A STUDY OF OPERATIONAL CONTROL AND TRANSIENT RESPONSE OF ACTIVATED SLUDGE PROCESS USING LAWRENCE AND McCARTY KINETIC DESIGN MODEL

By

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LIST OF SYMBOLS

ATP - Adenosine TriPhosphate

BOD_5 - Five day biochemical oxygen demand, mg/litre

$C=X_R/X$ - Ratio of cell concentration in the recycle line X_R, to the cells in the reactor X

COD - Chemical oxygen demand, mg/litre

CSFD - Clarifier sludge flow demand

D - Dilution rate ($F/V=\overline{1}/t$) 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, t, in a completely mixed reactor, hr^{-1}

F - Rate of flow of influent substrate or wastewater, litre/day

F/M - Food to micro-organism ratio

F_c - Clarifier withdrawal flow

F_r - Recycle flow rate

F_w - Amount of sludge wasted daily, litres/day

GSA - Gould Sludge Age

K - Maximum substrate utilization rate

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/litre

MCRT(θ_c) - Sludge retention time (sludge age)

MLSS-X,$\overline{X}$ - Biological solids concentration in reactor, mg/litre

OUR	- Oxygen uptake rate
S_e	- Soluble effluent concentration, mg/litre
S_i	- Influent substrate concentration, mg/litre
S_R	- Substrate concentration in the recycle line, mg/litre
t	- Hydraulic detention time, hrs
TOC	- Total organic carbon
U	- Specific substrate utilization rate, day^{-1}
V	- Volume of mixed liquor in aerator, litres
X_e	- Biological solids concentration in carrier effluent, mg/litre
X_R	- Biological solids concentration in the recycle flow to the reactor, mg/litre
X_W	- Excess biological solids (sludge wasted), mg/day
Y_t	- True cell yield
α	- ratio of cell recycle flow F_R to the feed flow, F, $\alpha=F_R/F$
μ_n	- Net specific growth rate in continuous system with cell feedback, $time^{-1}$
μ_{max}	- Maximum specific growth rate for a system in exponential growth, $time^{-1}$

CHAPTER I

INTRODUCTION

Mankind's rapid progress towards a truly viable and advanced technological society; has had a profound impact on the earth's environment. Pollution of soil, water, and air has risen to such increasing proportions and magnitude, that governments all over the world had to step in and pass legislation to ensure clean air, water and soil. In the United States, with the passage of Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) (40), and the Clear Air Act, a basis for a prudent and pragmatic program with long term goals on reducing air and water pollution was laid down.

As a result of the above measures, states and EPA have set up stringent waste water effluent standards; therefore, it has become imperative that all the existing and future waste water treatment plants in the country operate efficiently and be able to meet the effluent guidelines satisfactorily. However, this seems to be becoming increasingly difficult and elusive due to the changing of characteristics of waste water as a result of dumping or discharge by industries and other consumers of all types of new organic compounds, heavy metals and other pollutants into the waste water treatment systems.

With an impending water crisis looming ahead, it is all the more important for Environmental Engineers to ensure that all the existing and future waste water treatment plants perform efficiently and meet the effluent standards, as the water obtained from these plants is most likely going to be recycled back to water treatment systems or be used for land irrigation or other industrial applications.

Since the passage of PL 92-500, multibillion dollar federal construction programs of waste water treatment facilities has been embarked upon all over the country. Technology is now currently available to produce almost any desired effluent quality. In spite of all this; a survey by EPA in 1976 showed that 33% to 50% of all the waste water treatment facilities do not meet the design criteria for BOD_5 and suspended solids removal in the effluents (45). A lot of public expenditure has already been incurred in construction of these waste water treatment facilities.

There are numerous reasons for this state of affairs, and the main ones are:

a. Poor or substandard equipment used in construction of the waste water treatement plant or facility.

b. Poor or inadequate design of the waste water treatment facility.

c. Inadequate or improper operations and maintenance of the treatment plant.

d. Inadequate laboratory facilities; and testing programs to monitor process control and equipment malfunctioning.

e. Poor process control.

It was also noticed that in waste water treatment plants, where regular preventive maintenance programs, operator training, routine process monitoring and lab tests were implemented, they achieved better operational control of the treatment facility, thereby meeting the design criteria or the effluent guidelines.

To improve operational control in a waste water treatment plant, we need a multipronged approach to evolve a good plan of management and operation of the treatment facility. This can be achieved only if we first examine and scrutinize each individual plant in detail for the above causes and also look into the past historical performance record of the treatment plant before any new operational strategies and modifications are recommended or implemented.

It is needless to emphasize the importance of process control in the overall performance of the treatment plant; hence we must study it in depth so as to enable us to indentify the key parameters, which can be controlled or varied to influence the actual process, and achieve better operational control of treatment plant.

Activated sludge has been extensively used as a waste water treatment process. This process has been studied in detail for the past three decades. Different kinetic models have been developed, though most of them are based on "steady state" or "quiscent" conditions, with an average influent flow rate; but this is not always the case in real life. The influent flow, concentration, and temperature vary with time and it is most difficult to regulate or control them; and this leaves us with the only other option--that is to achieve better process control (operational control). In this connection it is relevant to examine the suitability of Lawrence and McCarty's (24) kinetic model, which advocates control of activated sludge by the unifying parameter MCRT (θ_c) as an operational control parameter.

In order to control the operation of activated sludge process, we must be able to monitor the entire process--that is to find the influent strength, the treatment efficiency, etc. Therefore, we normally use BOD_5, COD and TOC analysis to monitor the performance of the treatment plant. Each test has its own inherent advantages and disadvantages. BOD_5 is a good test, but it requires five days for the test to be completed. COD test takes two hours and is expensive. Utilization of the carbon variable to describe the dynamic behavior of activated sludge when subjected to shock loads has been recommended (49). The carbon variable is a powerful tool as it is subject to much faster and more precise quantification in TOC analysis.

The main objective of the study was to evolve operational and control techniques to achieve enhanced activated sludge waste water treatment, using Lawrence and McCarty (24)Kinetic Model, and at the same time assess the effectiveness of TOC analysis in control and operation of waste water treatment plant. The secondary objective was to recommend control strategies to reduce the impact of quantitative shock loads.

CHAPTER II

LITERATURE REVIEW

Activated Sludge Control Methods

Activated sludge processes are now being widely used in waste water treatment plants all over the world. The main objective is to produce secondary effluent that meets the local or federal effluent standards being enforced in waste water treatment. Though most of the older plants were designed on an empirical or mass loading criteria, the design of newer plants are more or less based on new kinetic models and concepts developed in the last two decades. Operation and maintenance of the existing and new plants being built all over the country is of paramount importance. Due to increasing sophistication and automation in the waste water treatment plants, the need for well trained operators who are familiar with the activated sludge process and plant operations involving mechanical, hydraulic, electrical, and electronic equipment need not be emphasized.

There are various methods and operational control strategies available for the efficient operation and control of the activated sludge process. The operator must select proper operational parameters that provides the best performance at the least cost (40). The plant operator must be cost conscious and at the same time be committed to conservation of power and production of an effluent that meets the discharge requirements. Activated sludge process basically offers only four possible control actions: (1) sludge recycle ratio, (2) sludge wastage rate, (3) aeration rate, and (4) effluent recycle. Several important methods which have been evolved over the past and have received considerable attention are as follows (48, 46, 18, 20, 21, 24, 40):

1. Constant F/M ratio
2. Constant MLSS or MLVSS method
3. Constant MCRT (θ_c) method
4. Gould Sludge Age
5. Oxygen Uptake Rate Control method
6. Sludge Quality Control
7. Other Methods

We will briefly discuss these methods.

Constant MLSS or MLVSS Method

This is a very simple and reliable method; with limited laboratory work. The operator maintains a constant biomass concentration X in the aeration basin, by controlling sludge wastage F_w from the aeration basin; to obtain desired effluent quality. This method ignores the F/M ratio, and micro-organism growth rate for maintaining optimum system balance, and in addition it could lead to a process failure when subjected to shock loads (5, 6, 40).

Constant Food: Micro-organism Ratio (F/M)

The maintenance of a constant F/M ratio assures that the activated sludge process is being loaded at a rate micro-organisms are able to utilize most of the food supply and this will result in a more consistent plant operation and effluent quality.

F/M ratio is defined as

$$F/M = \frac{S_i}{Xt} = \frac{\text{food applied per day}}{\text{Mass of micro-organism in the system}} \quad (2.1)$$

F/M is based on MLVSS, and five day averages are used to calculate F/M. Once a typical F/M ratio is chosen, F_w is controlled to maintain the chosen F/M ratio.

Thus this method ensures the presence of adequate biological solids to any organic food loading. Some typical values for various activated sludge process are found in References 40 and 43.

F/M control is best when used in conjunction with MCRT (θ_c) control. Cashion (50) applied computer simulation and pilot plant study to evaluate instantaneous F/M control strategies; the results indicated that meaningful F/M ratio could not be achieved unless the system provided external solids storage in addition to the clarifier.

Constant Mean Cell Residence Time (MCRT - θ_c) Method

This is considered the best control method available to a plant operator. The value of θ_c describes the mean residence time of an activated sludge particle in the system and is a true measure of the age of activated sludge. When constant MCRT method is adopted, it automatically ensures maintenance of a constant F/M ratio, in addition F_w can be calculated, as suggested by Lawrence and McCarty (24).

$$\frac{1}{\theta_c} = YU - K_d \quad (2.2)$$

The daily wastage rate is determined by

$$F_w = \frac{VX/\theta_c - FX_e}{X_R - X_e} \tag{2.3}$$

MCRT (θ_c) selected should provide best effluent quality and should correspond to its related F/M loading.

Jenkins and Garrison (20) concluded in their paper that MCRT method was a kinetically rational basis for design, control and operation of activated sludge plants. The substrate removal rate can be measured by COD analysis, while other operational parameters can be determined quickly. Burchett and George (5) in their study suggested this method offered the following advantages:

1. Minimum operator attention
2. It is relatively inexpensive for automated control system
3. Provides more positive control
4. Process operation is more stable.

Constant Gould Sludge Age Control

This is based on the ratio of the lbs/day of influent waste water suspended matter to the solids inventory in the aeration tank. The Gould Sludge Age (GSA) is based on the assumption that the ratio between the BOD and suspended matter is fairly constant in waste water. The GSA ranges from 3 to 8 in most activated sludge plants. The control is established by wasting sludge to maintain a constant GSA which produces the best effluent quality (40).

Oxygen Uptake Rate Control Method

Haas (18) proposed a method of activated sludge control process based upon oxygen uptake rate, as it is a rapidly quantified activity parameter. It involves the measurement of all parameters in addition to oxygen uptake rate. θ_c and hydraulic detention time are selected on the basis of past experience for desired effluent quality. Oxygen uptake rate measured is compared with oxygen uptake rate calculated using the equation modeled in the paper. If the theoretical oxygen uptake rate is less than the measured oxygen uptake rate, recycle is increased; and if theoretical oxygen uptake rate is more than the measured oxygen uptake rate, recycle is decreased. Thus, S_i and oxygen uptake rate continuously monitored and changes in recycle are effected. Modeled adjustment of OUR through variation in cell recycle was considered theoretically analogous to direct control of F/M ratio. This model also demonstrated the responsiveness of the specific oxygen activity parameter in detecting shock loads of toxic and biodegradable materials. This method permits reagentless assays and can be adopted for automation. The change in process loading due to toxic wastes etc; can be compensated by adjustment of oxygen uptake rate.

Giona and Annesini (50) derived an expression showing a correlation between specific OUR and θ_c or temperature. The ratio between actual and maximum $\Delta O_2/\Delta S$ (oxygen utilization per unit substrate removal) was suggested as a possible process control parameter by Benfield and Randall (4).

Sludge Quality Control

This control program formulated by West (40, 48) involves the following tests and observations which are very quick and economical:

1. Thirty minute sludge settleability test
2. Measurement of sludge blanket depth
3. MLSS by centrifuge test
4. Recycle sludge concentration by centrifuge test
5. Secondary effluent turbidity
6. DO in the aeration tank.

West derived a formula for clarifier sludge flow demand (CSFD), which enabled the treatment plant operators to adjust the clarifier sludge flow to approximate the demand. The equation for CSFD is derived from the mass balance of the final clarifier only. Thus operators in every shift perform the above tests, and calculate CSFD and carry out the necessary adjustments in the treatment plant. Many operators find this method difficult to maintain a steady state condition, as they are either recycling sludge too much or wasting too much (51). Therefore, Carter (51) proposes another mathematical model to overcome the shortcomings of West's method. In brief, he writes a mass balance around the aeration tank and the final clarifier, and derives equations for F_W, F_R, F_C, solids produced, and Sludge Age. He advocates comparison of the Sludge Age calculated from the model to the theoretical Sludge Age, to assess the plant performance. The daily wastage F_W, to maintain a desired sludge age, can be calculated and accordingly the wastage F_W is controlled to achieve better steady state operation. The operator has to follow this sequence to attain proper control: (1) determine the theoretical sludge age, (2) solve for the "desired" solids produced as in the model, and (3) solve for F_r, F_c and F_w as modeled. Then make necessary control changes, based on the above results.

