STUDIES ON THE EFFECTS OF COMBINED QUALITATIVE AND QUANTITATIVE SHOCK LOADINGS ON AN ACTIVATED SLUDGE PROCESS WITH CONSTANT CONCENTRATION OF RECYCLE SLUDGE

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LIST OF SYMBOLS

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 sludge flow, l/day

k_d - Maintenance energy coefficient, or decay 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 one-half the maximum specific growth rate for the system, mg/l

S, $\bar{S}$ - 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 effluent, filtrate COD, mg/l

S_t, 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_1} - Concentration of substrate in the effluent of aerator #1, filtrate COD, mg/l

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

t - Hydraulic detention time, hrs

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

V - Volume of liquor in aerator #1, liters

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

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

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

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

Y_{t_B} - True mean cell yield obtained during growth at specific growth rate at or near μ_{max} (batch system)

Y_o - Observed mean cell yield obtained during growth at specific growth rate (continuous system with cell recycle)

Y_t - True cell yield

μ_n - Net specific growth rate in continuous system with cell feedback, hr^{-1}

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

α - Recycle flow ratio

θ_c - Sludge retention time, days

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

MLSS - Mixed liquor suspended solids

CHAPTER I

INTRODUCTION

With rapid industrialization and increase in population, the amount of pollutants entering the water resource is increasing. Increasing industrialization and introduction of new products to increase the comfort level of the community also increase the various kinds of pollutants entering the water resource. If the environmental engineering scientist does not provide economical solutions to the problem of pollution control, "safe water" will become one of the world's rare commodities. In point of fact, as industrialization and population expand, greater amounts of a safe water supply will be derived from treated waste water. This will require much more reliable delivery of high quality treatment plant effluent than now exists. A state has been reached wherein not only a generally improved quality of effluent is needed, but a reduction in short term fluctuations in effluent quality is necessary.

Activated sludge processes have a promising role to play in this regard. It has taken more than a decade to convince engineers that for design of biological treatment processes, conceptual design models rather than uncertain empirical rules are desirable. However,the design models which are most applicable to the activated sludge process are based on "steady state" conditions; thus a design is based on "average" flow even though everyone is aware that in the real world the influent entering the biological treatment unit is subjected to wide variation in flow conditions.

In addition to flow, there are also wide variations in quantity and quality of wastes and in other environmental conditions. In the main, these factors are neither taken into account in the design nor are provisions made so that the plant operator can overcome possible adverse effects of variable and environmental conditions. With this in mind, the development of kinetic models for design and operation of various modifications of such processes as well as studies of the biological responses to changes in environmental conditions, i. e., shock loads, have occupied a considerable amount of the investigative effort in the bioenvironmental engineering laboratories at Oklahoma State University.

The activated sludge model developed by Gaudy and his co-workers proposing operation with constant concentration of recycle sludge, X_R, as a control parameter is being studied for its possible operational advantages under relatively steady as well as variable adverse environmental conditions. The study herein reported forms a portion of this large-scale undertaking. In particular, this work is concerned with operational stability under qualitative shock loads, quantitative shock loads, combined qualitative and quantitative shock loads, combined quantitative and hydraulic shock loads, and the effect of recycle sludge concentration on the performance of the system.

CHAPTER II

LITERATURE REVIEW

The theory of continuous culture was developed by Monod (1) and Novick and Szilard (2). Further development of the theory was made by Herbert, Elsworth and Telling (3), and by Herbert (4). Since the above theory was developed for pure culture, experimentatl investigative effort was made in the Oklahoma State University bioenvironmental engineering laboratories to determine whether this theory is applicable to heterogeneous microbial populations. It was concluded, based on detailed investigative effort, that this theory applied to once-through continuous culture reactors was valid for heterogeneous populations (5, 6, 7, 8, 9). Herbert's model for growth in reactor systems employing cell feedback, i.e., cell recycle, employs a design constant, c, the sludge concentration factor, as the ratio between the concentration of recycle sludge, X_R, and the aeration tank suspended solids concentration, X. Because of the operational problems involved with this model, an improved model was developed by Ramanathan and Gaudy (6) using X_R, recycle sludge concentration, as one of the parameters instead of c. The mathematical and engineering rationale for this model has been presented by Gaudy and Ramanathan (7). This model did not include a term for the maintenance coefficient, k_d. Later, such a term was introduced by Srinivasaraghavan and Gaudy (8, 9, 10).

Srinivasaraghavan (10) operated the activated sludge system with constant concentration of recycle sludge in accordance with Gaudy's model. Comparison of observed steady state values of X, S, and X_w with the predicted values indicated close prediction with and without addition of the biological constant, k_d. There was little difference in the predictions of S and X. They also concluded there was considerable difference in predicted and observed X_w without the addition of the term k_d. The general conclusion in regard to the model is that it bestows a degree of stability on the activated sludge process under steady state. It was desirable to test the stability of an activated sludge system operated under this model to various types of shock loadings, and the current research was undertaken as part of this overall effort.

Shock Loads

Any sudden change in the environmental condition under which a biological system is operating may be termed a shock load. Even though it is one of the vital considerations in design and operation of a biological waste treatment system, because of the complexity of the problem and because of the long term experimental work involved, there are not many in either the applied or basic fields who engage in such research to assess and describe the response of heterogeneous microbial populations to changes in environment. A major portion of the work which has been done has been accomplished at Oklahoma State University.

The major types of shock loads can be grouped as follows: 1) quantitative shock loads; 2) toxic shock loads; 3) qualitative shock loads; 4) hydraulic shock loads; 5) pH shock loads; 6) temperature shock loads, and different combinations of these.

Based on shock load experiments carried out in a once-through system, George and Gaudy (11, 12, 13) concluded that rate of application of shock, dilution rate, D, concentration of biomass, diversity of population, and predominating microbial population at the time of application of shock play an important role in successful response.

Based on the pH, temperature, and hydraulic shock loads applied to the once-through system, George and Gaudy (11, 12, 13) concluded that a once-through system operating at a dilution rate of 0.125 hr^{-1} can accommodate a 100 percent increase or 50 percent decrease in dilution rate without appreciable substrate leakage. It has also been noted that the observed cell yield was related to dilution rate; i.e., it was lower for lower values of D.

Experiments carried out by Mor and Fiechter (14) using a culture of Saccharomyces cerevisiae revealed that when the system was subjected to a step increase in dilution rate, D, the steady state biomass concentration experienced "overshoot" to a higher value and then levelled off to a value higher than the preshock steady state concentration. When a decrease in dilution rate was applied, the reverse trend was observed.

Meers (15), based on his experiments, concluded that changes in dilution rate might bring on changes in predominating species.

Using glycerol as substrate in a once-through system, Yu (16) observed that severe leakage of substrate and washout of cells occurred when subjected to a hydraulic shock load. Age of the cell was found to be one of the important factors related to the degree of leakage.

Gaudy and Engelbrecht (17) investigated the effect of quantitative and qualitative shock loads on biomass harvested from an activated sludge unit. Their research led to the conclusion that temporary successful response to a quantitative shock load does not necessarily require the presence of an extracellular source of nitrogen, whereas extracellular nitrogen was needed for a successful response to the qualitative shock loading. The speed of acclimation to a qualitative shock as well as the eventual substrate removal rate depends on the chemical structure of the compound (17).

Two control mechanisms are important in considering response to qualitative shock. These are repression of enzyme synthesis and feedback inhibition of enzyme function. Repression regulates the rate of enzyme synthesis and controls the flow of metabolites through the pathway thus preventing the overproduction of end products. The other regulatory mechanism, feedback inhibition, acts on the biosynthetic pathway. The enzyme that catalyzes the first step in a biosynthetic pathway is inhibited by the ultimate product, thus controlling enzyme activity. Gaudy (18) has observed that in a heterogeneous population, presence of one compound can induce acclimation to another, or the presence of one compound can prevent the utilization of another compound.

Gaudy and Komolrit (18) also found that utilization of the carbon source to which the biomass has already been acclimated can be stopped by introducing another substrate. It has been concluded that the new control mechanism affects energy-yielding pathways and operates in a manner analogous to feedback inhibition. It has been shown in batch experiments that young cells which are acclimated to sorbitol or glycerol cannot utilize them in the presence of glucose.

The experiments conducted by Komolrit and Gaudy (18) using an activated sludge system without recycle revealed that keeping the total organic loading constant and changing the composition of the substrate to different combinations of glucose and sorbitol led to no disruption of the steady state. Glucose was readily used, leaving an insignificant amount of glucose in the system to cause interference with sorbitol metabolism. Small combined qualitative and quantitative shock loads resulted in the release of large amounts of metabolic intermediates. When higher concentrations of glucose were employed (three-fold quantitative and qualitative shock loads), the metabolism of sorbitol was almost completely blocked (18).

Based on the experiments conducted by Gaudy and Komolrit, cells growing at lower specific growth rates accommodate shock loading better (20). Also, it was concluded that cell concentration is one of the major factors in determining response to shock loads. Investigative work conducted by Gaudy and Komolrit revealed that heterogeneous populations acclimated to sorbitol or mannitol when subjected to shock loading with glucose along with sorbitol or mannitol can undergo immediate cessation of sorbitol or mannitol removal. However, with the use of "old cells," the sugar alcohol was removed concurrently with glucose.

Qualitative and Quantitative Shock Loads

Results of the studies on sequential substrate removal by Gaudy and his co-workers (21, 22, 23, 24, 25, 26) have shown that metabolic control mechanisms can play an important role in biological treatment systems. The experiments conducted by Prakasam and Dondero (27, 28) have confirmed the sequential removal of glucose and sorbitol by sorbitol-acclimated young cells. This confirmed the finding of Gaudy and his co-workers.

Grady and Gaudy (29, 30) conducted experiments using three substrate systems, glucose-lysine, fructose-lysine, and ribose-lysine; they grew cells on lysine in a batch reactor. After the cells were harvested they were grown on lysine, glucose, and a combination of lysine and glucose. The same approach was taken to the study of the other combined substrates, and it was concluded that the synthesis of lysine degrading enzymes was repressed due to the presence of glucose and fructose. Ribose, on the other hand, caused an increase in synthesis of lysine degrading enzyme systems.

Gaudy and Grady conducted similar experiments in a continuous flow system (31), and they observed similar catabolic repression in the continuous flow experiments. The degree of repression of lysine metabolism was greater for glucose than for ribose.

Chain and Mateles (32) grew heterogeneous populations in a continuous flow unit with multicomponent substrate (glucose and lactose or glucose and butyric acid along with yeast extract). They observed that glucose was the preferred substrate, and at high dilution rates utilization of the secondary carbon sources was greatly reduced.

Su (33) conducted experiments to find the biomass response to multicomponent substrate and hydraulic shock loads. A once-through system was employed. He concluded that about ten detention times are required to approach a new steady state condition after a change in dilution rate.

Gaudy and Turner (34) studied the effect of airflow rate on the response of activated sludge to shock loads with carbohydrate carbon source. They concluded that even zero dissolved oxygen in the reactor does not affect the biochemical efficiency of the system severely, and an increase in airflow rate increased the rapidity of response only marginally.

Ragthaidee (35) conducted quantitative shock load experiments in an extended aeration activated sludge system. He concluded that the system was able to take a five-fold quantitative shock without severe leakage, and 95 percent COD removal was observed throughout the study. They attributed the success of the response to higher biomass concentration and longer detention time (slow growth rate).

Various types of shock load experiments were carried out by Kiravanich (36) in batch, once-through and extended aeration systems. When the system was subjected to a combined quantitative and qualitative shock load, the extended aeration system was found to be free of disruption due to the shock load applied. Kiravanich also concurred with Ragthaidee in attributing the effect to the presence of a higher concentration of biomass in the extended aeration system.

Saleh (37) carried out quantitative and hydraulic shock load experiments using an activated sludge system operated with a constant concentration of recycle sludge, X_R. It has been concluded that a change in dilution rate from 0.125 to 0.25 did not produce any harmful effect, whereas changeover from $D = 0.125\ hr^{-1}$ to $0.5\ hr^{-1}$ gave a short-lived transient disturbance followed by rapid recovery. It was also concluded (37) that a 200 percent increase in feed concentration from 500 mg/l to 1500 mg/l glucose at $X_R = 8000$ mg/l gave a successful response, i.e., only a short-lived transient increase in effluent COD.

Experiments were carried out by Cooney and Wang (38) in a chemostat. Cells were grown with dual nutrient limitation (nitrogen and phosphorus) and an impulse shock was applied by increasing one of the limiting nutrients. From these experiments it was concluded that cells can be grown under dual nutrient limitation; the results verified the hypothesis that phosphate limitation restricts nucleic acid synthesis in the cells whereas nitrogen limitation restricts protein synthesis.

Cyclic Shock Loads

Six-fold quantitative and hydraulic cyclic shock load studies were conducted by Saleh (39). It was found that the system again produced a successful response. In response to a cyclic shock, the effluent parameters also showed a cyclic pattern and by day 16, the cyclic pattern of effluent parameters was attenuated.

Sundstrom, Klei and Brookman (40) applied a sinusoidal variation in the influent substrate concentration (glucose). A completely mixed activated sludge process with sludge recycling was employed. Based on the experimental data, it has been concluded that the Monod kinetic model was unsatisfactory in predicting the transient behavior of the system. It overestimated the variations in substrate concentration, and underestimated the biological solids concentration.

A random pulse-type quantitative shock load was applied to an activated sludge system by Knoop, Watts and Rohlich (41). The results were scrutinized by frequency response analysis derived by Rohlich and co-workers. They concluded that COD is not a proper parameter for measuring system response, and that frequency response analyses of operational plants will assist in the development of control models for the activated sludge process.

Ragan and Roper (42) investigated the response of a yeast culture to step changes in glucose feed concentration and dilution rate in a continuous culture chemostat. Based on these experiments with S. cerevisiae, they concluded that the culture showed an oscillatory response to the step change in feed rate and/or dilution rate, and that it seemed to be due to an inherently oscillatory nature of the growth pattern of the individual cells. The yield was not constant during the oscillations and was high during the nonbudding phase. They attributed this to the building up of carbohydrate reserve. It has also been pointed out that the ratio between rate of O_2 uptake and growth rate was not constant, and that the Monod model did not predict the response well.

The response of activated sludge to organic transient loadings was studied by Adams and Eckenfelder (43). An acivated sludge unit with internal recycle was employed. It was concluded that the average removal rate coefficient, K_1, appears to increase during the transient period. The endogenous rate of specific oxygen uptake also increased during the transient period. It was also observed that filamentous fragments increased as the transient organic loading increased. Threefold increase in organic loading for several days can be accommodated without appreciable increase of effluent soluble organic matter.

Ryu and Mateles (44) examined the transient response of E. coli B grown in a chemostat when subjected to step increases and decreases in temperature. They varied the temperature between 37 and 27, and 37 and 32. They observed a lag period at varying lengths between time of change in temperature and attainment of minimum or maximum transient growth rate. The peak or minimum value obtained was less than that predicted by the Arrhenius equation. Even though the Monod and Arrhenius models gave good prediction during steady state, they could not account for the effect of temperature on transient growth.

Chu, Erickson and Fan (45) investigated the dynamic behavior of a laboratory scale activated sludge biological waste treatment process with recycle and wasting of sludge when subjected to a step change in the influent concentration, recycle flow rate, and sludge wastage rate. The system behavior was assessed by measuring ATP, COD, and biological solids concentration. They concluded that for the same magnitude of step increase and decrease in influent concentration, the ATP concentration was not symmetrical. The ATP concentration did not have the same transient response as did MLSS. Time constants measured by COD values were found to be related to fluid mean cell residence time in the aeration tank.

Models of the Transient State

Attempts have been made to predict the transient behavior of the biomass when subjected to shock loads and to predict the substrate leakage during the transient. However, none of the transient approaches give a close prediction to the actual responses because of the complexity of various parameters involved.

Grady (46) made an attempt to predict the transient response of the system when subjected to a shock load by using an analog computer model. Even though there were no experimental data collected to verify the transient model it was generally concluded that the specific growth rate prior to shock was one of many factors for successful response, and lower growth rate yielded better response. For this model, the mass rate of substrate loading is of concern, and the mode of application does not come into the picture.

McLellan and Busch (47) defined the "reaction potential" of a mixed culture as the total mass of soluble organic carbon utilized by the unit mass of microorganisms in a given time. They concluded that a biomass has a reserve potential which is called upon during quantitative or hydraulic shocks.

Since for steady state operation of microbial growth reactors the Monod equation (48) seems to be reasonably applicable, most of the transient approaches have sought to modify this model for non-steady states. Powell (47) proposed a model taking into account the past history of the cells, and he included a term (reaction potential) similar to that suggested by McLellan and Busch (47). This model is yet to be substantiated by experimental work.

Koga and Humphrey (50) concluded that a factor to account for variable yield must be introduced to explain oscillatory behavior of the biomass. It was also concluded by Gaudy and Storer (51) that yield coefficient is not a constant during the transient response to a step increase in S_i. Using the kinetic equation of Teissier, an analog computer simulation of the activated sludge process was attempted by Ott and Bogan (52), but no experimental verification has been presented.

Andrews (53) has presented an analysis of dynamic behavior of the activated sludge process. He developed a model for growth of microorganisms on an inhibitory substrate. He used the following equation for growth:

$$\mu_{max} = \frac{\mu_{max}}{1 + K_s/S + S^2/K_I}$$

where K_I is termed the inhibition coefficient. Using the mathematical model, he made an attempt to study the transient response to both step increase of flow rate (three-fold) and step increase of feed concentration (four-fold). Since these results are not accompanied by experimental verification, its application is yet to be assessed. Most of the attempts to obtain transient models herein discussed are not substantiated by experimental data.

In closing, it would seem that while modeling of the transient response is a worthwhile undertaking, too much of it in place of experimental data in controlled experiments to assess actual response is a dangerous thing because while modelers are producing models, the stability of biological treatment plants in the field is undergoing constant attack by shock loads. The approach taken in this thesis was to gain information about shock loads which could be used to test subsequent model derivations but, above all, to gain information on the biological response which could help guide design and operation of treatment plants.

CHAPTER III

MATERIALS AND METHODS

Experimental Apparatus and Synthetic Wastewater

A pilot plant activated sludge unit with external sludge recycle and provision for maintaining concentration of recycle sludge constant as proposed by Gaudy and co-workers was employed in these studies (7, 10, 37). A flow diagram and sketch of the unit is shown in Figures 1 and 2. The effective volume of the aeration tank was two liters during aeration. The reactor was made of pyrex; the settling tank was also made of glass and of five-liter capacity. Air was supplied at a rate of 4000 cc/min to ensure that adequate oxygen concentration was maintained in the aeration tank. The sludge consistency tank was also aerated in order to keep the return sludge aerobic. Biomass was grown in a batch unit using the primary effluent from the Stillwater municipal treatment plant as seed.

Composition of nutrients for 500 mg/l glucose is shown in Table I.

General Operational Procedure

Continuous Flow Studies

The continuous flow unit was started by pumping feed from the feed tank at a flow rate of 4 ml/min, which provided a dilution rate of 0.12 hr^{-1}. The feed pump was a dual positive pump (Milton Roy Company,

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

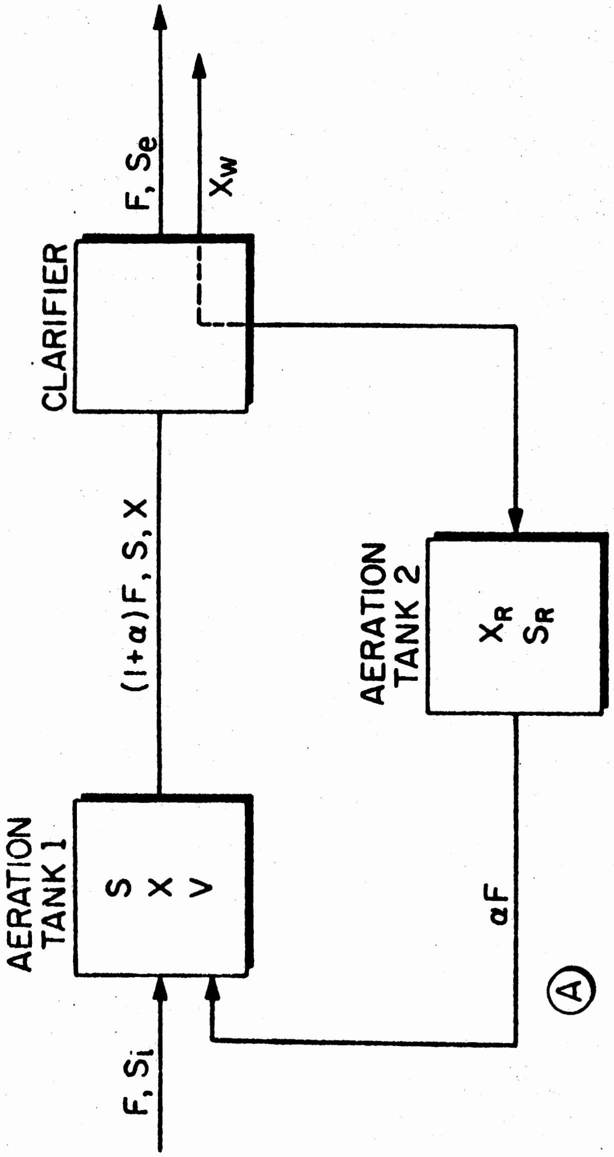

F, S_i
AERATION TANK 1
S
X
V
$(1+\alpha)F, S, X$
CLARIFIER
F, S_e
X_W
AERATION TANK 2
X_R
S_R
αF
Ⓐ

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

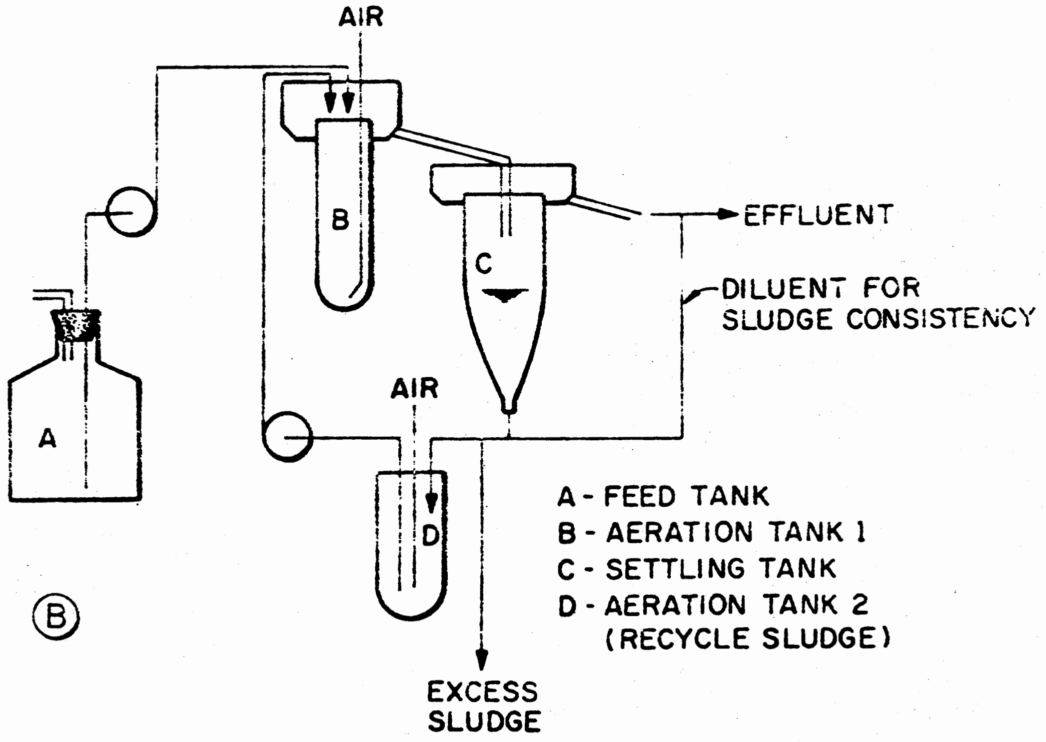

AIR
B
C
EFFLUENT
DILUENT FOR
SLUDGE CONSISTENCY
A
AIR
D
A - FEED TANK
B - AERATION TANK 1
C - SETTLING TANK
D - AERATION TANK 2
(RECYCLE SLUDGE)
EXCESS
SLUDGE
Ⓑ

TABLE I

MINERAL COMPOSITION OF SYNTHETIC WASTE PER 500 mg/l GLUCOSE COD

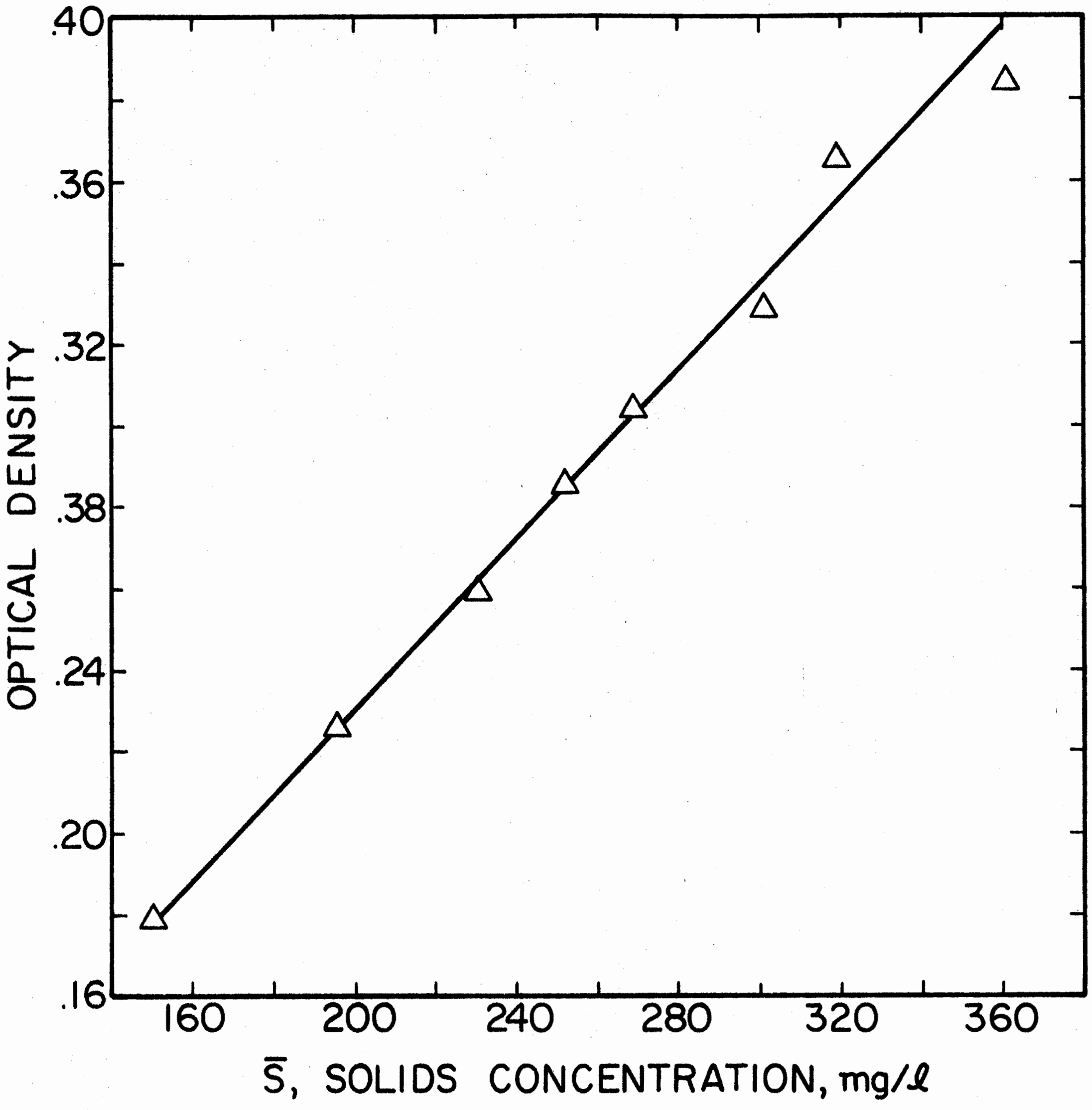
Constituents	Amount
Ammonium sulfate $(NH_4)_2SO_4$	250 mg/l
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	50 mg/l
Ferric chloride, $FeCl_3 \cdot 6H_2O$	0.25 mg/l
Manganous sulfate, $MnSO_4 \cdot H_2O$	5.0 mg/l
Calcium chloride, $CaCl_2$	3.75 mg/l
1 M Phosphate buffer solution (pH 7.0)	5 ml/l
Tap water	50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

Model MM1-B-96R). Clorox solution was used for cleaning the feed lines. When one feed line was in use, the other was cleaned and kept ready for use on alternate days. This procedure was followed to keep the lines free from bacterial growth. Aerator 1 was checked for complete mixing according to the method employed by Komolrit and Gaudy (18). Sludge was withdrawn from the clarifier at 12-hour or 24-hour intervals. With some exceptions, the recycle sludge concentration was always obtained by dilution of the underflow. A small volume of sludge was diluted and its optical density at a wave length of 540nm was measured. Using a standard optical density vs. sludge concentration curve previously prepared using known sludge concentrations, the underflow concentration from the clarifier was estimated and proper dilution was made to obtain the desired return sludge concentration. The return concentration was also measured gravimetrically.

The standard curve required for estimating the sludge concentration was obtained by measuring the optical density of the known concentrations of sludge in the range of 100 mg/l to 350 mg/l. A typical plot of this type is shown in Figure 3. From time to time a new standard curve was developed in order to ensure accuracy of the OD-concentration relationship.

Aeration tank 2 was filled with a sufficient volume of sludge to supply recycle sludge until the next withdrawl. Recycle sludge was pumped continuously from aerator 2 to aerator 1, and the pump used for this purpose was a Sigmamotor "finger" pump (Model T-8). The amount of sludge remaining in excess of the amount recirculated was recorded as excess sludge, X_w. In measuring X_w, the solids X_e in the effluent and the amount of solids taken out of the system due to sampling were also

Figure 3. Relation Between Optical Density and Solids Concentration


.40
.36
.32
.38
.24
.20
.16
OPTICAL DENSITY
160
200
240
280
320
360
$\bar{S}$, SOLIDS CONCENTRATION, mg/ℓ

taken into consideration. The same biomass was used throughout the study, i.e., the activated sludge developed from the initial sewage seed was never reseeded. The results represent a continuous history of the initial populations employed at the time of initiating growth. The system was operated under steady state conditions for a sufficient time to establish steady state conditions with respect to solids in the aerator, effluent soluble substrate, and excess sludge produced. After recording the steady state condition, various shock loadings were applied.

Batch Studies

When the system was in steady state during a continuous flow run, cells were taken from the unit for batch growth studies. The methodologies described by Gaudy et al. (54, 55) were followed to determine the biological constants μ_{max}, K_s, and Y_{t_B}. The growth medium was the same as that used for continuous flow operation. Initial substrate concentrations (glucose, sorbitol, or combinations of each) ranging from 100 mg/l to 1000 mg/l were employed. Cells were grown in 250-ml Erlenmeyer flasks, and the volume of growth medium including the initial inoculum was 40 ml. The amount of initial inoculum was exactly the same for all of the flasks, and it was so selected to give an initial optical density value of 0.046 (percent transmission = 90). These flasks were placed on an oscillating shaker (Eberbach) and the oscillation frequency was maintained at 100-110 oscillations/min. The optical density was measured at frequent intervals. The initial and maximum solids concentrations were measured to determine Y_{t_B}. The μ_{max} and K_s were determined by plotting $1/\mu$ vs. $1/s$.

Types of Shock Loadings Studied

Quantitative Shock Loads. In this type of shock, the system was subjected to a step increase in S_i without any change in dilution rate or in the quality of substrate.

Qualitative Shock Loads. In this type of shock, the system was subjected to change in the nature of substrate without change in the concentration. In this case, the substrate consisted of single carbon sources or combinations of carbon sources.

Quantitative and Qualitative Shock Loads. In this case, the system was subjected to a step increase in the concentration of S_i as well as a change in the nature of the substrate, S_i.

Cyclic Shock Loads. In this case, instead of a step increase, the system was subjected to a cyclic change in substrate concentration. The duration of the cycle was 12 hours, and the change in S_i was six-fold.

Quantitative and Hydraulic Shock Loads. In this case, the system was subjected to a simultaneous change in concentration of S_i as well as change in dilution rate, D.

Analytical Procedures

The following analyses were run:

Feed

COD (daily or on alternate days

Effluent

Filtrate COD (daily or on alternate days)

Supernatant COD (daily or on alternate days)
Suspended solids (daily or on alternate days)
NH_3-N (weekly)
NO_3-N (weekly)
Anthrone test (periodically)
Periodate test (periodically)
Filtrate BOD (periodically)
Supernatant BOD (periodically)

Analytical Techniques

Methods for the determination of the experimental parameters are given below:

Chemical Oxygen Demand (COD) Test. The COD technique was used to measure the strength of the organic compound in the feed, reactor and effluent. The procedure followed was that outlined in Standard Methods for the Examination of Water and Wastewater (56).

Anthrone Test. This test was used to measure the total carbohydrate content. The procedure employed was that given by Ramanathan, Gaudy and Cook (57). This test together with the COD test will indicate what fraction of the effluent was carbohydrate in nature.

Glucostat Test. This is an enzymatic test, and the procedure followed was that given by Ramanathan, Gaudy and Cook (57).

Biological Solids

The membrane filter technique was used to determine solids concentration; the method outlined in Standard Methods (56) was followed.

Ammonia Nitrogen. Periodically, ammonia nitrogen in the feed and effluent were measured. The method developed by Niss and described by Ecker and Lockhart (58) was used.

Nitrate Nitrogen. The Brucine method as described in Standard Methods (56) was used to determine nitrate nitrogen in the effluent.

pH. The Orion pH Meter (Model 701) was used to check the pH in the reactor.

CHAPTER IV

RESULTS

All shock load experiments were conducted using a continuously grown biomass which started from an initial seed of sludge. The system was never reinoculated after starting the continuous unit. The steady state parameters are shown in Table II in the same chronological order in which different shock loads were applied. The numbers shown in column 1 of Table II indicate the chronological sequence in which the shocks were applied; however, results are presented in accord with groupings of various types of shock (see column 2 for figure numbers). Five broad types of shock were investigated; these are presented in order in this chapter.

