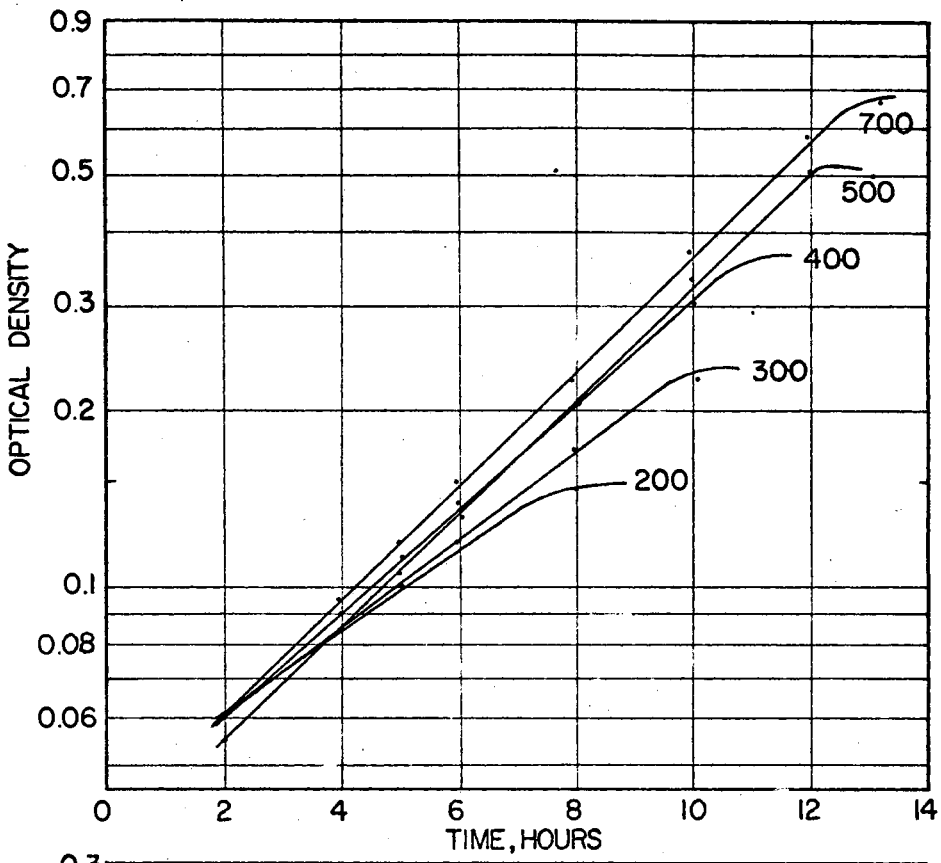

FEED, Si
ANALYSIS INDICATED, mg/ℓ
TOTAL COD, St
FILTRATE COD, Se
BIOLOGICAL SOLIDS, Xe
BOD5
EFFLUENT CHARACTERISTICS
TIME, DAYS
X, mg/ℓ
BIOLOGICAL SOLIDS, X
TIME, DAYS
RECYCLE SLUDGE CHARACTERISTICS
XR
PROTEIN
CARBOHYDRATE
SR
SR, mg/ℓ
XR, mg/ℓ
PROTEIN AND CARBOHYDRATE, %
TIME, DAYS
EXCESS SLUDGE PRODUCTION, Xw
Xw, mg/day
TIME, DAYS

concentration at S_i of 1000 at 15,000 and 10,000 mg/l X_R values. They were 3362 and 2275 mg/l, respectively. It is evident, therefore, that X is controlled mainly by X_R which, in turn, is a controllable parameter in this model. It is seen that the average X_R in this run was lower than the desired value of 10,000 mg/l. It is recalled that aerator #2 (the sludge consistency tank) was loaded with approximately 10,000 mg/l return sludge each twelve hours. Thus, it might be reasoned that portion of the biomass being pumped to aerator #1 could have undergone some amount of aerobic digestion during the 12-hour period. For this reason, biological solids concentration in aerator #2 was measured at the beginning and end of each 12-hour period (and often at more frequent intervals). Only during this run at S_i = 1000 mg/l was there any evidence for an autodigestive decrease in biological solids concentration. The average beginning concentration was 9840 mg/l, and the average ending concentration was 9470 mg/l. Thus, during this run, approximately 370 mg/l, on the average, was autodigested in aerator #2 during each charging period. The mean value for X_R calculated as the average of these values was 9655 mg/l. The excess sludge production in this case was 2600 mg/day on the average, and was relatively steady throughout the run.

Figures 17, 18, 19, and 20 show the batch growth pattern and relationship between μ and S_o, determined from the shaker experiments. The μ_{max} values varied over a wide range (0.25 to 0.83 hr^{-1}). As the curvatures of the hyperbolic curves indicate, the K_s values were also higher than those usually observed, though they were not abnormally high. Figure 21 shows the once-through continuous flow steady state characteristics, with a transient period between recycle and

Figure 17. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 10,000 mg/l. Experiment No. 1

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.25 hr^{-1} and 205 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
700
500
400
300
200
0
2
4
6
8
10
12
14
TIME, HOURS

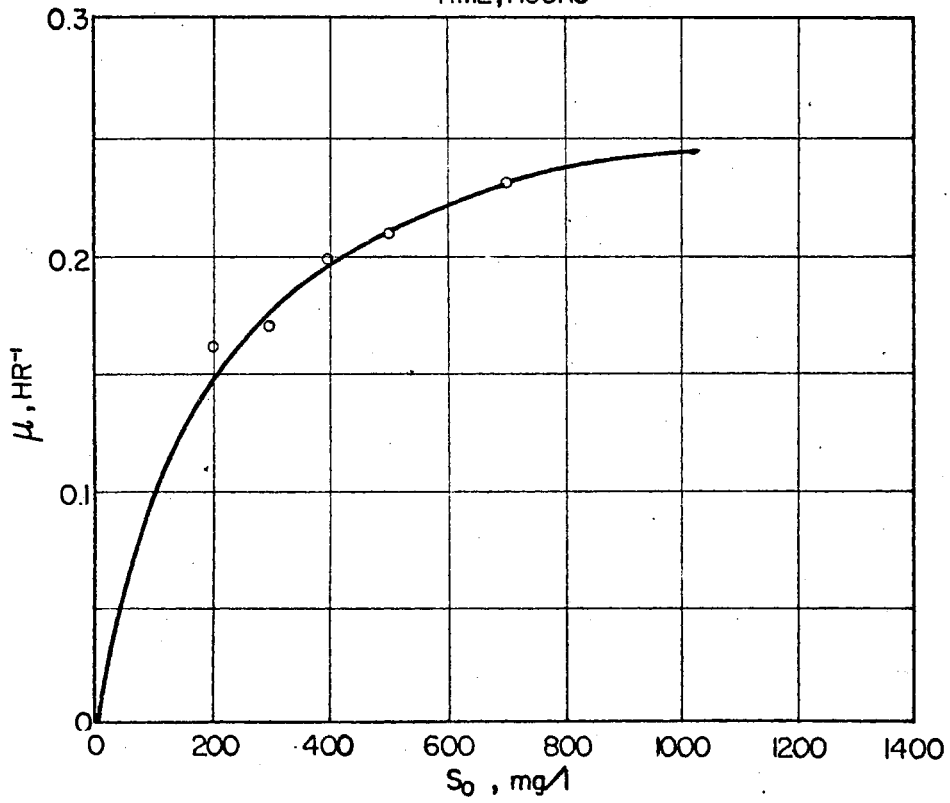
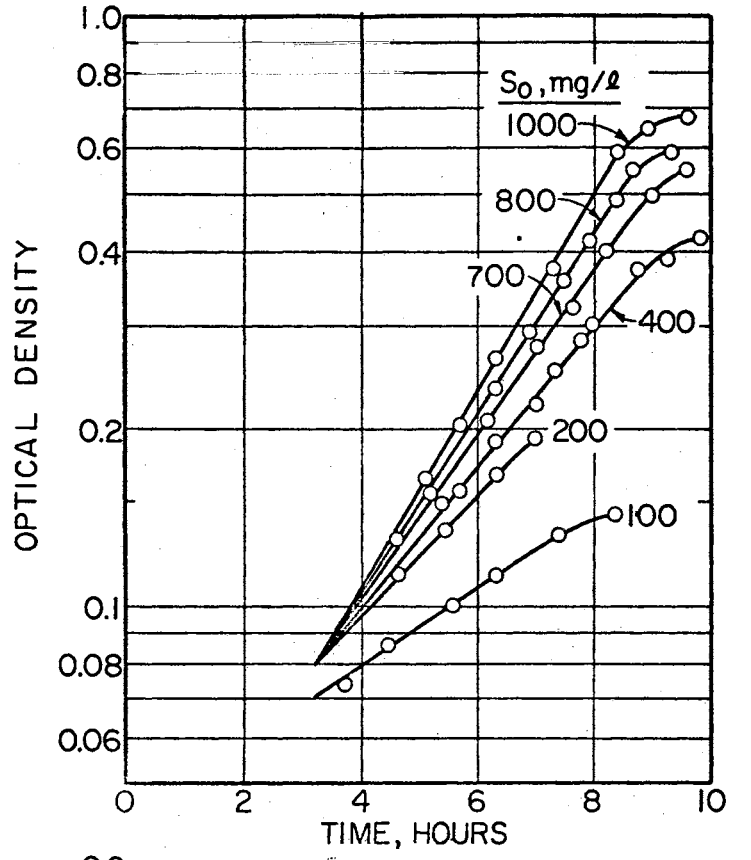

μ, HR⁻¹
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
S₀, mg/l

Figure 18. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 10,000 mg/l. Experiment No. 2

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.48 hr^{-1} and 226 mg/l, respectively


OPTICAL DENSITY
1.0
0.8
0.6
0.4
0.2
0.1
0.08
0.06
S_0, mg/ℓ
1000
800
700
400
200
100
0
2
4
6
8
10
TIME, HOURS

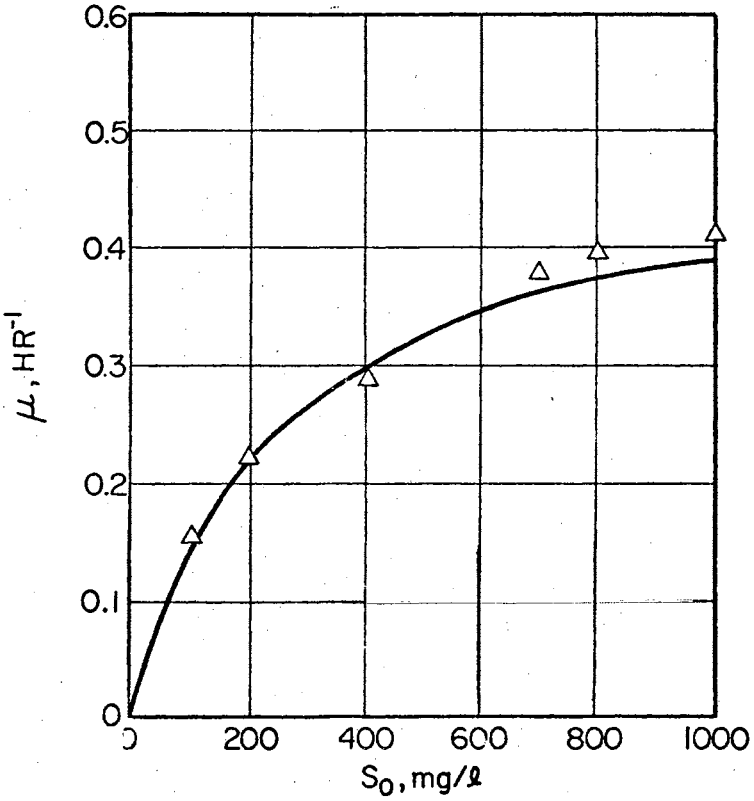
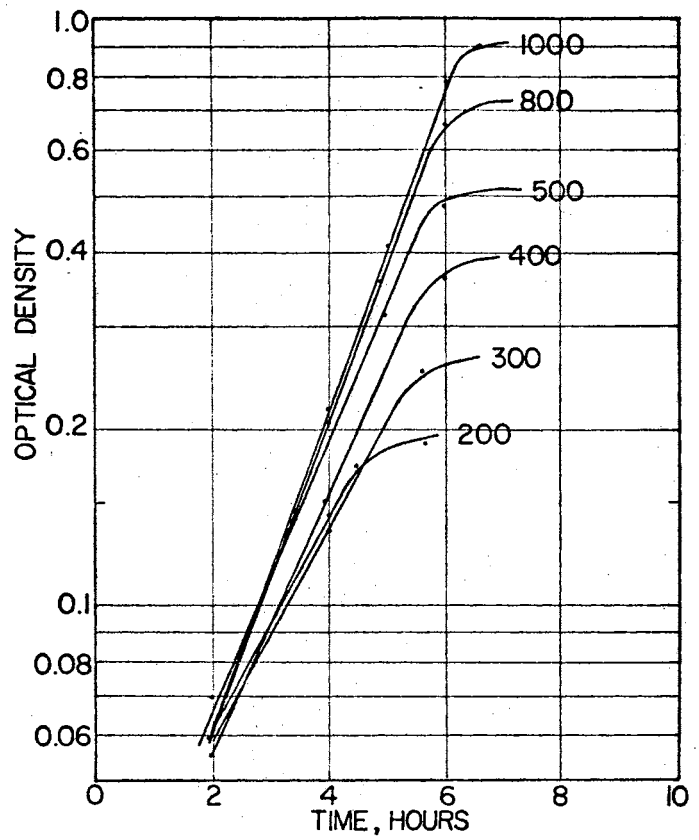

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
S_0, mg/ℓ

Figure 19. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 10,000 mg/l. Experiment No. 3

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.83 hr^{-1} and 175 mg/l, respectively


1.0
0.8
0.6
0.4
0.2
0.1
0.08
0.06
OPTICAL DENSITY
1000
800
500
400
300
200
0
2
4
6
8
10
TIME, HOURS

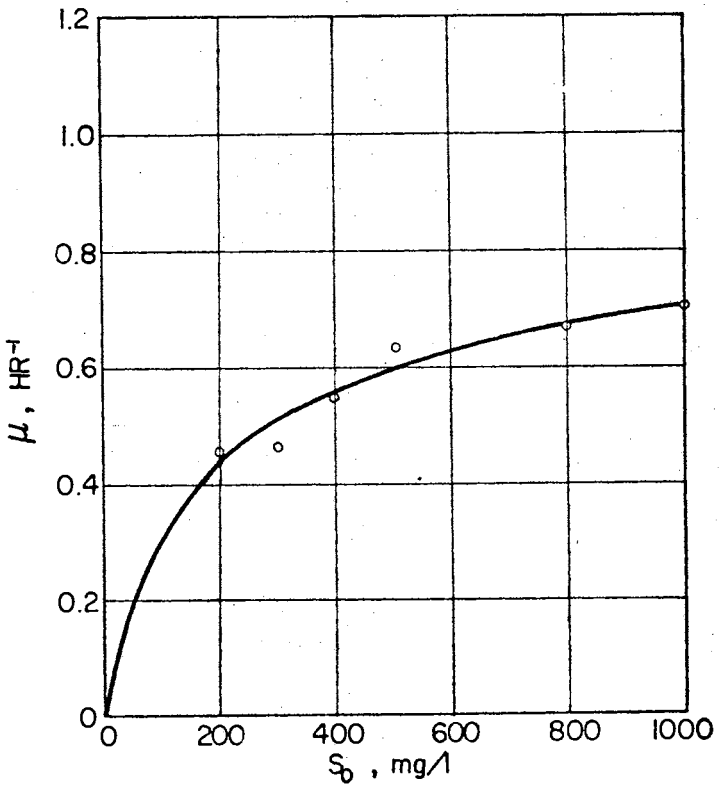
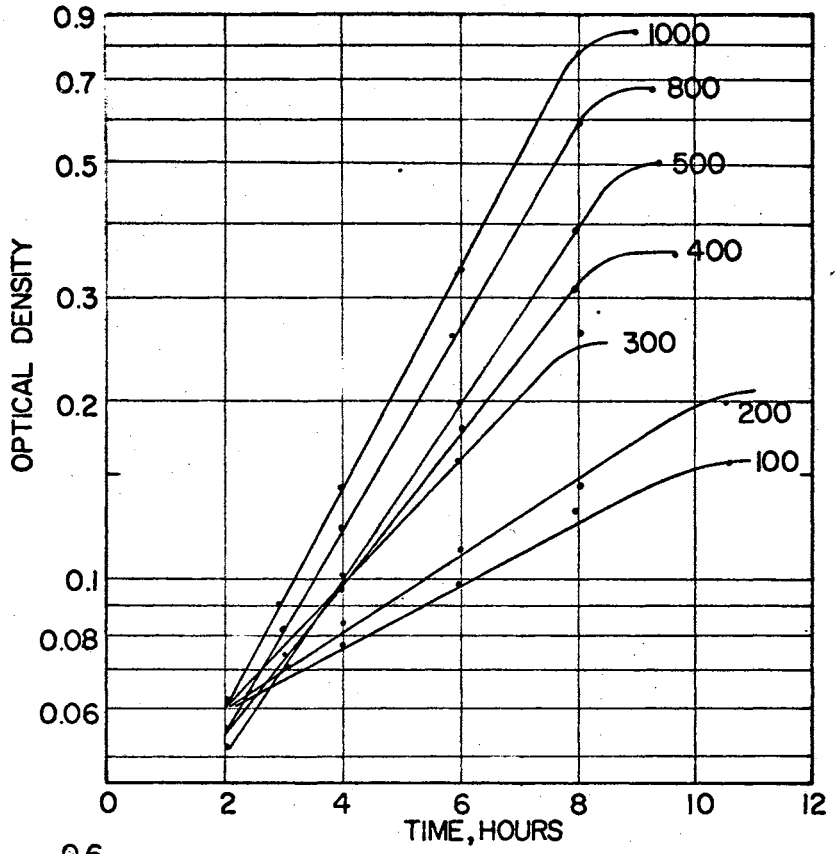

1.2
1.0
0.8
0.6
0.4
0.2
0
μ, HR⁻¹
0
200
400
600
800
1000
S₀, mg/l

Figure 20. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 10,000 mg/l. Experiment No. 4

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.63 hr^{-1} and 438 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
500
400
300
200
100
0
2
4
6
8
10
12
TIME, HOURS

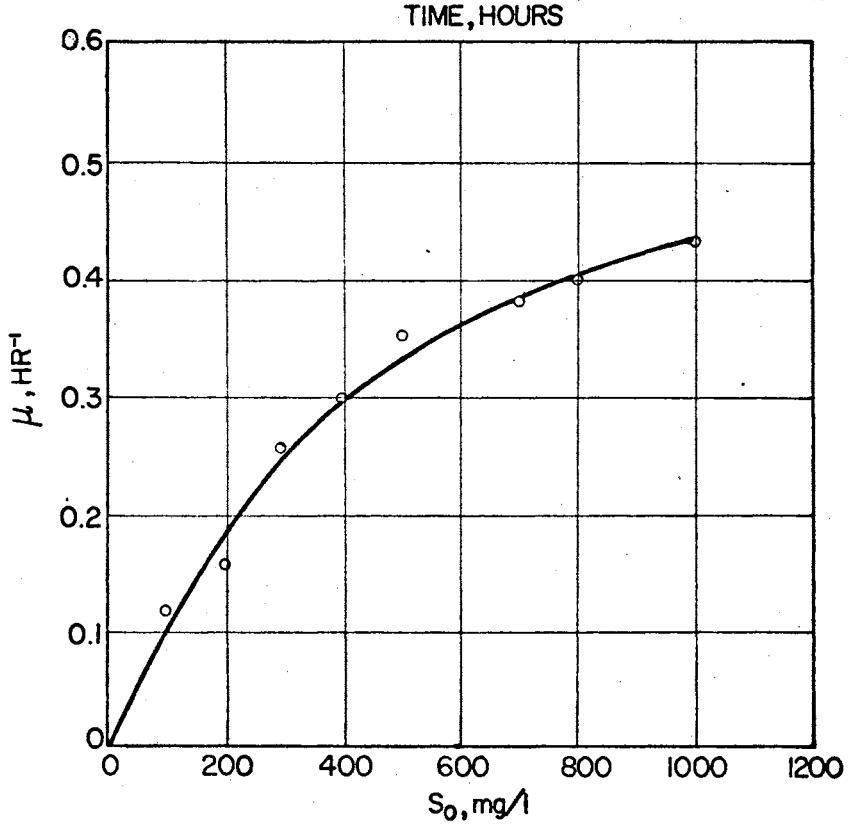
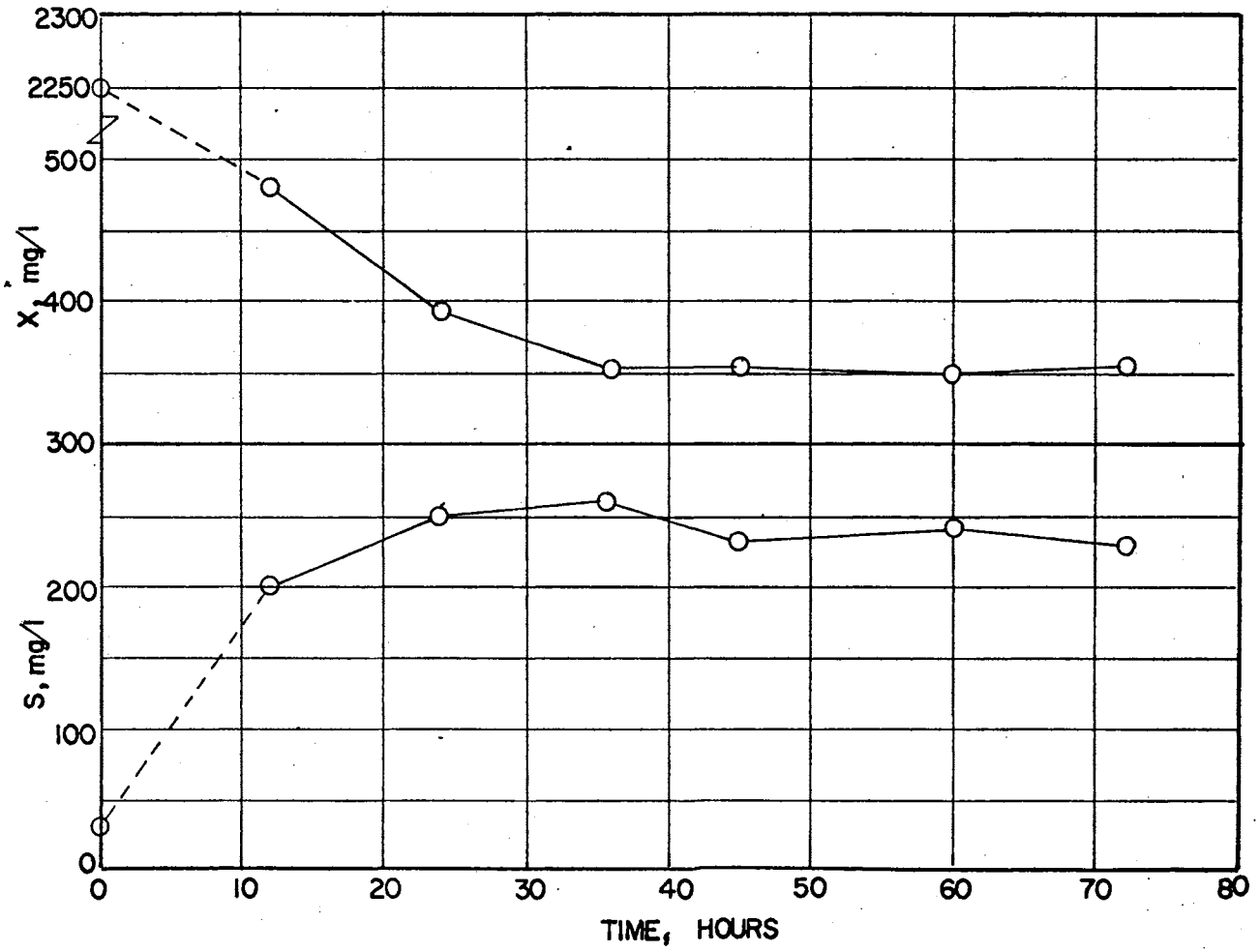

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 21. Performance of Once-through System at an S_i of 1000 mg/l Subsequent to Cessation of Recycle of Sludge of 10,000 mg/l X_R


2300
2250
500
400
300
200
100
0
X, mg/l
S, mg/l
0
10
20
30
40
50
60
70
80
TIME, HOURS

once-through operation, indicated by dotted lines. Unlike the previous two runs, there was no "second" rise in solids by the time the run was terminated at 70 hours after cessation of the recycle.

The next two continuous culture runs were made at an X_R of 5000 mg/l (see Tables X and XI). The S_i loadings were 500 and 1000 mg/l glucose. The steady state plots are shown in Figures 22 and 23. The average feed CODs were 519 and 1030 mg/l for these two runs. Throughout both runs, the effluent quality was excellent, yielding better than 94 percent efficiency based on supernatant COD and 98 percent based on filtrate COD. The mean effluent solids concentration of the run at lower loading was 15 mg/l, and at the higher loading it was 21 mg/l. Some samples recorded zero glucose in the effluent. The biological solids concentration varied over a very narrow range during both runs. The reason may have been due in part because of better estimation of X_R by the spectrophotometric method at the lower X_R level. It is conceivable that more accuracy in solids estimation is possible at lower X_R values, such as 5000 mg/l, where the amount of dilution needed to reach the linear range of the calibration curve of OD vs solids is less compared to an X_R of 15,000 mg/l. For these two runs, the difference between the high and low values of X_R was only 700 mg/l, with averages of 4965 and 4960 mg/l for the low and high loading runs, respectively. Fluctuations in X were minimal during both runs. Again, the influence of S_i on X was noted in these runs. The average biological solids concentrations were 1173 and 1405 mg/l at S_i's of 500 and 1000 mg/l, respectively, at the same X_R of 5000 mg/l. The filtrate COD of the recycle sludge was very low and in some cases zero COD was recorded. The amounts of excess sludge produced were 1303 mg/day for the 500 mg/l

TABLE X

STEADY STATE DATA AT S_i = 500 mg/l GLUCOSE, X_R = 5000 mg/l

Days	X mg/l	X_R mg/l	X_e mg/l	X_w mg/day	S_e mg/l	S_t mg/l	S_R mg/l	BOD_5 mg/l	Glucostat mg/l	Protein %	Carbo. %	Endog. O_2 Uptake mg/gm	NH_3-N Feed mg/l	NH_3-N Eff. mg/l
1	1194	5000	18	1210	0	20	10							
2	1150	5000	15	1320	20	20	20					9.9	55	35
3	1220	4850	22	1295	5	40	5	10.0	4.0	55	24.6			
4	1206	5000	18	5000	0	20	0							
5	1160	4900	18	1340	0	25	0					6.8	53	36
6	1208	5000	22	1305	40	60	5	5.0	0.0	56	20.0			
7	1130	5000	20	1260	10	30	0							
8	1290	5000	15	1200	0	20	10							
9	1115	4620	12	1290	10	35	0					4.6	56	36
10	1200	5080	10	1305	10	30	10	5.0	2.0	57	18.0			
11	1000	4980	20	1365	0	25	10							
12	1144	5080	25	1390	10	25	5		2.0	52	25.0	10.7	60	34
13	1216	5000	30	1300	40	65	0							
14	1148	5010	10	1310	10	25	0							
15	1128	5080	18	1300	15	35	10							
16	1154	5230	20	1295	20	50	15		0.0					
17	1210	5020	10	1245	10	30	10	7.5		50	19.0	9.5	49	32
18	1160	4620	16	1290	5	25	7.5		0.5					
19	1175	5080	12	1345	10	25	0	10.0		48	22.0			
20	1105	4710	10	1360	10	20	10.0					10.5	51	34
21	1150	5080	15	1380	20	35	5.0							
22	1185	4650	12	1290	10	25	5.0							
23	1200	5270	15	1240	15	35	0.0		2.0			7.5	53	32
24	1165	5000	5	1295	10	20	0.0	10.5						
25	1175	5100	8	1340	15	25	7.5		3.0	57	23.0			
26	1170	4900	10	1305	10	25	0.0					10.0	50	30.5
27	1200	4850	15	1300	15	40	15.0	15.0						
28	1210	5050	20	1340	10	40	25.0		5.0					
29	1170	4910	5	1260	10	10	0.0							
30	1170	4850	10	1250	10	20	10.0							

TABLE XI

STEADY STATE DATA AT S_i = 1000 mg/l GLUCOSE, X_R = 5000 mg/l

Days	X mg/l	X_e mg/l	X_R mg/l	X_w mg/day	S_e mg/l	S_t mg/l	S_R mg/l	BOD_5 mg/l	Glucostat mg/l	Protein %	Carbo. %	Endog. O_2 Uptake mg/gm	NH_3-N Feed mg/l	NH_3-N Eff. mg/l
1	1472	27	5000	2940	30	65	20							
2	1448	10	4910	2900	30	45	10		4			15	105	65
3	1330	27	5000	3060	0	45	5	15		55	18			
5	1372	27	4850	3090	80	100	10	20	4	57	20	12	103	60
6	1400	35	500	2960	30	65	25							
7	1388	20	4970	3060	20	55	10							
8	1360	20	4670	3120	10	40	15							
9	1400	35	5020	3070	30	70	10	15						
10	1390	20	4710	3010	50	75	15			51	21	11	110	66
11	1428	40	4910	2940	10	65	25	18	2					
12	1470	37	4850	3150	60	100	15			52	19			
13	1440	25	5040	3040	20	50	20					14	90	56
14	1460	20	5020	3050	10	40	15							
15	1416	20	4800	3100	30	60	10		5					
16	1404	5	4870	3120	50	55	15			49	17			
17	1350	40	4770	2940	15	60	0	5				15	102	50
18	1430	15	5350	3160	10	40	25		4	55	21			
19	1396	5180	3060	20	50	35	15							
20	1390	25	5100	3075	25	55	10							
21	1410	27	4900	3060	10	45	15					15	100	62
22	1390	10	5150	3100	30	50	10							
23	1360	7	5050	2890	15	30	15		3	57	20			
24	1380	10	5000	3200	10	20	10	10				13	110	65
25	1410	15	5100	3060	15	20	10		7					
26	1400	17	4900	3040	5	30	10	10						
27	1440	8	4970	3075	20	30	20					15	105	58
28	1395	15	5050	3025	25	45	15							
29	1450	20	4700	3000	30	55	7.5	17						
30	1400	15	4910	3090	30	50	20							

Figure 22. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l at an S_i of 500 mg/l

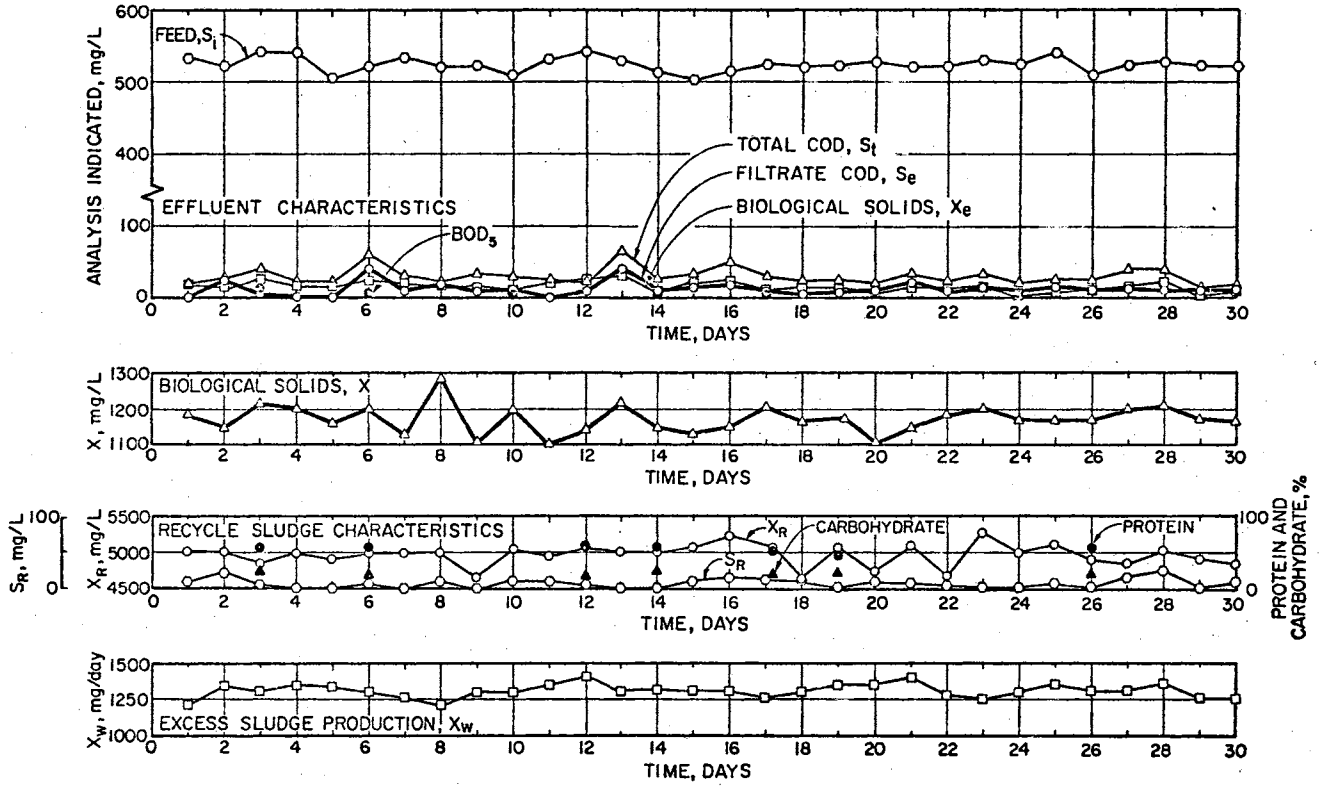
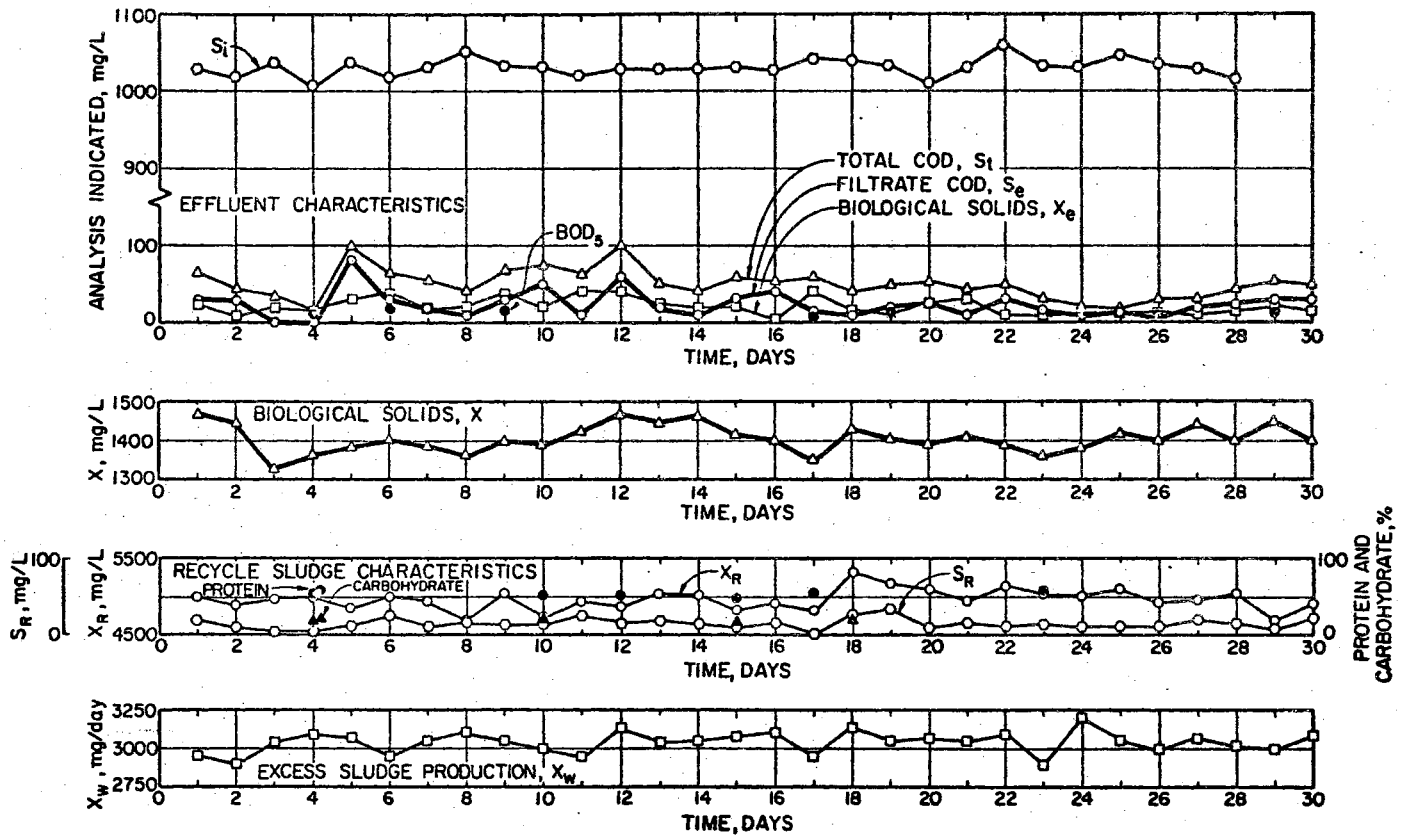

ANALYSIS INDICATED, mg/L
FEED, S_i
TOTAL COD, S_t
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X_e
EFFLUENT CHARACTERISTICS
BOD_5
TIME, DAYS
BIOLOGICAL SOLIDS, X
X, mg/L
RECYCLE SLUDGE CHARACTERISTICS
X_R
S_R
CARBOHYDRATE
PROTEIN
S_R, mg/L
X_R, mg/L
PROTEIN AND CARBOHYDRATE, %
EXCESS SLUDGE PRODUCTION, X_w,
X_w, mg/day

Figure 23. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l at an S_i of 1000 mg/l


ANALYSIS INDICATED, mg/L
1100
1000
900
100
0
S_i
EFFLUENT CHARACTERISTICS
BOD_5
TOTAL COD, S_t
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X_e
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
TIME, DAYS
X, mg/L
1500
1400
1300
BIOLOGICAL SOLIDS, X
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
TIME, DAYS
S_R, mg/L
100
0
X_R, mg/L
5500
4500
RECYCLE SLUDGE CHARACTERISTICS
PROTEIN
CARBOHYDRATE
X_R
S_R
100
0
PROTEIN AND CARBOHYDRATE, %
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
TIME, DAYS
X_w, mg/day
3250
3000
2750
EXCESS SLUDGE PRODUCTION, X_w
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
TIME, DAYS

feeding level, and 3050 mg/day at an S_i of 1000 mg/l.