Other Methods

In addition to the above, there are many more techniques and other operational strategies suggested. We shall examine a few briefly. Roper and Grady (33) elaborated the concept of hydraulic control of θ_c for activated sludge process to include loss of suspended solids in secondary clarifier effluent. They developed a calibration coefficient to relate the true θ_c value to its hydraulic approximation. Further it was related to a ratio of effluent suspended solids concentration to the concentration of substrate removed. A graphical technique is presented for determination of feasible sludge recycle ratios, integrated sludge settling characteristics influent substrate concentration, influent plant flow rate, and desired MLSS values into the recycle flow rate selection process.

Keinath, Ryckmann, Dana and Hofer (46) present a unified systems approach for design and operation of activated sludge process. They employ "settling flux approach" to monitor the operational state of activated sludge process. Settling flux curves or a batch flux plot is made. In addition, the recycle line and clarifier overflow rate line are also plotted on the same plot. The intersection of the two operating lines is defined as the "state point concept" and the clarifier is critically loaded. The state point shifts when:

1. There is an increase or decrease in S_i or F, due to consequent change in recycle line slope and clarifier overflow rate.

2. If there are changes in sludge settling characteristics (settling flux curves change).

3. F_w is increased or decreased to control θ_c; the state operating point goes up or down, which is compensated by increasing or decreasing F_r as the case may be to get critical loading of the clarifier. Thus one must make necessary changes in F_w or F_r so that the clarifier is always critically loaded.

Busby and Andrews (47) discuss several operational strategies. They demonstrate that application of ratio control to the sludge recycle flow rate to be beneficial. The best ratio was found to be a function of sludge settling and detention time in the aeration tank. They also investigated the effects of recycle flow rate in accordance with height of the sludge blanket in the clarifier. They recommended a sludge wastage using a control algorithm which controls sludge wastage; if the sludge blanket height falls below a preset level, the wastage is stopped until the blanket height builds up to the preset level. Using this strategy they were able to reduce X_e, i.e. prevent excessive loss of solids in the process effluent. Another technique they suggest is the manipulation of waste sludge flow, so that F_w is reduced when it is regulated as a function of time. Finally, they present the operational advantages of step feed configuration, which are as follows:

1. It can adjust the contacting pattern, for example it can increase MLVSS when there is an increase in organic loading.

2. Permits control of bulking sludge.

3. It prevents upsets caused by shock loads.

Cuny (53) suggests four alternative control strategies based upon controlled application of solids and effluent recycle. He compares the activated sludge process to a feedback control system and derives equations for process optimization. He treats the aeration basin as a bio-amplifier, sludge recycle as positive feedback and effluent recycle as negative feedback. Each alternative strategies he suggests have their own merits and demerits.

Dynamic Behavior of Completely Mixed Activated Sludge Systems With External Recycle

Herbert (19) showed that recycle of biological solids offers two more control variables, in addition to the dilution rate D, they are hydraulic recycle ratio α

$$\alpha = \frac{F_R}{F} \tag{2.4}$$

and recycle concentration factor C, which is the ratio of biological solids in the recycle line X_R and in the reactor X.

$$C = \frac{X_R}{X} \tag{2.5}$$

From mass balance equations, the following equations are derived

$$\mu_n = D(1 + \alpha - \alpha C) - K_d \tag{2.6}$$

or

$$\frac{1}{\theta_c} = \frac{F}{V} \left(1 + \alpha - \alpha \frac{X_R}{X}\right) - K_d \tag{2.7}$$

$$\alpha = \frac{1 - V/F\theta_c}{\frac{X_R}{X} - 1} \tag{2.8}$$

interpreting K_d as the maintenance coefficient (42, 11) we can rewrite equation (2.6) as

$$\mu_n = D(1 + \alpha - \alpha c) - K_d \qquad (2.9)$$

Gaudy and Srinivasaraghvan (11, 42) have proposed a constant microbial cell concentration in the recycle line as a system constant instead of $C = X_R/X$ as proposed by Herbert (11). They demonstrated, in their reseach work, that the model proposed offered better system control. The main drawbacks in Herbert's model seems to be the operational difficulty in trying to keep $C = X_R/X$ constant every time X varied.

Gaudy (42) is rather aggressive in promoting X_R as a control parameter in recycle systems. Once X_R is chosen, as a system control, it no longer depends upon X, subsequently S_e is affected by S_i. Increasing X_R or C will lower S_e. Grady and Williams (16) indicated that with heterogenous populations S_e will increase linearly with increase in S_i, whereas in Herbert's (19) model S_e remains constant irrespective of S_i value. Using X_R as a control parameter fairly reproducible results were obtained using their model. Their results indicate the presence of a pseudo state in $\overline{X}$ and $\overline{S}$. Their system follows the general trend of decrease in X_w as the growth rate μ_n is decreased (or MCRT (θ_c) is increased). The use of k_d - maintenance coefficient to evaluate X and S resulted in very little differences, however they found a significant difference in prediction of X_w at higher specific growth rate.

The dynamic behavior of completely mixed activated sludge was investigated by Chu, Erickson and Fan (15), by subjecting the activated sludge system with external recycle to step changes in S_i, α, and F_w. When the system was subjected to a three fold increase in S_i, the following events occurred.

1. Soluble COD and ATP in the aeration tank and effluent COD changed in the first thirty minutes following the change in S_i.
2. Recycle sludge concentration C was found to decrease during the first several hours.
3. MLSS in the aeration tank fluctuated during the initial five hours, before it increased and subsequently stabilized.

When the activated sludge system was subjected to a step increase in recycle flow rate, they obtained the following results:

1. X_R was found to be a constant; increased F_r did not alter X_R significantly.
2. X in the aeration tank increased at first, then decreased and finally increased to a steady state.
3. S_e - the effluent COD decreased

When sludge wasting (F_w) was increased, MLSS(X) decreased to a lower steady state value, X_R decreased, and S_e decreased nominally before reaching a steady state value. When sludge wasting (F_w) was decreased, MLSS(X) in the aeration basin increased, S_e increased, and X_e the effluent solids also increased.

The ATP/MLSS ratio was found to be dependent upon F/M ratio. Time constant analysis showed that MLSS time constants were directly related to MCRT. Soluble COD time constants were directly related to hydraulic retention time.

Adams and Eckenfelder (1) studied transient organic loadings in an internal recycle activated sludge system. They concluded that Eckenfelder's kinetic model satisfactorily predicted the transient and steady state response to organic shock loads. The average substrate removal coefficient K appears to increase under most transient conditions over steady state response values. Oxygen uptake as defined by the model, was found to be adequate for transient and steady state conditions. However, due to transient organic shock load, they noticed, that the microbial species in the system changed predominance; more filamentous growth was observed, and a loss of biological solids (an increase in X_e) in the effluent. Sludge settling deteriorated and endogeneous rate of specific oxygen uptake increased.

A successful response to transient shock loads is the achievement of a low steady value of S_e in the effluent, as predicted by the various kinetic models and well within the effluent guidelines, both during steady and transient operating conditions (42). Gaudy and his coworkers at Oklahoma State University studied extensively all types of shock loads and their impacts on activated sludge. All the results are well documented (10-14, 21, 23, 25, 26, 31, 32, 34).

Gaudy and Kivanich (42) found that with -50% step increase in S_i, the soluble S_e was constant before and after the increase. The microbial population X increased at a rate sufficient to consume additional S_i. As per Monods equation, there should have been no discernible change in S_e. However, the system may have responded to minute changes in S_e by minute changes in μ, thus increasing X continually with additional substrate and no change in S_e. This may have been due to the slow application of shock load ($D = 0.125\ hr^{-1}$) to permit the biomass to accomodate the change.

In another study Gaudy and Gaudy (12) adapted from Storer and Gaudy (37) found that there was a leakage in S_e, with a glucose feed, ($D = 0.244\ hr^{-1}$) and a three fold shock load. On analysis of the effluent they found that the effluent was not the original substrate but metabolic intermediates and/or end products of cells (42). Therefore, they concluded that the quantitative shock load terminated in a qualitative/quantitative shock load.

Thabaraj and Gaudy (39) found that in the initial response to an increase in S_i, there was no effluent substrate leakage S_e, and no discernible changes in microbial species; subsequently there was a severe dilute out of microbial cells and effluent S_e shot up, and most of it was due to original influent substrate, accompanied by a drastic change in predominance of the microbial species, i.e. bio-mass turned filamentous. Biomass X initially increased, then decreased and increased, before it dropped down on termination of the shock load. Thus there may be drastic changes in the predominating species in response to a change in S_i (or any other type of shock load).

Krishnan and Gaudy (23) studied the effect of dilution rate on the response of a heterogeneous Biomass in a once through reactor, and the system was subjected to a three fold and five fold step increase in S_i. Their findings were systems with higher hydraulic detention time $\overline{t}$ (linear dilution rate) leaked less substrate, but they were not able to explain whether this was due to slower growth rate or slower rate of application of shock load, nor were they sure whether it was the intensity of change in S_i or mass loading rate that was significant in course of its response. They found that cell recycle had a beneficial impact on the transient substrate leakage, in addition it seems to have smoothed out fluctuations in the effluent substrate curve during the transient phase. Thus it may be said that cells with a "slow growth" history before the shock can adjust more readily to the changes than a faster growth rate systems. Cell recycle slows the growth rate (lower values of μ and higher θ_c).

Saleh and Gaudy (34) studied response of activated sludge with external recycle and constant X_R to quantiative shock loads. They operated an activated sludge plant with external recycle at ($\bar{t}$ = 8 hr, α = 0.25, X_R = 8000 mg/l), which is typical of field treatment plants. In the first case, the unit was subjected to a three-fold shock load which was repeated one year later also. There was very little loss of either solubable substrate or biological solids in response to the step change. In the second case, when they subjected the unit to a sixfold shock load there was a significant leakage of solubable substrate and biological solids. The system recovered after a significant but rather short period of time from the shock load. There was an increase in filamentous micro-organism with the shock load, ultimately the unit recovered from the shock load, accompanied by a change in predominance of the micro-organisms.

Carl Parrot (53) studied the Lawrence McCarty (24) θ_c design model as an operational control method for activated sludge. He found that he was able to predict and attain successful response using Lawrence-McCarty kinetic model to operate an internal recycle activated sludge.

He was able to maintain consistent steady state operation. Throughout the study he was able to meet most of the predictions based on the model; including response to different shock loads. The various parameters monitored, like X, and S_e responded as predicted by the model. In fact, S_e was better (lower) than the predicted values. He found that use of TOC analysis in controlling the activated sludge process offers a great deal of flexibility in the daily operation control as it is an instantaneous, easily reproducible test and fairly reliable.

Manickam (27) found that a six fold quantitative shock led to substrate leakage, but he achieved some attenuation by increasing X_R from 5,000 to 10,000 mg/l. In general, he observed that the higher the recycle sludge concentration the better the response.

CHAPTER III

EXPERIMENTAL METHODS, MATERIALS AND KINETIC MODEL

Description of the Unit

A single bench scale pilot plant activated sludge unit was set up and operated, as depicted in Figure 1. External recycle of sludge from clarifier to the reactor was accomplished using a Colepalmer sludge recylce pump, in conjunction with a timer to control the sludge recycle flow rate. Another sludge pump, finger type (Sigma motor Model T-8), was used with a timer to waste sludge from the recycle line.

The unit basically comprised of a glass reactor for biological solids, outfitted with a stone aerator for air diffusion at 4,000 ml/min to ensure adequate oxygen concentration in MLSS for biological solids and in addition meet the mixing requirements. The effective MLSS volume was 2.4 liters. The clarifier volume was 5 liters. A Milton Roy pump was used to pump the synthetic waste from a 20 liter glass container into the Reactor. The flow diagram is shown in Figure 2.