Response to Qualitative Shock Loadings

500 mg/l Glucose→500 mg/l Sorbitol, X_R = 5000 mg/l

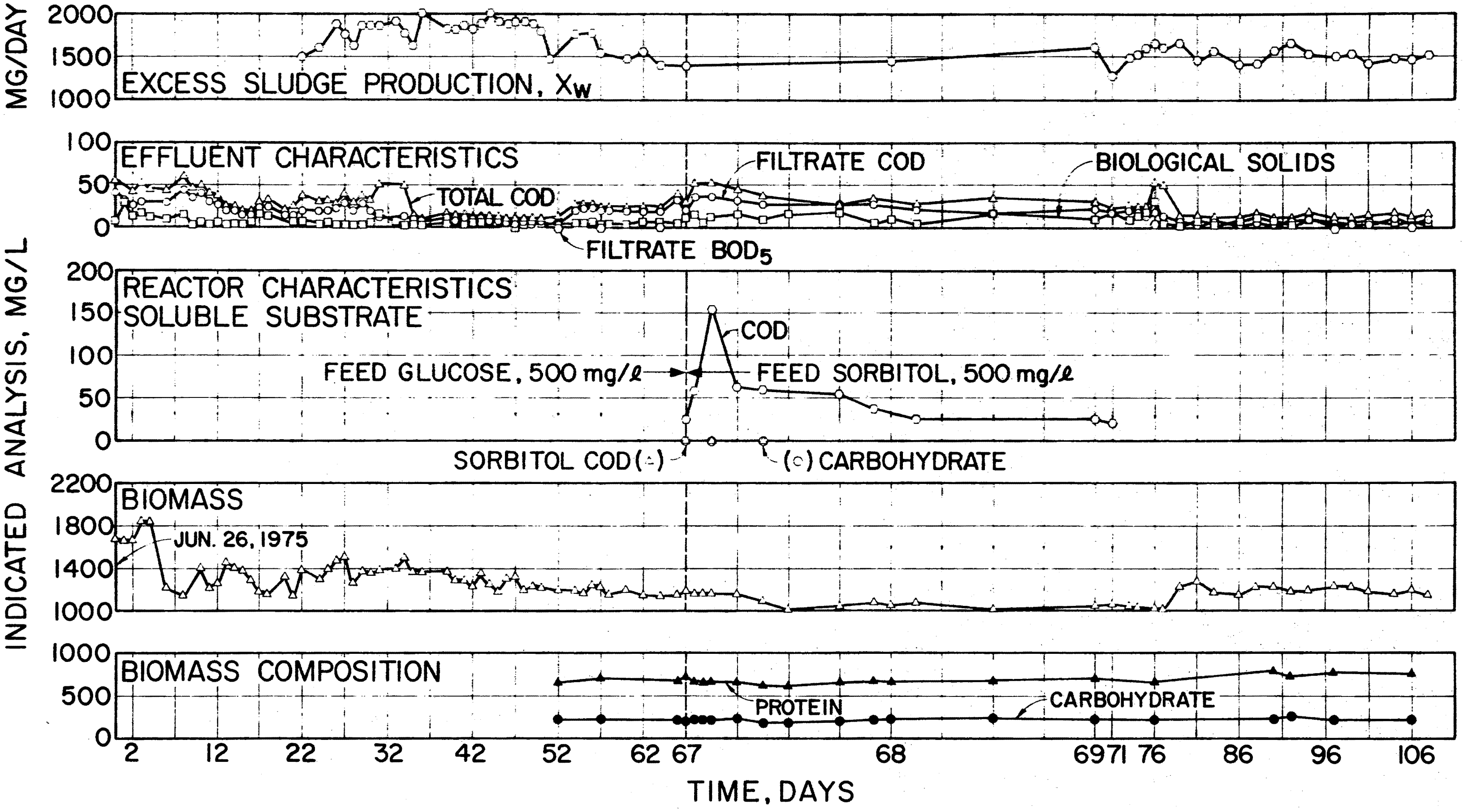
The system was run at a feed concentration of 500 mg/l glucose, and the recycle concentration was maintained at 5000 mg/l. The system was operated at steady state for 65 days, and the effluent quality was monitored (see Figure 4). A qualitative shock was administered by changing the influent substrate from glucose to sorbitol on day 66. The results are shown in expanded scale from day 66 to day 69 in Figure 4. There was an immediate response, indicated by a rise in soluble COD in the reactor. The disturbance lasted for approximately 24 hours, but

TABLE II

ANALYSIS OF STEADY STATE PERFORMANCE

				Effluent								Reactor #1									Recycle			
		Feed		COD		BOD$_5$										Biomass								
Line	Figure	mg/l		Total mg/l	Soluble mg/l	Total mg/l	Soluble mg/l	X_e mg/l	NH_3-N mg/l	NO_3-N mg/l	DO mg/l	pH	Temp °C	DO mg/l	X mg/l	CH_2O mg/l	%	Protein mg/l	%	O_2 Uptake	X_R	Soluble COD	X_w mg/day	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Remarks
1	4	517	glucose	26	21			6	22.3	0	2.9	7.2	22.9	5.3	1184	228	19.1	676	56.4	-	4876	11	1522	
2	4	509	sorbitol	14	6			7	24.6	0.1	3.2	7.2	20.7	4.9	1202	228	18.6	763	63.0		4892	11	1516	
3	9,10	2748	sorbitol	100	79			33	31.1	0	2.3	7.2	21.6	4.5	2317	510	22.1	1426	62.0		5173	38	8943	
4	10,24	606	sorbitol	37	27			7	22.3	0	3.4	7.2	20.1	5.5	1250	256	20.6	714	57.2		4861	16	1843	
5	5,24	1775	glucose + sorbitol 1/2	71	56			21	13.1	0	3.2	7.3	22.1	3.1	1816	377	20.7	1055	57.8		5089	40	5577	
6	6,7	1540	glucose + sorbitol 1/2	51	43			14	15.8	0	2.7	7.3	21.5	4.7	1630	334	21.2	941	59.7		5106	32	4339	
7	7	1573	glucose	40	35	15.1	7.7	22	83.1	0	3.1	7.3	21.0	4.8	1568	377	23.9	905	57.3		4978	35	3795	
8	11	2835	sorbitol	99	82	16.3	11.9	28	146.0	0	2.5	7.2	22.1	5.7	2343	509	21.6	1237	52.5	7.6	4962	42	9021	
9	11,12	605	sorbitol	29	15		5.1	21		0	3.1	7.3	22.0	5.0	1273	272	22.1	650	52.7	5.1	5073	12	1704	
10	13,14	532	sorbitol	27	17		2.3	18	7.4	0	2.1	7.3	22.5	4.0	2230	511	22.1	1174	53.3	4.0	10259	12	1265	
11	14,15	3217	sorbitol	94	81		8.0	22	135.0	0	1.8	7.2	22.4	3.6	3277	733	22.3	1726	52.5	5.5	10337	49	8592	
12	15,25	512	sorbitol	26	18	4.7	3.0	18	-	-	4.0	7.3	19.6	5.5	2274	524	23.2	1199	53.2	5.4	10238	8	1461	
13	25	1513	glucose	37	28	5.7	4.1	21	83.0	0	3.0	7.2	21.6	5.3	2530	619	24.4	1342	52.8	4.4	10348	20	3262	
14		2743	sorbitol	52	39	12.5	6.3	35	131.5	0	4.2	7.2	20.2	5.9	3124	719	23.1	1631	52.3	5.5	10160	30	7736	
15		502	glucose	21	14	4.1	2.3	16	27.5	0	3.9	7.3	20.3	6.8	2214	488	21.9	1290	57.9	4.2	10138	10	1274	
16	16	2812	sorbitol	66	47	14.0	8.0	26	135.5	0	3.4	7.2	21.3	4.2	3285	737	22.5	1799	54.9	5.8	10114	38	8683	
17	16,17	523	sorbitol	21	16	3.4	2.5	19	-	-	3.2	7.4	18.6	5.1	2238	510	22.9	1188	53.2	4.5	10109	11	1530	
18-A	19,20	515	sorbitol	31	21	-	-	26	-	-	-	-	-	-	2250	-	-	-	-	-	10180	-	1331	X_w = mg/12 hour
18-B	19,20	3117	sorbitol	52	37	-	-	32	-	-	-	-	-	-	3160	-	-	-	-	-	10154	-	2531	X_w = mg/12 hour
19	8,20	504	sorbitol	28	20	4.1	2.4	15	-	-	3.2	7.3	19.2	5.3	2234	517	23.1	1178	52.6	4.5	10189	16	1294	
20	8	506	glucose	35	24	4.8	2.3	23	36.0	1.8	4.1	7.5	21.6	6.5	3232	713	22.2	1847	57.4	3.9	15234	27	1043	
21	26	3080	sorbitol	64	46	15.0	8.5	34	147.0	8.9	3.2	7.3	21.6	6.6	4339	979	22.1	2606	58.9	5.3	15025	30	8753	
22	21,26	508	glucose	30	17	2.6	2.1	13	30.5	0	4.1	7.2	18.8	6.3	2288	506	22.5	1182	52.6	3.5	10120	12	1855	
23	21,22	1044	glucose	48	38	7.7	5.4	20	-	-	3.3	7.3	19.3	5.0	2549	576	22.5	1383	54.0	5.0	10211	19	7606	
24	22,23	514	glucose	22	15	3.4	2.1	12	-	-	3.1	7.3	19.0	5.9	1793	411	22.9	974	54.3	4.5	8134	12	1148	
25	23	1499	glucose	55	44	12.0	8.5	19	-	-	3.5	7.3	19.0	5.6	2344	514	22.1	1182	50.9	5.4	8246	31	9515	

Figure 4. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l and S_i = 500 mg/l Glucose Subjected to a Qualitative Shock Load by Changes in Substrate From Glucose to Sorbitol


MG/DAY
2000
1500
1000
EXCESS SLUDGE PRODUCTION, X_W
INDICATED ANALYSIS, MG/L
100
50
0
EFFLUENT CHARACTERISTICS
FILTRATE COD
BIOLOGICAL SOLIDS
TOTAL COD
FILTRATE BOD_5
200
150
100
50
0
REACTOR CHARACTERISTICS
SOLUBLE SUBSTRATE
COD
FEED GLUCOSE, 500 mg/ℓ
FEED SORBITOL, 500 mg/ℓ
SORBITOL COD (△)
(○) CARBOHYDRATE
2200
1800
1400
1000
BIOMASS
JUN. 26, 1975
1000
500
0
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
2
12
22
32
42
52
62
67
68
69
71
76
86
96
106
TIME, DAYS

did not result in a significant disturbance in the quality of effluent from the clarifier. This is due to the attenuation in leakage provided by the large clarifier and to the fact that some biological substrate removal took place. The system was run for some time in the new steady state condition to establish the average system behavior.

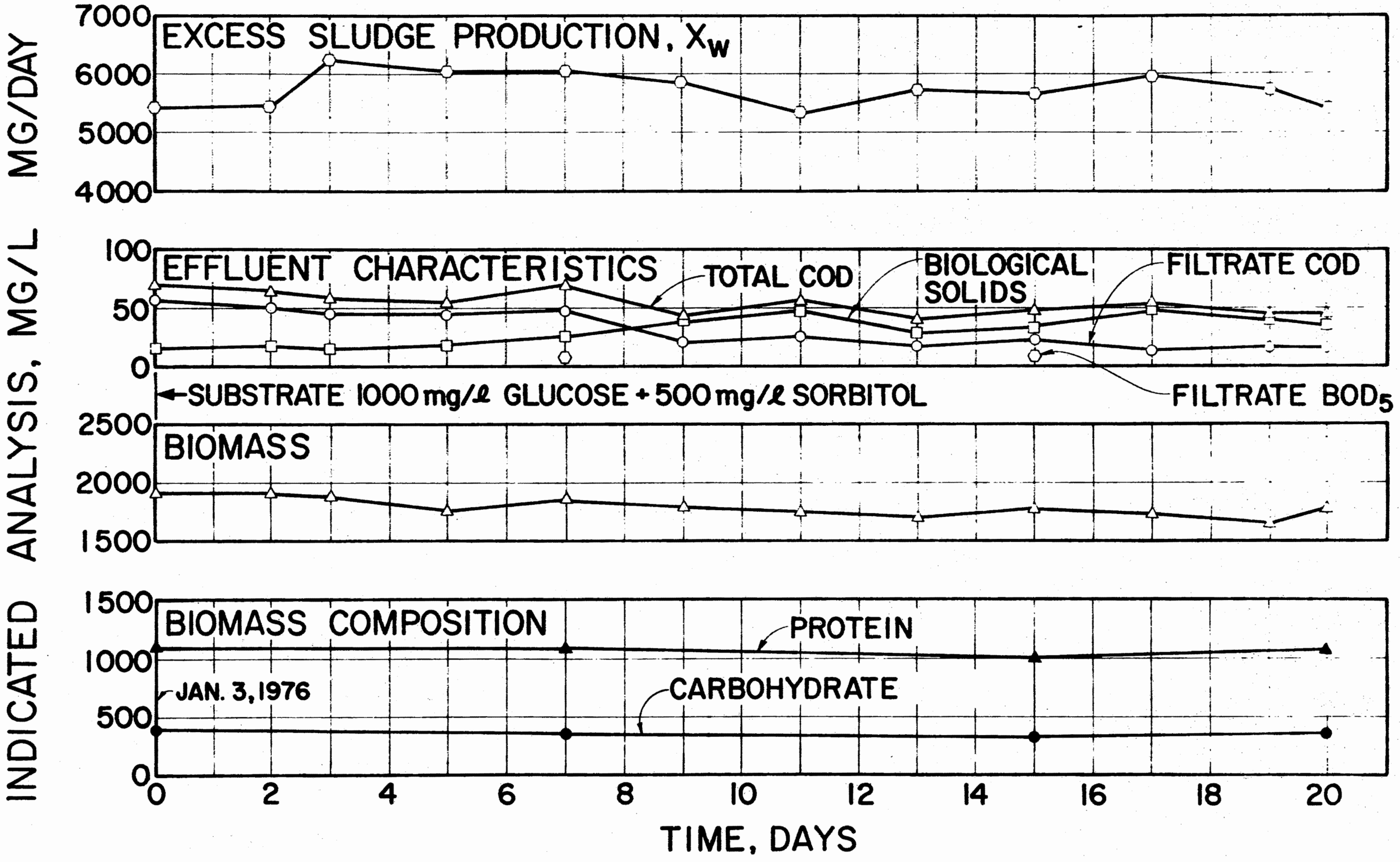
During the steady state, the excess sludge production at S_i = 500 mg/l glucose was 1522 mg/day, and at S_i = 500 mg/l sorbitol, was 1516 mg/day. Average pre- and post-shock steady values for the various parameters which were monitored are given in Table II. The pre-shock steady state values spanned days 51 to 66, and from day 79 to day 108 for post-shock steady state.

500 mg/l Glucose + 1000 mg/l Sorbitol→
1000 mg/l Glucose + 500 mg/l Sorbitol→
1500 mg/l Glucose, X_R = 5000 mg/l

A steady state was maintained for 46 days with an average S_i loading of 500 mg/l glucose plus 1000 mg/l sorbitol. The average values during steady state are given in Table II. On day 20, the system was subjected to a qualitative shock by changing the substrate composition to 1000 mg/l glucose plus 500 mg/l sorbitol. The performance of the system before, after, and during the shock are shown in Figures 5 and 6. The time scale is expanded during the transient phase from day 20 to day 22.

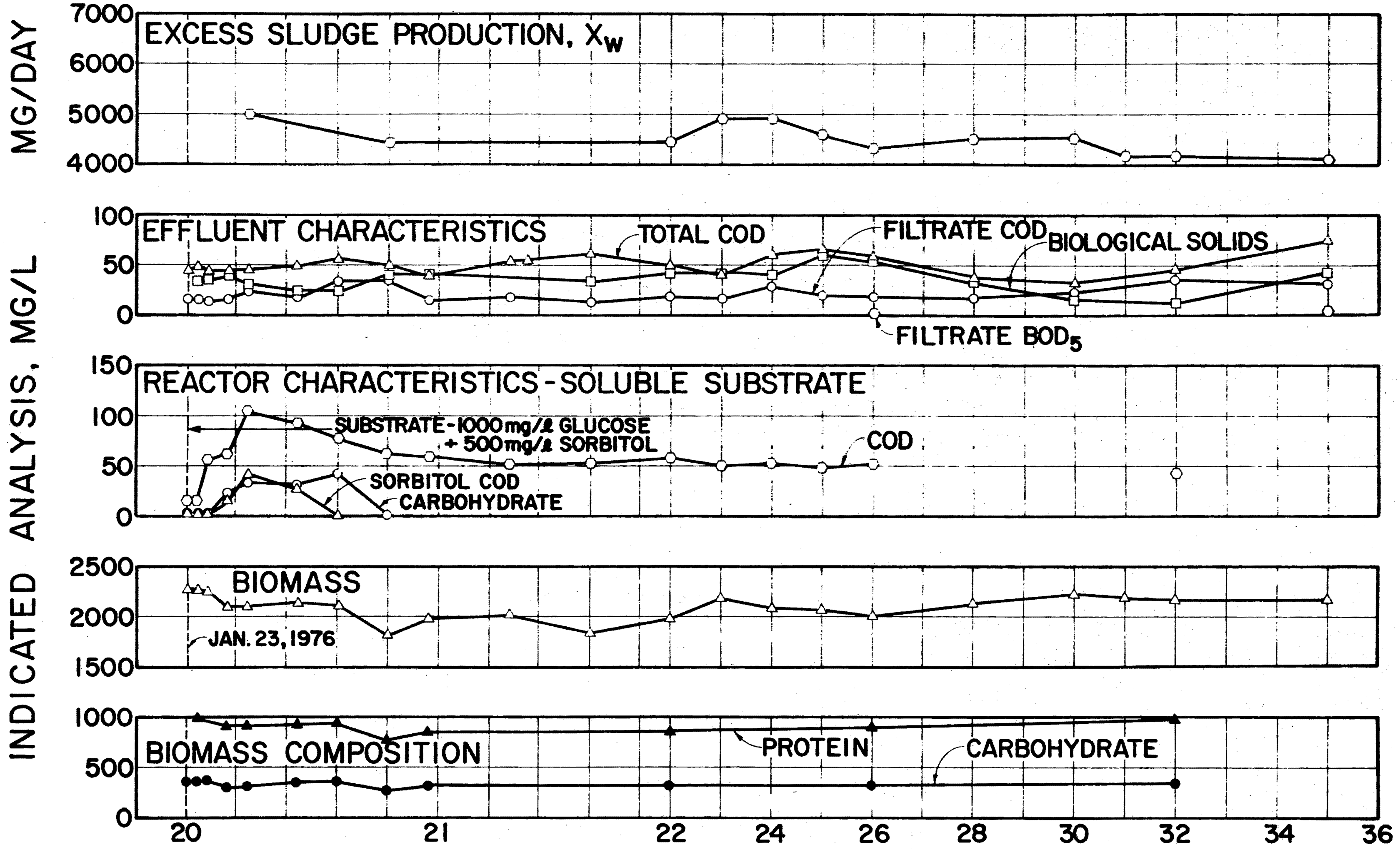
The effluent characteristics were monitored by measuring effluent total COD, filtrate COD, and biological solids. Filtrate BOD_5 was spot checked periodically. In addition to measuring the biomass concentration in the reactor, the protein and carbohydrate compositions were

Figure 5. Operational Characteristics of an Activated Sludge Process With Constant X_R of 5000 mg/l at an S_i of 500 mg/l Glucose + 1000 mg/l Sorbitol



INDICATED ANALYSIS, MG/L
MG/DAY
7000
6000
5000
4000
EXCESS SLUDGE PRODUCTION, X_W
100
50
0
EFFLUENT CHARACTERISTICS
TOTAL COD
BIOLOGICAL SOLIDS
FILTRATE COD
FILTRATE BOD_5
←SUBSTRATE 1000 mg/ℓ GLUCOSE + 500 mg/ℓ SORBITOL
2500
2000
1500
BIOMASS
1500
1000
500
0
BIOMASS COMPOSITION
PROTEIN
JAN. 3, 1976
CARBOHYDRATE
0
2
4
6
8
10
12
14
16
18
20
TIME, DAYS

Figure 6. Operational Characteristics of an Activated Sludge Process With Constant X_R of 5000 mg/l When Subjected to a Change in S_i From 500 mg/l Glucose + 1000 mg/l Sorbitol to 1000 mg/l Glucose + 500 mg/l Sorbitol


MG/DAY
7000
6000
5000
4000
EXCESS SLUDGE PRODUCTION, X_W
INDICATED ANALYSIS, MG/L
100
50
0
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
150
100
50
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
SUBSTRATE - 1000 mg/ℓ GLUCOSE + 500 mg/ℓ SORBITOL
COD
SORBITOL COD
CARBOHYDRATE
2500
2000
1500
BIOMASS
JAN. 23, 1976
1000
500
0
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
20
21
22
24
26
28
30
32
34
36

also determined. During the shock, reactor filtrate COD, sorbitol COD, and carbohydrate were also measured. The average biological solids concentration in the reactor was 1816 mg/l in the pre-shock steady state; the recycle sludge concentration was maintained at an average value of 5089 mg/l. Filtrate COD of the recycle sludge was 40 mg/l; the average excess sludge concentration was 5571 mg/day. The average protein and carbohydrate content of the biomass was 58 and 21 percent, respectively.

In response to the shock, there was a fluctuation in the biological solids concentration in the reactor. The biological solids concentration decreased from the average pre-shock steady level of 1816 mg/l to 1336 during shock, then returned to the post-steady state average value of 1630 mg/l. During the transient, there was leakage of substrate from the reactor as high as 108 mg/l. The maximum leakage of sorbitol COD was 42 mg/l; carbohydrate leakage was 42 mg/l. However, 15 hours after shock there was no detectable amount of sorbitol and carbohydrate in the reactor filtrate.

Corresponding to the disturbance in the reactor, there was only a slight disturbance in the plant (clarifier) effluent. There was a secondary response from day 24 to day 28, leading to the increase in solids concentration in the effluent. The post-shock steady state values spanned day 25 to day 35, shown in Figure 6. The average biomass concentration was 1540 mg/l in the post-shock steady state. The effluent total COD and filtrate COD values were 51 and 43 mg/l, respectively, which was slightly higher than pre-shock steady state values. The effluent solids concentration was 140 mg/l. The average protein and carbohydrate composition were 21 and 60 mg/l. The recycle concentration was maintained at 5106 mg/l. The filtrate COD in the return sludge line was 33 mg/l, which was slightly lower than the pre-shock value of 40 mg/l. The average excess sludge production was 4339 mg/day, which was lower than the pre-shock value of 5577 mg/l. The values of the steady state parameters are shown in Table II.

The biological constants for the biomass during the post- and pre-shock conditions are shown in Table III. The μ_{max}, K_s, and Y_{t_B} during pre-shock were 0.52 hr^{-1}, 169 mg/l, and 0.53; during post-shock they were 0.44 hr^{-1}, 380 mg/l, and 0.54.

1000 mg/l Glucose + 500 mg/l Sorbitol→ 1500 mg/l Glucose, X_R = 5000 mg/l

After running the system at steady state for 11 days with 1000 mg/l glucose plus 500 mg/l sorbitol, the system was subjected to a qualitative shock by changing the feed to 1500 mg/l glucose; Figure 7 shows the response of the system. The time scale was expanded during transient from day 8 to day 10. The biomass response can be better assessed by looking at the events occurring in aerator 1. As shown in Figure 7, there was no appreciable leakage from the reactor compared to the previous qualitative shock. It attained a maximum of 52 mg/l during the first day of the shock. There was no detectable amount of carbohydrate in the reactor filtrate during transient. Corresponding to the low amount of disturbance in the reactor, the filtrate from the clarifier was also low in COD. However, there was a sharp increase in the effluent suspended solids during the transient; it increased from 20 mg/l during pre-shock to 90 mg/l 21 hours after applying the shock. During this period, a change in predominance of species was observed.

TABLE III

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

Line 1	Figure 2	Y_{tB} 3	μ_{max} hr^{-1} 4	K_s mg/l 5	Feed
1	4	0.56	0.53	239	glucose
2	4	0.61	0.42	189	sorbitol
3	9,10	0.61	0.50	200	sorbitol
4	10,24	0.56	0.44	478	sorbitol
5	5,24	0.53	0.52	169	sorbitol 2:glucose 1
6	6,7	0.54	0.44	380	sorbitol 1:glucose 2
7	7	0.58	0.39	144	glucose
8	11	0.62	0.49	183	sorbitol
9	11,12	0.61	0.52	103	sorbitol
10	13,14	0.61	0.47	279	sorbitol
11	14,15	0.53	0.49	115	sorbitol
12	15,25	0.59	0.39	231	sorbitol
13	25	0.61	0.46	279	glucose
14		0.61	0.42	102	sorbitol
15		0.61	0.51	249	glucose
16	16	0.59	0.52	169	sorbitol
17	16,17	0.51	0.42	135	sorbitol
18-A	19,20	0.58	0.54	185	sorbitol
18-B	19,20	0.54	0.56	198	sorbitol
19	8,20	0.49	0.34	174	sorbitol
20	8	0.57	0.49	154	glucose
21	26	0.61	0.53	139	sorbitol
22	21,26	0.49	0.39	257	glucose
23	21,22	0,54	0,47	137	glucose
24	22,25	0.49	0.42	293	glucose
25	24	0.55	0.57	139	glucose

Combined average of glucose and sorbitol feed:

$\mu_{max} = 0.47$ hr^{-1}, $K_s = 204.6$ mg/l, $Y_{tB} = 0.57$

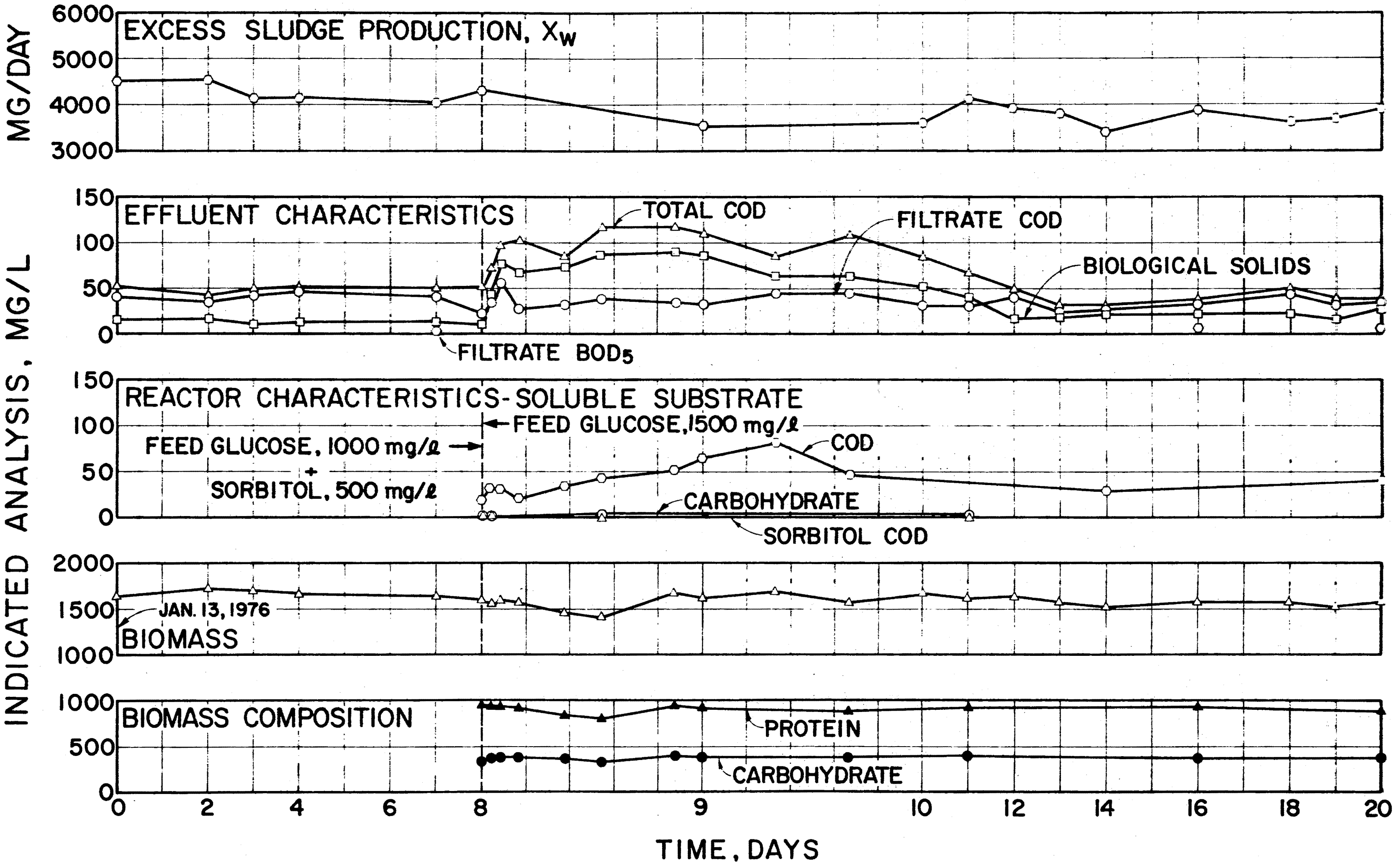
Average of glucose feed including combination of glucose and sorbitol feed

$\mu_{max} = 0.47$ hr^{-1}, $K_s = 221.8$, $Y_{tB} = 0.55$

Average of sorbitol feed including combination of glucose and sorbitol feed

$\mu_{max} = 0.47$ hr^{-1}, $K_s = 201.7$, $Y_{tB} = 0.57$

Figure 7. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l and S_i = 1000 mg/l Glucose + 500 mg/l Sorbitol Subjected to a Qualitative Shock Load by Changing the S_i to 1500 mg/l Glucose


EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
6000
5000
4000
3000
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
150
100
50
0
REACTOR CHARACTERISTICS-SOLUBLE SUBSTRATE
FEED GLUCOSE, 1500 mg/ℓ
FEED GLUCOSE, 1000 mg/ℓ + SORBITOL, 500 mg/ℓ
COD
CARBOHYDRATE
SORBITOL COD
INDICATED ANALYSIS, MG/L
2000
1500
1000
JAN. 13, 1976
BIOMASS
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
500
0
2
4
6
8
9
10
12
14
16
18
20
TIME, DAYS

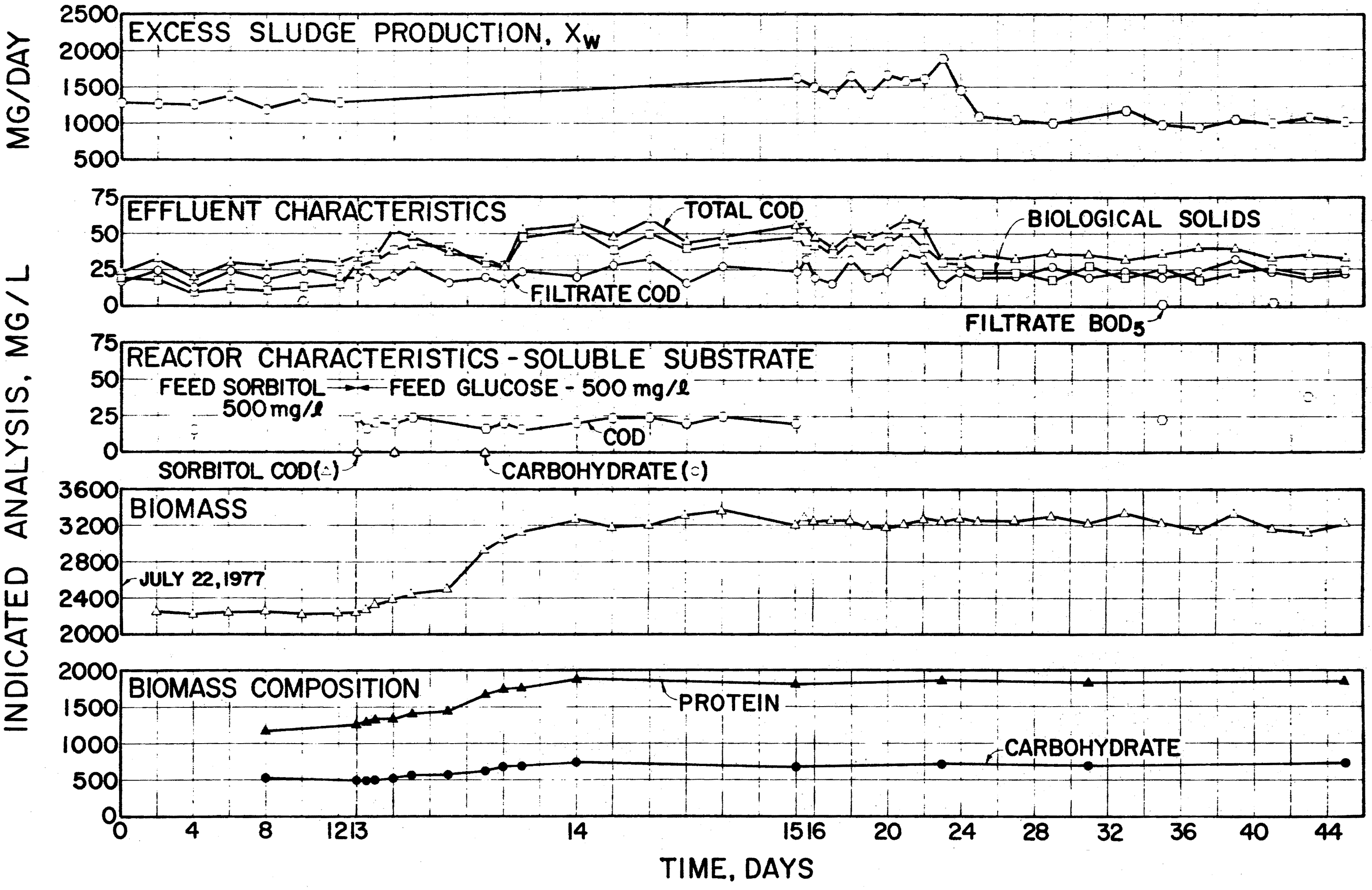
Increased numbers of rod-shaped highly mobile cells were observed. Protozoa decreased; even those present were small and in the dormant stage. At the end of the transient period--from day 10--the protozoa increased in numbers and were larger in size. Free (unflocculated) bacteria decreased. Corresponding to the increase in the effluent solids, there was an increase in the total COD of the effluent during the transient. The biomass concentration showed a slight dip from 1600 mg/l to 1418 mg/l at 13 hours into the shock. Thereafter it increased to 1675 mg/l at 21 hours after the shock was applied. The carbohydrate showed a slight increase from 21.3 percent to 24.1 percent, whereas protein content of the biomass showed a slight decrease from 59.7 to 56.8 percent. The system came to a steady state by day 12. The post-shock steady state values spanned day 12 to day 20. The biomass concentration during steady state was 1568 mg/l. influent concentration was 1573 mg/l. The effluent total and filtrate COD were 40 mg/l and 35 mg/l, respectively. Effluent filtrate BOD_5 was 7.7 mg/l; protein and carbohydrate composition were 57.3 percent and 23.9 percent, respectively. The excess sludge production was 3795 mg/day, compared to 4339 mg/day at pre-shock steady state. The biological constants μ_{max}, K_s, and Y_o were 0.39 hr^{-1}, 144 mg/l, and 0.58.

500 mg/l Sorbitol, X_R = 10,000 mg/l →
500 mg/l Glucose, X_R = 15,000 mg/l

A system was initially operated with an influent substrate concentration of 500 mg/l sorbitol and X_R = 10,000 mg/l. The pre-shock steady state values spanned day 0 to day 12; influent substrate concentration averaged 504 mg/l. The steady state effluent parameters

S_T, S_e, and X_e averaged 28 mg/l, 20 mg/l, and 16 mg/l. The effluent filtrate, BOD_5, was 2.4 mg/l. The biomass concentration averaged 2235 mg/l. The percent protein and carbohydrate compositions were 52.6 and 23.1, respectively. The excess sludge production averaged 1294 mg/l, and recycle sludge concentration averaged 10,189 mg/l. A shock was applied by changing the substrate from 500 mg/l sorbitol to 500 mg/l glucose. The recycle sludge concentration was increased simultaneously to 15,000 mg/l. In Figure 8 it is seen that there was no significant change in the reactor filtrate COD due to the shock. The biomass concentration increased after the shock due mainly to the increased recycle sludge concentration; the protein and carbohydrate contents also increased accordingly. There was disturbance in the effluent due mainly to the fluctuations in the effluent biological solids. Microscopic observation revealed changes in predominance. During the transient, filamentous organisms increased. The biomass became darker in color. Protozoa decreased. The sludge occasionally started to rise, and there were times (twice) when sludge was withdrawn, which prevented the rising condition. Free, unflocculated bacteria were observed. The sludge was somewhat fluffy in appearance; however, effluent filtrate did not show much variation due to shock. Eventually, the sludge regained its good settling characteristics. During the post-shock steady state, values spanned day 33 to day 45. The effluent parameters, S_T, S_e, and X_e, averaged 35 mg/l, 24 mg/l, and 23 mg/l. The filtrate BOD_5 of the effluent was 2.3 mg/l. The influent concentration averaged 506 mg/l COD. The biomass concentration in aerator 1 averaged 3232 mg/l. The percent protein and carbohydrate content averaged 57.8 and 22.4, respectively. The excess sludge

Figure 8. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l and S_i = 500 mg/l Sorbitol Subjected to a Simultaneous Change in S_i to 500 mg/l Glucose and X_R to 15,000 mg/l


EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
2500
2000
1500
1000
500
EFFLUENT CHARACTERISTICS
TOTAL COD
BIOLOGICAL SOLIDS
FILTRATE COD
FILTRATE BOD_5
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
FEED SORBITOL 500 mg/ℓ
FEED GLUCOSE - 500 mg/ℓ
COD
SORBITOL COD(△)
CARBOHYDRATE (○)
BIOMASS
JULY 22, 1977
3600
3200
2800
2400
2000
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
1500
1000
500
0
75
50
25
0
INDICATED ANALYSIS, MG/L
0
4
8
12
13
14
15
16
20
24
28
32
36
40
44
TIME, DAYS

production averaged 1043 mg/day, and return sludge concentration averaged 15,234 mg/l. The biological constants, μ_{max}, K_s, and Y_{t_B}, were 0.49 hr^{-1}, 154 mg/l, and 0.57.

Response to Quantitative Shock Loadings

Six-fold Step Increase: 500 mg/l Sorbitol, X_R = 5000 mg/l→3000 mg/l Sorbitol, X_R = 5000 mg/l

Table IV is presented for ready reference to the various shocks and figures showing the results.

Figure 9 shows the response when a system operating with X_R = 5000 mg/l and S_i = 500 mg/l sorbitol was subjected to a six-fold increase in S_i. The time scale is expanded from day 13 to day 20. The average biomass concentration during pre-shock steady state was 1212 mg/l; the average effluent total COD and filtrate COD were 14 mg/l and 6 mg/l. The effluent solids concentration was 7 mg/l. The percent protein and carbohydrate were 63.0 percent and 18.8 percent, respectively.

