STUDIES ON NEW MODES OF OPERATION FOR EXTENDED AERATION ACTIVATED SLUDGE

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Submitted to the Faculty of the Graduate College
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in partial fulfillment of the requirements
for the Degree of
DOCTOR OF PHILOSOPHY
May, 1980

Dedicated to my parents, Veera Reddy and Basawamma

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Thesis Approved:

Thesis Adviser

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ACKNOWLEDGMENTS

The author wishes to express sincere appreciation to his major adviser, Dr. A. F. Gaudy, Jr., for his constant encouragement and valuable assistance throughout the author's graduate studies and during the preparation of this thesis, and to Dr. Elizabeth T. Gaudy for her suggestions and advice.

Special appreciation is also extended to Dr. D. F. Kincannon for his suggestions and serving as a committee member. Dr. M. H. Bates and Dr. R. K. Gholson also deserve thanks for their cooperation and for serving as committee members.

Special appreciation is extended to my colleagues for their cooperation and understanding during the author's stay in this laboratory. Mrs. Grayce Wynd deserves special thanks for carefully and accurately typing this thesis, for her valuable friendship, and for offering help whenever needed.

A special thanks to my wife, Vanaja, for her patience and understanding during the author's course of study, and to my son, Navin, who provided the inspiration to complete this work.

The author wishes to express his gratitude to the School of Civil Engineering for its support through a graduate research associateship during the conduct of this investigation.

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S_i - Influent feed substrate concentration, mg/l

S_t - Total effluent COD, mg/l

S_e - Soluble effluent COD, mg/l

S_{R_1} - Soluble COD in reactor 1, mg/l

S_{R_3} - Soluble COD in reactor 3 (aerobic digester), mg/l

S_{R_2} - Soluble COD in reactor 2 (recycle reactor), mg/l

X_R - Recycle suspended solids concentration, mg/l

$\bar{X}$ - Reactor 1 suspended solids concentration, mg/l

X_e - Effluent suspended solids concentration, mg/l

X_w - Sludge produced per day: mg/day

$\bar{t}$ - Hydraulic detention time in reactor 1, hours

V_{R_3} - Volume of reactor 3 (aerobic digester), ml

V_{R_2} - Volume of reactor 2 (unit 2), ml

μ_m - Maximum specific growth rate, hr^{-1}

K_s - Saturation constant, mg/l

Y_{t_B} - Batch yield coefficient, mg/mg

K_d - Maintenance coefficient, day^{-1}

μ_n - Net specific growth rate, day^{-1}

CHAPTER I

INTRODUCTION

Biological treatment of wastewater is widely practiced in the world at the present time. Considerable research has been expended over the past few decades to understand the mechanisms and provide control strategies for efficient utilization of microorganisms through various operational schemes. Activated sludge is widely used in the treatment of wastewater, but there still exists considerable hiatus between the ability of microorganisms to remove organic matter and their utilization to the maximum potential available as measured by performance, reliability, and operational stability.

The criterion for process performance is high efficiency of removal of organic matter with the least amount of excess sludge production. Reliability of the process is measured as continued efficient performance throughout the life of the plant providing stable effluent condition even in adverse situations. To achieve any one or all of these objectives, researchers have developed different process modifications to meet specific needs.

The conventional activated sludge process with reasonably low hydraulic detention times provides good biochemical oxygen demand removal efficiencies, but does produce relatively significant amounts of sludge to be wasted and is susceptible to upset due to changes in inflow conditions. On the other hand, total oxidation activated sludge produces

little excess sludge. While it is relatively stable to changes in inflow conditions, it does require longer hydraulic detention times. To date, no single process modification has been able to provide all of the desired characteristics. The objective of this research is to seek ways to provide a stable mass of microorganisms with low specific growth rates while maintaining the hydraulic detention time within reasonable magnitudes, at the same time providing a source of biomass to meet any exigencies. While it is the ultimate aim of any researcher to achieve all of his stated objectives, it was realized that it is beyond the scope of this research to solve completely all the facets of the problem. However, it is the intent that this work provides a basis for further research in this direction. This work is specifically undertaken to study the feasibility of reducing hydraulic detention times in the total oxidation activated sludge process, and to study the feasibility of using aerobic digester solids as a ready source of biological solids during shock loads.

CHAPTER II

LITERATURE REVIEW

Ardern and Lockett (1) were the first to experiment with "activated sludge" by blowing air into sewage to treat the wastewater. They used a batch-operated system and retained settled biomass at the end of each batch feeding period to be re-used in the next, and called this settled sludge "activated sludge." The first major plant built in the United States utilizing the activated sludge principle was in Houston, Texas, in 1918, employing the continuous flow technique (2).

As understanding of the activated sludge process increased, various researchers proposed modifications to improve the efficiency of the process and to reduce the cost of aeration. Kessler, Rohlich and Smart (3) proposed tapered aeration, i.e., sizing the aeration facilities to meet the air requirements in a continuous operation. This approach was based on the understanding that in a continuous operation the oxygen requirements for activated sludge diminish rapidly as the treatment progresses. With mechanical aeration devices the size of the aerators was to be adjusted, and for diffused aeration devices it was suggested that more diffusers be placed at the head end with gradual reduction in their number as the demand for air decreased. In the tapered aeration process, the wastewater enters at one end and exits at the other end. But Gould (4) proposed a modification to tapered aeration to conserve the aeration tank capacity, called step aeration. The step aeration

process uses multiple-pass tanks. The first aeration tank was used for reaeration of return sludge. Sewage was added stepwise into each of the next three aeration tanks in a coordinated manner. The aerated mixed liquor from these tanks entered a sedimentation tank where the sludge being settled to the bottom was returned to the sludge reaeration tank and the clarified effluent was discharged. This operation was purported to produce well settled sludge with reaerated sludge of greater absorptive capacity to remove organic pollutants from the wastewaters.

Ulrich and Smith (5) utilized the absorptive properties of regenerated sludge and proposed a modification called the biosorption process (also called contact stabilization). In this modification, the regenerated activated sludge was brought into contact with wastewater and aerated for short periods of time; the process was reported to produce good organic matter removal efficiencies.

Pasveer (6) and Wuhrman (7) demonstrated in their studies that activated sludge with a completely mixed aeration tank could be used to produce greater efficiencies with high organic loadings per unit weight of sludge. They felt that activated sludge processes were not being utilized to maximum ability.

While the engineers were trying to find ways to better utilize the microorganisms to purify the wastewater, basic scientists tried to develop mathematical models to describe the growth pattern of the microorganisms. One of these descriptive equations was developed by Monod, and it has been widely accepted by most scientists and engineers in the field of water pollution control. Aided by the growth model developed by Monod and the chemostat as described by Novick and

Szillard (8), Herbert (9) developed a mathematical model to describe the growth of bacteria in a continuous flow stirred tank reactor with and without recycle. Herbert's model for recycle consists of a sludge concentration factor, c, which is the ratio of cell concentration, X_R, in the recycle to the cell concentration, $\bar{X}$ in the reactor. To test the applicability of Herbert's model, Ramanathan and Gaudy (10) set up a bench scale pilot plant with a separate makeup tank to maintain the X_R value at c times the $\bar{X}$ in the reactor by maintaining all other parameters constant, and showed that a constant c actually affects the steady state value of X in the system because of variations in cell yield due to heterogeneity of the populations. They proposed that the recycle cell concentration, X_R, be held constant rather than c. They further stated that constant X_R provides a sufficient mass of microorganisms to prevent complete dilute-out at higher dilution rates since the value of X would become asymtotic to a value of $X_R \left(\frac{\alpha}{1+\alpha}\right)$ at very high dilution rates (α = recycle flow/feed flow), and proposed a ready supply or "sink" of cells to recycle into the reactor when necessary.

Gaudy and Srinivasaraghavan (11) studied the above model, and concluded that employing X_R as a selectable engineering system constant provides a steady performance in effectively removing substrate over a wide range of feed concentrations. During these studies, Gaudy and Srinivasaraghavan (12) found that cell yield was depressed due to low values of specific growth rate, μ, and that this low growth rate in turn was caused by high return sludge concentration, X_R. This observation which was in accordance with the maintenance energy theory as Marr et al. (13), stated that

> . . . if a continuous culture is limited by the carbon source, a significant portion of the carbon source may be diverted

> from growth to time-dependent processes that do not result in an increase in the concentration of cells (p. 536).

A modification of the original equations proposed by Ramanathan and Gaudy was made by including a term for the maintenance coefficient, k_d (Srinivasaraghavan and Gaudy, 14) to improve the prediction of sludge production.

Apart from the development of the model, considerable effort was expended by Gaudy and his co-workers to study the activated sludge process response with respect to variations in the inflow conditions.

George and Gaudy (15) studied the effect of hydraulic shock loads on a completely mixed activated sludge system, and concluded that with a mean hydraulic residence time of approximately eight hours, the process can accommodate a step change of 100 percent without seriously affecting biochemical efficiency, and recommended that "in the interest of providing more steady and reliable performance with regard to substrate removal efficiency, activated sludge systems be afforded protection."

Krishnan and Gaudy (16) studied the response of activated sludge to quantitative shock loadings, and observed that cells with "slow" growth history before the shock can adjust more readily to change.

Saleh (17) studied the effect of hydraulic and quantitative shock loadings on the activated sludge process using constant X_R, and found that X_R concentrations above 12,000 mg/l exerted a dampening influence on the magnitude of transient disturbance. Manickam (18) also studied the response of the activated sludge process employing constant cell recycle concentration when subjected to qualitative, quantitative, hydraulic, and cyclic shock loads using glucose and sorbitol as carbon

source. He found that an increase in X_R attenuated the leakage of substrate from the reactor when the system was shocked to a six-fold quantitative change, and that the system operating with an X_R of 5000 mg/l successfully accommodated shocks consisting of glucose and sorbitol with a total S_i concentration of up to 1500 mg/l.

While the proper understanding and engineering control strategies of activated sludge were worked out, some researchers tried successfully to develop process variations to solve the problems of ultimate sludge disposal, bulking, and incidence of filamentous organisms.

The problem of ultimate sludge disposal or total oxidation was proposed originally by Porges et al. (19) in 1953. They suggested that

> . . . if endogenous respiration proceeds at a great enough rate, microorganisms oxidize their own tissue rapidly enough to keep the system in balance. Under such conditions, sludge does not accumulate. If autodigestion is not sufficient, sludge accumulates, making sludge disposal necessary (p. 262).

Kountz (20) in his analysis of the total oxidation process states that the activated sludge has a known and definite rate of production and a known and definite rate of removal. These two can and do become equal, resulting in a daily sludge removal rate equal to its daily production rate. Forney and Kountz (21) later studied a continuous system and concluded that total biooxidation was possible, and that the activated sludge reaches an equilibrium value in the reactor about twelve times the weight of influent organic matter used.

Symons and McKinney (22) studied the biochemistry of nitrogen in the synthesis of activated sludge, and concluded that conventional activated sludge systems cannot operate without wasting and without a gradual solids buildup unless some solids escape with the effluent. Washington and Symons (23) in a later study showed that volatile solids

accumulate on the average 11.5 percent of the ultimate BOD removed and that this accumulation contains mainly polysaccharides and some significant amounts of fatty acids and organic nitrogen.

McCarty and Broderson (24) also studied the extended aeration process and concluded that sludge accumulates in the total oxidation system and this accumulated sludge will be lost in the effluent in surges.

Gaudy, Ramanathan, Yang, and DeGeare (25) showed that the extended aeration activated sludge system without wasting can be operated with reasonably good biochemical efficiency and without continual solids accumulation.

Gaudy, Yang, and Obayashi (26) operated the extended aeration system for long durations without any sludge wasting. They found that the total oxidation system undergoes periodic increases as well as decreases in the sludge mass, and showed that this change in the concentration of biological solids does not affect the biochemical efficiency or the treatment capability of the sludge to remove the soluble organic matter from solution. They further studied the feasibility of using hydrolysis as a means of controlling biological solids, and suggested that hydrolysis aids the autodigestive process by providing for treatment of the organic waste and for sludge disposal.

Obayashi and Gaudy (27) used extracellular polysaccharides as food material and showed that bacteria metabolize extracellular polysaccharides. They concluded that the extracellular polysaccharides cannot be classified as biologically inert material, and these biological materials could be used as usable sources of organic carbon for growth of microorganisms in heterogeneous populations.

Yang and Gaudy (28) studied the use of hydrolysis to control the mixed liquor biological solids concentration and showed that the extended aeration process can be operated without natural periods of accumulation and de-accumulation of biological solids by hydrolyzing a part of the sludge in an autoclave, returning the solubilized sludge into the system.

Gaudy, Manickam, Saidi, and Reddy (29) studied the feasibility of using the total oxidation process as a sludge disposal system. Excess sludge from the secondary clarifier of the Stillwater municipal waste treatment plant was hydrolyzed and used as feed to the total oxidation system. During these studies, the authors showed that even though the sludge contains large percentages of inorganic portions, the cells retained the ability to remove the organic matter effectively; that this inorganic portion of the sludge does not continually increase but reaches a threshold value after which the excess ash will leak into the effluent.

Blachly (30) operated a batch-fed biological reactor with no wastage of solids or liquid portions using glucose as the sole carbon source. The results indicated that soluble residual organics did not build up above a certain level even after 613 days of operation, and the system did not approach a condition of biochemical failure. Substrate removal efficiencies as high as 99.8 percent were observed.

Thus, Gaudy and his co-workers (25, 26, 27, 28, 29) showed conclusively that total oxidation was theoretically sound and the system does not build up large amounts of inert organic as well as inorganic fractions, and that the biochemical efficiency of the sludge can be maintained for longer periods of operation.

Grady (31) investigated the feasibility of reducing the size of aeration basins without sacrificing the effluent quality. In his analysis he advocated three factors to be considered: 1) sludge age or net specific growth rate; 2) oxygen transfer efficiency, and 3) effect of shock loads.

Manickam and Gaudy (32) studied the effect of quantitative and qualitative shock loads, and showed that increasing the concentration of cells in the recycle flow in the activated sludge enhances favorable response leading to less leakage of soluble and suspended organic matter, and the values of μ_n, the net specific growth rate, and cell detention time, Θ_c, can be more directly controlled by the dosage of recycled sludge.

Adams and Eckenfelder (33) observed that an increase in transient organic loadings increases the proportions of filamentous organisms.

Kraus (34) as early as 1945 suggested the use of aerobically conditioned sludge and digester overflow liquor as a means of controlling bulking of activated sludges. He introduced anaerobically digested mixed liquor to maintain high suspended solids concentration and to reduce the incidence of bulking following the applications of shock loads. Recently, Cashion, Kienath, and Shuk (35) studied the performance by using F/M ratio as a control parameter, and concluded that meaningful F/M control can be achieved only when provision is made for the external storage of biological solids, and that without provision for external storage of biological solids, the benefits accrued would be negligible.

The foregoing review has been provided as background information for the present work undertaken by the author in which an activated

sludge bench-scale pilot plant with external recycle was used to study the feasibility of using aerobic digester solids as a ready source of cells to be used during shock loads and to study the feasibility of reducing hydraulic detention time in the total oxidation process.

CHAPTER III

MATERIALS AND METHODS

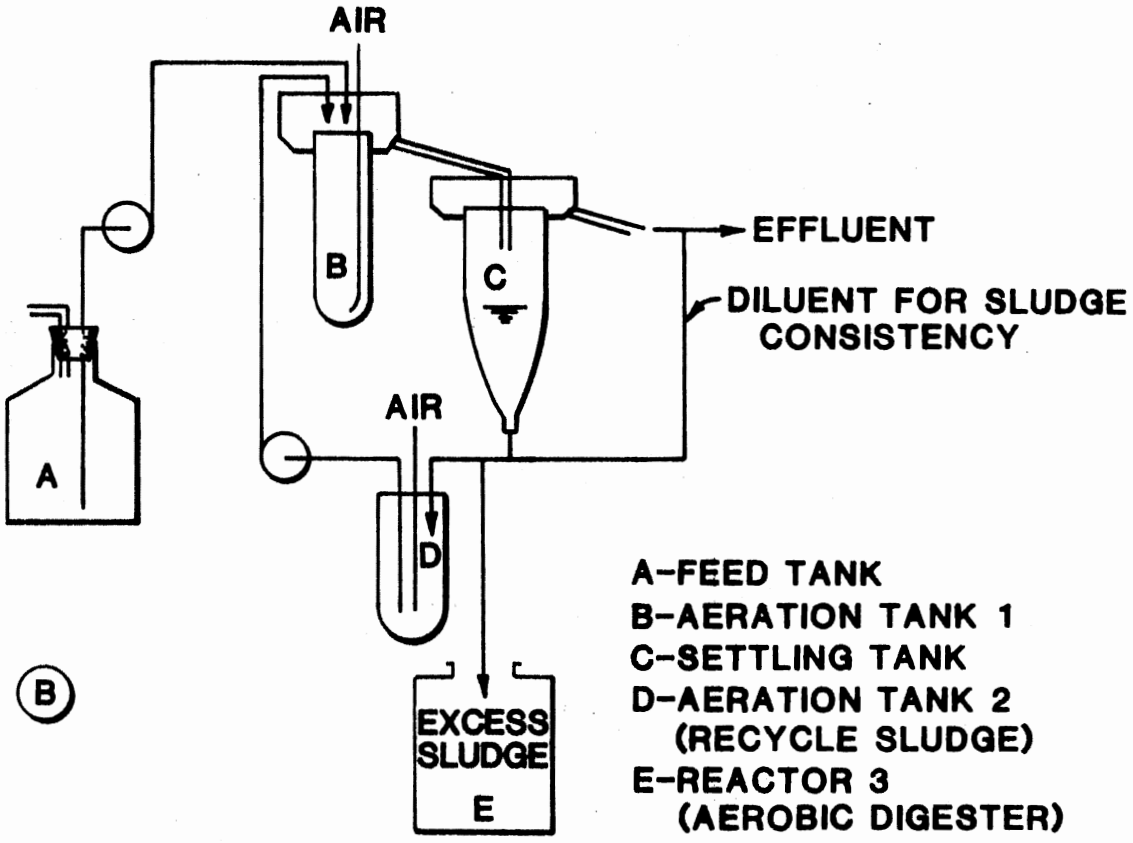
Two bench-scale activated sludge pilot plants were operated. Unit 1 was used to test whether aerobically digested biological solids could be used as a ready source of cells for recycle in case of shock loads. Unit 2 was employed to test the feasibility of reducing the hydraulic detention time in the aeration tank of a total oxidation extended aeration activated sludge process.

Experimental Apparatus and Procedures

Unit 1

This unit is shown in Figure 1. It consisted of reactor 1 to which synthetic feed solution and recycle biological solids were pumped at a constant rate. The mixed liquor from reactor 1 (2.2 liters) flowed into the clarifier (5 liters). Sludge from the bottom of the clarifier was withdrawn every 12 or 24 hours. The sludge concentration was assessed at the time of each withdrawal, using the linear portion of an optical density vs. concentration of biological solids curve. The required amount was diluted to a particular recycle biological solids concentration and transferred to the recycle reactor, reactor 2. Any excess sludge that was available after recycle needs were satisfied was transferred to reactor 3, which served as an aerobic digester. All

Figure 1. Activated Sludge Pilot Plant for Operation With Constant Recycle Sludge Concentration, X_R


AIR
EFFLUENT
DILUENT FOR SLUDGE CONSISTENCY
B
C
A
AIR
D
EXCESS SLUDGE
E
A-FEED TANK
B-AERATION TANK 1
C-SETTLING TANK
D-AERATION TANK 2
(RECYCLE SLUDGE)
E-REACTOR 3
(AEROBIC DIGESTER)

(B)

three reactors were supplied with diffused air to keep a sufficient amount of DO and to maintain complete mixing condition.

The feed solution was pumped from the feed bottle to reactor 1, using a dual positive displacement pump manufactured by the Milton Roy Company. A sigmamotor Model TS finger pump was used to pump the recycle solids. The recycle flow rate was always maintained at a recycle to feed flow ratio (α) of 0.25. The feed was adjusted to maintain the desired hydraulic detention time in reactor 1. The feed was prepared each 48 hours. The feed lines were thoroughly cleaned with a concentration of Clorox solution for 30 minutes to keep the feed lines devoid of any bacterial growth, and flushed with distilled water. Composition of the nutrients used for 500 mg/l glucose is shown in Table I.

TABLE I

COMPOSITION OF SYNTHETIC FEED SOLUTION

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

Unit 2

The experimental apparatus and procedures were similar for this pilot plant (Figure 2), except that an aerobic digester was not employed. All of the excess sludge was kept in reactor 2, but only a fixed concentration of recycle cells was pumped to the reactor at a constant $\alpha = 0.25$. Any excess of cells was mixed with the next day's underflow from the bottom of the clarifier. After it was made to the fixed recycle cell concentration, X_R, the total volume of reactor 2 was noted every day and the X_R concentration was determined by optical density and verified by measuring suspended solids. The volume of reactor 1 was 2.112 liters, and the clarifier was of 5-liter volume.

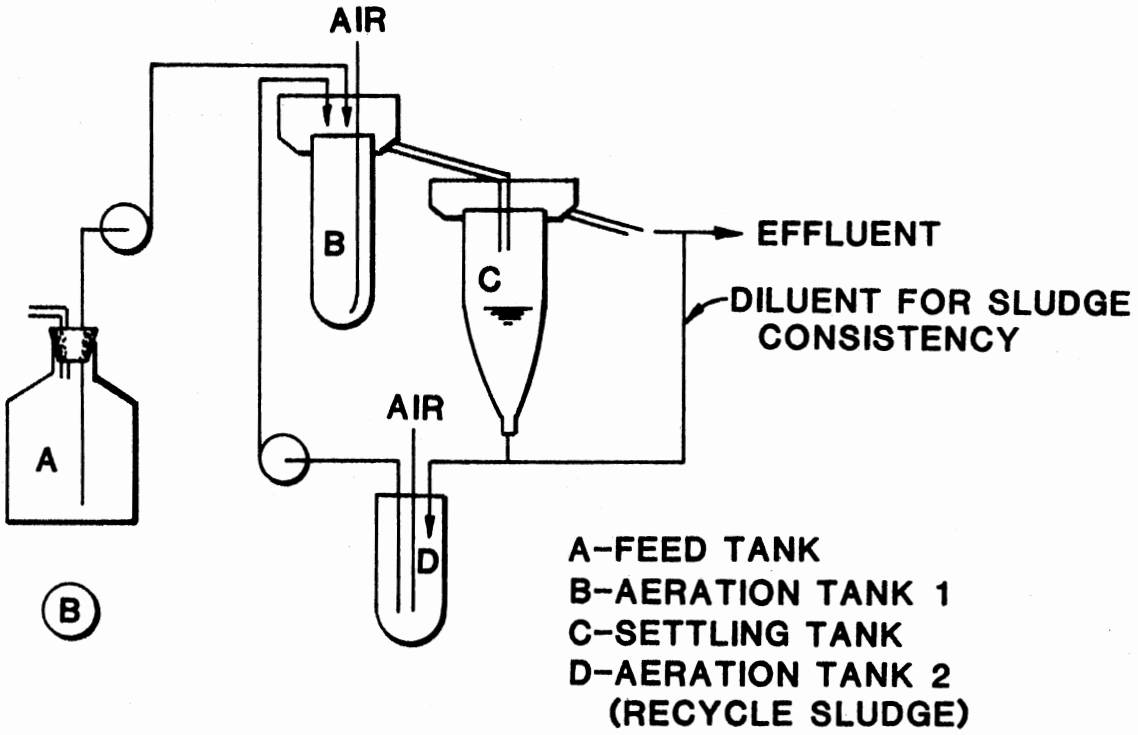
Description of Experimental Phases

In this section, the experimental procedures are described for the five different phases of the experimentation studied.