Synthetic Waste Composition

The synthetic waste utilized during this study is listed in Table I. All the constituents were mixed with tap water proportionally to yield an average BOD of 280 mg/l for steady state operation. However, during shock loads the proportion of constituents was increased

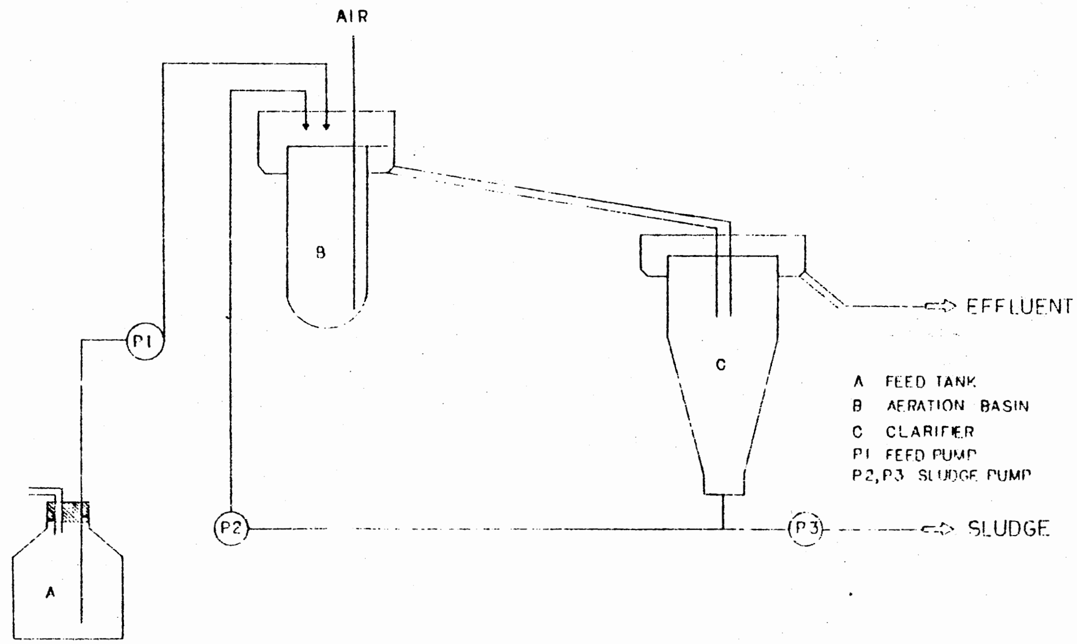

Figure 1. Activated Sludge Unit With External Recycle and Wastage From Recycle Line

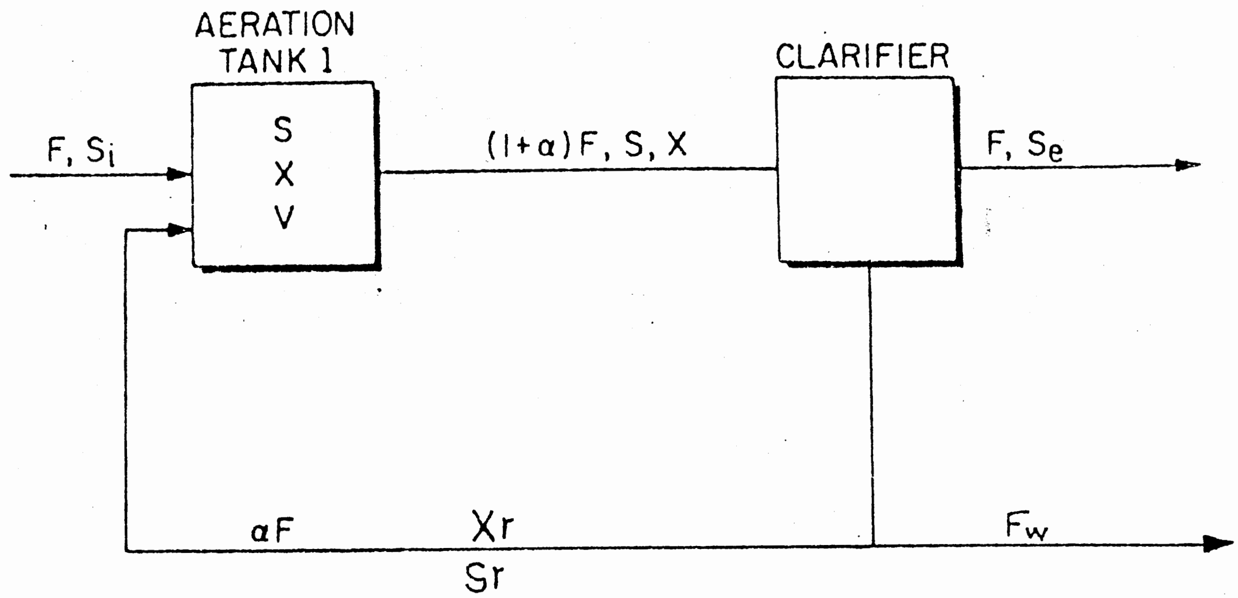

Figure 2. Flow Diagram for Model Employing External Recycle and Wastage From the Recycle Line

TABLE I

COMPOSITION OF SYNTHETIC WASTE

CONSTITUENTS	CONCENTRATION (mg/l)	QUANTITY
ORGANIC		
Acetic Acid	73.47	113 ml/liter
Ethyl Alcohol	57.96	113 ml/liter
Ethylene Glycol	81.40	113 ml/liter
Glutamic Acid	73.45	113 gms/liter
Glucose	73.45	113 gms/liter
Phenol	14.69	22.6 gms/liter
INORGANIC		
Ammonium Sulfate	130	200 gms/liter
Magnesium Sulfate	52	80 gms/liter
Manganous Sulfate	5.2	8 gms/liter
Calcium Chloride	5.2	8 gms/liter
Ferric Chloride	0.26	0.4 gms/liter
Ortho Phosphoric Acid	18.78	15.75 ml/liter

BOD_5 of 130 ml of Synthetic Waste = 280 mg/l.

proportionally to yield the desired influent substrate concentration values.

General Operation of the Unit

The continuous flow unit was started by pumping influent synthetic waste from the feed container by the Milton Roy pump at 5 ml/min so that the hydraulic retention time was 8 hours. The dilution rate of 0.125 hr^{-1} was maintained throughout the study. The initial biological seed for the system was obtained from the activated sludge treatment plant, located in Ponca City, Oklahoma. The Biomass developed from this seed was utilized for the entire study. The mixed liquor from the reactor overflowed into the clarifier by gravity. The sludge settling in the clarifier was recycled and wasted from the sludge recycle line as dictated by the Lawrence-McCarty kinetic model predictions which were evaluated in advance. This system was operated from May 1980 to February 1981 at a constant MCRT (θ_c) of 10 days in accordance with Lawrence and McCarty Kinetic Model. Five quantitative shock loads under different operating parameters were inflicted on the system; these are described later in this chapter. The unit was administered shock loads for 48 hours only when it was always operating in a steady state condition, this transient phenomenon lasted approximately 12 days for each shock load, before the unit was returned to steady state operation once again.

Types of Influent Shock Loads

Five different step increases in the influent substrate concentration S_i (each lasting 48 hours) were made during the course of this study. The unit was operated at steady state in accordance with Lawrence and McCarty Kinetic Model. MCRT (θ_c) of 10 days was maintained by controlling the sludge wastage F_W from the recycle line. No changes were made in the hydraulic detention time.

Run No. 1: S_i was doubled and α - the recycle ratio was varied to maintain a constant X_R/X ratio.

Run No. 2: S_i was doubled, and recycle ratio α was tripled at the same time.

Run No. 3: S_i was tripled and α was doubled during the same period.

Run No. 4: S_i was tripled and α was tripled for the same duration.

Run No. 5: S_i was tripled, and at the same time all the Biological solids in the clarifier were recycled into the aeration tank. α was kept constant throughout the run.

Analytical Procedures

The following analyses were performed in course of the study.

Suspended Solids

The membrane technique with a 0.45 micron filter paper was used to measure the total suspended solids in

a. Reactor mixed liquor - X

b. Effluent from the clarifier - X_e

c. Biological solids in the recycle line - X_R

Total Organic Carbon (TOC) Test

The total organic carbon in the influent S_i and soluble effluent S_e was measured with the Beckman model No. 915 TOC analyzer.

Biochemical Oxygen Demand (BOD_5)

This test was used to measure the influent substrate concentration S_i and the soluable effluent substrate concentration S_e. In order to determine the soluable BOD_5, the effluent sample is filtered through a 0.45 micron (membrane) filter paper. A Beckman DO probe was used to determine the initial and final DO concentration after it was calibrated. The samples were incubated for 5 days at 20°C after measuring the initial DO. Necessary seed and dilution water corrections were incorporated into the test.

Lawrence-McCarty Kinetic Model

This model advocates the maintenance of MCRT (θ_c) as the primary control parameters. It is also the reciprocal of net microbial growth μ_n. From the model, the following equations are utilized to make predictions.

$$\theta_c = \frac{VX}{F_w X_R + (F-F_w)X_e} \tag{3.1}$$

$$F_w = \frac{\frac{VX}{\theta_c} - F\,X_e}{X_R = X_e} \tag{3.2}$$

$$S_e = \frac{K_s(1+K_d\theta_c)}{\theta_c(Y_t K-K_d)-1} \tag{3.3}$$

$$X = \frac{F\ \theta_c\ Y_t(S_i-S_e)}{V(1+K_d\ \theta_c)} \tag{3.4}$$

$$\frac{1}{\theta_c} = \frac{F}{V}\ (1+\alpha\ -\ \alpha\ \frac{X_R}{X}) \tag{3.5}$$

$$\alpha = \frac{1-V/(F\ \theta_c)}{\frac{X_R}{X} - 1} \tag{3.6}$$

The other control parameters at our disposal is hydraulic recycle ratio α, which is the ratio of cell recycle flow F_r to the feed flow F

$$\alpha = \frac{F_r}{F} \tag{3.7}$$

and the cell recycle concentration factor C, which is the ratio of cell concentration in the recycle line X_R and in the reactor X.

$$C = \frac{X_R}{X} \tag{3.8}$$

The kinetic constants used in this study were obtained from units being operated in Bioenvironmental Labs, Oklahoma State University, using the same synthetic waste, but with internal recycle of sludge.

TABLE II

KINETIC CONSTANTS USED IN THE MODEL

Parameter	BOD_5	TOC
K	1.4 days	2.0 days
K_s	0.7 mg/l	110 mg/l
K_d	0.13 day^{-1}	.06 day^{-1}
Y_t	0.45	0.81

In order to operate the unit using Lawrence and McCarty model, the following parameters are monitored continuously, F, F_r, F_w, X, X_e, X_r, S_i and S_e. Once these are known, the equations 3.1 to 3.8 are used to determine the necessary control changes required, in the following sequence:

1. Evaluate F_w from equation 3.2, to control sludge wastage from recycle line, which is set on the sludge wastage pump, in order to acheive an MCRT (θ_c) of 10 days.
2. Predict α by equation 3.6, and compare it in the α in equation 3.7. Adjust F_r to get the desired α if necessary.
3. Predict the value of X using equation 3.4 and compare with actual X, and vary α either to increase or decrease X as necessary.

4. Predict the value of S_e using equation 3.3. Try to control the value of S_e by varying X in the aeration basin by means of manipulating α or F_w.

The unit is continuously monitored and different control strategies are adopted to acheive the desired objectives, and total process control.

Kinetic constants listed in Table II for BOD_5 and TOC were used in making the above predictions. Since the unit was operated at a MCRT (θ_c) of 10 days, S_e as calculated in step 4 above for BOD_5 is 0.4 mg/l, and for TOC is 12.05 mg/l. The suspended solids in the effluent X_e is set at 5 mg/l. Thus the main objective of the unit is to achieve the above standards set for S_e and X_e, both during steady state and transient operation.

CHAPTER IV

RESULTS

The results of the experimental work are presented in this chapter. Normal predictions of unit performance was made using kinetic constants listed in Table II and the Lawrence and McCarty kinetic model and compared with the actual performance. The effluent substrate S_e, can be calculated using the kinetic model.

$$S_e = \frac{K_s(1 + K_d\theta_c)}{\theta_c(Y_tK - K_d)-1} \qquad (4.1)$$

For a MCRT (θ_c) = 10 days, the effluent substrate concentration according to equation 4.1 and constants from Table II would be:

For BOD_5:

$$S_e = \frac{0.7\ (1 + 0.13 \times 10)}{10(0.45 \times 1.4 - 0.13)-1}$$

$$= 0.40 \text{ mg/l}$$

For TOC:

$$S_e = \frac{110(1 + 0.06 \times 10)}{10(0.81 \times 2 - .06)-1}$$

$$= 12.05 \text{ mg/l}$$

The effluent suspended solids, X_e, is difficult to predict. It was assumed that X_e would be equal to or less than 5 mg/l. In order to predict the values of MLSS-X for both TOC and BOD_5 equation 3.4 was used.

$$X = \frac{F}{V} \frac{\theta_c(Y_t)(S_i - S_e)}{(1 + K_d\theta_c)}$$

a typical calculation for $S_i(BOD_5)$ = 265 mg/l and S_i(TOC) = 154 mg/l, $S_e(BOD_5)$ = 2 mg/l and S_e(TOC) = 29 mg/l, all other parameters are constant.

$$X(BOD_5) = \frac{7.2 \times 10(0.45)(265-2)}{2.4\ (1 + 0.06 \times 10)}$$

$$X = 1551 \text{ mg/l}$$

$$X(TOC) = \frac{7.2 \times 10(0.81)(154-29)}{2.4\ (1 + 0.06 \times 10)}$$

$$= 2143 \text{ mg/l}$$

Overall the performance of the unit was quite satisfactory. The pH of the mixed liqour in the aeration basin ranged from 7 to 8. The DO level in the aeration basin varied between 5 to 6 mg/l. Sludge settling in the clarifier was quite good, both during the steady state and transient periods. Predictions, and actual results for transient periods are listed in Tables III to VII. The data is also plotted in Figures 3 to 7.