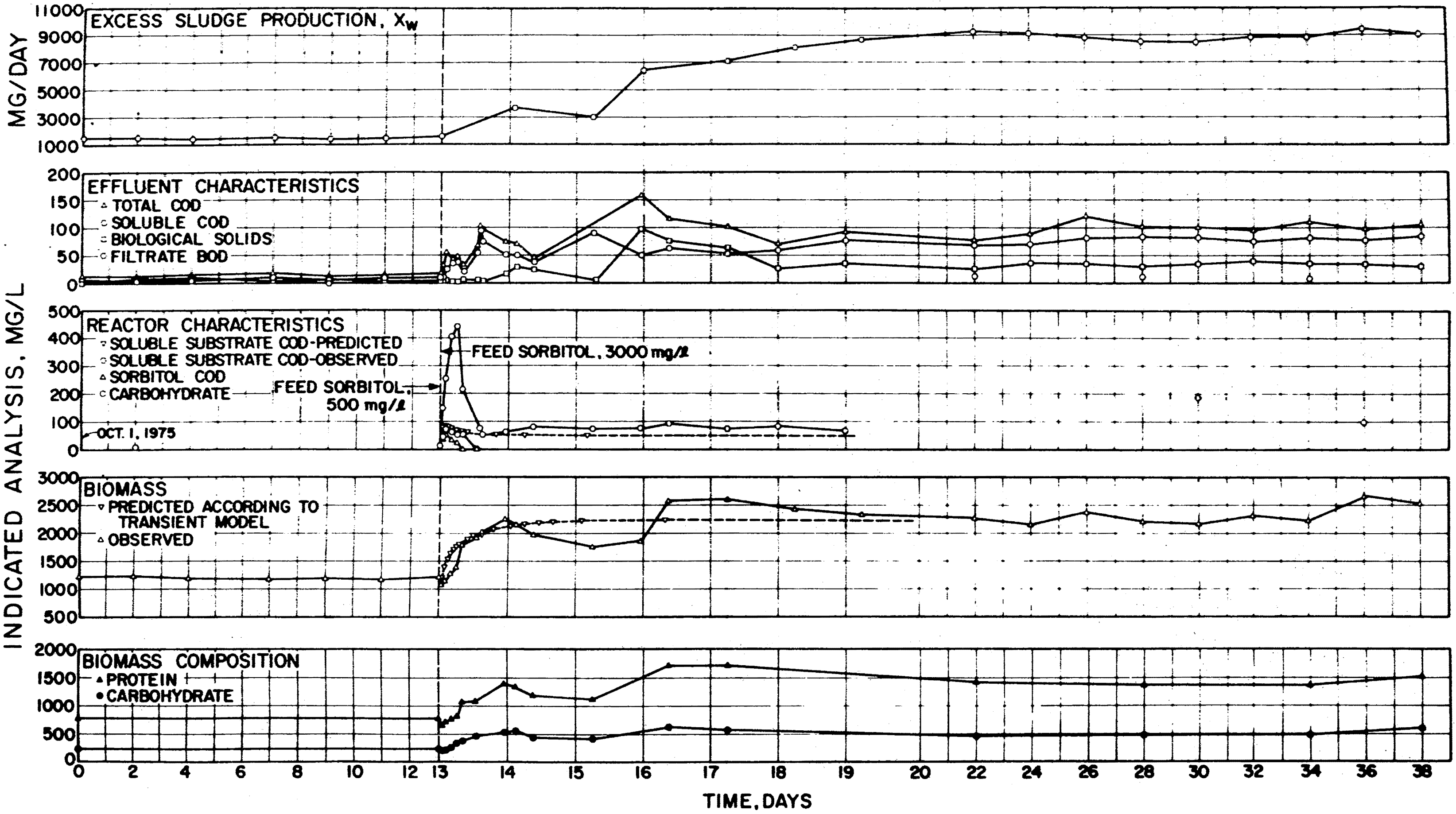
The recycle sludge concentration was maintained at 4892 mg/l, and filtrate COD in the recycle line was 11 mg/l. The excess sludge concentration was 1516 mg/day. The shock was applied on day 13. In response to the shock, the biomass showed a steep rise for 23 hours, and reached a value of 2255 mg/l. This was followed by a drop in concentration to 1860 mg/l by day 16. Again there was another increase up to 2600 mg/l, and subsequently the solids concentration levelled off. In the reactor during the shock, the filtrate COD rose very steeply to a value of 442 mg/l within six hours after the shock. This was followed by a steep decrease in COD to 55 mg/l 14 hours into the shock.

TABLE IV

OUTLINE OF EXPERIMENTAL PLAN FOR QUANTITATIVE SHOCK LOAD STUDIES AT VARIOUS X_R VALUES

Steady State	Transient	Steady State	Figure
Sorbitol S_i = 500 mg/l X_R = 5000 mg/l	6-fold Change in S_i	Sorbitol S_i = 3000 mg/l X_R = 5000 mg/l	9
Sorbitol S_i = 3000 mg/l X_R = 5000 mg/l	6-fold Change in S_i	Sorbitol S_i = 500 mg/l X_R = 5000 mg/l	10
Sorbitol S_i = 3000 mg/l X_R = 5000 mg/l	6-fold Change in S_i	Sorbitol S_i = 500 mg/l X_R = 5000 mg/l	11
Sorbitol S_i = 500 mg/l X_R = 5000 mg/l	2-fold Change in X_R	Sorbitol S_i = 500 mg/l X_R = 10,000 mg/l	12 & 13
Sorbitol S_i = 500 mg/l X_R = 1000 mg/l	6-fold Change in S_i	Sorbitol S_i = 3000 mg/l X_R = 10,000 mg/l	14
Sorbitol S_i = 3000 mg/l X_R = 10,000 mg/l	6-fold Change in S_i	Sorbitol S_i = 500 mg/l X_R = 10,000 mg/l	15
Sorbitol S_i = 3000 mg/l X_R = 10,000 mg/l	6-fold Change in S_i	Sorbitol S_i = 500 mg/l X_R = 10,000 mg/l	16

Figure 9. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l at an S_i of 500 mg/l Sorbitol Quantitatively Shock Loaded by a Change in S_i to 3000 mg/l Sorbitol



MG/DAY
11000
9000
7000
5000
3000
1000
EXCESS SLUDGE PRODUCTION, X_w
200
150
100
50
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
BIOLOGICAL SOLIDS
FILTRATE BOD
INDICATED ANALYSIS, MG/L
500
400
300
200
100
0
REACTOR CHARACTERISTICS
SOLUBLE SUBSTRATE COD-PREDICTED
SOLUBLE SUBSTRATE COD-OBSERVED
SORBITOL COD
CARBOHYDRATE
FEED SORBITOL, 500 mg/ℓ
FEED SORBITOL, 3000 mg/ℓ
OCT. 1, 1975
3000
2500
2000
1500
1000
500
BIOMASS
PREDICTED ACCORDING TO TRANSIENT MODEL
OBSERVED
2000
1500
1000
500
0
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
0
2
4
6
8
10
12
13
14
15
16
17
18
19
20
22
24
26
28
30
32
34
36
38
TIME, DAYS

Subsequently, the filtrate COD levelled off. During this period, leakage of sorbitol and carbohydrate was observed. The maximum leakage of sorbitol was 52 mg/l two hours after the shock was applied; maximum leakage of carbohydrate was 74 mg/l at two hours after the shock. Inverted triangles connected by dotted lines in the lower part of Figure 9 in the biomass characteristics represents the predicted biomass concentration in the reactor in response to the shock as proposed by Chen (59). It can be seen that the transient model did not predict transient behavior very well. Also in the upper part of Figure 22, shown as reactor characteristics, the open triangles connected by dotted lines represent the predicted substrate concentration in the reactor.

Compared to events in the reactor, the effluent parameter total COD, filtrate COD, and solids showed a greater variation and fluctuation during the shock. The effluent solids concentration increased significantly to a high of 98 mg/l during the transient period. It was also noticed that filamentous organisms started to predominate, and during post-shock steady state, filaments were found in great numbers. During the transient, the protozoa decreased and bacteria with granules were observed. The post-shock steady state values spanned day 22 to day 38. The filtrate COD of the effluent, even after reaching steady state, was 79 mg/l compared to a pre-shock steady state value of 6 mg/l. The percent carbohydrate and protein of the biomass showed a similtaneous increase after shock. However, protein percent showed a relatively steeper rise. The protein and carbohydrate composition of biomass in the post-shock steady state were 62.0 percent and 22.1 percent, respectively.

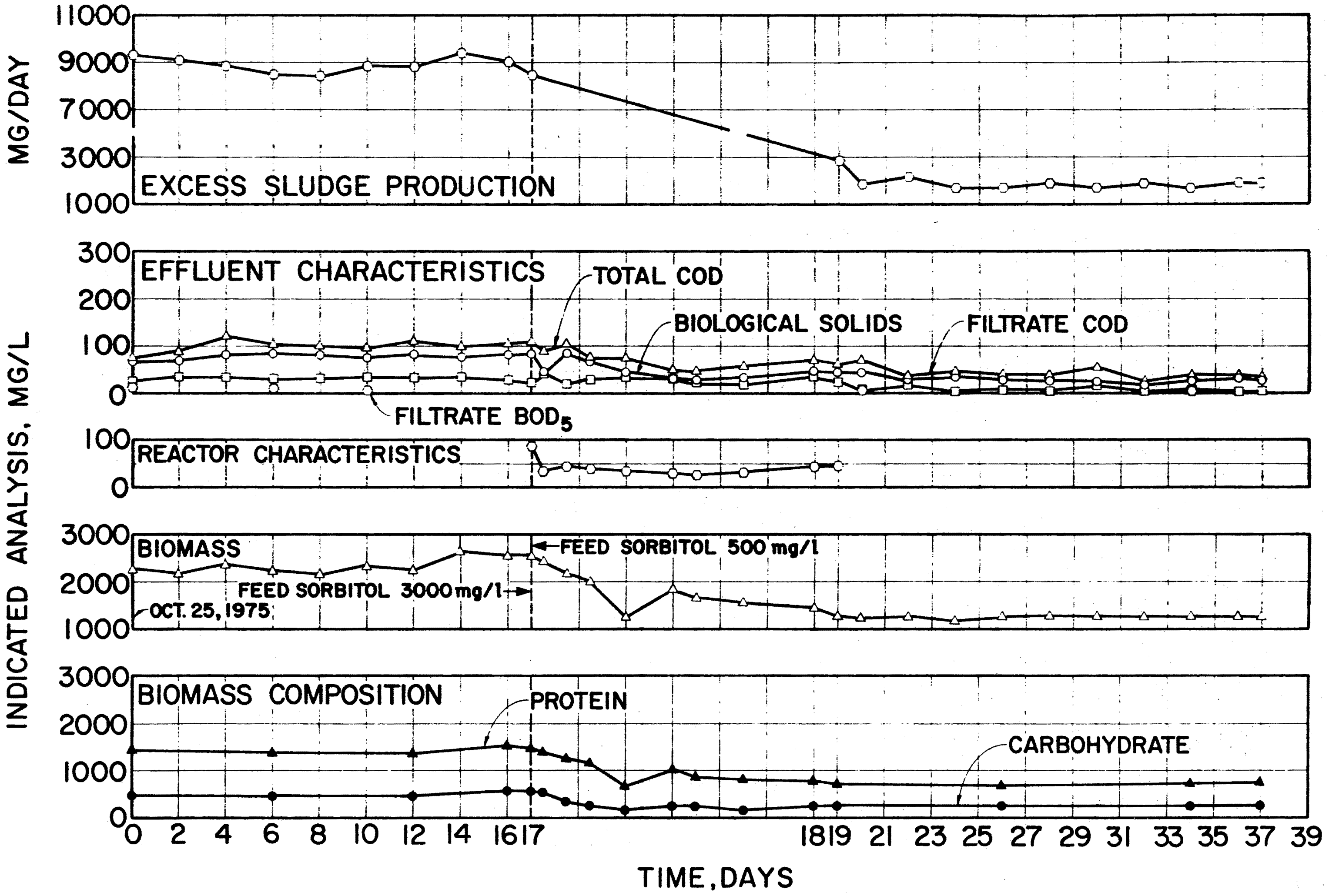
Effluent filtrate BOD_5 value increased to 11.2 mg/l during post-shock steady state, compared to a pre-shock steady state value of 2.2

mg/l. Excess sludge production increased after the shock, and showed an average value of 8943 mg/day during steady state. The recycle sludge concentration was maintained at 5173 mg/l. The effluent total COD and filtrate COD were 100 mg/l and 79 mg/l during steady state. The effluent solids concentration was 33 mg/l. The average biomass concentration was 2317 mg/l. The biological constants, μ_{max}, K_s, and Y_{t_B}, were 0.5 hr^{-1}, 200 mg/l, and 0.61.

Six-fold Step Decrease: 3000 mg/l Sorbitol, X_R = 5000 mg/l→500 mg/l Sorbitol, X_R = 5000 mg/l

After operating the system in steady state at S_i = 3000 mg/l sorbitol for 17 days (day 22 to day 38), the system was shocked by lowering the S_i to 500 mg/l sorbitol (Figure 10). In response to the shock, the filtrate COD in the reactor decreased from 85 mg/l to 29 mg/l within 14 hours after administering the shock. Biomass concentration decreased from 2550 mg/l to 1210 mg/l within eight hours after the shock. The protein and carbohydrate content decreased in proportion to the decrease in biomass concentration. Effluent total COD, filtrate COD, and solids concentration showed gradual decrease after the shock. The post-steady state values spanned day 22 to day 33. The total effluent COD, filtrate COD and solids concentration were 37 mg/l, 27 mg/l, and 7 mg/l, respectively. The steady state biomass concentration was 1250 mg/l. The percent protein and carbohydrate contents were 57.2 and 20.6, respectively. The excess sludge production averaged 1853 mg/day. The recycle sludge concentration was maintained at 4856 mg/l. During the steady state after the stepdown in S_i, the filamentous organisms decreased and almost disappeared from the system.

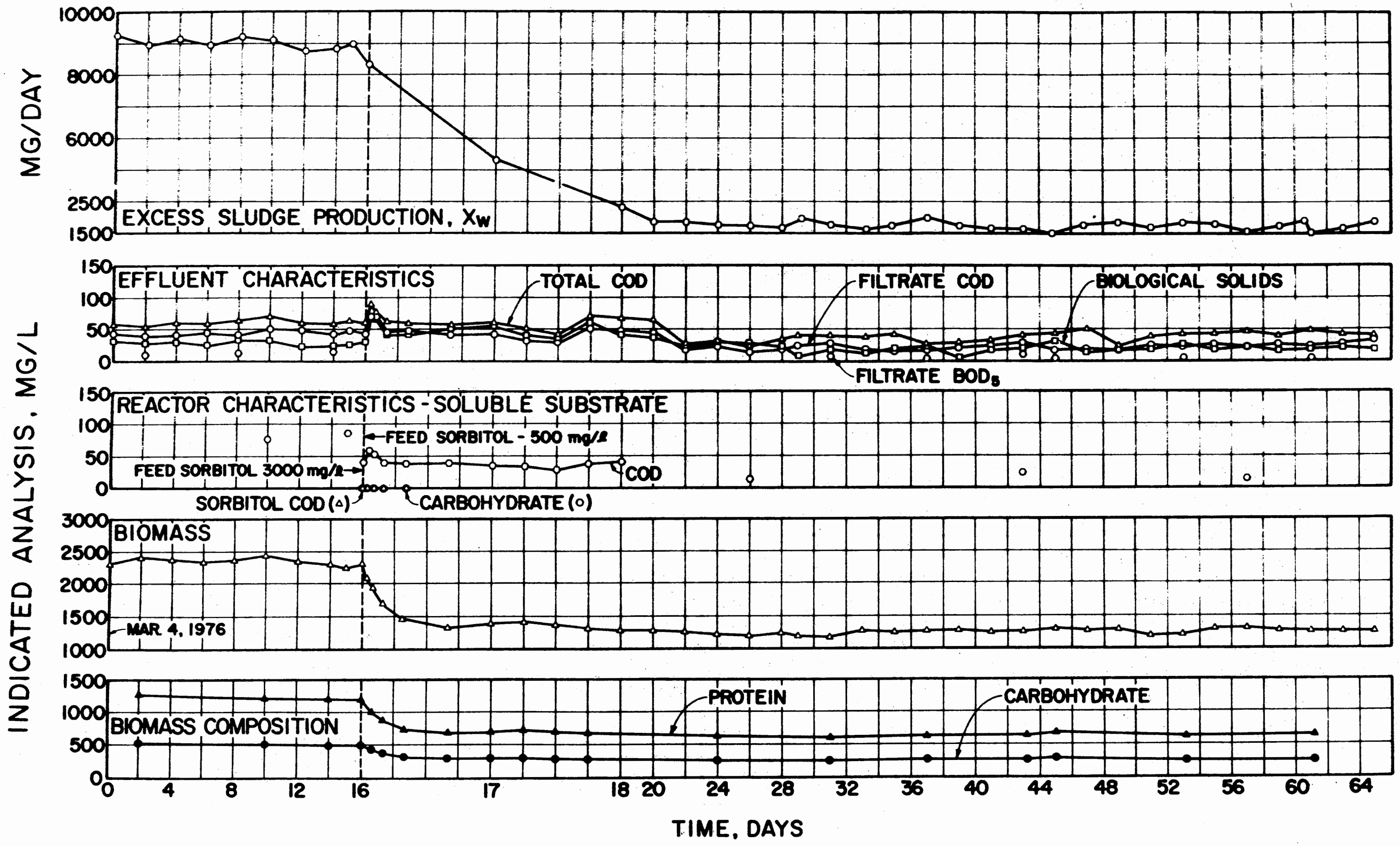
Figure 10. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l at an S_i of 3000 mg/l Sorbitol Quantitatively Shock Loaded by a Change in S_i to 500 mg/l Sorbitol


MG/DAY
11000
9000
7000
3000
1000
EXCESS SLUDGE PRODUCTION
300
200
100
0
EFFLUENT CHARACTERISTICS
TOTAL COD
BIOLOGICAL SOLIDS
FILTRATE COD
FILTRATE BOD5
100
0
REACTOR CHARACTERISTICS
3000
2000
1000
BIOMASS
FEED SORBITOL 500 mg/l
FEED SORBITOL 3000 mg/l
OCT. 25, 1975
3000
2000
1000
0
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
INDICATED ANALYSIS, MG/L
0 2 4 6 8 10 12 14 16 17 18 19 21 23 25 27 29 31 33 35 37 39
TIME, DAYS

In order to assess the effect of X_R on a six-fold step increase in S_i, a system which was operating at X_R = 5000 mg/l and S_i = 3000 mg/l was first subjected to stepdown by lowering the S_i to 500 mg/l sorbitol. The pre-shock transient and post-shock behavior of the system are shown in Figure 11. This shock is similar to that presented in Figure 10. As evident from the reactor characteristics shown in Figure 11, this shock did not affect the filtrate COD except for the slight initial disturbance. Original substrate did not leak from the reactor; the same was true for the effluent parameters. There was a secondary response in the system from the middle of the 17th day, as evidenced by the fluctuation in effluent characteristics. During this period, a slight change in color of the biomass was observed. The color changed from brownish-yellow to light yellow. The excess sludge production decreased to an average post-shock steady state value of 1704 mg/l. The post-shock steady state values spanned day 53 to day 65, and average effluent S_T, S_e, and X_e, were 29 mg/l, 15 mg/l, and 21 mg/l. The average steady state effluent filtrate COD at S_i = 3000 mg/l had been 82 mg/l during pre-shock steady state condition, which spanned day 0 to day 15. Effluent filtrate BOD_5 was 5.1 mg/l at post-shock steady condition, whereas it was 11.9 mg/l in the pre-shock steady state. The average biomass concentration was 2230 mg/l. The percent protein and carbohydrate compositions of the biomass were 53.3 mg/l and 22.2 mg/l, respectively. The average excess sludge production was 1704 mg/day. The recycle sludge concentration was maintained at 5073 mg/l. The steady state parameters are tabulated in Table III.

The biological constants, μ_{max}, K_s, and Y_{t_B}, were 0.51 hr^{-1}, 103 mg/l, and 0.61 (see Table III).

Figure 11. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l at an S_i of 3000 mg/l Sorbitol Quantitatively Shock Loaded by a Change in S_i to 500 mg/l Sorbitol


MG/DAY
10000
8000
6000
2500
1500
EXCESS SLUDGE PRODUCTION, X_W
150
100
50
0
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
150
100
50
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
FEED SORBITOL - 500 mg/ℓ
FEED SORBITOL 3000 mg/ℓ
COD
SORBITOL COD (△)
CARBOHYDRATE (○)
INDICATED ANALYSIS, MG/L
3000
2500
2000
1500
1000
BIOMASS
MAR 4, 1976
1500
1000
500
0
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
0
4
8
12
16
17
18
20
24
28
32
36
40
44
48
52
56
60
64
TIME, DAYS

Two-fold Step Increase in X_R: 5000 mg/l→10,000 mg/l

As shown in Figures 12 and 13, the recycle sludge concentration was changed from X_R = 5000 mg/l to X_R = 10,000 mg/l, with S_i = 500 mg/l. The time scale was expanded from day 14 to day 17 during the transient. There was only a slight increase in reactor filtrate COD from 20 mg/l to 45 mg/l during the first four hours into the shock. There was no leakage of original substrate. Correspondingly, during the shock there was fluctuation in effluent characteristics. The effluent solids fluctuated between 22 mg/l to 48 mg/l. This lead to a fluctuation in total effluent COD. The increase in biomass concentration in the reactor and corresponding increase in the protein carbohydrate content were due to the higher recycle sludge concentration. The post-shock steady state values spanned day 66 to day 91 (Figure 13), and excess sludge production was 1265 mg/day compared to a pre-shock steady state value of 1704 mg/day. The pre-shock steady state values spanned day 6 to day 12 (Figure 12) for the S_i of 500 mg/l. There was only a slight difference in effluent filtrate COD between X_R = 5000 and X_R = 10,000 mg/l. It was 15 mg/l at X_R = 5000 mg/l, and 17 mg/l at X_R = 10,000 mg/l; however, the corresponding BOD_5 values were 5.1 mg/l and 2.3 mg/l, respectively.

The post-shock steady state biomass in aerator 1 was 2230 mg/l, and percent protein and carbohydrate composition were 53.3 and 22.2, respectively. The recycle concentration was maintained at 10,259 mg/l. Overall leakage of substrate and disturbances in the system due to the shock were minimal. The biological constants, μ_{max}, K_s, and Y_{t_B}, were

Figure 12. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l at an S_i of 500 mg/l Sorbitol Subjected to a Change in X_R to 10,000 mg/l

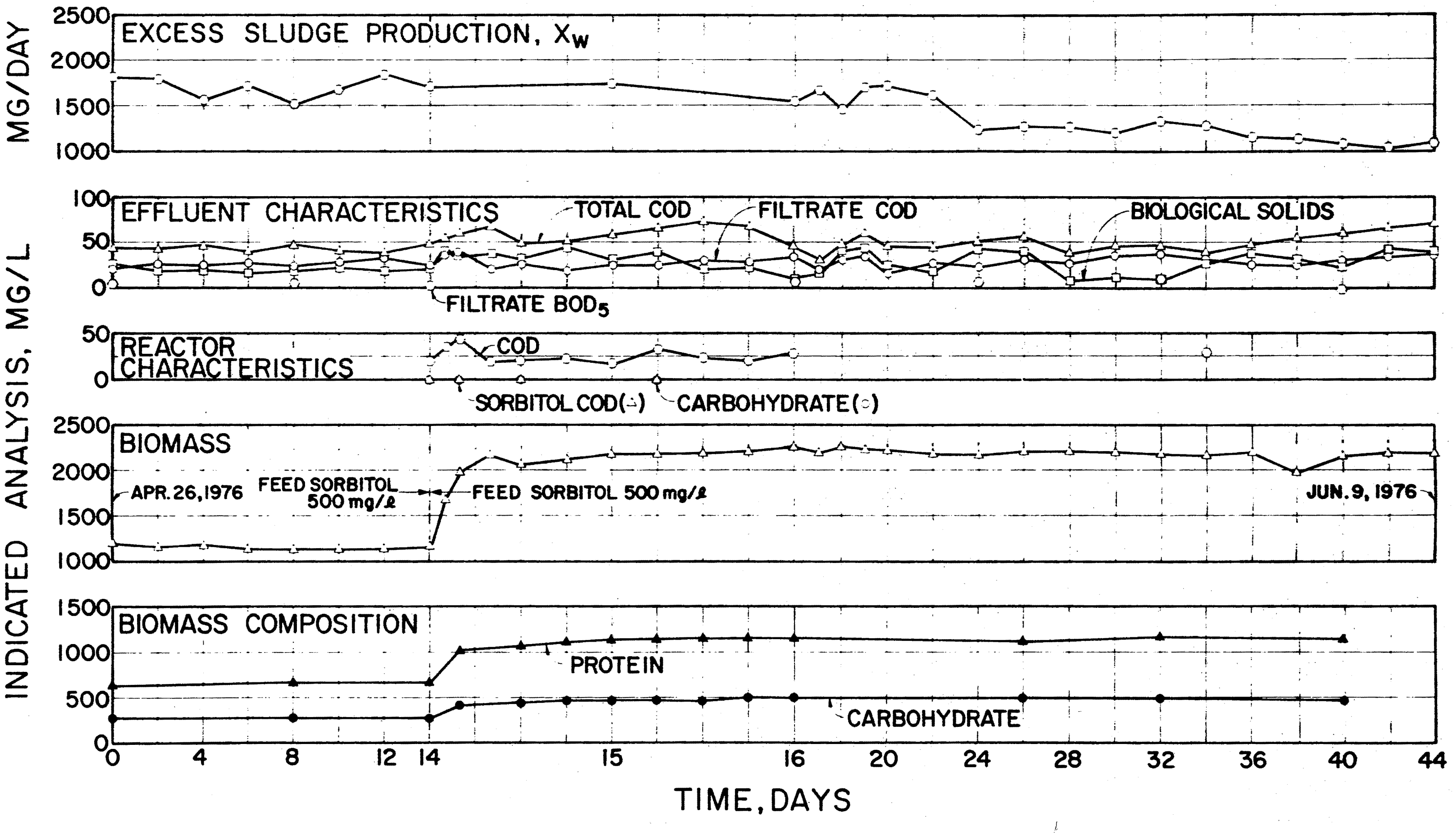
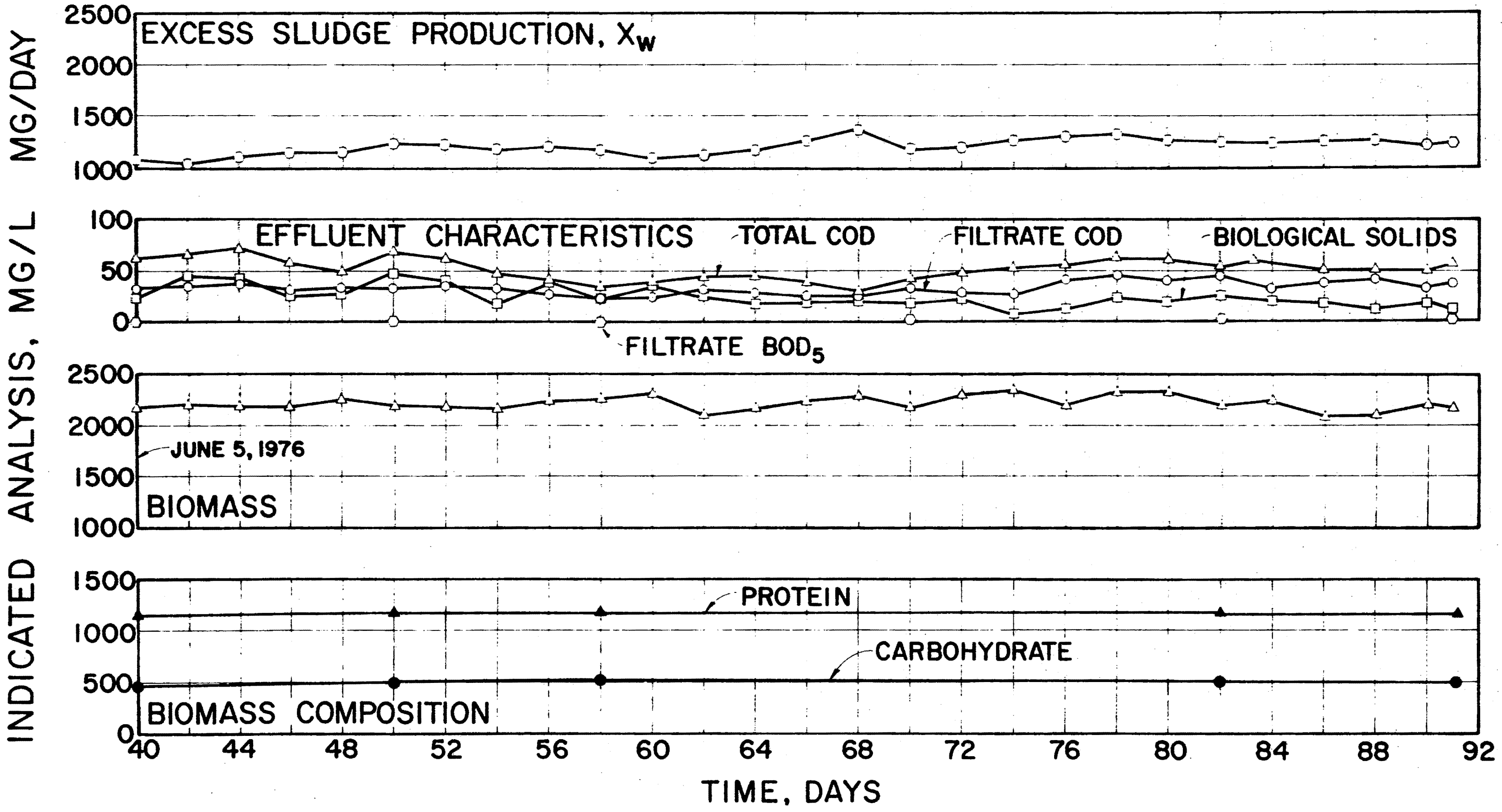

EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
2500
2000
1500
1000
EFFLUENT CHARACTERISTICS
100
50
0
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD$_5$
REACTOR CHARACTERISTICS
50
0
COD
SORBITOL COD(△)
CARBOHYDRATE(○)
BIOMASS
2500
2000
1500
1000
APR. 26, 1976
FEED SORBITOL 500 mg/ℓ
FEED SORBITOL 500 mg/ℓ
JUN. 9, 1976
BIOMASS COMPOSITION
1500
1000
500
0
PROTEIN
CARBOHYDRATE
INDICATED ANALYSIS, MG/L
0
4
8
12
14
15
16
20
24
28
32
36
40
44
TIME, DAYS

Figure 13. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l and an S_i of 500 mg/l Sorbitol



EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
2500
2000
1500
1000
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
100
50
0
BIOMASS
JUNE 5, 1976
2500
2000
1500
1000
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
1500
1000
500
0
INDICATED ANALYSIS, MG/L
40
44
48
52
56
60
64
68
72
76
80
84
88
92
TIME, DAYS

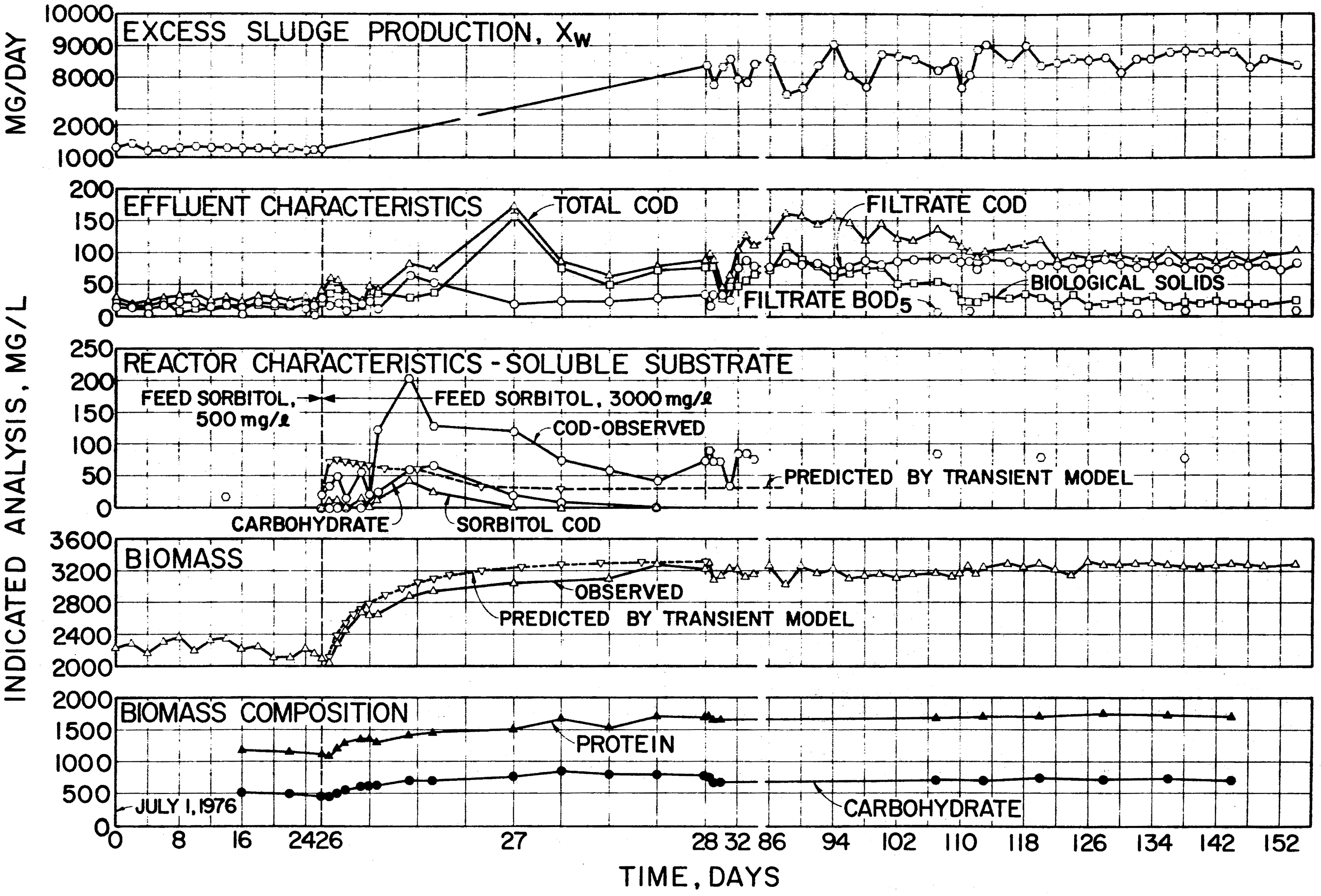
$0.47\ hr^{-1}$, 279 mg/l, and 0.61. The steady state parameters are shown in Table II.

Six-fold Step Increase: 500 mg/l Sorbitol →3000 mg/l Sorbitol, X_R = 10,000 mg/l

After operating the system at S_i = 500 mg/l and X_R = 10,000, the system was subjected to a six-fold step increase in S_i. The pre-shock steady state values spanned day 0 to day 25 (shown in Table II). Figure 14 shows the response of the system to this shock. During the initial six hours into the shock there was no appreciable amount of leakage (15-42 mg/l). From hour 6 to hour 10 there was a steep increase in the reactor filtrate COD from 20 mg/l to 205 mg/l. A portion of the COD consisted of sorbitol. The original substrate and some carbohydrate were found in the filtrate. The maximum sorbitol leakage was 42 mg/l, which occurred 11 hours into the shock, and carbohydrate leakage was 68 mg/l, which occurred 14 hours after applying the shock. In the lower part of Figure 14 shown as biomass characteristics, the inverted triangles connected by dotted lines represent the biomass concentration in the reactor predicted according to the equation proposed by Chen (59). In the upper part of the Figure, shown as reactor characteristics, the inverted triangles connected by a dotted line represent the predicted soluble substrate in the reactor during the transient after the shock.

By day 31 there was a change in predominance in the system. The biomass in the reactor changed from yellow to a brownhish-yellow color. The sludge in the settling tank needed aeration three times a day to keep it from going anaerobic. From day 34 to day 86, the system was

Figure 14. Operational Characteristics for an Activated Sludge Process Operating With Constant X_R of 10,000 mg/l and an S_i of 500 mg/l Sorbitol Quantitatively Shock Loaded by a Change in S_i to 3000 mg/l Sorbitol


EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
10000
9000
8000
2000
1000
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
200
150
100
50
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
FEED SORBITOL, 500 mg/ℓ
FEED SORBITOL, 3000 mg/ℓ
COD-OBSERVED
PREDICTED BY TRANSIENT MODEL
CARBOHYDRATE
SORBITOL COD
250
200
150
100
50
0
BIOMASS
OBSERVED
PREDICTED BY TRANSIENT MODEL
3600
3200
2800
2400
2000
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
JULY 1, 1976
2000
1500
1000
500
0
INDICATED ANALYSIS, MG/L
0
8
16
24
26
27
28
32
86
94
102
110
118
126
134
142
152
TIME, DAYS

operated at S_i = 3000 mg/l but without taking data. The data were taken again beginning on day 86, and the system was operated for a considerably long period to determine if the effluent filtrate COD would improve in the long run. However, it did not improve very much.

The post-shock effluent parameters spanned day 116 to day 144; S_T, S_e, and X_e were 94 mg/l, 81 mg/l, and 22 mg/l. The average biomass concentration was 3277 mg/l. The percent protein and carbohydrate composition were 52.5 and 22.3, respectively. The average excess sludge production was 8542 mg/day. The recycle sludge concentration was maintained at 10,337 mg/l. The biological constants, μ_{max}, K_s, and Y_{t_B}, were 0.49 hr^{-1}, 115 mg/l, and 0.57. Effluent filtrate BOD_5 was 8 mg/l at X_R = 10,000 mg/l compared to 11.3 mg/l at X_R = 5000 mg/l.

The effluent parameters also showed a wide fluctuation during the transient period. The biological solids concentration in the effluent rose to 158 mg/l at 24 hours after the shock. During this period, the protozoa polulation was diminishing, filaments were increasing, and there was an increase in the amount of free (unflocculated) bacteria. The effluent looked very turbid. It was only by day 110 that the effluent became much clearer. There was considerable difference between the COD concentration in the reactor and the soluble COD exiting the settling tank. This was due partly to the attenuating effect of the oversized clarifier and due partly to the biological activity in the settling tank. Even though the system reached steady state with reference to soluble substrate by day 110, the system could not be said to be in steady state until day 122.

