A STUDY OF THE LAWRENCE AND McCARTY θ_c DESIGN MODEL AS AN OPERATIONAL CONTROL METHOD FOR THE ACTIVATED SLUDGE PROCESS

By

CARL DAVID PARROTT

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1974

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
July, 1980

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Thesis Approved:

Don F. Kincannon
Thesis Adviser

Marcia H. Bates

T. S. Manickam.

Norman N. Durham
Dean of Graduate College

ACKNOWLEDGMENTS

The author sincerely appreciates the help rendered by the following individuals and organizations during the course of this study:

Dr. Don F. Kincannon, thesis adviser, for his valuable advice, encouragement, and assistance throughout the course of the research and the writing of this thesis.

Dr. Richard N. Devries, E.P.A. Agency Fellowship Grant sponsor for his assistance in making my E.P.A. Fellowship Grant possible and for his valuable advice and encouragement throughout my studies in bioenvironmental engineering at Oklahoma State University.

Dr. Marcia H. Bates, committee member, for her valuable advice and encouragement during my final year in bioenvironmental engineering at Oklahoma State University.

Dr. T. S. Manickam, committee member, for his valuable advice and assistance throughout my research at the Oklahoma State University Bioenvironmental Laboratories.

Ms. Charlene Fries for her careful and accurate typing of this thesis.

All of my colleagues in the bioenvironmental engineering laboratories for their cooperation and help during the course of this study.

Mr. Charles D. Newton, Chief of the Water Quality Service of the Oklahoma State Department of Health, for his assistance in making my E.P.A. Fellowship Grant possible.

The Oklahoma State Department of Health and the Environmental Protection Agency for making my E.P.A. Fellowship Grant possible, and thus my completion of this study.

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Symbol

F_w - Amount of wastage flow rate per day

F - Influent hydraulic flow rate

K - Maximum substrate utilization rate

k_d - Maintenance energy coefficient

K_s - Saturation constant

S_i - Influent substrate concentration

S_e - Soluble effluent substrate concentration

V - Volume

X - Biological solids concentration in the aeration tank

X_e - Biological solids concentration in the clarifier effluent

X_R - Biological solids concentration in the recycle flow to the reactor

Y_t - True sludge or cell yield

θ_c - Mean cell residence time (MCRT)

CHAPTER I

INTRODUCTION

Water pollution control legislation enacted in the past decade has created the need for the design and operation of wastewater treatment processes with increased emphasis on the effluent standards that the process will achieve. This increased concern for effluent quality has convinced many bio-environmental engineers that the use of mathematical models based on microbiological kinetic constants in the design and operation of wastewater treatment processes is much more desirable than the empirical methods used in the past. These design models are particularly applicable to the design and operation of the conventional activated sludge system.

One mathematical model used in the design of the conventional activated sludge process is the Lawrence and McCarty (1) mean cell residence time model. This model has been shown by Kincannon and Gaudy (2) to be a workable design method, but its merits as an operational control method have not been evaluated adequately. This study has made an attempt to do this.

A good workable operational control method is needed in this country as shown by a survey made in 1975 by the Environmental Protection Agency which revealed that only 54 percent of those activated sludge plants surveyed were producing an effluent below the standards set by the Federal Water Pollution Control Act Amendments of 1972 (PL 92-500)

(3). Operational problems often arise because the influent substrate concentration and hydraulic flow rate to most wastewater treatment plants are constantly changing and the microorganism populations in the system cannot adjust rapidly enough to these changes without operational modifications to help keep the system in balance. The operator cannot be solely blamed for no response or a late response because the operational changes needed in these situations cannot be made without knowledge of the magnitude of the changes in the influent as they occur. Current analytical techniques in common use today for evaluating influent substrate concentration cannot deliver the results quickly enough. For instance the biochemical oxygen demand test takes five days to complete and the chemical oxygen demand test requires at least a three hour lag time.

The total organic carbon analyzer may be able to fill this gap. With this in mind the Lawrence and McCarty θ_c model was employed as an operational control method at different hydraulic flow rates and influent substrate concentrations to evaluate its ability to make predictions of "steady state" conditions using BOD_5 data as a basis for the predictions and TOC data as a test of its usefulness in this respect.

CHAPTER II

LITERATURE REVIEW

Activated Sludge Control Methods

There are many methods of control of the activated sludge process in use today. All essentially have the same objectives in mind; to produce a soluble effluent of acceptable quality, and to establish a population of biological solids that will settle well in the secondary clarifier thus allowing few solids to escape through the effluent.

One of the simpliest methods of control that requires a minimal amount of laboratory work is the maintenance of a constant mixed liquor volatile suspended solids (MLVSS) concentration in the aeration basin. To accomplish this the operator must select a MLVSS concentration that seems to produce a desired effluent then waste just enough solids daily to maintain that solids level. This method works very well as long as the influent substate concentration (S_i) and hydraulic flow rate (F) remain fairly constant, however if the S_i or F should fluctuate the food to microorganism (F/M) ratio can be upset which can cause drastic changes in the effluent characteristics (4, 5 and 6). A detailed example for calculating the sludge wastage per day for this method can be found elsewhere (4).

Another method used that seems to have more merit than the above method is the maintenance of a constant F/M ratio by sludge wastage. This method assures proper organic loading to the system by keeping a mass of microorganisms in the system sufficient to utilize most of the influent substrate available. BOD, ΔCOD, or ΔTOC can be used to measure the food so that the portion of the TOC and COD not available to the microorganisms will not be included in the calculation. The concentration of microorganisms can be approximated in the aeration basin by the MLVSS concentration in the reactor. This may not be an accurate measurement of the viable microorganisms in the system (5). Typical ranges for F/M loadings as well as example calculations can be found in the E.P.A. Process Control Manual. Also given is a plot of sludge volume index vs. F/M ratio that shows that the settleability of sludge in the final clarifier is effected by the F/M ratio (4). Cushion, Keinath, and Schule (7) found that the extent of control that an operator has on F/M ratio is limited unless and external storage for biological solids is provided so that a substantial resource of microorganisms can be used in times of increase in influent substrate concentration to maintain a proper F/M ratio.

Also mentioned in the E.P.A. Process Control Manual for Aerobic Biological Wastewater Treatment Facilities (4) is the constant Gould sludge age control method. The GSA method is based on the theory that the BOD and suspended solids concentration of the influent are fairly constant. Thus with this method only the suspended solids of the influent, the suspended solids in the aeration tank, and the influent flow rate are needed to determine the Gould sludge age. Then the wastage sludge can be determined to maintain the GSA that will produce the desired effluent quality. This method was first used by Gould on the control of a plant in New York City. This method will of course present problems if the BOD to suspended solids ratio in the influent changes.

Again, example calculations for this method can be found in the E.P.A. Process Contol Manual (4) mentioned above.

Sludge quality control is another method mentioned in the E.P.A. manual (4). This method may be used alone or with other methods. Many control tests can be utilized in carrying out this method. They include the 30 minute sludge settleability test, measurement of the sludge blanket depth in the final clarifier, MLSS concentration by centrifuge test on aeration basin and return sludge, secondary effluent turbidity, dissolved oxygen in the aeration basin, microscopic examination of MLSS, aeration basin observations, and secondary clarifier observations. The data taken from the control tests mentioned above are plotted on graphs against time. The trends that produced the optimum process performance are then utilized to maintain the system at a sludge quality level that will produce the best effluent. Details on this control method can be found in reference number 4.

Two oxygen uptake rate control methods are given by Benefield, Randall, and King (6), and by Haas (8). These methods claim better control because fluctuations in influent loading can be compensated for quickly. Oxygen uptake rate will increase with increase in influent concentration or hydraulic flow rate (9) which will tell the operator to adjust return sludge flow and sludge wastage rate to compensate for this. Constant laboratory study and mathematical manipulation is required to carry out these methods, but if used properly they may have great merit.

Maintaining a constant specific substrate utilization rate within the aeration tank can be used as a control method. With this method the operator monitors the influent and soluble effluent for BOD, COD, or TOC.

The specific substrate utilization rate is then found and the solids wastage is adjusted to achieve the specific substate utilization rate desired (6). Details for finding specific substrate utilization are given by Kincannon and Gaudy (2).

The last method to be discussed is the mean cell residence time method. This method is similar to the specific substrate utilization rate method but in this method provisions for predicting the sludge wastage per day are also available. The F/M ratio can be controlled by the MCRT method as well. For these reasons this method is considered the best control technique available given current technology (4).

The MCRT is defined as the reciprocal of the growth rate of the microorganisms in the system (2). The operator selects the MCRT that will give the best soluble effluent in terms of COD, BOD, or TOC and the F/M ratio that will give a sludge with a good sludge volume index. Example calculations for determining the wastage flow to reach the desired MCRT are given in the E.P.A. Manual (4) as well as graphs for determining daily wastage flows graphically. One plot given allows for solids in the effluent and the other does not.

Other methods for hydraulically controlling the mean cell residence time have been suggested by Garrett (10), Burchett and Tchobanoglous (11), Walker (5), and Roper and Grady (3). These methods ignore the biological solids in the reactor or in the effluent, or both which can significantly effect the MCRT if many biological solids are being lost through the effluent.

Jenkins and Garrison (12) came up with the first kinetically rational means of controlling the MCRT (θ_c) in 1968. This method utilized the Monod theory (13) of microbial growth rate's relationship to the concentration of the growth-limiting substrate. Lawrence and McCarty (1) later expanded on the model of Jenkins and Garrison (12) to include anaerobic digestion, and aerated lagoons as well as conventional activated sludge. A mimimum θ_c (θ_c^m) was also introduced at which wash out of the biological solids will occur. The Lawrence and McCarty (1) θ_c method is used in this study as the operational method employed. Further detail of procedure and equations used will be given in Chapter III.

Effects of Fluctuations in Influent Substrate Concentration and Hydraulic Flow Rate

The Monod theory (13) states that the influent substrate concentration has no effect on the soluble effluent concentration achieved, thus when applied to the activated sludge system the soluble effluent concentration is only dependent on the mean cell residence time. The concentration of biological solids in the reactor increases with an increase in influent substrate concentration or hydraulic flow rate to utilize all substrate available, thus giving a fixed soluble effluent concentration under steady state conditions. This is the basis of the Lawrence and McCarty (1) mean cell residence time (θ_c) model as well as other kinetic models (2).

Grady and Williams (14), however, dispute this theory and contend that the soluble effluent achieved will fluctuate with fluctuations in influent substrate concentration and thus postulate that in the operation of an activated sludge system a concentration of influent substrate can be reached for which the design θ_c must be increased to achieve the design effluent. Benefield and Randall (15) also adhere to this theory. Manickam and Gaudy (16) approached this theory and concluded that there was an increase in soluble effluent COD, but that this increase was not significant enough at growth rates encountered in the conventional activated sludge process to warrant the modification of current models.

Internal recycle pilot plant studies for the evaluation of changes in steady state conditions as predicted by mean cell residence time methods have been limited. Adams and Eckenfelder (17) used this type of system in their study of transient state conditions produced by short increases in influent TOC but employed an operational method developed by Garrett and Sawyer (18). The turbidity of the effluent, caused by dispersed growth of rod shaped and spherical as well as short filamentous bacteria, showed an increase with increases in the average organic loading. Using synthetic influent substrates it was determined that the systems could tolerate up to three times the normal loading for up to 12 hours a day for several days without a significant increase in effluent soluble organic matter. This was also observed by Saleh and Gaudy (19) at Oklahoma State University.

Other studies on fluctuations of influent substrate concentration and hydraulic flow rate have been conducted by Dr. Anthony F. Gaudy, Jr., at Oklahoma State University using once-through and external cell recycle systems with sludge thickening tanks (16, 19, 20, 21, 22, and 23). These will be covered in the next few paragraphs.

Thabaraj and Gaudy (20) found that in a once-through system with a secondary clarifier that after an increase in influent COD there may be an initial increase in the biological solids in the reactor followed by a decrease in biological solids in the reactor, then followed by a second increase in solids in the reactor to a new steady state condition accompanied by very little solids leakage out the effluent.

Krishman and Gaudy (21) using once-through and cell recycle systems, employing the Herbert kinetic model (24) in their operational control, found an increase in detention time to reflect a more rapid recovery from increases in influent substrate concentration, as observed by Grady and Schaezler in Reference (21), before them. In comparing the once-through systems with all recycle systems, the cell recycle systems showed much quicker response than the once-through systems reflecting the lower growth rate in recycle systems. This conclusion was supportive of Gaudy and co-workers' model (2) used in the next study by Saleh and Gaudy (19).