Run I (A Two Fold Step Increase in S_i and α-Recycle Ratio Varied With C = X_R/X Ratio)

The unit was operated at steady state for several days before it was subjected to the shock load. A two fold shock load was administered for 48 hours. The influent substrate concentration S_i was doubled from a steady state TOC value - 150 mg/l to 305 mg/l and BOD_5 - 290 mg/l to 630 mg/l. The following changes were noticed during this transient phase:

1. MLSS-X - (Refer to Figure 3 and Table III.) As per the model predictions X should average around 2,000 mg/l during steady state and around 4,000 mg/l during the shock load period, but as can be seen from the actual X monitored prior to the shock load the steady state values of biomass X was much lower than the predicted value of X by the kinetic model for both BOD_5 and TOC; X rose gradually to a peak value of 3920 mg/l in 3.5 days, instead of the instantaneous increase predicted by the model, with an increase in S_i. The unit took almost 6 days to return to steady state operation after the onset of the shock load. The steady state value of Biomass X after the shock load was closer to the values of X predicted by BOD_5 rather than TOC.

2. Effluent Substrate Concentration - S_e - (Refer to Figure 3 and Table III.) The predicted values by the model for TOC = 12.05 mg/l and BOD_5 = 0.40 mg/l, were not attained. Leakage of substrate in the effluent was evident as TOC gradually increased within 18 hours to 42 mg/l, and this increase persisted for another 42 hours, before it dropped down to a steady value. The actual TOC was consistently higher than the predicted S_e - TOC. In the case of BOD_5 of the

TABLE III

RUN I - SUMMARY OF ACTUAL AND PREDICTED VALUES OF X, X_e, α, S_e AND F/M

Date (month/day)	S_i(mg/l) BOD_5	S_i(mg/l) TOC	X(mg/l) Actual	X(mg/l) Predictions Based on BOD_5	X(mg/l) Predictions Based on TOC	X_e (mg/l)	X_R/X	α Based on X_R/X	α Actual = F_R/F	F (l/day)	S_e (mg/l) Prediction Based on BOD_5	S_e (mg/l) Actual BOD_5	S_e (mg/l) Prediction Based on TOC	S_e (mg/l) Actual TOC	F_W (l/day)	F/M Based on BOD_5	F/M Based on TOC
11/9	270	150	1010	1583	2084	1	1.54	1.79	1.79	7.2	0.4	2	12	20	0.15	0.81	0.45
11/10	270	150	960	1583	2084	7	1.54	1.79	1.79	7.2	0.4	2	12	22	0.12	0.86	0.47
11/11 a.m.	630	305	920	3695	4424	7	2.00	0.97	0.96	7.2	0.4	10	12	27	0.09	2.08	1.00
11/11 p.m.	630	305	1310	3695	4424	3	2.80	0.54	0.54	7.2	0.4	10	12	27	0.08	1.46	0.71
11/12 a.m.	630	305	1810	3695	4424	15	1.95	1.02	1.00	7.2	0.4	3.5	12	27	0.09	1.05	0.47
11/12 p.m.	615	300	1790	3608	4349	4	1.75	1.34	1.35	7.2	0.4	6	12	42	0.13	1.04	0.51
11/13 a.m.	615	300	1980	3605	4349	9	1.19	5.09	5.00	7.2	0.4	4	12	37	0.17	0.94	0.46
11/13 p.m.	252	175	2970	1477	2461	7	1.12	8.06	8.00	7.2	0.4	6	12	43	0.19	0.26	0.18
11/14 a.m.	252	180	2520	1477	2537	15	1.07	13.81	13.80	7.2	0.4	5	12	40	0.18	0.30	0.22
11/14 p.m.	250	180	3920	1465	2537	10	0.99	--	13.80	7.2	0.4	3.2	12	46	0.22	0.19	0.14
11/15 a.m.	252	180	3470	1477	2537	9	1.01	96.67	13.80	7.2	0.4	5.3	12	39	0.22	0.22	0.16
11/15 p.m.	248	180	2620	1453	2537	34	1.02	48.34	13.80	7.2	0.4	2.3	12	30	0.14	0.29	0.21
11/16 a.m.	310	220	1970	1814	3141	16	1.02	48.34	13.80	7.2	0.4	5	12	21	0.18	0.48	0.34
11/16 p.m.	310	220	1130	1814	3141	9	0.96	--	13.80	7.2	0.4	7	12	15	0.19	0.83	0.59
11/17	310	220	1860	1814	3141	39	1.01	96.67	13.80	7.2	0.4	10	12	20	0.10	0.51	0.36
11/18	310	220	2030	1814	3141	10	1.27	3.58	3.50	7.2	0.4	10	12	15	0.08	0.46	0.33
11/19	252	150	1650	1477	2084	9	1.47	2.06	2.00	7.2	0.4	6	12	16	0.13	0.46	0.28
11/20	248	154	2800	1453	2144	9	1.66	1.47	1.46	7.2	0.4	4.7	12	16	0.13	0.27	0.17

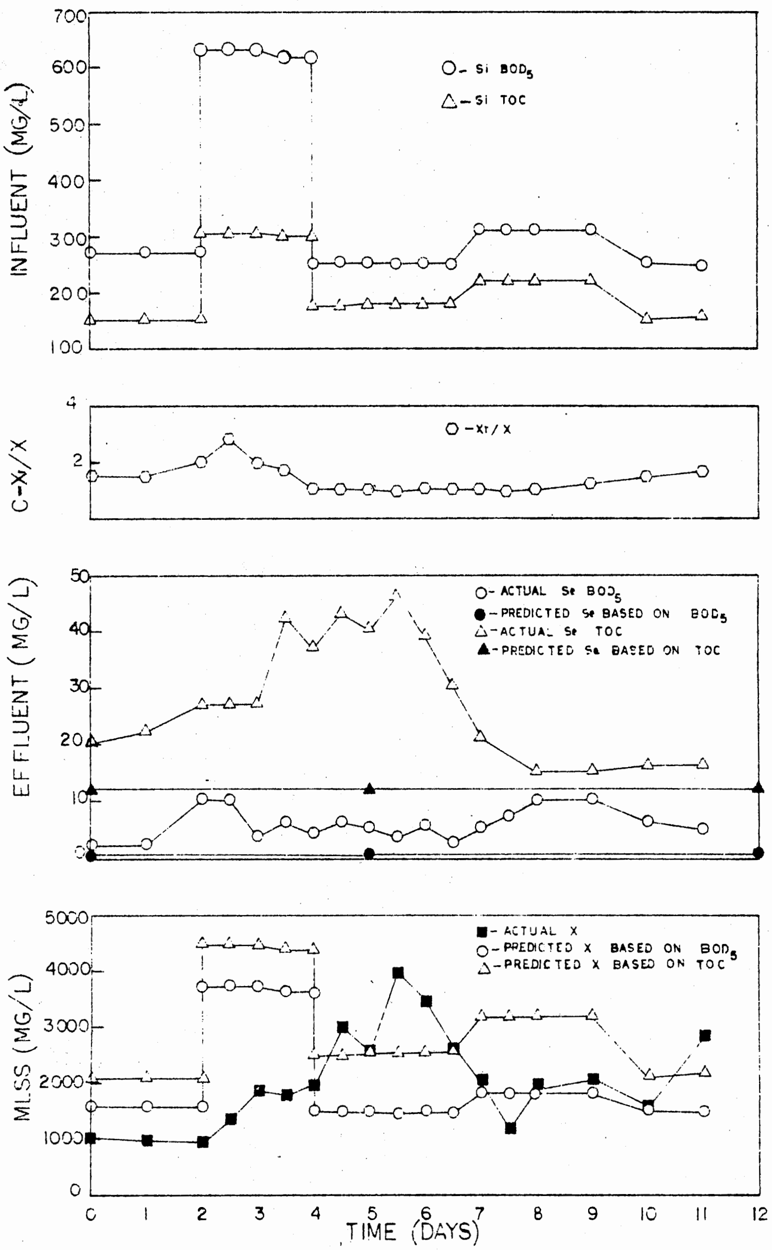

Figure 3. Plot of Actual and Predicted Values of X, X_R/X, S_i and S_e of Run I for Both TOC and BOD_5 Analysis

effluent, leakage of substrate occurred at two separate times, initially with 12 hours of the onset of shock load, then it steadied around 5 mg/l; shortly there was second leakage accompanied by an increase in BOD_5. BOD_5 was well above the predicted values.

3. Effluent Suspended Solids - X_e - (Refer to Table III.) There was a significant loss of biological solids in the effluent. X_e rose after the fourth day. Subsequently it lowered, but the unit could not attain the X_e value of 5 mg/l.

4. $C = {}^{X}R/X$ Ratio and α - (Refer to Figure 3 and Table III.) The ratio X_R/X varied with the shock load, it increased to a value of 2.8 and decreased to 0.99 on the fourth day. The recycle ratio, α, was increased to a peak of 13.8 from 0.54 during the transient period, though the calculated values were much higher for α, they were ignored, as it was not practical to increase recyle to those high rates. Eventually X_R/X increased and α was lowered to the calculated values.

5. F:M Ratio - (Refer to Table III.) The food to micro-organism ratio varied with MLSS-$\overline{X}$. However, it was tripled or quadrupled during the shock load period due to increased S_i, which indicated that the biological soilds ought to be increased to bring down the F/M ratio. Accordingly α was increased, and the F/M ratio dropped as MLSS increased gradually, but by then S_i was also dropped back to steady state value. It was generally within the recommended values.

Run II (Two Fold Step Increase in S_i and
α-Recycle Ratio is Tripled)

The shock load was inflicted on the unit after it was operated at steady state for several days. BOD_5 and TOC of the influent substrate

TABLE IV

RUN II - SUMMARY OF ACTUAL AND PREDICTED VALUES OF X, X_e, α, S_e AND F/M

Date (month/day)	S_i (mg/l) BOD_5	S_i (mg/l) TOC	X (mg/l) Actual	X (mg/l) Predictions Based on BOD_5	X (mg/l) Predictions Based on TOC	X_e (mg/l)	X_R/X	α Based on X_R/X	α Actual = F_R/F	F (1/day)	S_e (mg/l) Prediction Based on BOD_5	S_e (mg/l) Actual BOD_5	S_e (mg/l) Prediction Based on TOC	S_e (mg/l) Actual TOC	F_w (1/day)	F/M Based on BOD_5	F/M Based on TOC
11/20	248	154	2800	1453	2144	9	1.66	1.47	0.45	7.2	0.4	4.7	12	16	0.13	0.27	0.17
11/21	250	154	2630	1465	2144	3	1.74	1.30	0.45	7.2	0.4	2.8	12	3	0.13	0.29	0.18
11/22 a.m.	600	301	1920	3511	4364	7	1.65	1.49	0.45	7.2	0.4	3.5	12	8	0.13	0.43	0.25
11/22 p.m.	600	301	2660	3511	4364	4	1.58	1.67	1.48	7.2	0.4	3.5	12	4	0.15	0.68	0.34
11/23 a.m.	600	308	2360	3511	4470	3	1.73	1.32	1.48	7.2	0.4	6.0	12	6	0.13	0.77	0.40
11/23 p.m.	600	308	2520	3511	4470	7	1.52	1.86	1.48	7.2	0.4	4.1	12	14	0.14	0.72	0.37
11/24 a.m.	600	310	2880	3511	4500	7	1.40	2.42	1.48	7.2	0.4	4.0	12	4	0.16	0.63	0.33
11/24 p.m.	308	178	2280	1806	2507	7	1.24	4.03	1.48	7.2	0.4	3.8	12	7	0.18	0.41	0.24
11/25 a.m.	307	179	2790	1802	2521	6	1.76	1.27	1.48	7.2	0.4	4.5	12	13	0.14	0.33	0.19
11/25 p.m.	307	180	2770	1800	2537	10	1.76	1.27	1.48	7.2	0.4	3.0	12	5	0.12	0.34	0.20
11/26 a.m.	307	180	2710	1800	2539	3	1.35	2.76	1.48	7.2	0.4	2.0	12	14	0.17	0.34	0.20
11/26 p.m.	300	181	2440	1759	2552	5	1.50	1.93	1.48	7.2	0.4	3.0	12	23	0.15	0.37	0.22
11/27	300	186	2440	1759	2627	5	1.24	4.03	1.48	7.2	0.4	3.0	12	2	0.18	0.37	0.23
11/28	300	183	2350	1759	2582	5	1.25	3.87	0.50	7.2	0.4	4.0	12	18	0.18	0.39	0.24
11/29	285	185	1550	1670	2612	8	0.83	--	0.50	7.2	0.4	3.0	12	6	0.25	0.56	0.36
11/30	285	183	2510	1670	2582	13	1.42	2.30	0.50	7.2	0.4	4.0	12	8	0.14	0.54	0.22