Phase 1. Experiments to Test the Feasibility of Using Aerobic Digester Solids for Recycle Biomass on a Shock Load Basis

During this stage of the experiments, aerobic digester solids at different conditions were introduced as recycle sludge without any change in either the flow rates or the nature of the inflow feed substrate or its concentration. In all of these experiments, the needed recycle solids were taken from reactor 3 instead of from the bottom of the clarifier on a one-time basis only. That is, of a sudden, the recycle sludge was switched from clarifier underflow to aerobically digesting sludge, and the effect of this sludge change on the biochemical

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


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

and ecological behavior of the system was assessed. During these experiments, α = 0.25, S_i = 500 mg/l glucose, and constant X_R of 8000 mg/l was maintained.

Samples of feed COD, reactor COD, total and soluble clarifier COD were taken. Samples for MLSS recycle suspended solids concentration and clarifier suspended solids concentration were also taken.

Phase 2. Experiments Using Reactor 3 Solids for Recycle Biomass on a Regular Basis

In these studies, the activated sludge pilot plant was operated with recycle biological solids taken from reactor 3 on a regular basis, and the clarifier underflow was transferred directly to reactor 3. During these experiments, the recycle solids concentration, X_R, was maintained at 8000 mg/l. Sludge for the recycle was taken from reactor 3 each 24 hours. Suspended solids from the clarifier underflow were measured every 12 or 24 hours. The concentration of this underflow was adjusted to 8000 mg/l using a standard linear OD vs. concentration of suspended solids curve. Also each day before taking the sludge for recycle, the volume of reactor 3 contents were noted. After transferring the recycle cells to reactor 2, samples were taken to determine the suspended solids concentration and soluble substrate concentration.

Phase 3. Quantitative Shock Loading to a System Using Aerobic Digester Solids Regularly as Recycle Biomass, X_R

a) With recycle solids concentration controlled at 8000 mg/l: In this phase of operation, the activated sludge was subjected to 8000

mg/l: In this phase of operation, the activated sludge was subjected to a 3-fold quantitative increase in the inflow substrate concentration to observe the response of this mode of operation with respect to performance and process stability.

b) Experiments without the constant recycle solids concentration and taking X_R directly from reactor 3 regularly: During this phase of operation, the clarifier underflow was added directly to reactor 3 as it was without any adjustment in concentration to give maximum concentration that the cells could compact to with the least amount of underflow. Reactor 3 biological solids were then transferred to reactor 2, as it was without adjusting to any particular designated concentration level, allowing the optimum suspended solids concentration to be recycled. The feed substrate concentration was maintained at 1500 mg/l glucose during this stage of operation, and the hydraulic detention time was also maintained at 8 hours; the recycle flow rate, α, was kept at 0.25.

Phase 4. Shock Load Experiment With Uncontrolled Sludge Recycle Concentration

After allowing the Phase 3b operation to attain a steady state for a sufficient time, the activated sludge unit was subjected to a 3-fold cyclic hydraulic shock load with a constant feed substrate concentration of 1500 mg/l of glucose. The hydraulic detention time in reactor 1 was cyclically altered from 12 hours to 4 hours every 12-hour period. The recycle flow ratio, α, was maintained constant at 0.25.

Phase 5. Experiments to Study the Feasibility of Reducing Hydraulic Detention Time in Extended Aeration Activated Sludge

Unit 2 was operated throughout as a total oxidation activated sludge process with constant X_R. The X_R concentration was maintained at 10,000 mg/l. Unit 2 was operated at two different hydraulic detention times; i.e., at t = 16 hours and t = 12 hours. The feed substrate concentration during the steady state operation was maintained at 500 mg/l of glucose. The recycle flow ratio, α, was kept constant at 0.25. Sludge from the bottom of the clarifier was taken every 12 or 24 hours, and was mixed with the sludge already present in reactor 2. Then the reactor 2 sludge concentration was adjusted to 10,000 mg/l and the volume of the recycle sludge in reactor 2 was noted. After completing the steady state runs, unit 2 was subjected to a 3-fold quantitative shock load by increasing the feed substrate concentration from 500 mg/l to 1500 mg/l. Also, this unit was administered a cyclic quantitative shock load, with feed substrate concentration changed every 12 hours from 500 mg/l to 1500 mg/l, followed by a one-time step increase to 3000 mg/l. Unit 2 was again subjected to a cyclic quantitative shock load from 500 mg/l to 5000 mg/l every 12 hours. Throughout this cyclic quantitative shock load experiment, no effort was made to maintain the X_R concentration in recycle constant. The recycle reactor was allowed to attain the concentration, the compaction in the underflow dictated by the clarifier.

Batch Growth Studies

When the activated sludge pilot plant was under a steady state,

batch growth studies were performed using the seed from reactor 1 and reactor 3. A series of 250-ml Erlenmeyer flasks with initial substrate concentrations ranging from 100 mg/l to 1000 mg/l were employed. The substrate used in these studies was the same as that used in the pilot plants (glucose). The volume in the Erlenmeyer flasks was 40 ml. The initial inoculation in the flasks was kept low--always nearer to an optical density of 0.046 (90 percent transmission). These flasks were then placed on an Eberbach oscillating shaker with a frequency of 100-110 oscillations/min. Then the optical density was measured at frequent intervals until the logarithmic growth was complete. At the end of the log phase, the biological solids concentration in the 1000-ml flasks were measured to determine Y_{t_B}. The μ_{max} and K_s were determined by plotting $1/\mu$ vs. $1/S$, and S/μ vs. S. These constants were then checked by plotting the theoretical curves.

Analytical Procedures

The following analyses were made on the activated sludge pilot plants:

Feed - chemical oxygen demand (COD) every other day

Effluent - filtrate COD	daily or on alternate days
total COD	
suspended solids	
NH_4 - N	periodically
NH_3 - N	
Filtrate BOD	
Supernatant BOD	

Recycle - suspended solids daily or on alternate days

Filtrate COD - periodically

O_2 uptake - periodically

Mixed liquor - suspended solids daily or on alternate days

O_2 uptake - periodically

Analytical Techniques

Methods for determination of experimental parameters are given below:

Chemical Oxygen Demand Test (COD). This test was used to measure the strength of the organic matter in the feed, reactor, and effluent. The procedure followed was as outlined in Standard Methods for the Examination of Water and Wastewater (36).

Biological Solids. The membrane filter technique was used to determine the suspended solids concentration. The procedures followed were the same as in Standard Methods for the Examination of Water and Wastewater (36).

Ammonia Nitrogen. The analytical method described by Ecker and Lockhart (37) was used.

Nitrate Nitrogen. The Brucine Method as described in Standard Methods for the Examination of Water and Wastewater (36) was employed.

CHAPTER IV

RESULTS

The results are presented in five general phases. The first four phases involve pilot plant unit 1, which was used to study the feasibility of employing aerobic digester from the biological solids in the recycle of an activated sludge when there is an impending shock load. Pilot plant unit 2 was used to study the feasibility of reducing the hydraulic detention time in a total oxidation activated sludge. The results for the second unit will be presented in phase 5. It is also noted that the results for each phase are presented in chronological order. It is recalled that unit 1 was started with a sewage seed taken from the Stillwater municipal wastewater treatment plant. The second unit was previously operated by a colleague, Dr. T. S. Manickam, in his study of the effects of quantitative and qualitative shock loads on activated sludge. This activated sludge was developed on glucose and sorbitol as carbon source. The seeding population had been obtained from municipal sewage. The statistical analysis of the steady state data obtained during this work for unit 1 and for unit 2 are given in Table II.

Phase 1. Studies on the Feasibility of Using Digester Solids as Recycle Sludge

In all, there were nine experiments during this phase of the study.

TABLE II

STATISTICAL ANALYSIS FOR ALL STEADY STATE RUNS

Line	Fig.	Analysis Indicated (mg/l)	N	Mean	S.D. (σ)	C.V. (%)	Range	Remarks
1	3	S_i	15	526	13	2.55	516-556	Steady state - day 6/29/77 to 7/25/77
		S_T	28	42	8	20.30	29-59	
		S_e	28	29	7	25.63	8-41	
		X_e	28	12	8	71.28	4-40	
		$\bar{X}$	28	1775	70	4.15	1645-1895	
		X_R	28	8021	179	2.23	7710-8500	
		X_w	28	1570	126	8.02	1388-1717	
2	3&4	S_i	16	539	26	4.97	491-577	Steady state day 8/3/77 to 9/3/77
		S_T	32	41	7	19.29	24-52	
		S_e	32	23	7	31.02	4-36	
		X_e	32	13	6	46.97	2-24	
		$\bar{X}$	32	1757	69	3.95	1624-1857	
		X_R	32	7958	145	1.82	7630-8260	
		X_w	32	1618	164	10.18	1300-1935	
3	4&5	S_i	8	571	24	4.23	528-596	Steady state day 9/10/77 to 9/27/77
		S_T	17	51	18	36.28	24-104	
		S_e	17	28	8	29.55	16-44	
		X_e	18	24	11	45.83	10-60	
		$\bar{X}$	18	1850	44	2.37	1804-1884	
		X_R	18	8084	174	2.16	7780-8490	
		X_w	18	1708	168	9.83	1369-1921	
4	5&6	S_i	12	535	23	4.42	500-581	Steady state from day 10/11/77 tp 11/6/77
		S_T	14	57	19	33.95	28-84	
		S_e	14	26	5	20.94	13-33	
		X_e	14	27	20	74.55	0-74	
		$\bar{X}$	13	1769	59	4.69	1624-1860	
		X_R	13	8004	243	3.03	7600-8390	
		X_w	27	1557	142	9.17	1283-1867	
5	6&7	S_i	21	560	24	4.27	503-601	Steady state from day day 11/16/77 to 12/26/77
		S_T	20	48	15	32.53	24-89	
		S_e	20	28	12	44.85	4-59	
		X_e	21	17	16	93.28	0-52	
		$\bar{X}$	21	1782	89	5.05	1660-1948	
		X_R	21	7948	268	3.38	7600-8590	
		X_w	21	1419	91	6.47	1279-1574	

TABLE II (Continued)

Line	Fig.	Analysis Indicated (mg/l)	N	Mean	S.D. (σ)	C.V. (%)	Range	Remarks
6	7	S_i	17	575	21	3.80	532-604	Steady state from day 1/5/78 to 2/20/78
		S_T	23	59	48	81.4	12-194	
		S_e	23	23	16	69.33	8-87	
		X_e	24	29	36	122.8	0-87	
		$\bar{X}$	24	1768	46	2.65	1698-1876	
		X_R	24	8014	224	2.80	7740-8370	
		X_w	24	1387	66	4.76	1299-1517	
7	8	S_i	15	557	38	7.0	500-625	Steady state from day 3/1/78 to 4/6/78
		S_T	17	34	19	57.1	12-80	
		S_e	17	20	8	42.94	8-32	
		X_e	18	9	10	103.2	0-32	
		$\bar{X}$	18	1740	56	3.27	1664-1868	
		X_R	17	7966	152	1.92	7700-8170	
		X_w	17	1395	64	4.66	1251-1478	
8	9	S_i	14	580	15	2.58	558-600	Steady state from day 4/22/78 to 5/20/78
		S_T	13	48	12	24.49	32-68	
		S_e	13	32	8	24.24	20-48	
		X_e	15	16	16	100.0	0-45	
		$\bar{X}$	15	1793	65	3.68	1716-1948	
		X_R	15	8189	363	4.43	7510-8710	
		X_w	15	1418	117	8.32	1201-1536	
9	9&10	S_i	39	561	56	10.16	411-641	Steady state from day 6/1/78 to 8/24/78
		S_T	40	85	39	45.34	36-169	
		S_e	41	41	12	31.70	16-68	
		X_e	43	46	37	80.43	0-175	
		$\bar{X}$	42	1777	45	2.53	1708-1932	
		X_R	43	8000	258	3.24	7180-8670	
		X_w	43	1374	95	6.98	1140-1591	
10	10	S_i	5	494	52	10.52	428-552	Steady state from day 8/26/78 to 9/5/78
		S_T	6	55	14	26.34	40-100	
		S_e	6	34	7	20.58	24-52	
		X_e	6	23	10	41.68	10-37	
		$\bar{X}$	6	1745	71	4.13	1720-1840	
		X_R	6	8111	158	1.94	7920-8300	
		X_w	6	1476	54	3.66	1422-1552	

TABLE II (Continued)

Line	Fig.	Analysis Indicated (mg/l)	N	Mean	S.D. (σ)	C.V. (%)	Range	Remarks
11	10	S_i	5	524	14	2.67	508-540	Steady state from day 9/9/78 to 9/19/78
		S_T	5	52	12	25.0	44-84	
		S_e	6	28	3	13.55	24-32	
		X_e	6	23	9	38.83	10-35	
		$\bar{X}$	6	1704	107	6.27	1568-1816	
		X_R	5	8050	213	2.66	7810-8350	
		X_w	6	1411	89	6.38	1296-1511	
12	11	S_i	42	545	57	10.51	415-642	Steady state from day 9/20-78 to 12/12/78
		S_T	43	63	19	30.15	32-97	
		S_e	43	35	11	31.42	12-52	
		S_{R_3}	36	286	28	9.79	20-792	
		$V_{R_{3ml}}$	75	3083	454	14.72	2440-3900	
		X_e	43	31	18	58.06	0-82	
		$\bar{X}$	43	1645	136	8.26	1420-1884	
		X_R	42	7907	615	7.77	6240-8900	
13	12	S_i	4	513	41	7.79	467-568	Steady state from day 12/14/78 to 12/20/78
		S_T	4	67	22	32.87	44-96	
		S_e	4	31	9	29.05	24-44	
		S_{R_3}	4	37	8	21.62	28-44	
		$V_{R_{3ml}}$	7	3478	94	2.70	3300-3600	
		X_e	4	27	15	55.55	15-50	
		$\bar{X}$	4	1652	58	3.51	1656-1884	
		X_R	4	8230	376	4.56	7850-8750	
14	12	S_i	8	525	33	6.28	464-578	Steady state from day 1/27/79 to 2/15/79
		S_T	11	62	16	25.80	32-92	
		S_{R_1}	9	35	16	45.71	16-68	
		S_e	11	26	11	42.30	0-40	
		S_{R_3}	9	59	22	37.28	24-92	
		$V_{R_{3ml}}$	20	8145	1090	13.38	6600-9800	
		X_e	11	31	16	51.61	12-60	
		$\bar{X}$	11	1671	89	5.3	1512-1788	
		X_R	11	7919	326	4.11	7608-8468	

TABLE II (Continued)

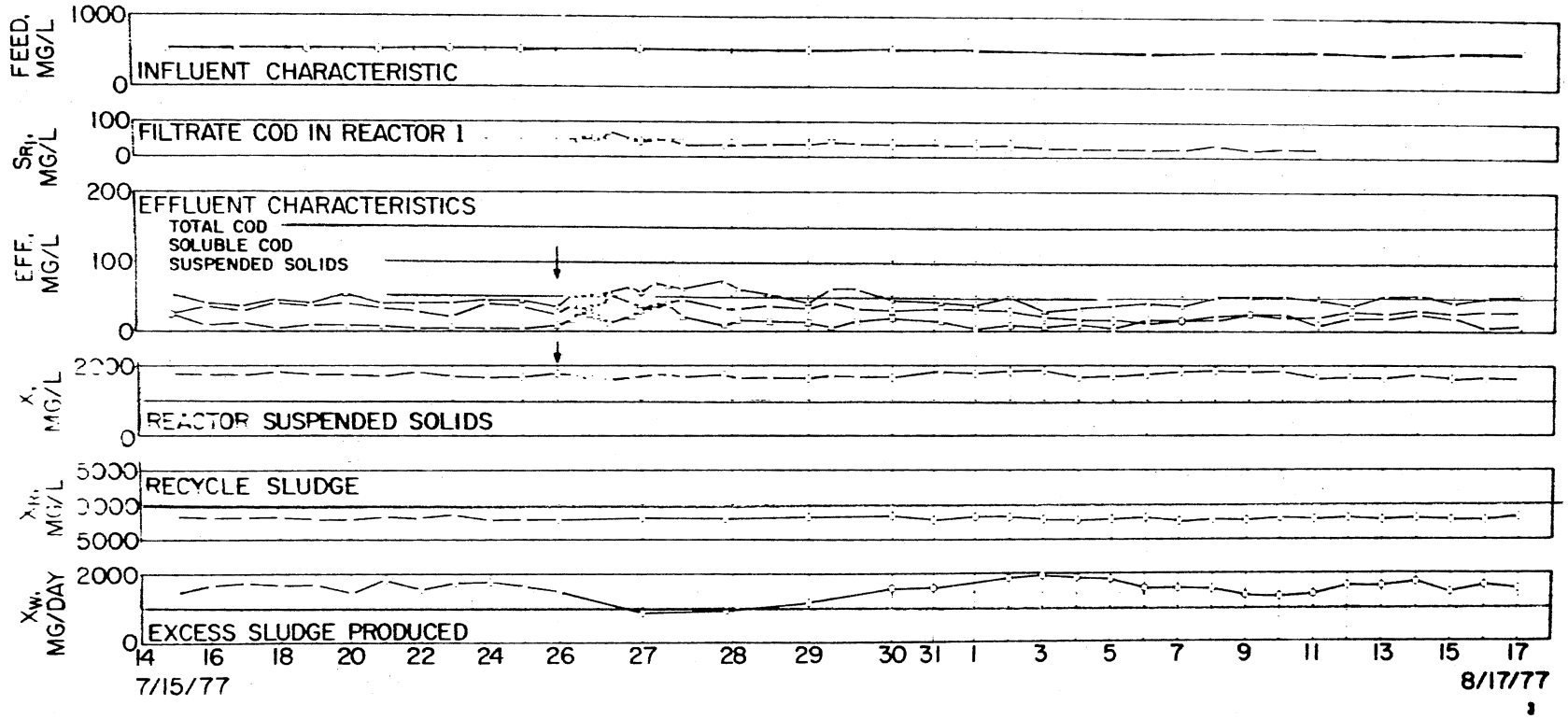
Line	Fig.	Analysis Indicated (mg/l)	N	Mean	S.D. (σ)	C.V. (%)	Range	Remarks
15	14	S_i	4	1627	61	3.74	1568-1696	Steady state from day 4/5/79 to 4/30/79
		S_T	20	48	18	37.5	20-64	
		S_{R_1}	17	37	7	18.91	20-48	
		S_e	21	30	9	30.0	4-44	
		S_{R_3}	19	59	24	40.67	30-108	
		$V_{R_{3ml}}$	20	3685	1885	51.15	3300-5000	
		X_e	19	21	14	66.66	5-67	
		$\bar{X}$	20	5025	588	11.70	3488-6368	
		X_R	20	18759	2498	13.31	15276-25924	
16	16	S_i	31	526	35	6.65	440-624	Steady state data for unit 2 from day 8/14/78 to 10/15/78
		S_T	30	49	12	24.48	20-76	
		S_e	30	31	18	58.06	20-68	
		$V_{R_{2ml}}$	32	957	40	4.28	870-1020	
		X_e	32	28	24	85.71	4-48	
		$\bar{X}$	32	2106	317	15.05	1639-2640	
		X_R	32	9312	771	8.27	8020-10400	
17	17	S_i	30	521	33	6.33	439-556	Steady state data for unit 2 from day 10/14/78 to 12/14/78
		S_T	29	42	22	52.38	4-90	
		S_e	30	22	12	54.54	0-40	
		$V_{R_{2ml}}$	30	988	41	4.14	920-1075	
		X_e	30	23	13	56.54	0-44	
		$\bar{X}$	30	2173	182	8.37	1900-2633	
		X_R	30	10065	868	8.62	8260-11940	
18	18	S_i	29	529	24	4.53	463-560	Steady state data for unit 2 from day 1/3/79 to 3/4/79
		S_T	28	44	20	45.45	12-96	
		S_e	29	23	12	52.17	0-60	
		$V_{R_{2ml}}$	29	1245	63	5.06	1150-1375	
		X_e	28	21	14	66.66	0-56	
		$\bar{X}$	29	2261	181	8.00	1939-2600	
		X_R	29	10283	1020	9.91	8500-12000	
19	19	S_i	17	1622	74	4.56	1444-1774	Steady state data for unit 2 from day 3/10/79 to 4/11/79
		S_T	17	60	10	16.67	40-76	
		S_{R_1}	6	44	16	36.36	20-68	
		S_e	17	38	9	23.68	16-56	
		$V_{R_{2ml}}$	17	1555	95	6.10	1420-1760	
		X_e	17	24	14	58.33	0-46	
		$\bar{X}$	17	2477	238	9.60	2012-2884	
		X_R	17	11611	1202	10.35	9720-13580	

The main effort was to see if the aerobic digester cells had any effect on the quality of the effluent when used as recycle sludge. It was necessary to determine whether the digester cells caused any disruption in the stability of the system; only then could such a biomass be considered for use as an extra source of cells for recycle during periods of external shock loads. Also during this phase, sludge was taken from reactor 3 (aerobic digester), hydrolyzed in an autoclave, and added to the digester in controlled quantities to see if any improvement could be achieved in the activity of the aerobically digesting cells before they were introduced into the recycle line. All through this phase, the influent substrate concentration was maintained at 500 mg/l glucose and the recycle sludge concentration, X_R, was kept at 8000 mg/l. In effect, this experimentation comprised a shock load study with the "shock" being sudden introduction of reactor 3 (aerobic digester) cells without any change in any of the other operating conditions of the activated sludge process. The shock then consisted of an abrupt change in the source of recycle solids. The change in recycle biological solids was generally accomplished over a 24-hour period. At the end of the 24-hour period, the sludge which accumulated in the underflow of the clarifier constituted the recycle sludge. Only twice during this phase of the investigation was there an insufficnet volume of digester sludge to satisfy the daily (24-hour) need. On these occasions, the sludge from the aerobic digester had undergone digestion for long periods without any addition of fresh excess sludge.

Figure 3 shows the system response when cells from reactor 3 were used as recycle biological solids instead of cells from the bottom of the clarifier. The vertical arrow (7-26-77) shows the time when the

Figure 3. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l, Shock Loaded With Sludge From Reactor 3

From 7/15/77 to 8/17/77 - shock loaded on 7/26/77.


FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
S_{R_1}, MG/L
100
0
FILTRATE COD IN REACTOR 1
EFF., MG/L
200
100
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
X, MG/L
2000
0
REACTOR SUSPENDED SOLIDS
X_R, MG/L
5000
5000
RECYCLE SLUDGE
X_w, MG/DAY
2000
0
EXCESS SLUDGE PRODUCED
14 16 18 20 22 24 26 27 28 29 30 31 1 3 5 7 9 11 13 15 17
7/15/77
8/17/77

switch in source of recycle cells was made. It is noted that before being introduced into the recycle, the sludge had undergone a period of accelerated autodigestion during which a very high amount of foaming was observed. During this period, the foaming caused a loss in the total volume of sludge in the reactor (mostly liquid) and an increase in the biological solids concentration. During that time, reactor 3 volume was adjusted to the original level with tap water. The foaming stopped a week before the cells were introduced into the recycle, and the volatile solids percentage in reactor 3 cells was 60 percent, whereas it was somewhat lower (55 percent) in reactor 1. However, approximately one month before this switch, volatile solids in reactor 3 was running at 30 percent--indicating that it was very well digested. Apparently the foaming had removed a considerable portion of inorganic solids and the sludge in reactor 3 at the time of the switch in recycle solids was fresher ("younger") than it was prior to the foaming. During the experiment, shown in Figure 3, there was no serious perturbance in the effluent quality of the system. Before the switch, the X_e, S_e, and total substrate leakage into the effluent were on average 12 mg/l, 29 mg/l, and 42 mg/l, respectively. During the shock, the maximum biological solids leakage in the effluent was 38 mg/l, the effluent, soluble substrate level reached a maximum of 52 mg/l. The soluble COD in the reactor rose gradually to 60 mg/l, attained a maximum of 72 mg/l, and rapidly came back to pre-shock level. Overall, the response was very encouraging; there was little transient disturbance and the steady state data for S_t, S_e, and X_e after the shock remained close to the values before the shock. The soluble substrate associated with the recycle sludge was 232 mg/l, and NH_4-N concentration was rather

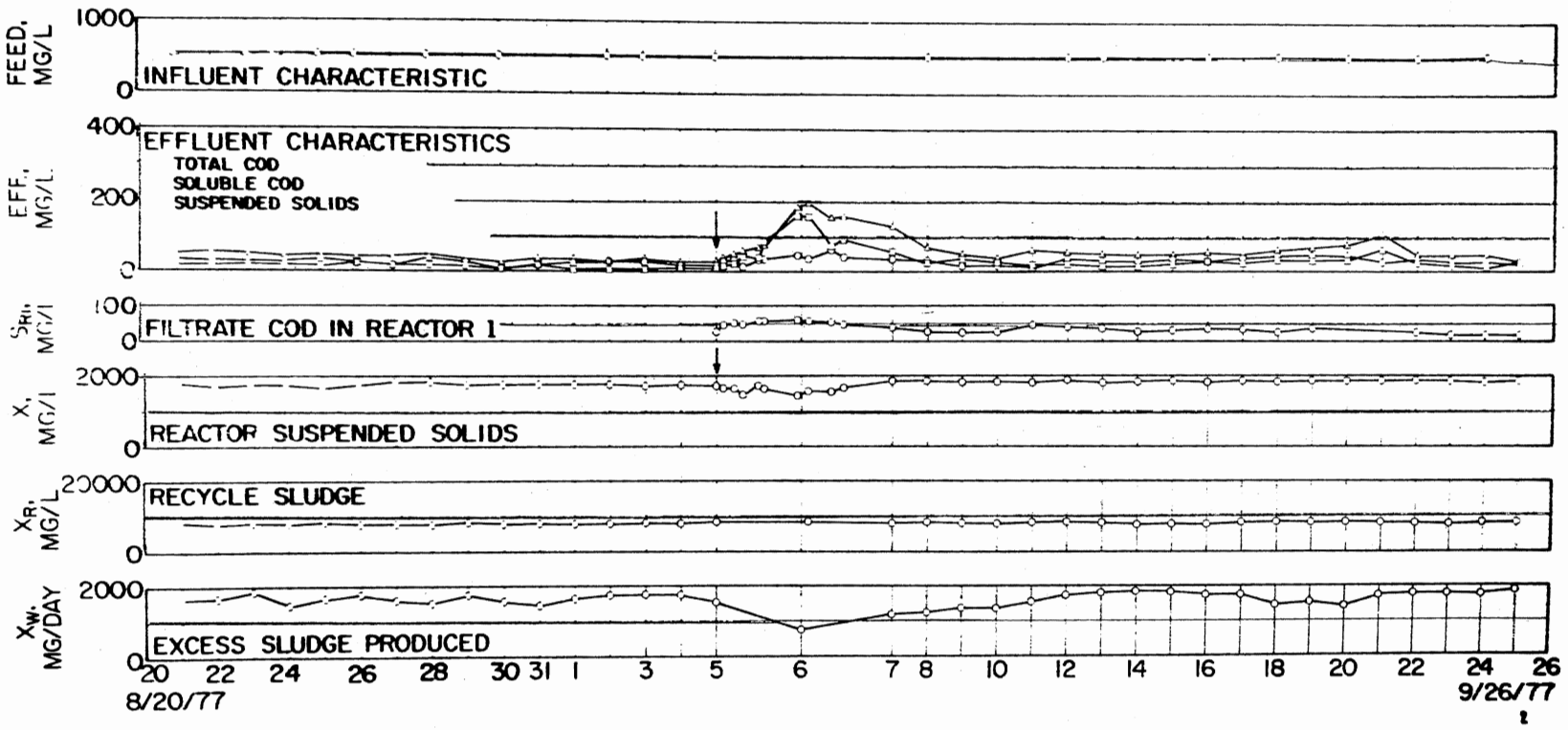
high at 128 mg/l. The O_2 uptake of the recycle sludge was low--2.1 mg/g/hr. Batch growth studies were conducted during this stage of operation on both reactor 1 and reactor 3 cells. These results are reported in the Appendix. Thirty-eight days before the shock load, the μ_{max} for reactor 1 cells was high compared to that for reactor 3 cells. The reactor 1 μ_{max} decreased from 0.480 hr^{-1} initially to 0.33 hr^{-1} on the day of the switch. On the other hand, reactor 3 μ_{max} increased marginally from 0.226 hr^{-1}. At the time of the shock load it was 0.275 hr^{-1}, but in all of these studies, K_s values of reactor 3 remained somewhat low--51 mg/l and 34 mg/l--except when it was undergoing accelerated autodigestion, when it rose to 160 mg/l. The reactor 1 K_s values remained high for the first two batch studies--485 mg/l and 480 mg/l--but dropped to a value of 250 mg/l on the day reactor 3 cells were used for recycle solids. During this period the Y_{t_B} values also showed some fluctuation.

It is interesting to note (see Figure 3) that the excess sludge production, indicative of the value of observed yield, Y_o, decreased rather sharply after the switch in source of recycle sludge. After a few days, X_w returned to pre-shock levels.

Figure 4 shows results for a shock load experiment similar to that shown in Figure 3, but in this case, reactor 3 had not been fed with any fresh sludge for a 5-day period immediately prior to the shock. Before the shock load, the X_e, S_e, and S_t in the effluent were 13 mg/l, 23 mg/l, and 41 mg/l, respectively. The average reactor biological solids concentration was 1757 mg/l, but after reactor 3 cells were used for the recycle sludge, the reactor suspended solids concentration decreased from an initial value of 1704 mg/l to a low 1492

Figure 4. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Shock Loaded With Sludge From Reactor 3 Starved Without the Addition of any Fresh Sludge for Five Days Before the Shock Load

From 8/20/77 to 9/26/77 - shock loaded on 9/5/77.


FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
EFF., MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
S_{RI}, MG/I
100
0
FILTRATE COD IN REACTOR 1
X, MG/I
2000
0
REACTOR SUSPENDED SOLIDS
X_R, MG/L
20000
0
RECYCLE SLUDGE
X_W, MG/DAY
2000
0
EXCESS SLUDGE PRODUCED
20 22 24 26 28 30 31 1 3 5 6 7 8 10 12 14 16 18 20 22 24 26
8/20/77
9/26/77

mg/l and fluctuated some time before coming back to 1876 mg/l by the third day after the shock. During the same time, there was an increase in the S_e value to about 60 mg/l from a pre-shock value of 12 mg/l. Also, the substrate concentration in the reactor, S_R, increased before coming back to the pre-shock level. But the effluent solids did not show the same kind of moderate response. The X_e values in the effluent gradually increased from 8 mg/l to a high of 158 mg/l by the end of the first day after making the switch. Even though the initial response of the system was good, by the end of the first day, the clarifier became turbid and sludge rising was observed. Overall, the reactor soluble substrate concentration remained rather low, but due to the effluent solids leakage the total COD concentration was considerably higher--nearly 200 mg/l by the end of 24 hours. Thereafter, it receded slowly to a more reasonable level.

After the shock, the steady state values for X_e, S_e, and S_t recorded were higher compared to their values before the shock by 11, 5, and 10 mg/l concentrations, respectively. Microscopic observation showed that there were protozoa present in the reactor 3 sludge and in reactor 1 before the shock load. However, little mobility of the protozoa was observed during the shock load. The reactor 3 biological solids in the batch studies exhibited a μ_{max} of 0.526 hr^{-1} five days before the shock when reactor 3 was being fed regularly with excess sludge, whereas when reactor 3 stopped receiving any fresh sludge for five days, the cells exhibited a lower μ_{max} value, 0.380 hr^{-1}. Also, the saturation constant, K_s, remained relatively constant at about 450 mg/l after five days, and the yield coefficient, Y_{t_B}, was reduced from 0.68 percent to 0.61 percent.

Figure 5 shows the results when the return sludge solids were not from the aerobic digester (reactor 3), but from the return sludge from another activated sludge plant. In this case, return sludge from the waste treatment facilities in Ponca City, Oklahoma, was used to determine if cells from sources other than from the same plant would have any adverse effect on the treatment capability of the activated sludge. The effluent characteristics before and after the shock remained the same except for a slight increase in effluent suspended solids. During the shock, the overall effluent quality remained excellent. The only effect was that there was an initial increase in the reactor mixed liquor suspended solids and a reduction in their level to around 1500 mg/l during the second half of the first day. But the suspended solids returned to normal levels after the second day of operation.

Figure 6 shows results for an experiment when fresh sludge was not added to reactor 3 for 30 days prior to its use for recycle sludge. The volume of recycle solids was sufficient for only 12 hours of the needed pumping rate. Thus, after this time, sludge from the clarifier was taken and added to reactor 2 to be recycled into reactor 1. The recycle supernatant contained a large amount of soluble substrate--514 mg/l. Also, due to digestion and release of NH_4-N into solution and its eventual nitrification to NO_3-N, the recycle supernatant contained large concentrations of NH_4-N and NO_3-N, 120 mg/l and 480 mg/l, respectively. Spot checks at the end of the day showed that most of the NH_4-N and NO_3-N exited in the effluent. The reactor substrate concentration increased steadily from 24 mg/l to a high of 108 mg/l in 14 hours, and then decreased. The increased S_t passed through the clarifier but was attenuated; S_e increased to about 76 mg/l. The major

Figure 5. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Shock Loaded With Return Sludge From the Ponca City, Oklahoma, Wastewater Treatment Plant

From 9/22/77 to 11/8/77 - shock loaded on 9/28/77.

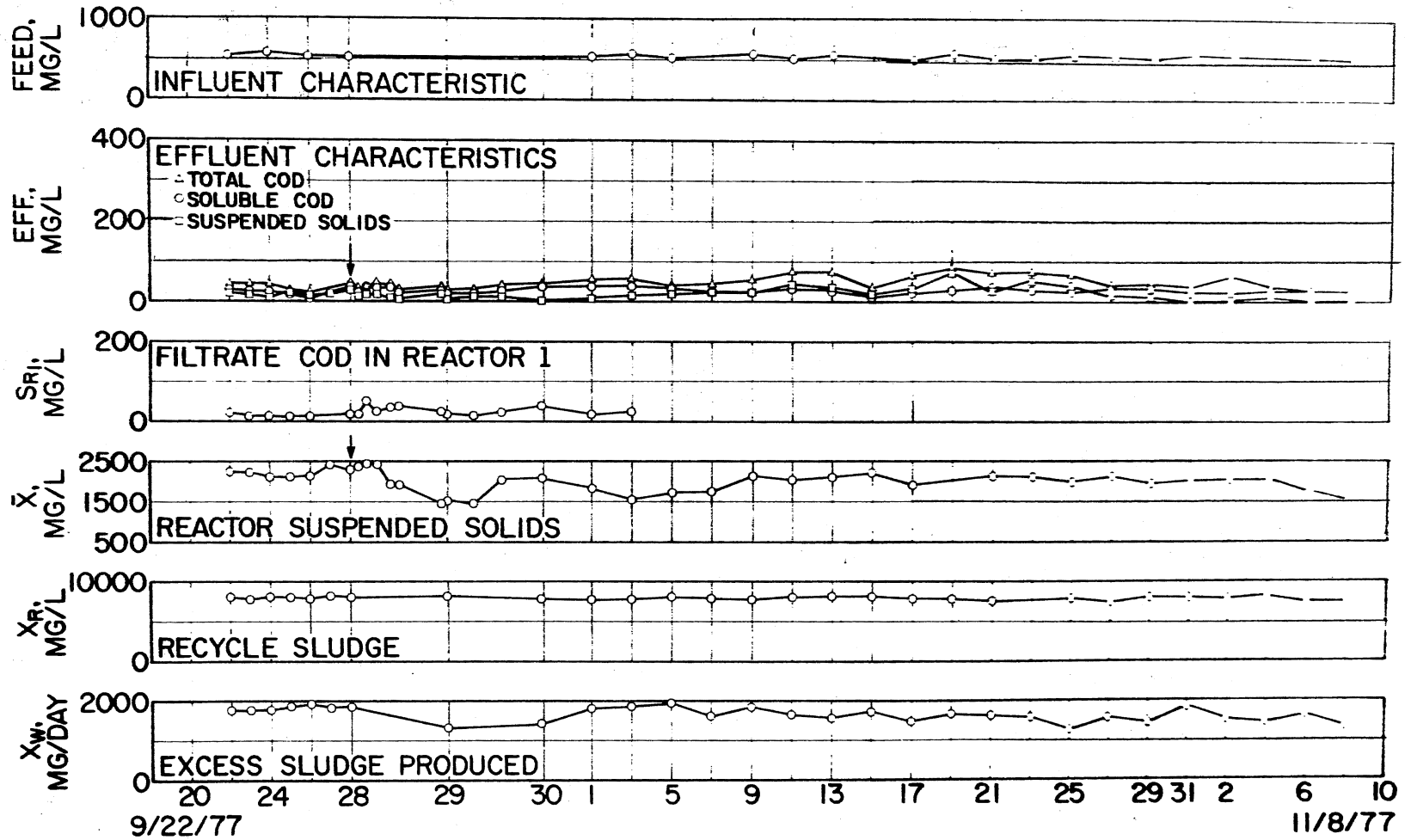
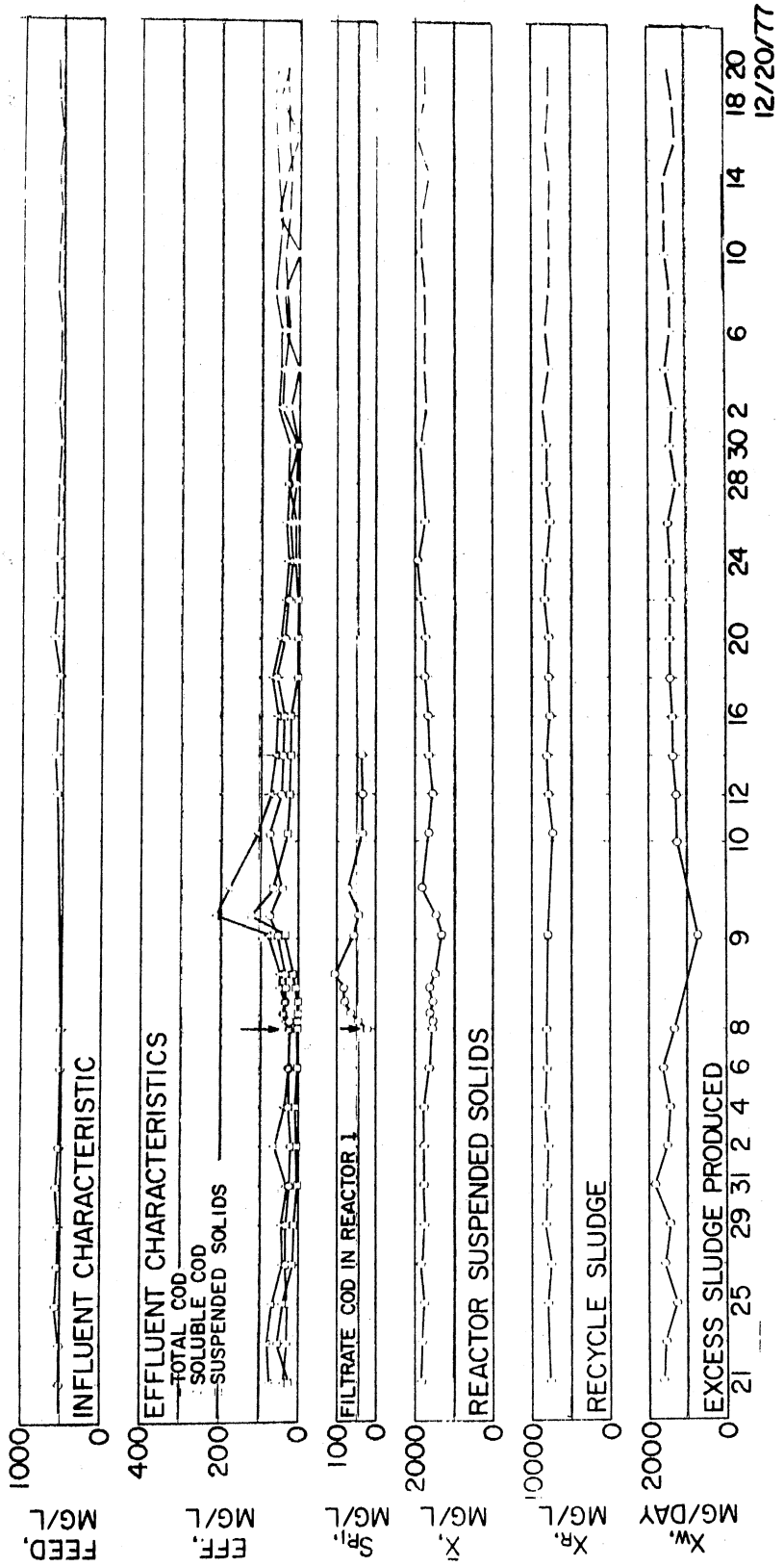

FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
EFF., MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
S_{RI}, MG/L
200
0
FILTRATE COD IN REACTOR 1
$\bar{X}$, MG/L
2500
1500
500
REACTOR SUSPENDED SOLIDS
X_R, MG/L
10000
0
RECYCLE SLUDGE
X_W, MG/DAY
2000
0
EXCESS SLUDGE PRODUCED
20 24 28 29 30 1 5 9 13 17 21 25 29 31 2 6 10
9/22/77
11/8/77

Figure 6. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Shock Loaded With Return Sludge From Reactor 3 Which was not Added any Fresh Sludge for 30 Days

Reactor 3 sludge lasted only 12 hours from 10/21/77 to 12/20/77 - shock loaded on 11/8/77.

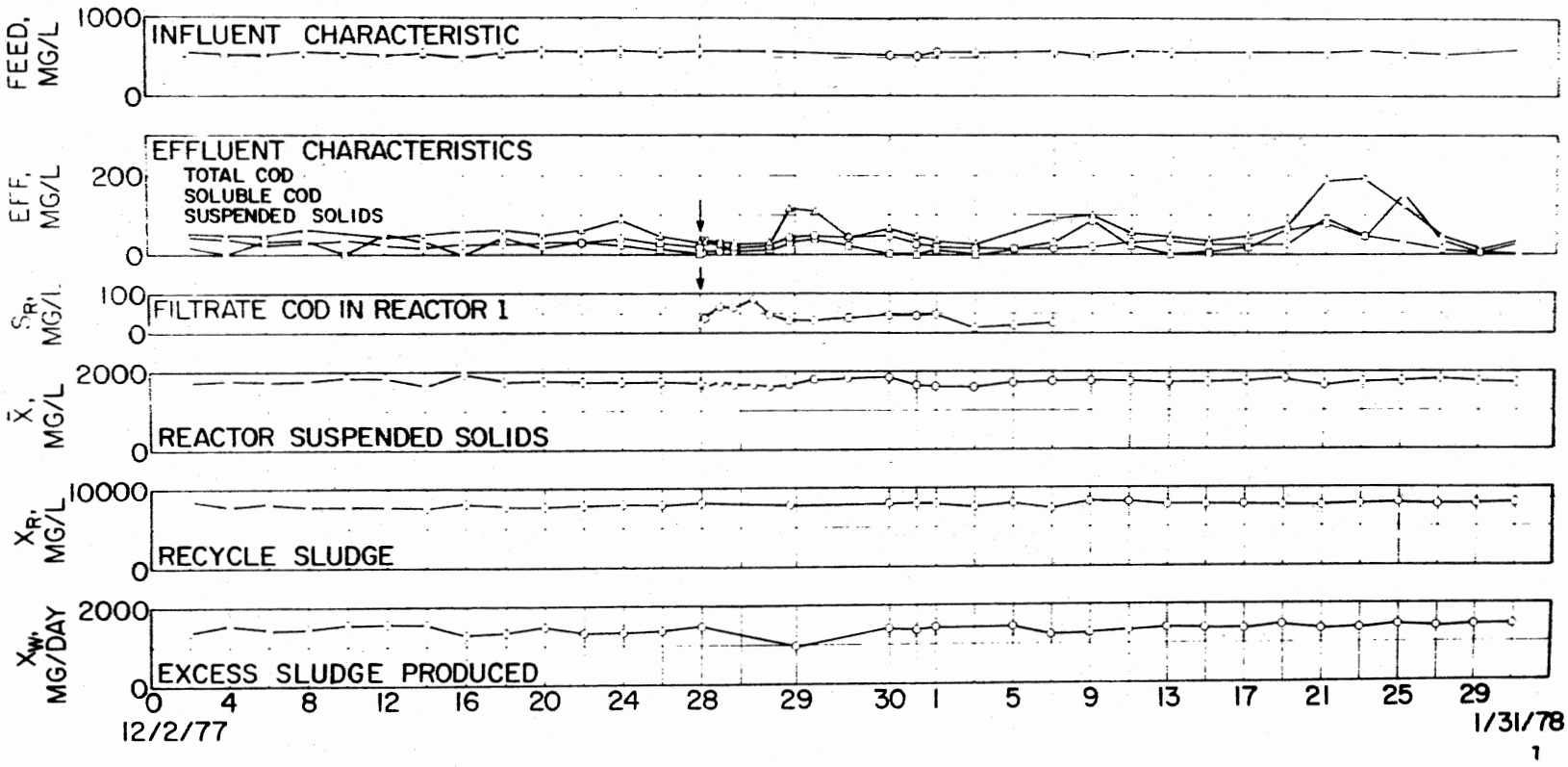

FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
EFF., MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
Sr1, MG/L
100
0
FILTRATE COD IN REACTOR 1
X̄, MG/L
2000
0
REACTOR SUSPENDED SOLIDS
Xr, MG/L
10000
0
RECYCLE SLUDGE
Xw, MG/DAY
2000
0
EXCESS SLUDGE PRODUCED
21 25 29 31 2 4 6 8 9 10 12 16 20 24 28 30 2 6 10 14 18 20
12/20/77

effect was the problem of sludge rising, which caused a substantial increase in the X_e; the highest value recorded was 120 mg/l. This, in turn, increased the S_t value to a high of 212 mg/l. Gradually, the effluent quality improved to the pre-shock load levels by the fourth day. Also during the shock, the reactor mixed liquor concentration decreased. The long period of digestion of reactor 3 solids caused a decrease in the volatile fraction of the recycle sludge to 29 percent, whereas the mixed liquor volatile solids was 59 percent.