Saleh and Gaudy (19) employed a constant sludge recycle concentrations, (X_R), of 5000 mg/ℓ. A threefold increase and a sixfold increase were applied to the influent in terms of COD until a new steady state was reached, then the influent COD wad dropped back to the previous level. In each case the biological solids increased to a peak level above the predicted steady state and then dropped back to a steady state very close to that predicted. The response times to reach a new steady state with respect to biological solids in the reactor were about 3.5 and 6 days, respectively. Filamentous growth was observed in the transient state of the sixfold increase in COD. Solids were lost out the effluent up to a peak of 380 mg/ℓ but no appreciable increase in the soluble effluent COD was noticed. When the influent COD's were decreased, the previous steady state conditions were reached without any changes in effluent quality with respect to effluent suspended solids or soluble COD concentration.

Manickam (22) in his studies of increases in influent COD comparing sludge recycle rates of 5,000 mg/ℓ and 10,000 mg/ℓ found that the sixfold increase in sorbital concentration in terms of COD led to a considerable change in effluent quality and that the increase in X_R attenuated this change. The biological solids in the reactor (X_R) increased rapidly after the increase in influent COD but did not show much of an overshooting of the predicted X as observed by Saleh and Gaudy (19). When the influent COD was decreased no appreciable change in the effluent suspended solids was observed but the soluble COD in the effluent decreased. An overshoot in X was observed in dropping from 3,000 mg/ℓ to 500 mg/ℓ COD of sorbitol at a sludge recycle concentration of 5,000 mg/ℓ.

George and Gaudy (23) did studies on changes in hydraulic loading using a once-through system with a final clarifier and another model for operational control. They found that a 50 percent increase in hydraulic flow rate (F) did not cause any significant changes in effluent quality. Biological solids did not show any appreciable increase either. A 100 percent increase in flow rate caused a transient increase in total effluent COD with no appreciable increase in anthrone COD indicating an increase in metabolic intermediate by-products. This increase in F caused the biological solids in the reactor to increase as expected. An equalization basin was recommended in anticipation of increases in F of greater than 100 percent.

Mor and Fiechter (25) in a pure culture study observed that an increase in hydraulic flow rate caused an increase in biological solids concentration in the reactor to reflect an overshoot similar to that mentioned with increases in influent substrate concentrations.

Su (26) in his Ph.D. studies at Oklahoma State University concluded that after a change in dilution rate was made in a once-through system at least 10 dilution times were required to reach a new steady state.

CHAPTER III

EXPERIMENTAL APPARATUS AND SYNTHETIC FEED CONSTITUENTS

Experimental Apparatus

The pilot plant employed in this study was an internal recycle activated sludge system similar to the one shown in Figure 1. It consisted of a three liter aeration basin and a one and one-half liter sedimentation basin in a Plexiglas frame with an adjustable baffle to separate the two basins. Air was provided to the aeration basin by two stone diffusers with air passing through a cotton filter and flow meter to assure clean air at an adequate flow rate. The baffle was placed close to the bottom of the tank to maintain a constant recycle of sludge while at the same time maintaining quiescent conditions in the sedimentation basin. A 20 liter plastic bottle was used to mix and hold the feed for pumping. The flow rate to the reactor was held at a constant rate by a variable flow dual, positive displacement pump (Milton & Roy Model DB-1-175 R). The flow rate was checked twice daily.

The heterogeneous biological population employed in this study was obtained from anaerobic digester sludge taken from the Stillwater Municipal Wastewater Treatment Facility. This sludge was also used in the reactors from which the kinetic constants utilized in this study were taken. The room temperature of the laboratory was maintained fairly

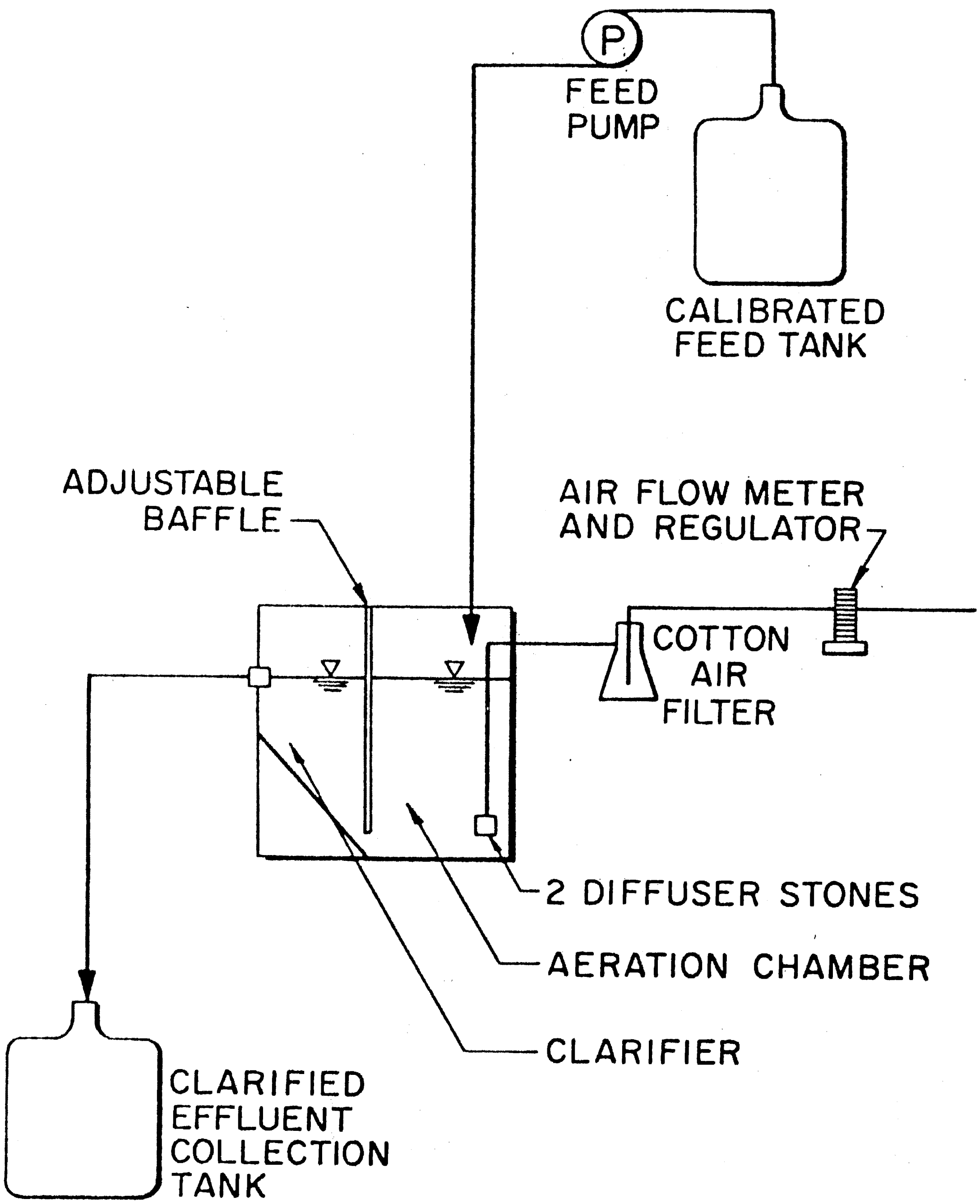

Figure 1. Activated Sludge Pilot Plant
With Internal Recycle

constant throughout the study and the pH in the reactor was held between 6 and 8 by addition of sodium hydroxide if needed.

Feed Preparation

A synthetic waste was used in this study with organic and inorganic constituents, as shown in Table I. These constituents were mixed with tap water in varying amounts to form the desired concentration of carbonaceous waste needed. The mixture required to produce an average BOD_5 of 250 mg/ℓ is given at the bottom of the table. The nutrients and minerals required for growth and synthesis by the heterogeneous microbial population employed were provided by the inorganic constituents as can be seen.

General Operational Procedure

The continuous flow internal recycle reactor described above was operated from December 6, 1979, to May 2, 1980, at a constant mean cell residence time of approximately 3.33 days using the Lawrence and McCarty (1) mean cell residence time (θ_c) design model as the means of operational control. Three basic types of changes in the influent were made during this time. Between each change a steady state condition was reached as determined by data collection.

Types of Influent Changes

Increase in Influent Substrate Concentration

In this type of change a step increase in influent substrate concentration was made without any change in the hydraulic flow rate.

TABLE I

FEED CONSTITUENTS

Organic Feed Constituents	
Ethylene Glycol	113 ml/ℓ
Ethyl Alcohol	113 ml/ℓ
Acetic Acid	113 ml/ℓ
Glutomic Acid	113 gms/ℓ
Phenol	22.6 gms/ℓ
Fill to 1 Liter with Distilled Water	

Inorganic Feed Constituents	
$(NH_4)_2\ SO_4$	200 gms/ℓ
$Mg\ SO_4 \cdot 7H_2O$	80 gms/ℓ
K_2HPO_4	48 gms/ℓ
C_aCl_2	8 gms/ℓ
$F_eCl_3 \cdot 6H_2O$	0.4 gms/ℓ
Fill to 1 Liter with Distilled Water	

For BOD_5 = 250 mg/ℓ add 40 ml of inorganic mix and 15 ml of organic mix and fill to 20 Liters with tap water.

Decrease in Influent Substrate Concentration

In this type of change a step decrease in influent concentration was made without any change in the hydraulic flow rate.

Increase in Hydraulic Flow Rate

In this type of change an increase in hydraulic flow rate was made with no appreciable change in the influent substrate concentration.

Analytical Procedures

Influent

Total organic carbon and five day biochemical oxygen demand samples were analyzed twice a week.

Effluent

Soluble TOC and BOD_5 samples were analyzed twice a week. Suspended solids were run from at least two days a week to daily.

Reactor

Mixed Liquor Suspended Solids were run from twice a week to daily.

Analytical Techniques

The methods employed for the analysis of the experimental data are given below.

Total Organic Carbon (TOC)

The TOC concentrations were determined by the use of the Beckman

TOC analyzer model number 915. This technique was used in finding both influent and soluble effluent total organic carbon concentrations.

Biochemical Oxygen Demand (BOD_5)

The BOD_5 procedure used was that given in Standard Methods for the Examination of Water and Wastewater (27). The probe method was used for determining dissolved oxygen.

Suspended Solids

The membrane filter technique as given in Reference (27) was used. The filter employed was a 0.45 micron Millipore filter.

Methods for Making Predictions

Predictions Based on BOD_5 Data

Kinetic constants for BOD_5 were first determined using Lawrence and McCarty's (1) θ_c method and data obtained from other units being run in the Oklahoma State University Bioenvironmental Engineering Laboratories that were seeded from the same source and run using the same synthetic feed. These BOD_5 kinetic constant values are shown in Table II. Using these kinetic constants, a θ_c was determined that would give a soluble effluent BOD_5 (S_e) of 5 mg/ℓ. The following equation was used:

$$\theta_c = \frac{K_s + S_e}{S_e (Y_t K - k_d) - K_s k_d} \qquad (3.1)$$

Symbol nomenclature is found in the List of Symbols. When the kinetic constants were plugged into this formula along with the S_e in BOD_5, a desired θ_c of 3.33 days was obtained. The reactor was maintained at this θ_c throughout the study when operating under steady state conditions.

TABLE II

KINETIC CONSTANTS USED FOR BOD_5 DATA PREDICTIONS

$K = 9$ days
$K_S = 60$ mg/ℓ
$Y_t = 0.65$
$k_d = 0.15$ days^{-1}

Predictions of biological solid concentrations in the reactor and sludge wastage flow rate per day to reach steady state conditions at the 3.33 day θ_c were made using the following two equations. Again, symbol nomenclature can be found in the List of Symbols. Equations (3.2) and (3.3) follow:

$$X = \frac{\theta_c \; F \; Y_t \; (S_i - S_e)}{V \; [1 + k_d \; (\theta_c)]} \tag{3.2}$$

$$F_w = \frac{VX/\theta_c - F \; X_e}{X_R - X_e} \tag{3.3}$$

The predicted X was used for X and X_R, since X_R is equal to X in an internal recycle unit. X_e was set at 10 mg/ℓ for this study. The approximate influent BOD_5 concentration expected was used at first for predictions; then after some influent BOD_5 samples were run, these predictions were adjusted for better accuracy. The sludge wastage was made once a day at approximately the same time from the mixed liquor obtained when the baffle was removed and the entire contents were mixed. Mixed liquor suspended solids tests were run on a part of this sludge wastage flow.