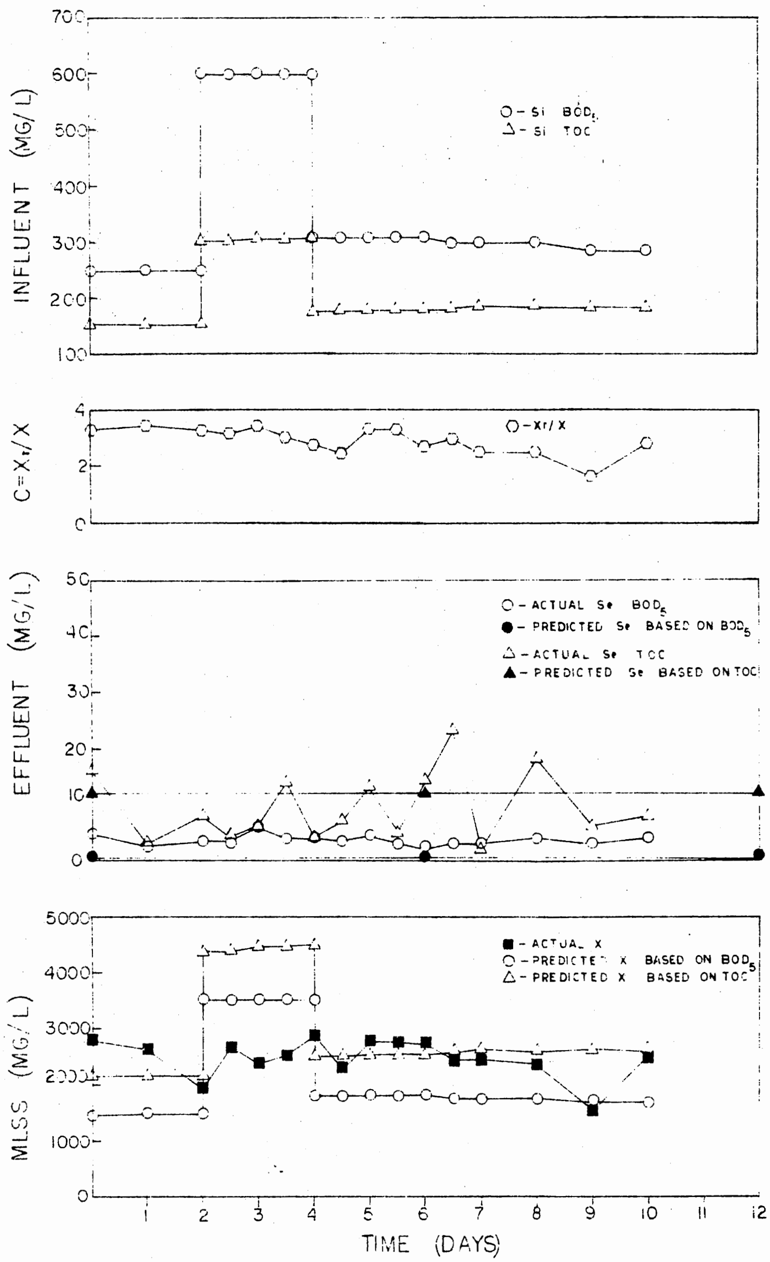

Figure 4. Plot of Actual and Predicted Values of X, X_R/X, S_i and S_e of Run II for Both TOC and BOD_5 Analysis

was increased to 600 mg/l and 308 mg/l respectively during the 48 hours shock load period. In this case α - the recycle ratio was tripled to observe its impact on the system. The following events occurred during this transient phase:

1. MLSS-X - (Refer to Figure 4 and Table IV.) Using the kinetic model, the steady state and transient values of X are evaluated; which are (1,500-2,000) mg/l for steady state and (3,500-4,500) mg/l during transient period. Before the shock load the value of Biomass X was greater than the value of X predicted for both BOD_5 and TOC. Once again the response of the unit was sluggish, X increased gradually to a peak value of 2,880 mg/l in 48 hours. It dropped back to steady state values, once the shock load was terminated. During this steady state period, X was closer to the predicted value for TOC than BOD_5; but during the transient period it was much below the predicted value.

2. Effluent Substrate Concentration - S_e - (Refer to Figure 4 and Table IV.) The predicted effluent substrate concentration are $S_e(BOD_5)$ = 0.40 mg/l, and S_e(TOC) = 12.05 mg/l. Actual S_e-BOD_5 was fairly close to the predicted value. The average BOD_5 for the entire run is 3.67 mg/l; whereas TOC of S_e fared much better, though it fluctuated quite a bit, it was within the predicted values of 12.05 mg/l. The average mean TOC for the run was 9.43 mg/l, which is below the predicted values.

3. Effluent Suspended Solids - X_e - (Refer to Table IV.) There was no significant loss of biological solids in the effluent. The sludge was settling well. However the set X_e = 5 mg/l could not be achieved in the run, the average X_e for the run was 6.37 mg/l, which was fairly close to the set X_e.

TABLE V

RUN III - SUMMARY OF ACTUAL AND PREDICTED VALUES OF X, X_e, α, S_e AND F/M

Date (month/day)	S_i(mg/l) BOD$_5$	S_i(mg/l) TOC	X(mg/l) Actual	X(mg/l) Predictions Based on BOD$_5$	X(mg/l) Predictions Based on TOC	X_e (mg/l)	X_R/X	α Based on X_R/X	α Actual = F_R/F	F (l/day)	S_e (mg/l) Prediction Based on BOD$_5$	S_e (mg/l) Actual BOD$_5$	S_e (mg/l) Prediction Based on TOC	S_e (mg/l) Actual TOC	F_w (l/day)	F/M Based on BOD$_5$	F/M Based on TOC
9/8	312	175	2500	1826	2461	2	2.28	0.75	0.45	7.2	0.4	3	12	22	0.10	0.38	0.21
9/9	310	178	2610	1814	2507	4	2.98	0.49	0.45	7.2	0.4	4	12	21	0.08	0.36	0.21
9/10 a.m.	1080	420	2850	6326	6161	4	2.03	0.94	1.00	7.2	0.4	6.5	12	23	0.11	1.15	0.45
9/10 p.m.	1100	420	3810	6454	6161	8	1.95	1.48	1.00	7.2	0.4	10.5	12	35	0.12	0.89	0.33
9/11 a.m.	1120	415	3960	6561	6085	3	2.00	0.96	1.00	7.2	0.4	8.7	12	30	0.12	0.86	0.32
9/11 p.m.	1115	415	5370	6352	6085	9	1.90	1.07	1.00	7.2	0.4	4.4	12	27	0.12	0.63	0.23
9/12 a.m.	1115	415	4820	6352	6085	10	1.90	1.07	1.00	7.2	0.4	1.2	12	25	0.12	0.70	0.26
9/12 p.m.	298	188	4725	1744	2658	6	2.10	0.88	1.00	7.2	0.4	2.1	12	21	0.11	0.19	0.12
9/13 a.m.	295	184	4100	1729	2597	2	2.50	0.64	1.00	7.2	0.4	3.6	12	32	0.09	0.22	0.14
9/13 p.m.	300	184	4060	1729	2597	4	1.74	1.31	1.00	7.2	0.4	5	12	38	0.13	0.22	0.14
9/14	300	187	4130	1759	2643	3	1.90	1.07	1.00	7.2	0.4	6.6	12	38	0.12	0.22	0.14
9/15	298	186	4170	1744	2627	4	1.76	1.27	1.00	7.2	0.4	6.8	12	21	0.13	0.22	0.14
9/16	300	188	3825	1759	2658	3	1.83	1.16	1.00	7.2	0.4	4	12	24	0.13	0.24	0.15
9/17	285	178	2880	1760	2507	2	2.28	0.75	1.00	7.2	0.4	2.9	12	21	0.10	0.30	0.19
9/18	287	178	2644	1682	2507	5	2.47	0.66	1.00	7.2	0.4	3.2	12	25	0.09	0.33	0.20

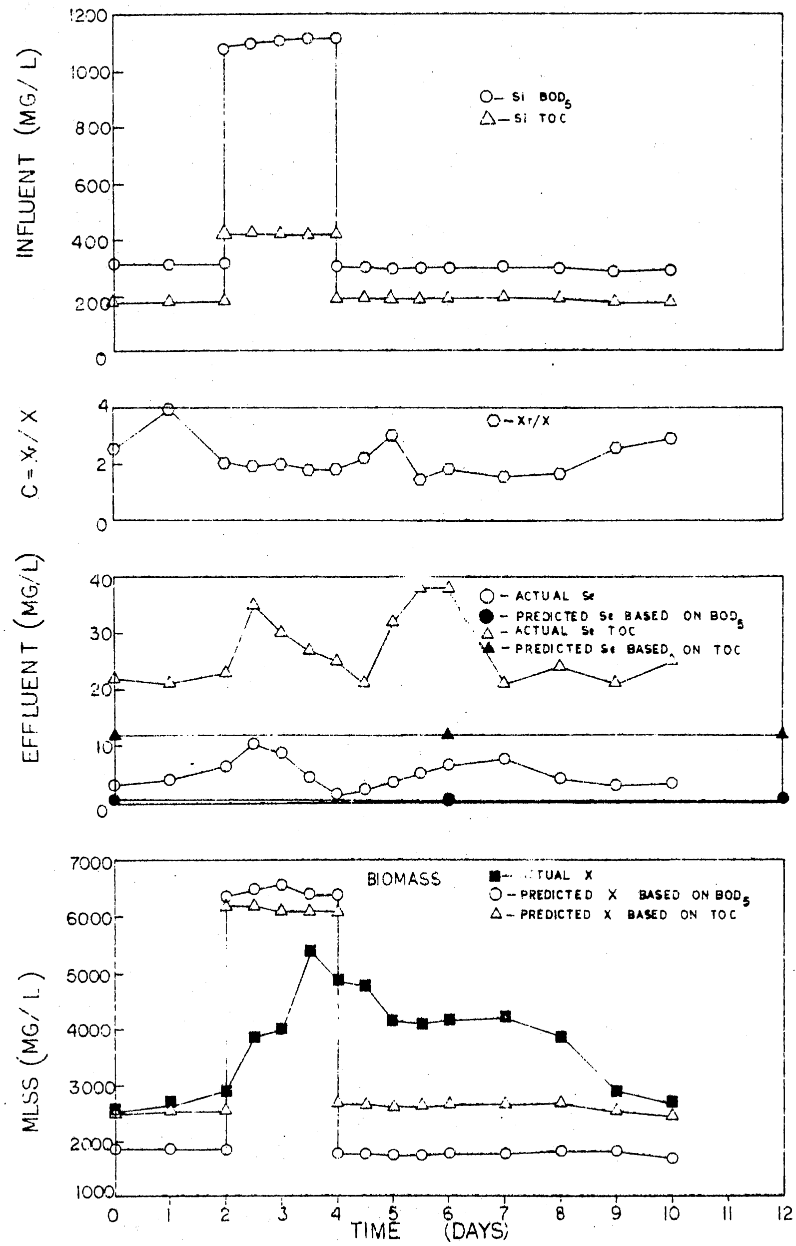

Figure 5. Plot of Actual and Predicted Values of X, X_R/X, S_i and S_e of Run III for Both TOC and BOD_5 Analysis

4. C = X_R/X ratio - (Refer to Figure 4 and Table IV.) It was quite steady, there were no drastic changes. The calculated recycle ratio was much higher than the α-recycle ratio of 1.5 that was used in the study.