The next shock load (Figure 7) was made using sludge from reactor 3 which had been allowed to aerate for 35 days without the addition of any fresh excess sludge. Reactor 3 volatile suspended solids concentration was close to that for the previous experiment at 34 percent, and the MLVSS was 59. During this prolonged period of aeration, reactor 3 sludge went through a period of accelerated autodigestion with associated heavy foaming. The reactor 3 supernatant soluble COD, NH_4-N, and NO_3-N concentrations steadily increased to concentrations of 514, 174, and 300 mg/l, respectively. This supernatant, along with the feed which was recycled into the reactor when the switch was made, caused a slight increase in the reactor soluble COD. The maximum recorded value was 87 mg/l. Fourteen hours after making the change, all of the reactor 3 sludge was used and almost all of the NH_4-N and most of the NO_3-N it contained had exited in the effluent. The biological solids which exited in the effluent was very small, reaching a maximum concentration of 40 mg/l, and the effluent was very clear 48 hours after the shock. In this experiment, the increase in the mixed liquor suspended solids was small and not as noticeable as in the previous experiment, but there appeared to be a secondary response which did cause

Figure 7. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Shock Loaded With Sludge From Reactor 3 Which was not Added any Fresh Sludge for 35 Days

Reactor 3 sludge lasted only 14 hours from 12/2/77 to 1/31/78 - shock loaded on 12/28/77.

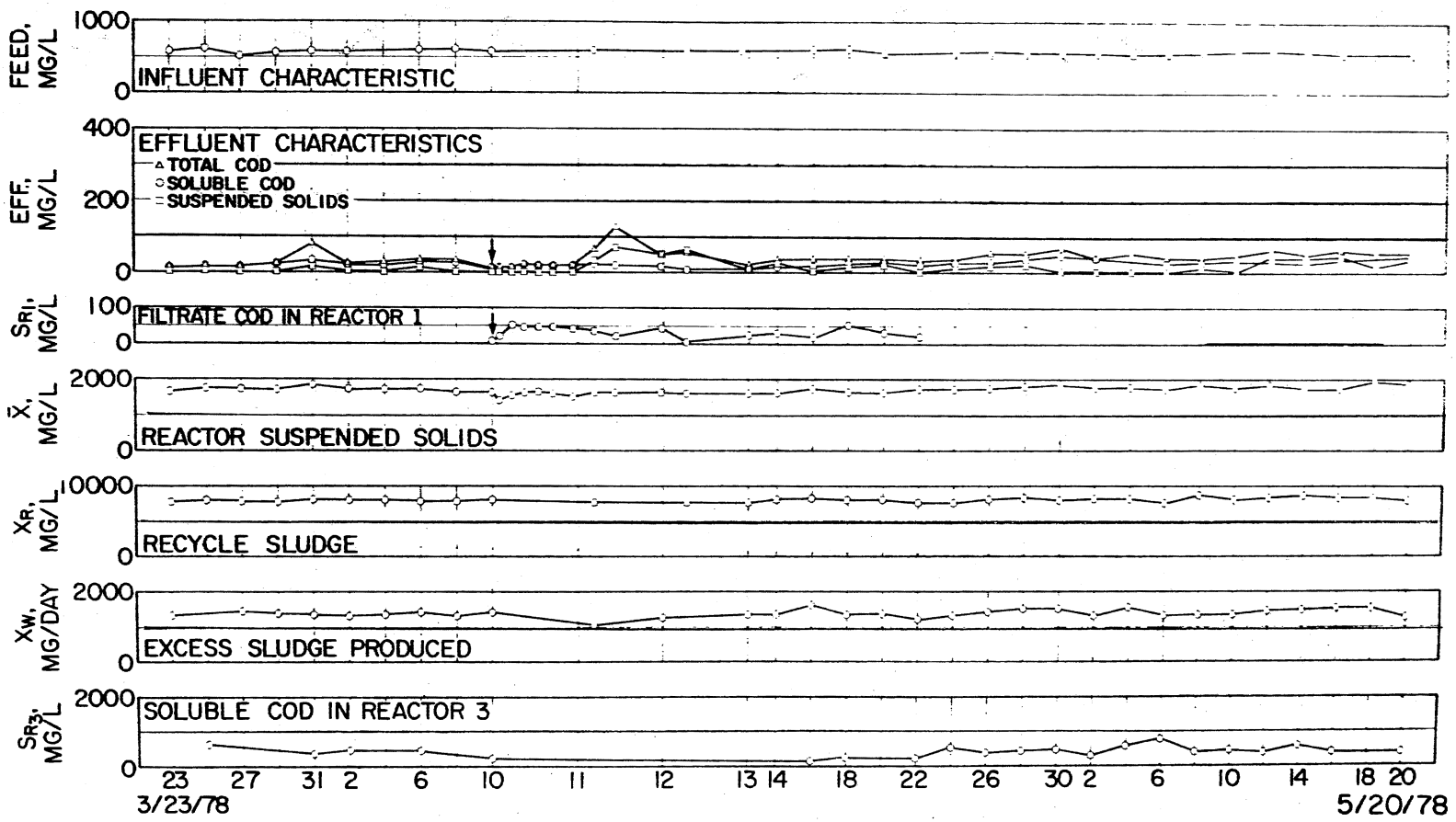

FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
EFF, MG/L
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
$S_{R'}$ MG/L
100
0
FILTRATE COD IN REACTOR 1
$\bar{X}$, MG/L
2000
0
REACTOR SUSPENDED SOLIDS
$X_{R'}$ MG/L
10000
0
RECYCLE SLUDGE
$X_{W'}$ MG/DAY
2000
0
EXCESS SLUDGE PRODUCED
0 4 8 12 16 20 24 28 29 30 1 5 9 13 17 21 25 29
12/2/77
1/31/78
1

considerable disruption in effluent quality. Slightly a week after the change in recycle solids, filamentous organisms gained predominance over flocculated bacteria. During this shift in predominant organisms, an increase in the effluent solids was observed. After the filaments took over, the solids leakage was less and effluent clarity returned. But when bacteria appeared to regain predominance over filaments later in January, both the S_e and X_e values increased substantially. By the end of the month, the effluent quality returned to normal.

Prior to the next shock load (Figure 8), reactor 3 biological solids were fed hydrolyzed excess sluge. Initially, 1000 mg/l per day of hydrolysate was added to reactor 3 for a period of five days. Then reactor 3 was not given any hydrolyzed sludge for two weeks. The hydrolysate dosage addition was then repeated for another five days. After a gap of two days, hydrolysate was again added at a reduced rate of 250 mg/l for two days. The reactor 3 biological solids were then introduced into the recycle to determine their effect. The addition of hydrolysate caused an increase in the endogenous O_2 uptake values (for washed sludge) from low values of 3-5 mg/g/hr to a high value of above 10 mg/g/hr. After the addition of hydrolysate was discontinued, the O_2 uptake values declined to the original levels. The endogenous O_2 uptake of reactor 3 solids at the time they were recycled was 2.4 mg/g/hr whereas reactor 1 exhibited a slightly higher O_2 uptake of 3.6 mg/g/hr. The addition of hydrolysate to reactor 3 sludge increased its maximum specific growth rate, μ_{max}, from 0.105 hr^{-1} to 0.180 hr^{-1}. Also, the saturation constant, K_s, increased from 63 mg/l to 216 mg/l, whereas the batch yield coefficient, Y_{t_B}, increased from 40.8 percent to 55.5 percent. Just before the reactor 3 solids were switched,

Figure 8. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Shock Loaded With Sludge from Reactor 3 Which was Treated With 1000 mg/l of Sludge Hydrolysate for Three Days Before Shock Loading

From 3/23/78 to 5/20/78 - shock loaded on 4/10/78. Concentration of hydrolysate added to reactor 3 on 3/7/78 - 3/12/78, 1000 mg/l; on 3/29 - 4/3/78, 1000 mg/l; on 4/5-6/78, 250 mg/l.

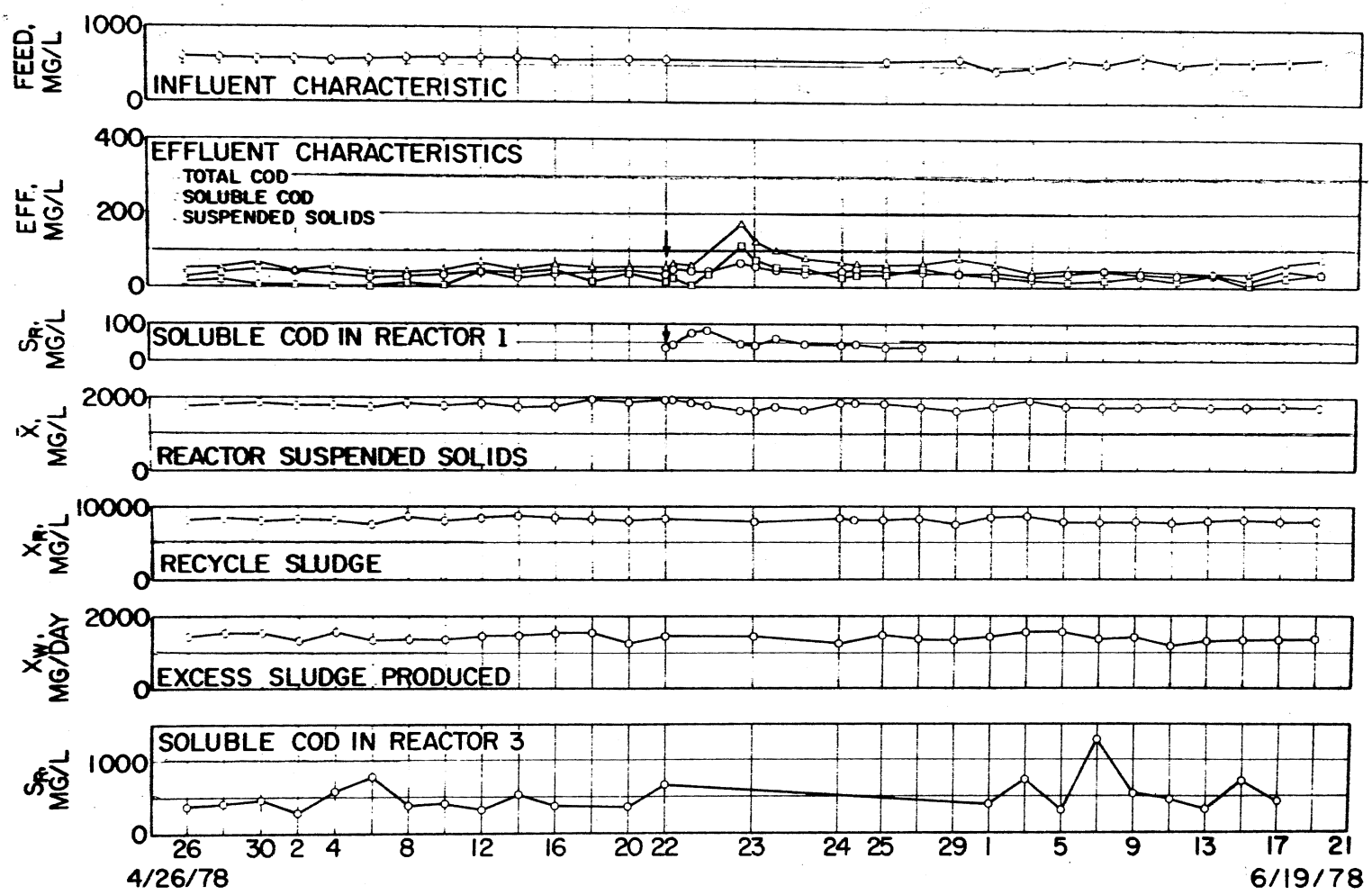

FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
EFF., MG/L
400
200
0
EFFLUENT CHARACTERISTICS
△ TOTAL COD
○ SOLUBLE COD
= SUSPENDED SOLIDS
S_{R1}, MG/L
100
0
FILTRATE COD IN REACTOR 1
$\bar{X}$, MG/L
2000
0
REACTOR SUSPENDED SOLIDS
X_R, MG/L
10000
0
RECYCLE SLUDGE
X_W, MG/DAY
2000
0
EXCESS SLUDGE PRODUCED
S_{R3}, MG/L
2000
0
SOLUBLE COD IN REACTOR 3
23 27 31 2 6 10 11 12 13 14 18 22 26 30 2 6 10 14 18 20
3/23/78
5/20/78

batch growth studies yielded close values of μ_{max}, 0.177 hr^{-1} for reactor 1 compared to 0.180 hr^{-1} for reactor 3, but the K_s value for reactor 3 cells was 216 mg/l, whereas it was only 79 mg/l for seed from reactor 1. The yield value for reactor 3 was 55.5 percent compared to 62.8 percent for reactor 1. The supernatant of the recycle cells was 204 mg/l COD, 102 mg/l NH_4-N, and 45 mg/l NO_3-N. The effluent quality for two weeks before the introduction of reactor 3 cells was very good with an average X_e of 4 mg/l and the average S_e of 22 mg/l. The same trend continued after the switch was made; however, after 22½ hours, rising sludge in the clarifier increased biological solids in the effluent; it rose to a maximum of 70 mg/l. The increase pushed the total substrate leakage to a high of 127 mg/l. The clarifier soluble COD remained steady during the first day at about 20 mg/l from an initial low of 8 mg/l. The only noticeable change was in the level of soluble COD in reactor 1. This rose to 53 mg/l in 5½ hours from an initial value of 8 mg/l and remained steady at 45 to 50 mg/l during the day and showed some minor fluctuation. Even though a recycle NH_4-N concentration of 102 mg/l was pumped to the reactor, very little leakage of NH_4-N was observed in the effluent. Overall, the only problem observed was the increased level of clarifier suspended solids due to rising sludge. The removal capability for soluble COD was unchanged even though the recycle supernatant contained 204 mg/l of soluble COD.

For the next experiment (Figure 9), the reactor 3 cells were fed regularly with 1000 mg/l hydrolysate. This caused a general increase in the O_2 uptake activity of the cells. The O_2 uptake in reactor 3 on the day of the switch was 7.5 mg/g/hr--essentially the same as for reactor 1 sludge. The soluble COD in the recycle was relatively high

Figure 9. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Shock Loaded With Sludge From Reactor 3 Which was Treated With 1000 mg/l of Sludge Hydrolysate With Regular Periodicity

Form 4/26/78 to 6/19/78 - shock loaded on 5/22/78.


FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
EFF, MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
S_R, MG/L
100
0
SOLUBLE COD IN REACTOR 1
$\bar{X}$, MG/L
2000
0
REACTOR SUSPENDED SOLIDS
X_R, MG/L
10000
0
RECYCLE SLUDGE
X_W, MG/DAY
2000
0
EXCESS SLUDGE PRODUCED
S_R, MG/L
1000
0
SOLUBLE COD IN REACTOR 3
26 30 2 4 8 12 16 20 22 23 24 25 29 1 5 9 13 17 21
4/26/78
6/19/78

at 652 mg/l of COD. The NH_4-N concentration was 44.4 mg/l. The NO_3-N concentration was 125 mg/l. The addition of hydrolysate to reactor 3 had increased its maximum specific growth rate from 0.173 hr^{-1} to 0.432 hr^{-1}. The K_s value initially was 156 mg/l, but after three additions, it increased to 484 mg/l. No significant increase in yield value was observed. Y_{t_B} initially was 54.4 percent compared to 56.8 percent after the addition. After the switch was made, there was a decrease in the reactor MLSS from an initial concentration of 1932 mg/l to 1630 mg/l at 20.50 hours. Thereafter it rose to its previous level. The S_e value in general increased to approximately 65 mg/l, but returned to the original level rather quickly. The soluble COD in reactor 1 gradually increased from an initial value of 36 mg/l to 82 mg/l, 11½ hours after the switch in return sludge, and stabilized between 30 to 50 mg/l. The only deleterious effect in this experiment was the increase in clarifier suspended solids level due to rising sludge. This caused an increase in the total amount of COD in the effluent. In this experiment, the recycle NH_4-N concentration observed was 44.4 mg/l, the feed NH_4-N concentration was 53 mg/l, but no NH_4-N leakage was observed in the effluent. It is interesting to note that during this experiment, reactor 3 sludge was under a state of accelerated autodigestion when it was introduced into the recycle. The volatile fraction of the reactor 3 sludge was about 49.3 percent compared to previous values of near 30 percent for digested sludge. This may have been due to the regular addition of hydrolysate. Compared to this, the organic fraction of the mixed liquor sludge in reactor 1 was close to 56.3 percent. Review of the steady state values for the previous shock when the reactor 3 sludge was treated periodically for a

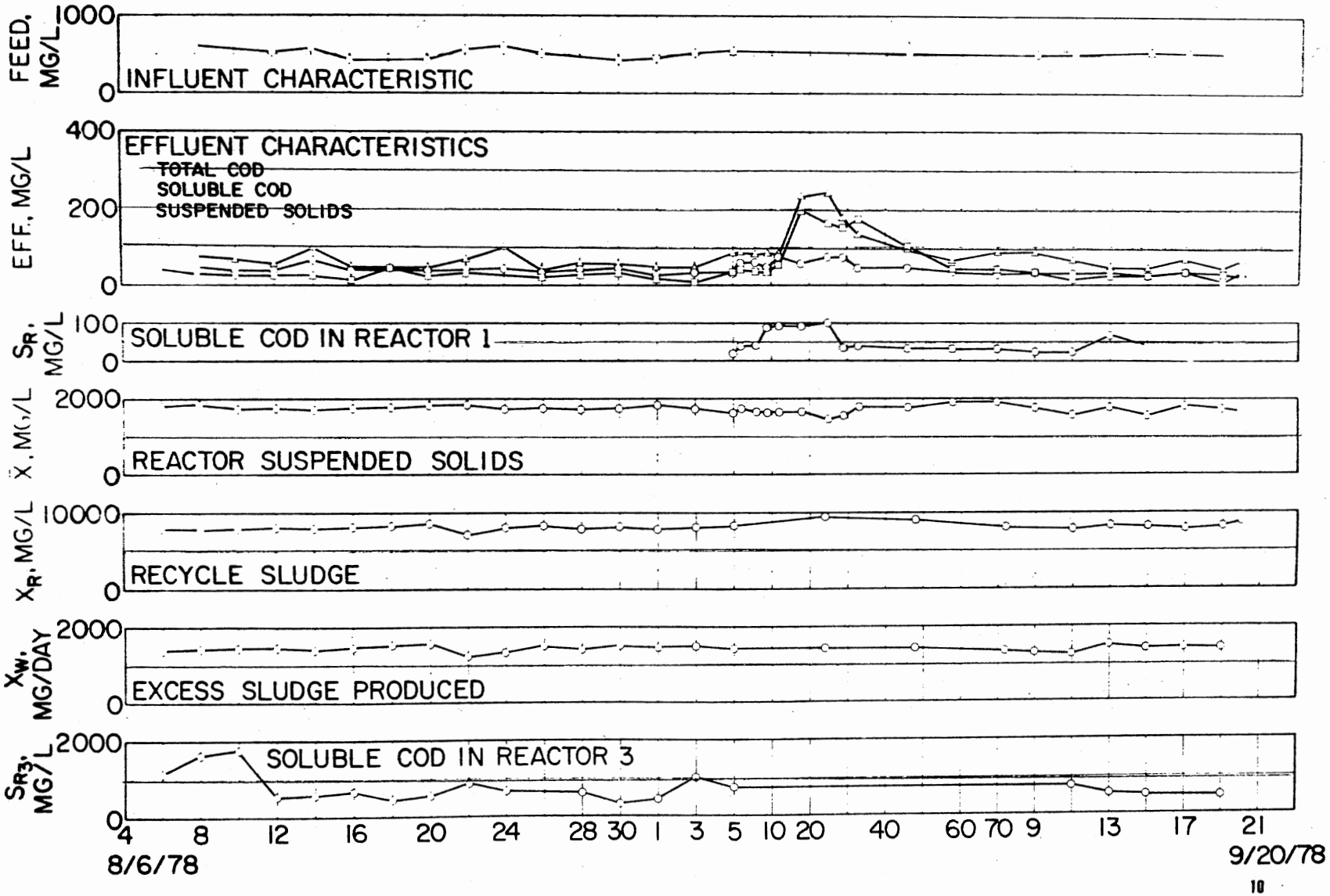
a few days with 1000 mg/l of hydrolysate show the mean X_e value, after the application of shock, increased from 9 mg/l to 16 mg/l value. The S_e values also increased-- from 20 mg/l to 32 mg/l. Similarly in this experiment, the mean X_e value rose from 16 mg/l to 46 mg/l. The steady state value of S_e rose from 32 to 41 mg/l. Also in the post-shock period, the activated sludge experienced a change in predominant species, from clumped floc to filaments.

For the next experiment (Figure 10), the reactor 3 cells were treated regularly each day with 100 mg/l of hydrolysis products. All through this period, the foaming due to accelerated autodigestion continued. The batch growth studies performed before the addition of the hydrolysate and 12 days after the addition of hydrolysate showed an increase in μ_{max} value from 0.416 hr^{-1} to 0.581^{-1} and a decrease in K_s value of 766 mg/l to 139 mg/l, with only a marginal increase in Y_{t_B} values of 47.2 percent to 50.4 percent. The soluble COD in reactor 3 exhibited wide fluctuation, from 320 mg/l to 1774 mg/l. On the day of the shock it was 760 mg/l, and this COD was recycled to reactor 2 along with the sludge. The recycle NH_4-N was 168.4 mg/l and NO_3-N concentration was 132.5 mg/l. The reactor filtrate COD increased gradually to levels above 100 mg/l 25 hours after the switch. For the first 12 hours after the shock, no real increase in X_e values was observed, but after that period, rising sludge caused an increase in effluent solids level to 195 mg/l. Over the next three days, X_e slowly decreased to its former level. The NH_4-N in the recycle--unlike the last two experiments--was not completely utilized. There was a slight leakage from a low of 2.8 mg/l to a high of 11.2 mg/l at the 12-hour period.

This concludes the first phase of results. During this phase, the

Figure 10. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Shock Loaded With Sludge From Reactor 3 Which was Treated With 100 mg/l of Hydrolysate Every Day

From 8/6/78 to 9/20/78 - shock loaded on 9/5/78.


FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
EFF., MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
S_R, MG/L
100
0
SOLUBLE COD IN REACTOR 1
$\bar{X}$, MG/L
2000
0
REACTOR SUSPENDED SOLIDS
X_R, MG/L
10000
0
RECYCLE SLUDGE
X_w, MG/DAY
2000
0
EXCESS SLUDGE PRODUCED
S_{R3}, MG/L
2000
0
SOLUBLE COD IN REACTOR 3
4 8 12 16 20 24 28 30 1 3 5 10 20 40 60 70 9 13 17 21
8/6/78
9/20/78
10

results show in general that when reactor 3 cells are batch fed with excess sludge from the activated sludge pilot plant, the "activity" as measured by volatile faction of the suspended solids and O_2 uptake markedly differ from that of cells from reactor 1. The biokinetic constants, μ_{max}, K_s, and Y_{t_B} also show wide differences between reactor 1 and reactor 3 cells. Also there is considerable variation in values for cells from the same reactor. In the first experiment (Figure 1), the maximum specific growth rates were close to 0.33 hr^{-1} for reactor 1 cells compared to 0.275 hr^{-1} for reactor 3 cells and the lower K_s value of reactor 3 cells at 34 mg/l compared to a value of 250 mg/l for reactor 1 cells may help explain the excellent stability in effluent quality during the shock period. Also during this time, VSS concentration in reactor 3 was high at 60 percent compared to 55 percent in reactor 1. However, in a similar experiment (not shown here) when the reactor 3 VSS concentration was 43 percent compared to 61.6 percent for reactor 1, the effluent turbidity due to leakage of clarifier solids was high. Initially, the clarifier used was a 2-liter smaller settling tank, and the X_e went up to a high of 688 mg/l during the first day. But after the usual 5-liter clarifier was placed in the line the next day, there was only a marginal improvement in the turbidity of the effluent. The leakage of suspended solids through the clarifier continued for nearly 12 days, though in reduced amounts. In both cases, the leakage of soluble COD from the reactor was minimum. Thus, one cannot generally expect similar responses from reactor 3 biological solids at random times at least with respect to settleability and clarity of the effluent.

The studies shown in Figures 4, 6, and 7 were run to determine

the effect of varying the degree of sludge digestion on the ability of reactor 3 cells to respond when placed in a growth environment. In these cases, the recycle supernatant was very high in soluble COD and NH_4-N due to digestion of cells. Also, partial nitrification of NH_4-N provided an additional disparity in the comparitive environments of reactor 1 and 3 sludges. In all of these experiments (including the one where sludge was not digested), irrespective of the stage of digestion, sludge rising in the clarifier was the major problem. To avoid this problem, continuous withdrawal of sludge from the clarifier may provide a solution. Also, the supernatant from the recycle may be the cause for high turbidity due to digestion and eventual release of cell constituents into solution. Aerobic digestion of reactor 3 cells invariably caused reduction in the filterability of the cells compared to that of fresh excess sludge. However, when sludge aged for 35 days was introduced into the system, there was a change in the predominant species, resulting in the proliferation of filaments and leading to bulking of the sludge and loss of effluent quality during the shifts in population.

The studies shown in Figures 8 and 9 were made to determine the feasibility of using hydrolysate of the sludge to improve its condition before it was used as the recycle. When hydrolysate was added, either intermittently or regularly every day, the activity of the sludge showed improvement, observed as increases in O_2 uptake and μ_{max} values. At the time the cells were switched, the maximum specific growth rate for cells in one experiment (Figure 8) was 0.180 hr^{-1} for reactor 3, compared to 0.177 hr^{-1} for reactor 1. However, similarity of μ_{max} values for sludge used in developing results shown in Figure 3 did not

provide for efficient stability during the switch in sludge. For experiments shown in Figure 8, the O_2 uptake value in reactor 3 was low at 2.4 mg/g/hr. Also it was low at 3.62 mg/g/hr in reactor 1. There was little or no disturbance in effluent quality. Similarly in another experiment (Figure 9), the disturbance was small. In this case, the O_2 uptake rates for reactor 3 cells and reactor 1 biological solids were similar but at a higher level--7.45 mg/g/hr and 7.53 mg/g/hr, respectively. This indicates that an increase in O_2 uptake does not necessarily enhance the biochemical efficiency and biologal stability of the system. However, the results do provide an indication that sludges with similar O_2 uptake rates may be able to make the transition with less perturbance of effluent quality.

For the results shown in Figure 10, reactor 3 cells were treated with 100 mg/l of hydrolysate regularly. The maximum specific growth rate for reactor 3 cells increased from 0.416 hr^{-1} to 0.581 hr^{-1} due to the addition of hydrolysate. The O_2 uptake value of the recycle sludge before recycle was 5.25 mg/g/hr. Even though the O_2 uptake was high, the effluent suspended solids leakage this time was significantly higher and took nearly 40 hours to come to reasonable levels. In all of these experiments, reactor 3 cells did show the ability to remove soluble substrate with little transient leakage. They also removed the NH_3-N supplied in the feed and in part, the recycle NH_4-N. The major disadvantages to the use of aerobically digested sludge for recycle were rising sludge, increased effluent turbidity and, in some cases, predominance changes which led to undesirable amounts of filamentous organisms in the sludge. The treatment of the sludge with hydrolysate before using it for recycle requires further study since the current results

are inconclusive. However, they do indicate such a practice would have to be approached with caution. The optimum dosage and best sludge activity parameters to assess or predict sludge compatibility need further study. However, feeding of hydrolysate does seem to increase the values of maximum specific growth rate. In these studies it did not always decrease the saturation constant, K_s. In this regard, only mixed results were obtained. Reactor 3 underwent, periodically, accelerated autodigestion; the occurrence of this phenomenon cannot be predicted. During such periods, most of the supernatant foamed out of the reactor, increasing the concentration of suspended solids in the reactor as well as increasing the supernatant COD and NH_4-N values. Most of the NH_4-N was converted into NO_3-N due to long detention times involved.

While the purpose of this research was to study the feasibility of using aerobic digester solids during shock loads, the digester supernatant may create an additional burden on the system due to unpredictably large quantities of organic substrates leaked from the cells from time to time as well as the provision of nitrogen, mostly in the form of NO_3-N. It may be necessary to devise operational control strategies for the digestion of sludge in reactor 3 to assure that this sludge can be used to achieve greater stability of the system during shock loads. Some attempts to overcome these problems are related and discussed in the next three sections of this chapter.

The only replacement recycle sludge of the current study that did not derive from aerobically digested excess pilot plant activated sludge was that from the Ponca City activated sludge plant. When this sludge was used, there was no transient disruption in treatment

efficiency. The success of this experiment would seem to indicate that the use of a "healthy" activated sludge facilitates the transfer process and that if aerobic digester sludge is to be used as a source of biomass for activated sludge, controlled freshening procedures should be sought.

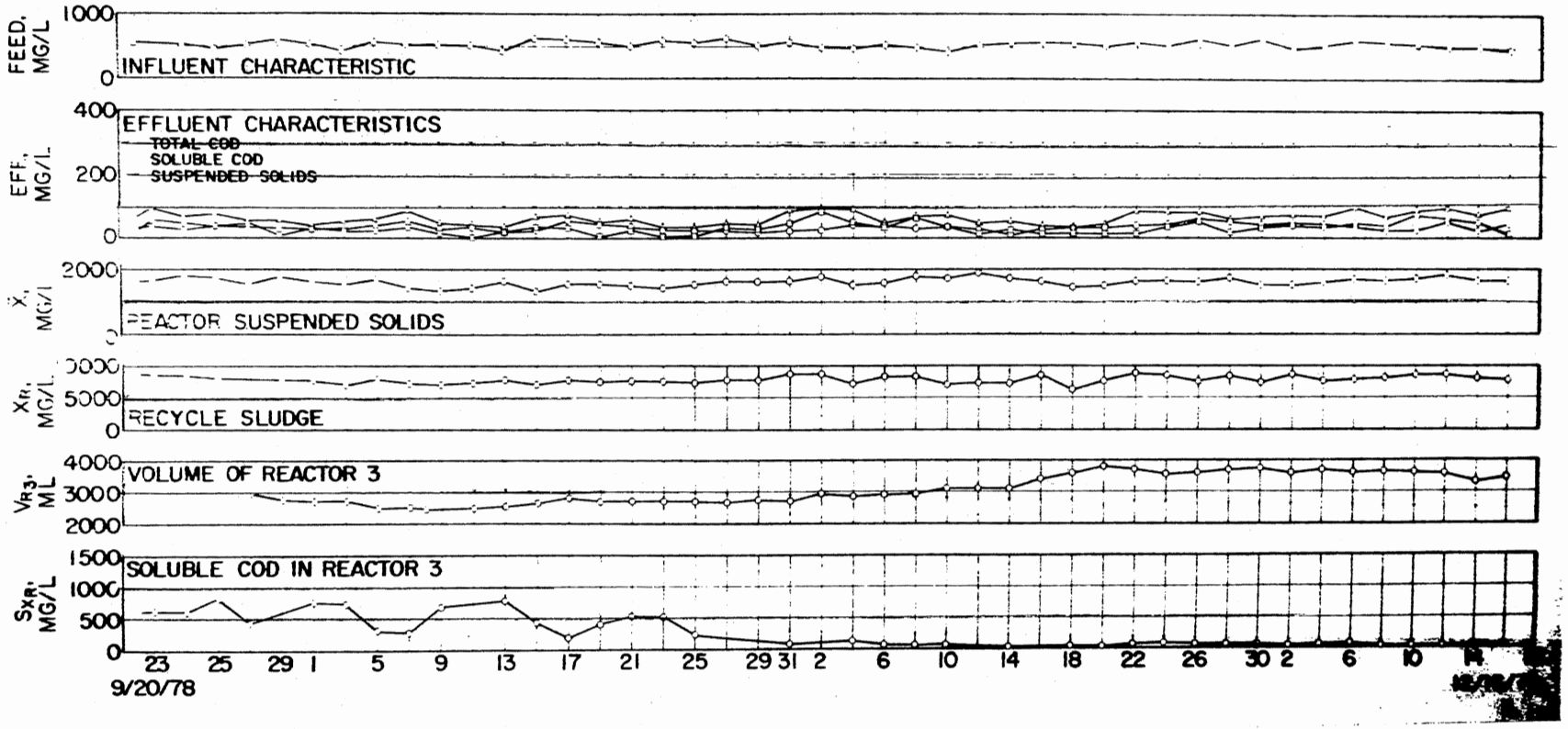
Phase 2: Experiments Using Reactor 3 Solids for Recycle Biomass on a Regular Basis

In the next experiment, recycle sludge was obtained from the aerobic digester on a regular daily (routine) basis. For the results shown in Figure 11, recycle sludge was obtained from reactor 3 at a constant recycle concentration (X_R) of 8000 mg/l. Every day, the sludge from the bottom of the clarifier was withdrawn and made up to a concentration of 8000 mg/l. Then this sludge was added to reactor 3. Reactor 3 volume was noted every day.

Sludge for recycle was then transferred to reactor 2. The reactor 2 suspended solids concentration (see recycle sludge concentration Figure 11) and its soluble COD were determined regularly along with all of the other parameters that were generally monitored. The feed glucose concentration was kept the same as in the previous studies, 500 mg/l glucose. When this phase of operation was started (9/20/78), the reactor 3 solids were experiencing heavy foaming and considerable amounts of filaments were noticed in both reactor 3 and reactor 1. Also, reactor 3 supernatant contained approximately 500 mg/l of organic matter measured as COD and 90 mg/l NH_4-N and 52.5 mg/l NO_3-N. Also, the cells exhibited a similar type of sludge rising in the clarifier, as was the case near the close of the previous experimental phase. However, this time the sludge rising continued for 32 days before it

Figure 11. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l With Recycle Sludge Regularly Taken From Reactor 3

From 9/20/78 to 12/16/78.


FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
EFF., MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
X, MG/L
2000
0
REACTOR SUSPENDED SOLIDS
XR, MG/L
5000
0
RECYCLE SLUDGE
VR3, ML
4000
3000
2000
VOLUME OF REACTOR 3
SXR, MG/L
1500
1000
500
0
SOLUBLE COD IN REACTOR 3
23 25 29 1 5 9 13 17 21 25 29 31 2 6 10 14 18 22 26 30 2 6 10
9/20/78

abated. The foaming was reduced in the first two weeks of operation; further foaming occurred but only slightly. During the next three months of operation, the sludge did not go into an accelerated phase of autodigestion as those that were experienced before. There was a general reduction in the amount of filamentous organisms in the system, i.e., the filaments began to disappear. The sludge concentration in the clarifier underflow began to increase and reached concentrations in excess of 15,000 mg/l. Previously, the sludge had compacted to between 8000 mg/l and 10,000 mg/l. Microscopic examination showed that the sludge consisted almost entirely of small cocci and a very large number of protozoa were present. The effluent was very clear and the little turbidity in the clarifier which was present during the initial stages of operation, disappeared. The high concentrations of supernatant COD in reactor 3 persisted for nearly 40 days, ranging from a minimum of 200 mg/l to a maximum of 832 mg/l COD in spite of the fact that reactor 3 liquor was diluted by the sludge from clarifier underflow which was almost 1.5 and 2.0 times the volume of the sludge that was remaining in reactor 3 (the volume left in reactor 3 after the recycle sludge was taken and transferred to the recycle reactor) and contained little or no soluble COD when added to reactor 3. Also, the reactor 3 volume remained fairly constant between 2.45 and 2.7 liters, with a few values above 2.9 liters. The above values pertain to volumes after the addition of clarifier underflow but before withdrawing the sludge for recycle. During this time period, the soluble COD in the clarifier ranged between 20 mg/l and 56 mg/l, with an average S_e of 32.50 mg/l. For the same period, the average value in reactor 3 was 506 mg/l. By November 6, 1978, and thereafter,

the reactor 3 soluble COD remained lower than 70 mg/l except for one value which registered at 93 mg/l. At the same time, the reactor 3 volume increased slightly and reached steady level at around 3.5 to 3.8 liters at a sludge concentration of 8000 mg/l. This rise in the reactor 3 volume indicates that the cell population needed this additional detention time to make up for the slower rate of digestion during the latter part of the experimental period shown in Figure 11. During the entire period (9/20/78 to 12/12/78) the soluble COD in the effluent averaged 35 mg/l, the suspended solids concentration 31 mg/l, and the total COD 63 mg/l. During the period (9/20/78 to 12/16/78) the initial NH_4-N and NO_3-N concentrations in the recycle were 90 mg/l and 57 mg/l. As this entire mode of operation proceeded, there was an initial decline in the NH_4-N concentration to 13.2 mg/l followed by a slow buildup to 54 mg/l. Then there were very large fluctuations with highs around 50 mg/l and lows approaching zero mg/l near the end of three months of operation. In contrast, the NO_3-N in the recycle after initially fluctuating between 25 and 50 mg/l, stabilized at 10 mg/l or less. During the period in Figure 11, the clarifier NH_4-N was recorded at 8.4 mg/l, 0, 12.4, 14, and 18.8 mg/l. The NO_3-N in the clarifier effluent was also very low--ranging from 2.5 mg/l to a high of 10 mg/l.

After about 40 days of operation, soluble COD in reactor 3 was very low but it was generally slightly higher than the clarifier filtrate COD. At this time, the volume of sludge in reactor 3 started to increase from the range 2.5 to 2.7 liters to about 3.5 to 3.8 liters, and stabilized at that volume. This brings up two questions: 1) In the early part of the experiment, why was there persistently high

soluble COD in reactor 3 even though it was being diluted by daily addition of nearly twice the volume of clarifier underflow than was retained in reactor 3? 2) Why were the lower levels of soluble COD maintained in reactor 3 in the later part of the experiment when reactor 3 was used as an integral part of a flow sheet in the process rather than a mere aerobic digester?

One could hypothesize that the previous rate of autodigestion which was very high prior to the regular introduction of reactor 3 biological solids simply continued for a time after the change in the mode of operation. Rapid cell lysis may introduce some difficultly metabolized products into solution causing periodic buildup of COD as well as NH_4-N concentration. It is noted that two-thirds of reactor 3 cells were freshly added each day and these cells had been growing in a steady state exponential phase for quite a long time. So the continued persistence of rapid autolysis may have been due to the shock effect when these cells were introduced to reactor 3. It might be further argued that there were biological forces in reactor 3 which contributed to the rapid autodigestion and buildup of soluble COD. These may include bacterial and viral attack. It seems possible that when the cells in reactor 3 were not releasing excessive amounts of cell products into solution (as measured by an elevated concentration of soluble COD), only oxidation of internal storage material was taking place for maintenance purposes. Perhaps it is only when the external factors such as higher form predators and/or viruses are operating on the cells that a buildup of soluble organic material occurs. The above statements may or may not be valid, but they do serve to point out the need for concomitant study of ecological changes within the

sludge. How best these ecological agents, if they can be quantitavely detected and assessed for effect can be used to maximize the digestion of cells to engineering advantage is a matter of useful conjecture. A partial utilization may be seeking ways and means to control digestion with mostly internal metabolic storage substrate of the cells being used for endogenous respiration prior to use of aerobic digester contents for recycle sludge. This way, the cells could maintain the structural integrity and functionality for their employment as a ready source of feeding population for recycle. It may be feasible to conduct aerobic digestion in two phases, using a short hydraulic detention time to "burn off" internal stores, followed by longer detention time to effect maximum sludge reduction. The supply of recycle cells would be taken from the first phase digester. Much more study is needed to determine under which conditions internal stores are used prior to digestion by ecological factors external to the cells.

In general, it would appear that this mode of operation using aerobically digesting sludge appears to be successful compared to the means of obtaining recycle sludge in the previous phase of the study. It is significant to note that the total volatile fraction of the reactor 3 sludge was 80.3 percent during this experiment (slightly higher than the reactor 1 volatile solids of 78.4 percent). However, during the batch operation, reactor 3 sludge exhibited a VSS of 30 to 40 percent. The average steady state performance of the activated sludge during the period 9/20 to 12/12/78 was S_e = 35 mg/l, X_e = 31 mg/l. During this period, the average S_i was 545 mg/l, X_R = 7907 mg/l, and $\bar{X}$ = 1645 mg/l. The average volume of reactor 3 during this period was 3.1 liters and on average, 1.7 liters of this volume was

taken each day to provide the daily recycle volume in reactor 2, the sludge makeup tank.

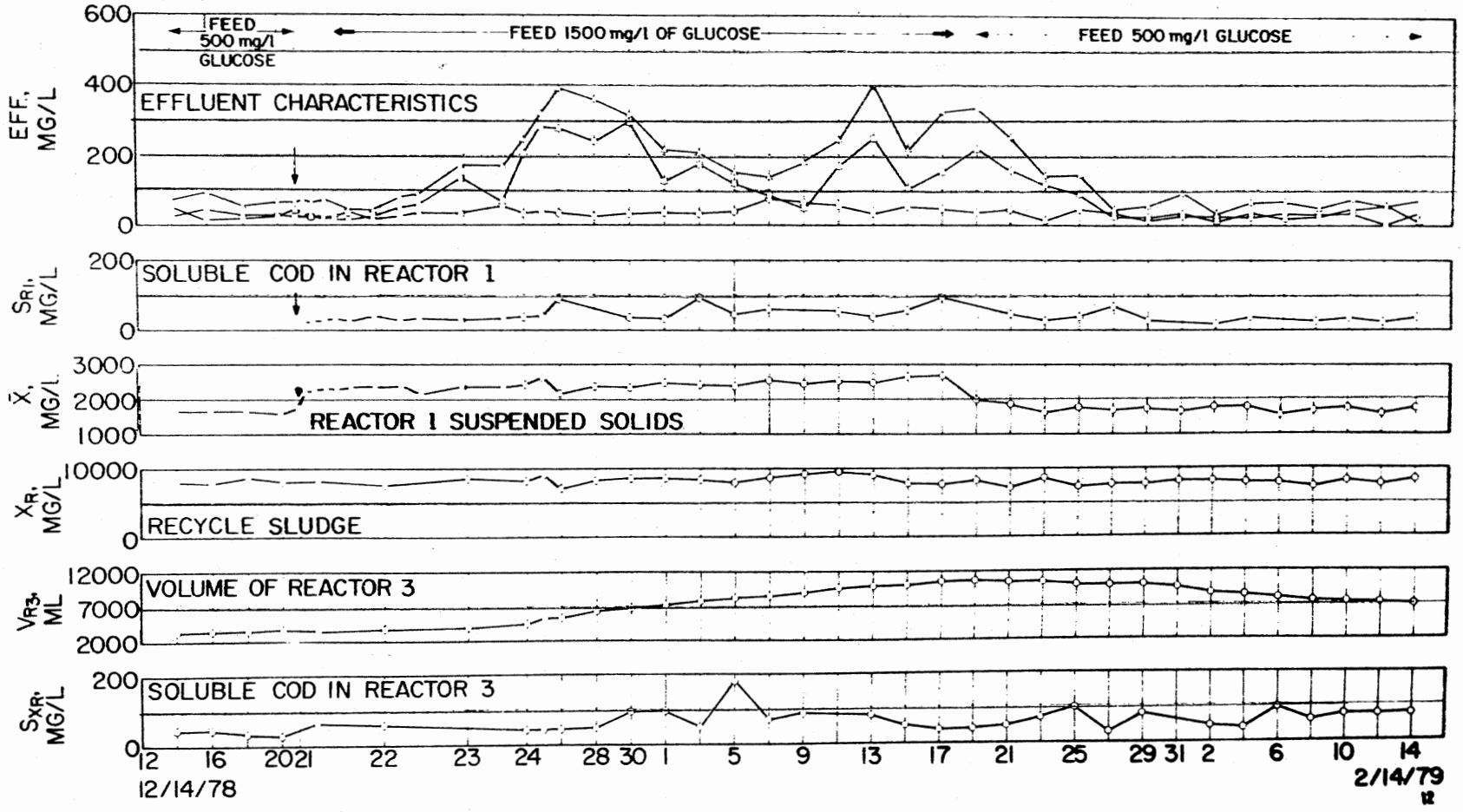
Phase 3a: Quantitative Shock Loading to a System Using Aerobic Digester Solids Regularly as Recycle Biomass, X_R, With Recycle Solids Concentration Controlled at 8000 mg/l

In order to gain some information on the stability of this mode of operation during shock loadings, the unit was subjected to a 3-fold quantitative increase in the feed glucose concentration. The results are shown in Figure 12.

The average steady state performance of the unit during the week prior to the shock load was S_e = 31 mg/l, X_e = 27 mg/l, $\bar{X}$ = 1652 mg/l. The soluble COD in reactor 3 was 37 mg/l, and X_R = 8231 mg/l, with the average reactor 3 volume = 3.5 liters. In response to the shock, the $\bar{X}$ in the reactor rose from an initial concentration of 1760 mg/l to 2202 mg/l in two hours, and the biological solids concentration stabilized at a value somewhat above 2300 mg/l. For the first 35 hours after the shock, the X_e concentration fluctuated around the average value before the shock, but at the end of the second day, i.e., at the 47th hour, X_e rose to a high of 135 mg/l. The mixed liquor filtrate COD and clarifier soluble COD remained the same as the pre-shock values --between 20 to 40 mg/l. However, after the 47th hour, the effluent solids concentration increased enormously and S_t values increased correspondingly. The clarifier effluent suspended solids concentration remained high, varying from 50 to 295 during the next 30 days. All through this period, the S_e and S_R values remained low. The average

Figure 12. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Shock Loaded With a 3-fold Increase in the S_i to 1500 mg/l Glucose. The Recycle Sludge was Made Regularly From Reactor 3

From 12/14/78 to 2/14/79 - shock loaded on 12/21/78.