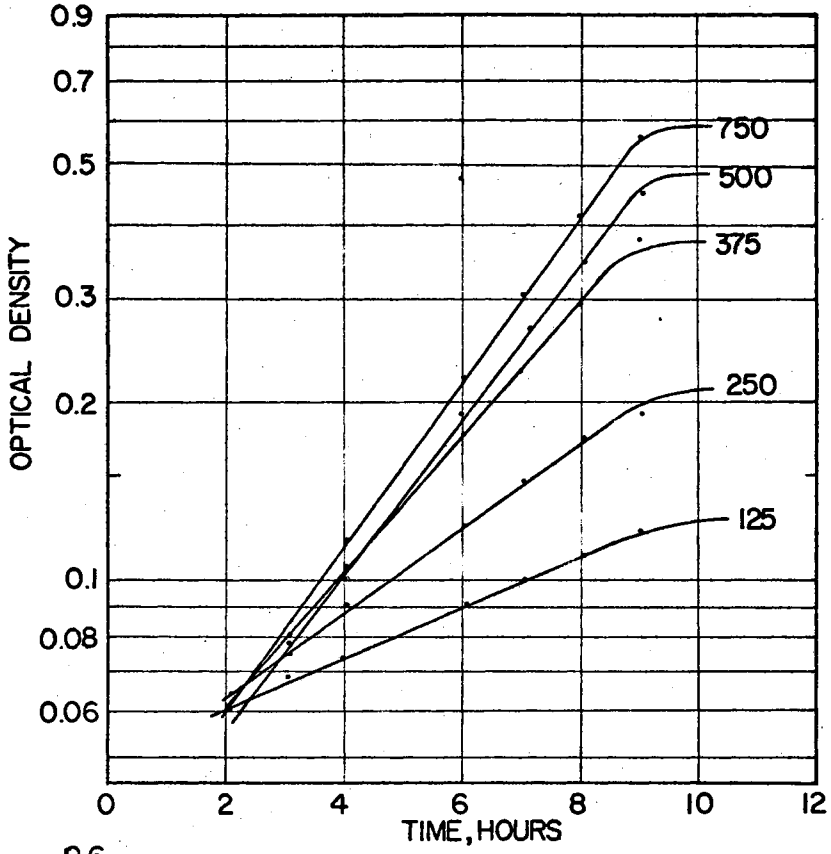
The batch growth plots obtained during the run at 500 mg/l glucose and an X_R of 5000 mg/l are shown in Figures 24, 25, 26, and 27. The μ_{max} varied from 0.35 to 0.50, while K_s ranged from 218 to 386 mg/l, with an average of 295 mg/l. From Figures 28, 29, 30, and 31 it is seen that the μ_{max} did not vary as much for the run at the higher loading while K_s was still fairly high. Figures 32 and 33 are the plots of the once-through data at an S_i of 500 and 1000 mg/l, respectively, after recycle was stopped.

The results of the shock load experiments are shown in Figures 34 and 35. The S_i was increased from 519 to 1640 mg/l (approximately 3.2-fold) in one case (Figure 34), and from 1030 to 3600 mg/l (approximately 3.5-fold) in the other experiment (Figure 35). The X_R values for the two runs were 4600 and 5085 mg/l, respectively. The parameters monitored were the biological solids concentration in the aerator, X, effluent filtrate and supernatant COD, carbohydrate (anthrone COD) of effluent filtrate, and solids concentration in the clarifier overflow. At the lower loading, the solids concentration in the aerator, X, increased sharply from approximately 1170 to 1700 mg/l in about nine hours, and stayed fairly steady at the new value until the experiment was terminated. The effluent characteristics measured by the COD and solids do not indicate any leakage of substrate from the unit. The biochemical efficiency and settling characteristics of the sludge were not affected to any extent. The anthrone COD values of effluent filtrate (not shown) were lower than the total COD in the effluent.

In the case of the higher loading, the solids concentration in the reactor, X, was 1540 mg/l at the time shock was applied. The time taken

Figure 24. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 5000 mg/l. Experiment No. 1

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.42 hr^{-1} and 200 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
750
500
375
250
125
0
2
4
6
8
10
12
TIME, HOURS

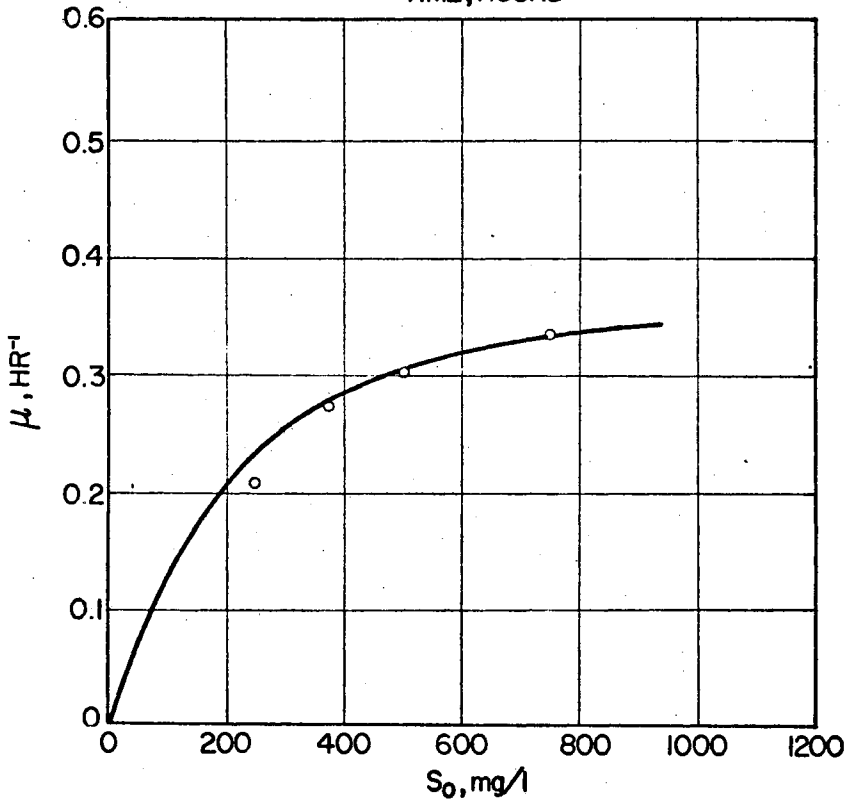
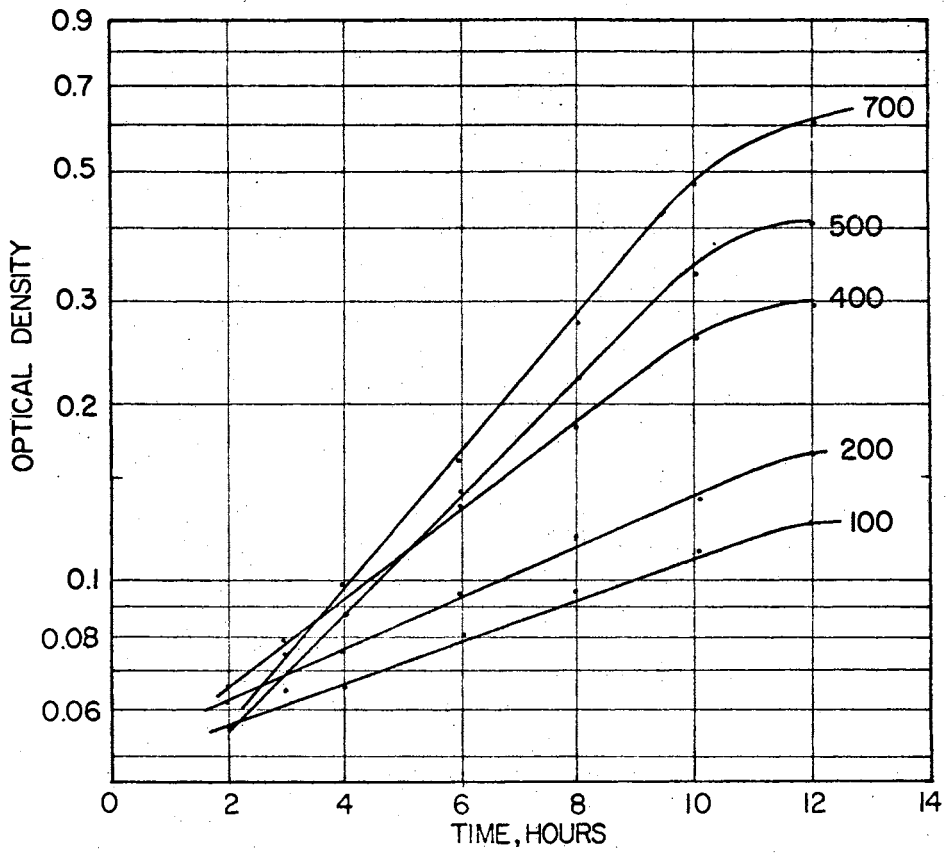

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 25. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 5000 mg/l. Experiment No. 2

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.50 hr^{-1} and 590 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
700
500
400
200
100
0
2
4
6
8
10
12
14
TIME, HOURS

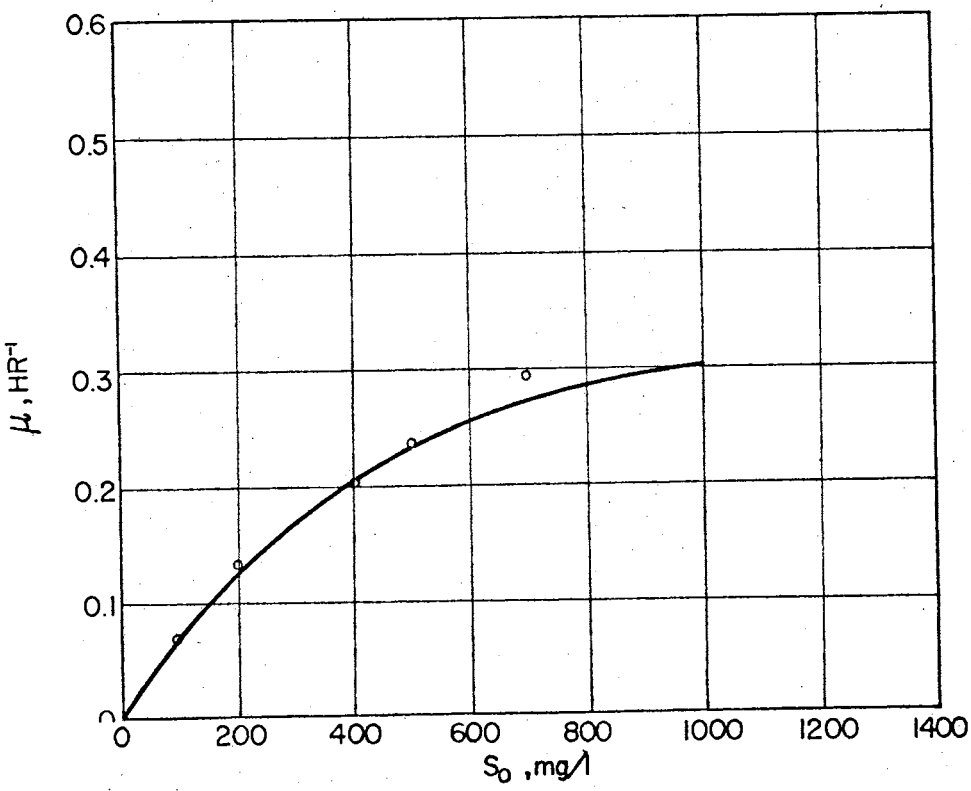
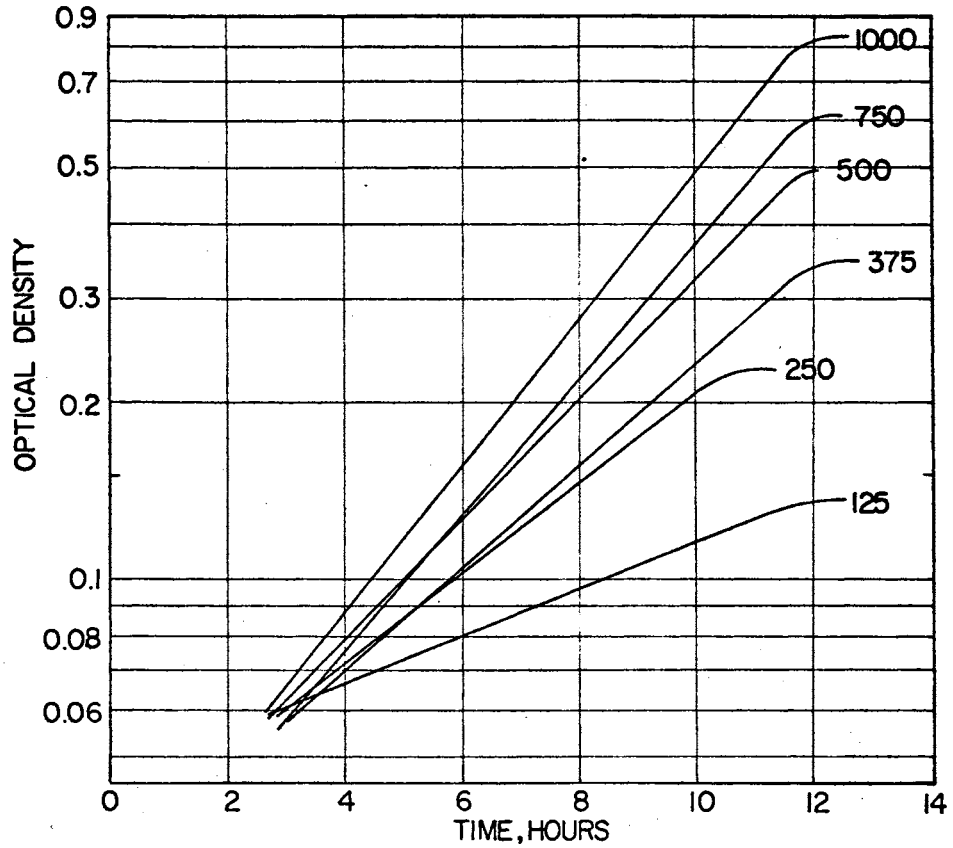

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
S₀, mg/l

Figure 26. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 5000 mg/l. Experiment No. 3

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.35 hr^{-1} and 218 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
750
500
375
250
125
0
2
4
6
8
10
12
14
TIME, HOURS

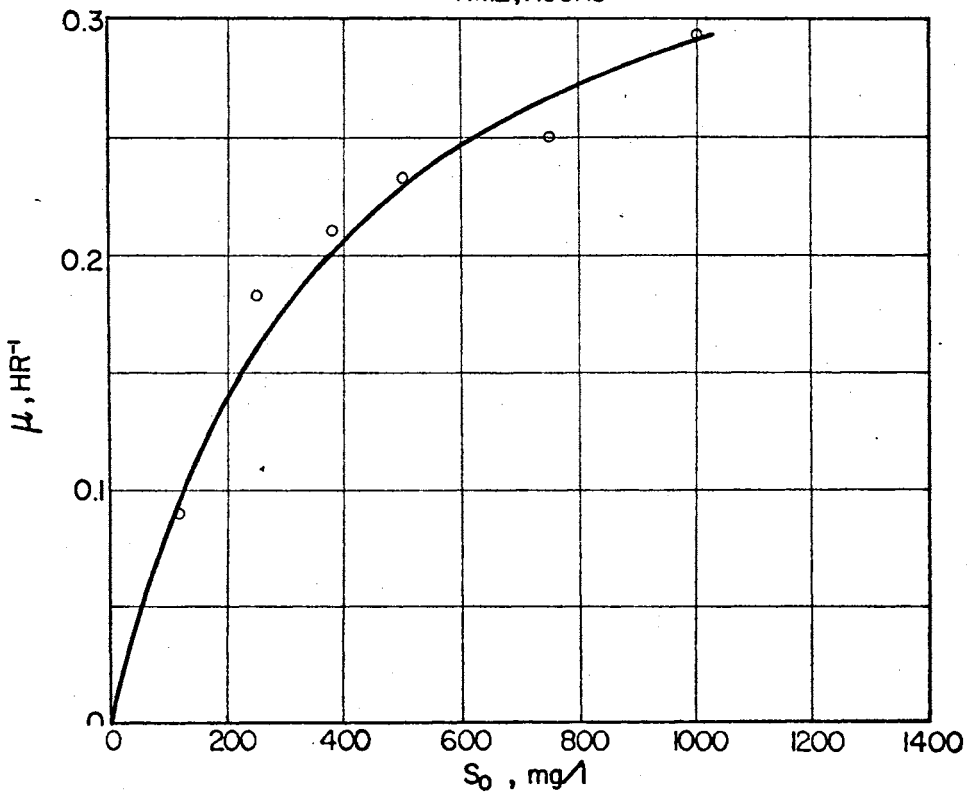

μ, HR⁻¹
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
S₀ , mg/l

Figure 27. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 5000 mg/l. Experiment No. 4

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.38 hr^{-1} and 386 mg/l, respectively

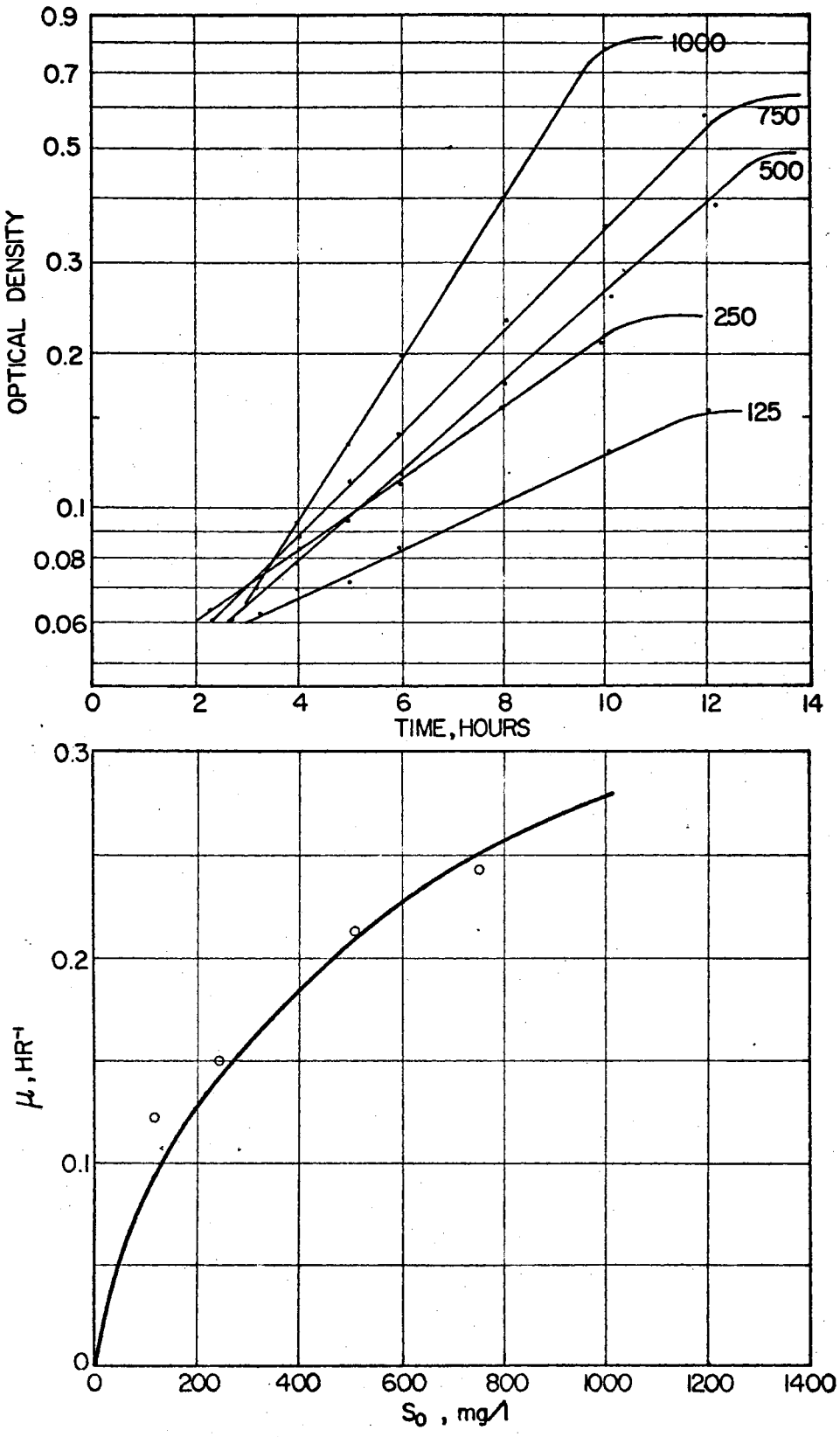
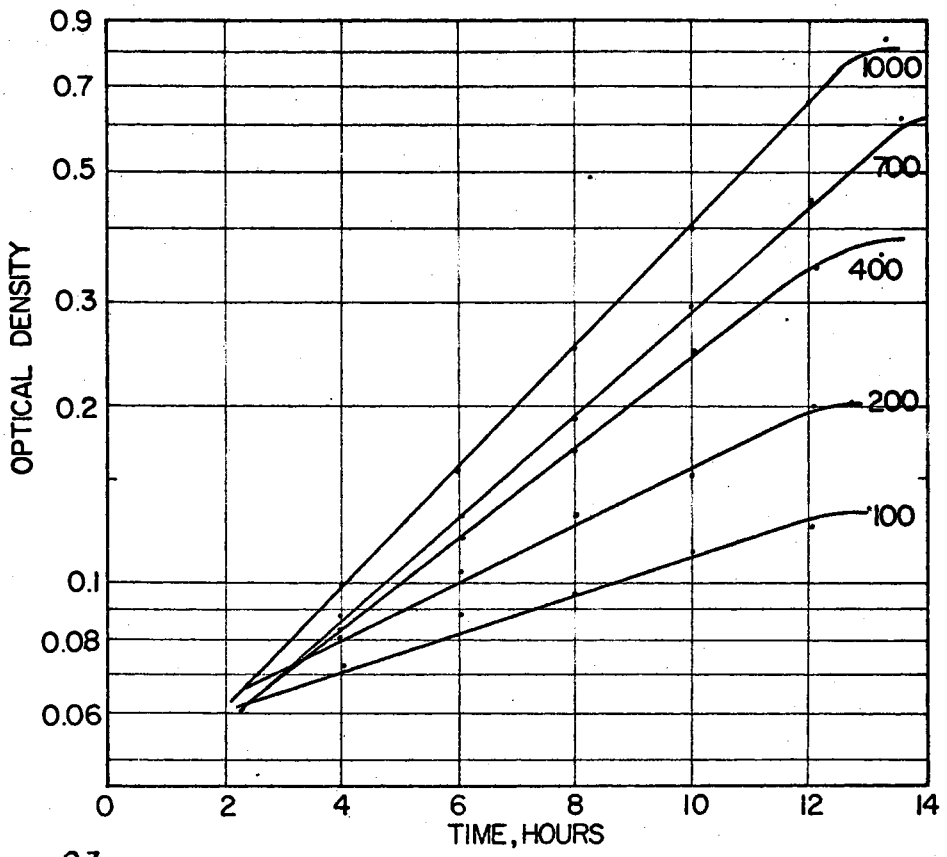

0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
OPTICAL DENSITY
1000
750
500
250
125
0
2
4
6
8
10
12
14
TIME, HOURS
0.3
0.2
0.1
0
μ, HR⁻¹
0
200
400
600
800
1000
1200
1400
S₀ , mg/l

Figure 28. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 5000 mg/l. Experiment No. 1

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.30 hr^{-1} and 315 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
700
400
200
100
0
2
4
6
8
10
12
14
TIME, HOURS

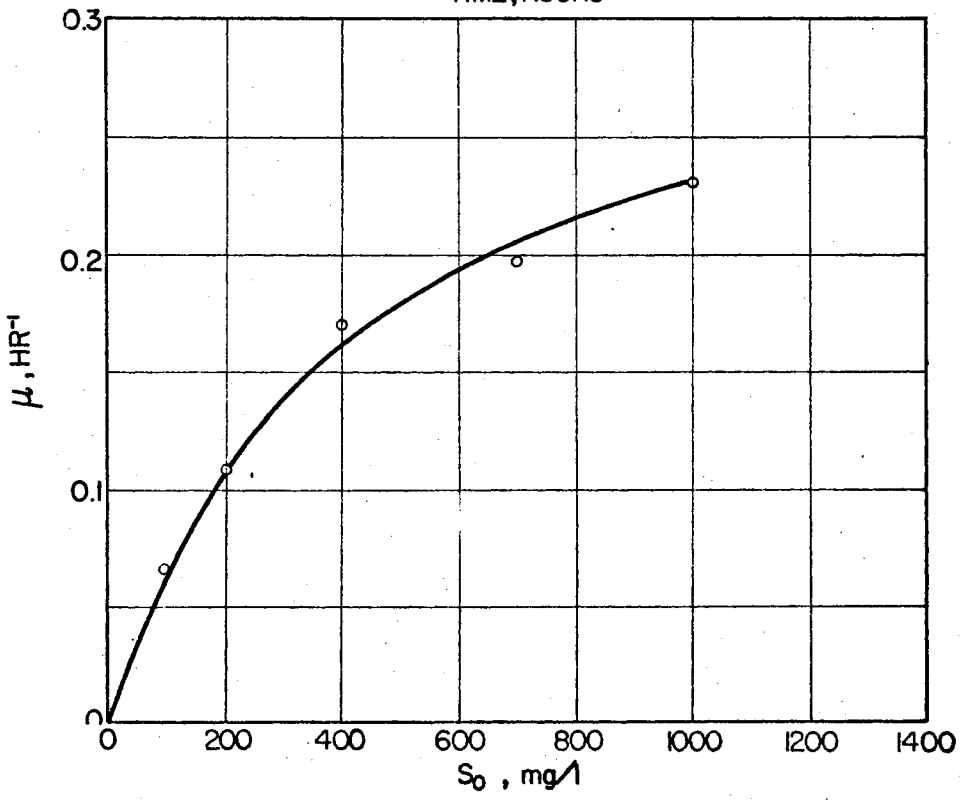

μ, HR⁻¹
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
S₀, mg/l

Figure 29. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 5000 mg/l. Experiment No. 2

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 30 hr^{-1} and 230 mg/l, respectively

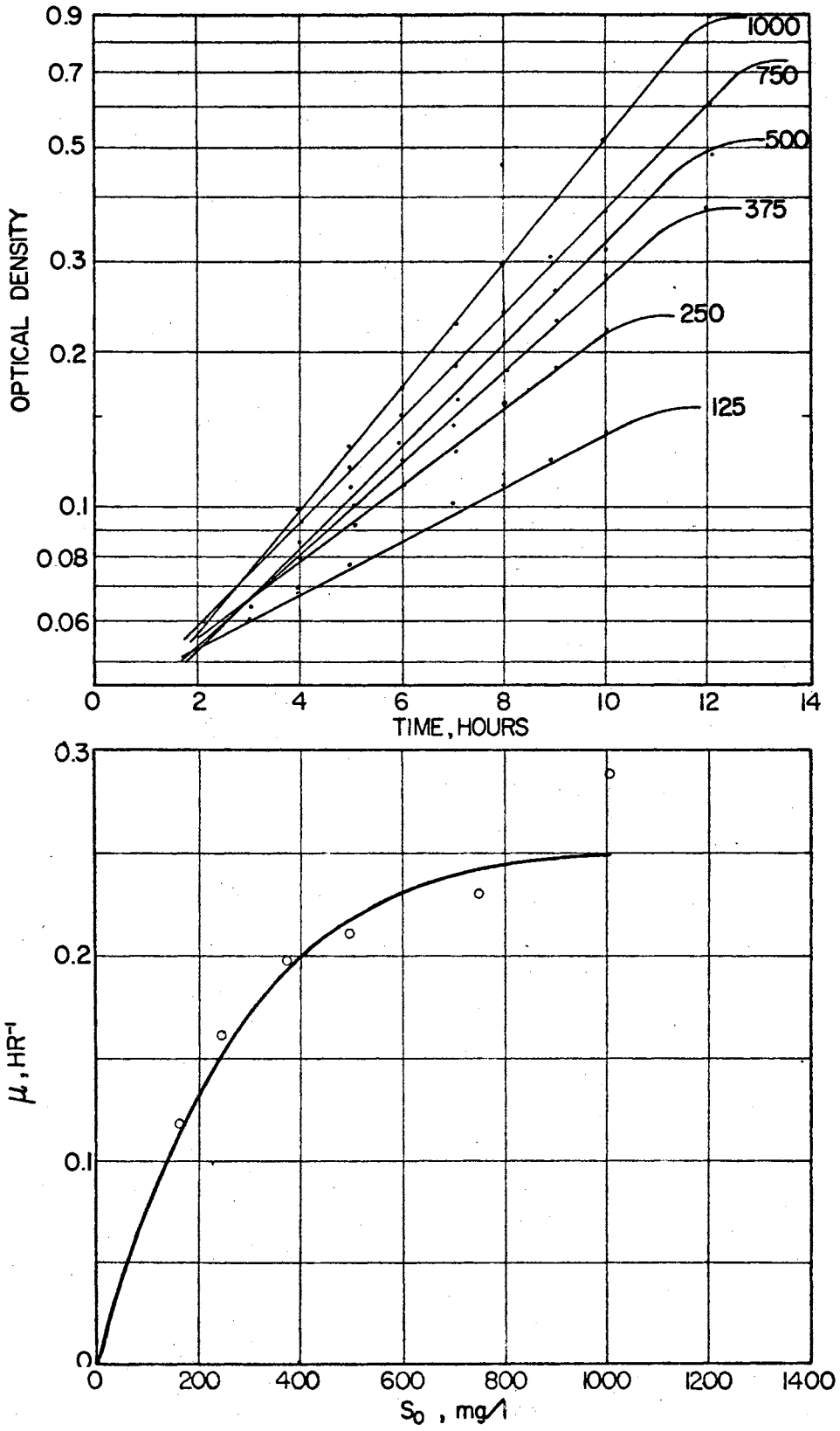

OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
750
500
375
250
125
0
2
4
6
8
10
12
14
TIME, HOURS
μ, HR⁻¹
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
S₀, mg/l

Figure 30. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 5000 mg/l. Experiment No. 3

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are $30\ hr^{-1}$ and 105 mg/l, respectively