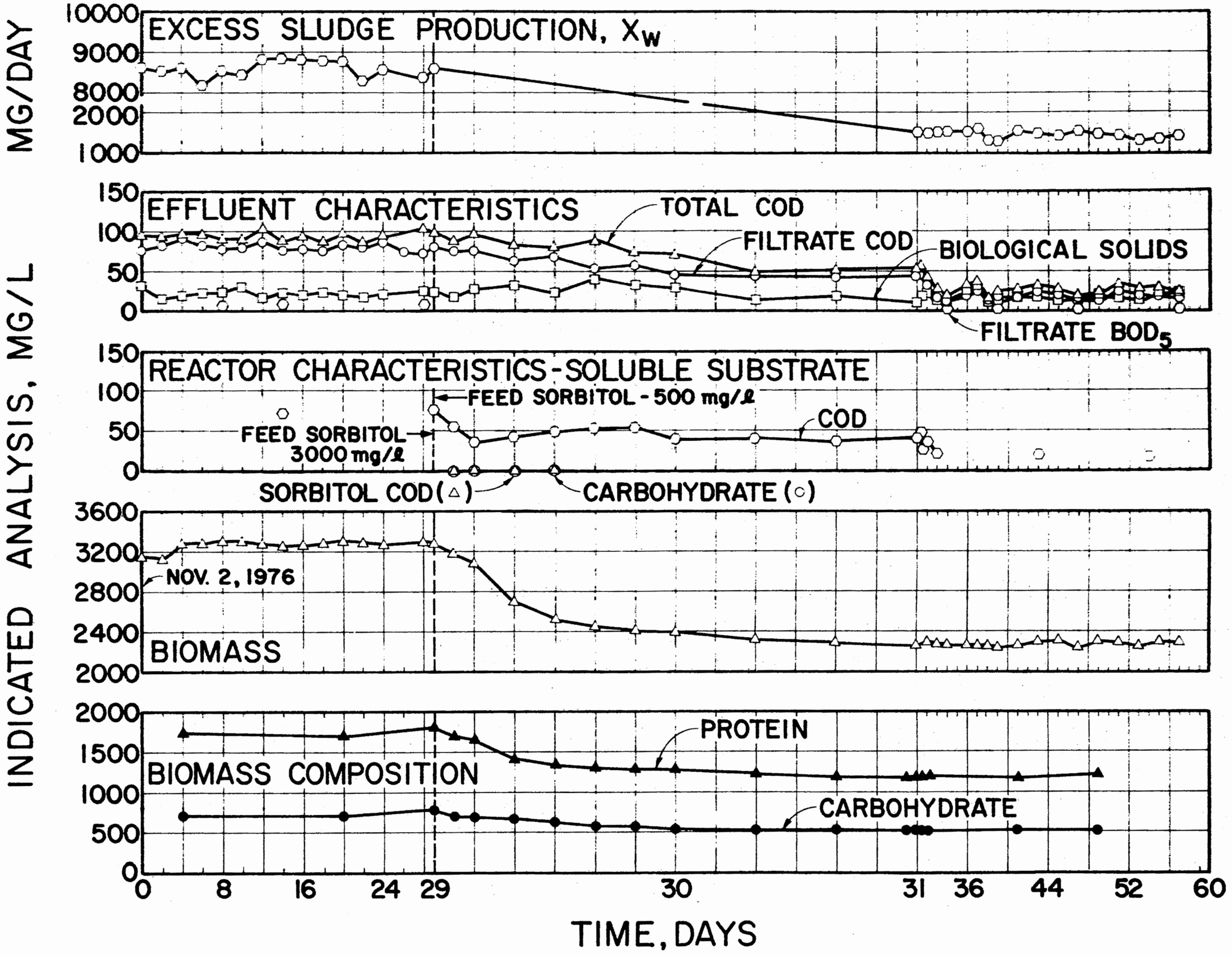
The biomass showed an immediate response to the shock as evidenced by the steep rise in concentration. There was a corresponding rise in the protein and carbohydrate content of the biomass; the excess sludge production increased due to the six-fold rise in S_i.

Six-fold Step Decrease: 3000 mg/l Sorbitol →500 mg/l Sorbitol, X_R = 10,000 mg/l

After operating at steady state with S_i = 3000 mg/l, the system was subjected to a six-fold decrease in S_i. The pre-shock steady state values spanned day 0 to day 28, as shown in Table II. The response is shown in Figure 15. The time scale is expanded during the shock from day 29 to day 31. The reactor biomass underwent an immediate decrease in concentration in response to the shock. The reactor filtrate COD decreased from 76 mg/l to 36 mg/l within four hours after applying the shock, and it stayed in that range. The quality of the clarifier effluent was not disturbed, and by day 38 it became rather steady. The post-shock steady state values spanned day 41 to day 57, as shown in Table II. The excess sludge production decreased, and during post-shock steady state it averaged 1461 mg/day. The effluent parameters, S_T, S_e, and X_e, during post-shock steady state were 26 mg/l, 18 mg/l, and 18 mg/l, compared to 94 mg/l, 81 mg/l, and 22 mg/l during pre-shock steady state. The average biomass concentration in the post-steady state was 2274 mg/l.

The protein and carbohydrate concentrations of the sludge decreased due to the decrease in biomass concentration; the percent composition of protein and carbohydrate were 53.2 and 23.2, respectively, in the post-shock steady state. The recycle sludge concentration was maintained at 10,238 mg/l. The biological constants, μ_{max}, K_s, and Y_{t_B}, were 0.39 hr^{-1}, 231 mg/l, and 0.59.

Figure 15. Operational Characteristics for an Activated Sludge Process Operating With Constant X_R of 10,000 mg/l and an S_i of 3000 mg/l Sorbitol Quantitatively Shock Loaded by a Change in S_i to 500 mg/l Sorbitol



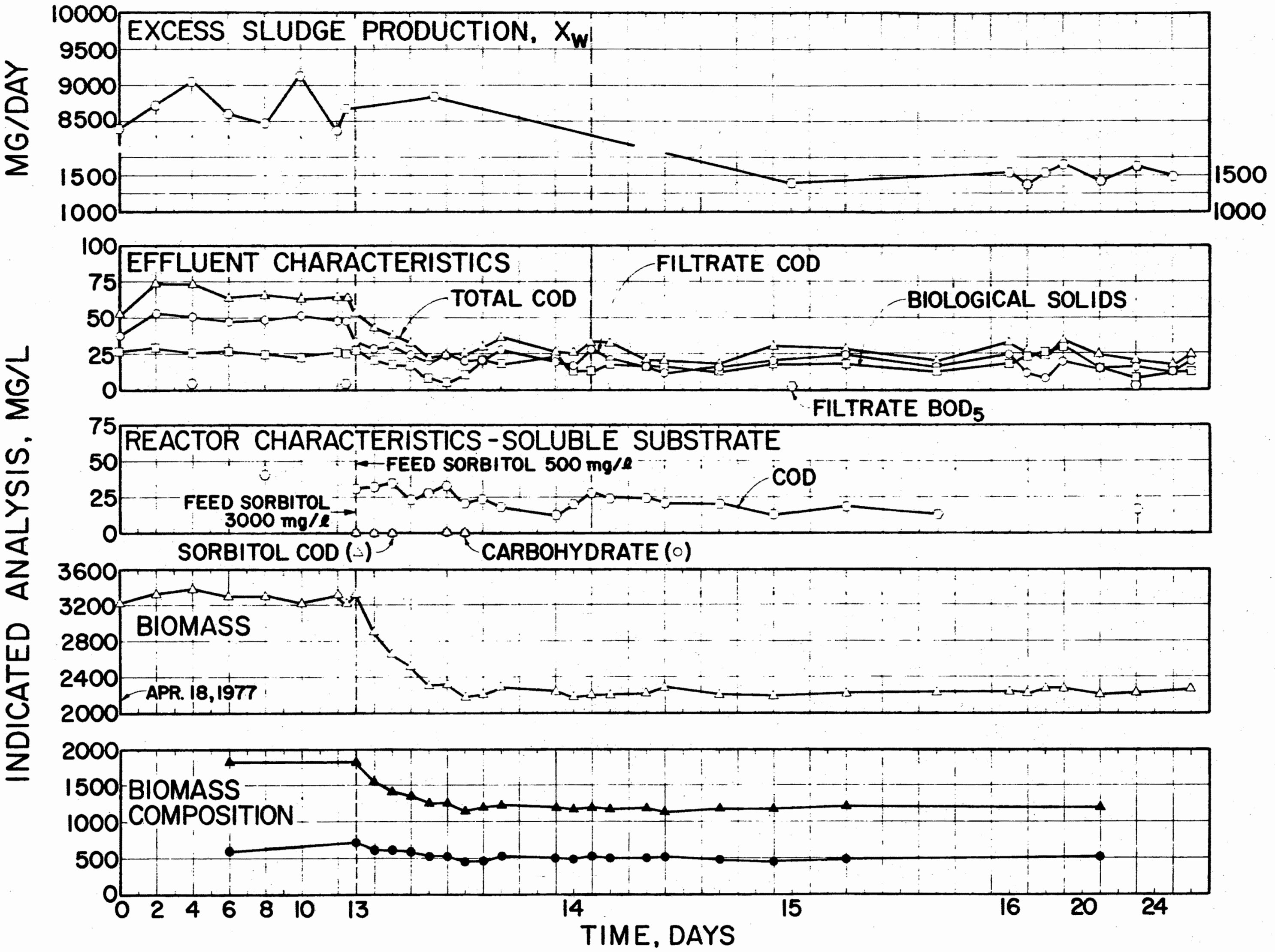
EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
10000
9000
8000
2000
1000
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD5
150
100
50
0
REACTOR CHARACTERISTICS-SOLUBLE SUBSTRATE
FEED SORBITOL - 500 mg/ℓ
FEED SORBITOL 3000 mg/ℓ
COD
SORBITOL COD (△)
CARBOHYDRATE (○)
150
100
50
0
INDICATED ANALYSIS, MG/L
3600
3200
2800
2400
2000
NOV. 2, 1976
BIOMASS
2000
1500
1000
500
0
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
0
8
16
24
29
30
31
36
44
52
60
TIME, DAYS

A similar six-fold stepdown quantitative shock was applied again after a few months while preparing the system for another type of shock.

Prior to the shock, the system was operated with an average influent substrate of 2812 mg/l. The pre-shock steady state values spanned day 0 to day 14, as shown in Table II. The effluent parameters, S_T, S_e and X_e, averaged 66 mg/l, 47 mg/l, and 26 mg/l. The effluent filtrate BOD_5 was 8 mg/l. The biomass concentrations averaged 3285 mg/l. The percent compositions of protein and carbohydrate were 54.9 and 22.5. The excess sludge production averaged 8632 mg/l, and the recycle sludge concentration was maintained at an average value of 10,114 mg/l. On day 13, the system was subjected to a stepdown quantitative shock by changing the influent substrate concentration from 3000 mg/l sorbitol to 500 mg/l sorbitol. The response of the system is shown in Figure 16; the steady state values are shown in Table II. The reactor and effluent characteristics show that there was no appreciable disturbance due to the shock.

The reactor filtrate COD varied between 12 mg/l and 36 mg/l. The effluent, S_T, varied between 18 mg/l and 56 mg/l, S_e between 12 and 32 mg/l, and X_e between 12 mg/l and 28 mg/l during the transient stage. The biomass and corresponding protein and carbohydrate content decreased in response to the reduction in influent substrate concentration. The post-shock steady state values spanned day 16 to day 26; the biomass concentration averaged 2238 mg/l. The percent composition of protein and carbohydrate averaged 53.2 and 22.8, respectively. The effluent parameters, S_T, S_e, and X_e, averaged 24 mg/l, 16 mg/l, and 19 mg/l. The effluent filtrate BOD_5 was 2.5 mg/l. The excess sludge production

Figure 16. Operational Characteristics for an Activated Sludge Process Operating With a Constant X_R of 10,000 mg/l and an S_i of 3000 mg/l Sorbitol Subjected to a Repeated Quantitative Shock Load of Change in S_i to 500 mg/l Sorbitol


EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
10000
9500
9000
8500
1500
1000
1500
1000
EFFLUENT CHARACTERISTICS
FILTRATE COD
TOTAL COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
100
75
50
25
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
FEED SORBITOL 500 mg/ℓ
FEED SORBITOL 3000 mg/ℓ
COD
SORBITOL COD (△)
CARBOHYDRATE (○)
75
50
25
0
INDICATED ANALYSIS, MG/L
BIOMASS
APR. 18, 1977
3600
3200
2800
2400
2000
BIOMASS COMPOSITION
2000
1500
1000
500
0
0
2
4
6
8
10
13
14
15
16
20
24
TIME, DAYS

averaged 1530 mg/day, and recycle sludge concentration averaged 10,109 mg/l.

The biological constants, μ_{max}, K_s, and Y_{t_B}, determined by batch growth study were 0.42 hr^{-1}, 135 mg/l, and 0.51. Overall response was similar to that observed in the previous case.

Cyclic Quantitative Shock Loads

An experiment was designed to study the effect of cyclic quantitative shock loads. For this purpose, the system was operated with S_i = 500 mg/l sorbitol and X_R = 10,000 mg/l under steady state for 11 days (Figure 17). The steady state values spanned day 0 to day 10, and the average steady state parameters are shown in Table II. The effluent total COD, filtrate COD, and solids concentration were 25 mg/l, 16 mg/l, and 19 mg/l. The effluent filtrate BOD_5 value was 2.5 mg/l. The average biomass concentration in aerator 1 was 2238 mg/l. The percent protein and carbohydrate content were 53.2 and 22.8, respectively. The excess sludge production averaged 1530 mg/day; the recycle sludge concentration was maintained at 10,109 mg/l. The biological constants were μ_{max} = 0.42 hr^{-1}, K_s = 135 mg/l, and Y_{t_B} = 0.51.

The system was subjected to a cyclic quantitative shock load by changing the S_i concentration to 3000 mg/l at 6 A.M. and to 500 mg/l at 6 P.M. This procedure was followed throughout the cyclic shock load period. The system performance is shown in Figures 17, 18, and 20. The time scale is expanded from day 11 to day 16 in Figure 17, and from day 16 to day 20 in Figure 18. The time scale for day 42 is shown on an expanded scale in Figure 19. When the shock was applied for the first time on day 11, there was a considerable leakage of substrate.

Figure 17. Operational Characteristics for an Activated Sludge Process Operating With a Constant X_R of 10,000 mg/l and an S_i of 500 mg/l Subjected to a Cyclic Quantitative Shock Loading at an S_i of 500 mg/l Sorbitol and 3000 mg/l Sorbitol Every 12-hour Period. Excess Sludge Production is mg/Day From 0-11 Day and mg/12 Hour From Day 11.5 to 20

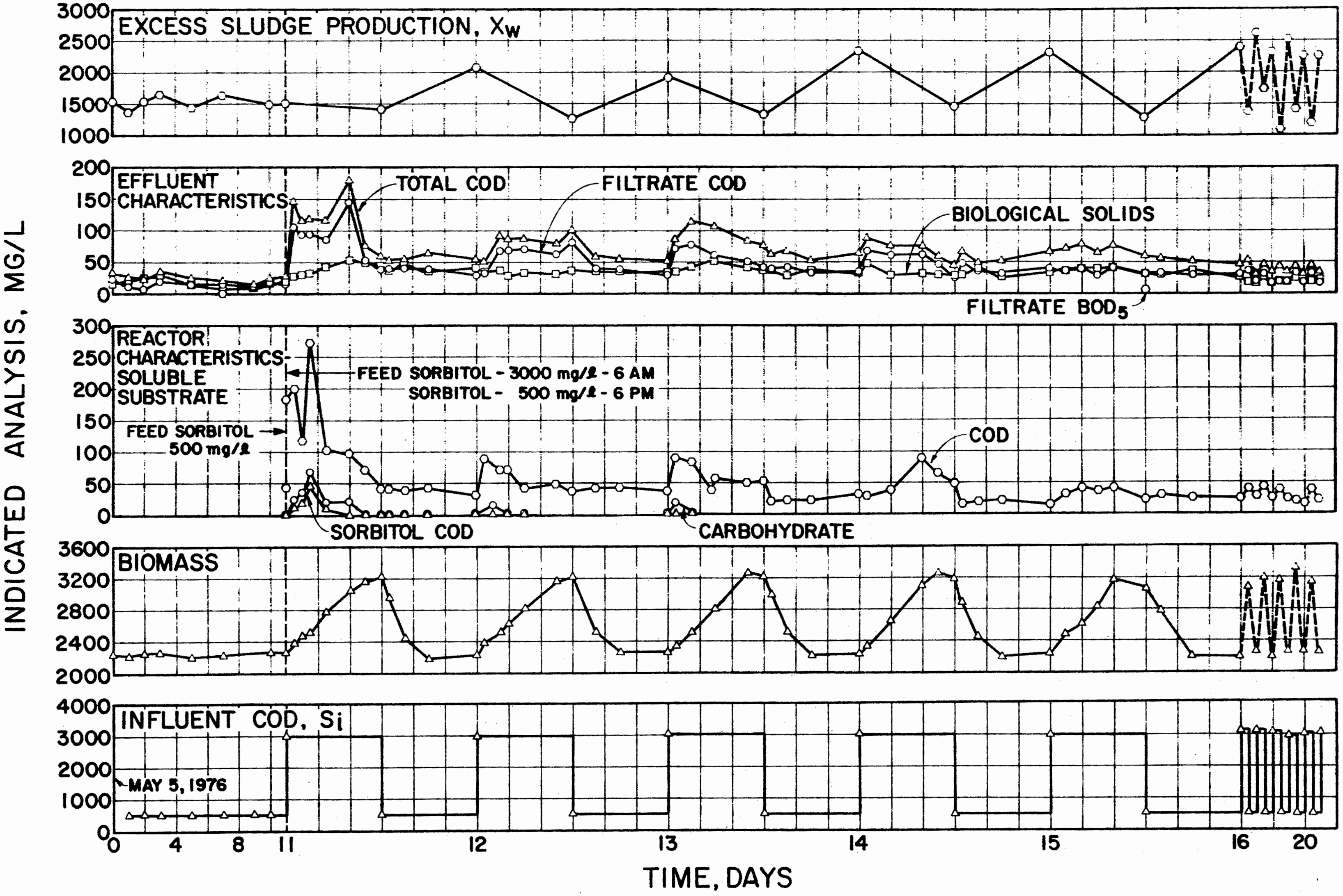

EXCESS SLUDGE PRODUCTION, X_W
3000
2500
2000
1500
1000
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
200
150
100
50
0
REACTOR CHARACTERISTICS-SOLUBLE SUBSTRATE
FEED SORBITOL - 3000 mg/ℓ - 6 AM
SORBITOL - 500 mg/ℓ - 6 PM
FEED SORBITOL 500 mg/ℓ
COD
SORBITOL COD
CARBOHYDRATE
300
250
200
150
100
50
0
BIOMASS
3600
3200
2800
2400
2000
INFLUENT COD, S_i
MAY 5, 1976
4000
3000
2000
1000
0
INDICATED ANALYSIS, MG/L
0
4
8
11
12
13
14
15
16
20
TIME, DAYS

Figure 18. Operational Characteristics for an Activated Sludge Process Operating With a Constant X_R of 10,000 mg/l and With a Cyclic Loading of 500 mg/l Sorbitol and 3000 mg/l Sorbitol at Every 12-hour Period From Day 16 to Day 42 After Shock

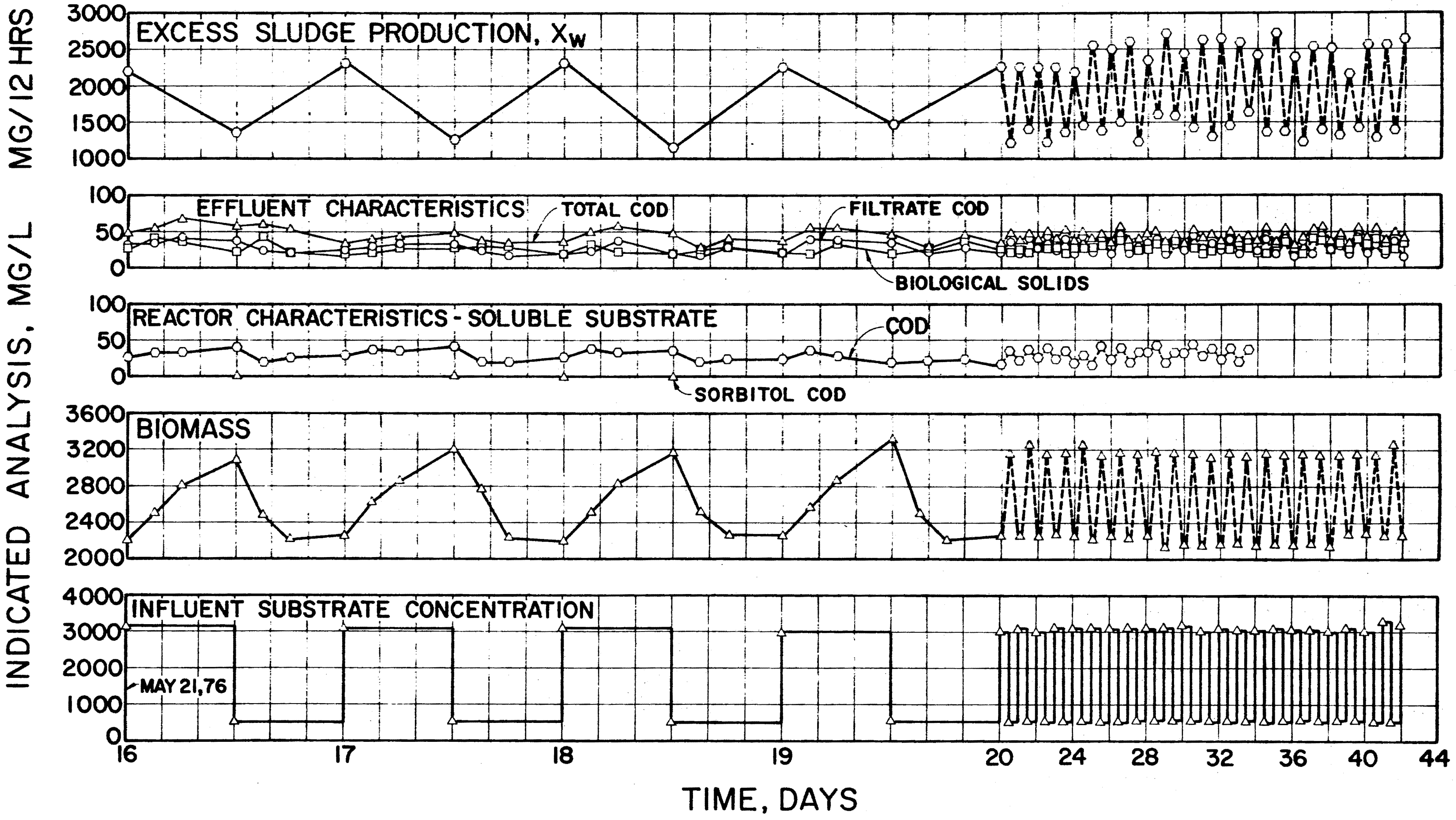

MG/12 HRS
3000
2500
2000
1500
1000
EXCESS SLUDGE PRODUCTION, X_W
INDICATED ANALYSIS, MG/L
100
50
0
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
100
50
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
COD
SORBITOL COD
3600
3200
2800
2400
2000
BIOMASS
4000
3000
2000
1000
0
INFLUENT SUBSTRATE CONCENTRATION
MAY 21,76
16
17
18
19
20
24
28
32
36
40
44
TIME, DAYS

Figure 19. Operational Characteristics for an Activated Sludge Process Operating With a Constant X_R of 10,000 mg/l and With a Cyclic Loading of 500 mg/l Sorbitol and 3000 mg/l Sorbitol at Every 12-hour Period From Day 42 to Day 56 After Shock

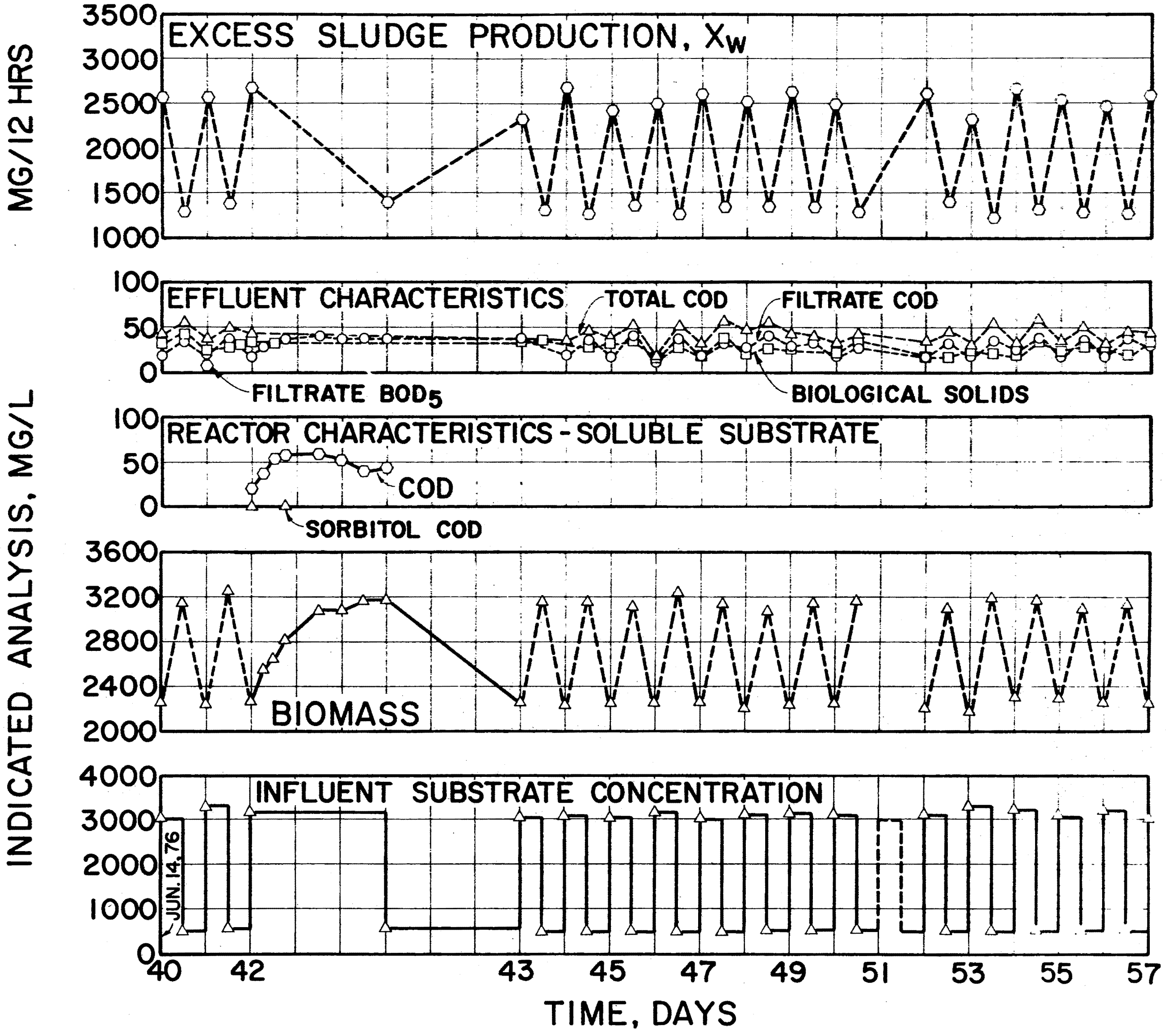
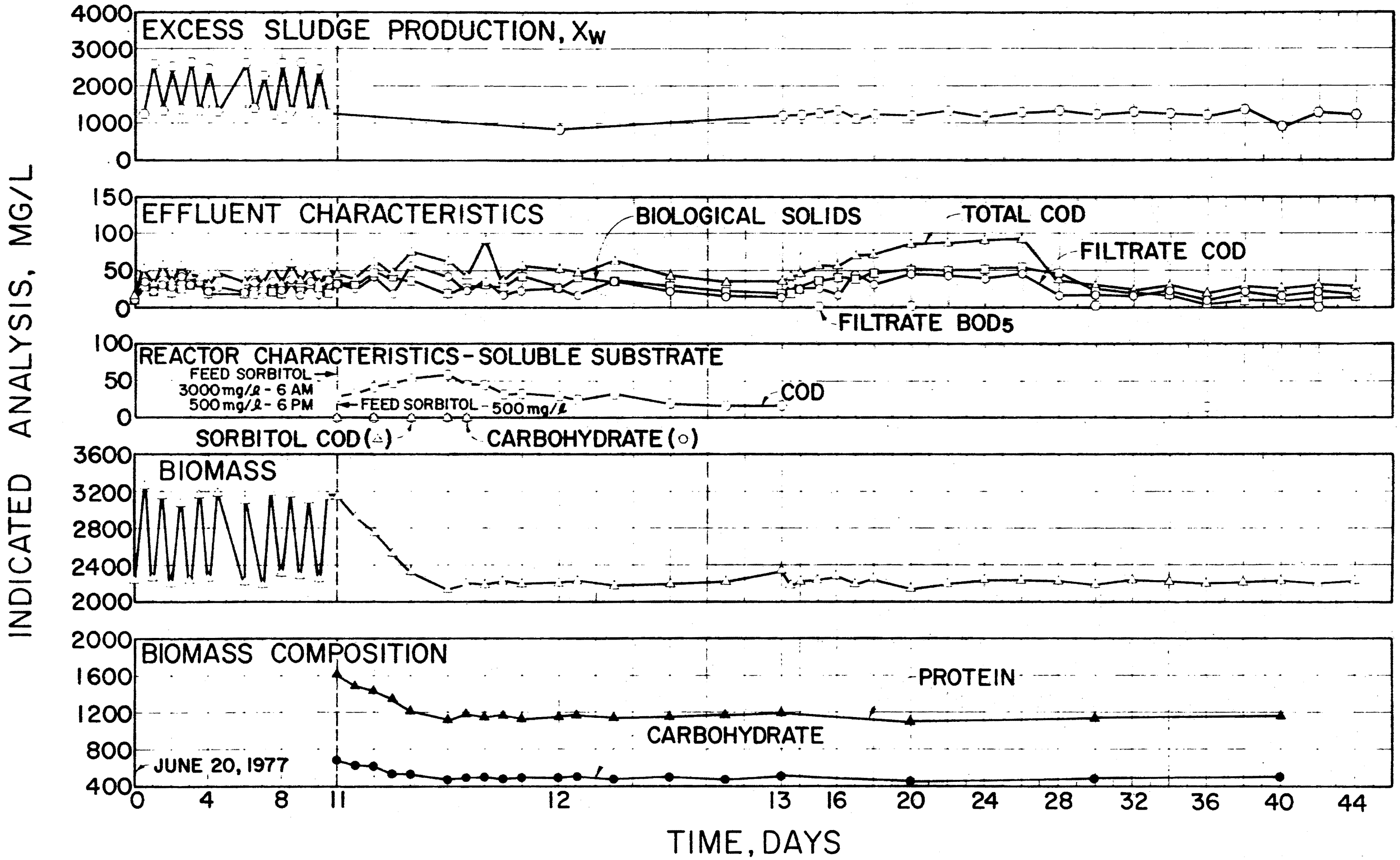

EXCESS SLUDGE PRODUCTION, X_W
MG/12 HRS
3500
3000
2500
2000
1500
1000
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
FILTRATE BOD$_5$
BIOLOGICAL SOLIDS
100
50
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
COD
SORBITOL COD
BIOMASS
3600
3200
2800
2400
2000
INFLUENT SUBSTRATE CONCENTRATION
JUN. 14, 76
4000
3000
2000
1000
0
INDICATED ANALYSIS, MG/L
40
42
43
45
47
49
51
53
55
57
TIME, DAYS

Figure 20. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l and With a Cyclic Loading S_i of 500 mg/l Sorbitol and 3000 mg/l Sorbitol at Every 12-hour Period Subjected to a Constant S_i of 500 mg/l Sorbitol. Excess Sludge Production in mg/12 Hour 0 to 11 Day, and in mg/Day in 12 to Day 44


EXCESS SLUDGE PRODUCTION, X_W
EFFLUENT CHARACTERISTICS
BIOLOGICAL SOLIDS
TOTAL COD
FILTRATE COD
FILTRATE BOD5
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
FEED SORBITOL
3000 mg/ℓ - 6 AM
500 mg/ℓ - 6 PM
FEED SORBITOL - 500 mg/ℓ
COD
SORBITOL COD (△)
CARBOHYDRATE (○)
BIOMASS
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
JUNE 20, 1977
INDICATED ANALYSIS, MG/L
TIME, DAYS
4000
3000
2000
1000
0
150
100
50
0
100
50
0
3600
3200
2800
2400
2000
2000
1600
1200
800
400
0
4
8
11
12
13
16
20
24
28
32
36
40
44

Within three hours after the shock, the reactor filtrate COD increased from 43 mg/l to 272 mg/l. Then the leakage gradually decreased to 43 mg/l within 12 hours. During these first 12 hours there was a significant leakage of sorbitol; the highest concentration recorded was 70 mg/l. The highest carbohydrate leakage was 48 mg/l. During the next cycle, leakage of soluble substrate from the reactor was decreased considerably. Also, there was no leakage of sorbitol this time. However, there was leakage of carbohydrate to the extent of 22 mg/l. But by day 14, soluble substrate exiting the reactor consisted of neither sorbitol nor carbohydrate. The COD leakage from the reactor attenuated considerably by day 15, but the pulsation in reactor COD is seen to exist even on day 15 not a decided peak such as existed earlier. The biomass concentration increased and decreased as the load was pulsed. Corresponding to the fluctuations in the reactor characteristics, there were fluctuations in the clarifier effluent characteristics. As the cycle was repeated, the leakage became attenuated. By day 16 (five days after administering the shock) the system almost came to a steady state condition. During day 42 (see Figure 19), frequent sampling was again made to check whether there was any cyclic leakage of substrate. No appreciable leakage was observed. The system had apparently come to a rather steady condition with respect to substrate. The steady state variation in the effluent filtration COD was as follows: the average peak and trough values in S_e were 37 and 21 mg/l. The post-shock steady state values spanned days 39 to 56. During this period, two samples were taken each 24 hours, and at the end of the high feed period (6 P.M.) and one at the end of the low feed period (6 A.M.), average effluent solids concentrations were 23 and 26 mg/l.

The average biomass concentration for high feed was 3160 mg/l, and for low feed was 2250 mg/l. The excess sludge production was 2531 for high feed, and 1331 for low feed. The statistical analysis for the combined data corresponding to high feed one and low feed one combined is also shown in Table V (see discussion). The combined averages of S_T, S_e, and X_e of the effluent were 43.1, 28.5, and 28.6 mg/l, respectively. The average excess sludge production was 1917 mg/day.

The biological constants for the system were determined on samples taken at 6 A.M. and 6 P.M. There was no appreciable difference in the biological constants between the two samples; the 6 A.M. sample gave μ_{max}, K_s, and Y_{t_B} values of 0.54 hr^{-1}, 185 mg/l, and 0.58, while for the 6 P.M. sample they were 0.56 hr^{-1}, 198 mg/l, and 0.54.

Cyclic 500 mg/l/3000 mg/l Sorbitol→ 500 mg/l Sorbitol, X_R = 10,000 mg/l

After operating in steady state under cyclic loading, the system was subjected to a shock by changing from cyclic to constant S_i of 500 mg/l sorbitol. As shown in Figure 20, there was not much disturbance in effluent quality, and this was due to higher suspended solids rather than to increase in filtrate COD. However, by day 14 there was a secondary response in which the effluent filtrate COD increased. The filtrate COD rose and ranged between 88 mg/l to 96 mg/l, then came down to 30 by day 31. By day 31, the effluent solids decreased to 24 mg/l. There was a change in species predominance indicated by a change in color of the biomass to somewhat whitish between day 22 to day 30. By day 31, the color changed to golden brown. The average steady state effluent total COD was 28 mg/l, filtrate COD was 20 mg/l, and suspended solids concentration was 15 mg/l. The average biomass concentration was 2234 mg/l; the excess sludge production was 1294 mg/l. The recycle sludge concentration was 10,189 mg/l; the filtrate BOD_5 was 2.4 mg/l. The biological constants, μ_{max}, K_s, and Y_{t_B} were 0.34 hr^{-1}, 174 mg/l, and 0.49.