5. F:M Ratio - (Refer to Table IV.) The variation in the F/M ratio was considerably lower when compared with other runs, as the actual X was quite high and constant during the steady state. It doubled during the shock load period, and dropped down to a steady value after the shock had ended. Tripling α did not decrease F/M ratio during the shock load.

Run III (Three Fold Step Increase in S_i and α-Recycle Ratio Doubled)

As in the previous runs, a steady state operation with MCRT(θ_C) of 10 days was maintained by controlling sludge wastage F_W as predicted by the model. A three-fold step increase in S_i was made so that BOD_5 - was increased from 310 mg/l to 1120 mg/l, and TOC was increased from 175 mg/l to 420 mg/l. The observations made are given below:

1. MLSS-X - (Refer to Figure 5 and Table V.) The kinetic model predicted an average value of X(1,700-2,500) mg/l during the steady state period and (6,000-6,500) mg/l during the transient period. Prior to the shock load the observed biomass-X was very close to the values predicted by TOC and higher than the values predicted by BOD_5. Actual X increased gradually to a peak value of 5,370 mg/l within 36 hours of the onset of the shock load. It decreased also slowly with termination of the shock load. It took 5 days for the unit to recover from the

TABLE VI

RUN IV - SUMMARY OF ACTUAL AND PREDICTED VALUES OF X, X_e, α, S_e AND F/M

Date (month/day)	S_i (mg/l)		X (mg/l)			X_e' (mg/l)	X_R/X	α Based on X_R/X	α Actual = F_R/F	F (1/day)	S_e (mg/l)				F_w (1/day)	F/M	
	BOD_5	TOC	Actual	Predictions Based on BOD_5	Predictions Based on TOC						Prediction Based on BOD_5	Actual BOD_5	Prediction Based on TOC	Actual TOC		Based on BOD_5	Based on TOC
9/30	285	168	1240	1670	2356	4	2.64	0.59	0.48	7.2	0.4	1.5	12	21	0.08	0.70	0.41
10/1	290	165	1620	1700	2310	4	2.76	0.55	0.48	7.2	0.4	1.0	12	24	0.08	0.54	0.31
10/2 a.m.	292	163	1760	1712	2280	1	2.38	0.70	0.48	7.2	0.4	2.5	12	23	0.10	0.50	0.28
10/2 p.m.	1110	427	2230	6444	6267	7	1.79	1.22	1.54	7.2	0.4	9.4	12	54	0.12	1.51	0.58
10/3 a.m.	1120	422	2610	6561	6191	10	1.39	2.48	1.54	7.2	0.4	3.1	12	30	0.15	1.30	0.49
10/3 p.m.	1115	424	2700	6352	6221	13	1.83	1.17	1.54	7.2	0.4	6.9	12	29	0.11	1.25	0.48
10/4 a.m.	1120	421	6650	6561	6176	10	0.72	--	1.54	7.2	0.4	5.6	12	24	0.32	0.52	0.19
10/4 p.m.	1114	425	3520	6350	6236	7	1.77	1.26	1.54	7.2	0.4	2.8	12	20	0.13	0.96	0.37
10/5 a.m.	285	175	3256	1670	2461	7	1.86	1.12	1.54	7.2	0.4	5.6	12	26	0.12	0.27	0.16
10/5 p.m.	283	178	3030	1660	2507	10	1.65	1.49	1.54	7.2	0.4	3.6	12	23	0.13	0.28	0.18
10/6 a.m.	264	169	3220	1547	2371	8	1.77	1.26	1.54	7.2	0.4	5.6	12	20	0.13	0.25	0.16
10/6 p.m.	262	167	3040	1540	2341	10	1.63	1.53	1.54	7.2	0.4	7.0	12	22	0.13	0.26	0.17
10/7	260	172	3000	1523	2416	4	1.53	1.82	1.54	7.2	0.4	1.5	12	21	0.15	0.26	0.17
10/8	285	178	2436	1670	2507	5	1.75	1.29	0.5	7.2	0.4	2.1	12	18	0.13	0.35	0.22
10/9	284	180	1845	1664	2537	4	2.08	0.90	0.5	7.2	0.4	2.5	12	22	0.11	0.47	0.30
10/10	285	177	1715	1670	2492	7	1.89	1.09	0.5	7.2	0.4	1.8	12	21	0.11	0.50	0.31

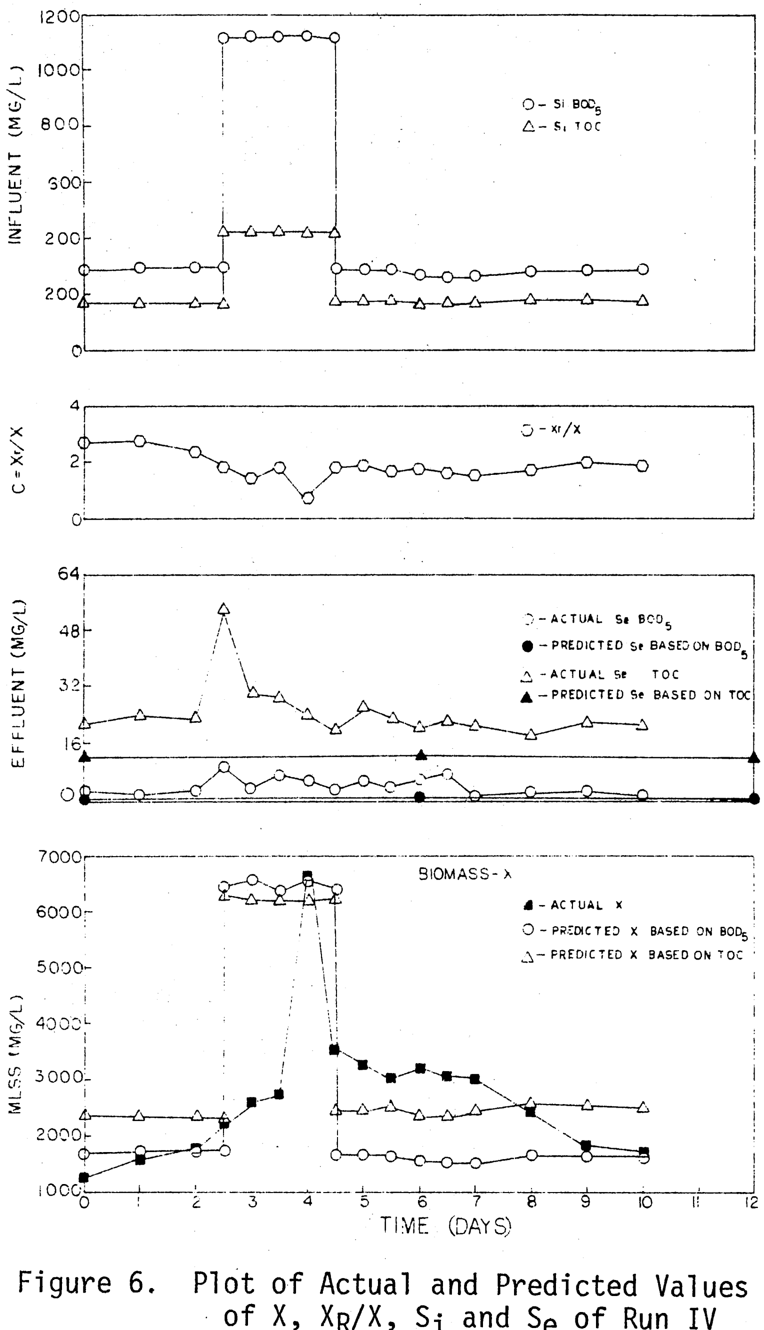

Figure 6. Plot of Actual and Predicted Values of X, X_R/X, S_i and S_e of Run IV for Both TOC and BOD_5 Analysis

shock load. After the shock load, observed biomass X decreased slowly over the next 5 days. The steady state biomass was much higher than the steady state values predicted for both TOC and BOD_5. Only on the fifth day X reached a steady state level closer to the value predicted by TOC.

2. Effluent Substrate Concentration - S_e - (Refer to Figure 5 and Table V.) The predicted values of $S_e(BOD_5)$ = 0.40 mg/l and $S_e(TOC)$ = 12.05 mg/l are the same. A significant leakage of substrate occurred 24 hours after the onset of the shock load; then it gradually decreased during the next 48 hours. During this period the shock load was terminated. Once again there was a substantial substrate leakage 24 hours after the shock load was terminated. Both BOD_5 and TOC reflect the leakage. The mean (BOD_5) was 4.83 mg/l and TOC was 26.80 mg/l which are well above the predicted values.

3. Effluent Suspended Solids - X_e - (Refer to Table V.) In this run the set objective of X_e = 5 mg/l was attained. The average mean value was 4.6 mg/l during this run. The biological solids settled extremely well, and the effluent was clear.

4. $C = X_R/X$ Ratio - (Refer to Figure 5 and Table V.) This ratio was quite consistent throughout the entire run. α - the recycle ratio was doubled with the onset of shock load. The calculated α was quite close to the actual α, throughout, except a few times.

5. F:M Ratio - (Refer to Table V.) F/M ratio was within the specified limits, though being 3 to 4 times higher during the shock load period than the steady state values. X did not increase rapidly

enough, as required by the model, even with α being doubled during this run. F/M reached steady state values after the shock load was over.

Run IV (Three Fold Step Increase in S_i and Tripling α-Recycle Ratio)

In this run, α-the recycle ratio was tripled with the onset of the shock load. The unit was under steady state operation prior to the shock load, at an MCRT (θ_c) of 10 days. The increase in the influent substrate concentration was for BOD_5 from 292 mg/l to 1120 mg/l and TOC from 163 mg/l to 427 mg/l. The following observations were made:

1. <u>MLSS-X</u> -(Refer to Figure 6 and Table VI.) The model predicted an average value of X to be (1,500 to 2,500) mg/l during the steady state and around (6,000-6,500) mg/l during the transient period. The model predicts an instantaneous increase of biological solids X at the time shock load begins. Actual MLSS-X was fairly close to the steady state model predictions prior to the shock load, as seen in Figure 6. However, during the transient period the increase in X was rather slow and gradual. It did go up to 6,650 mg/l in 48 hours which was above the predicted value. Biomass X decreased steadily, after release of the shock. After three days it dropped to a level, inbetween the predicted steady state levels for both TOC and BOD_5.

2. <u>Effluent Substrate Concentration - S_e</u> - (Refer to Figure 6 and Table VI.) The predicted values for $S_e(BOD_5)$ = 0.40 mg/l and $S_e(TOC)$ - 12.05 mg/l. In this run the average TOC during the steady state period was around 20 mg/l and BOD_5 5 mg/l. There was a leakage

TABLE VII

RUN V - SUMMARY OF ACTUAL AND PREDICTED VALUES OF X, X_e, α, S_e AND F/M

Date	S_i(mg/l)		X(mg/l)					α	α		S_e (mg/l)					F/M	
(month/day)	BOD_5	TOC	Actual	Predictions Based on BOD_5	Predictions Based on TOC	X_e (mg/l)	X_R/X	Based on X_R/X	Actual = F_R/F	F (1/day)	Prediction Based on BOD_5	Actual BOD_5	Prediction Based on TOC	Actual TOC	F_w (1/day)	Based on BOD_5	Based on TOC
2/9	265	154	3020	1551	2143	1	1.39	2.48	0.27	7.2	0.4	2	12	29	0.17	0.27	0.15
2/10	265	154	2560	1551	2143	1	1.10	9.67	0.25	7.2	0.4	1.3	12	32	0.22	0.31	0.18
2/11	275	156	1940	1601	2173	1	1.82	1.18	0.26	7.2	0.4	1.1	12	43	0.13	0.43	0.24
2/12 a.m.	1110	473	1530	6502	6960	10	2.39	0.70	0.21	7.2	0.4	1.25	12	44	0.10	2.20	0.94
2/12 p.m.	1140	473	2470	6678	6960	8	1.64	1.51	0.27	7.2	0.4	5.1	12	43	0.13	1.40	0.58
2/13 a.m.	1140	475	2730	6678	6990	7	2.61	0.60	0.21	7.2	0.4	20	12	46.5	0.08	1.27	0.53
2/13 p.m.	1110	475	3370	6502	6990	25	1.40	2.42	0.21	7.2	0.4	30	12	84	0.13	1.00	0.43
2/14 a.m.	1110	475	3770	6502	6990	32	1.47	2.06	0.25	7.2	0.4	88	12	145	0.12	0.26	0.13
2/14 p.m.	326	168	6000	1908	2355	70	1.32	3.02	0.25	7.2	0.4	76	12	133	0.12	0.16	0.08
2/15 a.m.	326	173	2650	1908	2430	15	1.50	1.93	0.21	7.2	0.4	57	12	34.5	0.13	0.37	0.20
2/15 p.m.	326	171	2730	1908	2400	38	1.62	1.56	0.25	7.2	0.4	16.8	12	19.5	0.09	0.36	0.19
2/16 a.m.	300	168	2940	1755	2355	19	1.72	1.34	0.24	7.2	0.4	14	12	19.5	0.11	0.31	0.17
2/16 p.m.	300	162	2440	1755	2264	28	1.84	1.15	0.20	7.2	0.4	2.25	12	32.5	0.09	0.37	0.22
2/17 a.m.	264	163	2190	1545	2279	9	3.10	0.46	0.27	7.2	0.4	1.5	12	39.5	0.07	0.37	0.23
2/17 p.m.	267	163	1880	1562	2279	10	1.81	1.19	0.26	7.2	0.4	7.6	12	46.5	0.12	0.43	0.26
2/18	264	163	1800	1545	2279	12	1.94	1.03	0.26	7.2	0.4	24.2	12	96	0.10	0.44	0.27
2/19	270	163	2780	1580	2279	5	1.76	1.27	0.20	7.2	0.4	4.1	12	5	0.13	0.29	0.18
2/20	270	163	1630	1580	2279	6	3.74	0.35	0.24	7.2	0.4	2.2	12	32.5	0.06	0.50	0.30