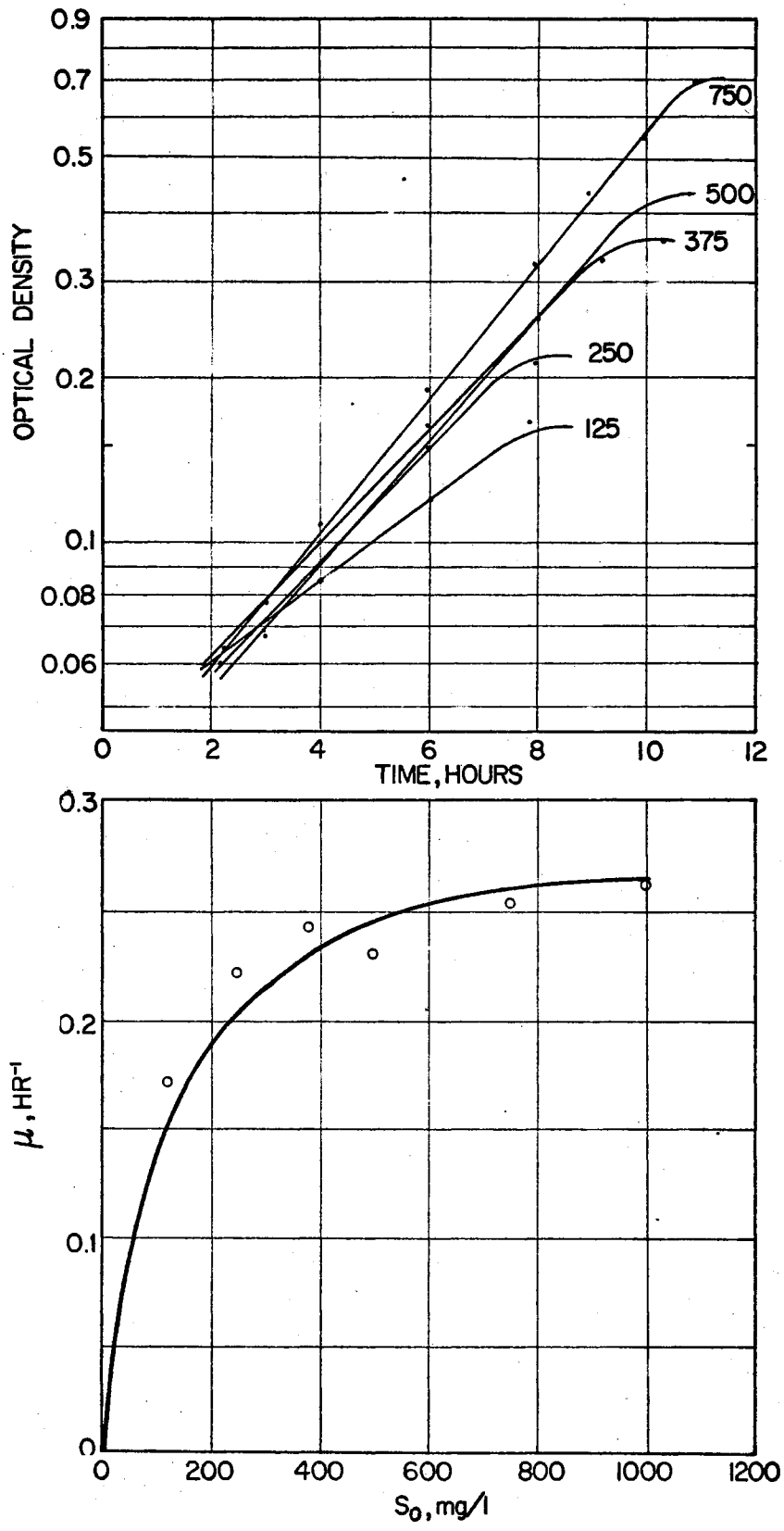
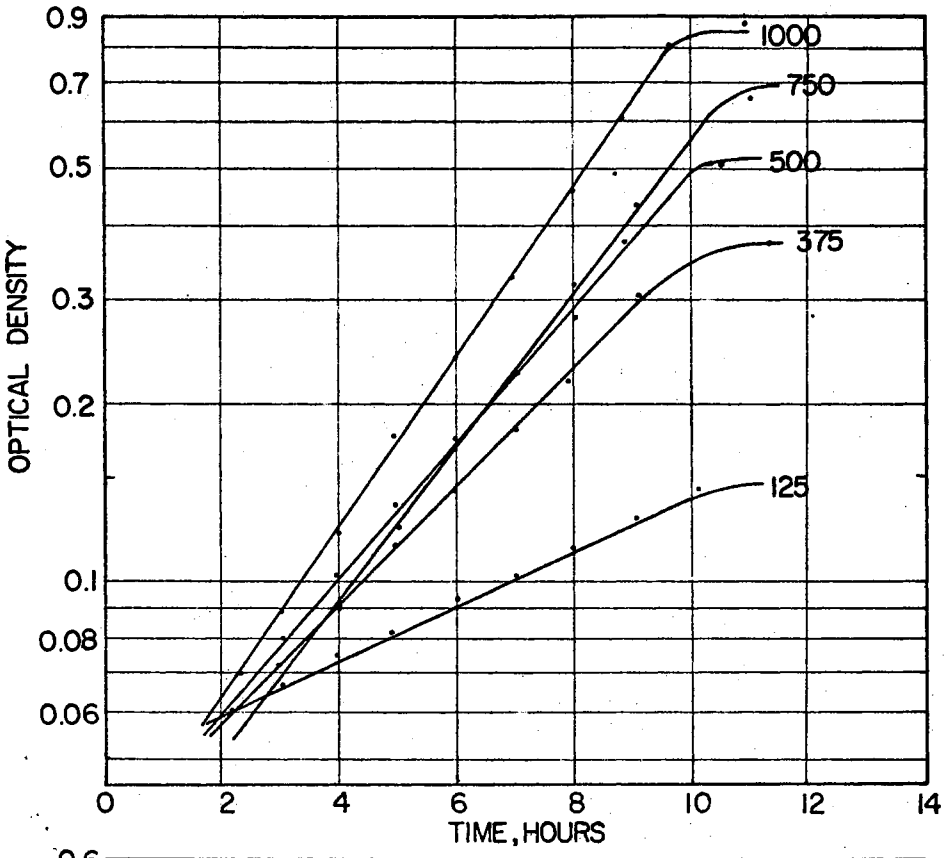

0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
OPTICAL DENSITY
750
500
375
250
125
0
2
4
6
8
10
12
TIME, HOURS
0.3
0.2
0.1
0
μ, HR⁻¹
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 31. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 1000 mg/l and X_R of 5000 mg/l. Experiment No. 4

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.42 hr^{-1} and 313 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
750
500
375
125
0
2
4
6
8
10
12
14
TIME, HOURS

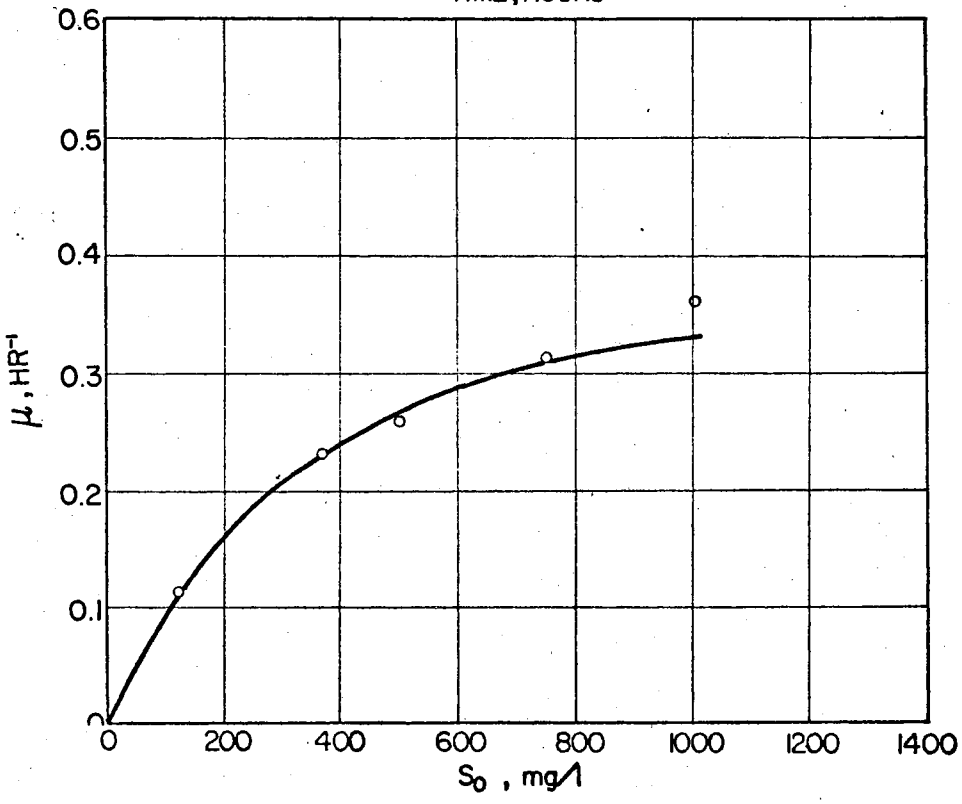

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
1400
S₀, mg/l

Figure 32. Performance of Once-through System at an S_i of 500 mg/l Subsequent to Cessation of Recycle of Sludge of 5000 mg/l X_R

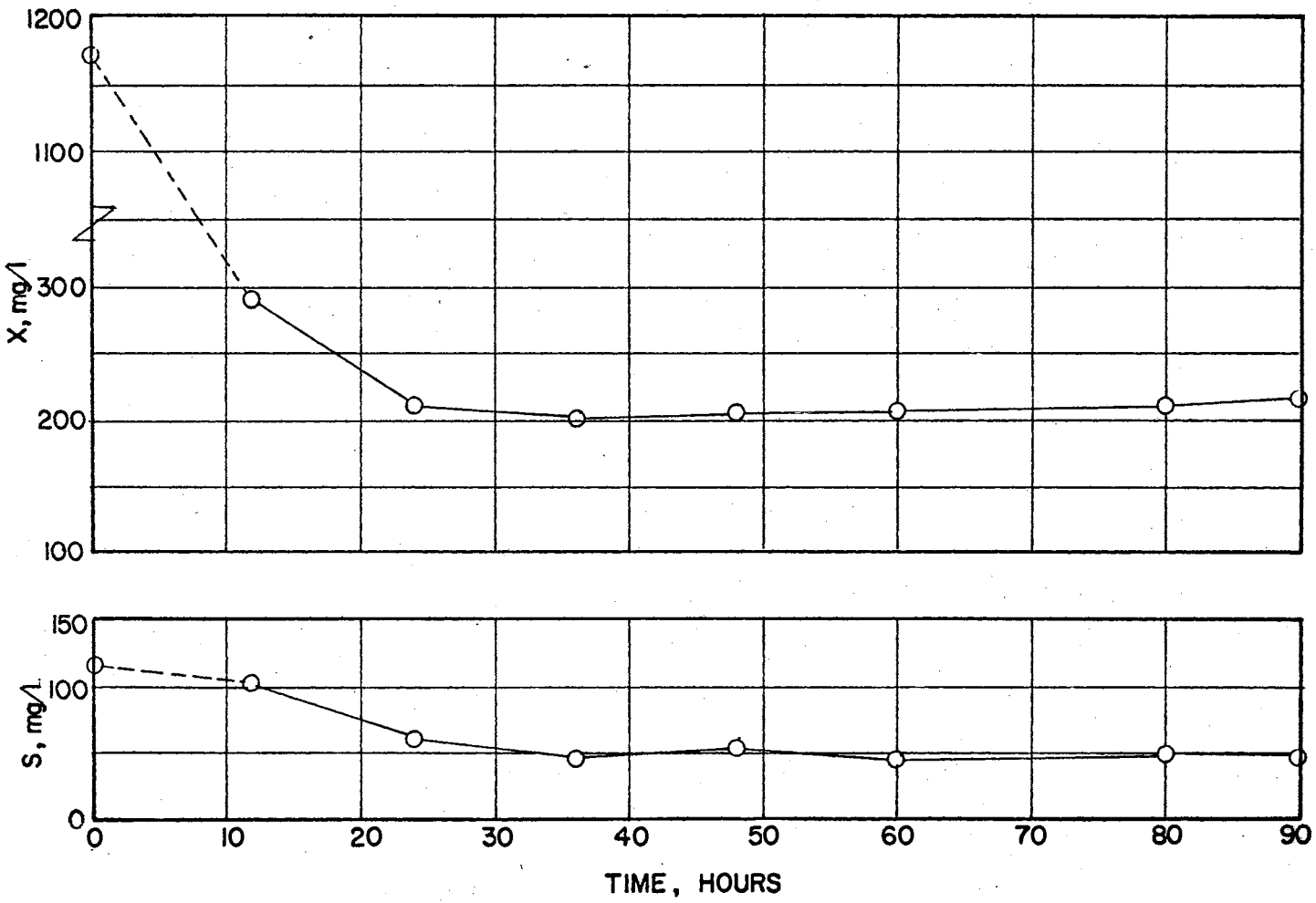

1200
1100
300
200
100
X, mg/l
150
100
0
S, mg/l
0
10
20
30
40
50
60
70
80
90
TIME, HOURS

Figure 33. Performance of Once-through System at an S_i of 1000 mg/l Subsequent to Cessation of Recycle of Sludge of 5000 mg/l X_R

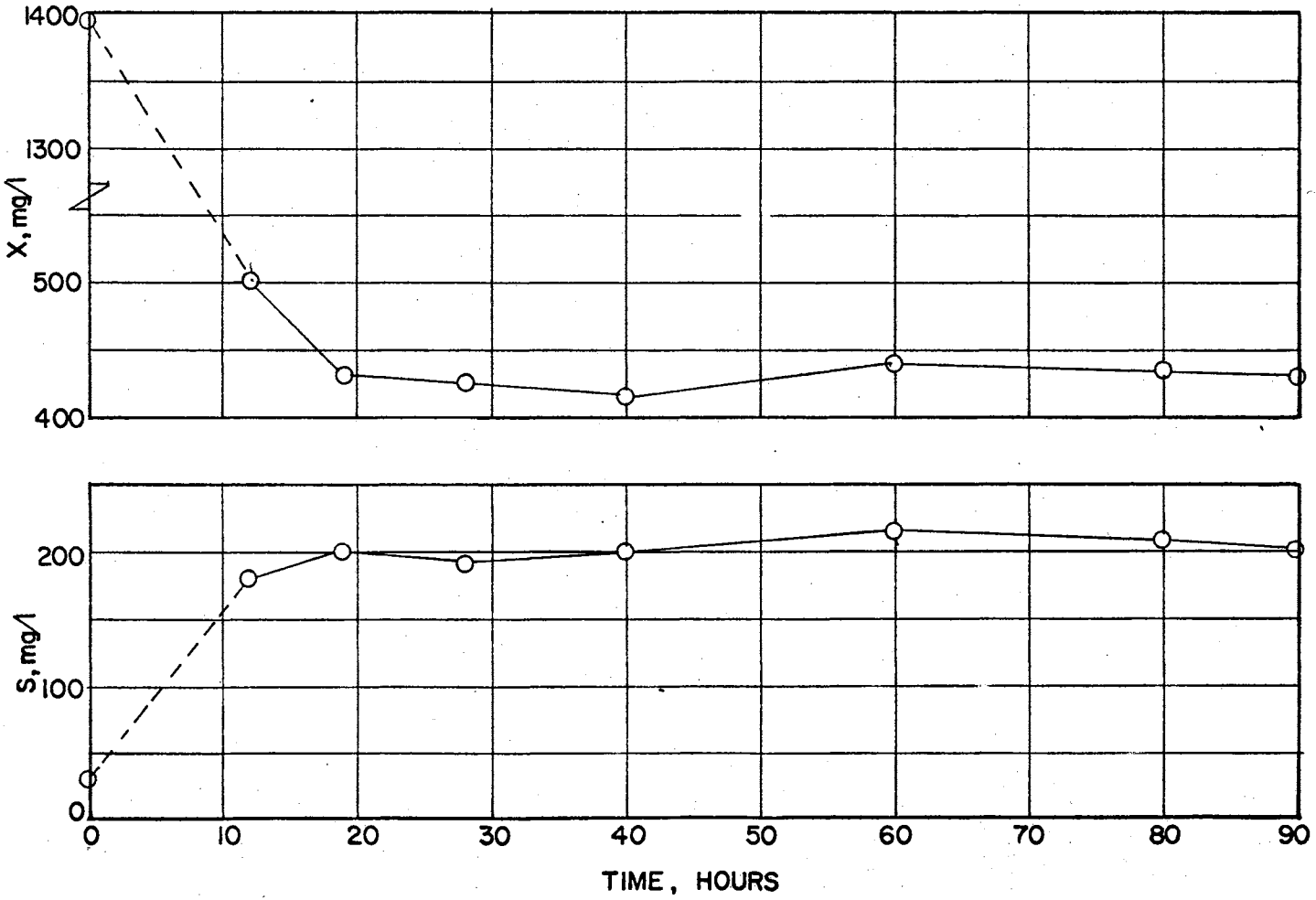

1400
1300
500
400
X, mg/l
200
100
0
S, mg/l
0
10
20
30
40
50
60
70
80
90
TIME, HOURS

Figure 34. Response of Completely Mixed Activated Sludge Pilot Plant Operating at an X_R of 5000 mg/l and an S_i of 500 mg/l Glucose to a Three-fold Increase in S_i (from 519 to 1640 mg/l COD)

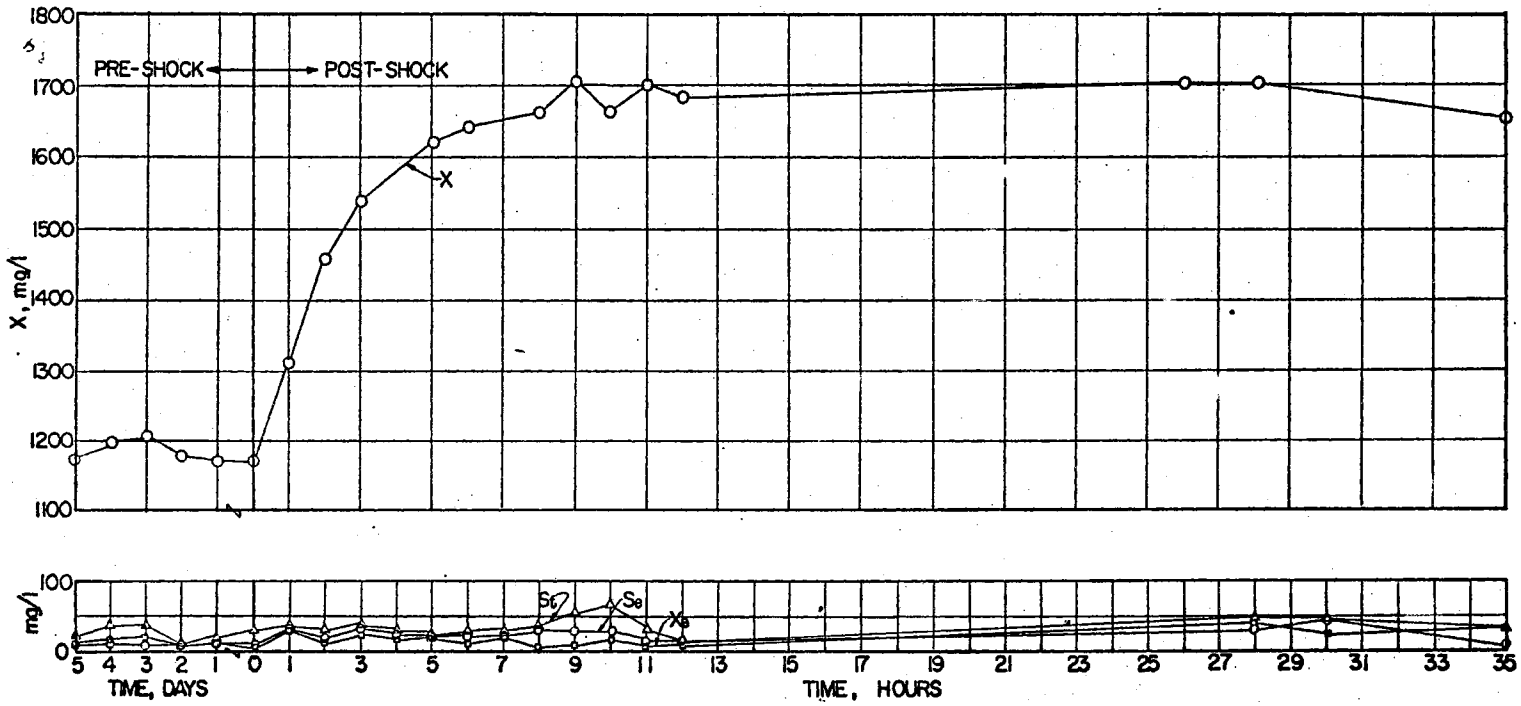
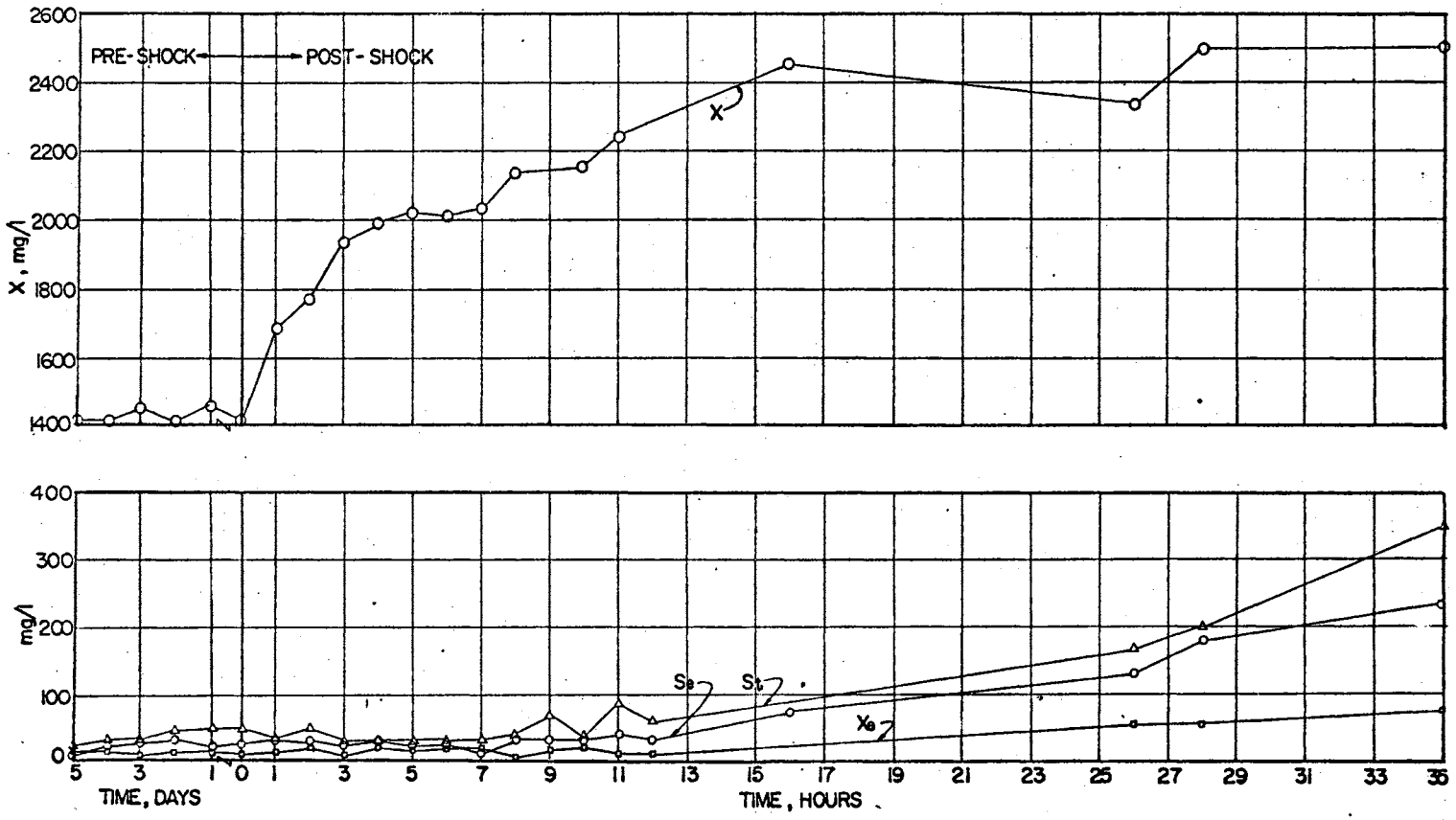

PRE-SHOCK
POST-SHOCK
X
X, mg/l
1800
1700
1600
1500
1400
1300
1200
1100
mg/l
100
0
S_6
S_8
X_8
5 4 3 2 1 0 1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
TIME, DAYS
TIME, HOURS

Figure 35. Response of Completely Mixed Activated Sludge Pilot Plant Operating at an X_R of 5000 mg/l and an S_i of 1000 mg/l Glucose to a Three-fold Increase in S_i (from 1030 to 3600 mg/l COD)


PRE-SHOCK
POST-SHOCK
X
X, mg/l
2600
2400
2200
2000
1800
1600
1400
mg/l
400
300
200
100
0
Se
Si
Xa
5 3 1 0 1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35
TIME, DAYS
TIME, HOURS

for reaching the new steady state value in X was about 16 hours. It is noted from Figure 35 that the effluent quality did not change until twelve hours after shock was applied. The effluent COD and solids increased steadily thereafter. The solids in the effluent reached 75 mg/l, S_e was 230 mg/l, and the system appeared to be continuing to deteriorate at the time the experiment was terminated.

Four runs were made to evaluate the reproducibility of the model. In all of these four runs, the X_R was the same, i.e., 10,000 mg/l. In order to study the reproducibility at low and high loadings, two of these four runs were made at a 500-mg/l loading, and the other two runs were performed at 2000 mg/l. One of the two runs at each loading was twenty days long, and the other, ten days. The only difference between the two runs was that the sludge consisted of heterogeneous populations developed from different initial inocula from the sewage treatment plant. For convenience of presentation, the 20-day and 10-day runs at 500 mg/l loadings are designated A and B, respectively, and the 20- and 10-day runs at 2000 mg/l loadings are designated C and D, respectively. The steady state data for runs A and B are shown in Tables XII and XIII and plotted in Figures 36 and 37. Similarly, Table XIV, Figure 38, and Table XV and Figure 39 correspond to runs C and D, respectively.

The mean feed COD values for runs A and B were 504 and 506 mg/l, respectively, and for runs C and D, they were 2010 and 2090 mg/l, respectively. Effluent characteristics, shown in the top part of the graph, were measured by filtrate COD of the effluent, suspended solids concentration, total COD in the clarifier effluent, and a few 5-day BOD samples. Even the most conservative measure of efficiency, i.e., supernatant COD, indicated average values of 91 and 94 percent at the

TABLE XII

STEADY STATE DATA AT S_i = 500 mg/l GLUCOSE, X_R = 10,000 mg/l (20-day run)

Days	X mg/l	X_R mg/l	X_e mg/l	X_w mg/d	S_e mg/l	S_t mg/l	S_R mg/l	Protein %	Carbo. %	BOD_5 mg/l	NH_3-N Feed mg/l	NH_3-N Eff. mg/l
1	2140	9800	30	1100	80	60	20			10.5	52	39
2	2200	10090	15	990	20	30	10	45	27			
3	2160	9800	0	1000	30	35	15			5.5	41	27
4	2140	9700	10	980	40	55	15	47	25			
5	2110	10650	35	1080	50	55	10					
6	2210	10700	0	1200	30	50	10	36.5	31	10.5	48	36
7	2110	9700	35	1050	0	20	10					
8	2180	10100	15	900	10	20	15					
9	2140	10080	35	950	20	50	5	46.5			45	31
10	2130	10010	40	1040	40	65	10					
11	2165	9100	20	950	40	55	10			15.5	58	41
12	2180	9500	30	890	50	70	10	47.5	31			
13	2130	9700	18	940	30	45	5			10.5	43	28
14	2135	10080	40	1020	20	65	10					
15	2005	10100	45	1200	40	70	5					
16	2250	10500	30	1000	15	25	0			15.5	51	36
17	2120	9900	25	900	20	40	10					
18	2130	9800	30	1000	35	30	5	52.5	27			
19	2140	9990	40	1020	15	30	10			10.5	49	33
20	2190	10200	15	1100	20	20	0					

TABLE XIII

STEADY STATE DATA AT S_i = 500 mg/l GLUCOSE, X_R = 10,000 mg/l (10-day run)

Days	X mg/l	X_e mg/l	X_R mg/l	X_w mg/day	S_e mg/l	S_t mg/l	S_R mg/l	BOD_5 mg/l	Protein %	Carbo. %	NH_3-N Feed mg/l	NH_3-N Eff. mg/l
1	2120	10	10000	1010	10	30	10		50	32	50	35
2	2210	10	9900	1000	15	25	5				55	39
3	2080	25	9875	980	5	25	0	10	47.5	30		
4	2135	30	10200	1210	10	40	5				49	34
5	2100	10	9900	1070	15	20	10		52.5	32	46	32
6	2160	0	10150	1040	15	15	5	5				
7	2180	5	10100	980	0	15	10		46.5	32	52	38
8	2080	10	9980	990	20	35	10	10				
9	2000	15	9670	1010	25	45	15		48	30	45	30
10	2110	10	9900	1000	30	35	10					

Figure 36. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l (20-day run)

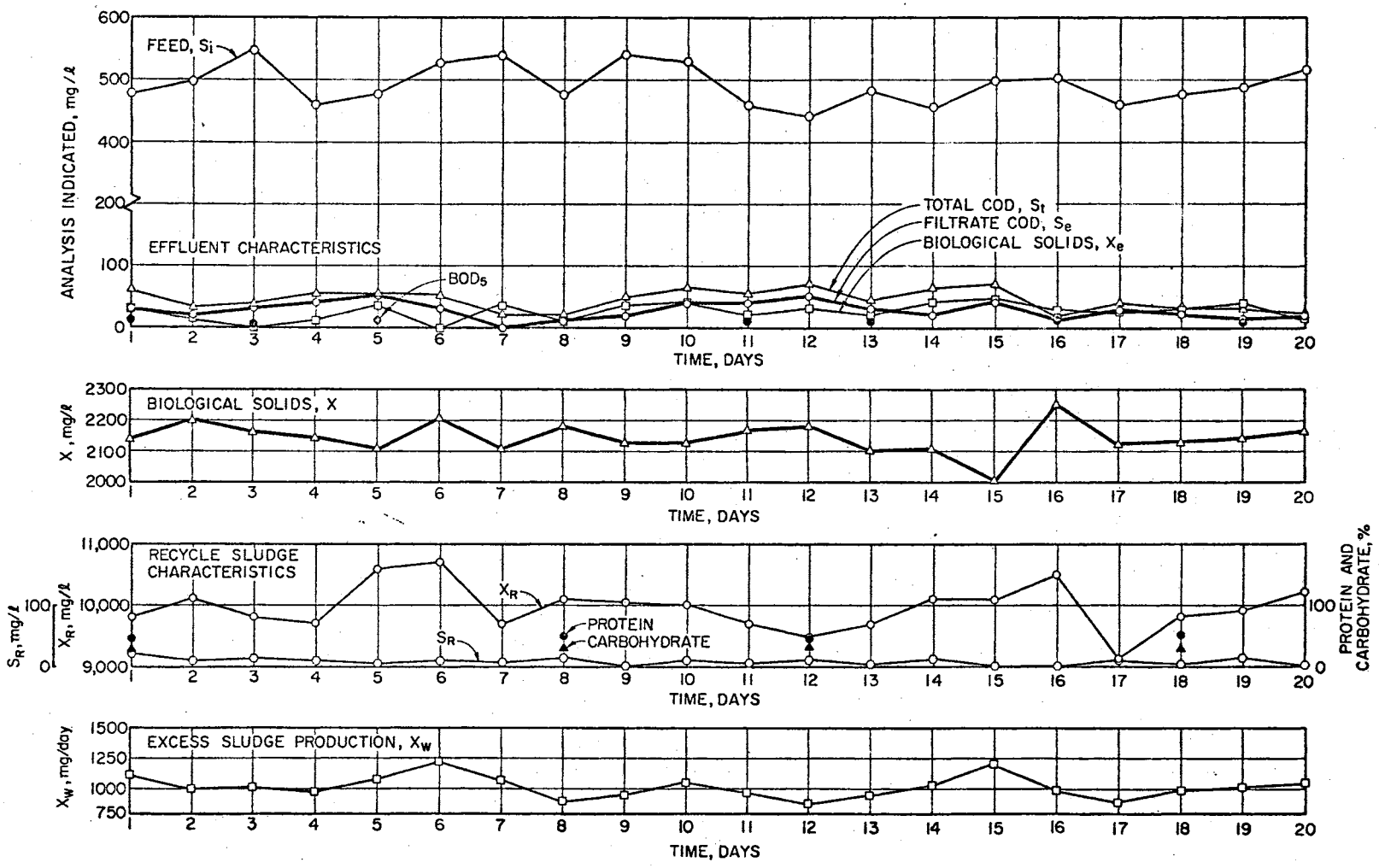

FEED, Si
EFFLUENT CHARACTERISTICS
BOD5
TOTAL COD, St
FILTRATE COD, Se
BIOLOGICAL SOLIDS, Xe
ANALYSIS INDICATED, mg/ℓ
TIME, DAYS
BIOLOGICAL SOLIDS, X
X, mg/ℓ
RECYCLE SLUDGE CHARACTERISTICS
XR
SR
PROTEIN
CARBOHYDRATE
SR, mg/ℓ
XR, mg/ℓ
PROTEIN AND CARBOHYDRATE, %
EXCESS SLUDGE PRODUCTION, Xw
Xw, mg/day

Figure 37. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l (10-day run)

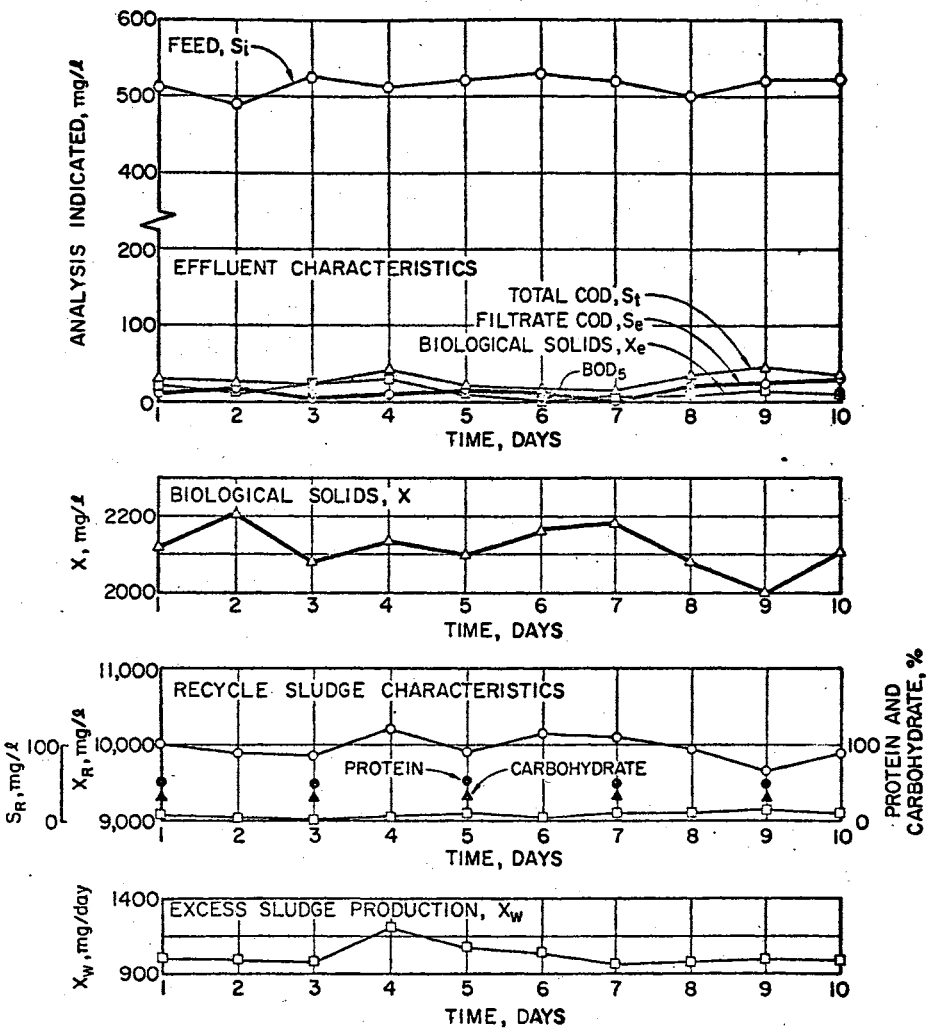

ANALYSIS INDICATED, mg/ℓ
600
500
400
200
100
0
FEED, Si
EFFLUENT CHARACTERISTICS
TOTAL COD, St
FILTRATE COD, Se
BIOLOGICAL SOLIDS, Xe
BOD5
1 2 3 4 5 6 7 8 9 10
TIME, DAYS
X, mg/ℓ
2200
2000
BIOLOGICAL SOLIDS, X
1 2 3 4 5 6 7 8 9 10
TIME, DAYS
SR, mg/ℓ
100
0
XR, mg/ℓ
11,000
10,000
9,000
RECYCLE SLUDGE CHARACTERISTICS
PROTEIN
CARBOHYDRATE
100
0
PROTEIN AND CARBOHYDRATE, %
1 2 3 4 5 6 7 8 9 10
TIME, DAYS
Xw, mg/day
1400
900
EXCESS SLUDGE PRODUCTION, Xw
1 2 3 4 5 6 7 8 9 10
TIME, DAYS

TABLE XIV

STEADY STATE DATA AT S_i = 2000 mg/l GLUCOSE, X_R = 10,000 mg/l (20-day run)

Days	X mg/l	X_R mg/l	X_e mg/l	X_w mg/d	S_e mg/l	S_t mg/l	S_R mg/l	Protein %	Carbo. %	BOD_5 mg/l	NH_3-N Feed mg/l	NH_3-N Eff. mg/l
1	3080	10700	37	6410	10	25	10			15.0	190	121
2	2900	10600	40	6215	50	90	0	40.0	31.5			
3	2890	10200	10	6000	30	50	15			17.0	165	95
4	2850	9700	5	6400	45	65	12	39.0	32.0			
5	2900	9820	50	6320	50	55	10					
6	2810	9670	15	6400	40	65	10			15.5	205	127
7	2840	10170	2	6050	0	30	5					
8	2890	10100	20	6250	30	55	15					
9	2950	9980	15	6500	40	70	10					
10	2870	10560	40	6700	15	40	5					
11	2890	10400	25	6300	10	26	10	39.0	27.0	25.0		
12	2850	10300	30	6100	90	95	25					
13	2800	10640	10	6300	50	60	10			15.0	175	110
14	2790	9680	17	6020	60	70	15					
15	2850	10600	20	5900	60	90	15					
16	2860	10200	20	6200	60	80	15	36.5	36.0	10.0	190	125
17	2900	9800	15	6300	35	75	0					
18	3010	9500	18	6450	40	65	5					
19	2860	10800	35	6500	15	40	10			15.0	214	140
20	2875	9700	40	6420	25	45	15	42.0	40.0			