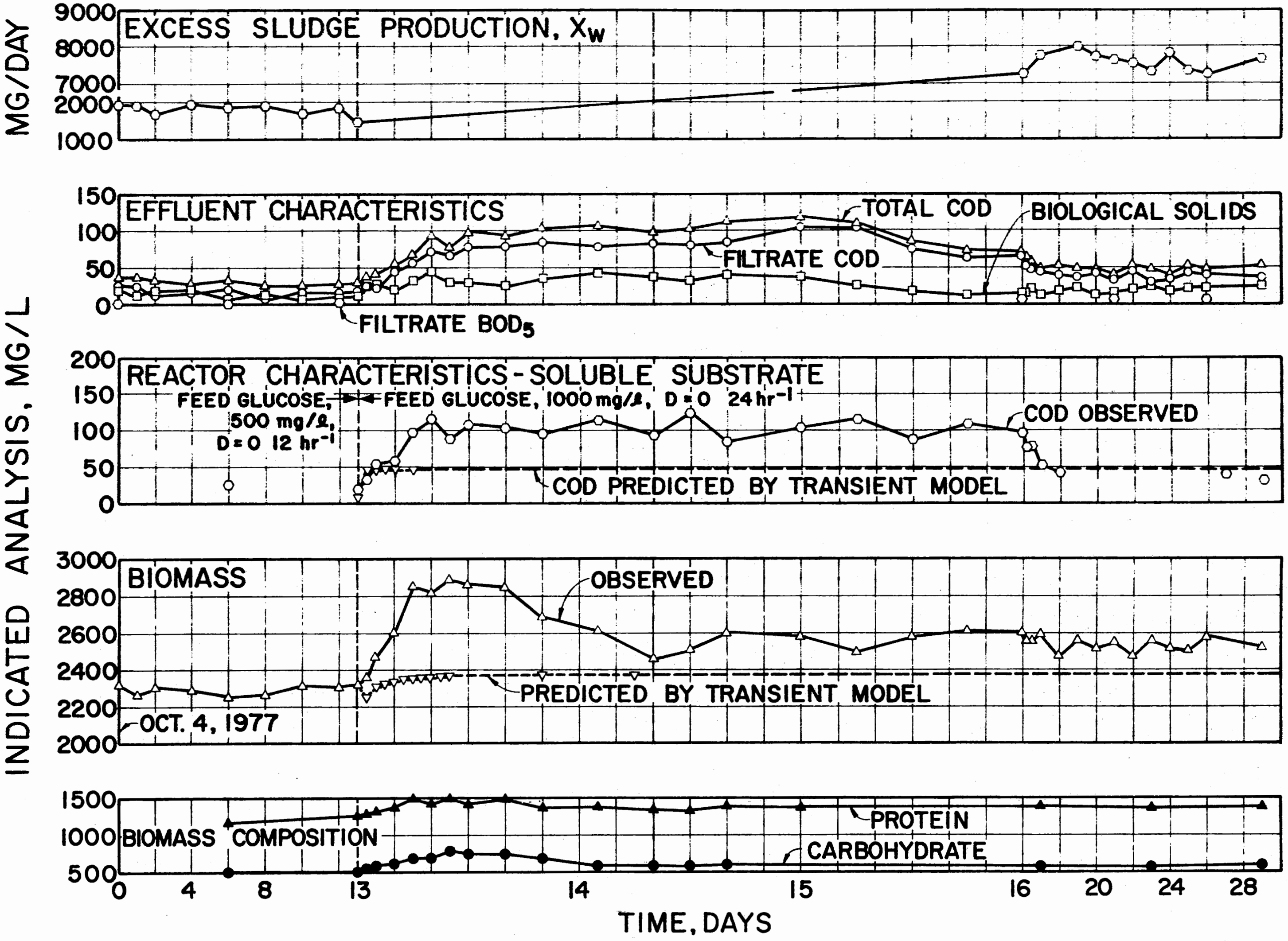
Combined Hydraulic and Quantitative Shock Loads

Four-fold Step Increase: 500 mg/l Glucose, $D = 0.12\ hr^{-1}$, $X_R = 10,000$ mg/l→1000 mg/l Glucose, $D = 0.24\ hr^{-1}$, $X_R = 10,000$ mg/l

After 13 days of steady state operation (from day 0 to day 12) at $S_i = 500$ mg/l glucose and $X_R = 10,000$ mg/l, an activated sludge system was subjected to a two-fold step increase in S_i as well as a two-fold increase in flow rate--thus the mass loading increased four-fold. In Figure 21 the time scale has been expanded from day 13 to day 15 to give a better idea about the transient behavior.

The biomass concentration in aerator 1 increased immediately in response to the shock, and reached a value of 2906 mg/l in the first 10 hours after the shock was applied. It stayed about the same for the next six hours and started to decrease and eventually reached an average value of 2549 mg/l. Inverted triangles connected by a dotted line represent the predicted biomass concentration in the reactor in response to the shock as proposed by Chen (59). It can be seen that the transient mathematical model did not predict the initial rise in solids very well. In regard to reactor characteristics, it can be seen that the filtrate COD exiting the reactor increased to 116 mg/l within eight

Figure 21. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l and an S_i of 500 mg/l Glucose Subjected to a Hydraulic and Quantitative Shock Loading by a Change in D and S_i From 0.12 to 0.24 hr^{-1} and From 500 mg/l Glucose to 1000 mg/ Glucose, Respectively


MG/DAY
9000
8000
7000
2000
1000
EXCESS SLUDGE PRODUCTION, X_W
INDICATED ANALYSIS, MG/L
150
100
50
0
EFFLUENT CHARACTERISTICS
TOTAL COD
BIOLOGICAL SOLIDS
FILTRATE COD
FILTRATE BOD_5
200
150
100
50
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
FEED GLUCOSE, 500 mg/ℓ, D = 0 12 hr^{-1}
FEED GLUCOSE, 1000 mg/ℓ, D = 0 24 hr^{-1}
COD OBSERVED
COD PREDICTED BY TRANSIENT MODEL
3000
2800
2600
2400
2200
2000
BIOMASS
OBSERVED
PREDICTED BY TRANSIENT MODEL
OCT. 4, 1977
1500
1000
500
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
0
4
8
13
14
15
16
20
24
28
TIME, DAYS

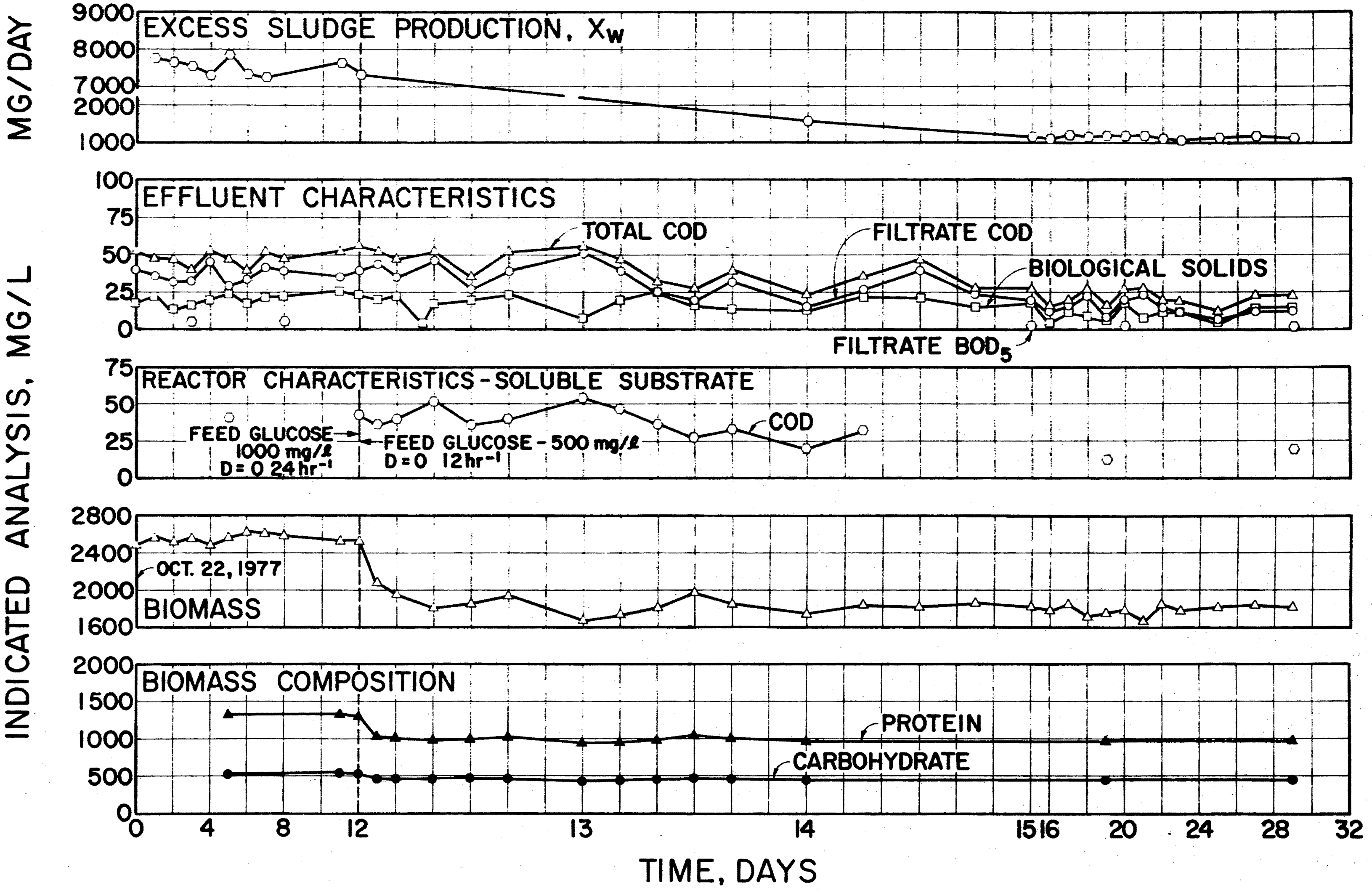
hours after the shock and stayed almost at that point until day 18. All clarifier effluent parameters increased and fluctuated during the period in which reactor filtrate was high. Filtrate COD leakage from the reactor ranged between 45 mg/l to 106 mg/l during transient, whereas the clarifier effluent filtrate COD ranged between 48 mg/l and 118 mg/l. The total effluent COD, S_T, ranged between 54 mg/l and 118 mg/l. There was not that much of an increase in the effluent solids during the transient state; they ranged between 20 mg/l and 42 mg/l. The post-shock steady state values were averaged from 18 to 29 days, and are shown in Table II. The average effluent parameters, S_T, S_e, and X_e during the steady state were 48 mg/l, 38 mg/l, and 20 mg/l. The effluent filtrate BOD_5 was 5.4 mg/l.

The protein and carbohydrate contents were 54 and 22.5 percent, respectively. The excess sludge production was on the average 7606 mg/day. The recycle sludge concentration was maintained at 10,211 mg/l.

Four-fold Step Decrease: 100 mg/l Glucose, $D = 0.24\ hr^{-1}$, $X_R = 10,000$ mg/l→500 mg/l Glucose, $D = 0.12\ hr^{-1}$, $X_R = 8000$ mg/l

After running the system in the new steady state for 12 days (from 0 to 11 days, the influent, S_i, was lowered to 500 mg/l and the flow rate was reduced by half in order to prepare the pilot plant for a next quantitative and hydraulic shock. The recycle sludge concentration, X_R, was also lowered simultaneously from 10,000 mg/l to 8000 mg/l. From Figure 22 and from the steady state parameters shown in Table II it is seen that there was not much of a disturbance in performance due to this change. The biomass concentration in the reactor dropped from 2520 mg/l

Figure 22. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l and an S_i of 1000 mg/l Glucose Subjected to a Hydraulic and Quantitative Shock Loading by a Change in D and S_i From 0.24 to 0.120 hr^{-1} and From 1000 mg/l Glucose to 500 mg/l Glucose, Respectively, With Simultaneous Change in X_R to 8000 mg/l

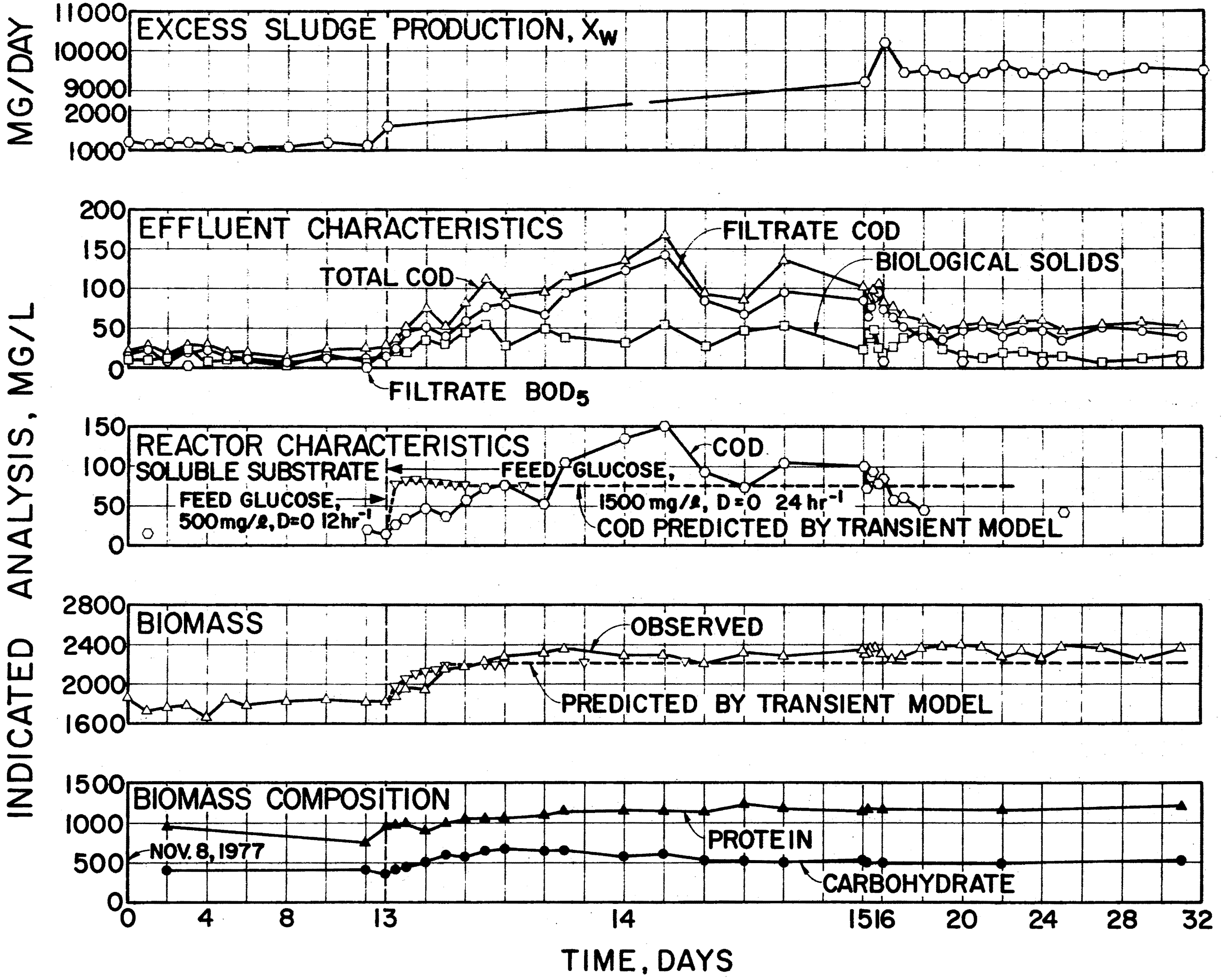

MG/DAY
9000
8000
7000
2000
1000
EXCESS SLUDGE PRODUCTION, X_W
INDICATED ANALYSIS, MG/L
100
75
50
25
0
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
75
50
25
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
FEED GLUCOSE 1000 mg/ℓ D = 0.24 hr⁻¹
FEED GLUCOSE - 500 mg/ℓ D = 0.12 hr⁻¹
COD
2800
2400
2000
1600
OCT. 22, 1977
BIOMASS
2000
1500
1000
500
0
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
0
4
8
12
13
14
15
16
20
24
28
32
TIME, DAYS

to 1680 mg/l during the transient in response to lowering of mass loading and recycle concentration. The average effluent parameters, S_T, S_e, and X_e, during steady state were 22 mg/l, 15 mg/l, and 12 mg/l (averaged from day 17 to day 29). Average biomass concentration during steady state was 1793 mg/l, and the percent protein and carbohydrate compositions were 54.3 and 22.9, respectively. The excess sludge production averaged 1148 mg/day, and the recycle sludge concentration was maintained at an average value of 8134 mg/l.

Six-fold Step Increase: 500 mg/l Glucose, $D = 0.12\ hr^{-1}$, $X_R = 8000$ mg/l→1500 mg/l Glucose, $D = 0.24\ hr^{-1}$, $X_R = 8000$ mg/l

After operating the system in steady state for 13 days (from day 0 to day 12) with $S_i = 500$ mg/l and $D = 0.12\ hr^{-1}$, it was subjected to a quantitative and hydraulic shock loading by increasing the S_i to 1500 mg/l and $D = 0.24\ hr^{-1}$. The behavior of the system is shown in Figure 23, and steady state parameters are shown in Table II. By looking at the events in the reactor, it is seen that there is greater leakage of soluble COD from the reactor compared to the previous quantitative and hydraulic shock load (Figure 22). There was an increase in COD from 20 mg/l to 48 mg/l in the first four hours followed by a decrease to 36 mg/l in the next two hours. This was again followed by another increase to 76 mg/l by a drop to 52 mg/l and another steep increase to 152 mg/l by the 28th hour after the shock. From these results it is evident that the system was undergoing a considerable disturbance due to the shock. However, there was not that much fluctuation in solids in the reactor. The biomass concentration rose from 1838 mg/l to 2346

Figure 23. Operational Characteristics for an Activated Sludge Process With Constant X_R of 8000 mg/l and an S_i of 500 mg/l Glucose Subjected to a Hydraulic and Quantitative Shock Loading by a Change in D and S_i From 0.120 to 0.24 hr^{-1} and From 500 mg/l Glucose to 1500 mg/l Glucose


EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
11000
10000
9000
2000
1000
EFFLUENT CHARACTERISTICS
FILTRATE COD
BIOLOGICAL SOLIDS
TOTAL COD
FILTRATE BOD_5
200
150
100
50
0
REACTOR CHARACTERISTICS
SOLUBLE SUBSTRATE
COD
FEED GLUCOSE, 500mg/ℓ, D=0 12hr^{-1}
FEED GLUCOSE, 1500 mg/ℓ, D=0 24 hr^{-1}
COD PREDICTED BY TRANSIENT MODEL
150
100
50
0
BIOMASS
OBSERVED
PREDICTED BY TRANSIENT MODEL
2800
2400
2000
1600
BIOMASS COMPOSITION
NOV. 8, 1977
PROTEIN
CARBOHYDRATE
1500
1000
500
0
INDICATED ANALYSIS, MG/L
0
4
8
13
14
15
16
20
24
28
32
TIME, DAYS

mg/l in the first 18 hours, and during steady state it averaged 2344 mg/l. The inverted triangles connected by dashed lines represent the predicted value of biomass and filtrate COD in the reactor according to the transient calculations of Chen. The prediction of biomass increase seems to be relatively better than in the previous case; however, there is a wide deviation between the observed and predicted filtrate in the reactor.

The variations in the reactor filtrate COD were reflected in the quality of the effluent exiting the settling tank (see Figure 23). All of the effluent parameters, S_T, S_e, and X_e, fluctuated greatly. The S_T value ranged between 36 mg/l to 136 mg/l, S_e between 24 mg/l and 146 mg/l, and X_e between 16 to 56 mg/l. The system came to a steady state by day 20. The steady state average values from day 18 to day 31 for S_T, S_e, and X_e were 55 mg/l, 44 mg/l, and 19 mg/l. The steady state biomass concentration averaged 2344 mg/l; protein and carbohydrate were 50.8 percent and 22.1 percent. During the transient, the rise in carbohydrate slightly outpaced the rise in protein and then decreased as protein concentration increased, indicating some evidence of oxidative assimilation. The excess sludge production averaged 1515 mg/l. The recycle sludge concentration was maintained at an average value of 8246 mg/l. During the latter part of the transient, microscopic observation indicated that filaments were increasing, and during the ensuing state, filaments greatly predominated. Protozoa were increasing; they were of a rather large size and very motile.

The biological constants, μ_{max}, K_s, and Y_{t_B}, during steady state were 0.57 hr^{-1}, 139 mg/l, and 0.55.

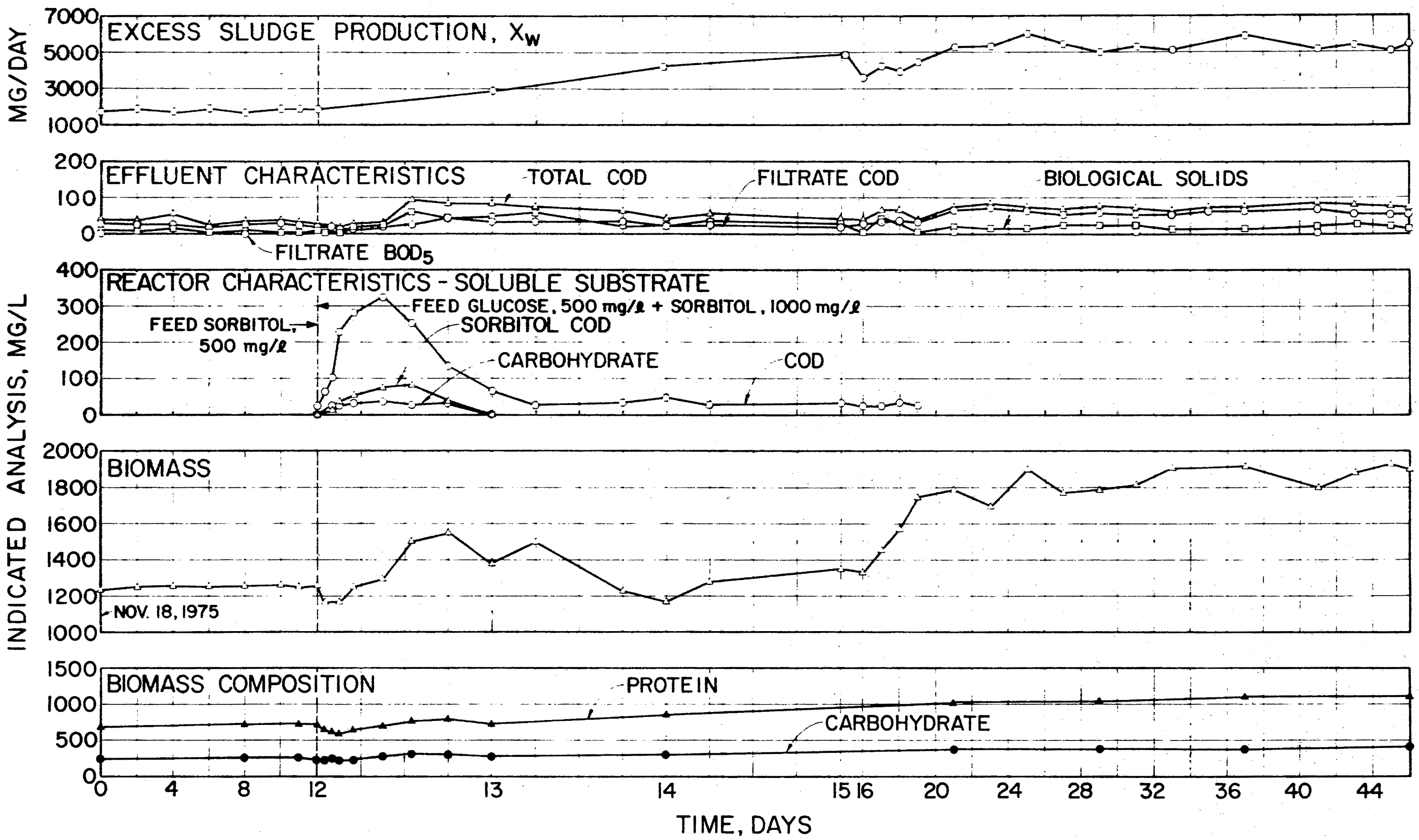
Qualitative and Quantitative Shock Loading

Three-fold Step Increase: 500 mg/l Sorbitol, X_R = 5000 mg/l→500 mg/l Glucose Plus 1000 mg/l Sorbitol, X_R = 5000 mg/l

A system was operated in steady state for 12 days (from day 0 to day 25, Figure 24) at S_i = 500 mg/l sorbitol with X_R = 5000 mg/l. On day 12, the system was subjected to a qualitative and quantitative shock loading by changing the influent substrate from 500 mg/l sorbitol to 500 mg/l glucose and 1000 mg/l sorbitol, as shown in Figure 24. The time scale was expanded during transient from day 12 to day 15. The pre-shock state effluent parameters, S_T, S_e, and X_e were averaged from day 0 to day 11 at 37 mg/l, 27 mg/l, and 7 mg/l, respectively. The effluent filtrate BOD_5 was 5.5 mg/l; the influent COD averaged 606 mg/l. The biomass concentration averaged 1250 mg/l, and the percent protein and carbohydrate compositions were 57.2 and 20.6, respectively. The excess sludge production was 1853 mg/day, and the recycle sludge concentration averaged 4861 mg/l.

After the shock was administered, there was a lag in the response of the biomass for five hours, and there was a drop in biomass concentration to 1164 mg/l from 1255 mg/l by the third hour. Five hours after the shock, the biomass responded and rose to 1550 mg/l by the 18th hour; however, the biomass concentration fluctuated until day 21. From day 21 it became nearly steady. In the reactor there was considerable leakage of soluble COD during the first 24 hours, and a maximum of 325 mg/l was observed nine hours after the shock. During this period, there was considerable leakage of both sorbitol and carbohydrate. The peak

Figure 24. Operational Characteristics for an Activated Sludge Process With Constant X_R of 5000 mg/l and an S_i 500 mg/l Sorbitol Subjected to a Quantitative and Qualitative Shock Loading by Changing the S_i to 500 mg/l Glucose + 1000 mg/l Sorbitol


EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
7000
5000
3000
1000
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
200
100
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
FEED SORBITOL, 500 mg/ℓ
FEED GLUCOSE, 500 mg/ℓ + SORBITOL, 1000 mg/ℓ
SORBITOL COD
CARBOHYDRATE
COD
400
300
200
100
0
BIOMASS
NOV. 18, 1975
2000
1800
1600
1400
1200
1000
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
1500
1000
500
0
INDICATED ANALYSIS, MG/L
0
4
8
12
13
14
15
16
20
24
28
32
36
40
44
TIME, DAYS

sorbitol leakage of 82 mg/l was observed at the thirteenth hour, and maximum carbohydrate leakage of 38 mg/l was observed at the ninth hour.

The transient response exhibited by the clarifier effluent was not as severe as that observed in the reactor. The attenuation of the leakage in the settling tank was due partly to the oversized clarifier and due partly to the continuation of metabolism in the clarifier. Nine hours after the shock, the effluent parameters, S_T, S_e, and X_e, increased. During the transient, S_T varied between 96 mg/l and 38 mg/l; S_e varied between 44 and 20 mg/l; X_e varied between 60 mg/l and 6 mg/l. A secondary response coincided with a change in predominating species. A filtrate COD, which stayed at 32 mg/l for seven days after the shock, began increasing to 69 mg/l on day nine, and total effluent COD increased correspondingly. The excess sludge production which was 1853 mg/day before the shock, increased to an average steady state value of 5577 mg/day. The system was adjudged to have come to a steady state approximately nine days after the shock.

The average biomass concentration during post-shock steady state was 1816 mg/l at an average from 46 days of steady state operation. Protein and carbohydrate compositions were 57.8 and 20.6, respectively. The effluent parameters, S_T, S_e, and X_e averaged 7 mg/l, 56 mg/l, and 21 mg/l. The effluent filtrate BOD_5 was 7.8 mg/l. The recycle sludge concentration was maintained at an average value of 5089 mg/l.

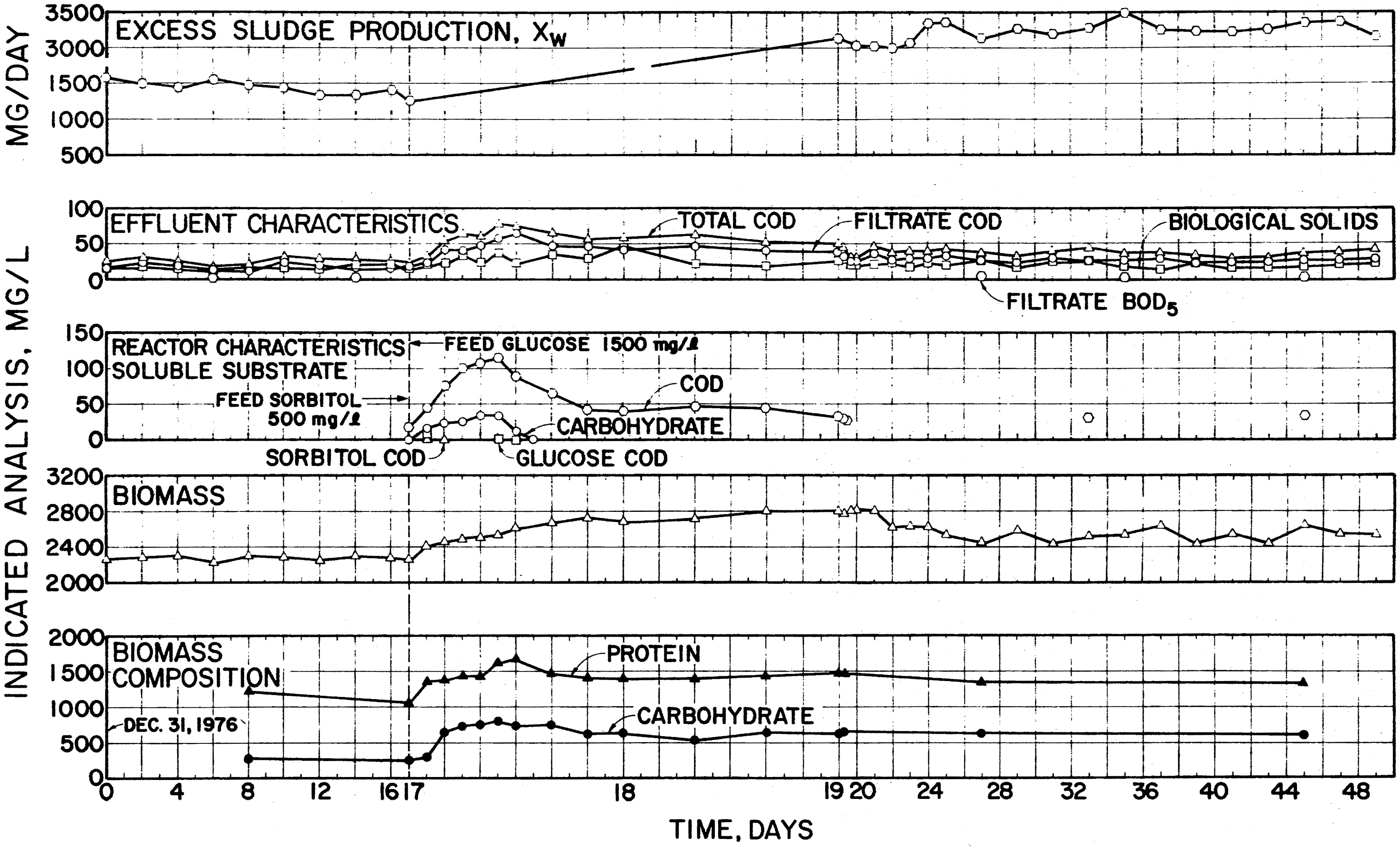
The biological constants, μ_{max}, K_s, and Y_{t_B}, were 0.52 hr^{-1}, 169 mg/l, and 0.59.

Three-fold Step Increase: 500 mg/l Sorbitol, X_R = 10,000 mg/l→1500 Glucose, X_R = 10,000 mg/l

A system was operated under steady state for 17 days (from day 0 to day 16) with an average S_i of 526 mg/l COD sorbitol (Figure 25). The steady state effluent parameters, S_T, S_e, and X_e, before shock averaged 26 mg/l, 18 mg/l, and 22 mg/l, respectively. The filtrate BOD_5 of the effluent was 3 mg/l. The biomass concentration in aerator 1 averaged 2274 mg/l. The protein and carbohydrate contents were 53.2 and 23.2 percent, respectively. The excess sludge production averaged 1461 mg/day, and the recycle sludge concentration was maintained at 10,238 mg/l.

The system was subjected to a shock by changing the influent, S_i, from 500 mg/l sorbitol to 1500 mg/l glucose, as shown in Figure 25. Even though glucose might be considered a more readily available substrate than sorbitol, the three-fold increase in S_i from 500 mg/l glucose to 1500 mg/l at X_R at X_R = 8000 reported by Saleh and Gaudy (37) gave much less soluble substrate leakage than that reported here. Thus this three-fold quantitative-qualitative shock led to a more deleterious leakage of substrate. There was considerable leakage of soluble COD from the reactor. The soluble COD increased from 18 mg/l to a peak value of 115 mg/l within ten hours after administering the shock, then there was a gradual reduction to a value of 26 mg/l 64 hours after the shock. The biomass also showed a rapid response and increased to 2732 mg/l within 20 hours. After day 21, there was a reduction in the biomass concentration in aerator 1, and during post-shock steady state, X

Figure 25. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l and an S_i of 500 mg/l Sorbitol Subjected to a Quantitative and Qualitative Shock Loading by Changing the S_i to 1500 mg/l Glucose


EXCESS SLUDGE PRODUCTION, X_W
MG/DAY
3500
3000
1500
1000
500
EFFLUENT CHARACTERISTICS
TOTAL COD
FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
100
50
0
REACTOR CHARACTERISTICS
SOLUBLE SUBSTRATE
FEED GLUCOSE 1500 mg/ℓ
FEED SORBITOL 500 mg/ℓ
COD
CARBOHYDRATE
SORBITOL COD
GLUCOSE COD
150
100
50
0
BIOMASS
3200
2800
2400
2000
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
DEC. 31, 1976
2000
1500
1000
500
0
INDICATED ANALYSIS, MG/L
0
4
8
12
16
17
18
19
20
24
28
32
36
40
44
48
TIME, DAYS

averaged 2530 mg/l. The protein and carbohydrate rose together, and in the new steady state they averaged 52.8 percent and 24.4 percent, respectively.

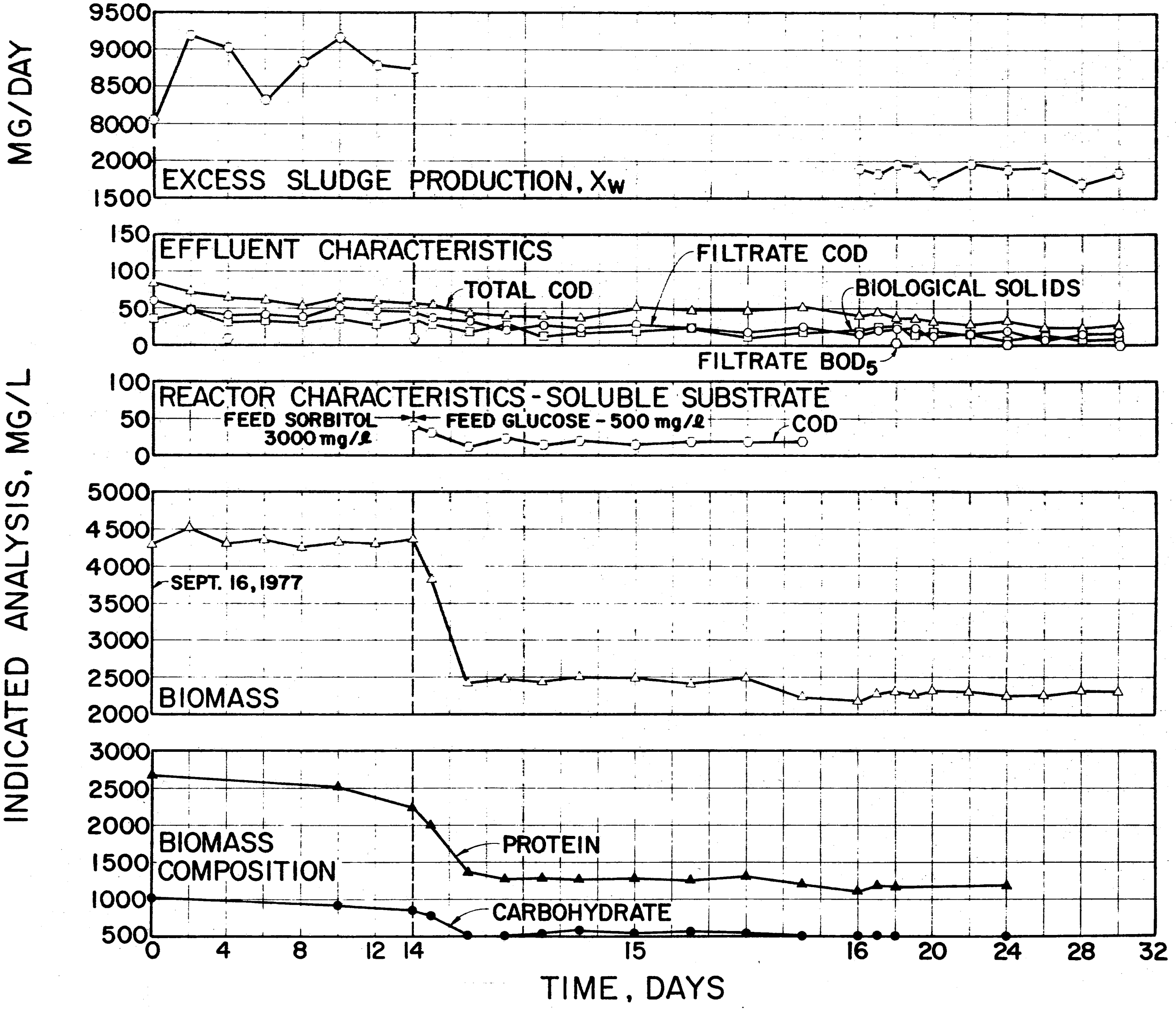
The fluctuations in the soluble COD effluent quality were similar to those in the reactor clarifier, but they were less severe; i.e., the clarifier helped to attenuate the leakage. During the transient, effluent S_T ranged from 30 mg/l to 77 mg/l, and S_e ranged from 22 mg/l to 68 mg/l; X_e varied from 18 mg/l to 40 mg/l. The system came to a steady state by day 24. The biomass composition in aerator 1 averaged 2530 mg/l; the protein and carbohydrate contents were 52.8 mg/l and 24.4 mg/l. respectively. The range of effluent parameters, S_T, S_e, and X_e, were 30-44 mg/l, 24-32 mg/l, and 14-28 mg/l. The steady state period spanned day 24 to day 49. The average steady state effluent parameters, S_T, S_e, and X_e, were 37 mg/l, 28 mg/l, and 21 mg/l; the average effluent filtrate BOD_5 was 4.1 mg/l. The excess sludge production average to 3262 mg/day and the recycle sludge concentration was maintained on average at 10,348 mg/l. During post-shock steady state, the biological constants, μ_{max}, K_s, and Y_{t_B}, were 0.46 hr^{-1}, 279 mg/l, and 0.61.