Predictions Based on TOC Data

Kinetic constants for TOC were determined using Lawrence and McCarty's (1) θ_c method and data obtained from other units being run in the Oklahoma State University Bioenvironmental Laboratories that were seeded from the same source and run using the same synthetic feed. These TOC kinetic constants are shown in Table III. Since sufficient data were not available to determine the kinetic constants for TOC until the end of April, the TOC data could not be used to predict X and F_w during the study; these data were only used as a check after the study to determine if they could have been useful in the operational control of the unit using Lawrence and McCarty's θ_c method.

TABLE III

KINETIC CONSTANTS USED FOR TOC PREDICTIONS

$K = 1.63$ days
$K_s = 181.7$ mg/ℓ
$Y_t = 0.92$
$k_d = 0.022$ days^{-1}

In using the TOC kinetic constants, the soluble effluent TOC first had to be determined at a θ_c of 3.33 days. Thus Equation (3.1) was rearranged and solved for S_e. Equation (3.4) was used:

$$S_e = \frac{K_s(1 + k_d \theta_c)}{\theta_c(Y_t K - k_d) - 1} \tag{3.4}$$

Symbol nomenclature can again be found in the List of Symbols. When the kinetic constants obtained were plugged into Equation (3.4), along with the θ_c used for this study of 3.33 days, an S_e of 49.7 mg/ℓ in terms of TOC was obtained.

Equations (3.2) and (3.3) for the predicted X and F_w given in the previous section were again used to determine what these values would have been using TOC data.

Since the S_e actually achieved during the study was much lower than predicted, the average S_i and S_e values obtained as well as the average S_i and predicted S_e values were used to make predictions to illustrate the effect of adjusting the kinetic constants to compensate for the differences shown in the predicted S_e and the actual S_e. The same trend was shown in the S_e predictions in terms of BOD_5, so the same procedure was used with BOD_5 data.

CHAPTER IV

RESULTS

Changes in Influent Substrate Concentration and Hydraulic Flow Rate

Increase in Influent Substrate Concentration (S_i)

There were two increases made in the influent substrate concentration. They were on the average from 231 to 330 mg/ℓ (a 43% increase) and from 184 to 466 mg/ℓ (a 154% increase), as recorded in terms of BOD_5. In TOC, they were from 155 to 200 mg/ℓ (a 29% increase) and from 124 to 276 mg/ℓ (a 123% increase). These average values are shown in Tables IV and V. The following sections will report on each of these increases in influent substrate concentration in detail.

Influent Increase Number I

This increase will be reported in the next two sections; first, in terms of BOD_5, and then in terms of TOC.

Influent BOD5 Increase Number I. The reactor was operated at an average influent BOD_5 concentration of 231 mg/ℓ and a flow rate of 8.9 liters per day from December 15, 1979, to January 4, 1980. During this time, the reactor was maintained in a steady state condition using Lawrence and McCarty's (1) mean cell residence time (θ_c) method to set the solids wastage rate, F_w, as detailed in the previous chapter. The

TABLE IV

AVERAGE BOD_5 DATA WITH PREDICTIONS AND PERCENT DEVIATION OF PREDICTIONS FROM AVERAGE VALUES ACHIEVED

Date	Avg S_i BOD (mg/ℓ)	Avg F (ℓ/day)	Avg X In Reactor $\frac{d_s}{d_t} = 0$ (mg/ℓ)	Avg Predicted X Using Average S_e (mg/ℓ)	% Deviation	Avg Predicted X Using $S_e = 5$ (mg/ℓ)	% Deviation	Set S_e (mg/ℓ)	Avg S_e Obtained $\frac{d_s}{d_t} = 0$ (mg/ℓ)	% Deviation	Set X_e (mg/ℓ)	Avg X_e Obtained $\frac{d_s}{d_t} = 0$ (mg/ℓ)	% Deviation	F_w used (mℓ/day)	F_w Obtained Using Predicted X & Avg S_i & S_e
12-15 to 1-4	231	8.9	1049	982	-6.8*	968	-8.4	5	2.0	+60	10	6.5	+35*	833	819
1-5 to 1-25	330	8.9	1461	1407	-3.8	1392	-5.0	5	1.4	+72	10	8.0	+20	846	844
1-26 to 2-16	150	8.9	724	639	-13.3	621	-16.6	5	1.0	+80	10	1.8	+82	780	774
2-17 to 3-19	184	12.0	895	1050	+14.8	1034	+13.4	5	1.7	+66	10	4.4	+56	780	794
3-20 to 4-12	466	12.0	2938	2681	-9.6	2661	-10.4	5	1.6	+68	10	5.3	+47	862	859
4-13 to 5-2	120	12.0	657	685	+4.1	664	-1.1	5	1.3	+74	10	5.5	+45	780	736

*Minus means prediction Lower than Avg. Obtained

*Plus means prediction Higher than Avg. Obtained

TABLE V

AVERAGE TOC DATA WITH PREDICTIONS AND PERCENT DEVIATION OF PREDICTIONS FROM AVERAGE VALUES ACHIEVED

Date	Avg S_i TOC (mg/ℓ)	Avg F (ℓ/day)	Avg X In Reactor $\frac{d_s}{d_t} = 0$ (mg/ℓ)	Avg Predicted X Using Avg S_e (mg/ℓ)	% Deviation	Avg Predicted X Using $S_e = 49.7$ (mg/ℓ)	% Deviation	Set S_e (mg/ℓ)	Avg S_e Obtained $\frac{d_s}{d_t} = 0$ (mg/ℓ)	% Deviation	Set X_e (mg/ℓ)	Avg X_e Obtained $\frac{d_s}{d_t} = 0$ (mg/ℓ)	% Deviation	F_w Used (mℓ/day)	F_w Obtained Using Predicted X & Avg S_i & S_e
12-15 to 1-4	155	8.9	1049	1177	+11*	893	-17.4*	49.7	16.0	+68	10	6.5	+35	833	832
1-5 to 1-25	200	8.9	1461	1450	-.8	1274	+14.6	49.7	29.0	+42	10	8.0	+20	846	845
1-26 to 2-15	111	8.9	724	791	+8.5	520	-39	49.7	17.7	+64	10	1.8	+82	781	798
2-17 to 3-19	124	12.0	895	1304	+30.6	851	-4.7	49.7	10.0	+80	10	4.4	+56	780	815
3-20 to 4-12	276	12.0	2938	2980	+1.5	2587	-13.6	49.7	15.0	+70	10	5.3	47	862	864
4-13 to 5-2	87	12.0	657	853	+23	431	-52	49.7	12.7	74	10	5.5	45	780	769

*Plus means prediction Higher than Avg. Obtained

*Minus means prediction Lower than Avg. Obtained predictions made and average results are shown in Table IV. On January 5, the influent BOD_5 concentration was increased to 330 mg/ℓ and the flow rate was held constant at 8.9 ℓ/day. At this time a new solids wastage rate was set to reach a new biological solids prediction maintaining the same θ_c of 3.33 days. Reactor and effluent characteristics for the steady state at 231 mg/ℓ, the transition period, and the new steady state reached at 300 mg/ℓ are shown on a day-to-day basis in Figure 2. The predictions for biological solids (X) and set effluent standards for effluent substrate concentration (S_e) and biological solids in the effluent (X_e) are also shown in Figure 2.

As can be seen, the steady state prediction for X was very good before the increase in influent BOD_5. When the influent concentration was changed on January 5 (day 25, Figure 2), the biological solids gradually increased to a peak of 1720 mg/ℓ on day 39, then dropped back to a steady state very close to the predicted value by day 41, 15 days later. The average X, two predictions of X, and the percent deviation of each prediction from the average X are shown in Table IV. The first prediction was made using the average S_i and S_e for the run, and the second was made using the average S_i and set S_e. The predictions were only 6.8 and 8.4 percent below the average X for the steady state before the increase in S_i, and only 3.8 and 5.0 percent lower than the average X for the steady state after the increase.

The S_e values through both the transient period and both steady state conditions were lower than that predicted for a θ_c of 3.33 days by Equation (1), as can be seen in Figure 2, and fluctuated very little over the entire run. The X_e values were on the average lower than the set X_e,

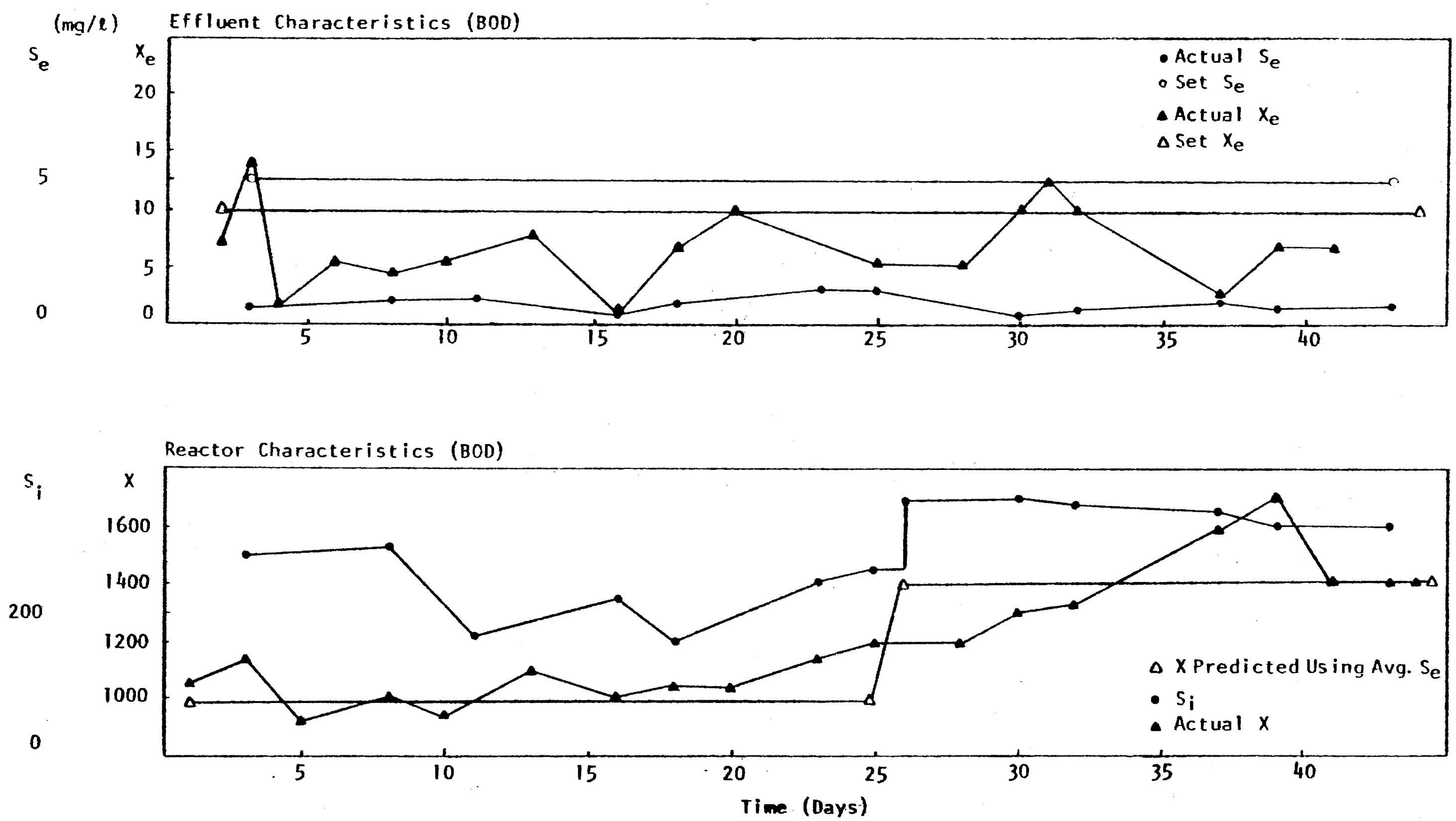

Figure 2. Daily Reactor and Effluent Characteristics for Influent BOD_5 Increase Number I Showing Effluent Standards and Predictions of X for Comparison

as can be seen in Table IV. Looking at Figure 2, however, it can be seen that the X_e was exceeded on day 31 and equalled on days 30 and 32. The settleability of the sludge was marginal at this time and some filamentous growth was noticed in the reactor.

Influent TOC Increase Number 1. This section covers the same increase in influent substrate concentration as the previous section in terms of TOC data taken. As stated in the previous chapter, since the kinetic constants for TOC could not be obtained until after the study was nearly completed, the TOC results are only given as a comparison to show that they could have been used successfully in predicting steady state conditions using Lawrence and McCarty's θ_c design model as an operational control method.