Figure 38. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 2000 mg/l (20-day run)

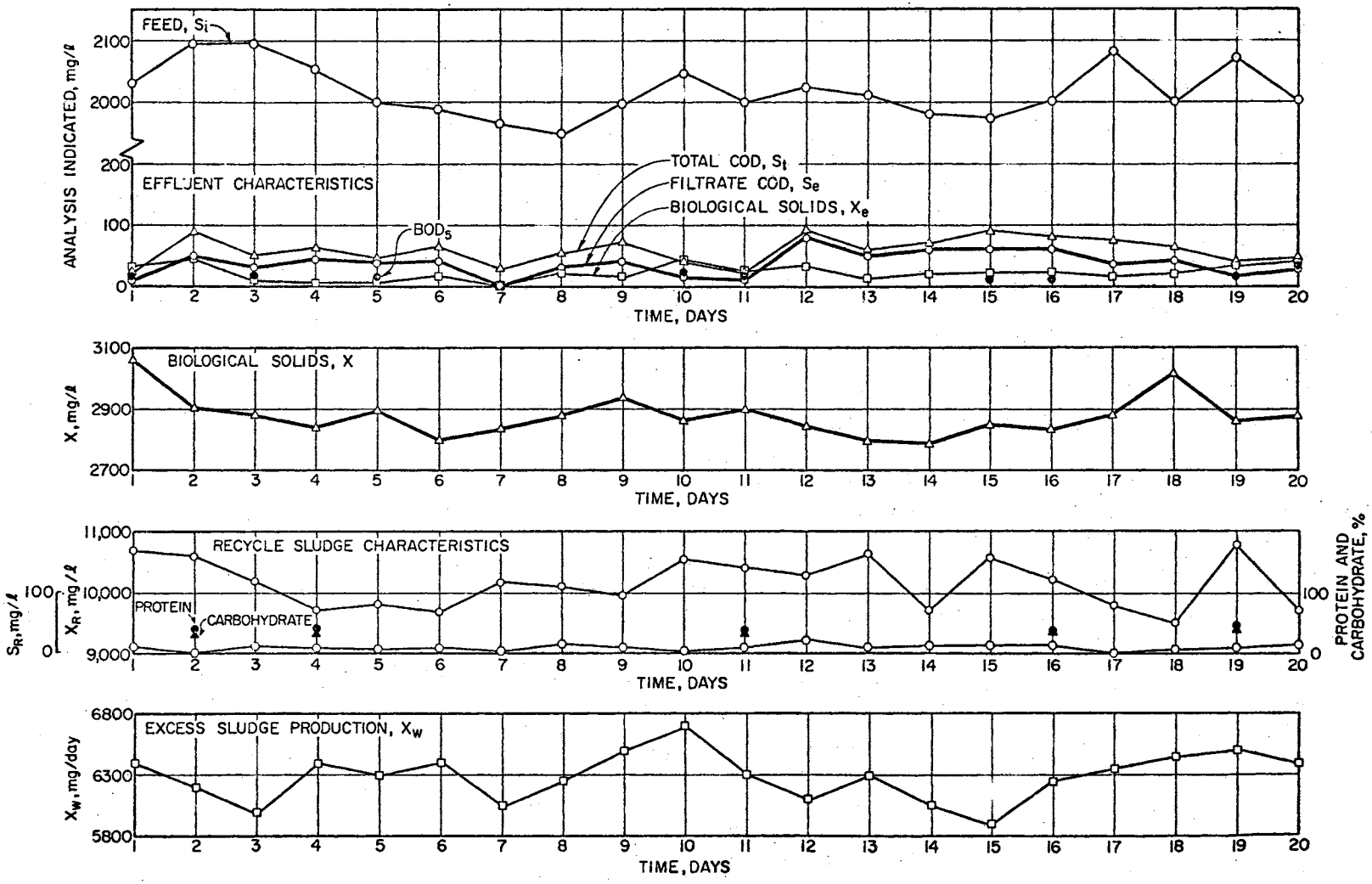
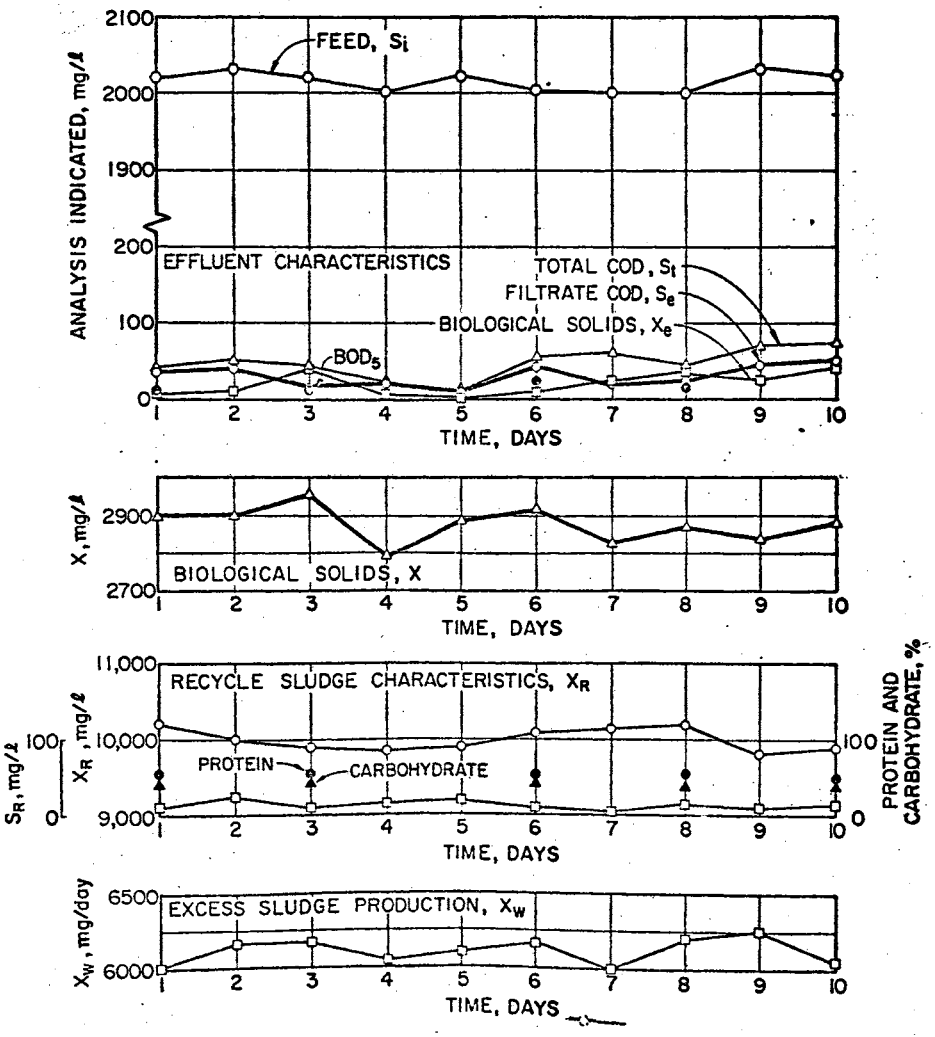

FEED, Si
EFFLUENT CHARACTERISTICS
TOTAL COD, St
FILTRATE COD, Se
BIOLOGICAL SOLIDS, Xe
BOD5
ANALYSIS INDICATED, mg/ℓ
TIME, DAYS
BIOLOGICAL SOLIDS, X
X, mg/ℓ
RECYCLE SLUDGE CHARACTERISTICS
PROTEIN
CARBOHYDRATE
SR, mg/ℓ
XR, mg/ℓ
PROTEIN AND CARBOHYDRATE, %
EXCESS SLUDGE PRODUCTION, Xw
Xw, mg/day

TABLE XV

STEADY STATE DATA AT S_i = 2000 mg/l GLUCOSE, X_R = 10,000 mg/l (10-day run)

Days	X mg/l	X_e mg/l	X_R mg/l	X_w mg/day	S_e mg/l	S_t mg/l	S_R mg/l	BOD_5 mg/l	Protein %	Carbo. %	NH_3-N Feed mg/l	NH_3-N Eff. mg/l
1	2890	5	10210	6005	35	40	10	10	55	40	195	110
2	2900	10	10010	6300	40	50	25				200	92
3	2960	40	9980	6350	15	45	10	15	53	42.5	190	105
4	2790	5	9890	6100	20	20	20		50	41		
5	2890	0	9900	6200	10	10	20				105	105
6	2920	10	10100	6320	45	55	10	25	55	38	185	98
7	2830	25	10150	6000	20	60	5		50	37		
8	2870	35	10200	6400	25	45	15	15			195	115
9	2840	25	9800	6500	45	70	10					
10	2880	40	9900	6100	50	75	15					

Figure 39. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 2000 mg/l (10-day run)


ANALYSIS INDICATED, mg/ℓ
FEED, S_i
EFFLUENT CHARACTERISTICS
TOTAL COD, S_t
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X_e
BOD_5
TIME, DAYS
X, mg/ℓ
BIOLOGICAL SOLIDS, X
TIME, DAYS
RECYCLE SLUDGE CHARACTERISTICS, X_R
S_R, mg/ℓ
X_R, mg/ℓ
PROTEIN
CARBOHYDRATE
PROTEIN AND CARBOHYDRATE, %
TIME, DAYS
X_w, mg/day
EXCESS SLUDGE PRODUCTION, X_w
TIME, DAYS

500 mg/l loading, and at the higher loading they were 97 and 98 percent. Of particular interest insofar as the model is concerned is the reproducibility of the values of $\bar{X}$ for each loading level. The average values at lower loading were 2150 mg/l during the 20-day run, and 2130 mg/l during the 10-day run. These are adjudged to be in excellent agreement for a biological system. For the higher loading, it so happened that the average of 20 and 10 determinations of X values during the steady state period came out to be the same, viz., 2885 mg/l. It is emphasized that such a result should not be taken as an indication that such reproducibility can be expected of this model. During the long run (20 day), the range for X was 2790 to 3080 mg/l, while during the short run (10 day), X varied between 2830 and 2960 mg/l. Thus, the fact that the means were exactly the same does indeed give a false impression of the degree of reproducibility. Another important parameter to be compared so far as reproducibility is concerned is the excess sludge production, X_w. For runs A and B, the average X_w values were 1015 and 1029 mg/day, respectively, and for runs C and D, the average values for X_w were 6280 and 6230 mg/day, respectively. Thus, the reproducibility of the resultant parameter X_w was also tested and found satisfactory. The reproducibility and effectiveness of the design and operational model are assessed in Table XVI, wherein the average values for all four runs are given.

Figures 40 and 41, and 42 and 43 are the plots of batch experiments conducted during runs A and B. The μ_{max} and K_s values also compared favorably. Figures 44 and 45, and 46 and 47 are the plots of batch experiments performed during runs C and D. The μ_{max} values and K_s values compared favorably. The once-through data for these four runs are shown in Figures 48, 49, 50, and 51.

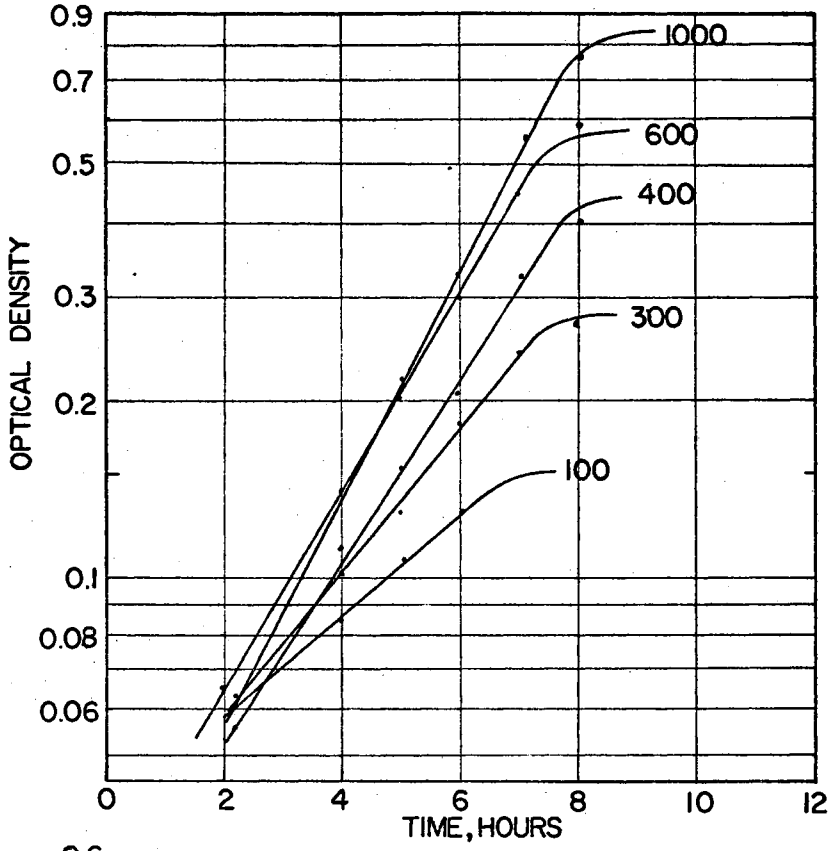
TABLE XVI

REPRODUCIBILITY OF MEAN STEADY STATE VALUES OF EFFLUENT SUBSTRATE AND BIOLOGICAL SOLIDS CONCENTRATION AT S_i VALUES OF 500 AND 2000 mg/l

Feed				Effluent											Biological Solids											
				Filtrate				Supernatant							20-day						10-day						
Nominal		Observed		20-day		10-day		20-day				10-day															
Glucose mg/l	COD mg/l	COD mg/l 20	COD mg/l 10	$\bar{S}_e$	%	$\bar{S}_e$	%	$\bar{S}_t$	%	BOD	$\bar{X}_e$	$\bar{S}_t$	%	BOD	$\bar{X}_e$	$\bar{X}$	$\bar{X}_R$	$\bar{S}_R$	Pro-tein	Carb.	$\bar{X}_W$	$\bar{X}$	$\bar{X}_R$	$\bar{S}_R$	Pro-tein	Carb.	$\bar{X}_W$
500	530	504	506	25	95	15	98	46	91	11	30	29	94	10	14	2150	9925	11	47	28	1015	2120	9970	8	49	32	1029
2000	2120	2010	2090	38	98	31	98	61	97	18	22	47	98	15	19	2885	10140	12	40	33	6280	2885	10010	14	53	41	6230

Figure 40. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 10,000 mg/l. Experiment No. 1 (20-day run)

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.48 hr^{-1} and 140 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
600
400
300
100
0
2
4
6
8
10
12
TIME, HOURS

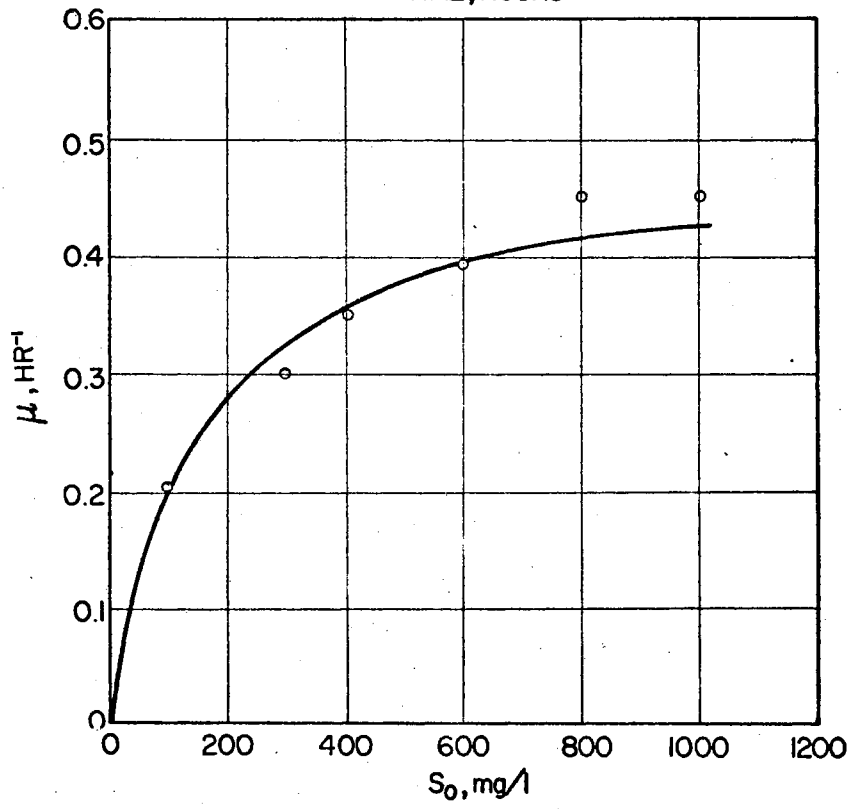
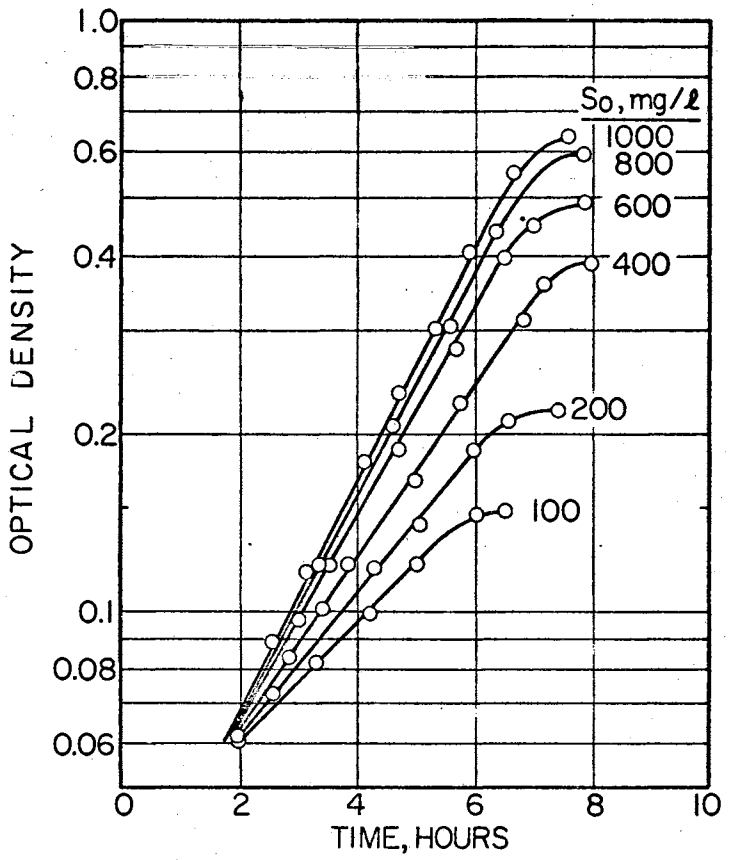

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 41. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 10,000 mg/l. Experiment No. 2 (20-day run)

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.51 hr^{-1} and 110 mg/l, respectively


OPTICAL DENSITY
1.0
0.8
0.6
0.4
0.2
0.1
0.08
0.06
So, mg/ℓ
1000
800
600
400
200
100
0
2
4
6
8
10
TIME, HOURS

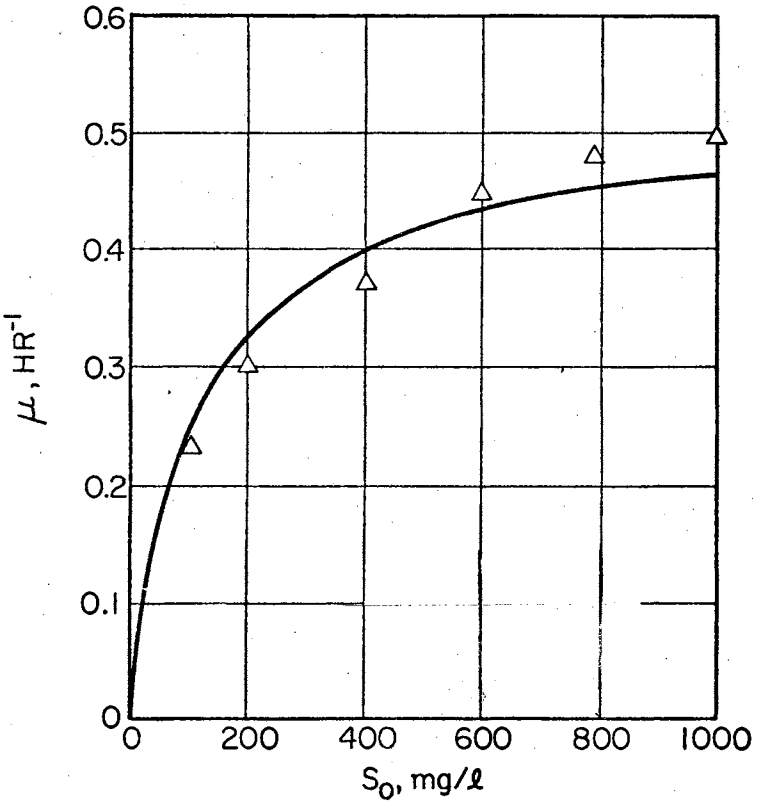
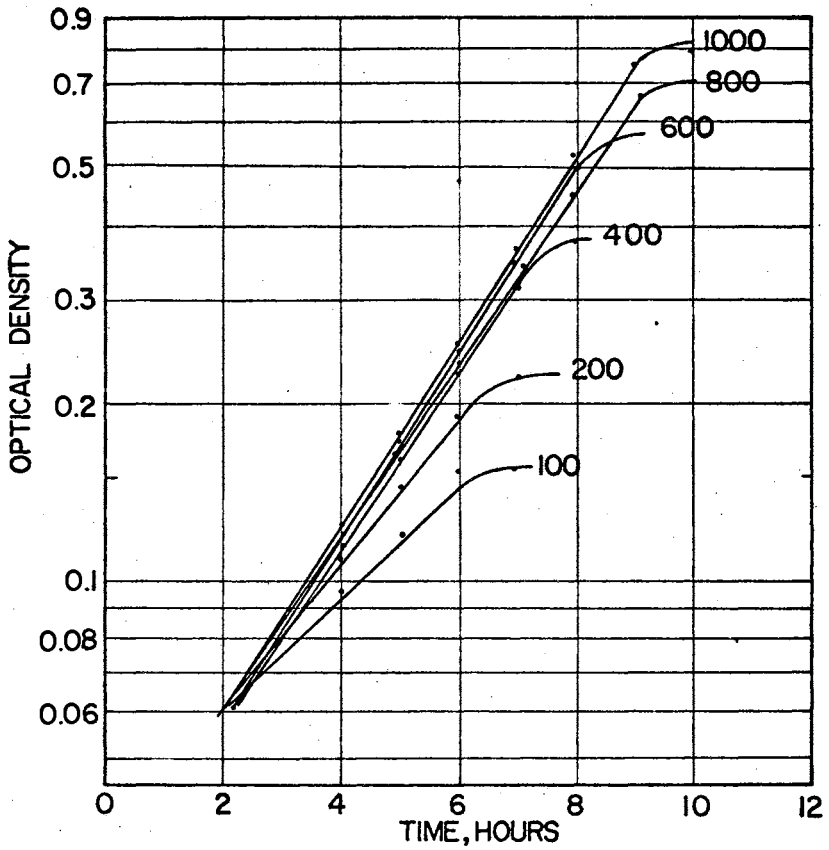

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
S0, mg/ℓ

Figure 42. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 10,000 mg/l. Experiment No. 3 (20-day run)

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.47 hr^{-1} and 95 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
600
400
200
100
0
2
4
6
8
10
12
TIME, HOURS

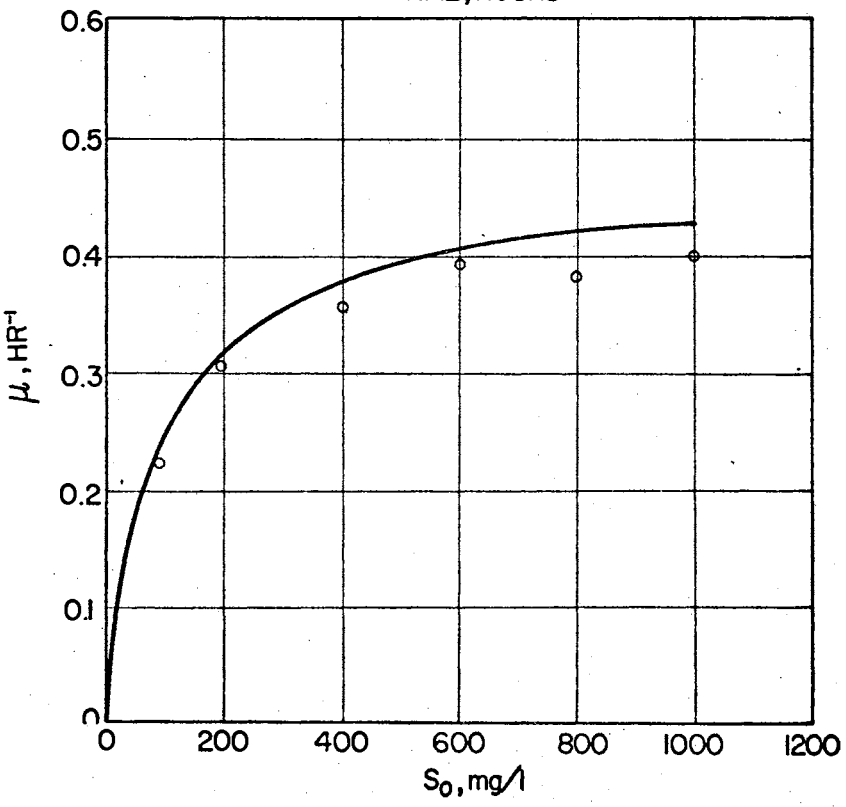
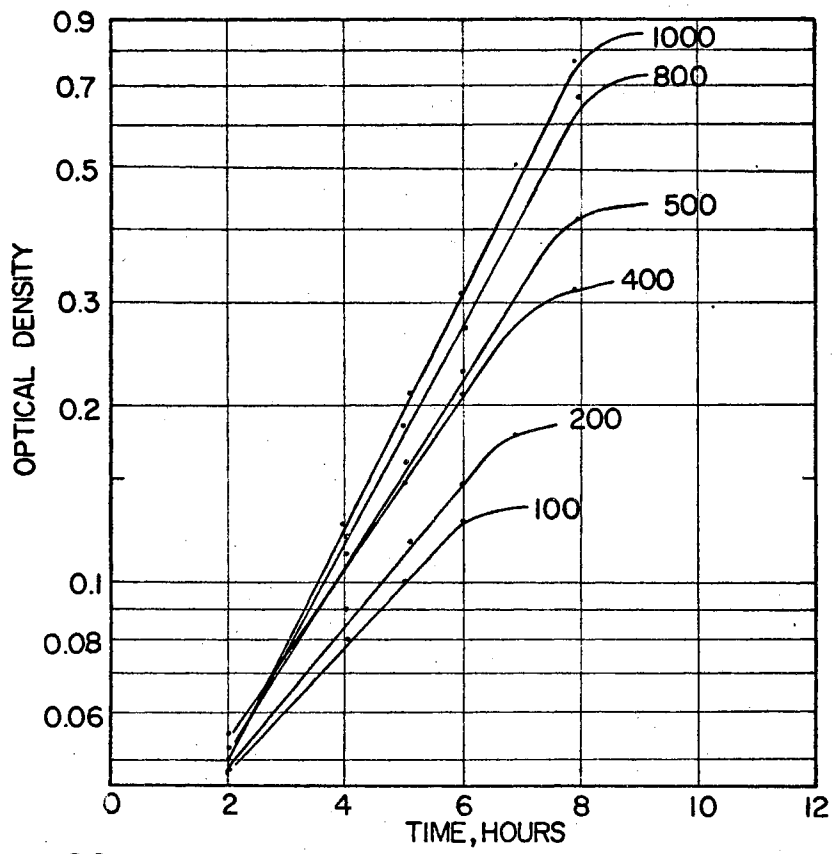

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 43. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 10,000 mg/l (10-day run)

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.52 hr^{-1} and 110 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
500
400
200
100
0
2
4
6
8
10
12
TIME, HOURS

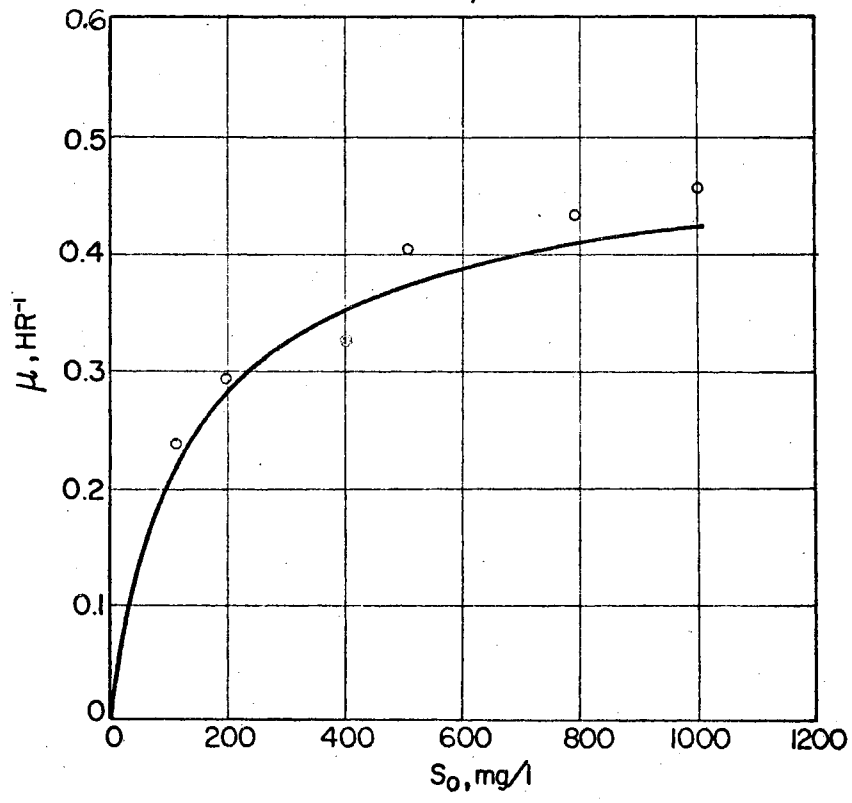
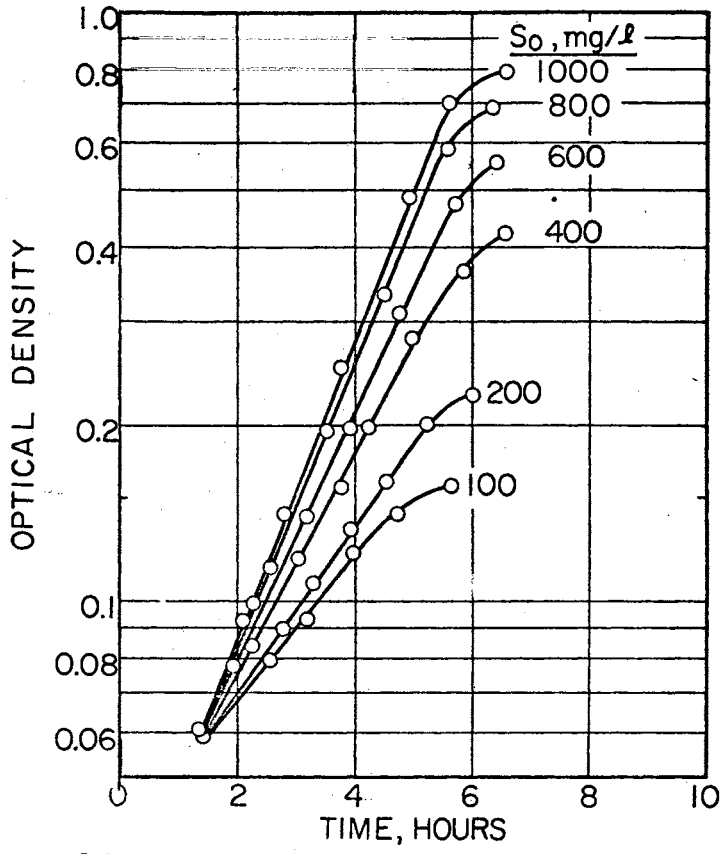

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 44. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 2000 mg/l and X_R of 10,000 mg/l. Experiment No. 1 (20-day run)

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.60 hr^{-1} and 110 mg/l, respectively


OPTICAL DENSITY
1.0
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0
2
4
6
8
10
TIME, HOURS
So, mg/ℓ
1000
800
600
400
200
100

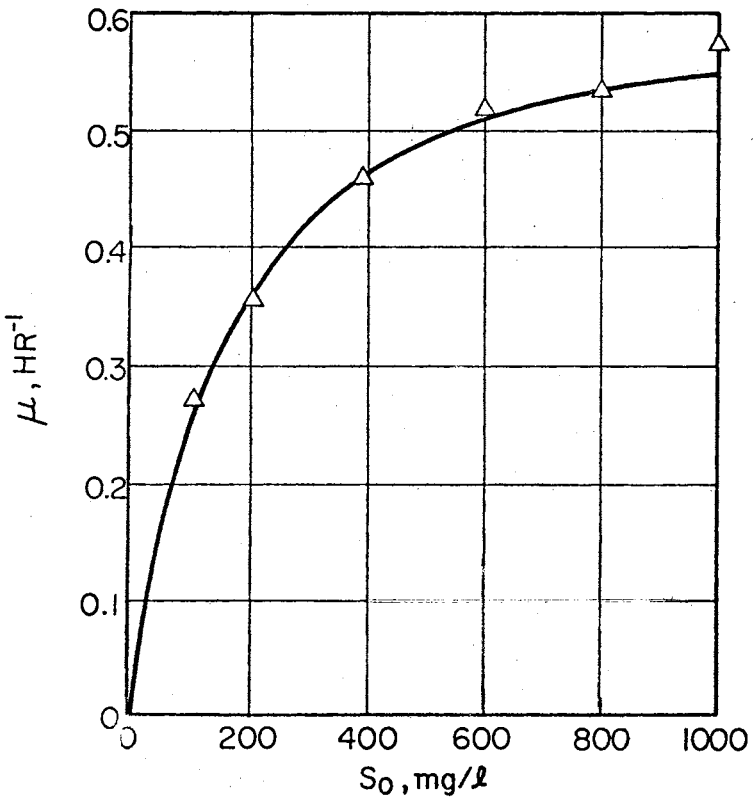
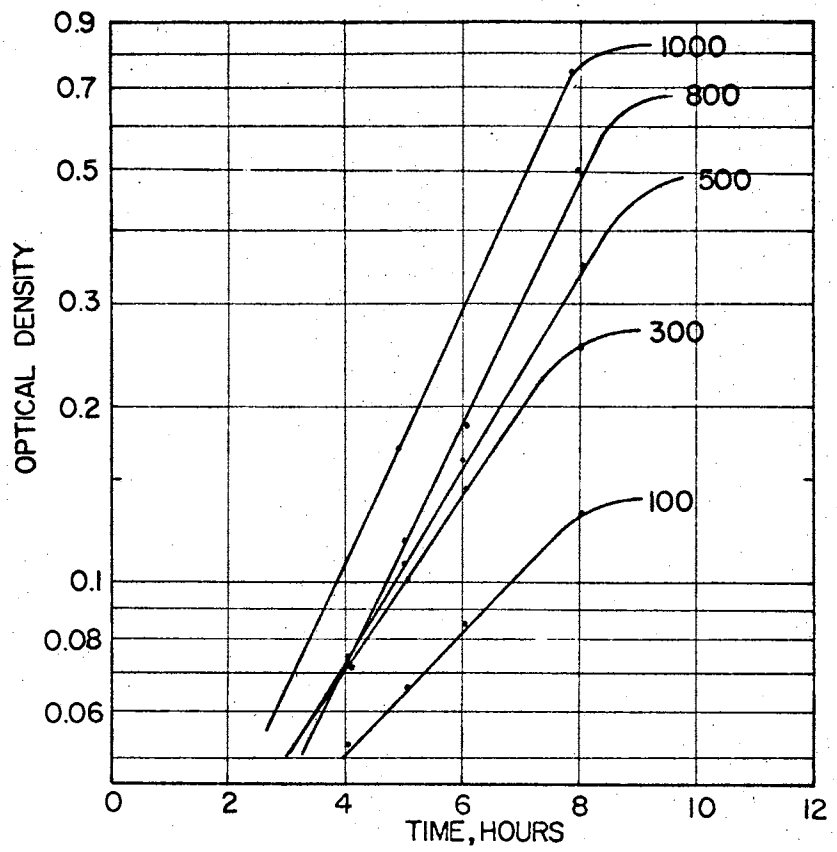