Six-fold Decrease: S_i = 3000 mg/l Sorbitol, X_R = 15,000 mg/l→500 mg/l Glucose, X_R = 10,000 mg/l

A system was operated under steady state for 14 days with an average influent substrate concentration of 3080 mg/l sorbitol (Figure 26). The recycle sludge concentration was maintained at 15,025 mg/l; the steady state parameters were averaged from day 0 to day 14. The excess sludge production averaged 8753 mg/day. The effluent parameters, S_T,

S_e, and X_e, averaged 64 mg/l, 46 mg/l, and 34 mg/l. The effluent filtrate BOD_5 was 8.5 mg/l; the biomass concentration averaged 4338 mg/l. The protein and carbohydrate contents were 58.9 and 22.1 percent, respectively. The reactor filtrate COD was almost the same as the filtrate COD of the effluent during steady state. The system was subjected to a shock on day 14 by changing influent substrate concentration from 3000 mg/l to 500 mg/l, and changing the substrate from sorbitol to glucose simultaneously. The recycle sludge concentration was reduced from 15,000 mg/l to 10,000 mg/l. There were no adverse effects, as can be seen in Figure 26. The effluent quality was improved in the post-steady state. Due to the reduction in substrate concentration and due partly to the reduction in recycle sludge concentration, the biomass concentration in aerator 1 decreased from 4364 mg/l to 2432 mg/l within 14 hours after the shock. The protein and carbohydrate concentrations were correspondingly reduced. The reactor filtrate COD decreased from 40 mg/l to 12 mg/l within six hours after the shock, and thereafter ranged from 12 mg/l to 24 mg/l. The post-shock steady state values were averaged from day 19 to day 31. The steady state effluent parameters, S_T, S_e, and X_e, averaged 30 mg/l, 17 mg/l, and 13 mg/l, respectively. The BOD_5 effluent filtrate was 2.0 mg/l; the biomass concentration in aerator 1 averaged 2288 mg/l. Protein and carbohydrate contents of the biomass were 52.6 and 22.5 percent. The excess sludge production averaged 1855 mg/day, and the recycle sludge concentration averaged 10,120 mg/l. The biological constants, μ_{max}, K_s, and Y_{t_B}, during post-shock steady state were 0.39 hr^{-1}, 257 mg/l, and 0.49.

Figure 26. Operational Characteristics for an Activated Sludge Process With a Constant X_R of 15,000 mg/l and an S_i of 3000 mg/l Sorbitol Subjected to a Quantitative and Qualitative Shock Loading by Changing the S_i to 500 mg/l Glucose With Simultaneous Change in X_R to 10,000 mg/l


MG/DAY
9500
9000
8500
8000
2000
1500
EXCESS SLUDGE PRODUCTION, X_W
150
100
50
0
EFFLUENT CHARACTERISTICS
FILTRATE COD
TOTAL COD
BIOLOGICAL SOLIDS
FILTRATE BOD_5
100
50
0
REACTOR CHARACTERISTICS - SOLUBLE SUBSTRATE
FEED SORBITOL 3000 mg/ℓ
FEED GLUCOSE - 500 mg/ℓ
COD
INDICATED ANALYSIS, MG/L
5000
4500
4000
3500
3000
2500
2000
SEPT. 16, 1977
BIOMASS
3000
2500
2000
1500
1000
500
BIOMASS COMPOSITION
PROTEIN
CARBOHYDRATE
0
4
8
12
14
15
16
20
24
28
32
TIME, DAYS

CHAPTER IV

DISCUSSION

Shock Loads

The purpose of this research was mainly to study the effect of various shock loads (quantitative, qualitative, and hydraulic shock in combination, as well as individually) on an activated sludge process operated with constant concentration of recycle sludge as a control parameter. In addition, a secondary aim was to explore the effects of recycle sludge concentration on the ability of the system to take certain kinds of shock.

One type of shock studied was qualitative shock. These shocks consisted of a switchover from glucose to sorbitol, or from soribtol to glucose, or to a combination of glucose and sorbitol. The qualitative shock load experiments were conducted with only one recycle sludge concentration, 5000 mg/l. This type of shock was applied to find the amount of leakage caused by changes in chemical composition of the carbon source.

Another type of shock studied was the quantitative shock consisting of a step increase in influent substrate concentration. The same degree of quantitative shock was applied with two different recycle sludge concentrations to determine whether higher concentration of return sludge helped to attenuate any ill effects of such shock.

A third mode of shock load investigated was cyclic shock as compared to a single step change. The purpose of this type of study was to determine whether repetition of a shock in a cyclic manner would cause a new steady state in effluent quality or a permanent cycling in effluent quality.

A fourth type of shock studied was a combined qualitative and quantitative shock load. An experimental matrix of shock was not planned for this type, but one came about as a consequence of running the previously described shock loading experiments.

Qualitative Shock Loading

Results of the qualitative shock loads are shown in Figures 4 through 8. Even a change from 500 mg/l glucose to 500 mg/l sorbitol gave a considerable although short-term leakage of substrate from the reactor (Figure 4). In this case the biomass had not been exposed to the sorbitol earlier, and it is apparent that it needed some time for acclimation. However, the leakage shown in the reactor did not pass through to the clarifier effluent. This was due partially to the oversized clarifier which had a detention time of 17 hours, depending upon the dilution rate employed. The clarifier not only acted as a surge tank, but it also permitted continuation of metabolism of substrate carried over from the reactor. The effect of an oversized clarifier is discussed in detail later. It is also interesting to note that the COD leakage from the reactor did not contain the original substrate. This indicates that the biomass was capable of dissimilating the sorbitol but could not convert the carbon source to final end products. The observations made here during step change change from 500 mg/l glucose to 500 mg/l sorbitol were made repeatedly in the subsequent experiments.

It was expected that equal concentrations of glucose or sorbitol would not necessarily yield the same residual COD. In the case of sorbitol, the effluent filtrate COD was 6 mg/l whereas for glucose it was 21 mg/l during the steady state. However, in subsequent experiments for the same influent substrate concentration of 500 mg/l sorbitol, the effluent COD was never again close to 6 mg/l; rather, it was approximately 20 mg/l. The biological constants were not the same before and after the shock. The biokinetic constants μ_{max}, K_s, and Y_{r_B} during preshock steady state at S_i = 500 mg/l glucose were 0.53 hr^{-1}, 239 mg/l and 0.56, whereas during the post-steady state at S_i = 500 mg/l sorbitol, the biological constants were 0.42, 189, and 0.61, respectively (see Table III). Compared to this shock, a change in substrate concentration from 500 mg/l glucose plus 1000 mg/l sorbitol to 1000 mg/l glucose plus 500 mg/l sorbitol led to leakage of more soluble COD from reactor 1. During the earlier period, sorbitol and glucose leakage was observed. Also, as shown in Figure 6, during the shock consisting of 1000 mg/l glucose plus 500 mg/l sorbitol, growth was partially curtailed during the early phases of substrate leakage, as evidenced by the decrease in biomass concentration in aerator 1. This seems to have been due to the presence of the higher concentration of glucose in the feed. Experiments conducted by Gaudy and Komolrit also revealed that glucose blocks the metabolism of sorbitol (20). However, it was also observed by Gaudy and Komolrit that for heterogeneous populations after acclimation to sorbitol and glucose, metabolism of both substrates was carried out simultaneously for more slowly growing, i.e., higher cell age, cells (21). When the system was subjected to a shock from 1000 mg/l glucose plus 500 mg/l sorbitol to 1500 mg/l glucose alone, there was no significant leakage (Figure 7). It seems that for the same organic loading a changeover to glucose from sorbitol plus glucose is easily accommodated without leakage of carbon source. Such a result is reasonable in view of the ready metabolic availability of glucose.

When one examines like organic loadings of 1500 mg/l, it is found that for the steady state condition the excess sludge production for 500 mg/l glucose plus 1000 mg/l sorbitol, feed was 5577 mg/day; for 1000 mg/l glucose plus 500 mg/l sorbitol, it was 4339 mg/day, and when the feed was comprised of only 1500 mg/l glucose, the excess sludge production was 3795 mg/day. Correspondingly, the biological solids concentration in the reactor was higher in the first instance and lower in the latter case. The main reason seems to have been due to selection of predominating species caused by the different substrates. The corresponding net specific growth rates, μ_n, were 1.6, 1.4, and 1.3 day^{-1}, and corresponding observed yields, Y_0, were 0.58, 0.51, and 0.46, respectively. Thus, a change in predominance was apparently reflected in changes in growth rate causing changes in X and μ_n for the same organic loadings. Further, as discussed later, the decay coefficient, K_d, for glucose was 0.18 day^{-1}, and for sorbitol it was 0.1 day^{-1}. This could also have been responsible for reduction in excess sludge production and biomass concentration in aerator 1 when the organic loading was comprised only of glucose, since specific growth rates in both cases were rather low. While running the batch growth studies with combined substrate, glucose:sorbitol 1:2 and 2:1, there was some slight indication of diauxic growth even though it was not very marked. The Y_{t_B} values were 0.53 and 0.54, respectively, for the combined substrates.

Thus, there was not much variation in yield from that which had been observed in the past for either glucose or sorbitol (60). The leakage from the reactor did not show up in the effluent from the clarifier; thus there is further indication that the oversized clarifier attenuated the effects of the shock and permitted reaction time for metabolism for substrate and for intermediates. This was also evident in subsequent shock loads in this research as well as in the previous experiments of Saleh and Gaudy (37).

Quantitative Shock Loading

Results for quantitative shock loads are shown in Figures 9 through 16. Figures 9 and 14 are of particular interest. Figure 9 showed the response of the system to a six-fold quantitative shock accomplished by changing the substrate concentration from 500 mg/l sorbitol to 3000 mg/l sorbitol with a recycled sludge concentration of 5000 mg/l. The peak leakage in the reactor, 442 mg/l COD, occurred at the sixth hour after application of the shock, and for about six hours it varied between 214 mg/l and 442 mg/l, whereas for the same six-fold shock with a return sludge concentration of 10,000 mg/l, the peak leakage from aerator 1 was 205 mg/l COD. The peak occurred eleven hours after application of the shock. The leakage ranged between 124 and 205 mg/l for seven hours during the peak period. This result clearly shows an attenuation effect of increased recycle sludge concentration. Furthermore, during the first six hours after application of the shock, the leakage was very small, varying between 12 and 56 mg/l. It is not clear why this delay in substrate leakage occurred. In both cases the COD leakage in the effluent was much lower than the COD entering the settling tank. Again, it is clear that the oversized clarifier assisted in attenuating substrate leakage from the overall system. As shown in Figure 9, there were large amounts of sorbitol and carbohydrate leakage from aerator 1. The maximum leakage of sorbitol was 52 mg/l and the maximum leakage of carbohydrate was 74 mg/l. Compared to this, the leakage at X_R = 10,000 mg/l was lower. The sorbitol leakage was 42 mg/l, whereas carbohydrate was 68 mg/l. In both cases the disruption in effluent quality was rather severe. This was due partly to an increase in effluent filtrate COD and due partly to an increase in the suspended solids concentration in the effluent. Microscopic observations indicated that the increase in solids concentration correlated with the disappearance of protozoa during the transient phase. Previous investigations conducted by Saleh and Gaudy for a six-fold step increase using glucose as substrate with X_R = 8000 mg/l showed a similar response (37). The effluent COD in the post-shock steady state was much higher than in the pre-shock condition, as shown in Table II. This is due partly to the increased residual COD at higher influent substrate concentration which is generally noted when using COD as a measure of S. Also, the specific growth rate was higher due to increased S_i. These aspects will be discussed more fully in a subsection dealing with the steady state operation.

Concerning the biomass, in both shocks the biomass showed a rapid response. The increase in biological solids concentration was in direct response to the increase in substrate concentration. It is interesting to note that the protein and carbohydrate contents showed more or less the same rate of increase; that is to say there was no evidence of oxidative assimilation of carbon source into carbohydrate storage products.

Krishnan and Gaudy (61) in investigations employing both once-through and cell recycle systems noted the same trend; however, some experiments conducted by Saleh and Gaudy have shown that carbohydrate content of the biomass increased more rapidly than protein in the early stages of the response (37). Thus, there would not appear to be any particular operational mode or range of specific growth rates which can act as a guide as to whether the oxidative assimilation response will occur as the first response to an increase in S_i.

At a later stage of the transient response there was a drop in carbohydrate content and an increase in protein content, indicating that oxidative assimilation was playing a major role in substrate removal during the transient period. It is not known if the relative values of the Monod constants could exert an effect on the occurrence of an early oxidative assimilation response. In the experiments carried out by Saleh and Gaudy (37), the μ_{max} and K_s values determined in batch growth studies were 0.61 hr^{-1} and 87 mg/l; in the present study, μ_{max} was 0.47 hr^{-1} and K_s was 279 mg/l. It might be argued that a biomass with low K_s value has a higher affinity for substrate. Converting the substrate to storage products may be relatively easier for organisms with low K_s compared to those with the higher K_s. Thus, a higher μ_{max} and lower K_s might have enabled faster uptake of substrate, leading to oxidative assimilation. The basic assumption here is that cells which can grow the most rapidly may do so by dint of the fact that they can capture substrate and retain it as stored carbon more rapidly than they can channel it into protein and nucleic acid synthesis.

In order to prepare the system for the shocks discussed above, it was subjected to the step-down quantitative shocks which were shown in

Figures 10 and 11; S_i was decreased from 3000 mg/l to 500 mg/l at X_R = 5000 mg/l, and in Figure 15 a similar step-down was made for a system operating with X_R = 10,000 mg/l. As expected, these step-downs did not cause any appreciable disturbance to the system.

Figure 12 showed results when X_R was stepped upward from 5000 mg/l to 10,000 mg/l with S_i remaining at 500 mg/l. There was no appreciable change in the system performance during the transient period except for a small short-lived leakage of soluble COD from aerator 1. Y. K. Chen, a colleague in the OSU bioenvironmental engineering laboratories, integrated the steady state model equations for the transient state response in S_e and X (59). Writing a mass balance around the reactor, the following expressions were obtained:

$$\frac{dx}{dt} V = FX_R + XV - k_d XV - (1 + \alpha)FX \qquad (2)$$

$$\frac{dS}{dt} V = FS_i - \frac{X}{Y} V - (1 + \alpha)FS \qquad (3)$$

Using Monod's equation for μ and integrating the above equations, the following expressions for transient conditions were obtained by Chen:

$$X_{(t)} = \frac{\alpha D X_R}{D(1 + \alpha) - \mu + k_d} + \left[X_{(o)} - \frac{\alpha D X_R}{D(1 + \alpha) - \mu + k_d} \right] \exp \left[\mu - k_d - D(1 + \alpha) \right] t \qquad (4)$$

$$S_{e(t)} = S_{(o)} \exp - \left[D(1 + \alpha) + \frac{\mu_{max} X}{Y\left(K_s + S\right)} \right] t$$

$$+ \frac{DS_i}{D(1 + \alpha) + \frac{\mu_{max} X}{Y\left(K_s + S\right)}} \left[1 - \exp - \left\{ D(1 + \alpha) + \frac{\mu_{max} X}{Y\left(K_s + S\right)} \right\} t \right] \quad (5)$$

where

$X_{(o)}$ = biological solids concentration at steady state

$S_{(o)}$ = effluent substrate concentration in steady state prior to the step change

S_i = transient influent substrate concentration

$S_{e(t)}$ = effluent substrate concentration at time t

In the derivation of the above equations, the following assumptions were made:

1) Cell yield is constant
2) μ varies instantaneously with change in S
3) k_d, μ_{max}, K_s, D, α, and X_R are all constant throughout the transient

When the transient equations were used to predict the transient substrate leakage and biomass response of systems subjected to quantitative shock loads and combined quantitative and hydraulic shock loads, the predicted values did not come very close to the observed values. Part of the reason could have been due to the changes in predominance of species, changes in biological constants, etc., as well as production of metabolic intermediates, all of which are not taken into account in the models because of practical as well as theoretical difficulties in determining and incorporating functions for the above mentioned factors into a model.

Cyclic Shock Loads

The purpose of this study was to find whether the substrate leakage oscillates continuously in response to a changing S_i or if, in time, the oscillation becomes attenuated if the cycle is maintained. As with the other shock loadings, the interest was in examining the stability of the model. When the cyclic shock, consisting of a six-fold quantitative increase, was applied to the system (Figures 17, 18, and 19), the initial leakage from aerator 1 with respect to sorbitol COD, carbohydrate, and soluble COD, resembled the six-fold step increase with sorbitol at X_R = 10,000 mg/l, shown in Figure 14. As the cycle was repeated for a prolonged period, the peak soluble COD in the reactor was lowered considerably. In point of fact, while the system continued to oscillate slightly with respect to soluble COD, it appeared to approach a pseudo-steady state. Calculation of the average of all of the small peaks after day 45 shows that the average soluble COD was as low as that obtained at a steady loading of 3000 mg/l S_i. Analyses of values for the troughs in the cycle show that the soluble COD was as low as the steady loading at 500 mg/l S_i. Thus, oscillation of the load did not lead to excessive oscillation in the effluent. The response observed here was similar to that observed by Saleh and Gaudy for a six-fold quantitative cyclic shock with glucose (37). These results also show that an activated sludge system operated with constant sludge recycle can withstand a severe six-fold quantitative cyclic shock.

After the fourth cycle, original substrate did not leak from the reactor at all, and soluble COD consisted of metabolic intermediates and/or end products. In time, the clarifier effluent also exhibited steadiness with respect to total COD, soluble COD, and solids in the clarifier effluent under the severe increase and decrease in S_i.

Combined Quantitative and Hydraulic Shock Loads

This type of shock was applied to determine the stability of the system under a combined shock as well as to find the predictability of the steady state parameters using the model equations. Herein an attempt is also made to compare the observed transient COD and biomass in aerator 1 with that predicted by the transient state equation suggested by Chen (59).

Figure 21 showed the response of the system when subjected to a two-fold quantitative and two-fold hydraulic shock with $X_R = 10{,}000$ mg/l. From the point of view of mass organic loading, it is equivalent to a four-fold hydraulic loading or a four-fold quantitative shock loading.

In the case of a purely hydraulic shock loading it was noted by Saleh that an initial washout of biological solids is followed by an increase in the biomass concentration (39). Hydraulic shock did not result in much difference between pre-shock and post-shock steady state biomass concentration at the relatively low rates employed. In the present study it would appear from the results shown in Figures 21 and 23 that the combination of increased S_i and increase in D seemed to cancel out the drop in biological solids concentration observed in Saleh's experiment (39). This could have been due to the fact that S_i tends to increase the biomass concentration and the increase in D from 0.12 to 0.24 hr^{-1} tended to lower the concentration initially. The combined quantitative and hydraulic shock load gave a slightly more adverse effect with respect to both the reactor and the clarifier effluent quality than a hydraulic shock of equivalent mass organic loading conducted by Saleh (39).

In Figure 23 the response of a system subjected to a combined quantitative (three-fold) and hydraulic (two-fold) shock at $X_R = 8000$ mg/l was shown. This shock is equivalent in mass loading to a six-fold quantitative shock. For the combined shock load, the peak leakage in the reactor reached 152 mg/l COD and in the effluent 146 mg/l COD was registered, whereas for a straight six-fold quantitative shock it has been reported by Saleh that the peak leakage of substrate in the effluent was 106 mg/l COD. However, when the same shock load was repeated by Saleh (39), there was a peak leakage of 512 mg/l COD from the reactor and 292 mg/l in the clarifier effluent. Thus, from the scant amount of data which are currently available on this type of combined step increase, it seems that a combined quantitative and hydraulic shock can be expected to be as deleterious as an equivalent (mass feed rate) quantitative shock.

During the current study, the combined quantitative (two-fold) and hydraulic (two-fold) shock caused a peak substrate leakage from the reactor of 124 mg/l COD and in the clarifier effluent, 118 mg/l soluble COD. Two equivalent hydraulic shock loading experiments consisting of a four-fold increase reported by Saleh (39) gave a peak substrate leakage of 114 mg/l in the reactor and 40 mg/l in the effluent in one experiment and 34 mg/l in the effluent in another experiment.

The transient equation developed by Chen (59) did not give a satisfactory prediction of the response. There were rather large differences between the COD observed and the COD predicted. It would seem that the prediction equations need to undergo much improvement and inclusion of factors accounting for production of metabolic end products, etc. Such improvements in modeling and predicting transient response will in all likelihood not be developed in the near future. The difficulties of modeling responses are many, and the importance of obtaining a bank of experimental results on various magnitudes of shock response is emphasized since these may be used to help determine, empirically, the magnitude of shock from which treatment plants must be protected.

The protein and carbohydrate content increased simultaneously in response to the shock in both the combined shock experiments, indicating that the response was a balanced one not involving the rapid formation of metabolic storage products. Thus, future modeling factors might omit storage functions and emphasize development of possible methods of handling the elaboration of metabolic intermediates. However, the oxidative assimilation capability (storage capability) is sometimes observed. The relative frequency of its occurrence and the factors determining its existence in any particular system cannot be determined with any certainty, and these would appear to be good subjects for further experimentation.

As has been observed by Krishnan and Gaudy in other studies, a step-down shock did not cause any deleterious effects (61). In the current study, a step-down quantitative shock accompanied by a step-down hydraulic shock, did not cause any significant leakage of COD.

Quantitative and Qualitative Shock Loads

These shocks were done as subsidiary experiments while preparing the system for other types of shock loads. The results are shown in Figures 24 through 26. As shown in Figure 24, when the system was subjected to a change of substrate from 500 mg/l sorbitol to 500 mg/l glucose + 1000 mg/l sorbitol at X_R = 5000 mg/l, there was a considerable leakage of soluble COD from the aeration tank. The leakage was comprised partly of sorbitol and of carbohydrate. This leakage seems to have been due partly to interference with sorbitol metabolism by the presence of glucose; however, after approximately ten hours the heterogeneous biomass was capable of removing both sorbitol and glucose concurrently. Similar observations were made by Komolrit and Gaudy (21) in more rapidly growing systems. In a batch unit, Su found that sorbitol-acclimated cells were capable of removing both glucose and sorbitol when a mixture of glucose, galactose, sorbitol, and xylose was fed (33).

As evidenced in previous experiments, the leakage from the clarifier was considerably lower than the amount of COD entering from reactor 1, again substantiating the action of a clarifier as a bioreactor.

The shock applied in Figure 25 was of the same magnitude in regard to organic loading as that shown in Figure 24, but in this case the change was from 500 mg/l sorbitol to 1500 mg/l glucose. Here the question of interference with sorbitol metabolism by glucose does not arise. Furthermore, the leakage is comparatively less than for the previous case. The leakage of substrate is due mainly to the increase in S_i rather than to a change in type of substrate. It is also interesting to note that initially the rise in carbohydrate content outpaced the rise in protein. At a later stage, protein conent showed a rise and carbohydrate content decreased. This result provides some evidence for synthesis of carbohydrate storage products which were later reduced to support the protein synthesis.

In general, in all of the shock load experiments it was found that the higher the recycle sludge concentration, the better was the response. Reasons for this are not all-together clear. However, any increase in biomass is expected to increase the fraction of cells in the biomass which could provide successful response. Also, the decrease in growth rate caused by higher concentration of X_R could be a major reason for more successful response. However, just why a slower growth rate should cause a more favorable response is not clear.

Effects of X_R on Shock Load Response

Regardless of the type of shock load, the effect of increasing X_R in attenuating the substrate leakage during the transient response was evident. To demonstrate this effect, two typical quantitative shock load responses to a six-fold step increase in S_i at X_R values of 5000 mg/l and 10,000 mg/l (shown in Figures 9 and 14) are chosen for more detailed analysis here. The reactor filtrate COD and effluent filtrate COD shown in those figures are redrawn in Figures 27 and 28 in an enlarged scale. The closed triangles in Figures 27 and 28 represent the observed substrate leakage from the reactor during the transient response. When the system was operating at X_R = 5000 mg/l, the peak leakage was 442 mg/l, and it was 205 mg/l at X_R = 10,000 mg/l,

Figure 27. Magnitude of Leakage of Soluble Organic Material in Reactor and Clarifier During a Six-fold Quantitative Shock Loading at an X_R of 5000 mg/l (data from transient phase of Figure 9)

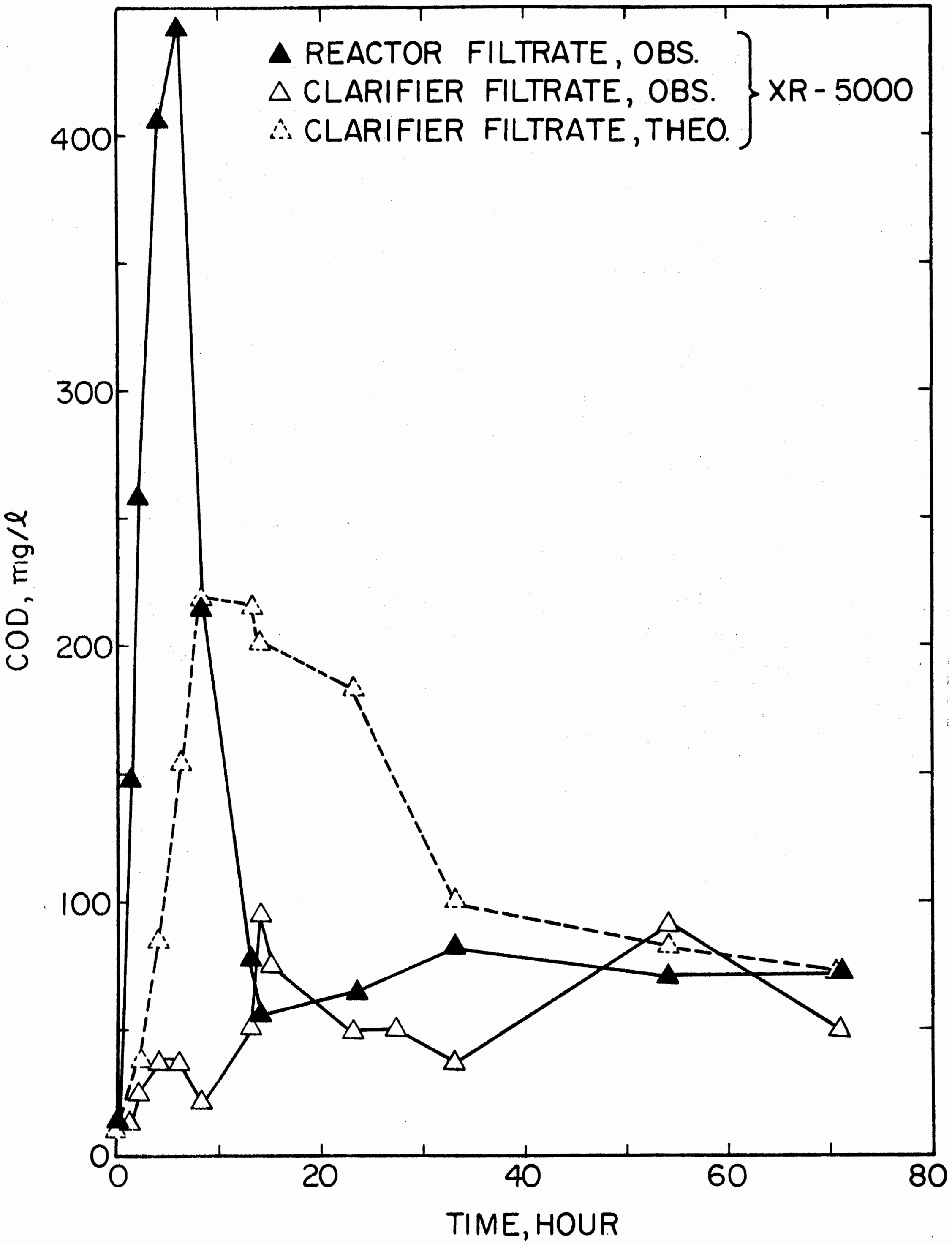
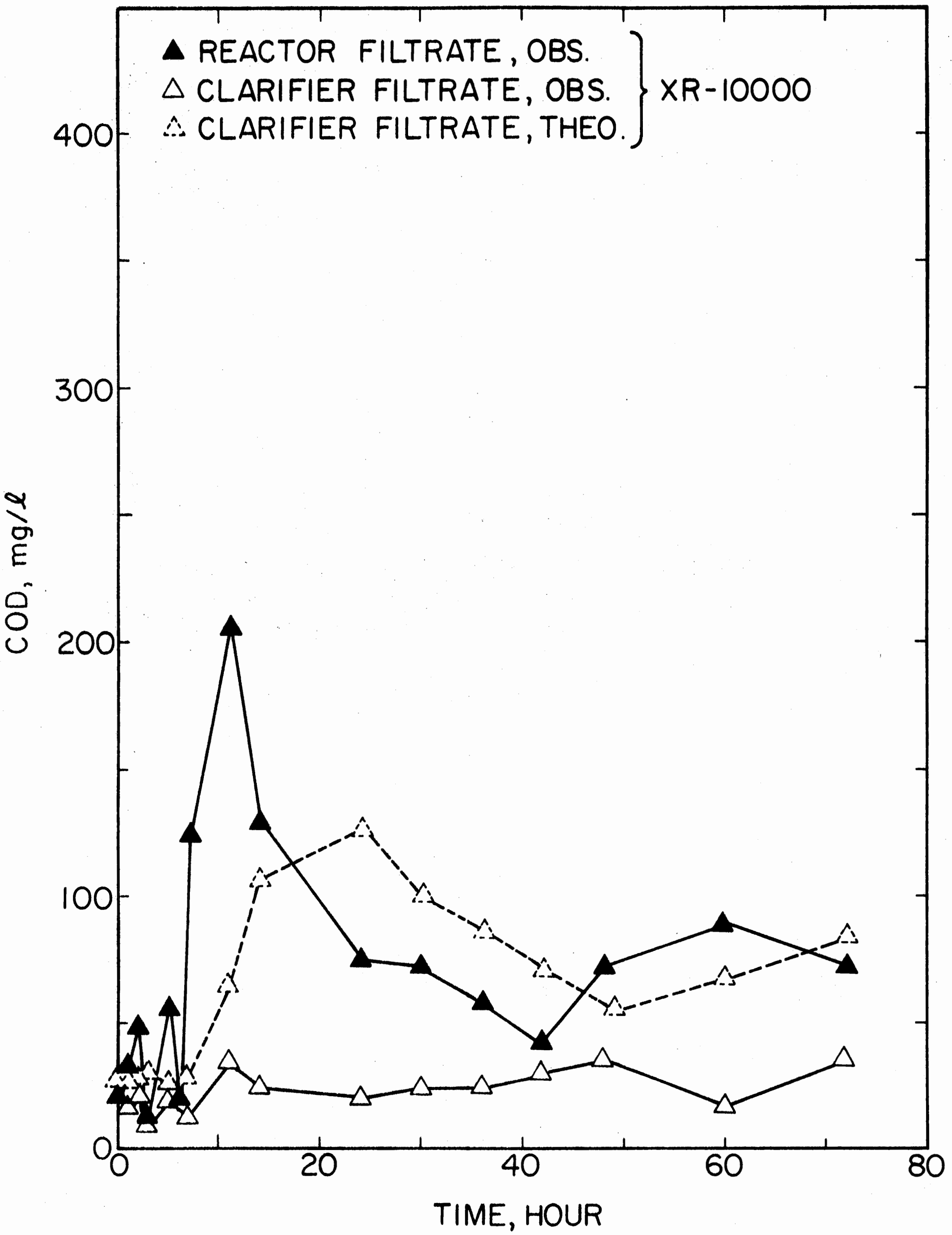

▲ REACTOR FILTRATE, OBS.
△ CLARIFIER FILTRATE, OBS.
△ CLARIFIER FILTRATE, THEO.
XR - 5000
COD, mg/ℓ
0
100
200
300
400
0
20
40
60
80
TIME, HOUR

Figure 28. Magnitude of Leakage of Soluble Organic Material in Reactor and Clarifier During a Six-fold Quantitative Shock Loading at an X_R of 10,000 mg/l (data from transient phase of Figure 14)


▲ REACTOR FILTRATE, OBS.
△ CLARIFIER FILTRATE, OBS.
△ CLARIFIER FILTRATE, THEO.
XR-10000
COD, mg/ℓ
0
100
200
300
400
0
20
40
60
80
TIME, HOUR

as shown in the figure. The attenuating effect of X_R during the shock is seen clearly in the figures; a similar attenuating effect was observed during combined quantitative and qualitative shock loading. Since these have already been reported by Manickam and Gaudy (62), the general outcome of these experiments need only be summarized here. The system was subjected to a two-fold quantitative and qualitative shock load at X_R = 5000 mg/l by changing the substrate from 1500 mg/l glucose to 3000 mg/l sorbitol. There was considerable leakage from the reactor; the leakage consisted of organic compounds other than the original substrate. When the system was subjected to an identical shock at X_R = 10,000 mg/l, the leakage was considerably lower than that for the system operating with an X_R = 5000 mg/l. When the system was operating with an X_R = 10,000 mg/l and was subjected to a six-fold quantitative and qualitative shock by changing the influent substrate concentration from 500 mg/l glucose to 3000 mg/l sorbitol, there was a large amount of leakage of soluble COD from the reactor. During the very early transient period, a small amount of this leakage consisted of sorbitol and carbohydrate (anthrone reaction), but after a few hours the leakage was entirely of organic compounds other than the original substrate. When a similar shock was applied at a high recycle sludge concentration--15,000 mg/l--the leakage from the reactor was reduced considerably. Overall, these experiments showed that increasing the concentrations of cells in the recycle flow to the activated sludge reactor enhanced favorable response to the shock loads herein discussed, leading to less leakage of soluble organic substrate. The betterment of response seems to be related in ways not yet fully known to specific growth rate and age and maturity of the biomass.

Effect of Clarifier Volume on Shock Load Response

In Figures 27 and 28 the open triangles conncected by dash lines represent the soluble COD that would have been in the clarifier effluent if the clarifier would have acted only as an equalization basin without any biological activity. The open triangles connected by the solid lines represent the observed soluble COD in the clarifier effluent. The area between these two lines represents the amount of substrate removed in the clarifier due to continuation of metabolic activity in the settling tank. These figures show not only the considerable surge tank capacity of the clarifier, but they also indicate that a considerable amount of COD was removed biologically in the clarifier. The same general effect, i.e., substrate removal in the clarifier, was observed for quantitative and qualitative shock loads at X_R = 5,000, 10,000, and 15,000 mg/l when S_i was changed from 500 to 1500 mg/l glucose to 3000 mg/l sorbitol (62). Such observations indicate clearly that the clarifier in addition to its equalization basin action will function as a biological treatment unit which can serve to polish the effluent. However, operational attention may be needed--depending upon the magnitude of the shock--to assure sufficient dissolved oxygen concentration in the clarifier to prevent adverse biochemical conditions leading to a rising sludge or adverse ecological conditions leading to a bulking sludge.

Analysis of Steady State Performance

The mean values in the steady state for all parameters examined are shown in Table II. It is seen that there was little or no nitrification taking place in the system. Thus, there is little doubt that the data do represent average results for a system limited by carbon source; that is to say, growth of nitrifying organisms did not complicate the kinetic system. It is also seen that the dissolved oxygen concentration in the reactor as well as in the clarifier indicates that the system was aerobic at all times. Also, the pH of the system did not vary and the temperature range was rather narrow; the protein and carbohydrate contents of the activated sludge were as expected of a normal biomass. It is also seen that the soluble COD in reactor 2 was rather low.

In Table V, critical parameters for feed and effluent substrate concentration as well as biomass and excess sludge are subject to statistical analysis. The number of samples used in the analysis varied--depending upon the individual runs. The lowest number of samples was seven, and the highest was 35. It can be seen from the standard deviations and coefficients of variation that for the most part the data grouped rather closely around the mean values. Also noted in the table are the figures numbers and the days included in the "steady state" average. In general, it was felt that the results and analysis shown in this table as well as a perusal of the steady state data shown in the figures indicates that the mean values obtained did represent at least pseudo-steady states in regard to the major parameters of operation for the model.