The reactor was subjected to a 29 percent increase in influent TOC concentration over the same time period outlined above. The average values, predictions, and percent deviations are shown in Table V. As before, X_e was set at 10 mg/ℓ, but the S_e value in terms of TOC had to be predicted using the kinetic constants obtained and the θ_c set by the BOD data, as detailed in the previous chapter. The S_e predicted was 49.7 mg/ℓ.

Since the actual S_e obtained was substantially lower than the predicted S_e, two predictions were made as before; one using the average influent TOC concentration and soluble effluent TOC concentration and the other using the average S_i and predicted S_e. The reactor and effluent characteristics for the steady state before the increase, the transition period and the steady state after the increase in influent TOC are shown in Figure 3 on a day-to-day basis. This time, both biological solids predictions are shown on the figure for comparison since the size of the predicted S_e made them come out so differently. The set X_e and predicted S_e are shown as before for comparisons.

As can be seen in Figure 3 and Table V, the X predictions came out very good using both methods with the best method being the first mentioned above, for that method gave better results at both steady states. As before the biological solids showed a gradual increase above predicted values then dropped back to a steady state value. This took 15 days as stated above.

The S_e values were again much lower than the predicted S_e with a slight increase in S_e shown after the increase. The X_e values as shown in the previous section went above the set value at one time on day 31.

<u>Influent Increase Number II</u>

Data on this increase will be reported in the next two sections in terms of BOD_5 and in terms of TOC prediction results, respectively.

<u>Influent BOD_5 Increase Number II</u>. The reactor was operated at an average influent BOD_5 concentration of 184 mg/ℓ and a flow rate of 12.0 liters per day from March 3 to March 20, 1980, under steady state conditions as predicted by the Lawrence and McCarty θ_c method. The predictions made and average results are shown in Table IV. On March 20, the influent BOD_5 concentration was increased to an average of 466 mg/ℓ with the hydraulic flow rate held constant at 12.0 liters per day. As can be seen the steady state condition solids predictions before and after the increase were very good. The steady state S_e's were again substantially below the set value. The X_e's obtained were also on the average well below the set X_e during steady state conditions.

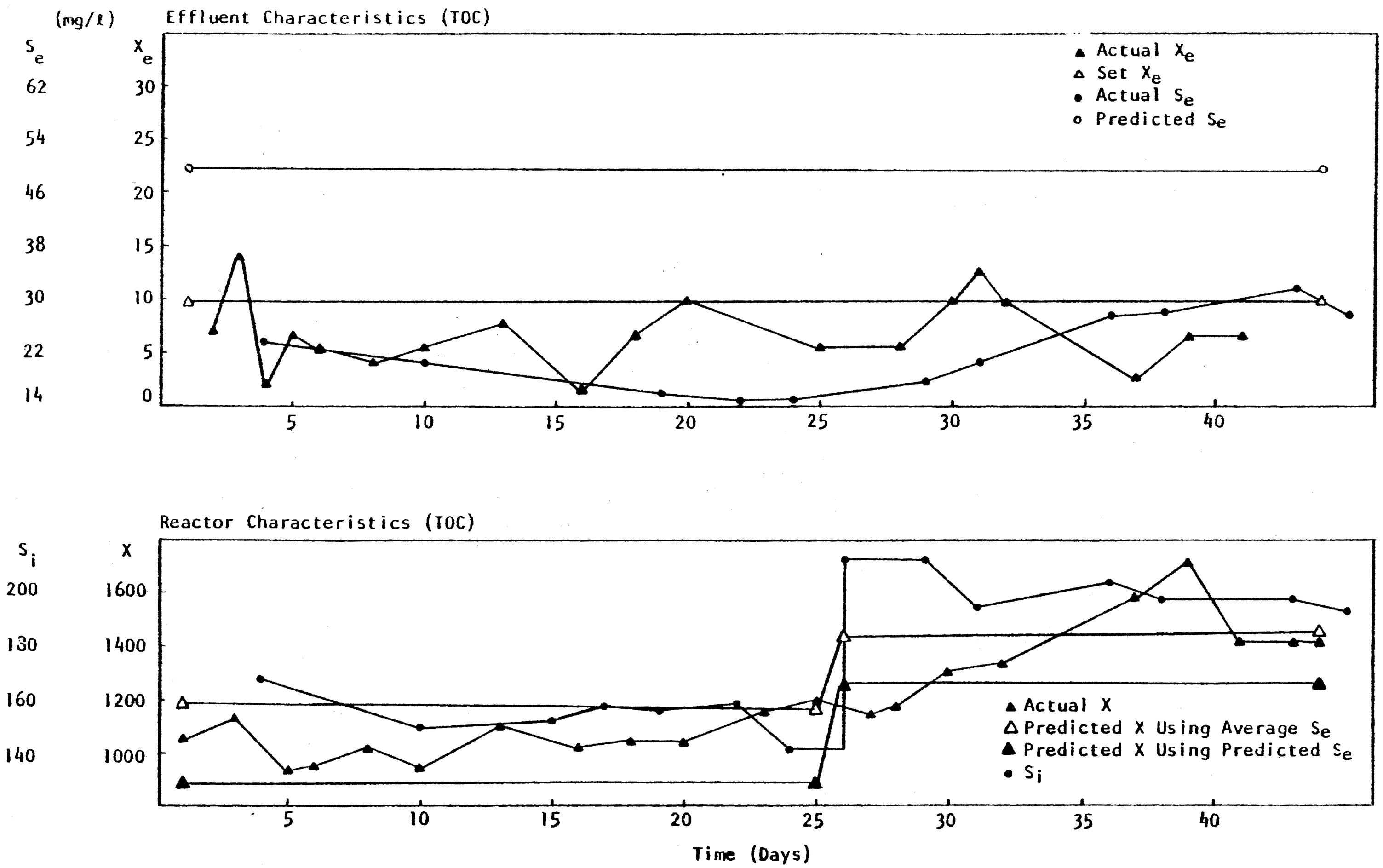

Figure 3. Daily Reactor and Effluent Characteristics for Influent TOC Increase Number I Showing Effluent Standards and Predictions of X for Comparison

The effluent characteristics and reactor characteristics can be seen on a daily basis in Figure 4. The predicted X using the average influent and soluble effluent BOD_5, the daily influent BOD_5, and the set S_e and X_e values are also shown for comparison. As can be seen after the increase in S_i on day 19 the biological solids concentration in the reactor made a rapid increase to 2150 mg/ℓ on day 21, then dropped off because of solids lost out the effluent from day 21 to day 25. During this four-day period the solids in the effluent peaked at 300 mg/ℓ, and the soluble effluent shot to a value greater than 8 mg/ℓ on day 25, and thus went above the effluent standard set at 5 mg/ℓ. The effluent solids leakage began to subside by day 25 and the biological solids in the reactor again made an increase to a steady state condition a bit above the X concentration predicted. By day 31 the steady state had been reached and the S_e and X_e had dropped to their previously low levels.

The biological solids wastage rate, F_w, used and the F_w predicted using average S_i and S_e from the entire run are both shown in Table IV and should be examined with the difference in the predicted X and the average X in mind. This will be discussed further in the next section.

Influent TOC Increase Number II. This section covers the same increase in S_i as the previous section in terms of TOC data taken. The reactor was subjected to a 123 percent increase in influent TOC concentration on day 19 of this period. The average values obtained, predictions, and percent deviations from the predictions for the steady state conditions are shown in Table V. Overall these predictions are very good and show the same trends as before in effluent quality, but the X prediction using the average influent and soluble effluent TOC concentrations was not as good as the X prediction using the average S_i and predicted S_e.

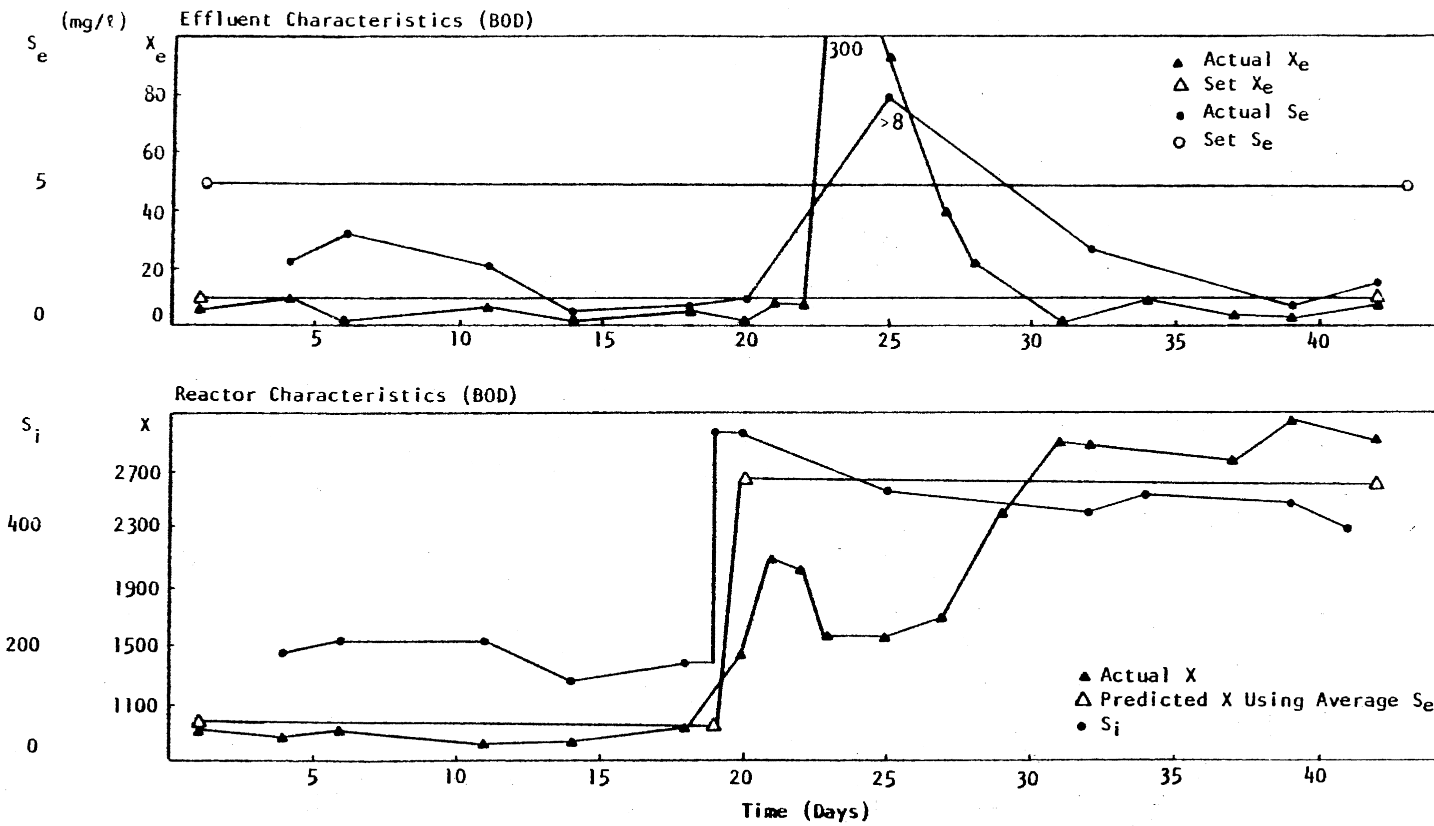

Figure 4. Daily Reactor and Effluent Characteristics for Influent BOD_5 Increase Number II Showing Effluent Standards and Predictions of X for Comparison

It should be noted here that the F_w used for this period, as for all periods, was predicted using the BOD_5 data. This time the BOD_5 data prediction was off a bit because the influent BOD_5 changed and it was not noticed until after the run, thus the F_w was 780 milliliters per day when it should have been 815 milliliters per day. The X predictions after the increase again showed a return to the previous trend of the average influent and soluble effluent TOC concentration giving the best prediction of X and the F_w used was again very close to the F_w predicted using TOC data.

The daily reactor and effluent characteristics predicted solids concentrations predicted soluble effluent TOC's, and set effluent solids concentrations are shown in Figure 5. As stated in the previous section the system was upset by the increase in S_i and a dispersed filamentous growth caused problems in reaching a steady state condition. The S_e value during the loss of solids from day 21 to day 25 peaked at 39.9 mg/ℓ on day 25, which was lower than the S_e value predicted for the soluble effluent TOC but was still high compared to the norm that had been established. By day 31 a new steady state was reached and the S_e went back down to a level comparable to the previously established norm.