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
So, mg/ℓ

Figure 45. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 2000 mg/l and X_R of 10,000 mg/l (20-day run) Experiment No. 2

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.56 hr^{-1} and 195 mg/l, respectively


0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
OPTICAL DENSITY
1000
800
500
300
100
0
2
4
6
8
10
12
TIME, HOURS

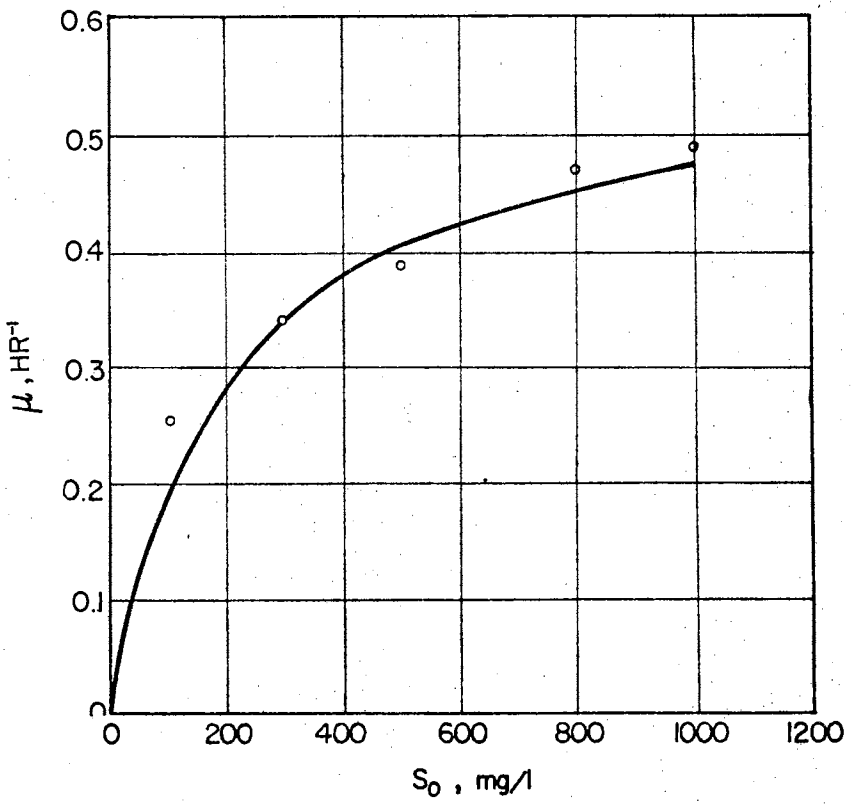
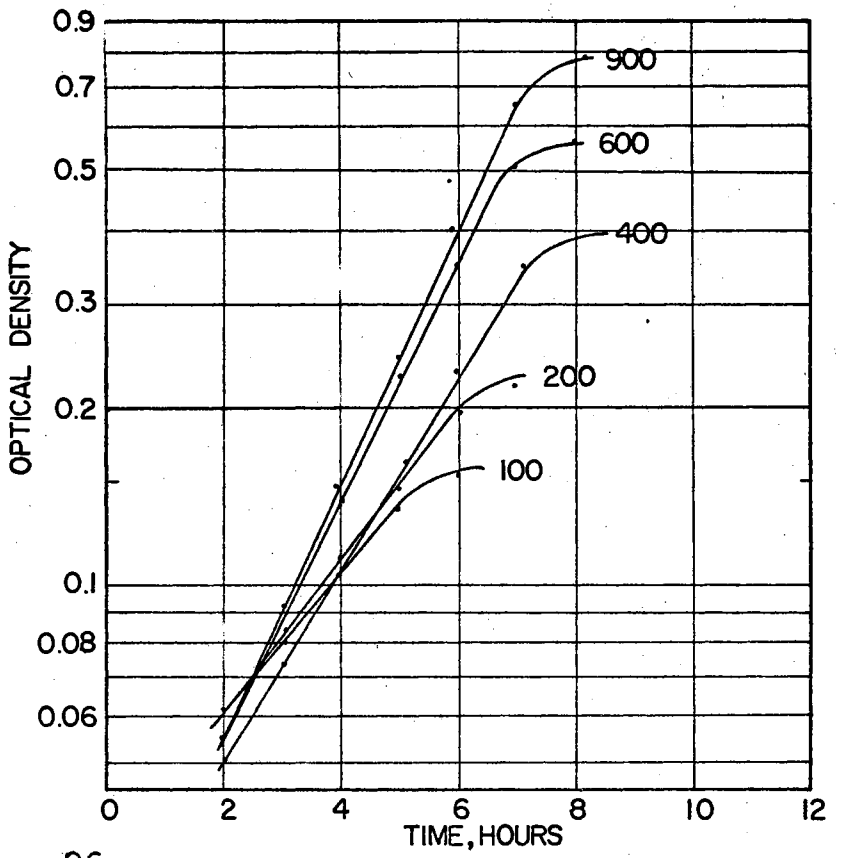

0.6
0.5
0.4
0.3
0.2
0.1
0
μ, HR⁻¹
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 46. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 2000 mg/l and X_R of 10,000 mg/l (20-day run) Experiment No. 3

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.58 hr^{-1} and 105 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
900
600
400
200
100
0
2
4
6
8
10
12
TIME, HOURS

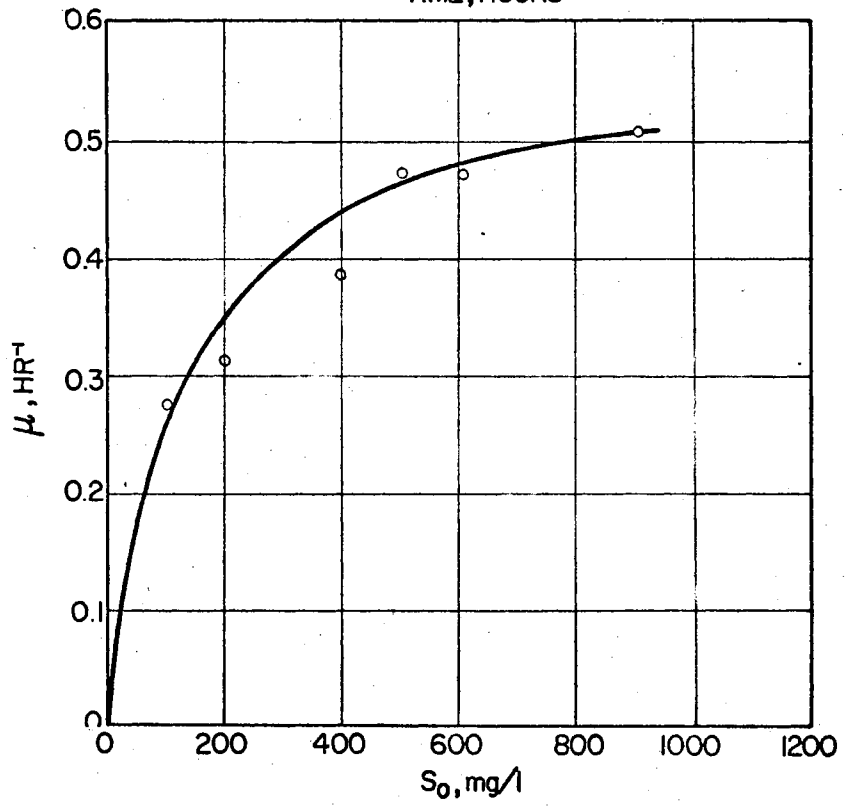
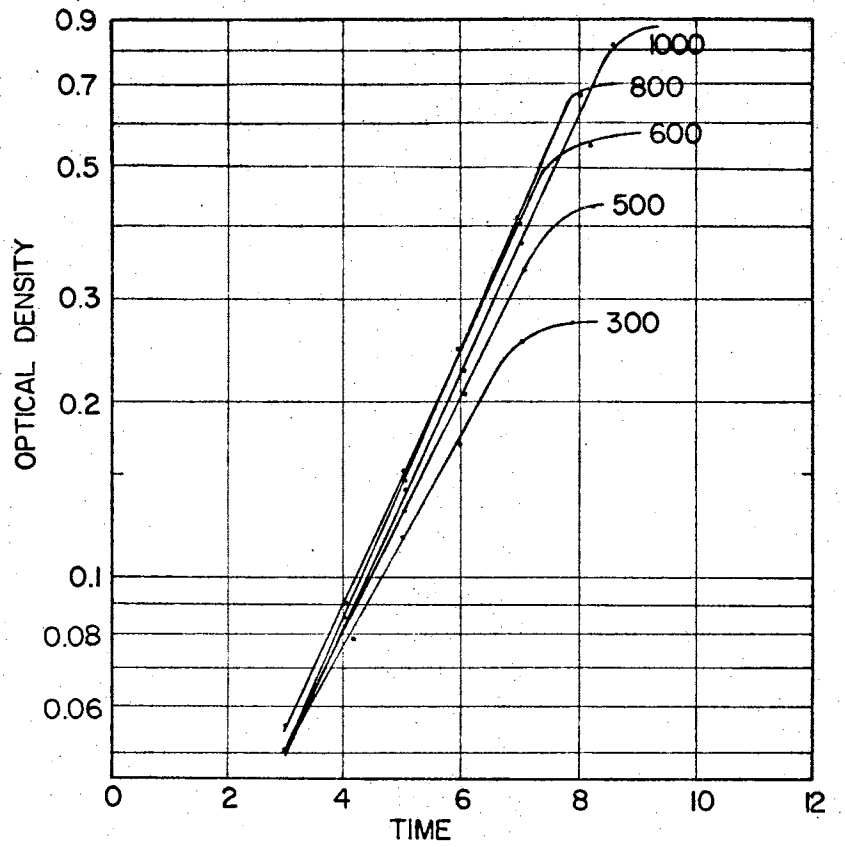

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 47. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 2000 mg/l and X_R of 10,000 mg/l (10-day run) Experiment No. 1

The μ_{max} and K_s values obtained from plot of $1/\mu_o$ vs $1/S_o$ are 0.56 hr^{-1} and 115 mg/l, respectively


OPTICAL DENSITY
0.9
0.7
0.5
0.3
0.2
0.1
0.08
0.06
1000
800
600
500
300
0
2
4
6
8
10
12
TIME

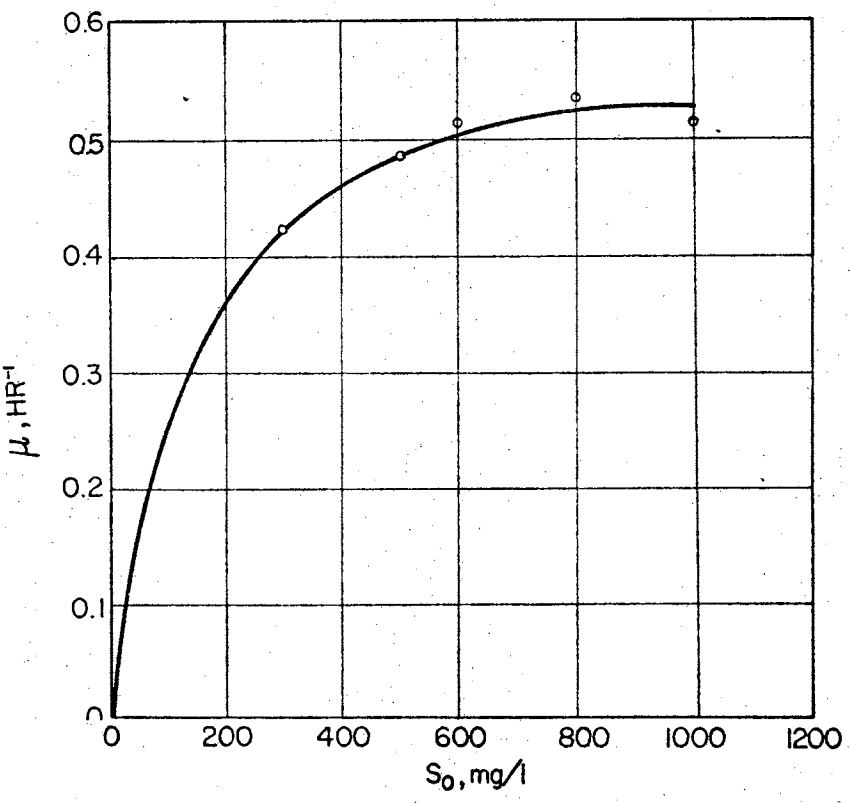

μ, HR⁻¹
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/l

Figure 48. Performance of Once-through System at an S_i of 500 mg/l Subsequent to Cessation of Recycle of Sludge of 10,000 mg/l X_R (20-day run)

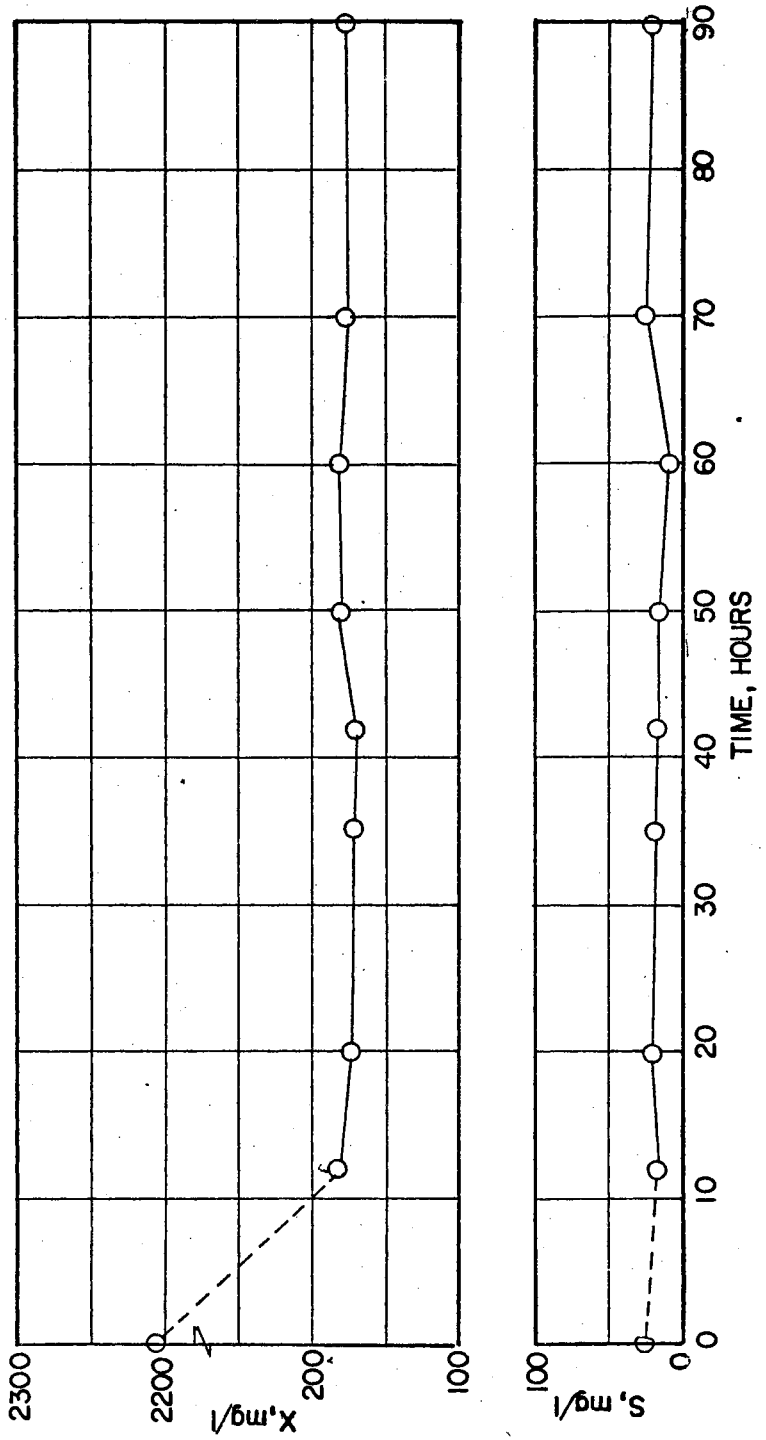

2300
2200
200
100
X, mg/l
100
0
S, mg/l
0
10
20
30
40
50
60
70
80
90
TIME, HOURS

Figure 49. Performance of Once-through System at an S_i of 500 mg/l Subsequent to Cessation of Recycle of Sludge of 10,000 mg/l X_R (10-day run)

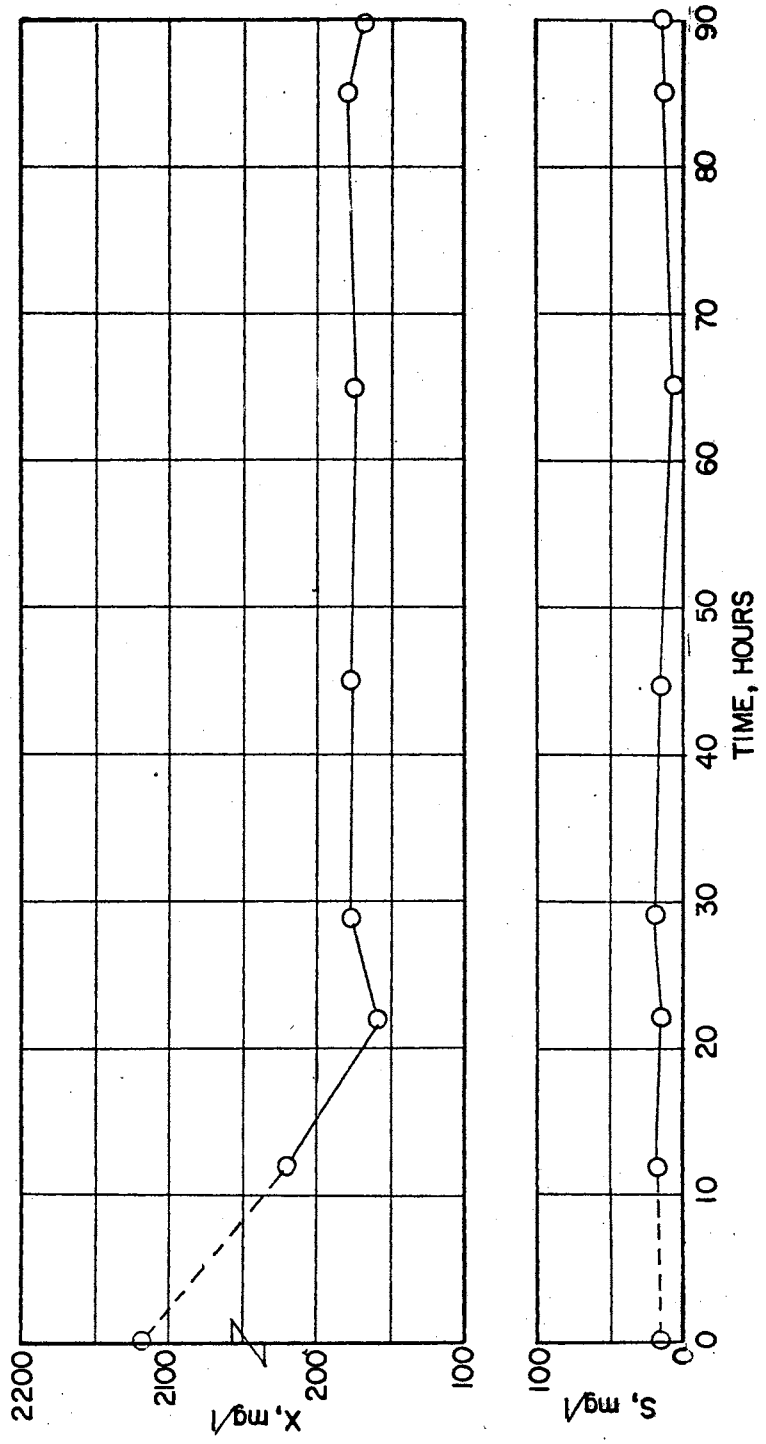

2200
2100
2000
1900
X, mg/l
100
90
80
70
60
50
40
30
20
10
0
TIME, HOURS
100
S, mg/l

Figure 50. Performance of Once-through System at an S_i of 2000 mg/l Subsequent to Cessation of Recycle of Sludge of 10,000 mg/l X_R (20-day run)

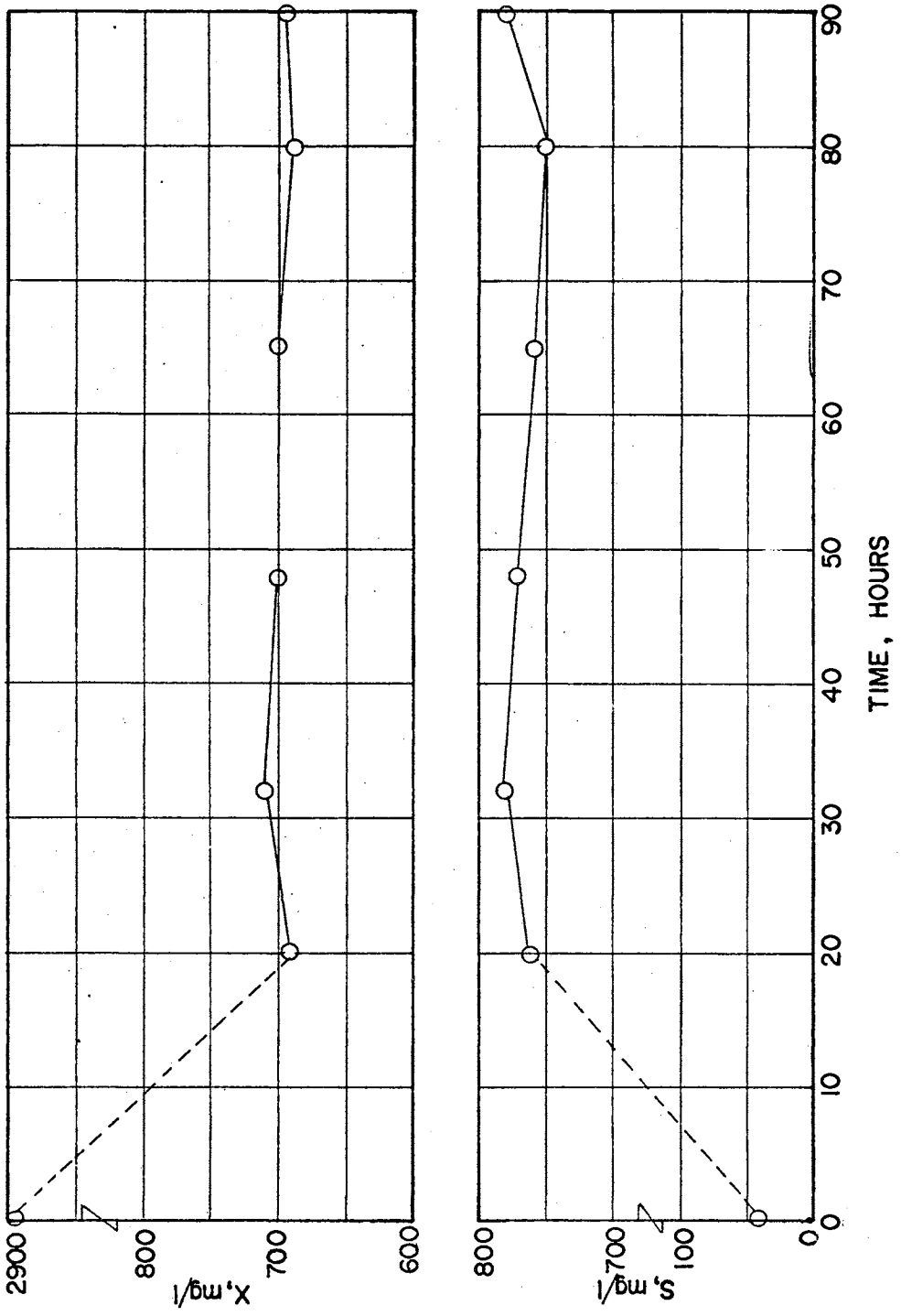
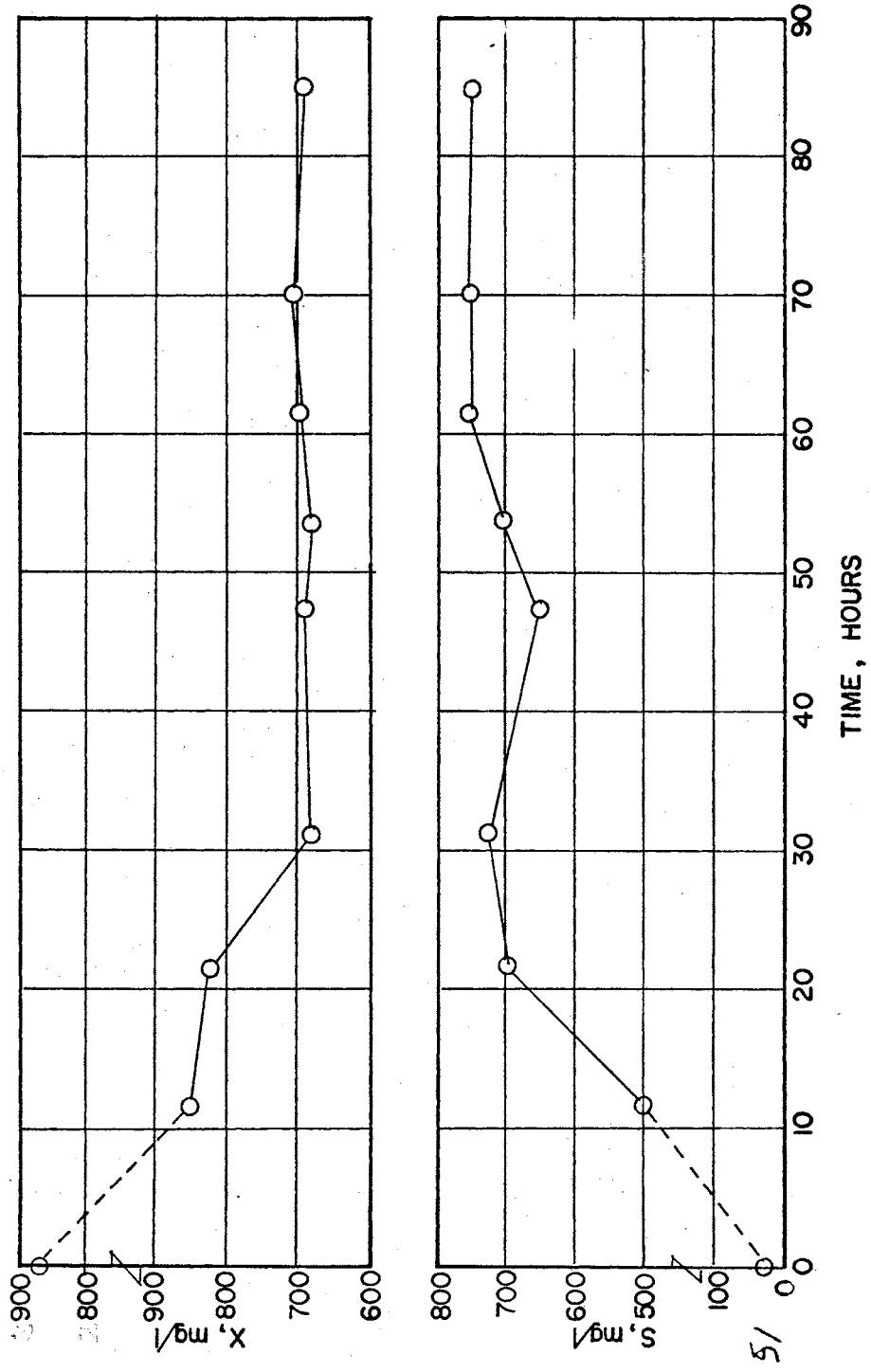

X, mg/l
2900
800
700
600
S, mg/l
800
700
100
0
0
10
20
30
40
50
60
70
80
90
TIME, HOURS

Figure 51. Performance of Once-through System at an S_i of 2000 mg/l Subsequent to Cessation of Recycle of Sludge of 10,000 mg/l X_R (10-day run)


X, mg/l
900
800
700
600
S, mg/l
800
700
600
500
100
0
0
10
20
30
40
50
60
70
80
90
TIME, HOURS
5/

A summary of the steady state continuous flow runs conducted in this investigation is given in Table XVII. The values given for various parameters in this table are the average of the number of individual determinations shown in Tables VI-XIV. The influent loadings are expressed in three different ways. The amount of glucose added per liter, the theoretical COD of this amount of glucose, and the observed COD in the feed are given. The runs made are arranged in increasing order of growth rate, μ, or decreasing order of cell age, Θ_c, in Table XVII for the convenience of discussion. From the summary of effluent filtrate COD, it is seen that the system operated at better than 95 percent efficiency throughout this investigation. The quality of the clarifier supernatant is expressed in terms of total COD, BOD, and solids concentration. The effect of X_R on X is readily seen by comparing the aerator solids of runs #1, 2, and 5. These runs were all made at the same loading of 500 mg/l glucose in the feed. The only differences in these runs were the X_R values. They were 15,000, 10,000, and 5000 mg/l in runs #1, 2, and 5, respectively, and the corresponding biological solids in the aerator were 3082, 2120, and 1173 mg/l. Another comparative observation that can be made from this table is the effect of S_i on X. For example, comparison of runs #2, 6, and 8, all of which were made with approximately 10,000 mg/l of X_R while the S_i loadings were 500, 1000, and 2000 mg/l, reveals that values of X (Table XVII) were 2120, 2275, and 2885 mg/l. The protein content of the sludge ranged from 40 to 54 percent, while carbohydrate content varied between 19 and 41 percent. During all runs, the filtrate COD of the recycle sludge was negligible compared to feed COD.

Table XVIII is a summary of the data calculated from batch

TABLE XVII

MEAN STEADY STATE VALUES OF FEED, EFFLUENT, AND BIOLOGICAL SOLIDS FOR THE ACTIVATED SLUDGE PROCESS AT D = 0.125 hr^{-1} WITH CONSTANT X_R

		Feed			Effluent						Biological Solids						
		Nominal			Filtrate		Supernatant					Recycle		Sludge			
Run #	μ_{c_R} hr^{-1}	Glucose mg/l	COD mg/l	Obs. COD mg/l	COD mg/l	Eff. %	COD mg/l	Eff. %	BOD mg/l	X_e mg/l	X mg/l	X_R mg/l	S_R mg/l	Pro. %	Carb. %	X_w mg/day	Fig. #
1	0.0062	500	530	520	20	96	62	88	8	42	3082	14810	10	47	19	914	5
2	0.0093	500	530	506	15	97	29	94	10	14	2120	9970	8	49	32	1029	37
3	0.0125	500	530	504	25	95	46	91	11	30	2150	9925	11	47	28	1015	36
4	0.0140	1000	1060	1010	48	95	90	91	26	40	3362	15300	17	54	25	2284	11
5	0.0239	500	530	519	12	98	30	94	9	15	1173	4965	7	54	23	1303	22
6	0.0240	1000	1060	1000	33	97	63	94	8	34	2275	9655	11	54	38	2600	16
7	0.0459	1000	1060	1030	24	98	50	95	14	21	1405	4960	14	54	20	3050	23
8	0.0464	2000	2120	2010	38	98	61	97	18	22	2885	10140	12	40	33	6280	38
9	0.0478	2000	2120	2090	31	98	47	98	15	19	2885	10010	14	53	41	6230	39

TABLE XVIII

VALUES OF THE "BIOLOGICAL CONSTANTS," MAXIMUM SPECIFIC GROWTH RATE, μ_{max}, SATURATION CONSTANT, K_s, AND CELL YIELD, Y, OBTAINED IN BATCH EXPERIMENTS USING CELLS HARVESTED FROM THE COMPLETELY MIXED REACTOR DURING CONTINUOUS FLOW STEADY STATE RUNS

Run #	S_i Glucose mg/l	Maximum Specific Growth Rate μ_{max}, 1/hr					Saturation Constant K_s, mg/l					Batch Yield Y_B, mg/mg				
		Ex 1	Ex 2	Ex 3	Ex 4	Ave.	Ex 1	Ex 2	Ex 3	Ex 4	Ave.	Ex o	Ex 2	Ex 3	Ex 4	Ave.
1	500	0.35	0.31	0.34		0.33	150	155	140		148	0.33	0.34	0.30		0.32
2	500	0.52				0.52	110				110	0.41				0.41
3	500	0.48	0.51	0.47		0.49	140	110	95		115	0.41	0.39	0.38		0.39
4	1000	0.51	0.50	0.49		0.50	110	95	140		115	0.43	0.44	0.42		0.43
5	500	0.42	0.50	0.35	0.38	0.41	200	590	218	386	422	0.44	0.46	0.41	0.46	0.44
6	1000	0.25	0.48	0.83	0.63	0.55	205	226	175	438	261	0.49	0.53	0.45	0.52	0.50
7	1000	0.30	0.30	0.30	0.42	0.33	315	230	105	313	240	0.49	0.54	0.48	0.53	0.51
8	2000	0.60	0.56	0.58		0.58	110	195	105		105	0.59	0.53	0.56		0.56
9	2000	0.56				0.56	115				115	0.54				0.54

experiments conducted during the continuous flow studies. This table gives the biological characteristics of the sludge. The number of batch growth experiments conducted varied, depending on the length of the continuous flow run. In most of the runs, μ_{max} and K_s obtained from individual batch experiments were approximately the same, although there was a wide range of μ_{max} and K_s on the whole. The μ_{max} varied between 0.25 and 0.83 hr^{-1}. There was no definite relationship between the growth rate of the continuous flow unit and μ_{max} values. The range of K_s values was between 95 and 580 mg/l. Batch yield, Y_B, values were calculated by measuring the initial and final solids and substrate concentrations during the batch growth experiments. The Y_B values observed from the batch experiments conducted during any one particular run were very close to each other. It is pointed out that there is a definite trend between the average Y_B and μ_{c_R} (the specific growth rate in the continuous flow with recycle) values, which will be discussed later. Overall, the Y_B values varied between 0.30 and 0.59.