It is interesting to determine if the mean values which were observed could be predicted using the model equations and appropriate values for the four biokinetic constants which describe the properties of the biomass. Values for μ_{max}, K_s, and Y_{t_B} obtained from the batch experiments which were run during each steady state operation are shown in Table III. The numerical value for K_d cannot be obtained

TABLE V

STATISTICAL ANALYSES FOR ALL STEADY STATE RUNS

Line (1)	Figure (2)	Analysis Indicated mg/l (3)	N (4)	Mean (5)	S-D* σ (6)	C.V. % (7)	Range (8)	Remarks
1	4	S_i	10	516.6	10	1.9	504- 538	substrate: glucose
		S_T	10	25.9	7	27.0	13- 42	steady state
		S_e	10	20.6	7	33.9	4- 34	day 51 to day 66
		X_e	10	5.8	2	34.4	4- 8	8-16-75 to 8-31-75
		X	10	1184.5	35	3.0	1145-1250	
		X_R	10	4876	165	3.38	4620-5100	
		X_w	10	1522	189	12.4	1242-1769	
2	4	S_i	14	509	14	2.8	459- 539	substrate: sorbitol
		S_T	14	13.7	2	27.4	12- 18	steady state
		S_e	14	6.3	2	31.8	4- 10	day 79 to day 108
		X_e	14	6.6	3	45.4	4- 14	9-13-75 to 10-12-75
		X	14	1202	38	3.2	1145-1285	
		X_R	14	4892	213	4.4	4500-5220	
		X_w	14	1516	80	5.3	1418-1664	
3	9,10	S_i	9	2748	99	7.2	2653-2943	substrate: sorbitol
		S_T	9	99.8	13	13.0	77- 121	steady state
		S_e	9	78.8	6	7.6	69- 86	day 22 to day 38 in Fig. 9
		X_e	9	33.1	4	12.1	26- 38	10-23-75 to 11-8-75
		X	9	2317	177	7.6	2145-2650	
		X_R	9	5173	126	2.4	4980-5430	
		X_w	9	8943	332	3.7	8411-9437	
4	10,24	S_i	7	606.1	21	3.5	574- 635	substrate: sorbitol
		S_T	7	37.0	9	24.3	22- 54	steady state
		S_e	7	27.0	5	18.5	18- 33	day 26 to day 37 in Fig. 10 or
		X_e	7	7.14	5	18.5	2- 16	day 0 to day 11 in Fig. 24
		X	7	1250	8	0.6	1234-1260	11-18-75 to 11-29-75
		X_R	7	4861	154	3.2	4640-4980	
		X_w	7	1853	111	6.0	1675-1962	
5	5,24	S_i	24	1775.3	51	2.9	1658-1842	substrate: 500 mg/l glucose +
		S_T	23	71.0	9	12.7	51- 89	1000 mg/l sorbitol
		S_e	23	56.1	9	16.0	44- 72	steady state
		X_e	23	21.0	6	28.6	12- 32	day 21 to day 46 in Fig. 24 +
		X	22	1815.9	85	4.7	1640-1926	day 0 to day 19 in Fig. 5
		X_R	22	5089	213	4.2	4640-5460	12-9-75 to 1-22-76
		X_w	22	5577	372	6.7	5003-6244	
6	6,7	S_i	7	1540	57	3.7	1468-1640	substrate: 1000 mg/l glucose +
		S_T	7	51	5	9.8	42- 60	500 mg/l sorbitol
		S_e	7	42.9	4	9.3	35- 48	steady state
		X_e	7	14.0	3	21.4	10- 18	day 25 to day 35 in Fig. 6
		X	7	1630	78	4.8	1496-1728	1-28-76 to 2-7-76
		X_R	7	5105.7	212	4.2	4860-5460	
		X_w	7	4339	215	5.0	4315-4592	
7	7	S_i	7	1573	44	2.8	1490-1644	substrate: glucose
		S_T	7	39.9	8	20.1	31- 51	steady state
		S_e	7	34.9	7	20.1	24- 45	day 12 to day 20
		X_e	7	22.3	4	17.9	18- 28	2-12-76 to 2-20-76
		X	7	1568	36	2.3	1518-1624	
		X_R	7	4978	135	2.7	4760-5160	
		X_w	7	3795	175	4.6	3461-3944	
8	11	S_i	9	2835	122	4.3	2670-3080	substrate: sorbitol
		S_T	9	99	8	8.1	84- 114	steady state
		S_e	9	81.9	5	6.1	76- 92	day 0 to day 15
		X_e	9	28.1	4	14.2	22- 32	3-4-76 to 3-19-76
		X	9	2343	64	2.7	2260-2450	
		X_R	9	4962	261	5.3	4589-5386	
		X_w	9	9021	166	1.8	8768-9264	
9	11,12	S_i	7	604.7	15	2.5	582- 627	substrate: sorbitol
		S_T	7	29.3	10	34.1	21- 46	steady state
		S_e	7	14.7	3	20.4	12- 19	day 53 to day 65 in Fig. 11 or
		X_e	7	20.6	3	14.6	26- 16	day 0 to day 12 in Fig. 12
		X	7	1273	41	3.2	1200-1328	4-26-76 to 5-8-76
		X_R	7	5073	295	5.8	4695-5408	
		X_w	7	1704	127	7.4	1517-1848	
10	13,14	S_i	14	532.1	18	3.4	492- 549	substrate: sorbitol
		S_T	14	27.0	4	14.8	20- 35	steady state
		S_e	14	17.3	4	23.1	12- 25	day 66 to day 91 in Fig. 13 or
		X_e	14	17.5	5	28.6	8- 25	day 0 to day 25 in Fig. 14
		X	14	2230	84	3.8	2108-2367	
		X_R	14	10259	555	5.4	9350-10900	
		X_w	14	1265	48	3.8	1198-1378	

TABLE V (Continued)

Line (1)	Figure (2)	Analysis Indicated mg/l (3)	N (4)	Mean (5)	S-D* σ (6)	C.V. % (7)	Range (8)	Remarks
11	14,15	S_i	15	3216.7	80	2.5	3070-3360	substrate: sorbitol
		S_T	14	93.8	6	6.4	84- 102	steady state
		S_e	15	80.8	5	6.2	74- 87	day 124 to day 152 in Fig. 14 or
		X_e	14	22.2	5	22.5	16- 32	day 0 to day 28 in Fig. 15
		X	14	3277.2	38	1.2	3160-3300	11-2-76 to 11-30-76
		X_R	14	10337.1	227	2.2	9980-10670	
		X_w	14	8592.2	210	2.4	8164-8843	
12	15,25	S_i	9	511.8	11	2.1	498- 527	substrate: sorbitol
		S_T	9	26.2	5	19.1	18- 32	steady state
		S_e	9	18.4	4	21.7	12- 24	day 41 to day 57 in Fig. 15
		X_e	9	18.4	3	16.3	14- 22	day 0 to day 16 in Fig. 25
		X	9	2273.7	24	1.0	2227-2304	
		X_R	9	10237.8	234	2.3	9860-10580	12-13-76 to 12-29-76
		X_W	9	1460.7	83	5.7	1344-1581	
13	25	S_i	14	1513	47	3.1	1445-1570	substrate: glucose
		S_T	14	37.3	4	10.7	32- 44	steadu state
		S_e	14	27.8	3	10.8	24- 32	day 24 to day 49
		X_e	14	21.1	4	18.9	14- 28	1-6-77 to 1-31-77
		X	14	2530	75	3.0	2430-2640	
		X_R	14	10348	259	2.5	9920-10800	
		X_w	14	3262	131	4.0	2956-3505	
14		S_i	9	2743	69	2.5	2630-2820	substrate: sorbitol
		S_T	9	51.6	7	13.6	42- 62	steady state
		S_e	9	38.7	3	7.8	36- 42	2-6-77 to 2-16-77
		X_e	9	35.3	7	19.8	22- 44	
		X	9	3124	70	2.2	3044-2224	
		X_R	9	10160	283	2.8	9740-10460	
		X_w	9	7736	214	2.8	7533-8148	
15		S_i	9	502	12	2.4	482- 514	substrate: glucose
		S_T	9	21.1	3	14.2	16- 24	steady state
		S_e	9	13.8	2	1.4	12- 16	3-12-77 to 3-28-77
		X_e	9	15.5	5	32.3	8- 24	
		X	9	2214	75	3.4	2116-2318	
		X_R	9	10138	310	3.1	9680-10620	
		X_w	9	1274	30	2.4	1211-1317	
16	16	S_i	8	2812	146	5.2	2620-3027	substrate: sorbitol
		S_T	8	65.5	5	7.6	56- 72	steady state
		S_e	8	46.9	5	10.7	38- 55	day 0 to day 13
		X_e	8	26.5	4	15.1	20- 32	4-18-77 to 5-1-77
		X	8	3285	62	1.9	3216-3386	
		X_R	8	10114	204	2.1	9780-10330	
		X_w	8	8683	283	3.3	8372-9121	
17	16,17	S_i	8	522.9	12	2.3	504- 543	substrate: sorbitol
		S_T	8	24.5	6	24.5	14- 34	steady state
		S_e	8	16.0	5	31.3	8- 24	day 16 to day 26 in Fig. 16 or
		X_e	7	19.1	8	41.9	8- 30	day 0 to day 10 in Fig. 17
		X	7	2238.3	25	1.1	2198-2268	5-5-77 to 5-15-77
		X_R	7	10108.6	265	2.6	9760-10460	
		X_w	7	1530.1	100	6.5	1373-1662	
18A	19,20	S_i	17	515	17	3.3	492- 536	sorbitol (cyclic)
		S_T	18	31	9.2	29.7	16- 38	6 PM
		S_e	18	21	5	23.8	12- 38	steady state
		X_e	18	26	8	30.8	12- 44	day 39 to day 56 in Fig. 19
		X	18	2250	30	1.3	2186-2314	6-13-77 to 6-30-77
		X_R	18	10180	240	2.4	9860-10620	
		X_w	17	1331	56	4.2	1243-1425	
18B	19,20	S_i	18	3117	92	3.0	2993-3293	sorbitol (cyclic)
		S_T	15	52	5	9.6	40- 60	6 AM
		S_e	16	37	4	10.8	56- 28	steady state
		X_e	16	32	8	25.0	18- 42	day 39 to day 56 in Fig. 20
		X	17	3160	51	1.6	3076-3264	6-13-77 to 6-30-77
		X_R	17	10154	200	2.0	9780-10620	
		X_w	18	2531	149	5.9	2154-2693	
18	19,20	S_T	34	43.1	10	0.26	16- 60	sorbitol (cyclic)
		S_e	34	28.5	9	31.5	12- 56	steady state
		X_e	34	28.6	8	28.0	12- 44	day 39 to day 56 in Fig. 19
		X	35	2691.9	463	17.2	2186-3264	6-13-77 to 6-30-77
		X_R	35	10167	219	2.2	9780-10620	combined statistical analysis
		X_w	35	1917.4	666	34.7	1243-2693	of 6 AM and 6 PM data

TABLE V (Continued)

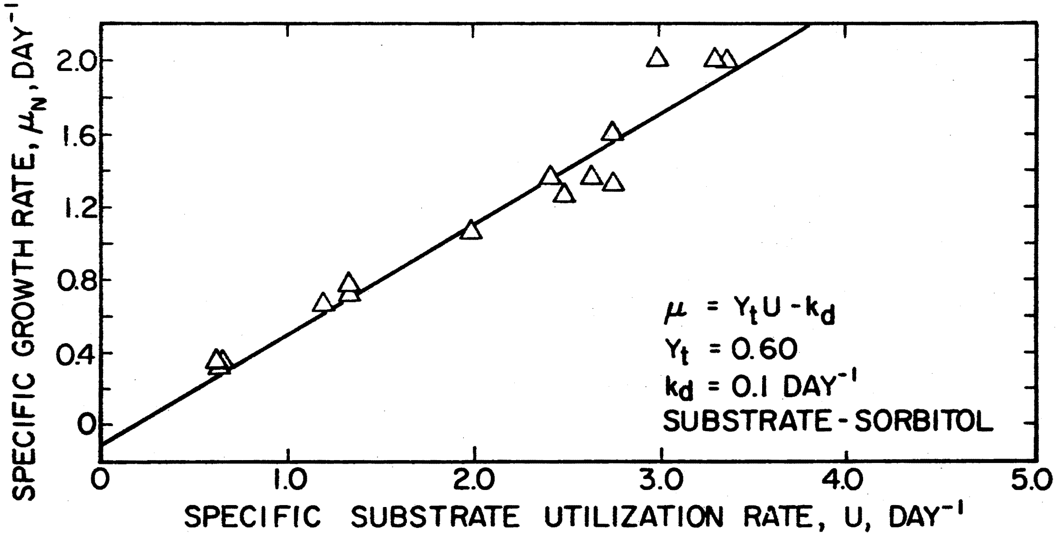
Line (1)	Figure (2)	Analysis Indicated mg/l (3)	N (4)	Mean (5)	S-D* σ (6)	C.V. % (7)	Range (8)	Remarks
19	8,20	S_i	7	504	20	4.0	477- 537	substrate: sorbitol
		S_T	7	28	5	17.9	20- 32	steady state
		S_e	7	20	5	25.0	12- 24	day 0 to day 12 in Fig. 8 or
		X_e	7	14.6	4	27.4	10- 20	day 32 to day 44 in Fig. 20
		X	7	2234	10	0.5	2218-2246	
		X_R	7	10189	234	2.3	9840-10480	
		X_w	7	1294	57	4.4	1208-1383	
20	8	S_i	7	506	26	5.1	476- 528	substrate: glucose
		S_T	7	35.4	4	11.3	32- 40	steady state
		S_e	7	24	4	16.7	20- 32	day 33 to day 45
		X_e	7	22.9	3	13.1	18- 26	8-24-77 to 9-5-77
		X	7	3232	97	3.0	3116-3336	
		X_R	7	15234	520	3.4	14560-15780	
		X_w	7	1043	79	7.6	947-1184	
21	26	S_i	8	3080	139	4.5	2941-3320	substrate: sorbitol
		S_T	8	64	10	15.6	52- 84	steady state
		S_e	8	46	8	17.4	36- 60	day 0 to day 14
		X_e	8	33.8	6	17.8	28- 48	9-16-77 to 9-30-77
		X	8	4339	84	1.9	4264-4524	
		X_R	8	15025	498	3.3	14080-15680	
		X_w	8	8753	401	4.6	8059-9204	
22	21,26	S_i	8	507.5	22	4.3	484- 544	substrate: glucose
		S_T	8	30	5	16.7	24- 36	D = 0.12 hr^{-1}
		S_e	8	17	6	35.3	8- 24	steady state
		X_e	8	13	5	38.5	8- 20	day 0 to day 12 in Fig. 21 or
		X	8	2287.5	26	1.1	2248-2312	day 19 to day 31 in Fig. 26
		X_R	8	10120	227	2.2	9760-10420	10-4-77 to 10-16-77
		X_w	8	1855	101	5.4	1693-1958	
23	21,22	S_i	10	1044.2	67	6.4	935-1130	substrate: glucose
		S_T	10	48	5	10.4	40- 52	D = 0.24 hr^{-1}
		S_e	10	37.8	5	13.3	30- 46	steady state
		X_R	10	20.0	4	20.0	12- 26	day 18 to day 29 in Fig. 21 or
		X	10	2548.7	49	1.9	2476-2584	day 0 to day 11 in Fig. 22
		X_R	10	10211	349	3.4	9780-10760	10-22-77 to 11-2-77
		X_w	10	7606	262	3.4	7262-8018	
24	22,23	S_i	10	513.8	22	4.3	480- 548	substrate: glucose
		S_T	10	22	5	22.7	12- 28	D = 0.12 hr^{-1}
		S_e	10	15.2	6	35.5	8- 24	steady state
		X_e	10	11.6	4	34.5		day 17 to day 29 in Fig. 22 or
		X	10	1793.2	63	3.5	1664-1862	day 0 to day 12 in Fig. 23
		X_R	10	8134	373	5	7460-8560	
		X_w	10	1148.4	52	4.5	1053-1223	11-18-77 to 11-20-77
25	23	S_i	11	1498.8	59	3.9	1415-1593	substrate
		S_T	11	54.7	4	7.3	48- 60	glucose
		S_e	11	44.4	6	13.5	36- 52	D = 0.24 hr^{-1}
		X_e	11	18.9	11	58.2	8- 48	
		X	11	2344.4	54	2.3	2246-2396	steady state
		X_R	11	8245.5	218	2.6	7880-8560	day 18 to day 31
		X_w	11	9515.3	89	1.0	9352-9687	11-26-77 - 12-9-78

*σ = standard deviation

from batch data but is readily obtained from the so-called maintenance plots of the continuous flow result. Such plots are usually made in one of two forms; Figure 29 shows both ways of obtaining values of both K_d and Y_t for the sorbitol data, while Figure 30 shows the values obtained using glucose. It can be seen that there were much more data on sorbitol than there were on glucose. Also, there was a greater amount of scatter in plotting points for glucose; however, previous studies in this laboratory on glucose provided additional data. Figure 31 represents a plot of all available results using glucose.

Using the numerical values for the biokinetic constants and the engineering parameters α, X_R, and D as well as the influent substrate concentrations of S_i, the values of S_e, X, and X_w were predicted using the model equations. These analytical results are given in Table VI. It can be seen that the prediction of biomass concentration, X, and excess sludge production, X_w, are rather good when compared to the experimentally observed average values. In general, the observed COD, S_e, is somewhat higher than the predicted values; however, if one estimates the BOD of the feed as 85 percent of the COD, the predicted values of S_e are somewhat closer to the observed effluent BOD_L values (compare columns 6 and 10). In this case, the observed values are lower than the predicted values. It is recalled that the BOD_5 observed values were obtained using seeding material from the reactor at the time of incubating the BODs. Thus, with respect to biochemical oxygen demand, exertable by the cells in the reactor, the system performance was better than that predicted by the model. However, one cannot preclude the fact that a new seed which might be found in a receiving stream could give a higher BOD value.

Figure 29. Plots of Maintenance Energy Equations to Determine "True Yield," Y_t, and Maintenance Coefficient, K_d (substrate:sorbitol)


SPECIFIC GROWTH RATE, μ_N, DAY^{-1}
2.0
1.6
1.2
0.8
0.4
0
0
1.0
2.0
3.0
4.0
5.0
SPECIFIC SUBSTRATE UTILIZATION RATE, U, DAY^{-1}
$\mu = Y_t U - k_d$
$Y_t = 0.60$
$k_d = 0.1$ DAY^{-1}
SUBSTRATE - SORBITOL

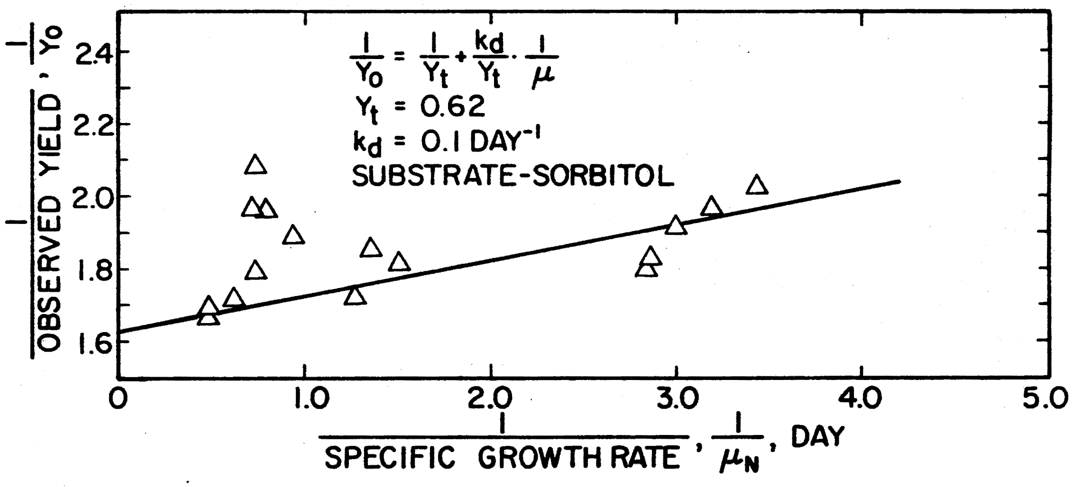

$\frac{1}{\text{OBSERVED YIELD}}$, $\frac{1}{Y_o}$
2.4
2.2
2.0
1.8
1.6
0
1.0
2.0
3.0
4.0
5.0
$\frac{1}{\text{SPECIFIC GROWTH RATE}}$, $\frac{1}{\mu_N}$, DAY
$\frac{1}{Y_0} = \frac{1}{Y_t} + \frac{k_d}{Y_t} \cdot \frac{1}{\mu}$
$Y_t = 0.62$
$k_d = 0.1$ DAY^{-1}
SUBSTRATE-SORBITOL

Figure 30. Plots of Maintenance Energy Equations to Determine "True Yield," Y_t, and Maintenance Coefficient, K_d (substrate:glucose)

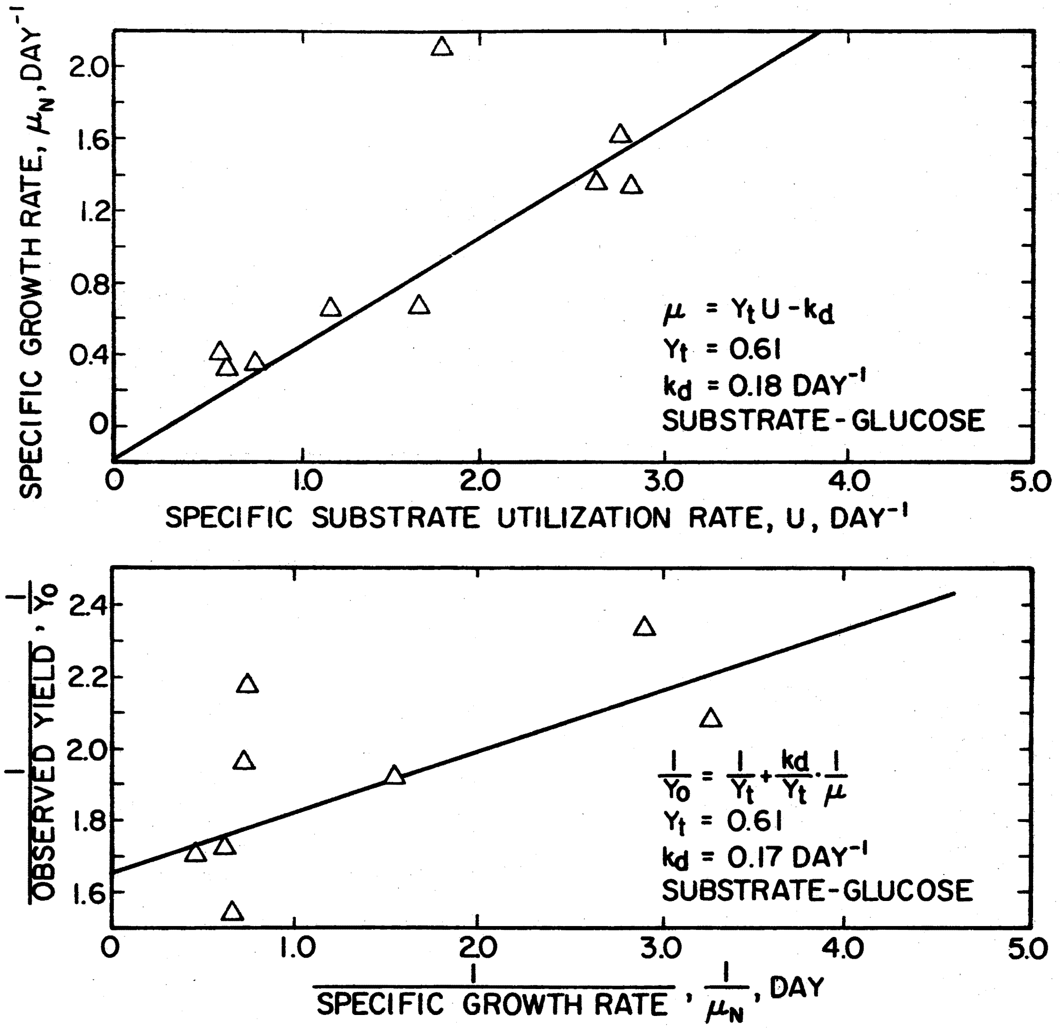
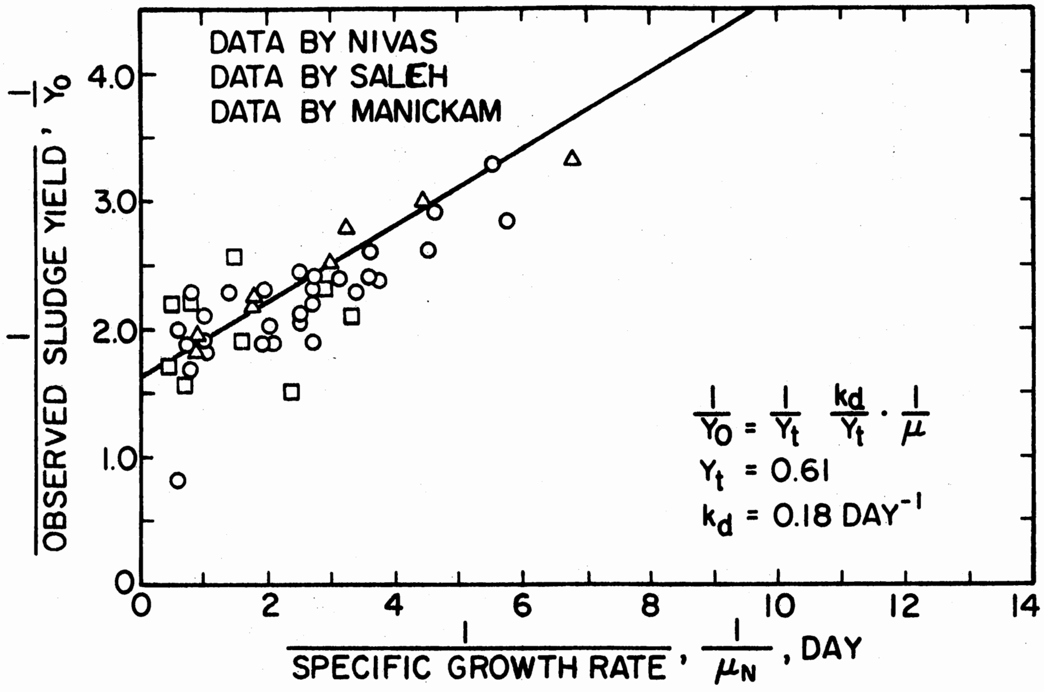

SPECIFIC GROWTH RATE, μ_N, DAY^{-1}
2.0
1.6
1.2
0.8
0.4
0
0
1.0
2.0
3.0
4.0
5.0
SPECIFIC SUBSTRATE UTILIZATION RATE, U, DAY^{-1}
$\mu = Y_t U - k_d$
$Y_t = 0.61$
$k_d = 0.18$ DAY^{-1}
SUBSTRATE-GLUCOSE
$\frac{1}{\text{OBSERVED YIELD}}, \frac{1}{Y_o}$
2.4
2.2
2.0
1.8
1.6
0
1.0
2.0
3.0
4.0
5.0
$\frac{1}{\text{SPECIFIC GROWTH RATE}}, \frac{1}{\mu_N}$, DAY
$\frac{1}{Y_o} = \frac{1}{Y_t} + \frac{k_d}{Y_t} \cdot \frac{1}{\mu}$
$Y_t = 0.61$
$k_d = 0.17$ DAY^{-1}
SUBSTRATE-GLUCOSE

Figure 31. Plots of Maintenance Energy Equations to Determine "True Yield," Y_t, and Maintenance Coefficient, K_d, Using Data Obtained by Srinivasaraghavan (10), Saleh (39), and Manickam (substrate: glucose)


DATA BY NIVAS
DATA BY SALEH
DATA BY MANICKAM
1 / OBSERVED SLUDGE YIELD, 1/Yo
4.0
3.0
2.0
1.0
0
0
2
4
6
8
10
12
14
1 / SPECIFIC GROWTH RATE, 1/μN, DAY
1/Yo = 1/Yt kd/Yt · 1/μ
Yt = 0.61
kd = 0.18 DAY⁻¹

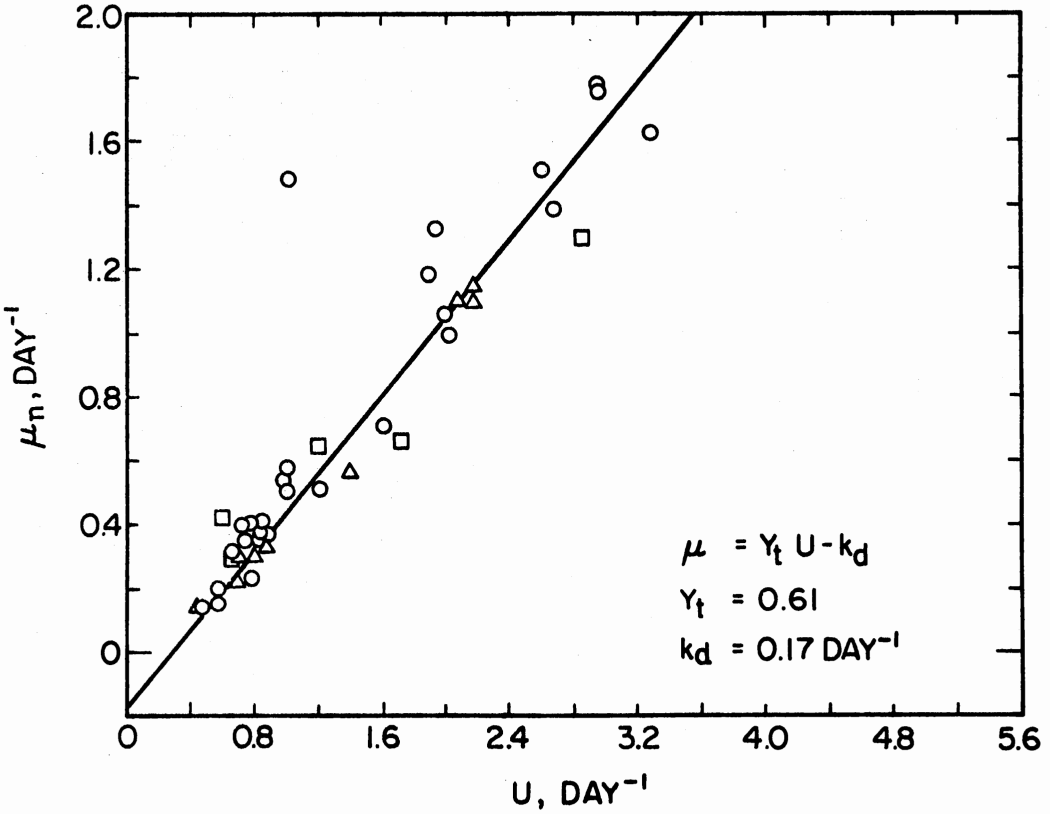

μn, DAY⁻¹
2.0
1.6
1.2
0.8
0.4
0
0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
U, DAY⁻¹
μ = Yt U - kd
Yt = 0.61
kd = 0.17 DAY⁻¹

TABLE VI

PREDICTION OF S, X, AND X_W FOR CONTINUOUS FLOW ACTIVATED SLUDGE PROCESS WITH CONSTANT CONCENTRATION OF RECYCLE SLUDGE

				Effluent Substrate Concentration, S, mg/l						Biological Solids, X, mg/l				Excess Sludge Production, X_w. mg/day			
		Influent		Observed		Predicted				Obser-ved	Predicted			Obser-ved	Predicted		
Line	Figure		Substrate	COD	BOD_L	I	II	III	IV		I	II	III		I	II	III
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	4	517	glucose	21	12.0	15	14	14	3	1184	1160	1142	1146	1522	1333	1200	1228
2	4	509	sorbitol	6	11.6	14	15	13	3	1202	1166	1183	1170	1516	1354	1474	1382
3	9,10	2748	sorbitol	79	40.4	42	42	44	17	2317	2287	2187	2201	8943	9015	8295	8400
4	10,24	606	sorbitol	27	13.6	40	37	16	8	1250	1210	1190	1206	1853	1712	1567	1684
5	5,24	1775	glucose:1 sorbitol:2	56	30.7	26	24	34	11	1816	1817	1710	1759	5577	5757	4985	5335
6	6,7	1540	glucose:2 sorbitol:1	43	27.7	64	59	31	6	1630	1687	1610	1660	4339	4793	4239	4596
7	7	1573	glucose	35	29.3	30	29	33	11	1568	1662	1627	1614	3795	4796	4548	4449
8	11	2835	sorbitol	82	42.2	41	41	46	18	2343	2288	2309	2198	9021	9328	9480	8679
9	11,12	605	sorbitol	15	13.1	7	7	15	8	1273	1270	1270	1247	1704	1840	1840	1675
10	13,14	532	sorbitol	17	6.2	10	10	7	3	2230	2243	2243	2228	1265	1375	1375	1272
11	14,15	3217	sorbitol	81	28.6	18	17	32	12	3277	3528	3429	3421	8711	10518	9092	9747
12	15,25	512	sorbitol	18	6.0	10	10	7	4	2274	2229	2222	2216	1461	1308	1254	1209
13	25	1513	glucose	28	16.3	27	27	19	6	2530	2658	2659	2618	3262	4240	4240	3949
14		2743	sorbitol	39	25.8	17	17	29	9	3124	3269	3269	3178	7736	8908	8908	8251
15		502	glucose	14	6.1	8	8	7	3	2214	2160	2160	2145	1274	950	950	847
16	16	2812	sorbitol	47	26.3	23	22	30	12	3285	3290	3247	3199	8683	9122	8812	8471
17	16,17	523	sorbitol	16	6.2	6	5	7	4	2238	2212	2172	2195	1530	1370	1084	1248
19	8,20	504	sorbitol	20	5.9	9	7	7	4	2234	2217	2172	2202	1294	1289	963	1186
20	8	506	glucose	24	4.2	4	4	5	3	3232	3135	3120	3119	1333	633	523	518
21	26	3080	sorbitol	46	20.9	15	15	24	12	4339	4377	4377	4277	8753	9881	9881	9159
22	21,26	508	glucose	17	6.2	12	9	7	3	2288	2157	2113	2144	1855	958	640	866
23	21,22	1044	glucose	38	23.8	20	18	28	8	2549	2478	2423	2441	7606	6268	5482	5746
24	22,23	514	glucose	15	8.8	15	12	9	7	1793	1780	1735	1768	1148	1099	783	1015
25	24	1499	glucose	44	40.6	27	25	47	12	2344	2307	2239	2250	9515	9465	8495	8647

BOD_L in column 6 $= \frac{BOD_5}{0.67}$

Predictions in columns 7, 12 and 16 are based on individual values of μ_{max} and K_s obtained by batch growth studies and Y_t obtained from maintenance plot

Predictions in columns 8, 13 and 17 are based on individual values of μ_{max} and K_s and Y_{tB} obtained by batch growth studies

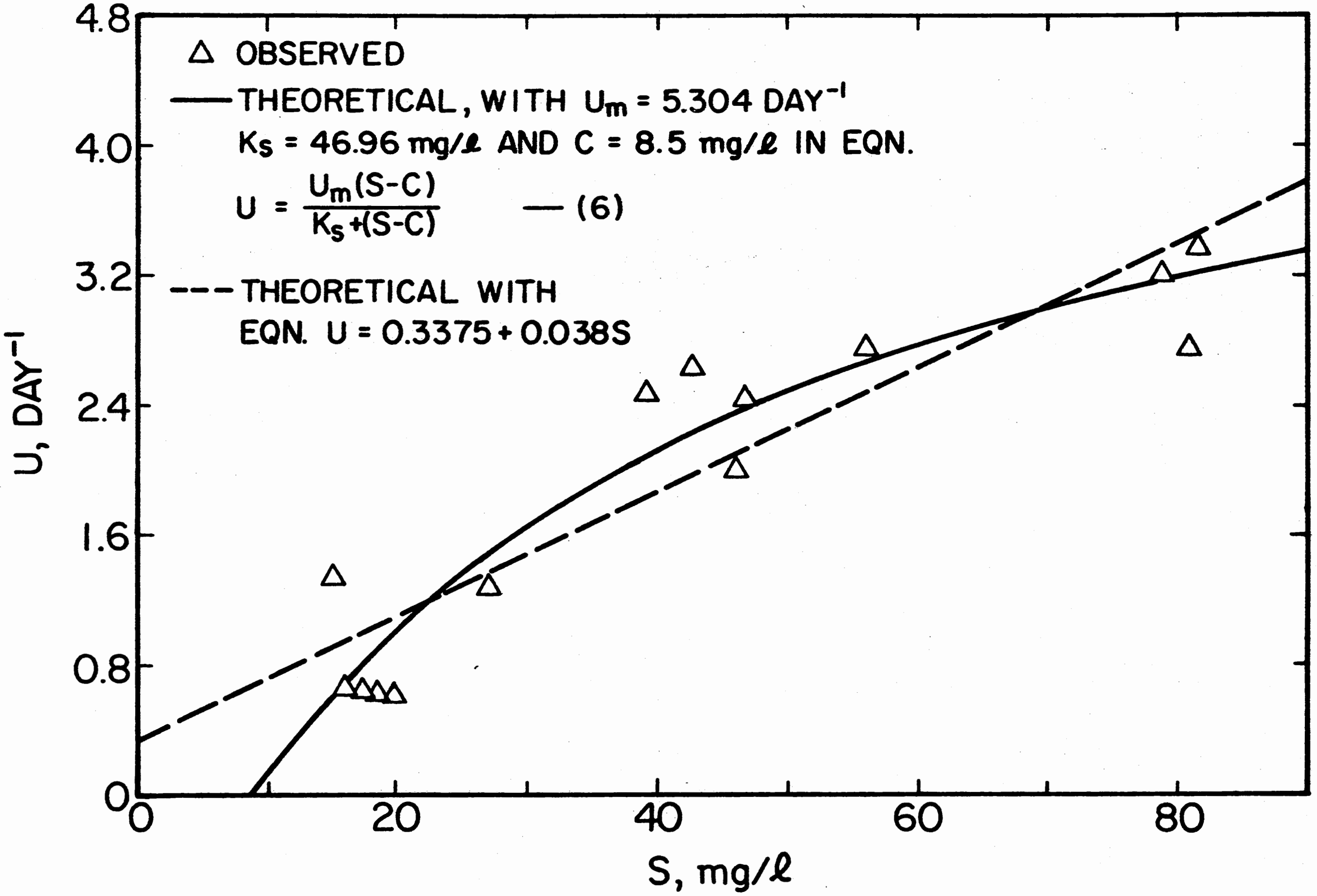
Predictions in columns 9, 14 and 18 are based on average values of $\mu_{max} = 0.47\ hr^{-1}$, $K_s = 204.6$ mg/l and $Y_{tB} = 0.57$ obtained from batch growth studies

Column 10 represents the predicted effluent, BOD_L assuming that the influent $BOD_L = 0.85 \times$ influent COD; $k_d = 0.1\ day^{-1}$ for sorbitol and combination of sorbitol and glucose, $k_d = 0.18\ day^{-1}$ for glucose

In regard to the residual COD, it has been noted generally in other work that it is considerably higher than that predicted when using the model equation when the chemical oxygen demand is used as a measure of substrate. There is considerable concern throughout the field regarding the nature of the residual COD. In the current results it can be seen that by any standard the system provided a very high treatment efficiency. However, in view of the effluent standards which may be imposed in the future, the existence of even low amounts of organic matter in an effluent is a matter of concern. There are various policy questions which need to be resolved; these require information in regard to the nature of the residual COD. If it is innocuous material which is non-biodegradable, it obviously would not represent the problem to the oxygen resources in the stream that a biodegradable residual would present. That is to say, the question is how much of the residual COD represents degradable material which should be charged against the efficiency of the process, and how much represents true nonbiodegradable humus. Thus, in assessing the ability of any model to predict the effluent quality, there would appear to be some basis for making a subtraction for the absolute residual COD--there is some baseline COD which does not represent substrate to be charged against the value of S_i. One possible approach would be to allow that the lowest residual COD for a particular system would be the soluble COD in reactor 2, the cell recycle aeration tank. This COD is generally considerably lower than the soluble COD in the effluent. In a sense, this high biomass-low feed portion of the system can be considered to represent the maximum COD level potential; therefore one could subtract this COD from the soluble COD in the effluent, COD_e, thus reducing the value of the effluent COD to be charged against S_i.