Decrease in Influent Substrate Concentration (S_i)

There were two decreases made in influent substrate concentration. They were on the average from 330 to 150 mg/ℓ, a 54 percent decrease, and from 466 to 120 mg/ℓ, a 74 percent decrease, as recorded in terms of BOD_5. In TOC they were from 200 to 111 mg/ℓ, a 45 percent decrease, and from 276 to 87 mg/ℓ, a 68 percent decrease. These average values are shown in Tables IV and V. The following sections will report on each of these decreases in detail.

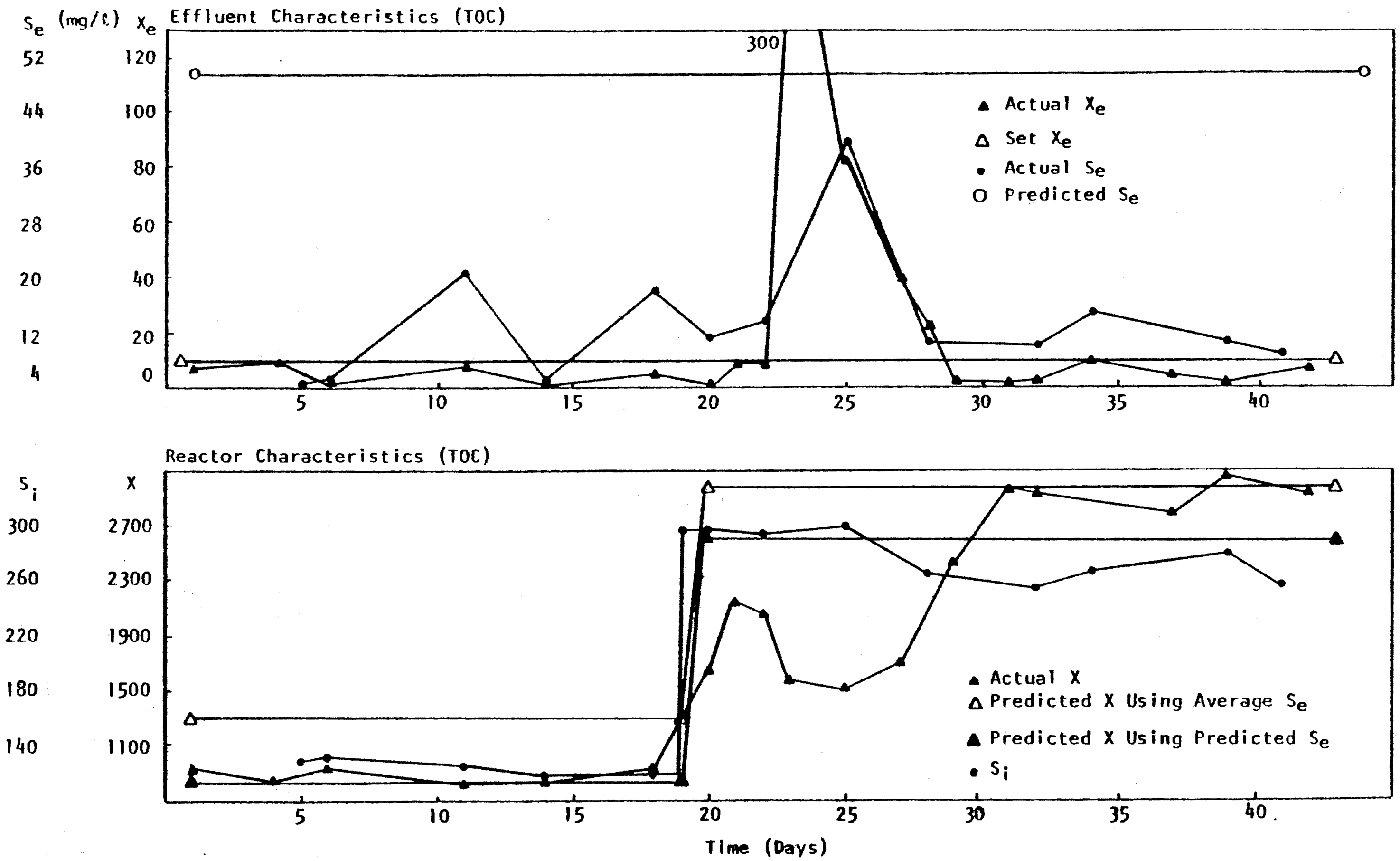

Figure 5. Daily Reactor and Effluent Characteristics for Influent TOC Increase Number II Showing Effluent Standards and Predictions of X for Comparison

Influent Decrease Number I

This decrease will be discussed in the next two sections in terms of BOD_5 and TOC prediction results, respectively.

Influent BOD_5 Decrease Number 1. The reactor was operated at an average influent BOD_5 concentration of 330 mg/ℓ, and a hydraulic flow rate of 8.9 liters per day from January 10 to January 26, 1980, under steady state conditions as predicted by the Lawrence and McCarty θ_c method. On January 27, the influent BOD_5 was decreased to an average of 150 mg/ℓ, and new steady state predictions were made. The flow rate was held constant.

The predictions, averages, and percent deviations are shown in Table IV. As can be seen again the steady state predictions before and after the decrease were very good. The steady state before the decrease shows that solids predictions were within reason with the best prediction again coming from the average S_i and S_e values obtained. The effluent values were the lowest shown during the entire study.

The reactor and effluent characteristics before the decrease, the transition period, and after the decrease are also shown on a day-to-day basis in Figure 6. Set and predicted values are again shown for comparison. The S_e and X_e's are very good for this period as shown in the Figure. The biological solids after the decrease in S_i gradually dropped to below the predicted value then came back to a steady state just above that predicted. The influent BOD_5 was decreased on day 18 and a new steady state for X was reached on day 30, 12 days later. The settleability of the sludge was not appreciably affected by this decrease in S_i.

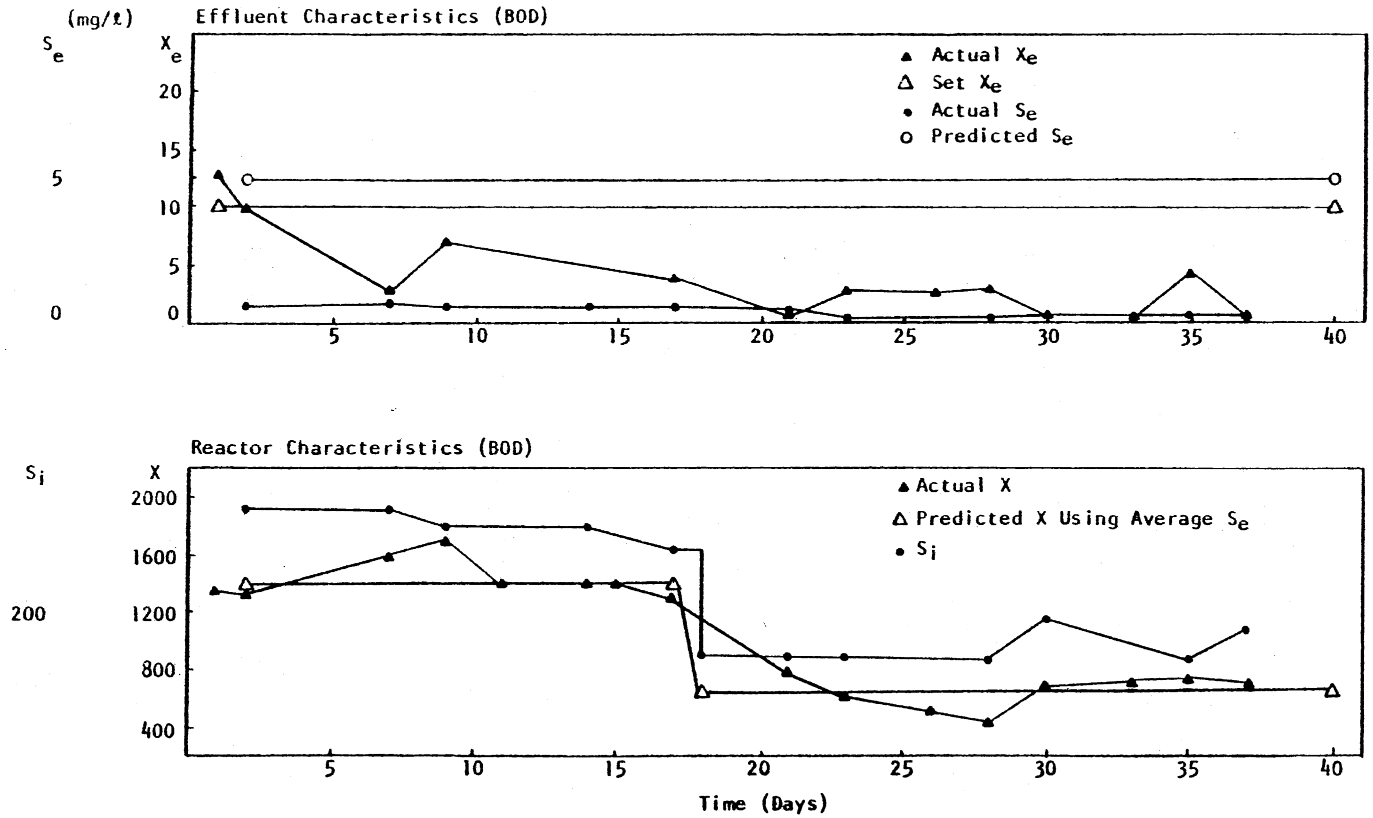

Figure 6. Daily Reactor and Effluent Characteristics for Influent BOD_5 Decrease Number I Showing Effluent Standards and Predictions of X for Comparison

Influent TOC Decrease Number I. This section covers the same decrease in S_i as the previous section in terms of TOC data taken. The reactor was subjected to a 45 percent decrease in influent TOC on day 18 of this period. The average values obtained, predictions, and percent deviations from the predictions are shown in Table V. The steady state predictions were again very good before and after the decrease was made in S_i. The predictions of X were again much better using the average influent and soluble effluent TOC concentrations obtained during the run. The predicted X after the decrease again may have been closer if the F_w from TOC data would have been used instead of that from BOD_5 data.

The reactor and effluent characteristics for this run are shown on a daily basis in Figure 7, along with X predictions, influent TOC concentrations, and S_e and X_e standards for comparison. As can be seen after the decrease, the solids concentration in the reactor also dropped below the X predictions made from TOC data and then increased to a level between the two predictions for X.

The S_e and X_e values were again very good and were never interrupted by the change. The X_e after the decrease improved as did the S_e.

Influent Decrease Number II

This decrease will be reported in the next two sections, first in terms of BOD_5, then in terms of TOC data prediction results.

Influent BOD_5 Decrease Number II. The reactor was operated at an influent BOD_5 concentration of 466 mg/ℓ, from April 1 to April 12, 1980, under steady state conditions. On April 12, the influent BOD_5 was decreased to 120 mg/ℓ, and new steady state predictions were made using Lawrence and McCarty's θ_c method.