FEED 500 mg/l GLUCOSE
FEED 1500 mg/l OF GLUCOSE
FEED 500 mg/l GLUCOSE
EFF., MG/L
600
400
200
0
EFFLUENT CHARACTERISTICS
S_{R1}, MG/L
200
0
SOLUBLE COD IN REACTOR 1
$\bar{X}$, MG/L
3000
2000
1000
REACTOR 1 SUSPENDED SOLIDS
X_R, MG/L
10000
0
RECYCLE SLUDGE
V_{R3}, ML
12000
7000
2000
VOLUME OF REACTOR 3
S_{XR}, MG/L
200
0
SOLUBLE COD IN REACTOR 3
12 16 20 21 22 23 24 28 30 1 5 9 13 17 21 25 29 31 2 6 10 14
12/14/78
2/14/79

S_e and S_R values during this period were 38 mg/l and 45 mg/l, respectively. The X_e and S_t values were 12 mg/l and 189 mg/l, respectively. The volume of sludge in reactor 3 during the same period increased steadily from an initial value of 3.5 liters to 10.6 liters. The concentration of sludge in reactor 3 was maintained close to 8000 mg/l--the same as the recycle biological solids concentration. Initially, the NH_4-N concentration in the effluent was negligible. Also the recycle NH_4-N concentration was zero. The NO_3-N concentration was zero. The NO_3-N concentration recorded in the recycle was 5 mg/l. During the shock load, the clarifier NH_4-N concentration gradually increased to 26 mg/l, 47 hours after increasing the feed glucose concentration to 1500 mg/l along with the NH_4 which was also increased proportionately. It increased slowly to 52.4 mg/l at the end of 30 days. During this period, the NO_3-N in the effluent remained low at approximately 5 mg/l.

It is clear that the 3-fold increase in feed concentration did not cause any adverse effect with respect to the removal of soluble substrate. However, it did increase leakage of biological solids through the clarifier. This problem was due mainly to new dispersed growth in the reactor and these new cells were unable to settle in the clarifier. This problem may have been caused by the high F/M ratio at 0.69. If the dispersed growth was caused by the increased F/M ratio, increasing the recycle biological solids concentration, X_R, above 8000 mg/l should be expected to yield better results. For convenience in these experiments, reactor 3 cells were diluted to the X_R concentration. This mode of operation may have contributed to dispersed growth during the higher S_i loading, but it is difficult to see how. In any

event, in field operations the sludge concentration in the aerobic digester would be higher than the recycle sludge concentration, thus X_R could be increased under shock load conditions.

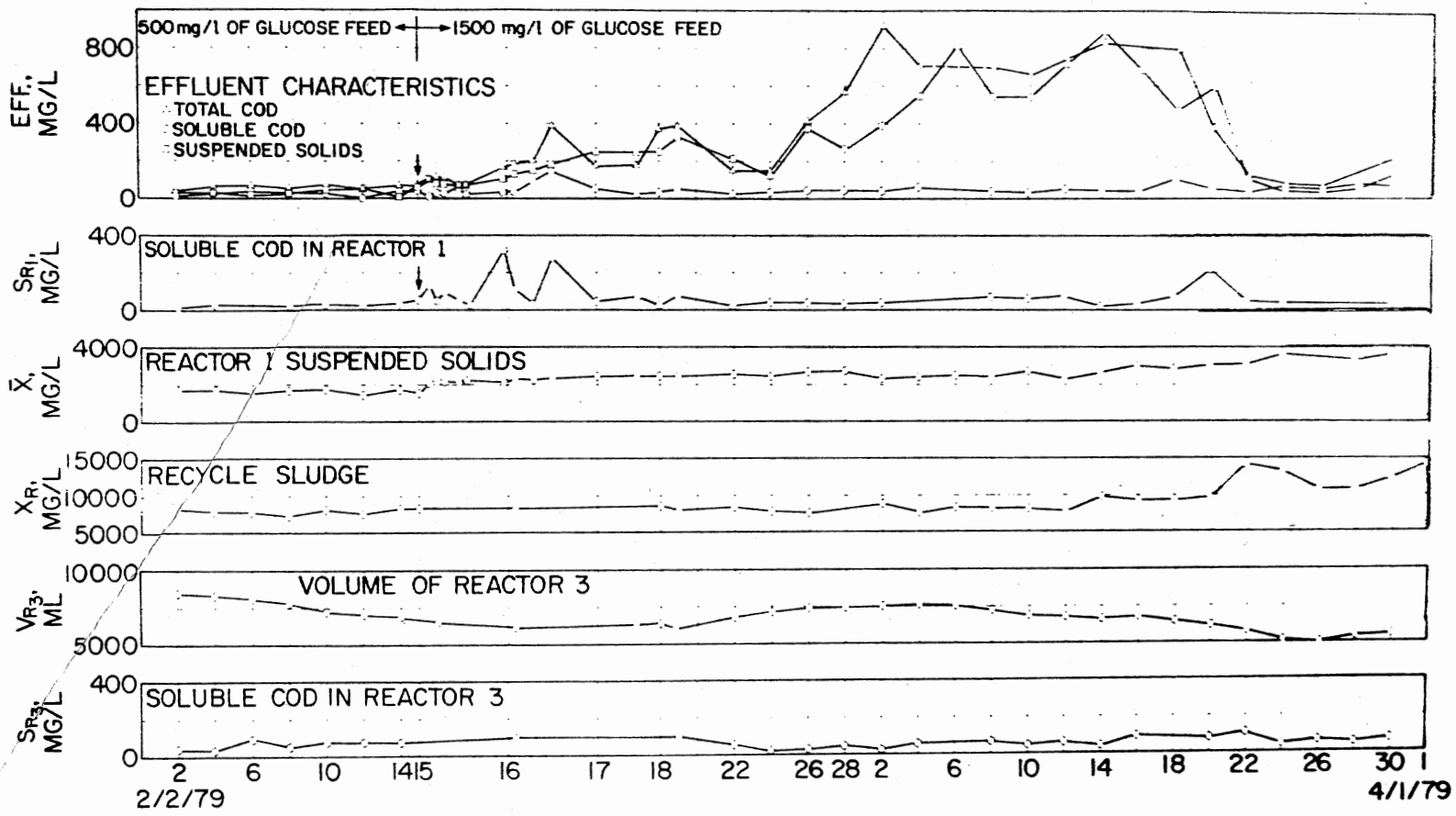
On January 19 the feed substrate concentration was reduced to 500 mg/l. By January 27 the effluent solids concentration gradually came to 27.5 mg/l and remained steady at low levels thereafter. Also because of the reduction in the feed substrate concentration the excess sludge produced was reduced, so there was a slow but steady decrease in the total volume of recycle sludge from 10.6 liters to 6.6 liters. Tbe concentration of this sludge was maintained at an average 7919 mg/l. During the same period (1/27/79 to 2/15/79) the average S_e and X_e were 27 mg/l and 32 mg/l compared to 35 mg/l and 31 mg/l for the earlier experiment (Figure 11--9/20/78 to 12/12/78) under similar conditions but with less volume of reactor 3 (3.082 liters compared to 8.145 liters). The average total effluent substrate concentrations were essentially the same. During this period (1/27 to 2/15/79) the average soluble substrate in reactor 3 filtrate was only 60 compared to 286 mg/l in the previous steady state period. The average filtrate COD of the clarifier effluent was 27 mg/l. Thus, the recycle solids contributed slightly to the plant loading. In the steady state period one week before the shock load the soluble COD in reactor 3 was only 37 mg/l. This higher reactor 3 soluble substrate (60 mg/l) in the steady state after the shock might have been due to the larger reactor 3 cell detention time associated with higher volumes of sludge which built up due to shock load. Also, the percentage of volatile solids in reactor 3 and in reactor 1 were less than that experienced during the period shown in Figure 11. The MLVSS were only 62 and 60.8 percent

for reactor 2 and reactor 3 sludges, respectively (1/19/79, feed still at 1500 mg/l glucose) compared to 78.4 percent and 80.26 percent during the steady state before the shock. Batch growth studies were made using seeds from reactor 1 and reactor 3 on 1/19/79 and 17 days after (2/6/79) reducing the feed substrate concentration to 500 mg/l glucose. On the last day of the shock load the μ_{max}, K_s, and Y_{t_B} when the seed was taken from reactor 1 were 0.204 hr^{-1}, 96 mg/l, and 0.66, and for reactor 3, seed was 0.232 hr^{-1}, 29 mg/l, and 0.52. Seventeen days after reducing the feed substrate concentration to 500 mg/l, μ_{max}, K_s, and Y_{t_B} values were for reactor 1, 0.459 hr^{-1}, 435 mg/l, and 0.65; for reactor 3 seed, 0.317 hr^{-1}, 124 mg/l, and 0.71.

The experimental results shown in Figure 11 gave an indication that the volume in reactor 3, i.e., inventory of sludge in reactor 3, may not be a very critical factor in the operation of the system with this reactor interconnected in the overall recycle stream. However, there was little doubt that the response to shock was not satisfactory with respect to effluent quality; the experiment bears repeating. Also, it was desirable to determine if a slower specific growth rate (or lower F/M) at the time of the shock would foster a better response. Accordingly, the experiment was repeated (feed substrate concentration was increased 3-fold from 500 mg/l to 1500 mg/l, keeping the X_R constant at 8000 mg/l). However, calcium oxide was added through the recycle so that 100 mg/l of CaO concentrations were maintained in the reactor to determine if this would help alleviate the expected problem of suspended solids carryover in the clarifier effluent. It can be seen in Figure 13 that the biomass responded rather quickly. Within three hours, the concentration in the reactor increased to 2052 mg/l

Figure 13. Operational Characteristics of an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Shock Loaded With a 3-fold Increase in the S_i to 1500 mg/l Glucose. The Recycle Sludge was Made Regularly From Reactor 3

From 2/2/79 to 4/1/79 - shock load started on 2/15/79; addition of 100 mg/l CaO started on 2/15/79, stopped on 2/26/79. March 14 onward, the recycle sludge concentration was not controlled.


500 mg/l OF GLUCOSE FEED
1500 mg/l OF GLUCOSE FEED
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
EFF., MG/L
800
400
0
SOLUBLE COD IN REACTOR 1
S_{R1}, MG/L
400
0
REACTOR 1 SUSPENDED SOLIDS
$\bar{X}$, MG/L
4000
0
RECYCLE SLUDGE
X_R, MG/L
15000
10000
5000
VOLUME OF REACTOR 3
V_{R3}, ML
10000
5000
SOLUBLE COD IN REACTOR 3
S_{R3}, MG/L
400
0
2 6 10 14 15 16 17 18 22 26 28 2 6 10 14 18 22 26 30 1
2/2/79
4/1/79

from an initial MLSS concentration of 1588 mg/l. Thereafter there was a gradual increase to 2456 mg/l by the end of the second day. The initial response with respect to the reactor filtrate COD was an increase from 54 mg/l to 131 mg/l, but it fluctuated around between 324 mg/l to 42 mg/l between 23 and 48 hours after administering the shock load. However, the soluble COD concentration exiting the clarifier remained rather low except for two values, which were 96 mg/l and 150 mg/l during the same period. The effluent suspended solids concentration remained fairly low during the first day. But from the second day onward the effluent solids leakage increased enormously and remained high for approximately one month, as can be seen in Figure 13. The addition of CaO appeared to be of no avail, so this procedure was terminated on February 26. However, it may have been of considerable benefit, judging by the tremendous increase in effluent solids leakage (to as high as above 800 mg/l) after terminating its addition to the system. Finally, on March 14, 1979, it was decided to increase the recycle solids concentration. The clarifier underflow was taken with as little amount of excess fluid as the compaction capacity of the sludge allowed. This change in operation increased the concentration of biological solids in reactor 3, thereby increasing the recycle biological solids concentration. This increase caused an expected gradual decrease in the volume of sludge in reactor 3, and a gradual increase in the recycle solids concentration which corresponded to a significant reduction in the leakage of effluent solids. Only 40 mg/l was recorded on March 24, 1979, compared to 895 mg/l on March 14, 1979. Decrease in suspended solids loss caused a further increase in X_R and $\bar{X}$. The results indicate that the change in operation

which provided the extra recycle solids concentration effected the decrease in the leakage of suspended solids. During the operation of this bench-scale pilot plant, it was observed that the compaction capacity of the sludge was very good. For example, during the operation of this unit, the clarifier underflow sludge concentration was consistently above 15,000 mg/l and sometimes as high as 25,000 mg/l. This observation was valid for phase 2 as well. However, during phase 2, the sludge concentration in the underflow was only around 8000 mg/l and never exceeded more than 10,000 mg/l. In both phase 1 and the mode of operation for phases 2 and 3, the activated sludge was equally effective in removing the influent COD from solution. It should also be noted that after initiating operation of the pilot plant with reactor 3 as the regular source of recycle sludge, there was an improvement in stability with respect to predominance changes and compaction of sludge.

In view of the improved operation when X_R was increased and the apparent enhanced compactability of sludge taken for recycle from the aerobic digestion tank (reactor 3), it seemed of value to study the system performance under conditions wherein efforts were made to use the highest X_R possible short of gravity thickening prior to recycle.

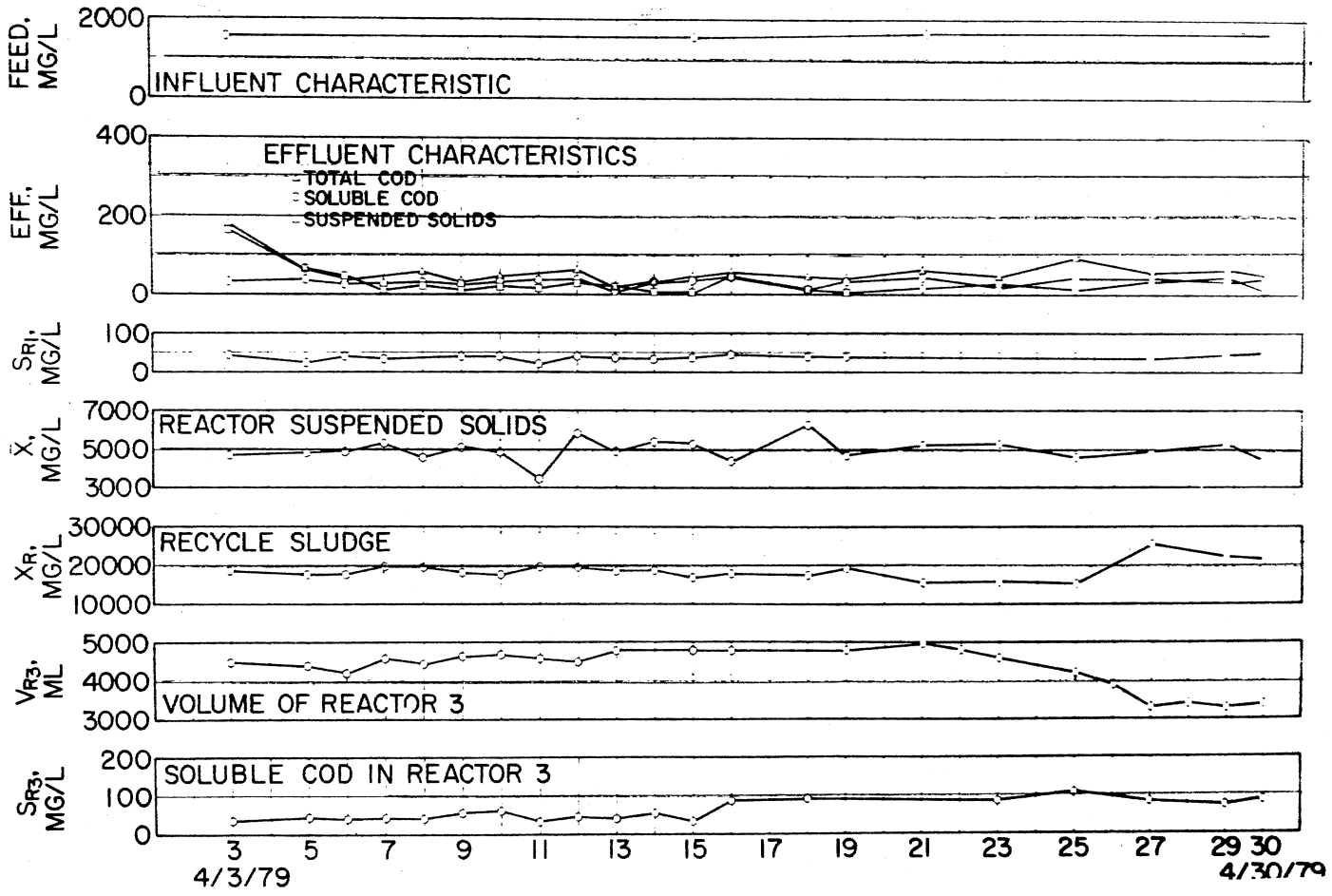
Phase 3b. Experiments Without the Constant Recycle Solids Concentration and Taking X_R Directly From Reactor 3 Regularly

On April 3, 1979, the cells in reactor 3 were allowed to settle by gravity for four hours, and the supernatant was carefully decanted in order to start the next experiment with a high X_R. The sludge in reactor 3 was aerated and the required amount (by volume) of sludge

for recycle was taken and transferred to reactor 2 for recycling into reactor 1. The recycle sludge concentration, X_R, on that day was 18,692 mg/l. The feed substrate concentration was maintained at 1500 mg/l glucose. On that day the reactor 3 supernatant was 32 mg/l COD. After one day of operation, the sludge from the bottom of the clarifier was withdrawn carefully so that underflow sludge was as concentrated as possible. Sometimes the sludge was withdrawn every 12 hours. After withdrawal the sludge was added to reactor 3. No attempt was made to adjust the concentration of the sludge added to reactor 3 or the sludge taken from reactor 3 for recycle. Whatever concentration prevailed in reactor 3 was in effect the recycle biological solids concentration. This mode of operation was continued, and X_e, S_e, S_t, S_{R_3}, $\bar{X}$, and X_R were monitored each day and occasionally on alternate days. The feed substrate concentration remained at 1500 mg/l glucose. Some of the operational results are shown in Figure 14. The recycle biological solids concentration, X_R, was in a pseudo steady state until April 19. The X_R values ranged from 16,888 mg/l to 19,112 mg/l; the concentration declined to 15,276 mg/l on the 25th and increased to a value slightly above 25,000 mg/l on April 27. These data indicate that the X_R concentration attainable by compaction in the clarifier was rather high; a condition not normally encountered in the field wherein recycle cells are not obtained from the aerobic digester. High compaction in the clarifier was occurring all through this period of operation. It is emphasized that in order to take operational advantage of this sludge characteristic, considerable care had to be exercized not to draw any excess water while withdrawing the sludge from the clarifier. Due to high recycle concentrations, the reactor

Figure 14. Operational Characteristics of an Activated Sludge Process at an S_i of 1500 mg/l and the Recycle Sludge was Taken Directly From Reactor 3 Regularly (steady state data)

From 4/3/79 to 4/30/79.


FEED, MG/L
2000
0
INFLUENT CHARACTERISTIC
EFF., MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
S_{R1}, MG/L
100
0
$\bar{X}$, MG/L
7000
5000
3000
REACTOR SUSPENDED SOLIDS
X_R, MG/L
30000
20000
10000
RECYCLE SLUDGE
V_{R3}, ML
5000
4000
3000
VOLUME OF REACTOR 3
S_{R3}, MG/L
200
100
0
SOLUBLE COD IN REACTOR 3
3
5
7
9
11
13
15
17
19
21
23
25
27
29
30
4/3/79
4/30/79

biological solids were maintained high; they were about 5000 mg/l most of the time. The volume in reactor 3 remained fairly steady around 4.4 to 5 liters, and decreased to 3.3 liters when X_R rose to a high of 25,924 mg/l because of still increasing compactability. The overall performance of the unit was excellent. Only an extremely long period of study could provide a basis for conclusions that sludge for recycle taken from an aerobic digester will provide better compaction than recycle cells obtained from the clarifier underflow. However, the current results augur well for the practice and it surely was evident that the performance with respect to effluent quality was excellent. The average X_e was 21 mg/l; $\bar{X}$ was 5025 mg/l, X_R was 18,759 mg/l. The soluble COD in the aeration tank was 37 mg/l; the clarifier effluent filtrate was on average, 30 mg/l. The reactor 3 supernatant COD was also low, 59 mg/l. This system performed better than one receiving 1/3 the substrate loading but with X_R = 8000 mg/l (compare these results with the performance shown in Figure 11).

Spot checks of NH_4-N and NO_3-N values in the effluent showed that between 40 to 60 percent of the NH_4-N in the feed was leaking into the effluent. The amount of nitrification recorded was negligible at about 10 mg/l in the clarifier and ranged from 16 to 19 mg/l in reactor 3.

A spot BOD_5 taken on April 14 showed a value of 4.6 mg/l for filtered effluent and 4.8 mg/l in the unfiltered effluent. It is interesting to note that growth studies performed on seed from both reactor 2 and reactor 3 (4/3/79) gave nearly identical biokinetic constants. When the seed was taken from reactor 1, the μ_{max}, K_s, and Y_{t_B} were 0.373 hr^{-1}, 939 mg/l, and 0.65, respectively. When the seed was

taken from reactor 3 (4/3/79), these values were 0.364 hr^{-1}, 818 mg/l, and 0.63, respectively. Also, the total volatile solids percentage remained essentially the same for reactor 1 and reactor 3 at 74 percent and 77 percent, respectively.

Phase 4: Hydraulic Shock Load Experiment With Uncontrolled Sludge Recycle Concentration

After the close of the previous phase of experimentation (36), a cyclic hydraulic shock load (Figure 15) was administered to the activated sludge pilot plant. The recycle flow ratio, α, was kept constant at 0.25. The influent feed substrate concentration was maintained at 1500 mg/l glucose. The recycle solids concentration was the same as the concentration in reactor 3. The shock load was initiated first by increasing the hydraulic detention time from eight hours (pre-shock) to 12 hours and then reducing it to four hours. Every 12 hours thereafter the $\bar{t}$ was switched from 12 to four hours until the experiment was terminated after nine days. Initially, when the $\bar{t}$ was changed from eight hours to 12 hours (9:00 A.M. 5/2/79), there was an increase in the reactor mixed liquor suspended solids from 4296 mg/l to 5280 mg/l, but when $\bar{t}$ was switched to four hours, there was a decrease in $\bar{X}$, initially to 4044 mg/l, but it recovered to 4512 mg/l. The cycling in reactor suspended solids continued for five days but gradually the amplitude attenuated. The soluble substrate (COD) leaking from the clarifier remained low and fairly constant throughout the period, as did the reactor filtrate which exhibited rather steady values. The average values of the data during the shock load are presented in Table III. The data show that average S_e concentration was 34 mg/l at

Figure 15. Operational Characteristics of an Activated Sludge Process With an S_i of 1500 mg/l Subjected to Cyclic Hydraulic Shock Loading from t = 12 Hours to t = 4 Hours Every 12 Hours. The Recycle Sludge was Taken Directly from Reactor 3 Regularly

From 5/2/79 to 4/11/79.