Another method which might be employed makes use of a procedure adapted by Eckenfelder (63). He has estimated values of residual substrate from a plot of specific substrate removal rate, U, vs. S_e, assuming the relationship between specific substrate removal rate or specific growth rate and substrate concentration to be linear rather than hyperbolic. Figure 32 shows such a plot for the continuous flow runs using sorbitol as substrate. It is apparent from the data points that it would be inappropriate to fit a straight line intercepting the positive S_e axis through these data (see dashed line for best linear fit). It will be recalled that in accordance with the Monod model, which is incorporated into the steady state equations of Gaudy and co-workers, this plot should not be a straight line in any event. One would expect it to be a rectangular hyperbola in much the same manner as a plot of the specific growth rate, μ, vs. S_e. If the equation of the curve, either straight line or rectangular hyperbola, did not intercept the positive X_e axis, one could not use that intercept as a measure of residual COD. It is seen from the data points that one might possibly fit the data to two types of rectangular hyperbola--first one intersecting the S_e axis and one through the origin. Equation (6) shown on the figure is the equation of a rectangular hyperbola intercepting the X axis at C. It was not possible to put this equation into a straight line form which would allow evaluation of the constants μ_{max}, K_s, and C. The method of least squares was used to fit the data to the equation; that is to say, the method of least squares was used to find the equation of the best fit to a rectangular hyperbola. This was done using SAS 76 (Statistical Analysis System) non-linear (64).

Figure 32. Plot of Substrate Utilization Rate, U, Day^{-1} vs. Soluble Substrate COD, S, mg/l in Effluent (substrate:sorbitol)


△ OBSERVED
— THEORETICAL, WITH U_m = 5.304 DAY^{-1}
K_s = 46.96 mg/ℓ AND C = 8.5 mg/ℓ IN EQN.
$U = \frac{U_m(S-C)}{K_s+(S-C)}$ — (6)
--- THEORETICAL WITH
EQN. U = 0.3375 + 0.038S
U, DAY^{-1}
S, mg/ℓ
0
0.8
1.6
2.4
3.2
4.0
4.8
0
20
40
60
80

The hyperbolic function for U vs. S not passing through the origin is of the form:

$$U = \frac{U_{max}\ (S - c)}{K_s + (S - c)} \tag{6}$$

This is of the form

$$U = A + \frac{B}{S - d} \tag{7}$$

where

$A = U_{max}$

$B = - U_{max}\ K_s$

$d = C - K_s$

The sum of squares of residuals, ψ, of the above equation is

$$\psi = \Sigma \left[U_i - \left\{ A + \frac{B}{S_i - C} \right\} \right]^2 \tag{8}$$

The normal equations are obtained by finding the partial differential of with respect to A, B, and C. They are

$$\frac{\partial \psi}{\partial A} = \Sigma \left[U_i - \left\{ A + \frac{B}{S_i - C} \right\} \right] = 0 \tag{9}$$

$$\frac{\partial \psi}{\partial B} = \Sigma \left[U_i - \left\{ A + \frac{B}{S_i - C} \right\} \right] \left[\frac{1}{S_i - C} \right] = 0 \tag{10}$$

$$\frac{\partial \psi}{\partial C} = \Sigma \left[U_i - \left\{ A + \frac{B}{S_i - C} \right\} \right] \left[\frac{B}{(S_i - c)^2} \right] = 0 \tag{11}$$

To solve the normal equations resulting from the application of the least squares method there were three alternative iterations methods, viz., Marquardt, Newtons-Gauss, and Gradient methods. All methods gave the same results (65, 66, 67). The method led to values of U_{max}, K_s, and C of 5.3 $days^{-1}$, 47 mg/l, and 8.5 mg/l, respectively. The solid line through the data intersecting the S_e axis at 8.5 is a line calculated according to equation (6) using these constants. Table VII shows the corrected observed COD_e for both methods described above. It is seen that while these corrections bring the observed more in line with the predicted S_e, the equations still predict a lower substrate concentration (as COD) than that which was observed.

It is well known that the value of S_e varies with μ. In the model herein used, the variation is described by the Monod equation. It may not be generally appreciated, but in the model, equations of Gaudy and co-workers, μ is affected by the value of S_i; for example, this is seen by inspection of equations (16) and (17). Thus, values of μ in the current study changed in accordance with S_i. It is recalled that the theory of continuous culture as discussed by Herbert indicates that μ as well as S_e is independent of S_i. In the foregoing analysis, no accounting was made for changes in S_e due to changes in specific growth rate, μ. Figures 33 and 34 show plots of the change in S_e due to increases in S_i for two different values of X_R (5000 mg/l in Figure 33 and 10,000 mg/l in Figure 34) used in this study. The curves in the bottom portions of both figures which show a rise in S_e at a decreasing rate for increases in S_i are values calculated from equation (22), whereas the lines drawn through the triangles in both figures indicate the trends for the actual observed COD_e. The plotting points for both

TABLE VII

CORRECTED OBSERVED VALUES OF EFFLUENT SOLUBLE SUBSTRATE CONCENTRATION

Line	Influent Substrate		Observed Effluent Filtrate	Corrected Observed Effluent Filtrate	
I	II	III	IV	IV-8.5	IV-S_R
1	517	glucose	20.6	12.1	7.3
2	529	sorbitol	6.3	-	-
3	2748	sorbitol	78.8	70.3	40.8
4	606	sorbitol	27.0	18.5	11.0
5	1775	glucose + sorbitol 1/2	56.1	47.6	15.7
6	1540	glucose + sorbitol 2/1	42.9	34.4	10.9
7	1573	glucose	34.9	26.4	-
8	2835	sorbitol	81.9	73.4	39.9
9	605	sorbitol	14.7	6.2	2.7
10	532	sorbitol	17.3	8.8	5.7
11	3217	sorbitol	80.8	72.3	31.7
12	512	sorbitol	18.4	9.9	10.4
13	1513	glucose	27.8	19.3	7.8
14	2743	sorbitol	38.7	30.2	8.7
15	502	glucose	13.8	5.3	3.8
16	2812	sorbitol	46.9	38.4	12.0
17	523	sorbitol	16.0	7.5	5.0
19	504	sorbitol	20.0	11.5	4.0
20	506	glucose	24.0	15.5	-
21	3080	sorbitol	46.0	37.5	16.0
22	508	glucose	17.0	8.5	5.0
23	1044	glucose	37.8	29.3	18.8
24	514	glucose	15.2	6.7	3.2
25	1499	glucose	44.4	35.9	13.4

Values in Column V are obtained by subtracting from column IV, 8.5 (non-biodegradable fraction) obtained from a plot of S vs U in Figure 32.

Values in column VI are obtained by subtracting from column IV, the corresponding soluble COD in reactor 2 shown in Table II.

Figure 33. Effect of Influent Substrate Concentration, S_i, mg/l and Specific Growth Rate, μ, Day^{-1} on Effluent Soluble Substrate Concentration, S_e, mg/l at X_R of 5000 mg/l. Average Values of $\mu_{max} = 0.47$ hr^{-1}. $K_s = 205$ mg/l, and $Y_{t_B} = 0.57$ Obtained From Batch Growth Studies Were Used

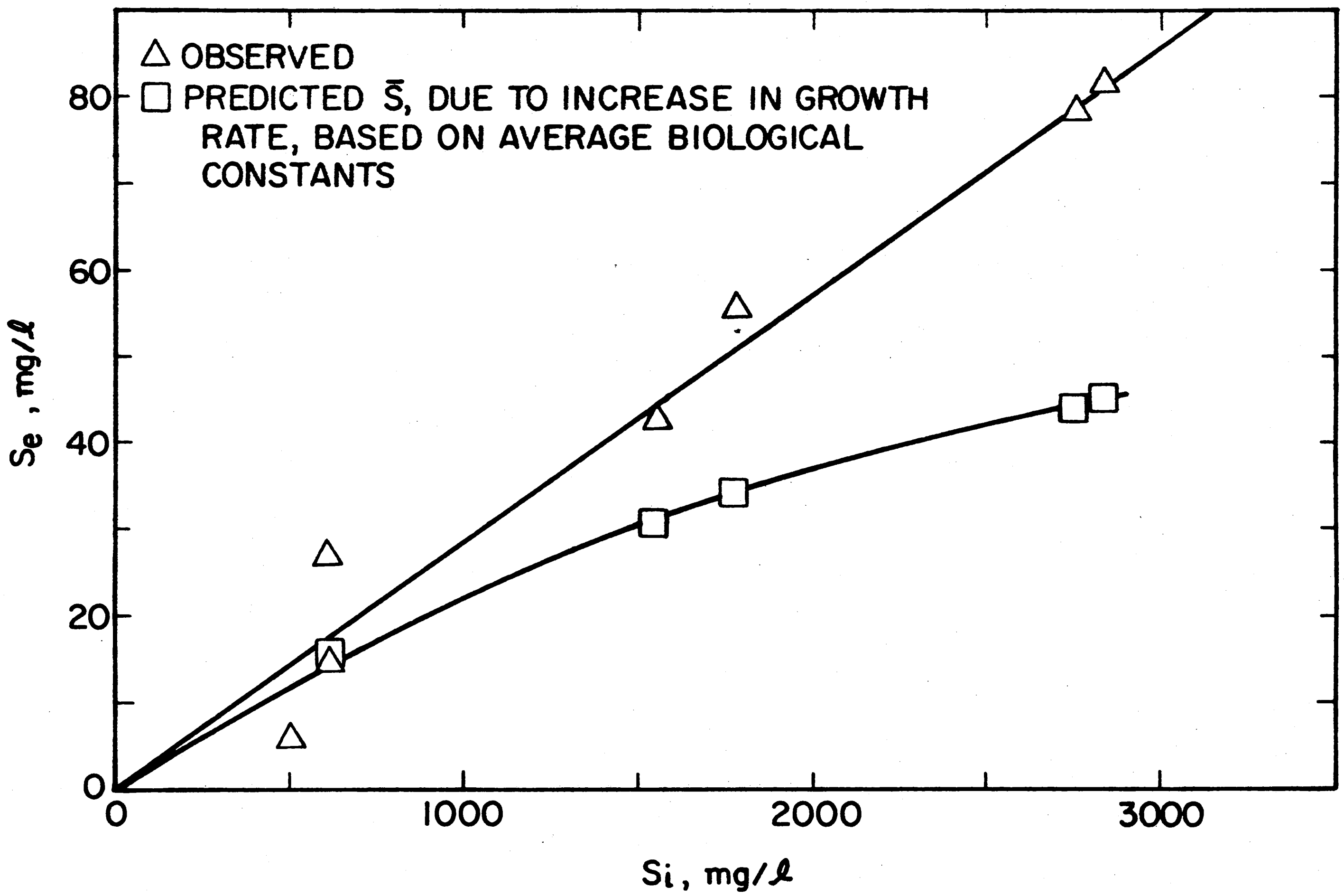
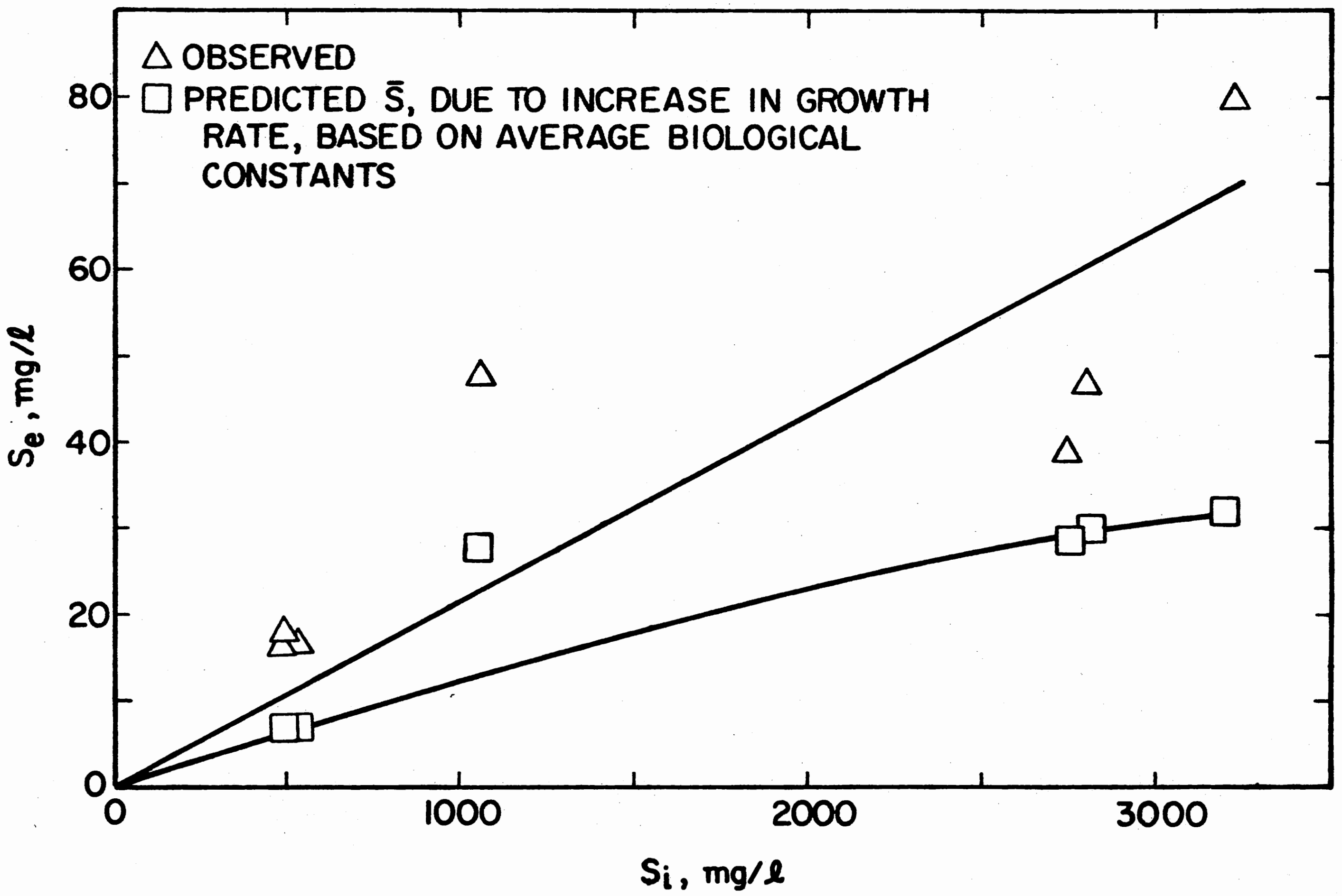

△ OBSERVED
□ PREDICTED $\bar{S}$, DUE TO INCREASE IN GROWTH RATE, BASED ON AVERAGE BIOLOGICAL CONSTANTS
S_e , mg/ℓ
0
20
40
60
80
S_i, mg/ℓ
0
1000
2000
3000

Figure 34. Effect of Influent Substrate Concentration, S_i, mg/l and Specific Growth Rate, μ, Day^{-1} on Effluent Soluble Substrate Concentration, S_e, mg/l at X_R of 10,000 mg/l. Average Values of μ_{max} = 0.47 hr^{-1}, K_s = 205 mg/l, and Y_{tB} = 0.57 obtained From Batch Growth Studies Were Used


△ OBSERVED
□ PREDICTED $\bar{S}$, DUE TO INCREASE IN GROWTH RATE, BASED ON AVERAGE BIOLOGICAL CONSTANTS
S_e, mg/ℓ
0
20
40
60
80
S_i, mg/ℓ
0
1000
2000
3000

curves can be seen in Table VI, columns 3 and 5 for observed values, and columns 3 and 9 for calculated values.

It is observed that these lines diverge; that is, as S_i was increased, the value of S_e over and above that which may be attributable to an increase in specific growth rate, μ, increases. The net increase in S_e with increasing S_i for both systems shown in Figures 33 and 34 are plotted in Figure 35. As could be surmised from the previous two figures, the increase in residual COD for increased S_i is slightly concave upward--the rate of increase in S_e increases as S_i is increased. However, over the range of S_i values in these studies, one could approximate the variation in S_e with S_i as a linear relationship. Also, it is seen that when one subtracts out the effect of the recycle solids concentration on μ, and therefore on S_e, the residual COD was essentially independent of X_R. There were not sufficient data points for glucose to subject the results to similar analysis. From the foregoing analysis, it can be seen that the biological constants μ_{max}, K_s, and Y_{t_B} gave very satisfactory predictions in X and X_w but not with respect to S_e. Also, it can be seen that the true yield value obtained from the maintenance plot, 0.61, was very close to the average cell yield values obtained in batch study, 0.57.

One may also determine values of μ_{max} and K_s from the continuous flow studies. In Figure 36 the plotted points represent the values of specific growth rate μ, calculated from the continuous flow data plotted against COD_e observed during each run. It is seen that the trends of the data are such that a rectangular hyperbola appears to provide the best mathematical description of the data. As with the case of specific substrate removal rate, U, the rectangular hyperbola may be plotted

Figure 35. Relationship Between Residual COD and S_i at X_R of 5000 mg/l and 10,000 mg/l

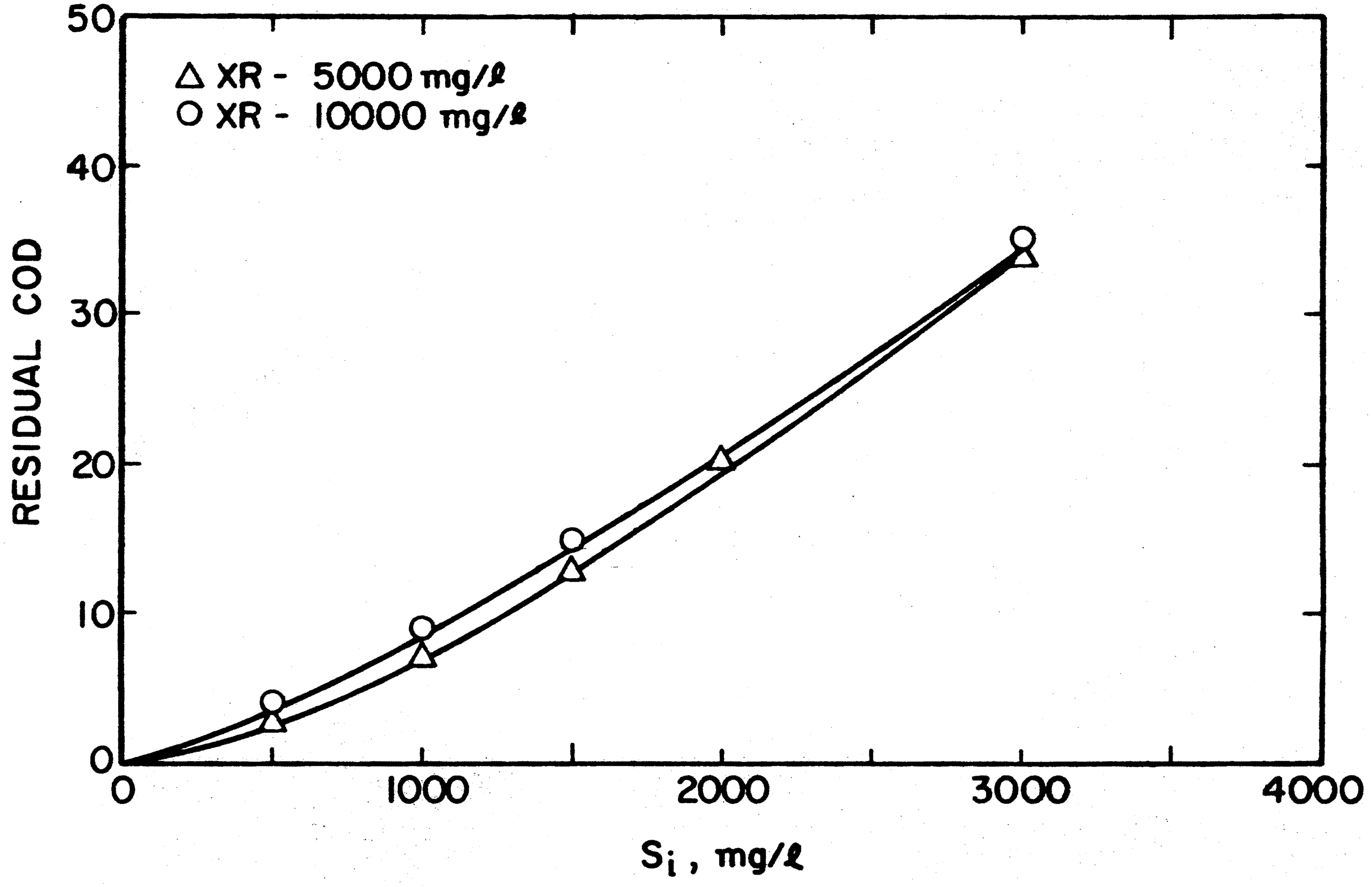
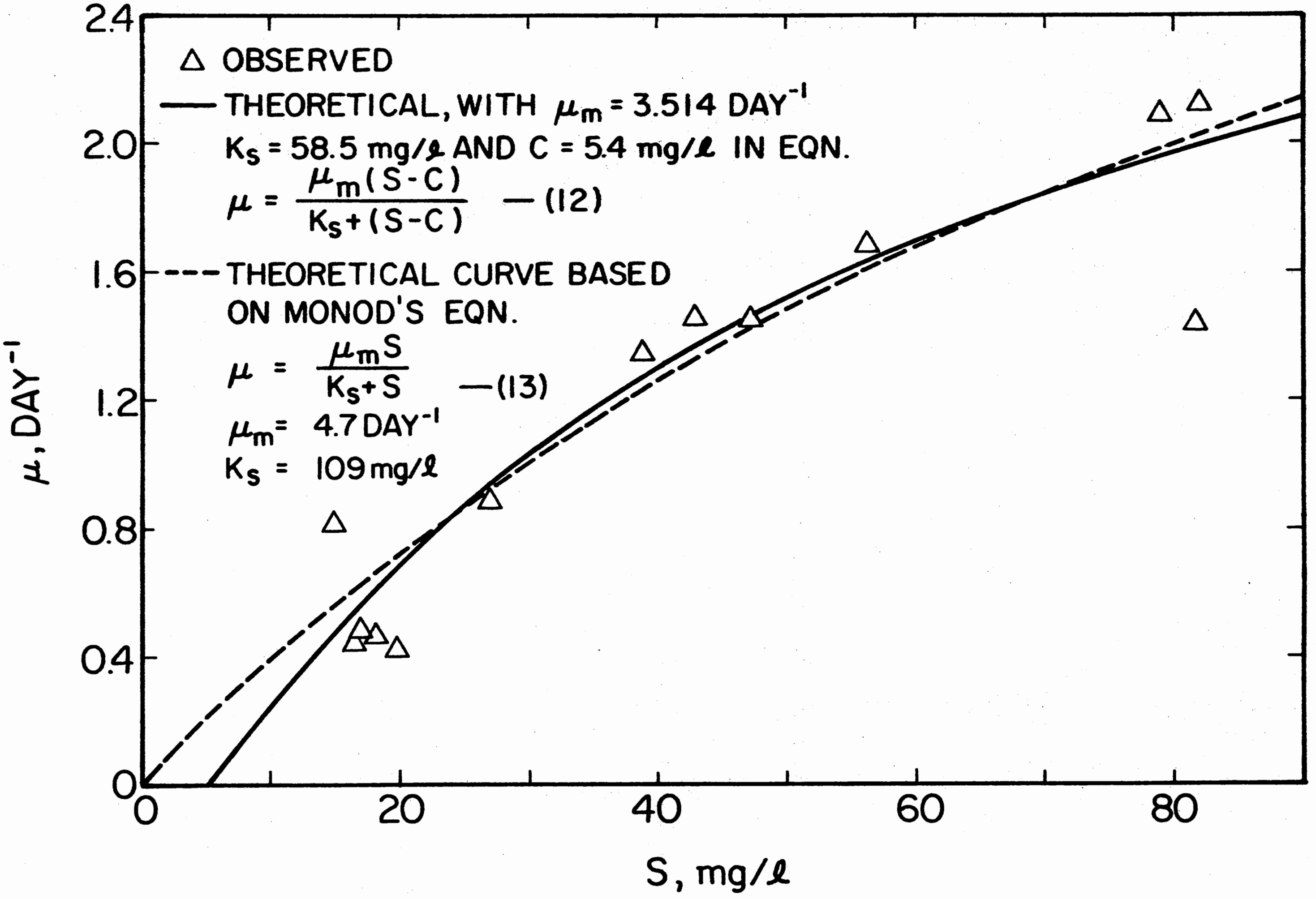

△ XR - 5000 mg/ℓ
○ XR - 10000 mg/ℓ
RESIDUAL COD
0
10
20
30
40
50
0
1000
2000
3000
4000
S_i , mg/ℓ

Figure 36. Relationship Between Specific Growth Rate, μ, Day^{-1} and Effluent Substrate Concentration, S_e, mg/l for Continuous Flow Unit


△ OBSERVED
THEORETICAL, WITH $\mu_m = 3.514$ DAY^{-1}
$K_s = 58.5$ mg/ℓ AND C = 5.4 mg/ℓ IN EQN.
$\mu = \frac{\mu_m (S-C)}{K_s + (S-C)}$ — (12)
THEORETICAL CURVE BASED ON MONOD'S EQN.
$\mu = \frac{\mu_m S}{K_s + S}$ — (13)
$\mu_m = 4.7$ DAY^{-1}
$K_s = 109$ mg/ℓ
μ, DAY^{-1}
2.4
2.0
1.6
1.2
0.8
0.4
0
0
20
40
60
80
S, mg/ℓ

through zero or it may be plotted to intercept positively the S_e axis. The solid curve on the figure is one plotted in accordance with equation (12) using the values of μ_{max}, K_s, and C shown on the figure. These were determined using the same procedures employed to establish the constants for Figure 32. Also shown on the figure (see dashed lines) is the calculated curve using the Monod equation through zero. The values of μ_{max} and K_s in this case were 4.7 $days^{-1}$ and 109 mg/l, respectively. The percent error of fit for the curve going through the axis was calculated to be 0.70 whereas the residual error for the rectangular hyperbola intersecting S_e was 0.68. It can be seen that μ_{max} and K_s were considerably higher in batch than they were for the continuous flow data (compare values in Figures 36 with those in Table III); μ_{max} values in batch were two to three times higher than for the continuous flow data whereas K_s values were more than double those obtained for the continuous flow data. It was of interest to use the values of K_s and μ_{max} obtained by both methods, together with values of true yield and the K_d value to predict values of S_e. Table VIII shows a comparison of calculated and observed values of S_e for the sorbitol runs. It is apparent that the calculated value using the values of μ_{max} and K_s from the continuous flow data gave a somewhat better prediction of S_e than did the batch values of μ_{max} and K_s. This does not seem surprising since the values for μ_{max} and K_s were calculated using values of S_e observed in the experimentation; it is possible to more closely reproduce the S_e values when the same values are used to estimate μ_{max} and K_s. This speaks well for the model but one cannot say that this mathematical exercise has predicted S_e values. Also, it should be borne in mind that there is yet insufficient information to

TABLE VIII

PREDICTION OF S, BASED ON BIOLOGICAL CONSTANTS OBTAINED FROM CONTINUOUS FLOW DATA

Line	Influent Substrate		Predicted Effluent Substrate Concentration, mg/l, Based on Continuous Flow Unit*	Observed Effluent Substrate mg/l
2	529	sorbitol	15.2	6.3
3	2748	sorbitol	82.5	78.8
4	606	sorbitol	18.3	27.0
5	1775	glucose:1 sorbitol:2	52.9	56.1
6	1540	glucose:2 sorbitol:1	45.4	42.9
8	2835	sorbitol	89.0	81.9
9	605	sorbitol	17.6	14.7
10	532	sorbitol	7.7	17.3
11	3217	sorbitol	47.9	80.8
12	512	sorbitol	7.4	18.4
14	2743	sorbitol	41.3	38.7
16	2812	sorbitol	42.5	46.9
17	523	sorbitol	7.7	16.0
19	504	sorbitol	7.3	20.0
21	3080	sorbitol	31.2	46.0

*μ_{max} = 3.51 day^{-1}
K_s = 58.5 mg/l
Y_t = 0.61

determine the difference between residual non-biological COD and COD which should be accounted for as usable carbon source. Considerably more research effort is warranted to determine the most usable measure of substrate for testing the accuracy of prediction by this model as well as other models for activated Sludge. The problem is complicated because while estimates of the accuracy of a model is important, it may not necessarily be substrate removal which is the essential consideration. The benefit that biological treatment plants may be expected to have is their ability to remove small amounts of non-biodegradable organic matter as well as organic substrates. Thus, even if it could be shown that a high residual COD was non-biodegradable at the treatment plant, it might still be necessary to remove the residual COD for other reasons. Thus, the interest of the field is not so much in obtaining a measure of substrate to predict veracity of models, but in devising systems which will remove organic matter.

CHAPTER V

CONCLUSIONS

The results of this investigation lead to the following conclusions:

1. A system operating at X_R of 5000 mg/l may be expected to accommodate a qualitative shock consisting of various ratios of sugar and sugar alcohol with total concentration of S_i as high as 1500 mg/l without seriously deleterious effects on effluent quality.

2. The fact that substrate leakage was higher when higher concentrations of glucose (1000 mg/l) along with sorbitol concentrations of 500 mg/l were applied indicates that even at the low specific growth rates extant in these systems, a more rapidly metabolized carbon source can interfere with metabolism of another.

3. A six-fold quantitative shock led to a considerable leakage from the reactor even though the clarifier attenuated the leakage. However, an increase in X_R from 5000 to 10,000 mg/l attenuated the leakage due to the six-fold quantitative shock.

4. A six-fold quantitative cyclic shock load consisting of sorbitol as substrate can be accommodated after a considerable period of transient upset. Ultimately the increased loading was accommodated without harmful effect on effluent quality.

5. These studies provide some indication that a combined quantitative and hydraulic shock leading to a four-fold increase in mass loading rates can give a slightly more adverse effect with respect to

effluent quality than a purely hydraulic shock of equivalent mass organic loading.

6. It seems that a combined six-fold quantitative and hydraulic shock is as deleterious as an equivalent (mass feed rate basis) quantitative shock load.

7. The predicted soluble CODs in the effluent were much lower than the observed values. However, proper correction for non-biodegradable COD of the effluent might bring predicted soluble COD closer to observed value.

8. The arithmetic plot of substrate utilization rate, U, vs. S in the effluent did not fit a straight line, but more closely followed a hyperbolic fit, not passing through the origin, than did a straight line.

9. An increase in S_i gave an increased S_e, and the increase in X_R did not reduce or change the non-biodegradable fraction of S_e.

10. When the present steady state data on glucose was included with previous data of Srinivasaraghavan and Saleh, the overall k_d was 0.18 day^{-1}, indicating that there was little change in k_d over a five-year period.

11. For sorbitol, the k_d value was 0.1 day^{-1}.

12. For prediction of X, S_e, and X_w for the activated sludge system with constant sludge recycle, use of the biological constants, μ_{max} and K_s obtained from the continuous flow data, gave calculated values of S_e closer to the observed values.

13. Based on three years of operational experience, this investigation is able to substantiate the conclusions of the two investigators who preceded him in the finding that the use of X_R as a control

parameter rather than the Herbert parameter c (recycle sludge concentration ratio) or the internal sludge recycle system is readily facilitated. That is to say, there are no particularly difficult or arduous operational tasks in this mode of pilot plant operation, and it would appear that the same will be true for large scale field operations.

CHAPTER VI

SUGGESTIONS FOR FUTURE STUDY

Based on the results of this study, the following suggestions are presented for future investigation on the activated sludge process using X_R as a control parameter.

1. Response of the system to a simultaneous change in X_R when it is subjected to a shock loading will give some additional information about the recirculation of higher concentrations of solids as a remedial measure for shock loading.

2. Studies should be made to use the biomass available from other systems such as aerobic digesters for recycle sludge to determine whether the physiological condition of the existing biomass is sufficiently close to that of the new source of recycle sludge so that the change in X_R does not itself act as a shock load. Such study should help to choose possible sources from which additional sludge could be obtained for higher concentration of X_R when needed. It would appear that sludge from an aerobic digester might prove worthy of investigation.

3. In order to determine the frequency of occurrence of the process of oxidative assimilation in response to shock loading, the same shock should be applied to systems with widely differing values of the biokinetic constants, particularly μ_{max} and K_s. The quantitative shock not accompanied by a concomitant increase in nitrogen source

would seem to provide a good test.

4. Experiments on cyclic qualitative shock loading (e.g., cycling of glucose and sorbitol every 12-hour period) should provide very interesting data on the ability of the biomass to accommodate to change.

5. In order to separate the effect of specific growth rate, μ, and biomass concentration, X, on ability to accommodate a shock load, experiments should be designed using very young cells as well as old cells, e.g., those obtained from an extended aeration system.

6. Growth study experiments with various combinations of substrates to determine μ_{max}, K_s, and Y_{t_B} should be conducted.

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APPENDIX

KINETIC EQUATIONS

$$\Theta_c = \frac{1}{\mu_n} \tag{13}$$

$$U = \frac{D\left[S_i - \bar{S}\right]}{X} \tag{14}$$

$$Y_o = \frac{\mu_n X}{D\left[S_i - (1+\alpha)\bar{S}\right]} \tag{15}$$

$$\mu_n = D\left(1+\alpha-\alpha\cdot\frac{X_R}{X}\right) \tag{16}$$

$$\bar{X} = \frac{Y\left[S_i-(1+\alpha)S\right] + \alpha XR}{1+\alpha + \frac{k_d}{D}} \tag{16}$$

$$aS^2+bS+c = 0 \tag{18}$$

$$a = \left[\mu_m-(1+\alpha)D-k_d\right] \tag{19}$$

$$b = D\left[S_i - (1+\alpha)K_s\right] - \frac{\mu_m}{1+\alpha}\left[S_i + \frac{\alpha XR}{Y_t}\right] + 1_d\left[\frac{S_i}{1+\alpha} - K_s\right] \tag{20}$$

$$C = K_s DS_i + \frac{K_d}{1+\alpha} K_s\ S_i \tag{21}$$

$$S = \frac{-b \pm \sqrt{b^2-4ac}}{2a} \tag{22}$$

$$Y_o = \frac{X_w}{F(s_i-\bar{S})} \tag{23}$$

$$Y_o = \frac{Y_t \mu_n}{\mu} \tag{24}$$

$$\mu_n = \frac{X_w}{V \cdot X} \tag{25}$$

$$\frac{1}{Y_o} = \frac{1}{\mu_n} \cdot \frac{k_d}{Y_t} + \frac{1}{Y_t} \tag{26}$$

$$\mu_n = Y_t\ U - k_d \tag{27}$$

VITA 2

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Doctor of Philosophy

Thesis: STUDIES ON THE EFFECTS OF COMBINED QUALITATIVE AND QUANTITATIVE SHOCK LOADINGS ON AN ACTIVATED SLUDGE PROCESS WITH CONSTANT CONCENTRATION OF RECYCLE SLUDGE

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