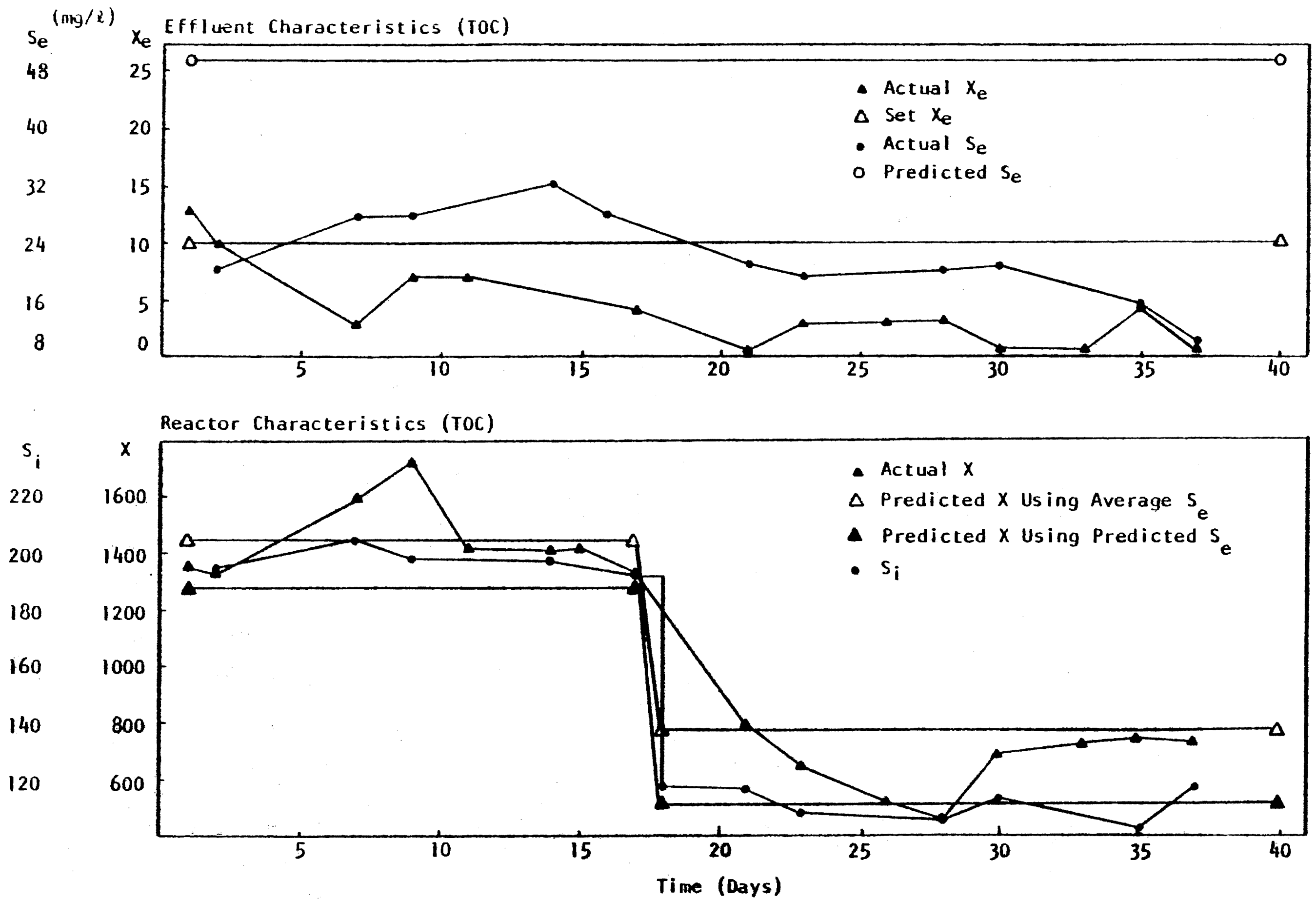

Figure 7. Daily Reactor and Effluent Characteristics for Influent TOC Decrease Number I Showing Effluent Standards and Predictions of X for Comparison

The predictions, averages, and percent deviations from the predictions are shown in Table IV. The steady state predictions before the decrease were very good and have been reported previously in this chapter. The steady state predictions after this decrease were also very good. The F_w used during this time was based on 150 mg/ℓ of BOD_5; so as shown in Table IV, 780 milliliters per day were wasted and based on an S_i of 120 mg/ℓ, 736 milliliters per day should have been wasted. This BOD_5 value may have been low.

The reactor and effluent characteristics on a daily basis are shown in Figure 8 along with influent BOD_5 concentration, X prediction, and S_e and X_e standards for comparisons. As can be seen on day 12 the decrease was made and by day 16 the solids in the reactor had dropped from an average of 2938 mg/ℓ to a concentration of a little over 700 mg/ℓ. Solids were lost above the standards from day 12 to day 20 but the S_e never showed any increase. A new steady state was reached by about day 23. This was 11 days after the change.

Influent TOC Decrease Number II. This section covers the same decrease in S_i as the previous section in terms of TOC data taken. The reactor was subjected to a 68 percent decrease in influent TOC concentration on day 12 of this run.

The average values obtained, predictions, and percent deviations from the predictions are shown again in Table V. The predictions for X made were again very good before the decrease and the effluent quality was below the standards predicted and set. The predictions of X after the decrease were not as good, but again the prediction using the average S_i and S_e was much better than the other prediction using the predicted S_e.

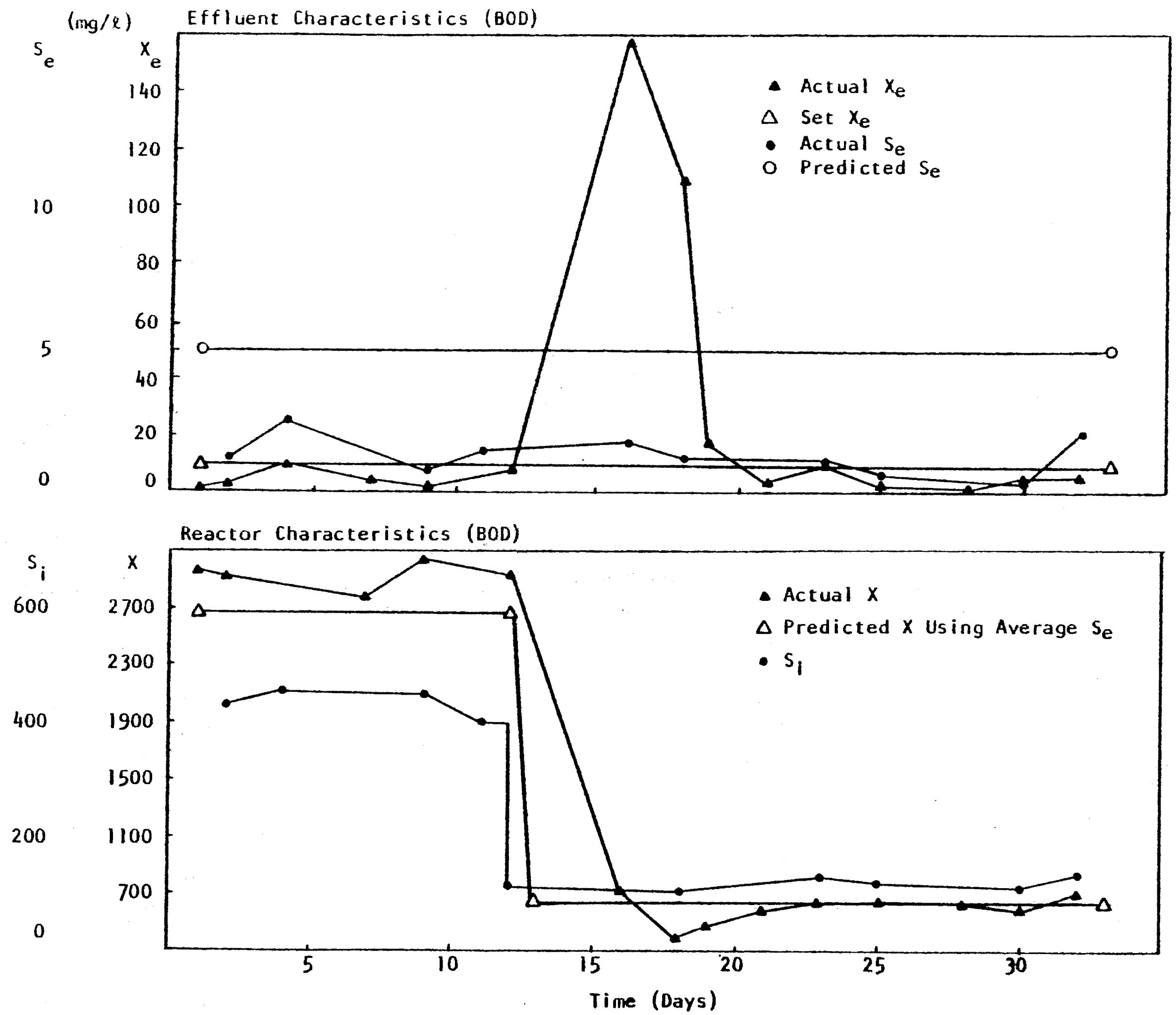

Figure 8. Reactor and Effluent Characteristics for Influent BOD_5 Decrease Number II Showing Effluent Standards and Predictions of X for Comparison

The S_e and X_e values during the steady state conditions were much lower than expected and the S_e showed no appreciable change during the entire run as can be seen in Figure 9.

The reactor and effluent characteristics can again be seen in Figure 9 as can the effluent TOC concentrations, solids predictions, and S_e and X_e standards. As shown before the reactor was upset drastically by the decrease in S_i.

Increase in Hydraulic Flow Rate (F)

Only one increase in hydraulic flow rate was administered during this study with no decreases observed. The flow rate was increased on February 17, 1980, from 8.9 liters per day to 12.0 liters per day. This was a change in detention time from 8 hours to 6 hours. The next two sections will give the prediction results using BOD_5 data and TOC data, respectively.

Prediction Results Using BOD_5 Data

The reactor was operated at an influent BOD_5 concentration of 150 mg/ℓ under steady state conditions from January 26 to February 16, 1980, at a flow rate of 8.9 liters per day. On February 17, the flow rate was increased to 12.0 liters per day and the average influent BOD_5 increased to 184 mg/ℓ unintentionally. A new steady state was assumed at this time and was maintained until March 19, 1980.

These steady state prediction results have been reported in previous portions of the Chapter. The steady state predictions were very good and a high quality effluent was obtained as shown in Table IV. The wastages per day were not as good as they should have been which could have been partially responsible for the variation from the predictions experienced.

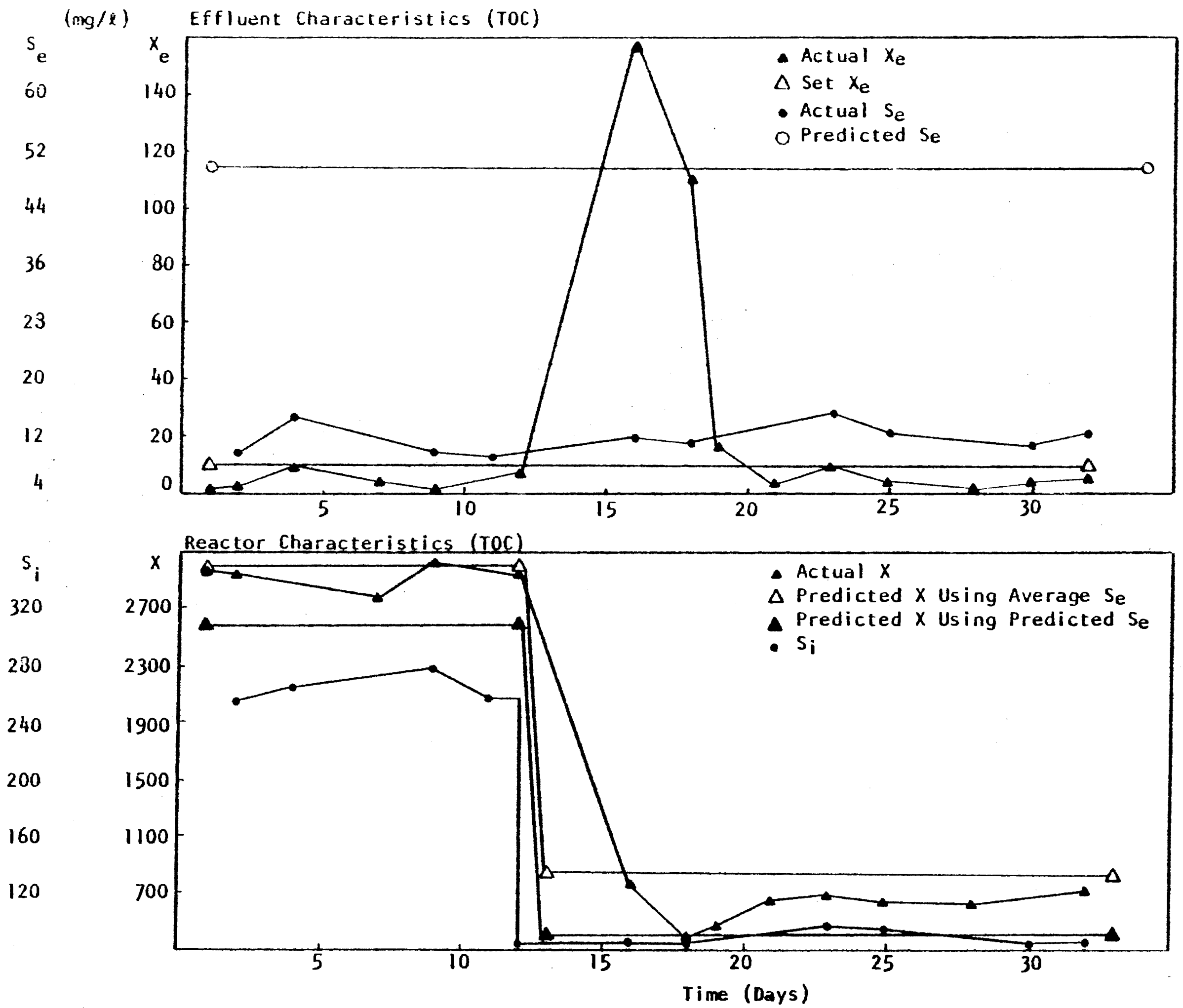

Figure 9. Daily Reactor and Effluent Characteristics for Influent TOC Decrease Number II Showing Effluent Standards and Predictions of X for Comparison

The reactor and effluent characteristics are shown on a daily basis in Figure 10. As can be seen the S_e stayed well below the predicted value throughout this run. The X_e value approached the X_e standard at one time after the increase, and may have exceeded the standard during the period when no data is shown, for the reactor was overcome with filamentous growth during this time. This upset was not overcome until about 13 days after the change, but as stated before the steady state conditions were reached and were accompanied by a high quality effluent.