The results obtained from the pure culture studies at 30°C are given in Tables XIX and XX. Table XIX is the summary of continuous flow data at D = 0.17 hr^{-1} (detention time of 24 hours). The mean cell concentration in the reactor was 412 mg/l at six hours detention time, and 335 mg/l at 24 hours detention time. The steady state data at each dilution rate are shown in Figure 52. The growth curves observed during the batch experiments performed during the once-through continuous flow chemostat operation at both dilution rates are shown in Figure 53. The specific growth rates calculated from these growth curves and the corresponding yield values are shown in Table XX. The μ values ranged from 0.42 to 0.60 hr^{-1} in the batch experiments conducted during the high

TABLE XIX

CONTINUOUS FLOW CHEMOSTAT DATA EMPLOYING *Escherichia intermedia* AT S_i = 1000 mg/l GLUCOSE (Temperature = 30°C)

	$D = \mu_c = 1/6\ hr^{-1}$			$D = \mu_c = 1/24\ hr^{-1}$		
Sample No.	X mg/l	ΔCOD mg/l	Y_c	X mg/l	ΔCOD mg/l	Y_c
1	390	1060	0.37	350	1040	0.34
2	393	1080	0.36	350	1040	0.34
3	430	1100	0.39	326	1060	0.30
4	433	1080	0.40	316	1040	0.30
5	413	1080	0.38			
Mean	412	1080	0.39	335	1043	0.32

TABLE XX

VALUES OF SPECIFIC GROWTH RATE, , AND CELL YIELD, Y, OBTAINED AT DIFFERENT SUBSTRATE CONCENTRATIONS, S_o, IN BATCH EXPERIMENTS EMPLOYING Escherichia intermedia (Temperature = 30°C)

$D = \mu_c = 1/6\ hr^{-1}$				$D = \mu_c = 1/24\ hr^{-1}$			
Expt. 1		Expt. 2		Expt. 1		Expt. 2	
μ_B	Y_B	μ_B	Y_B	μ_B	Y_B	μ_B	Y_B
0.43	0.40	0.42	0.36	0.43	0.33	0.39	0.27
0.53	0.38	0.46	0.35	0.42	0.32	0.43	0.32
0.50	0.35	0.50	0.37	0.43	0.32	0.53	0.31
0.55	0.37	0.50	0.36	0.46	0.34	0.53	0.32
0.58	0.36	0.53	0.38	0.46	0.32	0.55	0.31
0.60	0.37	0.53	0.38	0.48	0.33	0.55	0.32

Figure 52. Steady State Data From Once-through Chemostat Studies Employing Escherichia intermedia at Dilution Rates of 1/6 and 1/24 hr^{-1}

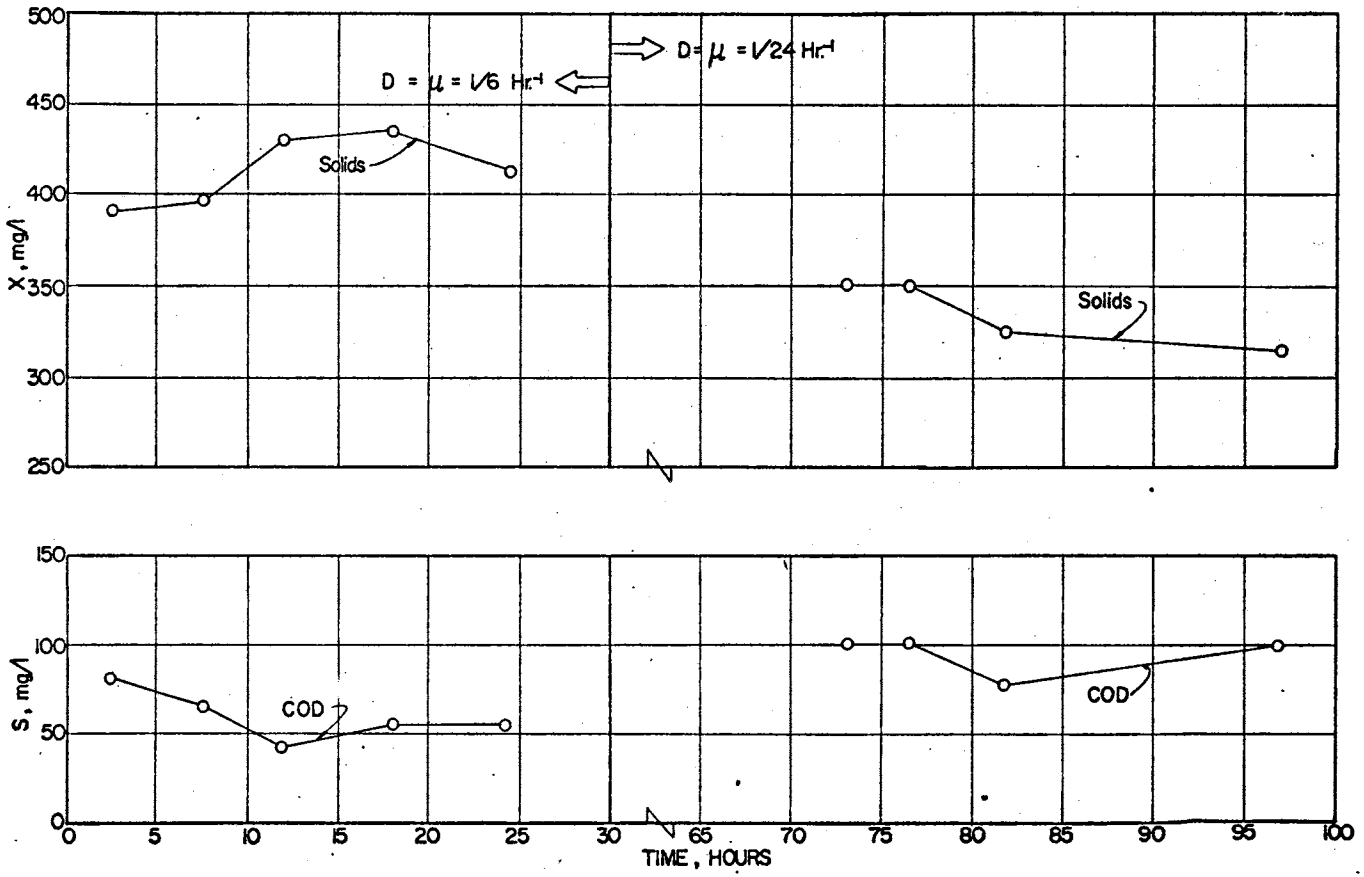
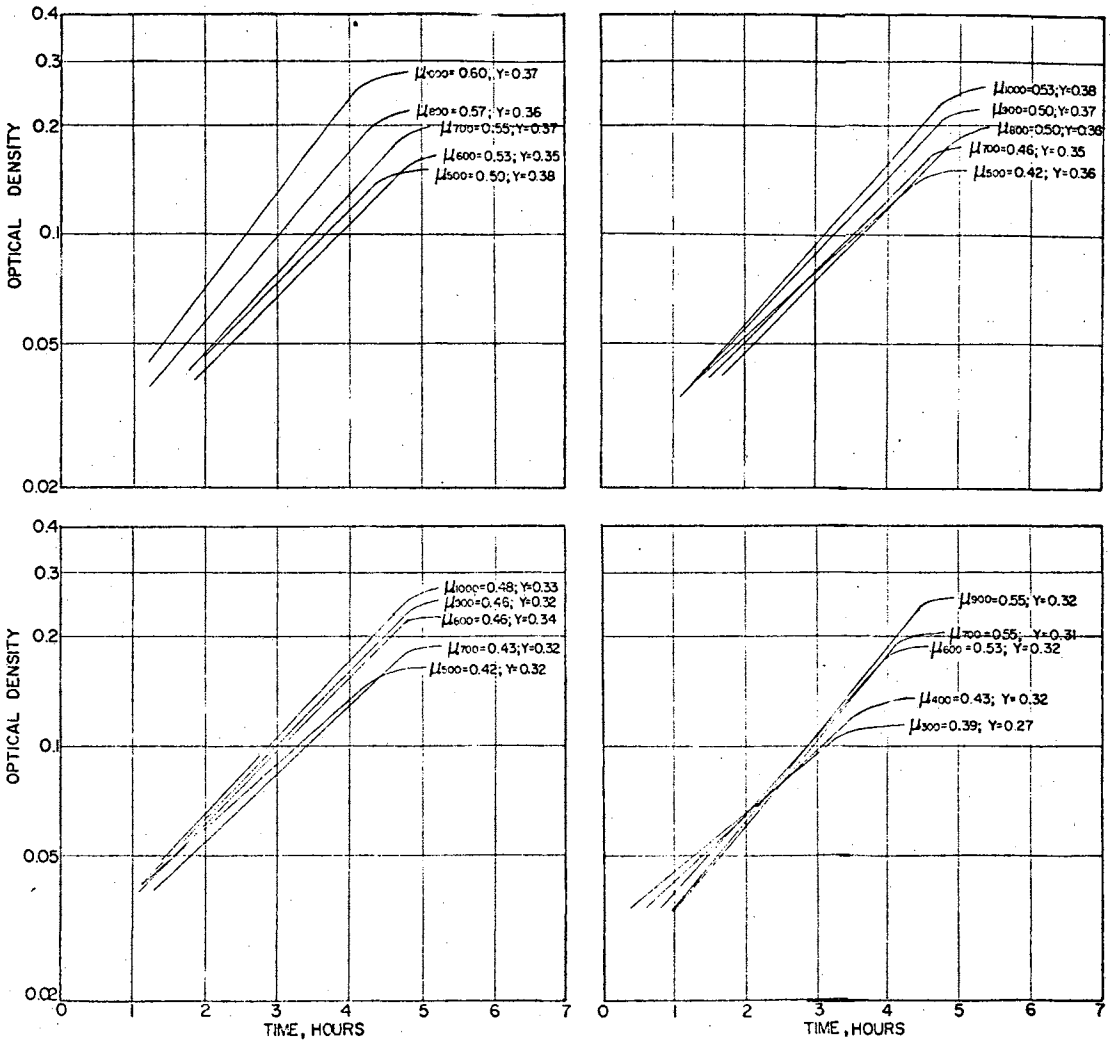

D = μ = 1/6 Hr.⁻¹
D = μ = 1/24 Hr.⁻¹
Solids
Solids
COD
COD
X, mg/l
S, mg/l
TIME, HOURS
500
450
400
350
300
250
150
100
50
0
0
5
10
15
20
25
30
65
70
75
80
85
90
95
100

Figure 53. Batch Growth Curves at Various Initial Substrate Concentrations for Cells Harvested From Pure Culture Chemostat Operating at an S_i of 1000 mg/l


OPTICAL DENSITY
0.4
0.3
0.2
0.1
0.05
0.02
μ1000= 0.60, Y= 0.37
μ900 = 0.57; Y= 0.36
μ700=0.55; Y=0.37
μ600=0.53; Y=0.35
μ500=0.50; Y=0.38
μ1000=053; Y=0.38
μ900=0.50; Y=0.37
μ800=0.50; Y=0.38
μ700=0.46; Y=0.35
μ500=0.42; Y=0.36
μ1000=0.48; Y=0.33
μ900=0.46; Y=0.32
μ800=0.46; Y=0.34
μ700=0.43; Y=0.32
μ500=0.42; Y=0.32
μ900=0.55; Y=0.32
μ700=0.55; Y=0.31
μ600=0.53; Y=0.32
μ400=0.43; Y=0.32
μ300=0.39; Y=0.27
0 1 2 3 4 5 6 7
TIME, HOURS
TIME, HOURS

growth rate run. The average yields observed in these two experiments were 0.37 and 0.37. The batch growth rates obtained from experiments performed during slower growth rate continuous runs varied from 0.39 to 0.55, and average Y values were 0.33 and 0.31.

CHAPTER VI

DISCUSSION

Analyses of performance characteristics at various organic loadings, S_i, and recycle solids concentration, X_R, of the activated sludge pilot plant employing constant X_R, indicate that the system delivered excellent effluent with respect to COD, both filtrate and total, and solids concentration. Also, the few determinations of 5-day BOD indicate high purification efficiency. The use of chemical oxygen demand as a parameter to evaluate the effluent quality is recognized as a conservative estimate, since the effluent COD/BOD ratio is usually found to be considerably higher than the initial or feed COD/BOD ratio. A better way to estimate the removable amount of substrate in a waste would be to run a COD test on the waste, i.e., initial COD minus the final COD (24) (59). This test would give a better estimate of the readily available substrate, i.e., S_i, than would sole reliance on the COD test. It is not unusual to observe a residual amount of COD even for a substrate as readily metabolized as glucose. Of this residual COD, only a fraction will be registered as carbohydrate if a test for anthrone COD is conducted. In later runs, as can be seen from Tables VII, VIII, X, and XI, glucostat tests were conducted on effluent filtrate to see if any glucose was present. The amount of glucose in the effluent was found to be 2 to 5 ppm, which is negligible. Although the exact nature of the residual COD is not known, it was found in the author's laboratories

to consist mainly of materials other than the original substrate (60). These materials may be excreted by the viable cells or may be the components of damaged or dead cells. It was shown that this residual COD is not permanently residual or inert material, but compounds which are metabolized more slowly than the original carbon source. These materials can be further treated by tertiary treatment by physical, chemical, or biological methods. The biochemical efficiency based on effluent filtrate COD in all of the runs made was 95 percent or better, and based on total or supernatant COD, except for one run when the effluent solids were a little higher than normal (40 mg/l), was above 90 percent. Even during this run, the efficiency was 88 percent and the BOD_5 was only 8 mg/l. The system performed effectively and steadily even at high loadings of 1000 and 2000 mg/l of S_i. Thus, the effluent was, on the average, very good; efficiency of substrate removal was high, and the value of $\bar{S}$ was very steady.

Another parameter to be analyzed in evaluating the steadiness of a model is the biological solids concentration, X, in the aeration tank. From the standpoint of testing the steadiness of the model, X is a more sensitive parameter than S. A close examination of the plots of steady state aerator biological solids, X, reveals that it did not fluctuate over a wide range during any loading, but rather remained steady within a narrow range. The rather small amount of variation which did occur can be caused by several factors. One of the reasons can be attributed to the limited fluctuation in X_R. Also, the net cell yield value in a biological system with heterogeneous population can vary, resulting in fluctuation in X value. However, the concentration of the reactor solids was dependent mainly on the concentration of recycle sludge, X_R,

since μ was maintained constant at 0.25 during all runs. Another factor that controls, to a lesser extent the value of X, is S_i. The effect of these two parameters, X_R and S_i, were brought out in the results section. Other factors that contribute to the specific value of X will be discussed later in this report. Analysis of the steady state plots of X at any loading shows beyond doubt that the X_R control helps maintain the system in steady state with minimum fluctuations.

Having analyzed the steadiness of the model in terms of $\bar{S}$ and $\bar{X}$, it would be appropriate to analyze the parameter of this model which contributed most to this steadiness--that is, the recycle solids concentration, X_R. The nominal X_R concentrations were 5000, 10,000, and 15,000 mg/l, and it is seen that these concentrations were approximated very closely. It can also be seen that it was possible to control the recycle sludge concentration at a value approximately equal to the desired concentration for rather long operational runs. In most cases, the range observed was $\pm$ 1000 mg/l at higher X_R, and $\pm$ 500 at lower X_R. It is interesting to note that in preparing the sludge to the desired consistency, optical density was used to estimate the concentration of sludge. The fact that, with experience, this rather simple method for obtaining the desired sludge consistency proved to be applicable, has ramifications for future automatic control for maintaining constant Y_R. The sludge consistency tank fulfilled its function effectively in enhancing attainment of a steady state, and can be used in an even more versatile manner in shock loading situations.

One of the assumptions made in the derivation of steady state equations for $\bar{X}$ and $\bar{S}$ was that the substrate concentration in the recycle sludge, S_R, was negligible. This assumption was validated through

measurement of the filtrate COD of the recycle sludge. In addition to substantiating the justification for assuming $S_R = 0$ in the equation, this observation attests to the fact that the residual COD in the effluent was subject to further removal.

Another parameter of importance in designing waste treatment facilities is the amount of excess sludge produced as a result of substrate removal. The amount of sludge production depends mainly on the yield value and the decay coefficient for a system. This study indicates that there are reasons to believe that cell yield or sludge produced is dependent on the growth rate or cell age. Figure 54 is a plot of observed yield vs growth rate, and Figure 55 is a plot of observed yield vs cell age. It is seen from these figures that in a continuous flow system, the higher the μ value, the higher is the cell yield, and cell yield decreases with increasing cell age. Thus, at higher growth rates, X_W is also higher. This can readily be seen by comparing X_W values at one particular S_i at different growth rates, e.g., at an S_i of 500 mg/l for specific growth rates of 0.0062, 0.0125, and 0.0239 hr^{-1} (0.15, 0.30, and 0.57 day^{-1}), X_W values observed were 914, 1015, and 1303 mg/day, respectively. At an S_i of 1000 mg/l, the excess sludge produced was 2284, 2600, and 3050 mg/day. The corresponding growth rates were 0.014, 0.024, and 0.046 hr^{-1} (0.34, 0.57, and 1.1 day^{-1}). Similar results were reported by other researchers in the pollution control field as well as in microbial literature (10)(19)(48).

Reproducibility and effectiveness of the design and operational model was assessed by running the pilot plant at identical conditions at different times with mixed cultures developed from different sewage inocula. These experiments definitely show that X_R control can produce

Figure 54. Relationship Between Cell Yield and Specific Growth Rate in Continuous System

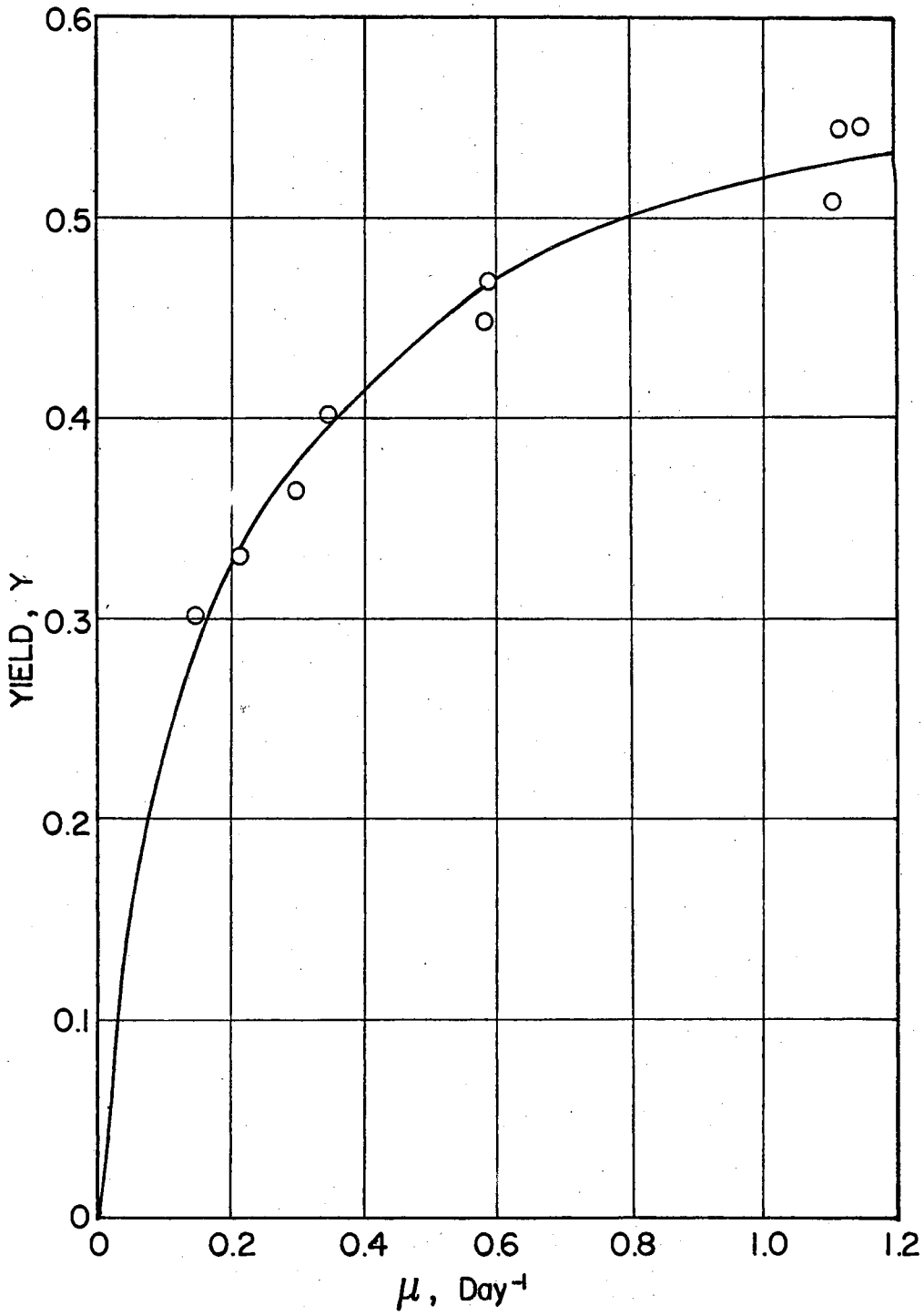
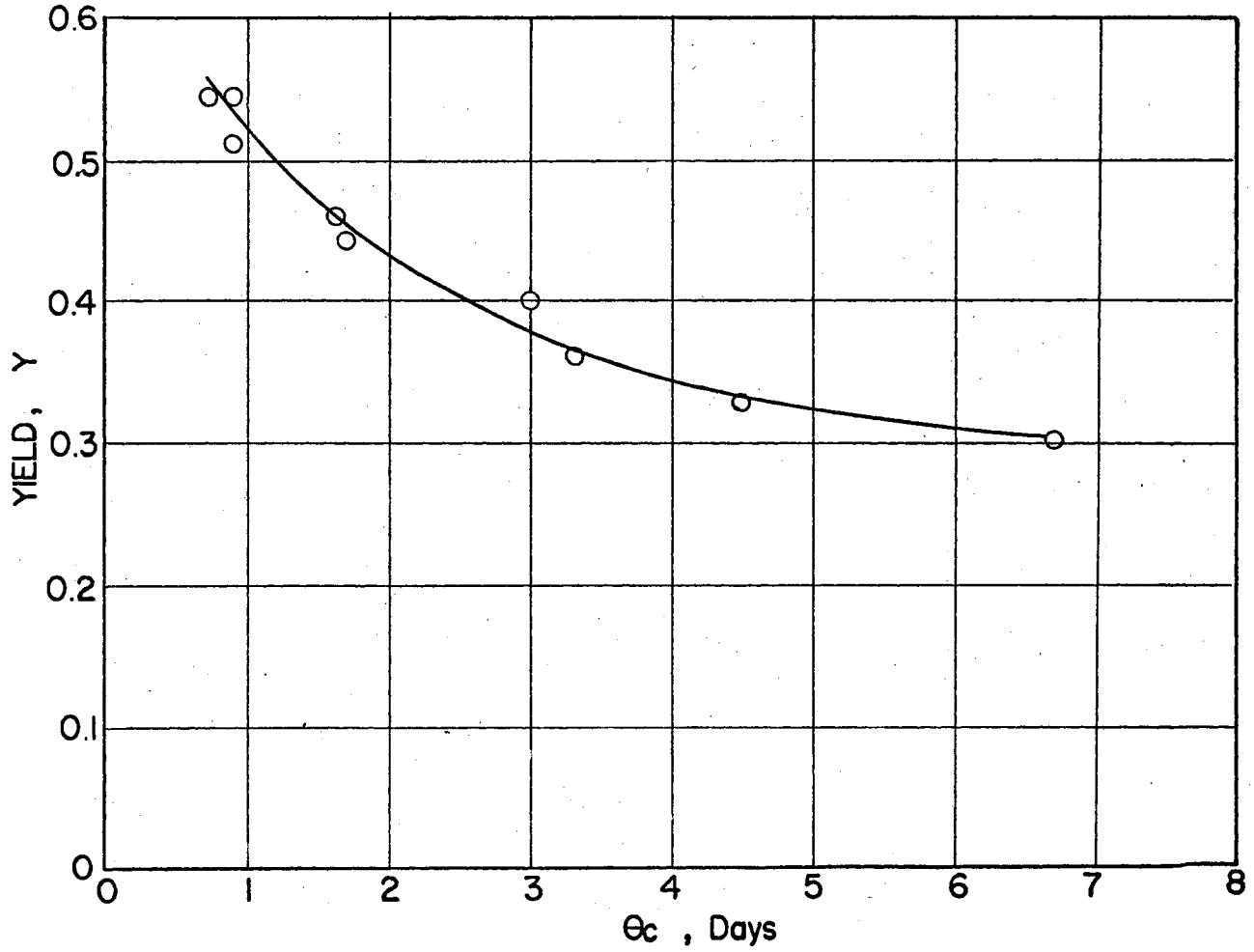

0.6
0.5
0.4
0.3
0.2
0.1
0
YIELD, Y
0
0.2
0.4
0.6
0.8
1.0
1.2
μ, Day⁻¹

Figure 55. Relationship Between Cell Yield and Cell Age in Continuous System


0.6
0.5
0.4
0.3
0.2
0.1
0
YIELD, Y
0
1
2
3
4
5
6
7
8
Θc , Days

comparable values of $\bar{X}$ and $\bar{S}$ under similar conditions of operation.

It is interesting now to compare the cell yield values obtained from batch growth experiments, Y_B, using cells harvested from the continuous flow system, with steady state yield values computed directly from the continuous flow pilot plant data with and without recycle, Y_{c_R} and Y_c, respectively. These cell yields obtained in three different ways and corresponding growth rates are compared in Table XXI. It is realized that the experimental data do not warrant calculation of μ_{c_R} to four decimals, but this was done in order to bring out the reproducibility between runs 2 and 3, and 8 and 9 (Figures 36 and 37, and 38 and 39). If the values were rounded off to two decimals, exact reproducibility may be assumed, which was not the case. There are some important observations that can be made from this table. By comparing runs 1, 2, and 5, the effect of recycling sludge on μ_{c_R} can be seen. First observation is that recycle diminishes μ_{c_R} dramatically (compare μ_c and μ_{c_R}). A second observation is the effect of X_R value on μ_{c_R} at the same loading. In runs 1, 2, and 5, the influent loading was 500 mg/l and X_R values were approximately 15,000, 10,000, and 5000 mg/l, respectively. The corresponding growth rates were 0.0062, 0.0093, and 0.0239 hr^{-1} (0.15, 0.22, and 0.57 day^{-1}). Thus, a decrease of X_R from 15,000 to 5000 mg/l caused a four-fold increase in μ_{c_R}. Another factor that controlled μ_{c_R} was S_i. In runs 2, 6, and 8 (Figures 37, 16, and 38), the recycle cell concentrations were approximately 10,000 mg/l and S_i values were 500, 1000, and 2000 mg/l glucose, respectively. The corresponding μ_{c_R} values were 0.0093, 0.0239, and 0.0464 hr^{-1}. Thus, an increase in S_i from 500 to 2000 mg/l caused a 4- to 5-fold increase in μ_{c_R}, which resulted in more sludge wastage due to the higher production

TABLE XXI

RELATIONSHIP BETWEEN SPECIFIC GROWTH RATE AND CELL YIELD UNDER DIFFERENT CONDITIONS OF CONTINUOUS AND BATCH GROWTH

Run #	S_i Glucose mg/l	Sp. Growth Rate, 1/hr			Cell Yield, mg/mg		
		μ_{c_R}	μ_B	μ_c	Y_{c_R}	Y_B	Y_c
1	500	0.0062	0.33	0.125	0.30	0.32	0.31
2	500	0.0093	0.52	0.125	0.33	0.41	0.36
3	500	0.0125	0.49	0.125	0.36	0.39	0.35
4	1000	0.0140	0.50	0.125	0.40	0.43	0.40
5	500	0.0239	0.44	0.125	0.44	0.44	0.46
6	1000	0.0240	0.55	0.125	0.46	0.50	0.46
7	1000	0.0459	0.33	0.125	0.51	0.51	0.53
8	2000	0.0464	0.58	0.125	0.54	0.56	0.53
9	2000	0.0478	0.56	0.125	0.54	0.54	0.53

of sludge.

It is important to observe the effect of growth rate or cell age on observed cell yield. From Figures 54 and 55 it is seen that cell yield decreases with decreasing μ and increases with increasing Θ_c. It is generally accepted that cell yield is affected by the cell age, i.e., the higher the cell age, the lower the yield, and vice versa. The common reason attributed to this phenomenon is usually the maintenance energy requirement, i.e., the utilization of exogenous substrate to maintain the status quo. The slow growing populations would require higher amounts of substrate for maintenance; therefore, less amounts of substrate are channelled to synthesis of fresh cells. Another theory postulated was the endogenous decay of cells--that is, a higher amount of autodigestion of cells at lower growth rates. To the author's knowledge, it has not been proven conclusively which, if either of these two theories is correct. The decrease in yield may be a manifestation of one or both phenomena acting together. Whatever the mechanism may be, it is experimentally observed that there is a decrease in yield when μ is decreased in continuous flow. According to the maintenance energy theory, the requirement of exogenous substrate is minimal at high growth rates. Therefore, cell yield should be maximum at μ_{max} or near μ_{max}. This is defined as "true yield." On the other hand, looking at the endogenous decay point of view, which is a result of starvation conditions, the highest cell yield should be obtained when cells are grown in the presence of excess substrate concentrations. Thus, batch experiments where cells are grown at high substrate concentrations and close to μ_{max}, should give "true yield."

A comparison of Y_{c_R} at low and high μ_{c_R} or Θ_c shows that it is in

accordance with the theory of maintenance requirement. At the same time, it would be expected that cells taken out of continuous flow pilot plants growing at a slower growth rate when grown under batch conditions would give a higher yield than in the continuous system. A horizontal comparison of Table XXI would reveal that this was not the case. The Y_B values instead of varying with μ_{max}, varied with μ_{c_R}, as did Y_{c_R}. A close examination of μ_{c_R} and μ_{max} reveals that there was a 10- to 50-fold increase in growth rates in batch growing systems compared to continuous systems. For such an enormous increase in growth rate, little or no difference was observed between Y_{c_R} and Y_B. This trend persisted in all runs, i.e., Y_B values were the same or close to Y_{c_R}, with the exception of the 10-day run at an S_i of 500 mg/l and an X_R of 10,000 mg/l (run 2). Even here the change in Y from 0.33 to 0.41 for a 50-fold increase in growth rate (μ_{c_R} = 0.0093 and μ_{max} = 0.52 hr^{-1}) is significantly less than the increase of yield from 0.30 to 0.54 for an 8-fold increase in μ_{c_R} (0.0062 and 0.0478 hr^{-1}). A similar trend can be observed by comparing μ_{c_R} and μ_c, and Y_{c_R} and Y_c for the other runs. The μ_c was always 0.125 hr^{-1}, which was held as a constant operational parameter throughout this investigation. Although μ_c was the same in all once-through studies made after recycling was stopped, when a run was completed the yield Y_c obtained was not the same in all runs. The yield value in once-through operation continued to be the same as it was during recycle operation. It was noted that after a prolonged period of operation as a once-through reactor subsequent to stopping the recycle operation, the cell yield began to increase somewhat. At least five detention times and generally more were required before the cell yield started climbing. This observation was made

during runs 1 and 4, when Y_c increased from 0.31 to 0.54, and 0.40 to 0.55, respectively. From all of these observations in continuous and batch experiment, it can be concluded that a rapid increase in yield was not accomplished for an increase in growth rate. The data suggest that one possible reason for the change in yield at lower growth rates may be selection of species with a lower "true yield" from the heterogeneous population. Ramanathan and Gaudy (61) have reported true yield values between 0.4 and 0.6 for cells grown in glucose minimal medium in batch reactors. Values below and above this range were also observed, although most of the values fell in this range. They attributed the variation in yield mainly to changes in species predominance in the heterogeneous population. A factor which could have limited the predominance change in the present studies is the high solids concentration in recycle, which can resist changes in species predominance and thus variations in yield, Y_{c_R}.

Results obtained from studies employing Escherichia intermedia at different growth rates also indicated a similar trend so far as the relationship between μ and Y is concerned. At a dilution rate of 1/6 hr^{-1}, Y_c was 0.39, and it decreased to 0.32 at D = 1/24 hr^{-1}. The batch yield values obtained over a spectrum of growth rates remained the same as in the continuous culture reactor from which the initial inoculum was obtained. Thus, the behavior of the single culture was found to be the same as that of a natural population. Although this makes the "selection of cells" theory rather weak, it is possible that various strains within a specie have different yields. During the course of this investigation, two different types of colonies, rough and smooth, have been noted. Separate batch experiments were conducted

to see if there was any difference in Y_B between the two strains. In all of the experiments conducted, there was about a five percent difference in yield between the two. Since this was not significant enough to cause as much difference in Y_c as was observed at high and low μ in continuous culture, this rough-smooth mutation was discounted as a possibility for explaining the difference in yield values at the two growth rates. Additional batch studies using cells taken from the continuous culture reactor as initial inoculum were made. After the completion of a batch determination of cell yield, a portion of the cells was transferred to another batch reactor, and another growth experiment to determine cell yield was made. The aim was to see if there would be an increase in yield upon the second batch transfer. The results indicated no increase in cell yield value.

Whatever the mechanism for the concept of cell maintenance energy requirement may be, the fact remains that there is a gradient in cell yield which is dependent on the growth rate or cell age. Thus, the analytical equations developed for the determination of Y_t and k_d can be used for design purposes. Linearization of observed yield was accomplished by employing two different methods. Two equations employed to determine the value of the "true yield," Y_t, and maintenance energy coefficient, k_d, are as follows:

$$\frac{1}{Y_o} = \frac{1}{\mu} \cdot \frac{k_d}{Y_t} + \frac{1}{Y_t} \tag{21}$$

$$\mu = Y_t U - k_d \tag{22}$$

Equation (21) was used by Marr, et al. (43), and equation (22) was

used by Schulze, et al. (44). Y_o and Y_t are observed and true yield values; the other symbols are used as previously defined. The data used to obtain these maintenance plots are shown in Table XXII. Figure 56 is the plot of these two equations. The plots are labelled as to equations employed and values for Y_t and k_d. It is seen from this figure that the data fit the equations very well. The "true yield" value from these plots was found to be 0.59, and k_d to be 0.14 day^{-1}. The maintenance coefficient, k_d, is somewhat higher than values previously reported in the literature (20)(62)(63)(64)(65). There could be several reasons for the difference in k_d values. Such factors as wastewater, carbon source, initial inoculum, mode of operation, biomass in the system, etc., may affect the k_d values. It would be highly speculative to attribute to any one particular parameter the major causative role for high or low values of k_d.