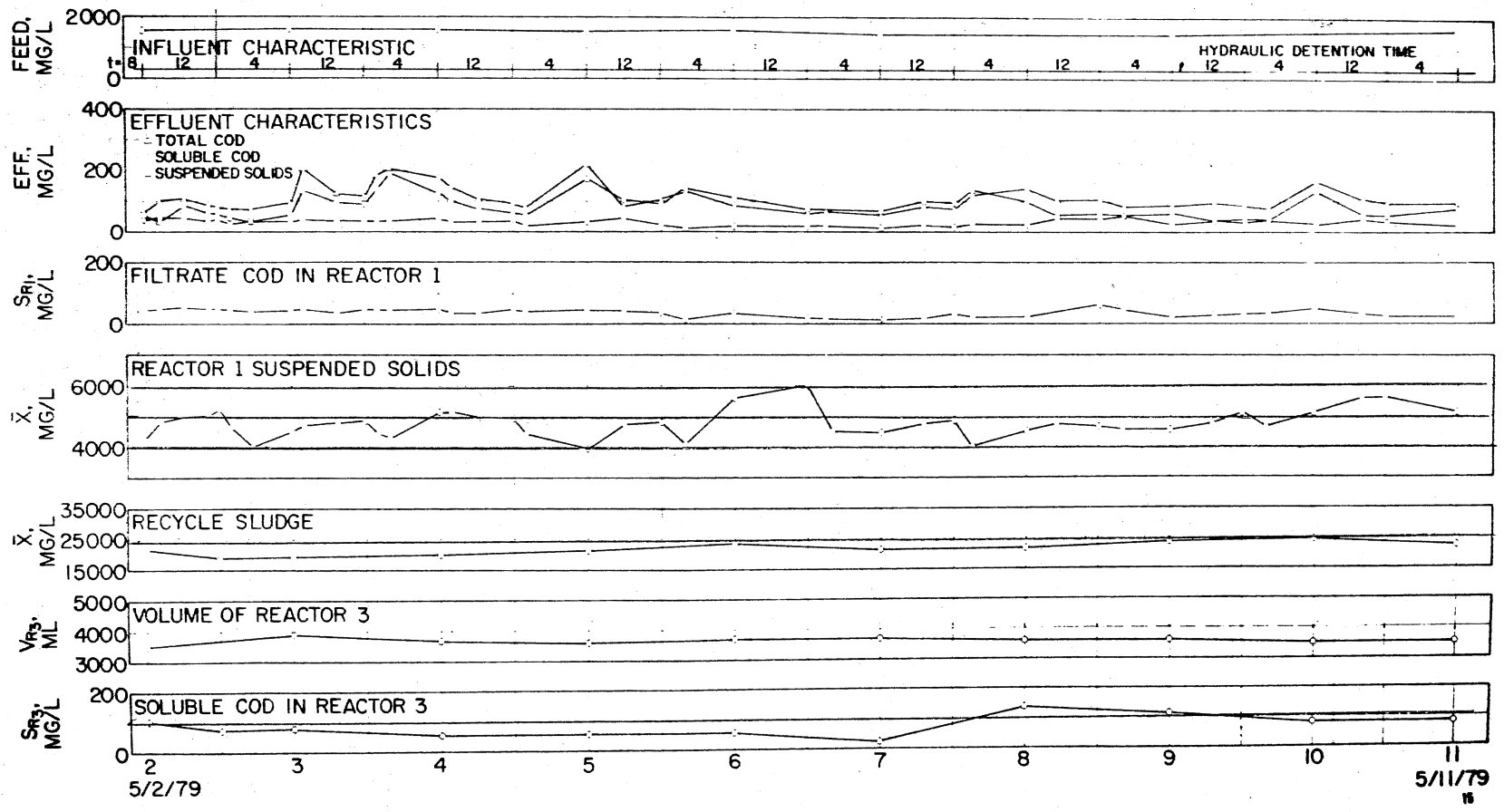

FEED, MG/L
2000
INFLUENT CHARACTERISTIC
t=
0
8
12
4
12
4
12
4
12
4
12
4
12
4
12
4
12
4
12
4
HYDRAULIC DETENTION TIME
EFF, MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
S_{R1}, MG/L
200
0
FILTRATE COD IN REACTOR 1
$\bar{X}$, MG/L
6000
4000
REACTOR 1 SUSPENDED SOLIDS
$\bar{X}$, MG/L
35000
25000
15000
RECYCLE SLUDGE
V_{R3}, ML
5000
4000
3000
VOLUME OF REACTOR 3
S_{R3}, MG/L
200
0
SOLUBLE COD IN REACTOR 3
2
3
4
5
6
7
8
9
10
11
5/2/79
5/11/79

TABLE III

AVERAGE CYCLIC HYDRAULIC SHOCK LOAD DATA AT S_i = 1500 mg/l GLUCOSE, RECYCLE SLUDGE (X_R) TAKEN FROM THE AEROBIC DIGESTER REGULARLY, WITH A CONSTANT VALUE OF RECYCLE FLOW RATIO, α, = 0.25*

Hydraulic Detention Time ($\bar{t}$)	$\bar{X}$ (mg/l)	X_e (mg/l)	X_R (mg/l)	V_{R_3} (ml)	S_i (mg/l)	S_t (mg/l)	S_R (mg/l)	S_e (mg/l)	S_{R_3} (mg/l)
$\bar{t}$ = 12 hrs	4769	81	21,695	3630	1559	108	38	34	75
$\bar{t}$ = 4 hrs	4744	88	21,756	3311	1559	102	37	30	75

*The cyclic variation in hydraulic detention time in reactor 1 is from $\bar{t}$ = 12 hours to $\bar{t}$ = 4 hours, applied every 12 hours. Before the shock load, the hydraulic detention time was eight hours.

$\bar{t}$ = 12 hours, and 30 mg/l when $\bar{t}$ = 4 hours. At the same time, the filtrate COD in the reactor was slightly higher at 38 mg/l and 37 mg/l, respectively. Throughout this period, the average reactor 3 filtrate COD remained at about 75 mg/l. It is seen from results presented in Table III that there was no appreciable difference in the average values for either loading. The X_R concentration remained constant at slightly above 21,500 mg/l. The volume of sludge in reactor 3 also remained fairly steady, fluctuating between 3.5 liters to 3.9 liters. The increase in S_t value was due to leakage of effluent suspended solids.

No significant amount of nitrification occurred during the shock loading period with most of the values determined remaining between 6 and 12 mg/l. However, the concentrations of NH_4-N in reactor 1 and reactor 3 showed a cyclic effect, fluctuating between 70 and 200 mg/l during the shock load period.

Phase 5: (Unit 2) Experiments to Study the Feasibility of Reducing Hydraulic Detention Time in Extended Aeration Activated Sludge

This phase of results contains operational performance data for a bench-scale activated sludge pilot other than the one employed in the previously reported studies. The new pilot plant was used to study the feasibility of reducing the hydraulic detention time in the total oxidation activated sludge process. However, the mode of operation differed in certain essentials from the usual type of extended aeration process since it involved the use of a separate recycle reactor to provide constant cell recycle concentration, X_R. Generally, an extended

aeration system is run with a hydraulic detention time of 24 hours or more. This study was made to determine if the performance of the process could be maintained steady with reasonably good effluent quality at hydraulic detention times lower than 24 hours. In this phase of study, the activated sludge process was operated at hydraulic detention times of 16 and 12 hours. The feed substrate concentration was 500 mg/l. The recycle biological solids, X_R, was maintained constant at 10,000 mg/l. Any excess sludge available in the process over and above the requirements for recycle at 10,000 mg/l were inventoried in the recycle reactor (reactor 2). The recycle flow ratio, α, was maintained at 0.25.

The operation of this phase of study was generally similar to phases 2 and 3, with some differences. Hydraulic detention time was only eight hours in both of the previous phases, and the recycle biological solids concentration was 8000 mg/l compared to 10,000 mg/l in this phase. Also, the excess sludge produced was kept in a separate vessel, reactor 3, which operated as a batch operated process, only serving as a source of recycle sludge whenever necessary to study its effects, as during phase 1, or as part of the regular flow sheet during phases 2 and 3.

Figures 16 and 17 are the plots of the steady state performance of the system during operation with a hydraulic detention time of 16 hours. Each figure shows a two-month operational period. Every day when the recycle concentration was made up in reactor 2, the volume of sludge was also measured to determine the fluctuation in the amount of sludge developed during this type of operation. This particular unit had previously been fed a combined carbon source consisting of glucose and sorbitol. After the author assumed operational responsibility for the

Figure 16. Operational Characteristics of an Extended Aeration Activated Sludge Process with Constant X_R of 10,000 mg/l at an S_i of 500 mg/l and With a Hydraulic Detention Time of 16 Hours

First part from 8/14/78 to 10/15/78.

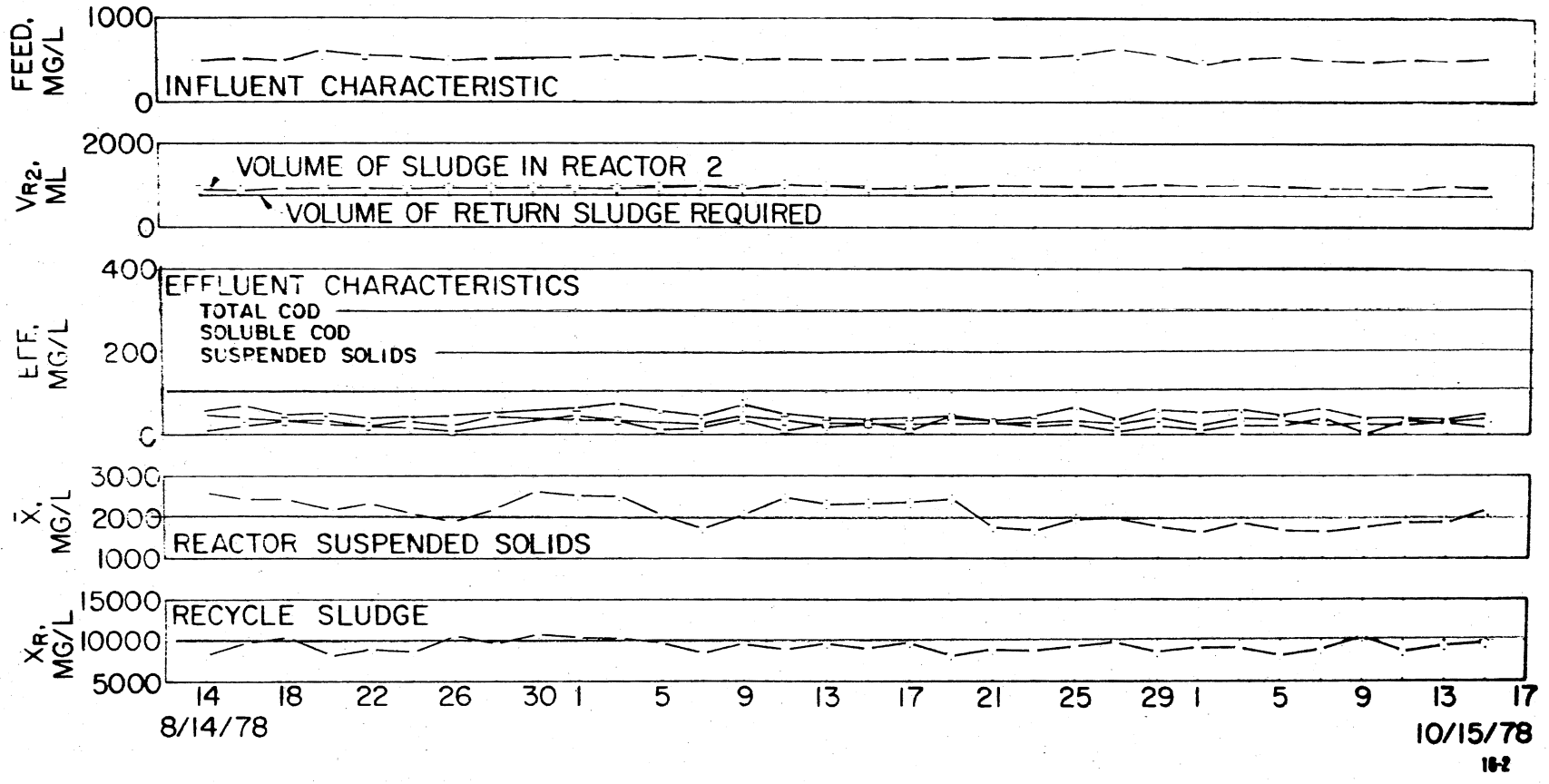
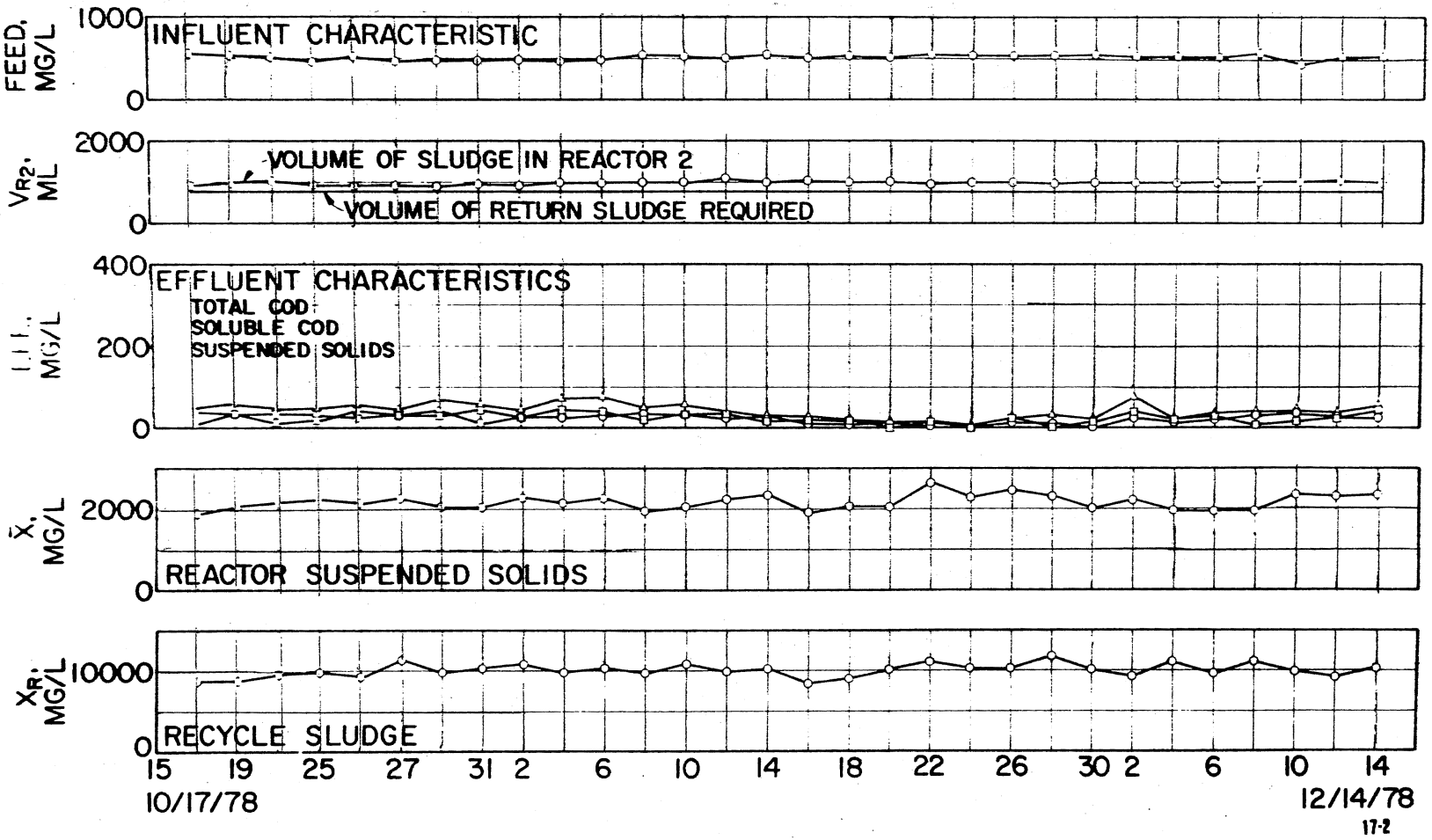

FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
V_{R2}, ML
2000
0
VOLUME OF SLUDGE IN REACTOR 2
VOLUME OF RETURN SLUDGE REQUIRED
EFF, MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
$\bar{X}$, MG/L
3000
2000
1000
REACTOR SUSPENDED SOLIDS
X_R, MG/L
15000
10000
5000
RECYCLE SLUDGE
14 18 22 26 30 1 5 9 13 17 21 25 29 1 5 9 13 17
8/14/78
10/15/78
16-2

Figure 17. Operational Characteristics of an Extended Aeration Activated Sludge Process With a Constant X_R of 10,000 mg/l at an S_i of 500 mg/l and a Hydraulic Detention Time of 16 Hours

Second part from 10/17/78 to 12/14/78.


FEED, MG/L
1000
0
INFLUENT CHARACTERISTIC
V_{R2}, ML
2000
0
VOLUME OF SLUDGE IN REACTOR 2
VOLUME OF RETURN SLUDGE REQUIRED
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
$\bar{X}$, MG/L
2000
0
REACTOR SUSPENDED SOLIDS
X_R, MG/L
10000
0
RECYCLE SLUDGE
15 19 25 27 31 2 6 10 14 18 22 26 30 2 6 10 14
10/17/78
12/14/78

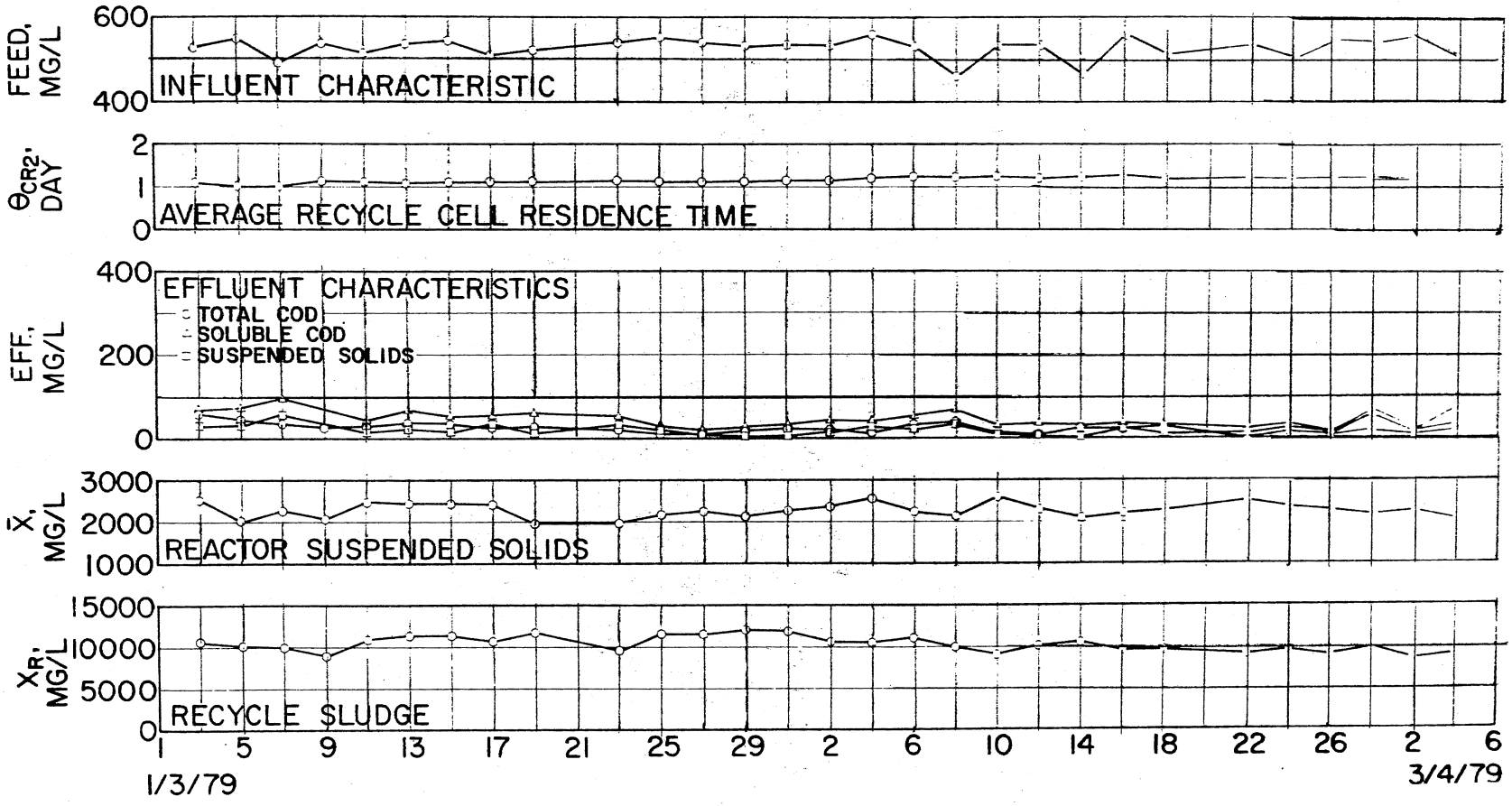
17-2

pilot plant, glucose became the sole carbon and energy source. In the initial phase of operation it was difficult to get the underflow concentration to 10,000 mg/l, but after the sludge aged, the underflow concentration improved steadily and it was always possible to get underflow sludge concentrations well above 10,000 mg/l. The statistical analysis of the data is presented in Table II. This shows that for the period covered in Figure 16, the average X_R was 9312 mg/l, with an $\bar{X}$ value of 2106 mg/l. The effluent quality for an average influent COD concentration of 526 mg/l was as follows: S_e = 41 mg/l; X_e = 28 mg/l, and total effluent COD, S_t, = 49 mg/l. However, during the latter two months of the study (Figure 17), the recycle biological solids concentration was 10,065 mg/l; $\bar{X}$ was 2173 mg/l, and the average S_e and X_e were somewhat lower--22 mg/l and 23 mg/l--than in the earlier part of the operational period. For the entire four-month period, the average excess sludge that remained in reactor 2 over and above the recycle requirements was 23 percent of the recycle biological solids needed. The solid line of the plot, time vs. volume of reactor 3, was the volume required for the recycle. The difference between the actual volume present and the volume of sludge needed for recycle at the X_R concentration on the particular day was recorded.

A plot of the steady state performance when the hydraulic detentiontime was 12 hours is presented in Figure 18. Except for the difference in the hydraulic detention time, operation of the unit was maintained the same as during the previous experiment. During the 61st day of operation, the sludge compacted to well above 10,000 mg/l. The average reactor biological solids, $\bar{X}$, was 2261 mg/l; the average X_R was 10,283 mg/l, and the average influent substrate concentration was 529

Figure 18. Operational Characteristics of an Extended Aeration Activated Sludge Process With a Constant X_R of 10,000 mg/l at an S_i of 500 mg/l and at a Hydraulic Detention Time of 12 Hours

From 1/3/79 to 3/4/79.