Prediction Results Using TOC Data

This period was, of course, the same as the previous section in terms of TOC data prediction results. As shown in Table V and stated in previous sections of the chapter the steady state prediction before this increase in F was very good and the effluent quality was also very good. The predictions after the increase in F were not as good as previously shown but the wastage flow was lower than needed during this time. The steady state was reached anyway however and a high quality effluent accompanied this.

The transition period was as stated above 13 days long and an upset shown by filamentous growth was encountered. The reactor and effluent characteristics are shown in Figure 11.

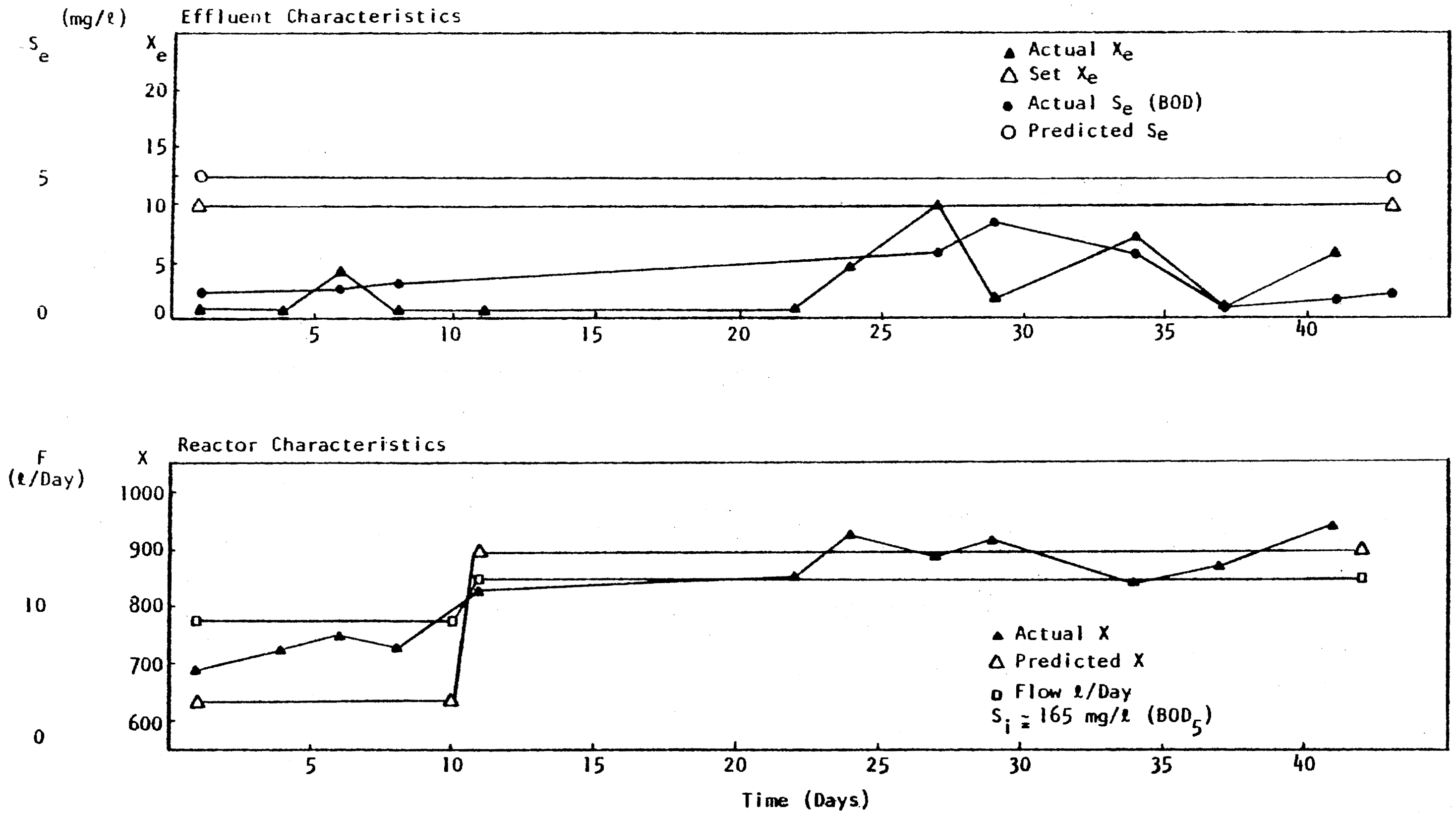

Figure 10. Daily Reactor and Effluent Characteristics in Terms of BOD_5 Data for the Increase in Hydraulic Flow Rate Showing Effluent Standards and Predictions of X for Comparison

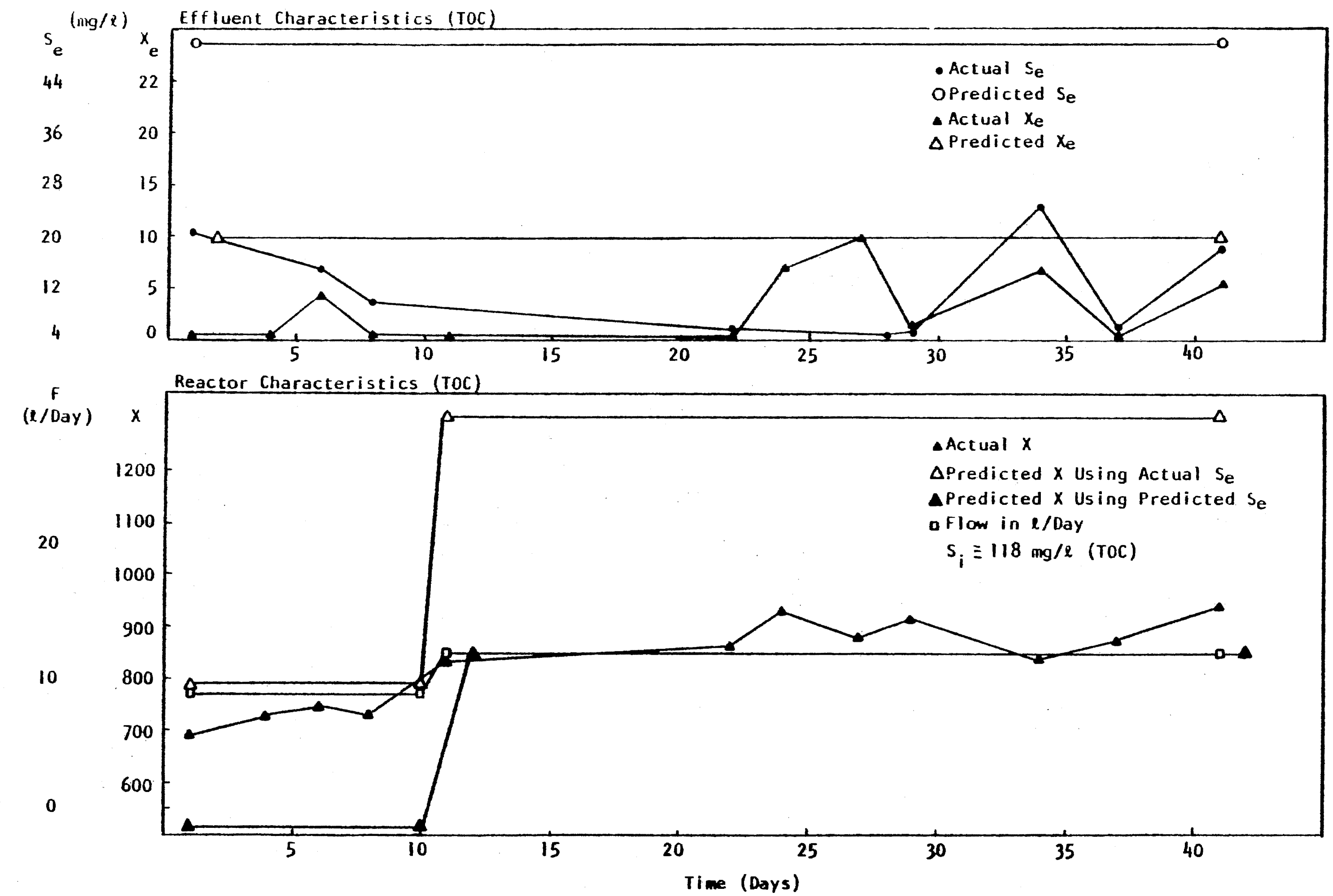

Figure 11. Daily Reactor and Effluent Characteristics in Terms of TOC Data for the Increase in Hydraulic Flow Rate Showing Effluent Standards and Predictions of X for Comparison

CHAPTER V

DISCUSSION

This chapter will attempt to explain the significance of the results given in the previous chapter. Comparisons found between the results of this study and previous works reviewed in Chapter II will be pointed out.

Steady State Condition Predictions

The Lawrence and McCarty (1) mean cell residence time (θ_c) model proved to be a very good method for predicting the steady state conditions required to achieve a high quality effluent in terms of soluble BOD_5 and TOC concentrations and suspended solids leakage. The soluble effluent concentration achieved under steady state conditions in both BOD_5 and TOC were much lower than predicted. This was probably caused by a difference in the efficiency of the microorganisms in the activated sludge pilot plant run for this study and the efficiency of the organisms in the pilot plant used for the determination of the kinetic constants. To compensate for this the kinetic constants should be adjusted so that the predicted S_e and the S_e achieved are closer to the same. In this study the average S_e achieved at each steady state was used in making predictions, after the study was completed, to illustrate the effect that adjusting the kinetic constants would have on the accuracy of the steady state biological solids concentration predictions.

As stated in the results and shown in Tables IV and V the steady state X predictions were always better using the average S_e achieved for the predictions, when the F_w used was not significantly different than the F_w value predicted using the final average S_i and S_e values to make the prediction. This was true for both BOD_5 and TOC data.

The soluble effluent BOD_5 concentration achieved during steady state conditions remained fairly constant throughout the study which is in support of the Lawrence and McCarty (1) design model as well as other kinetic models (2). The TOC in the effluent did go up a little on the average after the 29 percent increase in influent TOC reflecting a larger non-biodegradable fraction in the effluent as postulated by Manickam and Gaudy (16) using COD data.

The food to microorganism ratio was held fairly constant during all steady state conditions as shown on Table VI for BOD_5 and Table VII for TOC data. This is an advantage of the Lawrence and McCarty θ_c method of operational control during steady state conditions that makes it a favorable method, for a θ_c that gives a high quality S_e and a F/M ratio that will produce a settleable sludge can be selected for and maintained using this method.

Increase in Influent Substrate Concentration (S_i)

As stated in the previous chapter, there were two increases in influent substrate concentration. The first was a 43 percent increase in BOD_5 and a 29 percent increase in TOC. The second was a 154 percent increase in BOD_5 and a 123 percent increase in TOC.

The smaller increase in S_i caused an increase in biological solids

TABLE VI

BOD_5 F/M RATIOS FOR STEADY STATE AND TRANSIENT STATE CONDITIONS AND CHANGES MADE IN THIS RATIO

Date	Average S_i (BOD_5) (mg/ℓ)	Average X (mg/ℓ)	Flow F (ℓ/day)	Steady State F/M (BOD)	Transient State F/M (BOD)	Change in F/M Ratio
12/15 - 1/4	231	1049	8.9	0.65	0.93	+0.28
1/5 - 1/26	330	1461	8.9	0.67	0.30	-0.37
1/26 - 2/16	150	724	8.9	0.61	1.02	+0.41
2/17 - 3/19	184	895	12.0	0.82	2.08	+1.26
3/20 - 4/12	466	2938	12.0	0.63	0.16	-0.47
4/13 - 5/2	120	657	12.0	0.73		

TABLE VII

TOC F/M RATIOS FOR STEADY STATE AND TRANSIENT STATE CONDITIONS AND CHANGES MADE IN THIS RATIO

Date	Average $(S_i - S_e)$ (TOC in mg/ℓ)	Average X (mg/ℓ)	Flow F (ℓ/day)	Steady State F/M	Transition State F/M (TOC)	Changes in F/M Ratio
12/15 - 1/4	139	1049	8.9	0.39	0.52	+0.13
1/5 - 1/25	171	1461	8.9	0.35	0.17	-0.18
1/26 - 2/15	93.3	724	8.9	0.38	0.59	+0.21
2/17 - 3/19	114	895	12.0	0.51	1.19	+0.68
3/20 - 4/12	261	2938	12.0	0.36	0.10	-0.26
4/13 - 5/2	74.3	657	12.0	0.45		

in the reactor above that predicted then a drop back to the steady state condition. This "overshoot" phenomenon was also observed by Saleh and Gaudy (19).