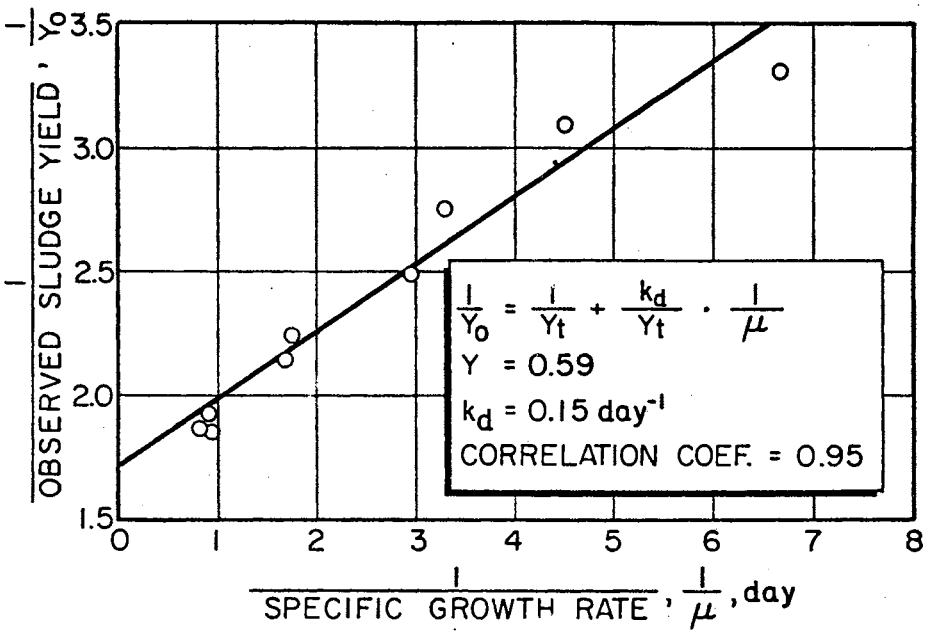
It was of interest to see the effect of inclusion of maintenance factors in the steady state model equations. The salient steps in derivation of these equations were outlined in the theoretical development section and were listed in Table II. By comparing equations in Tables I and II, it is seen that one term is added to equations for X, a, b, and c. Having obtained values for Y_t and k_d from experimental data, it was of interest to compare the predictive power of the modified equations with original equations without the cell maintenance coefficient. From Table XXIII it is seen that either set of equations predicts lower $\bar{S}$ than the observed $\bar{S}$ in the effluent. Of course, use of COD as a measure of microbial substrate in the effluent leads to a conservative estimate. The predicted values are closer to the values of glucose measured in the effluent; nevertheless, it is evident that

TABLE XXII

DATA EMPLOYED FOR MAINTENANCE PLOTS

Run #	S_i Glucose mg/l	μ_{c_R} 1/Day	Θ_c Day	U 1/Day	Y	1/Y
1	500	0.149	6.72	0.49	0.30	3.33
2	500	0.223	4.48	0.70	0.33	3.03
3	500	0.300	3.33	0.67	0.36	2.77
4	1000	0.336	2.97	0.86	0.40	2.50
5	500	0.574	1.74	1.30	0.45	2.25
6	1000	0.576	1.73	1.28	0.46	2.17
7	1000	1.102	0.91	2.15	0.51	1.96
8	2000	1.114	0.90	2.05	0.54	1.85
9	2000	1.147	0.87	2.14	0.54	1.85

Figure 56. Plots of Maintenance Energy Equations to Determine True Yield, Y_t, and Maintenance Coefficient, k_d


1/Yo, 1/OBSERVED SLUDGE YIELD
3.5
3.0
2.5
2.0
1.5
0
1
2
3
4
5
6
7
8
1/Yo = 1/Yt + kd/Yt · 1/μ
Y = 0.59
kd = 0.15 day-1
CORRELATION COEF. = 0.95
1/SPECIFIC GROWTH RATE, 1/μ, day

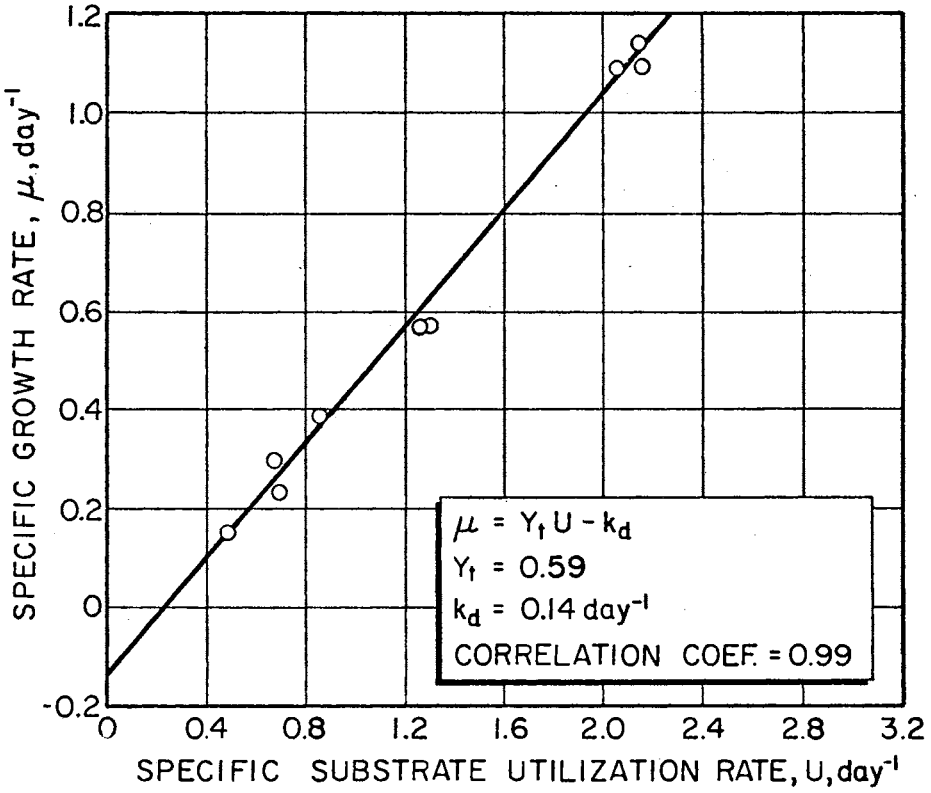

SPECIFIC GROWTH RATE, μ, day-1
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
μ = Yt U - kd
Yt = 0.59
kd = 0.14 day-1
CORRELATION COEF. = 0.99
SPECIFIC SUBSTRATE UTILIZATION RATE, U, day-1

TABLE XXIII

EFFECT OF MAINTENANCE COEFFICIENT, k_d, ON PREDICTED VALUES OF $\bar{S}$, $\bar{X}$, AND $\bar{X}_w$

Run #	S_i Glucose mg/l	Eff. Substrate, $\bar{S}$, mg/l			Biological Solids, $\bar{X}$, mg/l			Excess Sludge, X_w, mg/day		
			Predicted			Predicted			Predicted	
		Obs.	Y = 0.59 k_d = .14	Y = 0.59 k_d = 0.0	Obs.	Y = 0.59 k_d = .14	Y = 0.59 k_d = 0.0	Obs.	Y = 0.59 k_d = .14	Y = 0.59 k_d = 0.0
1	500	20	5.0	4.8	3082	3089	3204	914	953	1815
2	500	15	3.8	3.6	2120	2150	2230	1029	1170	1770
3	500	25	4.0	4.0	2150	2140	2211	1015	1162	1695
4	1000	48	5.2	5.0	3362	3406	3533	2284	2595	3547
5	500	12	28.6	27.7	1173	1177	1221	1303	1379	1710
6	1000	33	17.1	16.5	2275	2306	2393	2600	2812	3465
7	1000	24	43.7	42.4	1405	1400	1453	3050	3060	3457
8	2000	38	10.0	14.0	2885	2862	2968	6280	6255	7050
9	2000	31	11.9	11.6	2885	2874	2983	6230	6539	7357

there is little difference in the predicted values of $\bar{S}$ whether original or modified equations are used. Comparison of predicted and observed values of $\bar{X}$ leads to the conclusion that if one does not really require a very close prediction of X, there is little difference in using either of the two equations. But, definitely, the modified equation predicts $\bar{X}$ closer to the actual value. This will be more true at lower growth rates when the effect of k_d will be manifested more than at higher growth rates. Since the normal daily fluctuation in the aerator solids concentration will be of greater magnitude than the difference in predicted values by these two methods or any other method yet suggested, it will be acceptable to use either of these two equations.

Regarding prediction of excess sludge, it is seen that at high growth rates, the new model provides rather good prediction, but the original model without k_d does not predict X_w closely. At low μ, the model with k_d provides a very good estimate of X_w, whereas the one without k_d predicts about 50 percent more excess sludge than was observed experimentally. This result is reasonable, since k_d exerts greater effect as cell age increases. In general, the activated sludge process operates at slow growth rates or high sludge ages. Thus, inclusion of the maintenance term seems a useful refinement to the model to suit field conditions.

In this study, the model was subjected to preliminary testing for resistance to shock loads at recycle solids concentration of 5000 mg/l. The system performed effectively when loading was increased from 500 to 1500 mg/l. However, the system did not perform quite as efficiently when loading was increased from 1030 to 3600 mg/l. It is noted that X_R employed in this shock load study was 5000, which is much lower than

the value that is normally observed in the field. It is believed that the system would be able to absorb the shock better if higher values were employed. An alternative method suggested to alleviate any leakage of substrate would be to increase X_R or α during the period of shock so that a higher amount of cells would be recycled, thereby increasing X and reducing the load. The increasing of X_R or α in order to increase X needs a little more comment at this point. This method of control has been condoned by some of the researchers in the field who propose control by amount of sludge wasted. One of the arguments against the recycle ratio control is that it does not ensure an increased amount of cells to the aerator, because the mass balance around the whole system does not include X_R or α. But the unique feature of this model is the constant recycle sludge concentration. When a sludge consistency tank with constant solids concentration is placed in the recycle line, it is evident that an increase in X_R or α shall provide a higher amount of sludge dosage to the aerator.

CHAPTER VII

DEVELOPMENT OF DESIGN CURVES

In order to employ a method for designing wastewater treatment facilities, it is imperative that the designer have an idea of the behavior of the model in various operational conditions. Since the model proposed here employs various biological and hydraulic parameters, it would be of value if the effect of these parameters on the performance characteristics of the process were known. Since it will be practically impossible within reasonable time to run pilot plant studies at any level to observe the effects of different X_R, μ, D, K_s, k_d, μ_{max}, and Y on performance characteristics, computational analysis was performed (IBM 360) employing the new model equations derived (Table II). If all of the data developed by the computer were shown, this report would become voluminous. Therefore, the effect of changes in μ_{max} and K_s are discussed in the text with tables, and the effect of μ, D, Y, X_R, and k_d are plotted and discussed briefly in this section. The computational program is shown in the Appendix.

The effect of μ_{max} and K_s on $\bar{S}$, $\bar{X}$, μ, and X_w as calculated by computer are shown in Tables XXIV and XXV. The range of values employed for μ_{max} and K_s were 0.3 to 0.6 hr^{-1}, and 50 to 300 mg/l, respectively. This was the normal range of values observed most frequently in the author's laboratory in the last several years for heterogeneous populations. It is clearly seen that μ_{max} and K_s have little effect on $\bar{S}$, $\bar{X}$,

TABLE XXIV

EFFECT OF μ_{max} ON PREDICTED VALUES OF $\bar{S}$, $\bar{X}$, AND $\bar{X}_w$
(K_s = 100 mg/l, Y_1 = 0.6, k_d = 0.04 day^{-1},
D = 0.125 hr^{-1}, X_R = 10,000 mg/l)

S_i mg/l	μ_m hr^{-1}	$\bar{S}$ mg/l	$\bar{X}$ mg/l	$\bar{X}_w$ mg/l
250	0.3	3.0	2085	107
	0.4	2.0	2086	108
	0.5	2.0	2086	108
	0.6	2.0	2087	109
1000	0.3	11.0	2530	662
	0.4	8.0	2532	665
	0.5	7.0	2533	666
	0.6	5.0	2534	667

TABLE XXV

EFFECT OF K ON PREDICTED VALUES OF $\bar{S}$, $\bar{X}$, AND $\bar{X}_w$ (μ_{max} = 0.5 hr^{-1}, Y_1 = 0.6, k_d = 0.04 day^{-1}, D = 0.125 hr^{-1}, X_R = 10,000 mg/l)

S_i mg/l	K_s mg/l	$\bar{S}$ mg/l	$\bar{X}$ mg/l	$\bar{X}_w$ mg/l
250	50	1.0	2087	109
	100	2.0	2086	108
	150	3.0	2086	108
	200	4.0	2085	107
	250	5.0	2084	106
	300	5.0	2083	105
1000	50	3.0	2536	669
	100	6.0	2533	666
	150	10.0	2530	663
	200	13.0	2528	660
	250	16.0	2526	658
	300	19.0	2523	654

μ, or X_w at either low or high loadings. Similar results were observed for other values of S_i, α, D, k_d, Y, and X_R, as well.

Prediction of $\bar{S}$

It is found from the computer-aided calculations that Y and k_d do not affect $\bar{S}$. Figure 57 shows the values of $\bar{S}$ obtainable at various operational conditions, viz., D, α, and X_R. The three portions of Figure 57 correspond to loadings of 250, 600, and 1000 mg/l, as labelled. The values of $\bar{S}$ at various dilution rates, D, or detention times, $\bar{t}$. are traced at α of 0.15 and 0.30 for X_R values of 8000, 10,000, and 15,000 mg/l at each loading. The values of $\bar{S}$ for in-between values of α at a specific X_R will fall in the area between the two boundary lines shown. The shaded areas in Figure 57 indicate the $\bar{S}$ values at any t for an X_R of 10,000 mg/l, and α values between 0.15 and 0.3. Similar plots can be developed for S_i values from which $\bar{S}$ can be predicted.

Prediction of $\bar{X}$

In Figure 58, $\bar{X}$ is plotted against $\bar{t}$ at various values of α and X_R. The top portion of this plot is at an S_i loading of 1000 mg/l, and the bottom at an S_i loading of 250 mg/l. The purpose of this plot is to show that $\bar{t}$ does not affect X significantly within a normal range of operational conditions at both low and high loadings.

In Figure 59, all of the important factors that affect $\bar{X}$ significantly are shown. The main factors that affect $\bar{X}$ are found to be X_R, α, S_i, and Y. The range of X_R and α plotted in Figure 59 are 8000 to 15,000 mg/l, and 0.15 to 0.30, respectively. The values of $\bar{X}$ at an S_i of 250, 600, and 1000 mg/l are shown in this plot. The bottom portion

Figure 57. Effect of t (or D), α, X_R, S_i on $\bar{S}$ ($\mu_{max} = 0.5\ hr^{-1}$, $K_s = 100$ mg/l, $Y = 0.6$, $k_d = 0.04\ day^{-1}$)

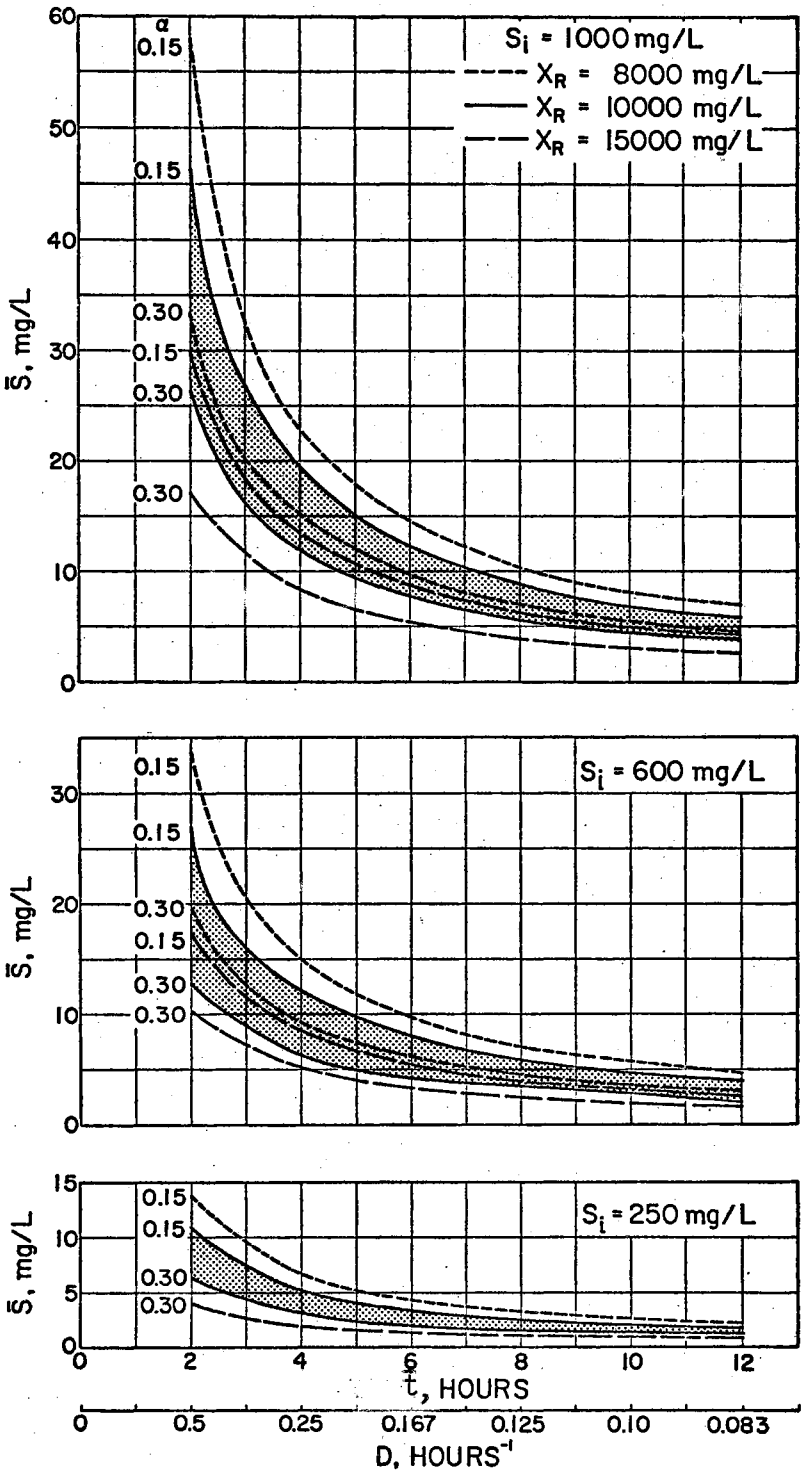

α
0.15
0.15
0.30
0.15
0.30
0.30
S_i = 1000 mg/L
X_R = 8000 mg/L
X_R = 10000 mg/L
X_R = 15000 mg/L
S_i = 600 mg/L
S_i = 250 mg/L
S, mg/L
t, HOURS
D, HOURS^{-1}
0
2
4
6
8
10
12
0.5
0.25
0.167
0.125
0.10
0.083

Figure 58. Effect of t (or D), α, X_R, and S_i on $\bar{X}$ (μ_{max} = 0.5 hr^{-1}, K_s = 100 mg/l, Y = 0.6, k_d = 0.04 day^{-1})

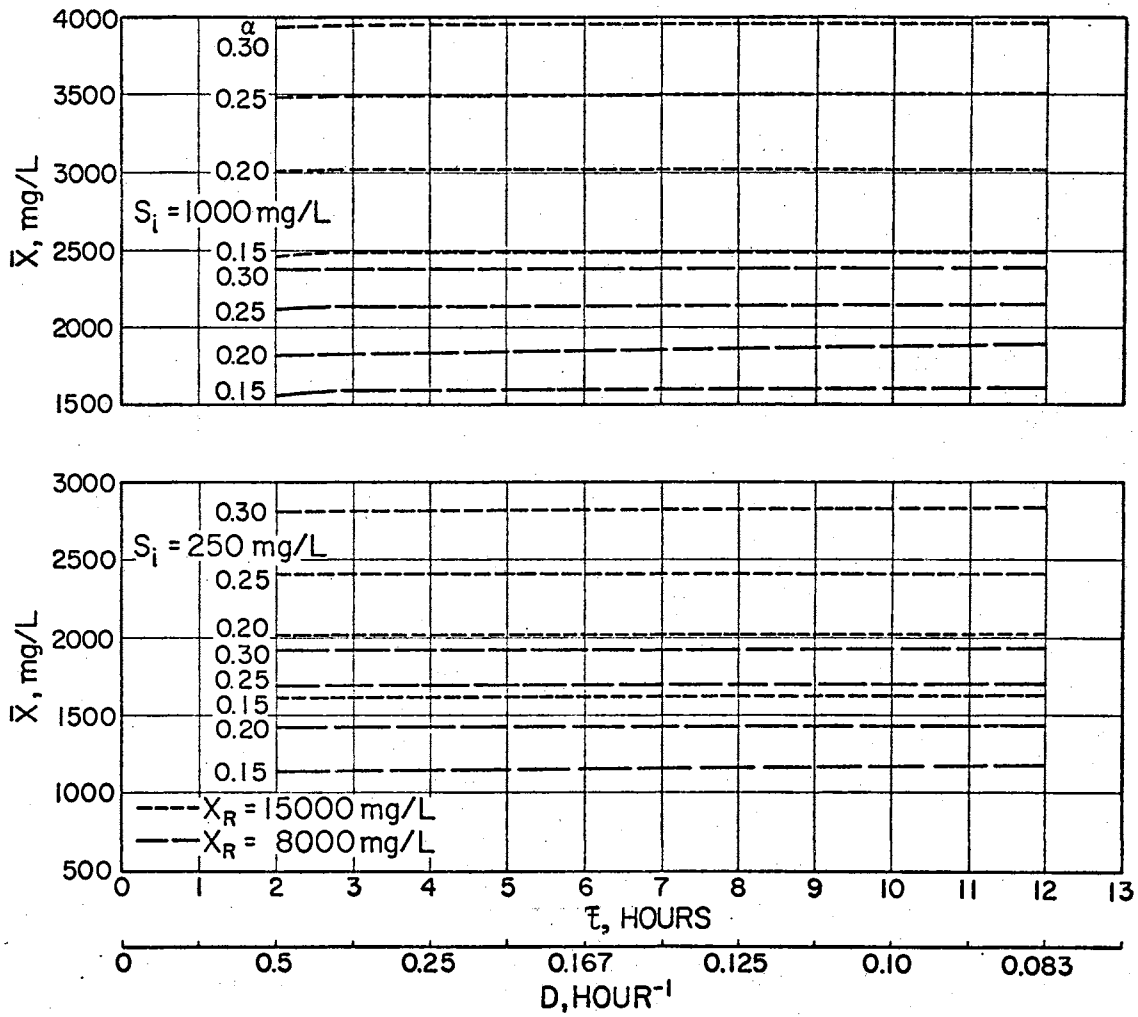
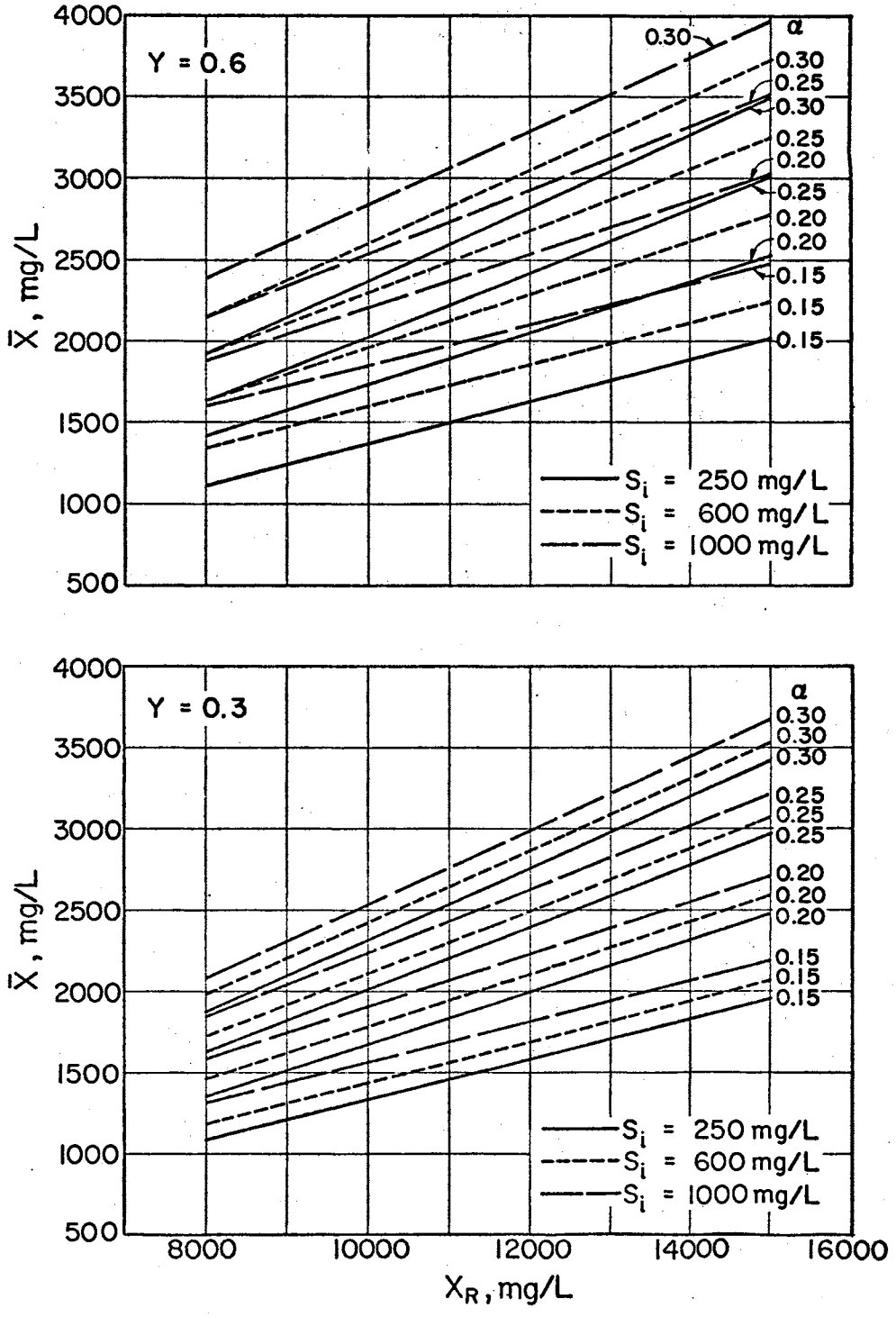

4000
3500
3000
2500
2000
1500
α
0.30
0.25
0.20
S_i = 1000 mg/L
0.15
0.30
0.25
0.20
0.15
$\bar{X}$, mg/L
3000
2500
2000
1500
1000
500
0.30
S_i = 250 mg/L
0.25
0.20
0.30
0.25
0.15
0.20
0.15
$\bar{X}$, mg/L
----X_R = 15000 mg/L
——X_R = 8000 mg/L
0 1 2 3 4 5 6 7 8 9 10 11 12 13
$\bar{t}$, HOURS
0 0.5 0.25 0.167 0.125 0.10 0.083
D, HOUR^{-1}

Figure 59. Effect of X_R, α, Y, and S_i on $\bar{X}$ (μ_{max} = 0.5 hr^{-1}, K_s = 100 mg/l, k_d = 0.04 day^{-1}, D = 0.125 hr^{-1})


Y = 0.6
Y = 0.3
α
0.30
0.25
0.20
0.15
S_i = 250 mg/L
S_i = 600 mg/L
S_i = 1000 mg/L
$\bar{X}$, mg/L
X_R, mg/L
4000
3500
3000
2500
2000
1500
1000
500
8000
10000
12000
14000
16000

of Figure 59 shows the predicted $\bar{X}$ for Y of 0.3, and the top portion corresponds to a Y value of 0.6.

Prediction of X_w

It is seen from Table II that the excess sludge, X_w, can be expressed in mg/day (equation 16) at mg/l of waste flow (equation 17). In Figures 60 and 61, X_w was calculated from equation (17) and is expressed in mg/l. To calculate the amount of total sludge produced per day (mg/day), the value predicted by this equation should be multiplied by flow rate, liter/day.

Figure 60 is a plot of $\bar{t}$ vs X_w at various values of α and X_R. The bottom portion of Figure 60 corresponds to a loading of 250 mg/l (S_i), and the top portion corresponds to a loading of 1000 mg/l. It is seen that $\bar{t}$ does not have any significant effect on sludge production at any α or X_R at either low or high loadings. The small difference in sludge production at lower $\bar{t}$ is the result of a relatively higher amount of S in the effluent at lower detention time (see Figure 58). Figure 61 is a plot of X_w vs k_d at various values of Y and X_R. The three portions of Figure 61 pertain to the loadings (S_i) labelled. It is noted that k_d and Y have significant effects on the amount of excess sludge produced. The effect of k_d is more pronounced at lower S_i concentrations and lower growth rates than at higher loadings and faster growth rates; the value of X_R also influences sludge production to a certain extent. Another important aspect of this plot is that it predicts the conditions at which the system is not operable for known Y and k_d. Thus, the selection of operational parameters, D, α, and X_R, can be suitably modified. For example, at an S_i of 250 mg/l, if Y and k_d were found to

Figure 60. Effect of $\bar{t}$ (or D), X_R, α, and S_i on X_w (μ_{max} = 0.5 hr^{-1} K_s = 100 mg/l, k_d = 0.04 day^{-1}, Y = 0.6)

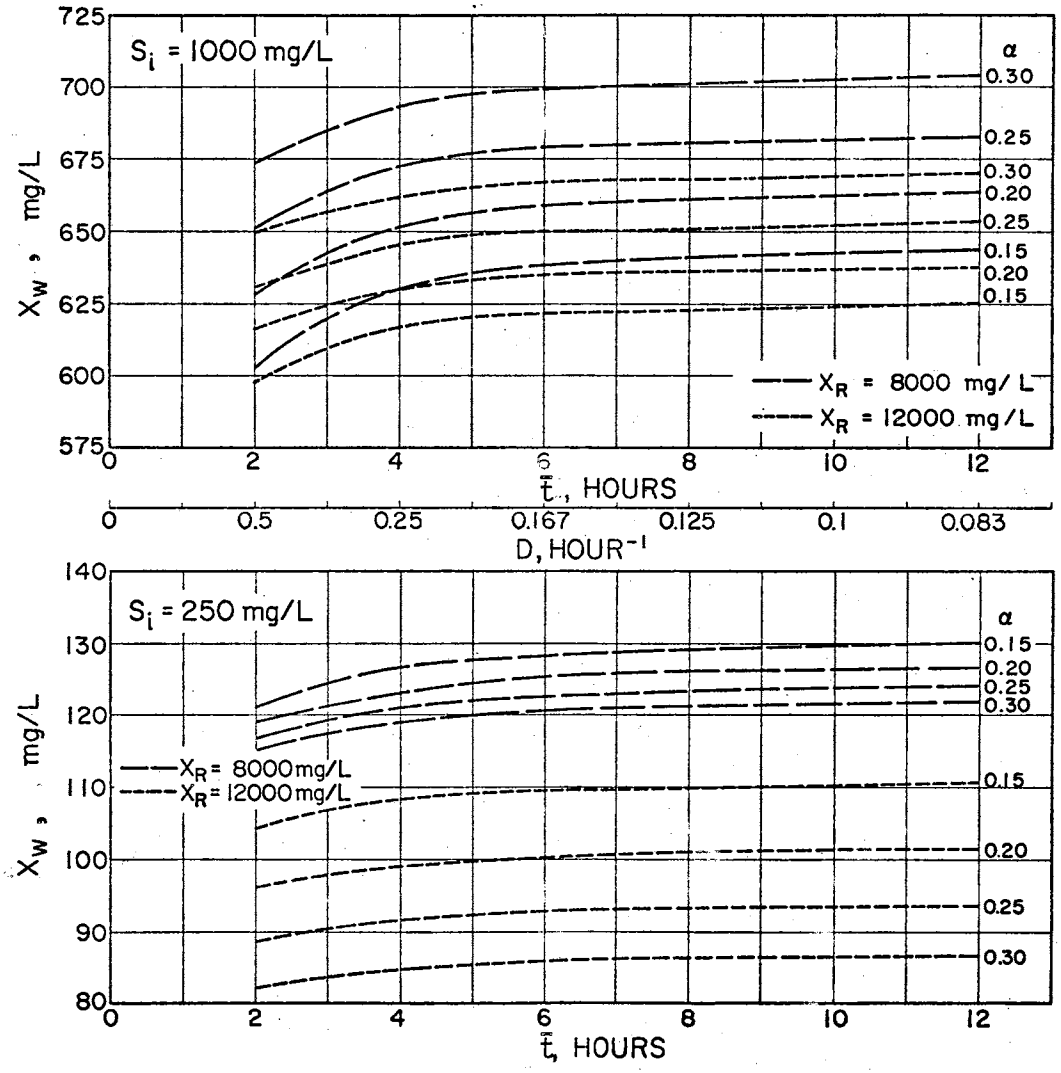
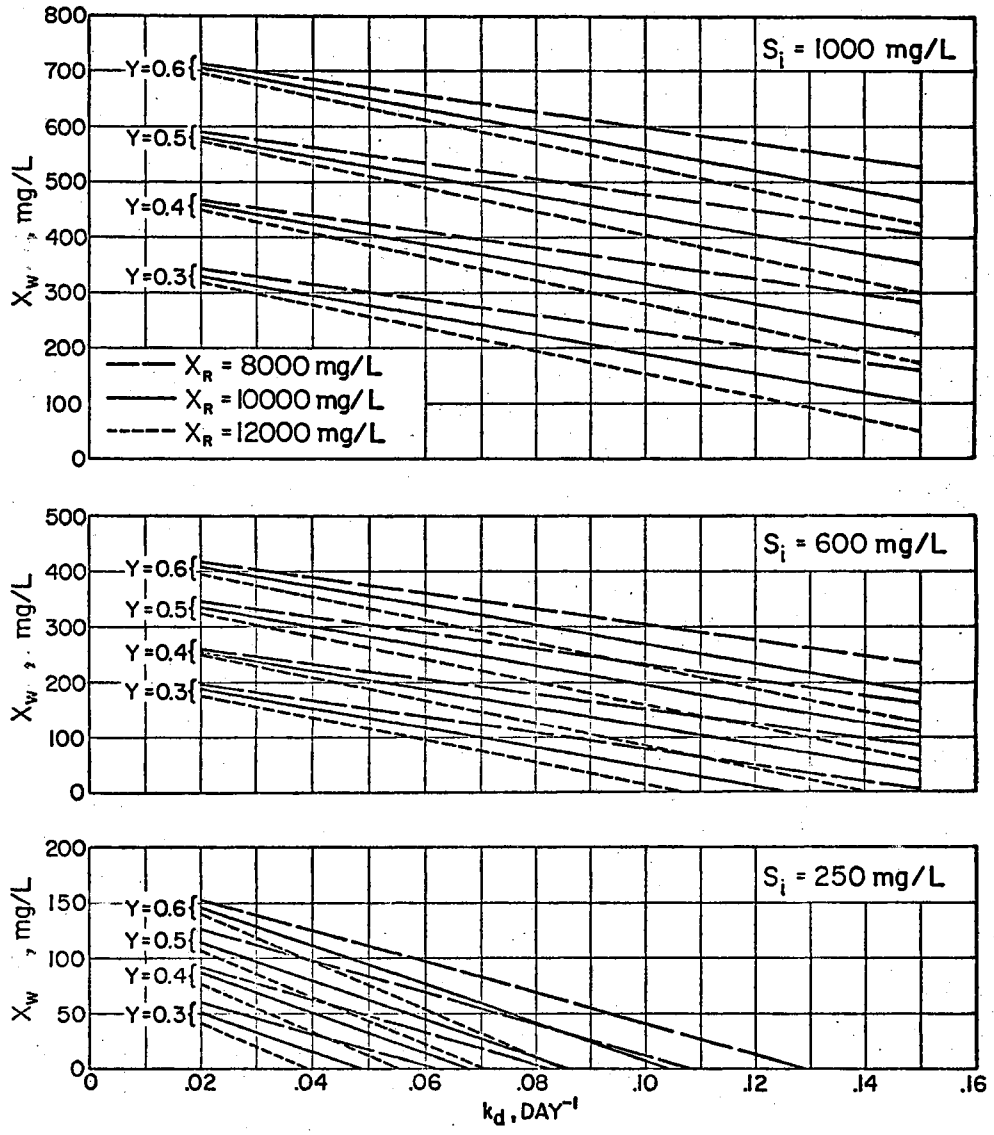

S_i = 1000 mg/L
α
0.30
0.25
0.30
0.20
0.25
0.15
0.20
0.15
X_R = 8000 mg/L
X_R = 12000 mg/L
X_w, mg/L
725
700
675
650
625
600
575
0
2
4
6
8
10
12
$\bar{t}$, HOURS
0
0.5
0.25
0.167
0.125
0.1
0.083
D, HOUR^{-1}
S_i = 250 mg/L
α
0.15
0.20
0.25
0.30
X_R = 8000 mg/L
X_R = 12000 mg/L
0.15
0.20
0.25
0.30
X_w, mg/L
140
130
120
110
100
90
80
0
2
4
6
8
10
12
$\bar{t}$, HOURS

Figure 61. Effect of k_d, Y, X_R, and S_i on X_w (μ_{max} = 0.5 hr^{-1}, K_s = 100 mg/l, α = 0.25, D = 0.125 hr^{-1})


S_i = 1000 mg/L
S_i = 600 mg/L
S_i = 250 mg/L
Y=0.6
Y=0.5
Y=0.4
Y=0.3
X_R = 8000 mg/L
X_R = 10000 mg/L
X_R = 12000 mg/L
X_w, mg/L
k_d, DAY^{-1}
0
100
200
300
400
500
600
700
800
50
150
.02
.04
.06
.08
.10
.12
.14
.16

be 0.5 and 0.08 day^{-1}, X_R of 12,000 mg/l is not feasible at an α of 0.25. A safe value for X_R will be 8000 mg/l at an α of 0.25. An alternate method will be to reduce α and operate at an X_R of 12,000 mg/l.

From Figure 62 it can be seen that k_d does not affect the value of $\bar{X}$ at various values of α and X_R. Also shown in Figure 62 is the effect of k_d on sludge production at different recycle ratios. It is noted that α does not affect the amount of sludge produced at higher k_d values. The effect of α on X_w is more at a higher X_R than at a lower X_R. An interesting observation from this plot is that at an X_R of 15,000 mg/l and k_d of 0.068 day^{-1}, the amount of excess sludge produced is the same for any values of α between 0.15 and 0.3 at an S_i of 1000 mg/l. Similar is the situation when X_R is 10,000 mg/l and k_d is 0.095 day^{-1}. A brief explanation for this occurrence is that in the range of α investigated, an increase in α decreases the specific growth rate and increases X. Since $X_w = \frac{\mu X}{D}$, there is at a certain k_d a convergence wherein the increase in X matches the decrease in μ and the products are identical.