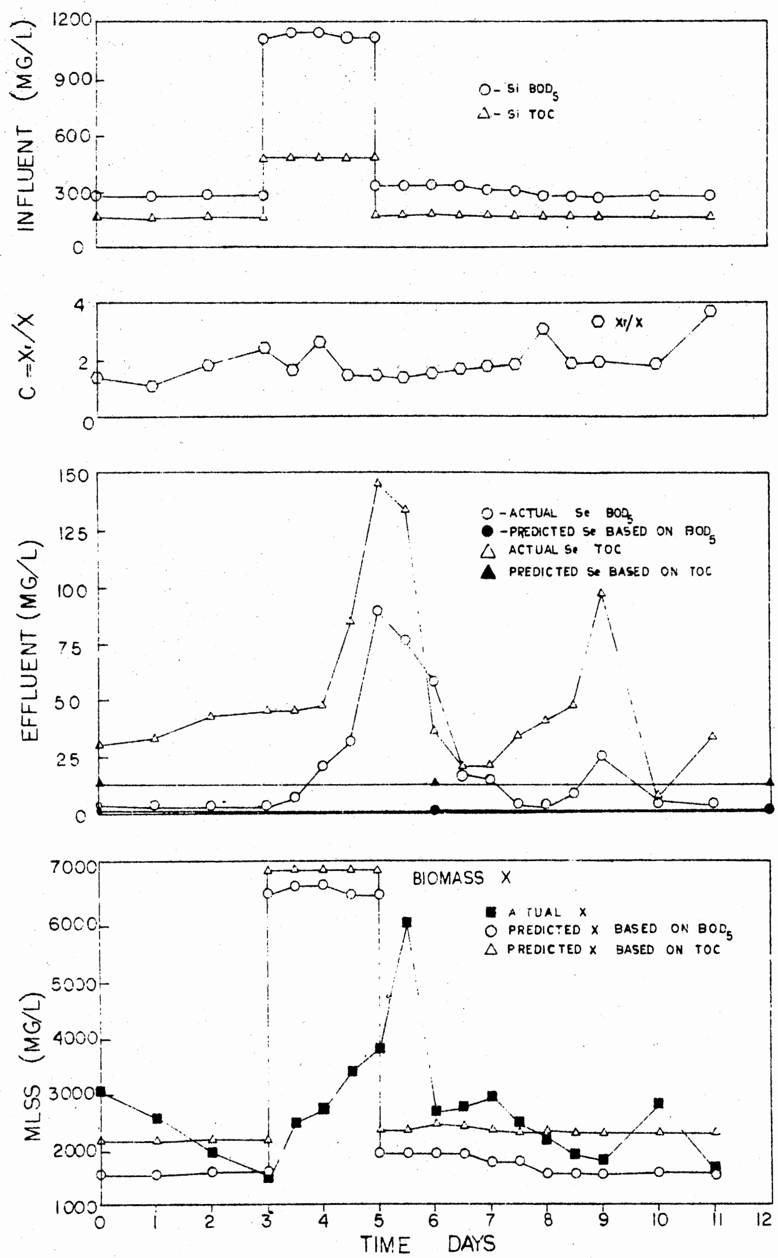

Figure 7. Plot of Actual and Predicted Values of X, X_R/X, S_i and S_e of Run V for Both TOC and BOD_5 Analysis

of substrate in the effluent as seen by the sharp increase in TOC and BOD_5 12 hours after the shock load began S_e-TOC gradually decreased to a steady value, while the S_e-BOD_5 fluctuated for 5 days before reaching a steady value. The mean average for S_e(TOC) = 24.80 mg/l and $S_e(BOD_5)$ = 3.90 mg/l. S_e(TOC) was above the predicted value, but $S_e(BOD_5)$ was fairly close to the predicted value.

3. Effluent Suspended Solids - X_e - (Refer to Table VI.) There was no significant change in X_e except for a nominal increase in X_e for 24 hours after the shock load, and also after 3 days, otherwise the sludge settled well, and there was no change in predominance of the biological solids. The mean value was 6.93 mg/l, which is slightly higher than the set value of X_e = 5 mg/l.

4. X_R/X Ratio - (Refer to Figure 6 and Table VI.) This ratio was quite steady throughout, except during the shock load period, when it decreased. Calculated and set α were fairly close throughout the run.

5. F:M Ratio - (Refer to Table V.) F/M ratio was well within the limits. F/M ratio was four to five times higher during the shock load period due to increased influent substrate concentration S_i, without corresponding increase in X. F/M reached a steady value after the shock load.

Run V (Three Fold Step Increase in S_i With a Simultaneous Transfer of all Biological Solids in the Clarifier to the Reactor)

The unit was operated at steady state several days before the shock load was inflicted on the system. As usual MCRT(θ_c) of 10 days was maintained in accordance with the model. In this particular experiment, all the biological solids in the clarifier were pumped into the reactor, at the beginning of the shock load, in order to increase the MLSS-X to the levels predicted by the kinetic model. The unit was subjected to a three fold step increase in the influent substrate i.e. an increase in BOD_5 of S_i from 265 mg/l to 1140 mg/l and TOC from 156 mg/ to 473 mg/l.

1. MLSS-X - (Refer to Figure 7 and Table VII.) The average predicted values by the model for solids in the reactor - X are (1,500-2,500) mg/l during steady state and (6,500-7,000), mg/l during the transient period. The actual X monitored was very close to the steady state values prior to the shock load, but during the shock load period, X rose gradually to a peak value of 6000 mg/l in 2.5 days and dropped back to steady state value immediately. The steady state values of actual biomass X, fluctuated between the predicted levels of X for both BOD_5 and TOC. Thus actual X was fairly close to the predicted values before and after the shock load.

2. Effluent Substrate Concentration - S_e - (Refer to Figure 7 and Table VII.) The model predicts $S_e(BOD_5)$ = 0.40 mg/l and S_e(TOC) = 12.05 mg/l during the entire run. If we examine the data in Table VII and Figure 7, during steady state S_e-BOD_5 is fairly close to the predicted value, though there was distinct leakage of substrate at two different times, that is at 36 hours and 6 days after the onset of shock load. S_e-TOC was higher than the predicted values during the entire run. It must be noted that maximum leakage of effluent substrate, both S_e-BOD_5 and TOC were well above the predicted values.

3. <u>Effluent Suspended Solids - X_e</u> - (Refer to Table VII.) There was some loss of biological solids, due to change in predominance from a flocculant to a filamentous growth. This lasted for nearly four days, after which X_e subsided to normal steady state value. It exceeded the set X_e 5 mg/l due to the shock load, as it was below 5 mg/l before the shock load during steady state.

4. <u>X_R/X Ratio</u> - (Refer to Figure 9 and Table VII.) This ratio was steady except for fluctuations during the shock load period. α was kept fixed at 0.25 throughout the run, except for recycling all the solids from the clarifier at the beginning of the shock load.

5. <u>F/M Ratio</u> - (Refer to Table VII.) F/M ratio was within the defined limits, except during the shock load period, it was high due to low MLSS-X concentration in the reactor even though all the biological solids were recycled into the reactor from the clarifier. F/M ratio was steady before and after the shock load.

CHAPTER V

DISCUSSION

The Lawrence-McCarty (24) kinetic model was used for operations and control of the unit throughout the study. Kinetic constants listed in Table II, which were generated from research units being run in the the OSU Bioenvironmental Engineering labs, were utilized in the equations. The kinetic model was used to predict the behavior of the system and to adopt necessary control strategies to obtain desired S_e. Since the unit was operated at MCRT(θ_c) of 10 days, the values of S_e-BOD_5 and TOC evaluated from the kinetic constants and Lawrence-McCarty model are 0.40 mg/l and 12.05 mg/l.

Examining Figures 3 to 7, one finds that the biological solids - X in the aeration basin, always increased gradually, in response to an influent shock load (increase in S_i) while the kinetic model predicts a sharp instantaneous increase in X as a response to an increase in S_i. It took more than 36 hours after the application of the shock load for biomass-X to increase to the levels predicted by the model, in spite of increasing α-the recycle ratio to aid in increasing X. Gaudy and Kiavanich (42) show that X increases in the reactor in a once through system, in a manner parallel to the dilute - in of influent S_i in the reactor; though in this case, it was not true. In experiments conducted by Saleh and Gaudy (34) biomass X took almost

36 to 48 hours to increase with the onset of an influent shock load, which seems to agree with this study's findings, even though Saleh and Gaudy use a constant recycle with MLSS in recycle line - X_R values ranging from 5,000 mg/l to 10,000 mg/l. X_R in this study increased with X, but never reached the desirable X_R/X ratio greater than or equal to 4. This may be one of the causes of sluggish increase of X in the reactor. With the onset of shock load, the biomass may respond in two ways (42), first it may increase replication i.e. synthesis of new cells, by rapidly consuming the influent substrate or it may resort to oxidative assimilation of substrate as storage products. The response of the biomass either way seems to have the same effect on the effluent subtrate.

Lawrence and McCarty's (24) kinetic model predicts an instantaneous increase in biomass X, as a response to an influent shock load or an increase in S_i. The system will reach a new steady state if the increase in S_i persists for a long duration. On termination of the shock load, or if there is a decrease in S_i, the kinetic model predicts a decrease in MLSS-X, instantaneously, after this decrease the process reaches a new steady state condition. It is clearly evident from the results of the five experimental runs, that the biomass-X increases and decreases gradually or slowly; although the kinetic model predicts a sharp (instanteous) increase or decrease with a variation in S_i. However if the fluctuations in S_i were to presist long enough the biomass X would increase to the new levels predicted by the kinetic model and reach a new steady state condition. This was shown by Parrot (53) in his study. The kinetic model was unable to predict accurately the transient responses to short term variations or pertubrations in S_i.

This poses a problem to the operator, who has to decide and opt for a suitable control strategy to combat the impact of the shock load.

In order to resolve this operational problem the effects of manipulating α-recycle ratio and F_w-sludge wastage were studied to let the process function as predicted by the kinetic model; thus control over α and F_w was exercized. MCRT (θ_c) of 10 days was successfully maintained by controlling F_w, while α-recycle ratio was doubled or tripled, and in one instance, all solids in the clarifier were recycled into the reactor, in order to achieve an instantaneous increase in biomass X and decrease in S_e of the effluent; as forecasted by the model.

Figures 3 to 7, show that by increasing α-the recycle ratio, a rapid increase in the biomass concentration X in the reactor could not be achieved as predicted by the kinetic model. However, greater attenuation of the substrate in the effluents with higher α was achieved. In the five different runs conducted, maximum substrate leakage occured in those runs in which α was not changed. Higher attenuation of substrate leakage was achieved, when α was tripled. Even though the biomass - X could not be be increased with the onset of the shock load, attenuate on the effluent substrate to a certain extent was noticed by increasing α, i.e. recycling more biomass-X. An ideal situation would be where biomass X in the reactor could be increased to the levels predicted by the kinetic model to achieve predicted S_e.

By trying to increase biomass X in the aeration basin an attempt is being made to decrease and stabilize the F/M ratio, which triples or quadruples on the application of a shock load down to a more reasonable value for better performance and better sludge settling in the process.