The larger increase in S_i caused an initial increase in the solids concentration in the reactor followed by a loss of solids through the effluent which was followed by a second increase to a steady state condition, as was also observed by Thabaraj and Gaudy (20) in a once-through system with final clarifier. The loss of solids was caused by a dispersed growth of filamentous bacteria, as observed by Adams and Eckenfelder (17) in internal recylce pilot plants, and by Saleh and Gaudy (19) and Manickam (22) in external recycle pilot plants.

The reduction in settleability observed after increases in influent substrate concentration accompanied a change in the F/M ratio. The F/M ratio in terms of BOD_5 was increased by 0.28 with the smaller increase in influent BOD_5 concentration and by 1.26 with the larger increase in influent BOD_5, as shown in Table VI. A similar trend was observed in the F/M ratio in terms of average TOC data, as shown in Table VII. These changes in the F/M ratio probably put the system close to the settleability range of the final clarifier with the smaller increase in S_i and out of the settleability range of the final clarifier with the larger increase in S_i for the unit was being operated above the recommended F/M ratio levels suggested in Reference (4) before the increases were made. The reactor was run above the recommended levels because the θ_c to produce a soluble effluent BOD_5 concentration of 5 mg/ℓ was chosen without regard for settleability as a test of the predictability of the model. This is not recommended in actual treatment plant operation.

The change in the F/M ratio accompanied by an increase in filamentous growth and thus a decrease in the settleability of the sludge will also increase the recovery time of the system. The recovery time was found to decrease as the detention time was increased by Krishnan and

Gaudy (21) reflecting a lower growth rate and higher θ_c. The higher the θ_c the more solids there are in the system thus giving a lower F/M ratio and more room for increase in S_i before an unsettleable sludge is produced. Then it stands to reason that the higher mean cell residence time will attenuate the recovery of a system subjected to an increase in S_i. However, it must be noted that designing a system for a higher MCRT requires a larger basin and will therefore cost more money so this is not the best solution.

Krishnan and Gaudy (21) also demonstrated that the recovery time can be decreased by using external recycle of sludge back from the clarifier to the aeration basin. The recycle of sludge will keep the F/M ratio from changing so drastically and thus keep the system from producing as much unsettleable growth. The degree of control that one has on the F/M ratio by recycling sludge is dependent on the amount of increase in influent substrate concentration the plant receives and the mass of biological solids available. This is why Gaudy has incorporated into his model an extra tank between the clarifier and the aeration basin for the storage of biological solids (2). The solids in the storage tank can be concentrated as shown by Manickam (22) to decrease response time and to attenuate leakage of substrate through the effluent.

As shown in this section the problems encountered in reaching a new steady state after an increase in the influent substrate concentration using the Lawrence and McCarty (1) θ_c model as an operational control method were due to the limitations of the internal recycle system employed rather than to the short-comings of the method.

Decrease in Influent Substrate Concentration (S_i)

There were two decreases in influent substrate concentration observed. The first and smallest decrease was a 54 percent decrease in influent BOD_5 and a 45 percent decrease in influent TOC. The second and largest was a 74 percent decrease in influent BOD_5 and a 68 percent decrease in influent TOC.

The smaller decrease in S_i had no real effect on the effluent quality even though it took 17 days to reach a steady state. Saleh and Gaudy (19) also found this to be true in their study using external recycle units although the transition period to a new steady state took only about one day to achieve. The biological solids concentration went down below the predicted value before coming back up to a new steady state as was seen by Manickam (22) in his study when decreasing sorbitol from a COD concentration of 3000 mg/ℓ to 500 mg/ℓ in an external recycle unit using a recycle concentration of 5000 mg/ℓ. The response time using external recycle units for the sixfold decrease in influent COD was shown to be a day to a day and a half.

The second decrease in S_i caused a drastic upset in the system. Solids were lost out the effluent for about eight days and a new steady state was reached after 11 days. The F/M ratio change after the decrease, as shown in Tables VI and VII for BOD_5 and TOC, respectively, was very high and must have caused a die-off due to starvation, and thus a high loss of solids. This upset may have been avoided if a more constant F/M ratio could have been maintained by external recycle. The sludge wastage rate could have been increased and the recycle rate decreased to maintain the F/M ratio at a more constant level.

Again problems in reaching a new steady state condition after a decrease in the influent substrate concentration were due to the limitations of the internal recycle system employed rather than the method of operational control used.

Increase in Hydraulic Flow Rate (F)

One increase in the hydraulic flow rate was observed during this study. This was an increase from 8.9 liters per day to 12.0 liters per day which reflects a change in detention time from 8 hours to 6 hours. The influent substrate concentration was held as constant as possible.

During the transition period between steady state conditions the F/M ratio was upset substantially causing a predominance of filamentous bacterial growth. The change in the F/M ratio in terms of BOD_5 and TOC are shown in Tables VI and VII, respectively. It took 13 days after the increase in F to reach a new steady state condition. This is the equivalent of 32 detention times, which is comparable to a study done by Su (26) who found using a once-through system that at least ten detention times were required to reach a new steady state after an increase in the hydraulic flow rate. As discussed before in the discussion on increases in S_i this increase in the length of the transition period after an increase in F could probably be attenuated using a cell recycle system to slow the growth rate and keep the F/M ratio more constant. As concluded by George and Gaudy (23) an equalization basin could be employed before the aeration basin if hydraulic flow rate increases of over 100 percent are anticipated.

Again the problems encountered in reaching a new steady state after an increase in hydraulic flow rate were caused by the limitations of the internal recycle system rather than the operational method employed.

TOC Data in Operational Control

Total Organic Carbon proved to be a good technique for the analysis of substrate concentration for use in operational control of steady state conditions in an internal recycle unit using the Lawrence and McCarty θ_c method. This can be seen by looking at Table V. When the F_w used was very close to the F_w obtained shown in this table the predictions of biological solids concentration using the average influent and effluent TOC were very good.

Influent BOD_5 concentrations would also need to be run periodically so that any change in the BOD_5:TOC ratio could be accounted for. This ratio would be important in changing the F/M ratio in terms of TOC to terms of BOD_5 so that the settleability of the solids could be monitored by the F/M ratio in terms of BOD_5. This would be necessary because the F/M ratio in terms of BOD_5 is more reflective of the biodegradable food available to the organisms and is more universal over a variety of wastes.

In actual treatment plant operation TOC may be better than any other technique available today for measuring the magnitude of changes in influent substrate concentration as they occur, for more timely operational control changes could be made to help attenuate upsets in steady state conditions and thus help alleviate fluctuations in effluent quality. TOC is also more reproducible than BOD_5 and at least as reproducible as COD.

Comparisons of Lawrence and McCarty's θ_c Method With Other Operational Methods

The Lawrence and McCarty θ_c method has proved to be a workable operational tool for the control of steady state conditions in the activated sludge wastewater treatment pilot plants and shows great promise in recycle plants, however the F/M ratio should be considered in picking an MCRT so that a settleable sludge can be maintained (4).

In comparing this method with the F/M ratio method given in the EPA manual (4) this method has its advantages because besides controlling the F/M ratio this method has the means for setting the MCRT needed to achieve a given S_e. After the kinetic constants have been found the Lawrence and McCarty method as outlined in Chapter III is just as easy as the F/M ratio method given in the EPA manual but the Lawrence and McCarty method also accounts for the kinetic characteristics of the sludge thus having a better basis for the predictions of the biological solids in the aeration basin and the F_w needed to achieve the MCRT associated with the best quality S_e. In short this θ_c method has the best characteristics of the F/M ratio method plus more fine tuned control of the system.

The Lawrence and McCarty θ_c method also has advantages over other control methods. The constant MLVSS method of course does not consider the influent substrate concentration and thus the F/M ratio, so an increase in S_i can come without any warning and the effluent characteristics can be drastically changed (4, 5, 6). The Gould sludge age method also does not consider the influent substrate concentration but only the ratio between the influent suspended solids and the influent BOD; so if this ratio is upset, the S_i can upset the F/M ratio again with no warning and thus cause the effluent to increase in substrate or suspended solids concentration or both (4).

The sludge quality control method discussed in Chapter II is more complicated than the Lawrence and McCarty θ_c method for it has too many parameters to investigate so the controls are unclear. The oxygen uptake rate does not look to be as direct a parameter of control as the actual S_i and S_e.

The method used to maintain a constant substrate utilization rate is a good method but the Lawrence and McCarty θ_c method also maintains a constant specific substrate utilization rate plus provides a means for predicting the F_w needed to maintain that rate. The methods given for hydraulically controlling the MCRT do not all consider the biological solids that are lost out the effluent which can effect the MCRT achieved and could also affect the effluent quality achieved (3, 4, 5, 10, 11). All these methods do not allow for the influent and soluble effluent concentration so the F/M rate can be upset if the S_i increases without warning.

CHAPTER VI

CONCLUSIONS

1. Although the transition periods between the steady state conditions were rather long in this study, the Lawrence and McCarty θ_c method did prove to be a useful tool in the prediction of sludge wastage flow to achieve a steady state condition with a high quality effluent. The long transition periods experienced were due mainly to the limitations of the system employed and not to the shortcomings of the control method used.

2. TOC proved to be a good indication of influent substrate concentration and could be used in conjunction with occasional BOD_5 samples for the operational control of an activated sludge system with the Lawrence and McCarty θ_c method used as the control method. If the soluble effluent concentration is found to be substantially higher or lower than predicted, this is an indication that the kinetic constants should be adjusted to compensate for this.

3. The F/M ratio should be monitored before initiating the Lawrence and McCarty θ_c method so that a settleable sludge is achieved and should be monitored throughout when changes in S_i or F are experienced, and so that recycle and wastage changes can be incorporated to minimize the change in the F/M ratio.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

The Lawrence and McCarty θ_c method was found to be a good method for the prediction of steady state conditions that could produce a high quality effluent using an internal recycle unit, but the transition states between the steady state conditions were very lengthy using this type system. Methods of reducing this transition period should be studied.

1. The use of an external recycle system with constant recycle sludge concentration could be evaluated at different S_i and F rates using the Lawrence and McCarty θ_c method for control with emphasis on keeping the F/M ratio at a constant level.

2. The use of an external recycle system with different recycle sludge concentrations and rates could also be evaluated at different S_i and F rates using the Lawrence and McCarty θ_c method for control with emphasis on keeping the F/M ratio constant by using proper recycle concentrations and rates.

3. This method should also be tested on actual conventional activated sludge plants for evaluation and analysis.

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VITA

Carl David Parrott

Candidate for the Degree of

Master of Science

Thesis: A STUDY OF THE LAWRENCE AND MCCARTY θ_c DESIGN MODEL AS AN OPERATIONAL CONTROL METHOD FOR THE ACTIVATED SLUDGE PROCESS.

Major Field: Bioenvironmental Engineering

Biographical:

Personal Data: Born in Shawnee, Oklahoma, June 6, 1952, Son of Mr. and Mrs. Roger D. Parrott of Chandler, Oklahoma.

Education: Graduated from Chandler High School, Chandler, Oklahoma, in May, 1970; received Bachelor of Science degree in Zoology from Oklahoma State University in May, 1974; attended Oklahoma University, Fall 1974, and Summer 1978; attended Oklahoma State University, 1977-1980; completed requirements for Master of Science in Bioenvironmental Engineering in July, 1980.

Professional Experience: Sanitarian, Comanche County, Oklahoma State Department of Health, August, 1976-March, 1977; Sanitarian, Payne County, Oklahoma State Department of Health, March, 1977-August, 1980.

Professional Organizations: Oklahoma Society of Registered Professional Sanitarians, Oklahoma Water Pollution Control Federation, Student Member, Oklahoma Chapter of the American Society of Civil Engineers.