The curves presented in this section can be used as a guideline for designing waste treatment facilities employing the activated sludge process. It is suggested that the designer obtain the following data by laboratory analysis before design alternatives can be considered:

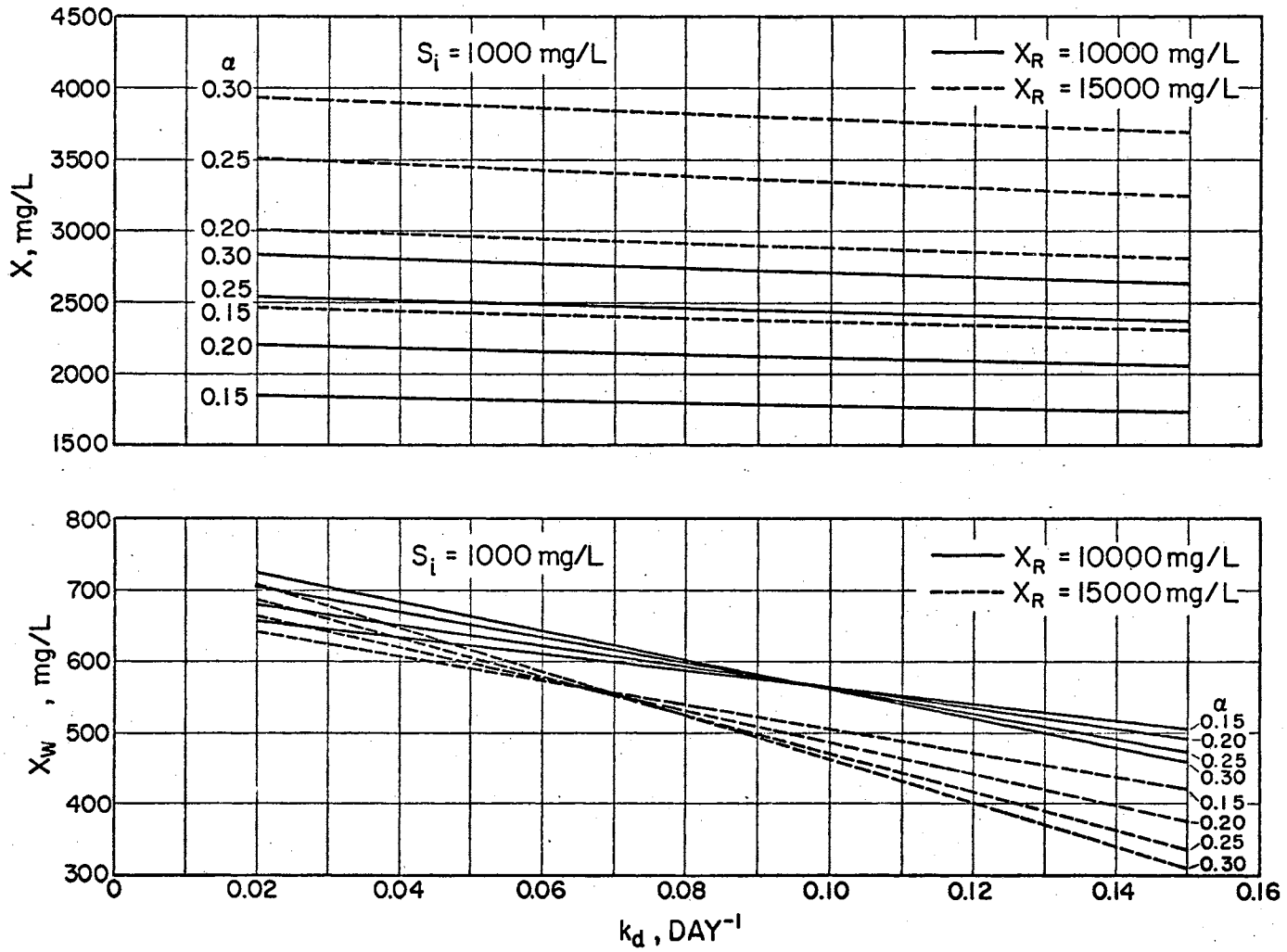
1) ΔCOD of waste: can be obtained by batch lab experiments to find the biodegradable portion of the wastewater to which the treatment facilities need to be designed.

2) μ_{max} and K_s: Batch growth experiments can be conducted by employing cells grown in a COD test to obtain these biological "constants."

Figure 62. (top) Effect of k_d, X_R, and α on $\bar{X}$ at S_i of 1000 mg/l ($\mu_{max} = 0.5\ hr^{-1}$, $K_s = 100$ mg/l, $D = 0.125\ hr^{-1}$, $Y \cong_{0.6}$)

(bottom) Effect of k_d, X_R, and α on $\bar{X}_w$ at S_i of 1000 mg/l

($\mu_{max} = 0.5\ hr^{-1}$, $K_s = 100$ mg/l, $D = 0.125\ hr^{-1}$, $Y = 0.6$)


4500
4000
3500
3000
2500
2000
1500
X, mg/L
α
0.30
0.25
0.20
0.30
0.25
0.15
0.20
0.15
S_i = 1000 mg/L
X_R = 10000 mg/L
X_R = 15000 mg/L
800
700
600
500
400
300
X_w , mg/L
S_i = 1000 mg/L
X_R = 10000 mg/L
X_R = 15000 mg/L
α
0.15
0.20
0.25
0.30
0.15
0.20
0.25
0.30
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
k_d , DAY^{-1}

3) Y and k_d: Continuous flow laboratory bench scale studies can be conducted at different growth rates and the results from this can be used to develop the maintenance plot to obtain values of Y and k_d. However, if such long-term studies are not feasible, a reasonable estimate of Y can be made by conducting batch experiments. A value for k_d may be obtained from the literature or by experience (most frequently reported range for k_d is between 0.02 and 0.08 day^{-1}).

After obtaining all of these parameters, the design curves can be consulted to select the operational conditions. If the effluent BOD or percent removal is specified, the detention time, $\bar{t}$, required can be selected from Figure 57 for any specific α and X_R of choice. At this particular combination of S_i, Y, α, and X_R, the value of $\bar{X}$ can be determined from Figure 59. The amount of excess sludge produced for which sludge handling facilities need to be provided can be read from Figure 61 at the specific Y, X_R, k_d, and S_i. An examination of the design curves indicate that more than one combination of D, α, and X_R is possible to achieve the same effluent quality. It is very important after selecting X_R, α, and D, to check from Figure 61 that it is feasible to operate under the chosen conditions at the specific k_d. If the selected combination of X_R, α, and D indicates zero or negative sludge production, these three operational parameters should be modified to arrive at a positive sludge production value without sacrificing effluent quality. If, however, various combinations of α, X_R, and D are found to give satisfactory treatment, the selection should be based on economic considerations, like tank volume, pumping costs, amount of excess sludge produced for which disposal facilities need to be provided. A basic rule of thumb is to design a system with the least

amount of excess sludge production, thereby reducing sludge disposal cost. However, by designing a system for slow growth rate or high Θ_c, the aeration tank volume may be increased to the point where the increase in secondary treatment cost may more than offset the reduction in sludge disposal costs. Also, by designing a system with higher sludge production, a higher amount of NH_3-N as well as phosphorous can be incorporated in the cells and thus reduce the cost of tertiary treatment.

It might seem possible from Figure 61 that a designer can so choose operational parameters to have zero sludge production (extended aeration-total oxidation process). However, it is not true due to the behavior of k_d. The cell decay is a combination of various phenomena occurring at the same time. The value of k_d obtained from the maintenance plot is a gross number over a wide range of growth rates or cell ages. This value can vary throughout the range of growth rates. Therefore, it will be inappropriate to use the model to design an extended aeration-total oxidation process.

In the literature review section of this report, two main approaches being practiced were discussed. It is of interest here to translate the approach suggested in this section to the design approaches which utilize F/M ratio and sludge residence time, Θ_c. To facilitate such a comparison, the growth rate, μ, or cell age, Θ_c, and F/M values are plotted against $\bar{t}$ at various values of X_R and α for an S_i of 250 mg/l in Figure 63. A similar plot for an S_i of 1000 is shown in Figure 64. The Θ_c values were calculated in accordance with equation (20). The F/M ratios were calculated in accordance with the following equation:

Figure 63. Effect of t (or D), X_R, and α on F/M Ratio and μ (or Θ_c) at S_i of 250 mg/l

($\mu_{max} = 0.5\ hr^{-1}$, $K_s = 100$ mg/l, $Y = 0.6$, and $k_d \cong 0.04\ day^{-1}$)

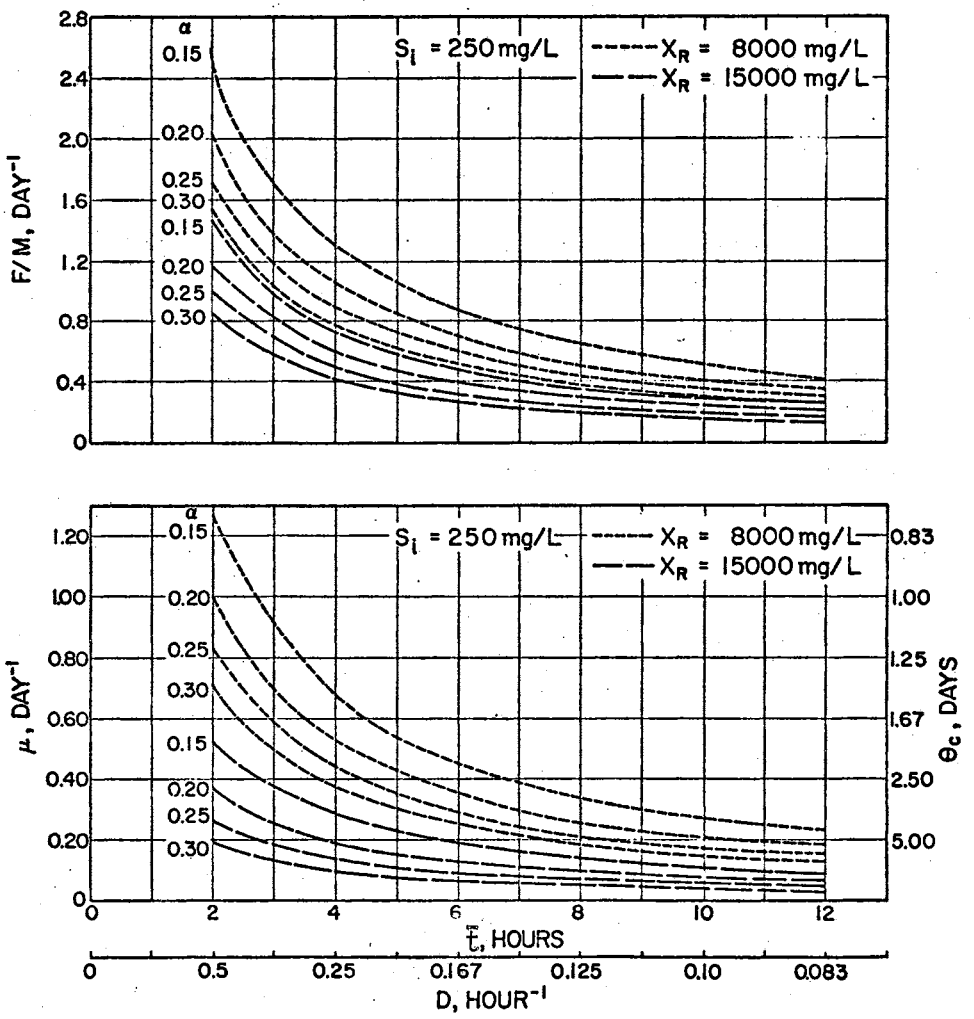
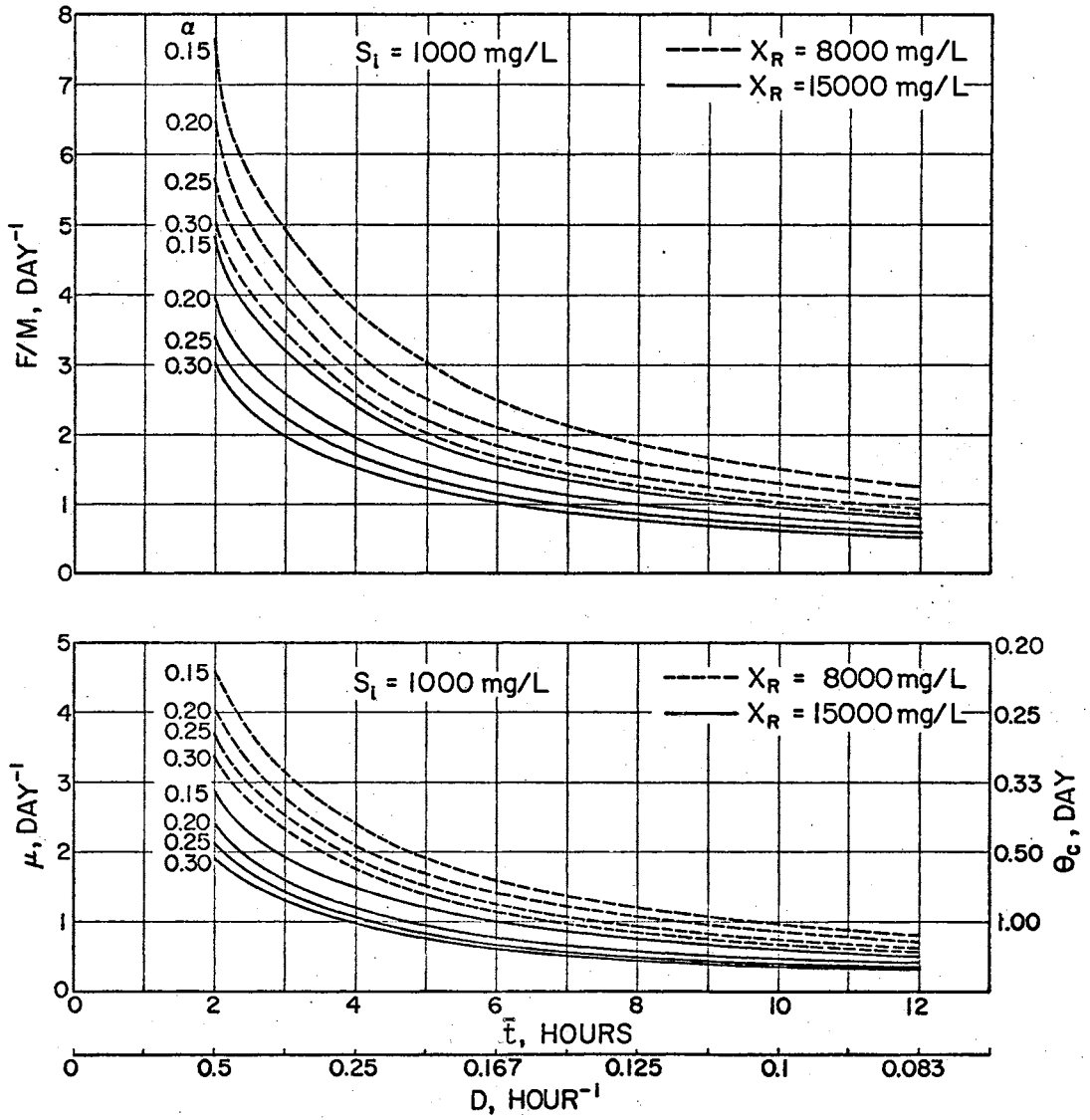

α
0.15
0.20
0.25
0.30
0.15
0.20
0.25
0.30
S_i = 250 mg/L
X_R = 8000 mg/L
X_R = 15000 mg/L
F/M, DAY^{-1}
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0
α
0.15
0.20
0.25
0.30
0.15
0.20
0.25
0.30
S_i = 250 mg/L
X_R = 8000 mg/L
X_R = 15000 mg/L
μ, DAY^{-1}
1.20
1.00
0.80
0.60
0.40
0.20
0
0.83
1.00
1.25
1.67
2.50
5.00
θ_c, DAYS
0
2
4
6
8
10
12
t, HOURS
0
0.5
0.25
0.167
0.125
0.10
0.083
D, HOUR^{-1}

Figure 64. Effect of t (or D), X_R, and α on F/M Ratio and μ (or θ_c) at S_i of 1000 mg/l

(μ_{max} = 0.5 hr^{-1}, K_s = 100 mg/l, Y = 0.6, and k_d = 0.04 day^{-1})


α
0.15
0.20
0.25
0.30
0.15
0.20
0.25
0.30
S_i = 1000 mg/L
X_R = 8000 mg/L
X_R = 15000 mg/L
F/M, DAY^{-1}
μ, DAY^{-1}
θ_c, DAY
0.20
0.25
0.33
0.50
1.00
$\bar{t}$, HOURS
D, HOUR^{-1}
0.5
0.25
0.167
0.125
0.1
0.083

$$F/M = F \cdot S_i \Big/ V \cdot \bar{X} = S_i \Big/ \bar{X} \qquad (23)$$

The biological constants used were the average ones employed for the design curves of Figures 57 through 62. These are noted in the legend of Figures 63 and 64. If a designer prefers to design a system to maintain a specific Θ_c or F/M ratio, he can still employ the model recommended herein by consulting Figures 63 or 64 to arrive at possible combinations of α, X_R, and D. For any chosen values of α, X_R and D, the effluent substrate concentration can be obtained from Figure 57. Conversely, if the designer has employed the model and approach to the design herein recommended and has obtained the design values of α, D, and X_R, he can check his design against accepted values of F/M and Θ_c by consulting Figures 63 and 64.

CHAPTER VIII

CONCLUSIONS

The results of this investigation support the following conclusions:

1) An activated sludge process can be operated without extraordinary operational effort according to the conditions that the recycle sludge concentration, X_R, is a selectable constant.

2) The experimental results provide justification for the basic assumptions made in derivation of model equations.

3) The experimental results also provide evidence that a rather steady state in $\bar{S}$ and $\bar{X}$ does ensue for prolonged periods of time, which is one of the conditions stipulated in deriving the model.

4) Runs conducted at similar conditions produced comparable results, indicating that the performance with regard to $\bar{X}$, $\bar{S}$, and $\bar{X}_w$ is fairly reproducible.

5) The system follows the general trend of decrease in X_w (or Y_{c_R}) as growth rate, μ, is decreased (or as cell age is increased).

6) Comparison of cell yield values obtained from batch experiments and continuous flow experiments with and without recycle indicate some reason for caution in ascribing the above phenomenon to the so-called "maintenance energy" concept as is usually stated. However, either of the analytical equations employed to express the kinetics of the concept can be used to handle the data.

7) Results of pure culture study support the above mentioned observation on yield in heterogeneous populations, and thus warrant caution against acceptance of theoretical validity of the maintenance energy concept.

8) Comparison of predicted values of $\bar{S}$, $\bar{X}$, and $\bar{X}_w$ by equations including the maintenance coefficient, k_d, and original equations without k_d prove that there was little difference in prediction of $\bar{S}$ and $\bar{X}$. However, there was a significant difference in the predicted values of $\bar{X}_w$. In the interest of refining the prediction of $\bar{X}_w$, those equations including the maintenance coefficient are recommended.

CHAPTER IX

SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this study, the following suggestions are presented for future investigation involving the constant cell feedback model for an activated sludge process:

1) Study the behavior of the model at other X_R, S_i, and D conditions.

2) Investigate possible methods of automatic measurement and control of X_R by employing a quicker physical-instrumental analysis for biological solids concentration.

3) Conduct runs at higher Θ_c or lower growth rate to recommend operational conditions of the model for nitrification purposes.

4) Test the performance of the model under various types of shock loads, and employ sludge consistency tank (aerator #2) as a dosage tank to control leakage of substrate, if any.

5) Study the operational ease and performance of the model on a full scale pilot plant employing a whole waste at a higher level.

6) Do a cost analysis of the additional expense involved by adding a sludge consistency tank, and provide engineering design details of this tank.

7) Try out the complete aerobic treatment flow sheet suggested by Gaudy and Gaudy (24) for carbon removal and sludge disposal.

SELECTED BIBLIOGRAPHY

1. Ramanathan, M., and Gaudy, A. F. Jr., Steady State Model for Activated Sludge With Constant Recycle Sludge Concentration." Biotechnology and Bioengineering, XIII, 125-145 (1971).

2. Helmers, E. N., Frame, J. D., Greenberg, A. E., and Sawyer, C. N., "Nutritional Requirements in the Biological Stabilization of Industrial Waste. II. Treatment With Domestic Sewage." Sewage and Industrial Waste, 23, 884-892 (1951).

3. Heukelekian, H., Orford, H. E., and Manganelli, R, "Factors Affecting the Quantity of Sludge Production in the Activated Sludge Process." Sewage and Industrial Wastes, 23, 945-956 (1951).

4. Hoover, R. S., and Porges, N., "Assimilation of Dairy Wastes by Activated Sludge. II. The Equation of Synthesis and Rate of Oxygen Utilization." Sewage and Industrial Wastes, 24, 306-316 (1952).

5. Eckenfelder, W. W. Jr., and O'Connor, D. J., "The Aerobic Treatment of Organic Wastes." Proceedings, Industrial Waste Conference, Purdue University, Lafayette, Indiana, 512-528 (1955).

6. Eckenfelder, W. W. Jr., "Theory and Practice of Activated Sludge Process Modifications." Water and Sewage Works, 108: 4: 145 (April 1961).

7. Eckenfelder, W. W. Jr., Industrial Water Pollution Control. McGraw-Hill, New York (1966).

8. Eckenfelder, W. W. Jr., Water Quality Engineering for Practicing Engineers. Barnes & Noble, New York (1970).

9. McKinney, R. E., "Mathematics of Complete-Mixing Activated Sludge." Journal of Sanitary Engineering Div., Proceedings ASCE, 88, SA3, 87-113 (1962).

10. Busch, A. W., "Treatibility vs Oxidizability of Industrial Wastes and Formulation of Process Design Criteria." Proceedings, Industrial Waste Conference, Purdue University, Lafayette, Indiana, 109-121 (1961).

11. Wernitznig, R. E., "Evaluation of the Busch Method for Activated Sludge Treatment Process Design." Master's Thesis, Oklahoma State University, Stillwater, Oklahoma (1974).

12. Grieves, R. B., Milbury, W. F., and Pipes, W. O., "A Mixing Model for Activated Sludge." Proceedings, Industrial Waste Conference, Purdue University, Lafayette, Indiana, 619-635 (1963).

13. Cholette, A., and Cloutier, I., "Mixing Efficiency Determination for Continuous Flow Systems." Canadian Journal of Chemical Engineering, 37, 105-112 (1959).

14. Schulze, K. L., "A Mathematical Model of the Activated Sludge Process." Developments in Industrial Microbiology, 5, 258-268 (1964).

15. Gaudy, A. F. Jr., Ramanathan, M., and Rao, B. S., "Kinetic Behavior of Heterogeneous Populations in Completely Mixed Reactors." Biotechnology and Bioengineering, IX, 387-411 (1967).

16. Garrett, M. T., and Sawyer, C. N., "Kinetics of Removal of Soluble BOD by Activated Sludge." Proceedings, Industrial Waste Conference, Purdue University, Lafayette, Indiana, 51-77 (1951).

17. Bhatla, M. N., Vernon, S., and Weston, R. F., "Design of Wastewater Treatment Plant From Laboratory Data." Journal Water Pollution Control Federation, 38, 601-613 (1966).

18. Lawrence, A. W., and McCarty, P. L., "Unified Basis for Biological Treatment Design and Operation." Journal of Sanitary Engineering Div., Proceedings ASCE, 96, SA3, 757-778 (1970).

19. Sherrard, J. H., and Schroeder, E. D., "Variation of Cell Yield and Growth Rate in the Completely Mixed Activated Sludge Process." Proceedings, Industrial Waste Conference, Purdue University, Lafayette, Indiana (1972).

20. Sherrard, J. H., and Schroeder, E. D., "Relationship Between the Observed Cell Yield Coefficient and Mean Cell Residence Time in the Completely Mixed Activated Sludge Process." Water Research, 6, 1039-1047 (1972).

21. Sherrard, J. H., and Schroeder, E. D., "Cell Yield and Growth Rate in Activated Sludge." Journal Water Pollution Control Federation, 45, 1889-1899 (1973).

22. Goodman, B. L., and Englande, A. J. Jr., "A Unified Model of the Activated Sludge Process." Journal Water Pollution Control Federation, 46, 312-329 (1974).

23. Stensel, H. D., and Shell, G. L., "Two Methods of Biological Treatment Design." Journal Water Pollution Control Federation, 46, 271-288 (1974).

24. Gaudy, A. F. Jr., and Gaudy, E. T., "Biological Concepts for Design and Operation of the Activated Sludge Process." Project Report for the Water Quality Office, EPA, September (1971).

25. Walker, L. F., "Hydraulically Controlling Solids Retention Time in Activated Sludge Process. Journal Water Pollution Control Federation, 43, 30-42 (1971).

26. Pirt, S. J., "The Maintenance Energy of Bacteria in Growing Cultures." Proceedings of the Royal Society, London, Ser. B. 163, 224-231 (1965).

27. Mallette, M. F., "Validity of the Concept of Energy of Maintenance." Ann. New York Academy of Sciences, 102, 521-535 (1963).

28. McGrew, S. B., and Mallette, M. F., "Energy of Maintenance in E. coli." J. Bacteriology, 83, 844-850 (1962).

29. Dawes, E. A., and Ribbons, D. W., "Some Aspects of Endogenous Metabolism of Bacteria." Bacteriological Reviews, 28, 126-149 (1964).

30. Rahn, O., Physiology of Bacteria. P. Blakinstons Son & Co., Philadelphia, Pa.

31. Lockhart, W. R., "Use of Microorganism for Studies of Growth and Morphogenesis." Bacteriol. Rev. 23, 8-17 (1959).

32. Lamanna, C., and Mallette, M. F., Basic Bacteriology. The Williams and Williams Co., Baltimore, Md. (1959).

33. Kandler, O., "Energetics in Tissue Culture." Ann. Biol., 59, 173-184 (1955).

34. Windisch, F., and Nordheim, W., "Anoxic Reaction of Cell Production After Anoxybiologically-Induced Cylostasis." Expermentia, 13, 155-156 (1957).

35. Maze, P., "Recherches sur la Modes d'utilisation du Carbone Ternaire par las Vegetaux et les Microbes." Ann. Inst. Pasteur, 16, 346-378 (1902).

36. Rottier, P. B., "Concentration of Nutrients on Growth of Polytoma uvella." Compt. Rend. Soc. Biol., 122, 776-780 (1936).

37. Monod, J., and Teissier, G., "La Concentration de l'aliment, Facteur Quantatif de l'accroisement des Population d'infusones." Compt. Rend., 202, 162-164 (1936).

38. Monod, J., Researches sur la Croissance des Cultures Bacteriennes. Hermann & Cie, Editeurs, Paris (1942).

39. Dagley, S., Dawes, E. A., and Morrison, G. A., "The Effect of Aeration on the Growth of A. Aerogenes and E. coli with Reference to the Pasteur Mechanism." J. Bacteriology, 61, 433-439 (1951).

40. Herbert, D., "Recent Progress in Microbiology. Some Principles of Continuous Culture." Intern. Congr. Microbiology, 7th, Stockholm, 381-396 (1958).

41. Battley, E. H., "Growth Reaction Equations for Saccharomyces cervisiae." Physiol. Plantarum, 13, 192-203 (1960).

42. Bauchop, T., and Elsden, S. R., "The Growth of Microorganisms in Relation to Their Energy Supply." J. Gen. Microbiol., 23, 457-469 (1960).

43. Marr, A. G., Nilson, E. H., and Clark, D. J., "The Maintenance Requirement of E. coli." Ann. New York Academy of Sciences, 102, 536-548 (1963).

44. Schulze, K. L., and Lipe, R. S., "Relationship Between Substrate Concentration, Growth Rate, and Respiration Rate of E. coli in Continuous Culture." Arch. Mikrobiol., 48, 1-20 (1964).

45. Hobson, P. N., "Continuous Culture of Some Anaerobic and Facultatively Anaerobic Rumen Bacteria." J. Gen. Microbiol. 38, 167-175 (1965).

46. Palumbo, S. A., and Witter, L. D., "Influence of Temperature on Glucose Utilization by Pseudomonas fluorescens." Applied Microbiology, 18, 137-141 (1969).

47. Mannett, R. H., and Nakayama, T. O. M., "Influence of Temperature on Substrate and Energy Conversion in P. fluorescens." Applied Microbiology, 22, 772-776 (1971).

48. Abbott, B. J., and Clamen, A., "The Relationship of Substrate, Growth Rate and Maintenance Coefficient to Single Cell Protein Production." Biotechnology and Bioengineering, XV, 117-127 (1973).

49. Ramanathan, M., and Gaudy, A. F. Jr., "Effect of High Substrate Concentration and Cell Feedback on Kinetic Behavior of Heterogeneous Populations in Completely Mixed Systems." Biotechnology and Bioengineering, XI, 207-237 (1969).

50. Herbert, D., "A Theoretical Analysis of Continuous Culture Systems." Soc. Chem. Ind. (London), Monograph No. 12, 21-53 (1956).

51. Komolrit, K., and Gaudy, A. F. Jr., "Biochemical Response of Continuous Flow Activated Sludge Processes to Qualitative Shock Loadings." Journal Water Pollution Control Federation, 38, 85-101 (1966).

52. Standard Methods for the Examination of Water, Sewage, and Industrial Wastes (13th Ed), American Public Health Association, New York (1971).

53. Peil, K. M., and Gaudy, A. F. Jr., "Kinetic Constants for Aerobic Growth of Microbial Populations Selected With Various Single Compounds and With Municipal Wastes as Substrates." Appl. Microbiology, 21, 253-256 (1971).

54. Breed, R. S., Murray, E. G. D., and Smith, N. R., Bergey's Manual of Determinative Bacteriology (7th Ed), The Williams & Wilkins Co., Baltimore, Md. (1957).

55. Ecker, R. E., and Lockhart, W. R., "Specific Effect of Limiting Nutrient on Physiological Events During Culture Growth." J. Bacteriology, 82, 511-516 (1961).

56. Gaudy, A. F. Jr., "Colorimetric Determination of Protein and Carbohydrate." Industrial Water Wastes, 7, 17-22 (1962).

57. Ramanathan, M., Gaudy, A. F. Jr., and Cook, E. E., Selected Analytical Methods for Research in Water Pollution Control. Manual M-2, Center for Water Research in Engineering - Bioenvironmental Engineering, Oklahoma State University, Stillwater, Oklahoma (1968).

58. Umbreit, W. W., Burris, R. H., and Stauffer, J. F., Manometric Techniques (4th Ed), Burgess, Philadelphia (1964).

59. Gaudy, A. F. Jr., and Gaudy, E. T., "ΔCOD gets Nod Over BOD Test." Industrial Waste Engineering, 9, 30-34 (1972).

60. Thabaraj, G. J., and Gaudy, A. F. Jr., "Effect of Initial Biological Solids Concentration and Nitrogen Supply on Metabolic Patterns During Substrate Removal and Endogenous Metabolism." Journal Water Pollution Control Federation, 43, 318-334 (1971).

61. Ramanathan, M., and Gaudy, A. F. Jr., "Studies on Sludge Yield in Aerobic Systems." Journal Water Pollution Control Federation, 44, 441-450 (1972).

62. McCarty, P. L., "Energetics and Bacterial Growth." Fifth Rudolph Research Conference, Rutgers University, New Brunswick, New Jersey (1963).

63. Eckoff, D. W., and Jenkins, D., "Activated Sludge Systems: Kinetics of the Steady and Transient States." Report on USPHS Research Grant No. WP-00787.

64. Eckenfelder, W. W., and Ford, D. L., Water Pollution Control. The Pemberton Press, Dallas, Texas (1970).

65. Stall, T. R., "Effect of Wastewater Stoichiometry and Mean Cell Residence Time in Phosphorus Removal in the Activated Sludge Process." Master's Thesis, Oklahoma State University, Stillwater, Oklahoma (1973).

APPENDIX

COMPUTER PROGRAM FOR THE PREDICTION OF $\bar{S}$, $\bar{X}$, X_w, μ, AND F/M AT VARIOUS OPERATIONAL CONDITIONS

```
      DIMENSION MUMAX(20),KS(20),Y(20),DECAY(20),RESO(20),ALPHA(20),D(20
     1)
      REAL KS,MUMAX,MU
  100 WRITE(6,5)
    5 FORMAT('1',6X,'SI',5X,'MUMAX',5X,'KS',7X,'Y',7X,'KD',7X,'XR',5X,'A
     1LPHA',6X,'D',8X,'S',8X,'X',7X'MU',7X,'XW',7X,'F/M'/)
      LINE=3
      SI=250.0
      READ(5,1)(MUMAX(IM),IM=1,4)
      READ(5,2)(KS(IK),IK=1,6)
      READ(5,1)(Y(IY),IY=1,4)
      READ(5,3)(DECAY(ID),ID=1,5)
      READ(5,1)(RESO(IR),IR=1,4)
      READ(5,1)(ALPHA(IA),IA=1,4)
      READ(5,2)(D(IT),IT=1,6)
    1 FORMAT(4F10.5)
    2 FORMAT(6F10.5)
    3 FORMAT(5F10.5)
      DO 10 IM=1,4
      DO 10 IK=1,6
      DO 10 IY=1,4
      DO 10 ID=1,5
      DO 10 IR=1,4
      DO 10 IA=1,4
      DO 10 IT=1,6
      A=MUMAX(IM)-(1.+ALPHA(IA))*D(IT)+DECAY(ID)
      B=D(IT)*(SI-(1.+ALPHA(IA))*KS(IK))-(MUMAX(IM)/(1.+ALPHA(IA)))*(SI+
     1(ALPHA(IA)*RESO(IR))/Y(IY))-DECAY(ID)*(KS(IK)+(SI/(1.+ALPHA(IA))))
      C=KS(IK)*D(IT)*SI+KS(IK)*DECAY(ID)*SI
      S=(-B-(B**2-4.*A*C)**0.5)/(2.*A)
      X=(Y(IY)*(SI-(1.+ALPHA(IA))*S))+ALPHA(IA)*RESO(IR)/(1.+ALPHA(IA)+D
     1ECAY(ID))
      MU=D(IT)*(1.+ALPHA(IA)-(ALPHA(IA)*RESO(IR)/X))
      XW=MU*X/(D(IT))
      FM=D(IT)*SI/X
      WRITE(6,6) SI,MUMAX(IM),KS(IK),Y(IY),DECAY(ID),RESO(IR),ALPHA(IA),
     1D(IT),S,X,MU,XW,FM
    6 FORMAT(' ',13(1X,F9.2))
      LINE=LINE+1
      IF(LINE-60)10,10,8
    8 WRITE(6,5)
      LINE=3
   10 CONTINUE
      STOP
      END
```

VITA

R. Srinivasaraghavan

Candidate for the Degree of

Doctor of Philosophy

Thesis: STUDIES ON A KINETIC MODEL FOR DESIGN AND OPERATION OF AN ACTIVATED SLUDGE PROCESS EMPLOYING CONSTANT CELL FEEDBACK

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Madras, India, August 25, 1948, the son of Rengachari and Kousalya Rengachari. Single.

Education: Graduated from Sri Rama-Krishna Mission High School, Madras, India, in May, 1964; received Bachelor of Technology degree in Chemical Engineering in May, 1970, from the University of Madras, Madras, India; Master of Science degree in Biological Engineering in May, 1972, from Rose-Hulman Institute of Technology, Terre Haute, Indiana, May, 1972; completed requirements for the Doctor of Philosophy degree at Oklahoma State University, Stillwater, in December, 1974.

Professional Experience: Research Assistant, Rose-Hulman Institute of Technology, Terre Haute, Indiana, 1970-1972; Research Assistant, Oklahoma State University, Stillwater, 1972-1974.