Several options are available to increase the biomass in the aeration basin. The first is to increase the recycle α, but this may not always contribute positively, especially if X_R in the recycle sludge is low. Therefore Gaudy (42) suggests, incorporation of an extra tank to receive and thicken sludge from the clarifier and recycle back with a constant X_R values ranging from 5,000 mg/l to 10,000 mg/l. This unfortunately adds to the operational costs and may not always be economically feasible. Gaudy and Manickam (26) show that they can achieve better attenuation of effluent substrate with higher X_R values. Reddy (44) in his Ph.D. thesis recommends the use of biological solids from an aerobic digester, as this provides a steady source of cells, which can be utilized, when a shock load is applied. He also states that the recycle of solids from such digesters improve sludge compaction, and also reduce the growth of filamentous micro-organisms, but this implies addition of an aerobic digester to the waste water treatment plant facility, which again is not economically attractive, unless it is already included in the initial plant design for aerobic sludge digestion.

The other alternative is to increase the aeration basin volume, to accommodate more biomass by recycle. This demands great flexibility in the design and construction of the aeration basin so that it is easy to increase or decrease the volume of the aeration basin, along with associated aeration equipment as and when required and this may not be economically feasible. Increased biomass concentration, implies operating the system at higher MCRT(θ_c) and lower specific growth rates μ_n, which means more aged cells and better response to shock loads. Gaudy and co-workers have shown that such a system was more resistant to leakage of S_e. (42). This method has not yet been fully researched and neither the economic feasibility studied.

On analysis of the effluent substrate concentration S_e for all five runs (Figures 3 to 7) it is clear that S_e-BOD_5 and TOC are much higher than the predicted values by the kinetic model.

TABLE VIII

PREDICTED AND ACTUAL MEAN VALUES FOR S_e FOR EACH RUN

Run Number	S_e-BOD_5 (mg/l)		S_e-TOC (mg/l)		X_e
	Predicted	Mean for Each Run	Predicted	Mean for Each Run	
1	0.4	5.66	12.05	27.90	11.83
2	0.4	3.67	12.05	9.43	6.37
3	0.4	4.83	12.05	26.80	4.6
4	0.4	3.90	12.05	24.80	6.93
5	0.4	19.60	12.05	51.33	16.5

The mean BOD_5 is less than or equal to 5 mg/l in the first four runs, which seems to be quite reasonable, as it is very difficult to achieve a BOD_5 of 0.4 mg/l in the effluent, though predicted by the model. The TOC values of S_e were rather high, and this is attributed to the production of intermediate compounds or non-biodegradeable material. In Run II S_e-TOC was lower than the predicted value, whereas in three other runs, it was twice the predicted value. In the last run both BOD_5 and TOC are high, indicating a substantial leakage of substrate in the effluent. The effects of the production of intermediate compounds have not yet been incorporated into the kinetic model, which is a drawback when using TOC analysis.

Another important aspect one must discuss here is the effect of the clarifier on the effluent substrate concentration S_e. Due to the large volume of clarifier and the presence of the biological solids, there seems to be some substrate removal by the biomass in the clarifier; thus the clarifier provides a little extra biological treatment and reduces both S_e and S_R (26).

It was also noted that, at least in two of the runs, the leakage of substrate in the effluent occurred distinctly at two different times after the application of the shock load, once during the shock load, and the other immediately after the unit returned to steady state conditions. Sudden decrease of S_i after the application of shock load may have been perceived as a shock by the biomass, which explains the latter leakage of substrate in the effluent. As if it were subjected to two different shock loads, i.e. (increase and decrease in S_i). This phenomenon was more prevalent in the runs with fixed or lower α. While it was not so evident in the runs when α was tripled.

The accuracy of the predictions for S_e and X by the kinetic model depend heavily upon the kinetic constants utilized. In this study, the predictions for X before and after the shock load are fairly close, but this was not the case with S_e, which was consistently higher for both TOC and BOD_5. It would have been more appropriate if the kinetic constants had been determined first before proceeding with the experimental work. This raises a very fundamental question about the very reliability of the bio-kinetic constants! The bio-kinetic constants utilized in this study were determined over a period of two years, using the same synthetic waste, in an internal recycle activated sludge units in Bio-Environmental Energy Laboratories of Oklahoma State University. It is now well understood that the bio-kinetic constants vary with different wastes and environmental conditions. Some authors refer to K_s, K, μ, Y_e, k_d, and μ_{max} as bio-chemical kinetic constants, while the latter prefer to call them kinetic coefficients. However, everyone agrees that these kinetic coefficients or constants exhibit some degree of variability, due to the heterogeneous nature of the microbial populations used in activated sludge systems.

The predictive equations derived from the kinetic model were based on the premise that a steady state would be maintained; ie $\frac{dx}{dt} \to 0$, and $\frac{ds}{dt} \to 0$ (42). It is also evident from this study that the predictions were not accurate during the transient stage; and the kinetic model may have to be modified to incorporate the transient phenomenon in the process, which is seen quite often due to variations in F and S_i and other environmental factors.

Therefore, it is quite sensible to determine the bio-kinetic constants or coefficients, and update the process control and operational strategies, as one cannot for certain tell when the characteristics of the wastewater or of the nature of microbial populations change.

A change in the predominance of the microorganisms was noticed only in those runs, in which a three fold shock load was inflicted. In those cases α-the recycle ratio was either constant or varied with the ratio X_R/X. This clearly indicates the beneficial effects of increased α-recycle ratio.

The leakage of biological solids in the effluent are shown in Table III for each run. The mean values are between 4.6 to 16.5. The higher loss of solids was in Runs I and V, and it was also in these runs higher leakage of substrate in the effluents occurred. Thus one can expect some temporary loss of solids in the effluent, due to shock loads. Greater F_w would have meant lower biomass in the reactor and vice versa (15). Wasting from the recycle line seems to have had no impact on X_R.

The recycle ratio α, was set, as predicted by the model, depending upon the ratio X_R/X. Since high X_R/X ratio was not achieved, the recycle ratio α, was on the higher side during steady state operation. In all but one run, α was either doubled or tripled arbitariarily, in order to increase biomass X in the aeration basin and decrease S_e in the effluent. Latest trends in return sludge recycling provide capacities of 50 to 100% of influent flow for large plants and up to 150% for smaller plants (43). Thus making it a very important tool in daily operational control of the activiated sludge treatment plant. α, can be manipulated to keep F/M ratio in the reactor constant, or reduce drastic variations; even though during the shock load periods, it cannot reduce the F/M ratio quickly and sharply as desired. A steady F/M ratio could be achieved using this model, as seen from the data in Tables III to VII.

TOC, BOD_5, COD Analysis

BOD_5 is an excellent and economical bioassay test, to measure the pollution potential of the influent and effluents in a waste water treatment plant (42). The only problem with this test is the time factor, it requires 5 days! In a dynamic situation such as the continuous flow activated sludge treatment plants, where operational changes are made on an hourly basis, one cannot wait for five days, but that does not necessarily mean this test should be abandoned, in favour of others, this test should be used in conjunction with other tests, due to its own advantages.

TOC is a quick and accurate test, the main problem with this test, is when metabolic intermediates are produced, as was the case in this study, the effluent TOC values are higher resulting in an awkward situation where TOC's are high and BOD's are low for which the kinetic model is not geared. However, this test could be used with the Lawrence McCarty model to acheive better operational control over an activated sludge system. The plant operator could monitor influent and effluent substrate concentration S_i and S_e, continuously and quickly adopt remedial control strategy to nullify the effect of increase in S_i or S_e, quite easily; by any control strategy he chooses.

COD tests are now available in package forms, like the Hach kit, it takes two hours to run the test. One can easily measure COD of the influent and effluents. This test is expensive, but accurate, and it can be used to monitor the performance of the waste water treatment plant easily.

In a five-week process study by Hawthorne and Sanders (48) they found a line or relationship between BOD vs TOC with a correlation coefficient of 0.81 and high degree of confidence of the regression, that they justify the use of TOC as a measure of substrate concentration and recommend incorporation of an on-line TOC analyzer in the design for automation of Chester waste water treatment plant in Pennslyvania.

As far as operational control of the activated sludge plant, it is more prudent to use TOC analysis due to its inherent advantages over BOD_5; primarily because this is an instantaneous test which is easily reproducible and can be automated in treatment plants for continuous measurement of S_i and S_e (48). In this study TOC analysis proved very satisfactory when used in conjunction with the Lawrence-McCarty kinetic model.

Comparison of Methods of Control

Reviewing the results of this study, it becomes quite evident which method offers the best possible control on the activated sludge process, it is obviously the MCRT(θ_c) method. This method incorporates two other methods, indirectly. Use of the Lawrence McCarty kinetic model, enables the operator to quickly adjust the operational aids at his disposal to effect remedial action. The operator will be able to use the model to predict S_e, X and determine F_w and α, for a constant

MCRT(θ_c). By making necessary changes in α or F_w, he is able to achieve positive control on the operation of the plant. Using this model, he can achieve the desired X, α, F_w, S_e, and this indirectly controls MLSS or MLVSS and F/M ratio. Thus, when there is shock load (increase or decrease in S_i), the operator cannot do much in MLSS or MLVSS and F/M ratio methods except try to control the biological solids in the reactor by controlling F_w, whereas using the kinetic model, he is able to control F/M ratio, as this is related to MCRT(θ_c) and also MLVSS, by increasing or decreasing α-the recycle ratio, and F_w. He can also achieve constant substrate utilization rate in Lawrence and McCarty method, without any difficulty.

GSA control technique assumes that the ratio between the BOD_5 and suspended matter is fairly constant, which is not the case always, especially during shock loads. Problems do arise when BOD to suspended solids ratio in the influent changes! This method is not kinetically rational, as it does not address characteristics of microbial growth etc.

In Oxygen Uptake Rate control method, MCRT (θ_c) and hydraulic detention time are selected arbitararily on past plant performance for the desired effluent quality. This method involves calculation of theoretical O_2 uptake, and then comparison with the actual measured O_2 uptake, and accordingly α-recycle ratio is varied. This permits us to control one parameter α only. This method is complex, and requires a well trained operator.

Sludge quality control is another method which has been tried out, and advocated by West (48, 40). This method requires relatively simple tests in comparision with the Lawrence and McCarty's (24) method; but it has many shortcomings, and operators often find it quite difficult to maintain a steady state, as they are either recycling too much or too less most of the time. This method is based critical loading of the secondary clarifier. Carter (51) proposed some modifications very recently, which allows the operator to control θ_c, F_w, F_r, and F_c. The operator has to calculate theoretical θ_c, and solve for F_w, F_r and F_c from the model. This method is quite involved and recent, it requires more study and experimental verification.

CHAPTER VI

CONCLUSIONS

1. The Lawrence and McCarty (24) kinetic model is a useful aid in operating activated sludge process, especially during steady state operation. The kinetic model has its limitations in modelling the dynamic response i.e. when the process is subject to rapid quantitative and qualitative influent pertubrations.

2. The dynamic response of the kinetic model to short duration shock loads or perturbration is far from satisfactory. It predicts a sharp and instantaneous increase in steady state levels of biomass X when subjected to a shock load; but the actual increase in biomass X to the new steady state level has always been gradual. However, during long duration perturbrations or shock loads, the model seems to give satisfactory predictions.

3. A high value of $C = {}^{X}R/X$ ratio is desired for better performance.

4. A three-fold shock load with low α, resulted in greater effluent substrate leakage, while higher α attenuated this leakage to a certain extent.

5. The activated sludge system can easily absorb three-fold shock loads of short duration, without any adverse impacts on the unit operation and S_e.

6. If the biomass X could be increased in the reactor, to the levels predicted by the kinetic model, then it may be possible to minimize or reduce any adverse impacts on the operation of the unit; especially leakage of S_e and X_e.

7. The activated sludge unit recovered quite quickly after each shock load, and resumed normal steady state operation. The average recovery time was four days after a 48 hour shock load.

8. TOC analysis provides us with a quick effective monitoring of the activated sludge process. Therefore, it is recommended for use in controlling the process; in addition it is easily adaptable for automation and computer control.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

Reviewing the results of this study, it is clear that the kinetic model is not satisfactory during transient conditions; therefore, further studies are recommended in the following areas:

1. The effects of effluent recycle (negative feedback) on the operation and control of activated sludge systems.

2. Study the effects of influent pertubrations at different sludge ages in an activated sludge system.

3. Research into the possibility to use extended aeration or total oxidation as a means of achieving better process and effluent quality.

4. A detailed study on the kinetic constants or coefficients as to why they vary with time, or type of wastes and their reliability.

5. Improve existing kinetic model or evolve a reliable new model to accurately predict the transient behavior of activated sludge systems.

6. Use an on-line TOC analyzer and Lawrence-McCarty (24) kinetic model in an actual treatment plant and study the effectiveness of the kinetic model.

7. Whether total process automation will achieve better operaational control and be cost effective!

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