FEED, MG/L
600
400
INFLUENT CHARACTERISTIC
θ_{CR2}, DAY
2
1
0
AVERAGE RECYCLE CELL RESIDENCE TIME
EFF., MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
$\bar{X}$, MG/L
3000
2000
1000
REACTOR SUSPENDED SOLIDS
X_R, MG/L
15000
10000
5000
0
RECYCLE SLUDGE
1 5 9 13 17 21 25 29 2 6 10 14 18 22 26 2 6
1/3/79
3/4/79

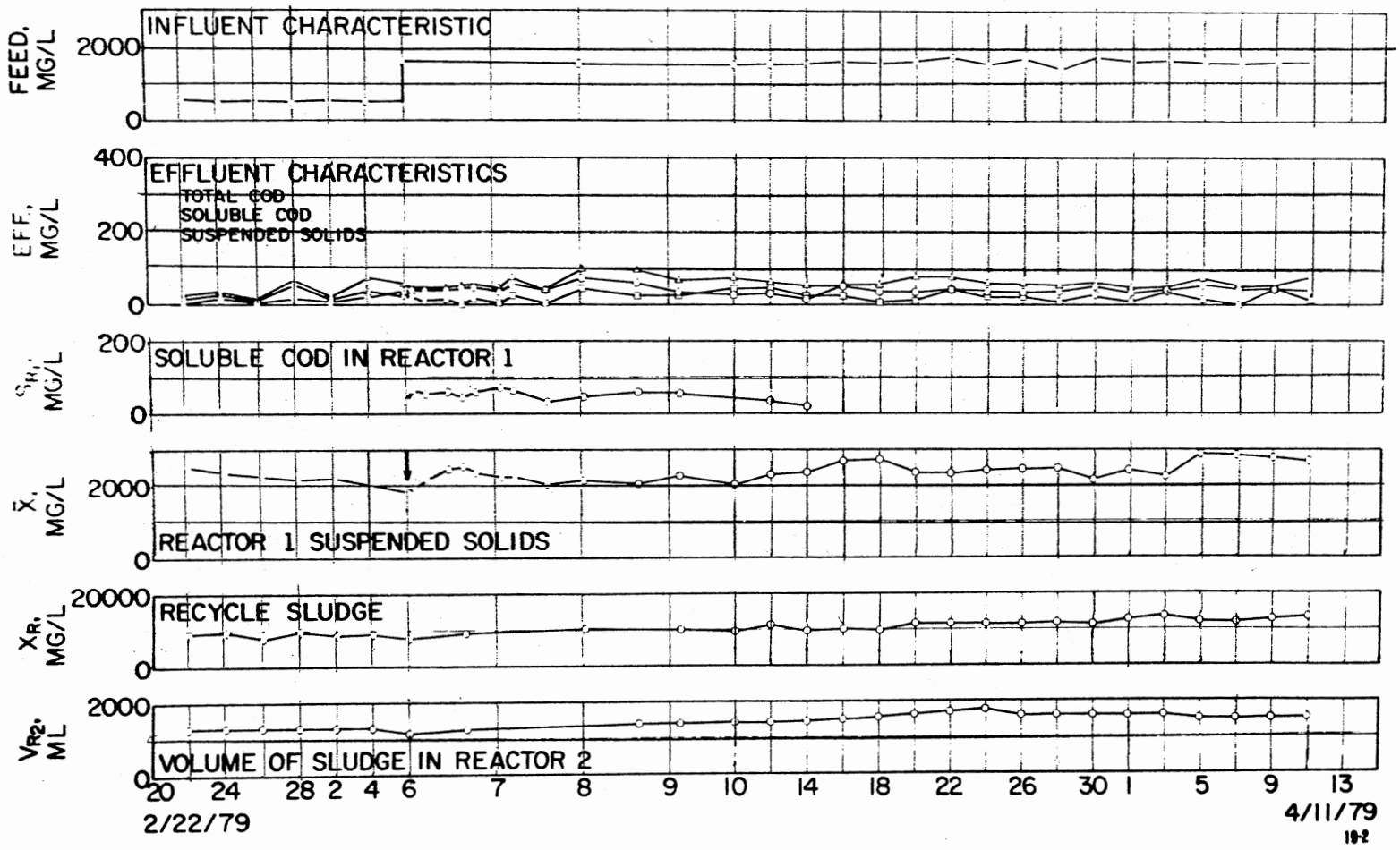
mg/l COD. The effluent soluble substrate, S_e, was 23 mg/l, with suspended solids leakage of 21 mg/l and an overall total COD leakage of 44 mg/l.

In Figure 18, the volume of the recycle solids present in reactor 2 is shown as a ratio of the total volume present to the recycle volume required, and is plotted as the reactor 2 cell residence time. The mean value for this ratio during the period of operation was 1.17; i.e., 17 percent of the recycle requirement was inventoried in reactor 2 as excess sludge during the period of operation. The system was in steady state, X_R was being controlled, and the excess sludge storage capacity, equivalent to that which would be channelled to an aerobic digester, was only 4.25 percent of the capacity of reactor 1 (0.25 x 0.17 = 4.25 percent).

In order to study the stability of this total oxidation process at constant X_R concentration, the pilot plant was subjected to a 3-fold quantitative increase in the influent substrate concentration from 500 to 1500 mg/l glucose (Figure 19). The hydraulic detention time was maintained at 12 hours; α was 0.25. The mixed liquor suspended solids concentration in reactor 1 increased from 1812 mg/l to 2504 mg/l in 15½ hours, and then it receded to approximately 2000 mg/l. The effluent suspended solids leakage was small; the maximum value (46 mg/l) was recorded two days after administering the shock. The COD in the mixed liquor filtrate, S_R, fluctuated between 32 and 72 mg/l after the shock. Fluctuations in reactor 1 COD were generally experienced in the clarifier soluble substrate COD values as well, but they were attenuated. The total effluent substrate, S_t, remained generally steady except for two values between days 8 and 9 when high concentrations close to 100

Figure 19. Operational Characteristics of an Extended Aeration Activated Sludge Process With a Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Subjected to a 3-fold Quantitative Increase in Feed S_i to 1500 mg/l and at a Hydraulic Detention Time of 12 Hours

From 2/22/79 to 4/11/79 - shock loaded on 2/6/79.


FEED, MG/L
2000
0
INFLUENT CHARACTERISTIC
EFF., MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
S_{R_1}, MG/L
200
0
SOLUBLE COD IN REACTOR 1
$\bar{X}$, MG/L
2000
0
REACTOR 1 SUSPENDED SOLIDS
X_R, MG/L
20000
0
RECYCLE SLUDGE
V_{R_2}, ML
2000
0
VOLUME OF SLUDGE IN REACTOR 2
20 24 28 2 4 6 7 8 9 10 14 18 22 26 30 1 5 9 13
2/22/79
4/11/79
19-2

mg/l were recorded. Interestingly, the S_t value of 100 mg/l at 48.50 hours after the shock coincides with the time of withdrawal of underflow sludge from the clarifier for recycle and, to some extent, this engineering procedure rather than ecological response accounts for suspended solids disturbance in the clarifier effluent. In general, the results indicate that the overall effect of the quantitative shock load on the performance of the system was negligible.

From March 20 onward, the recycle biological solids concentration was not controlled; all sludge was recycled. It can be seen that this caused a gradual increase in the concentration of cells in the recycle reactor to approximately 12,000 mg/l. The maximum concentration recorded was 13,580 mg/l. Also, the volume of the recycle sludge increased slightly. This change in the operation was put in effect to determine if the operator could minimize the volume requirements in the recycle reactor as well as utilize the maximum concentration of biological solids attainable for recycling. The data show the volume stabilized at approximately 1.5 liters, and the concentration of recycle sludge stabilized at approximately 13,000 mg/l.

Analytical determinations for NH_4-N and NO_3-N concentrations were made for samples taken from reactor 1 and from the clarifier effluent. During the transient, the reactor NH_4-N concentration remained relatively steady (between 72.5 mg/l to 82.7 mg/l) during the first day. But this value increased gradually to 197.5 mg/l, exceeding the concentration of NH_4-N (159 mg/l) in the feed, i.e., more than 100 percent leakage during the second and third days. A similar trend was generally observed in the NH_4-N concentration values in the clarifier effluent; however, after the sixth day, the NH_4-N concentration values

showed that at least one-third of the incoming NH_4-N was being utilized by the cells. However, the nitrates in the clarifier and in the reactor did not change appreciably. The maximum NO_3-N concentration recorded in reactor 1 was 12 mg/l, and the minimum was 6 mg/l. Generally, the clarifier NO_3-N was a few mg/l less than that in reactor 1. The overall effect of the 3-fold quantitative shock load on carbonaceous removals was negligible. It was decided to further test the shock load response of the system. A rather severe mode of administering the shock was employed, i.e., a cyclical or rhythmical shift in feed concentration (500 mg/l to 1500 mg/l to 500 mg/l) each 12 hours. The response data are shown in Figure 20. This 3-fold cyclic quantitative shock load was maintained for seven days (4/12/79 to 4/19/79). This was followed by a step increase of 3000 mg/l from 500 mg/l. Then the severity of the shock was further enhanced to a 10-fold cyclic quantitative increase in substrate from 500 mg/l to 5000 mg/l each 12 hours from 4/21/79 to 4/28/79. Throughout the experiment, α was maintained at 0.25.

The initial 3-fold cyclic increase did not cause any perturbance in the effluent quality. The effluent suspended solids, soluble COD as well as the total COD values were not affected. These results contrast to those of Saleh (17), who employed an X_R value of 10,000 mg/l.

The average data for each cycle is shown in Table IV. There was not much variation in the average values during each loading: $\bar{X}$ and S_t remained close to each other. There were no noticeable differences in the reactor filtrate COD values. The clarifier suspended solids leaked steadily with the averages of 25 mg/l and 28 mg/l in each phase of the cycle. However, most of the numbers remained close to or below the

Figure 20. Operational Characteristics of an Extended Aeration Activated Sludge Process With an S_i of 1500 mg/l Subjected to Cyclic Quantitative Shock Loads of

1500 mg/l - 500 mg/l - 4-12/79 to 4/19/79
500 mg/l-3000 mg/l - 4/19/79 to 4/20/79
500 mg/l-5000 mg/l - 4/21/79 to 4/28/79

Each concentration was applied for a 12-hour period; t was kept at 12 hours and X_R concentration was not maintained constant.

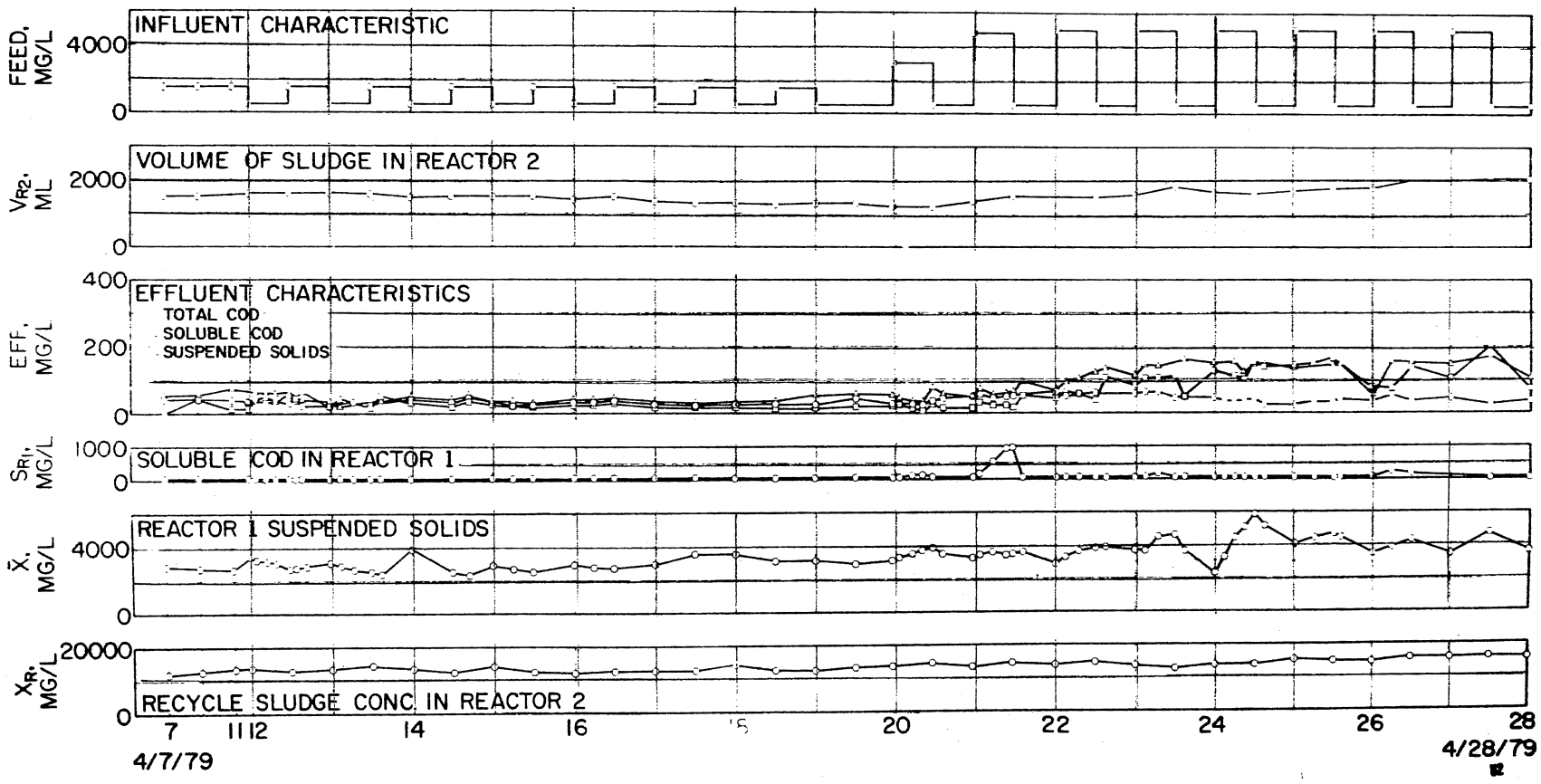

FEED, MG/L
4000
0
INFLUENT CHARACTERISTIC
V_{R2}, ML
2000
0
VOLUME OF SLUDGE IN REACTOR 2
EFF, MG/L
400
200
0
EFFLUENT CHARACTERISTICS
TOTAL COD
SOLUBLE COD
SUSPENDED SOLIDS
S_{R1}, MG/L
1000
0
SOLUBLE COD IN REACTOR 1
$\bar{X}$, MG/L
4000
0
REACTOR 1 SUSPENDED SOLIDS
X_R, MG/L
20000
0
RECYCLE SLUDGE CONC. IN REACTOR 2
7
11
12
14
16
18
20
22
24
26
28
4/7/79
4/28/79

TABLE IV

AVERAGE CYCLIC QUANTITATIVE SHOCK LOAD DATA OF AN EXTENDED AERATION ACTIVATED SLUDGE PROCESS WITH A S_i OF 1500 mg/l SUBJECTED TO A 3-FOLD CYCLIC QUANTITATIVE SHOCK LOAD OF 1500 mg/l TO 500 mg/l FOR A WEEK AND INCREASED TO 10-FOLD CYCLIC QUANTITATIVE SHOCK LOADS OF 500 mg/l TO 500 mg/l

Time 1979	S_i	$\bar{X}$ (mg/l)	X_e (mg/l)	X_R (mg/l)	V_{X_R} (ml)	S_i (mg/l)	S_t (mg/l)	S_e (mg/l)	S_R (mg/l)
4/12	500	3029	25	13,014	1437	518	42	31	34
to									
4/19	1500	2926	28	12,959	1433	1540	40	31	31
4/21	5000	3927	95	14,444	1767	5000	123	45	159
to									
4/29	500	4026	110	14,524	1796	500	138	42	57

average values for X_e. Only the reactor mixed liquor suspended solids fluctuated due to the cyclical shock, but the amplitude was very small. The average $\bar{X}$ values were 3029 mg/l and 2926 mg/l, and most of the values remained close to 3000 mg/l. The concentration of X_R in the recycle remained in a range of 12,160 mg/l to 14,180 mg/l; the average value was 13,014 mg/l during the 500 mg/l feed cycle period, and averaged 12,959 mg/l when the feed was 1500 mg/l. In general, the results show an overall steadiness of the system; it was not affected adversely by the cyclic application of the feed.

At the end of this shock load, the feed was maintained at 500 mg/l for 24 hours, then a one-time step increase to 3000 mg/l was made for the next cycle. During this step increase, the reactor filtrate COD increased from 42 mg/l to 128 mg/l during the first nine hours and then decreased to 96 mg/l at the end of the 12-hour load phase; i.e., the time at which the next cycle of 500 mg/l feed began. During the same period, the effluent soluble COD remained steady and the range of COD values was 23 to 32 mg/l; the X_e values remained very low. Overall, the one-step increase did not show much effect on the effluent quality. The only effect noticed was on the reactor 1 suspended solids, which increased from 3132 mg/l to 3824 mg/l at the end of 12 hours but decreased to 3220 mg/l after 12 hours feeding at 500 mg/l. The NH_4-N concentration in reactor 1 which had varied from 24 to 93 mg/l in the previous shock loading when the cyclic quantitative shock load was 3-fold, increased gradually to a maximum of 237 mg/l at the end of the 3000 mg/l cycle and gradually reduced to 66 mg/l at the end of the following 500 mg/l cycle. The protein content remained steady at around 50 percent, but the carbohydrate content of the sludge increased

substantially to 40 percent compared to 24 to 27 percent noted during the 3-fold cyclic shock load.

After this step increase to 3000 mg/l, the feed cycle was changed to 10-fold cyclic quantitative shock load; the feed concentrations were cycled from 500 mg/l to 5000 mg/l. The effect of this increase was most apparent on the mixed liquor filtrate COD. During the first cyclic increase to 5000 mg/l, the reactor filtrate COD increased from 46 mg/l to 933 mg/l, but this high COD was reduced as soon as the feed was switched to 500 mg/l. Within three hours after switching the feed to 500 mg/l, the reactor mixed liquor filtrate dropped to 23 mg/l and remained low thereafter. The mixed liquor suspended solids did not show the dramatic increase exhibited during the 6-fold step increase, but did increase slightly from 3220 mg/l to 3604 mg/l within four hours and thereafter fluctuated somewhat. The generally increased feed concentration influenced the overall recycle biological solids concentration; it increased from 12,000 to 13,000 mg/l to approximately 15,000 mg/l. The volume of the recycle sludge in reactor 2 gradually increased to 2125 mg/l by the end of the experiment. During the same period, the mixed liquor suspended solids fluctuated considerably, and the soluble COD in the clarifier increased slightly but came into a new pseudo steady state. During the same period, the average reactor mixed liquor COD, S_e, was 159 mg/l during the 5000 mg/l phase of the cycle, and 57 mg/l during the 500 mg/l loading. The comparable S_e values were 45 mg/l and 42 mg/l, respectively. Thus, the clarifier served as both a diluting basin and a biological reactor to reduce soluble COD. The effluent suspended solids leakage varied widely--from 14 mg/l initially to a high of 172 mg/l. But the average during

each cycle was 95 mg/l during the 5000 mg/l phase, and 110 during the 500 mg/l phase. There was less variation in total COD leakage than in the suspended solids concentrations. Generally, S_t remained close to the 140 mg/l level. The fluctuations in the effluent characteristics do not follow definable cyclic trends, unlike that of the mixed liquor suspended solids. The NH_4-N concentration in the reactor exhibited cyclic variation in its input to the clarifier. During the S_i = 500 to 1500 mg/l cyclic shock period (4/12/79 to 4/19/79), the NH_4-N concentrations in the clarifier remained between 40 to 61 mg/l. But the reactor 1 NH_4-N concentrations which were close to the clarifier levels until 4/15, increased to 95 mg/l and thereafter showed fluctuations between a minimum of 24 mg/l to above 90 mg/l. When the S_i concentration was increased to 3000 mg/l, NH_4-N concentrations in reactor 1 gradually increased to 237 mg/l and gradually decreased to 66 mg/l after the S_i concentration was reduced to 500 mg/l. A similar increase in reactor 1 NH_4-N concentration was observed during the 5000 mg/l to 500 mg/l cycle. When S_i concentration was increased to 5000 mg/l, the NH_4-N concentration in reactor 1 increased to 352 mg/l during the first cycle. This peak concentration was not attained during subsequent cycles. The maximum NH_4-N concentrations attained were always below 200 mg/l. However, there was no significant change in NO_3-N concentrations in the clarifier during both 1500 to 500 mg/l cycle and 5000 to 500 mg/l cycle. The NO_3-N concentrations generally were observed between 10 and 16 mg/l.

Comparison of these two successive shock loads shows that during the 3-fold quantitative cyclic shock load the average $\bar{X}$ concentrations remained around 3000 mg/l, and the average amount increased by close to

1000 mg/l during the 10-fold cyclic quantitative shock load. The difference in soluble COD in the effluent was only about 10 to 15 mg/l from approximately 31 mg/l to 45 mg/l. The recycle suspended solids concentration also increased on average from close to 13,000 mg/l level to about 14,500 mg/l, and the volume of recycle solids increased by more than 300 ml. The only disturbing trend was an increase in effluent suspended solids leakage, which was only 25 to 28 mg/l during the 3-fold shock but rose to 95 to 110 mg/l during the 10-fold cyclic shock period. This increase was the major contribution to the total COD leakage through the clarifier.

CHAPTER V

DISCUSSION

In Figures 3 to 10 were shown results of various experiments performed to study the feasibility of utilizing reactor 3 biological solids (i.e., aerobic digester solids) as a possible source of recycle cells to be introduced into the aeration tank when the need arose to increase MLSS rapidly, e.g., during periods of quantitative shock loads. In order to prove that these biological solids were capable of offsetting any adverse effects that could be imposed on the activated sludge process during different shock loads, it was necessary to show that these cells, upon introduction into reactor 1, through recycle, would not of themselves cause deterioration in the stability of the process. Admittedly, the mode of use of such sludge in this phase put the idea to a severe test. However, this was purposely designed to be so, and the results indicate that successful response of the sludge to the new environment (i.e., from a harsh autodigestive one to a growth situation) is not automatically assured in terms of effluent quality. Reactor 3 was simply a batch operated reactor which received excess sludge from the clarifier. It was difficult to predict the nature of the response these biological solids would provide in the new environment in reactor 1 in view of the fact that the environment in reactor 3 changed often due to internal biological (ecological) factors. When reactor 3 cells were introduced into recycle (Figure 3), there was no

appreciable change in the effluent quality--only an initial reduction in the reactor biological solids and an unusually high incidence of rising sludge was noticed. However, approximately one month earlier, introduction of reactor 2 cells into the recycle (not shown by figure in this thesis) was accompanied by excessive amounts of effluent suspended solids leakage. In both cases, the sludge removed soluble substrate (COD) from solution rather well. The only readily discernible difference in the sludge was the total volatile suspended solids content. The recycle cells in the experiment in Figure 3 were about 60 percent volatile, whereas the two values obtained earlier were 30.8 and 43 percent. The low volatile solids during the first experiment was reflected in the volatile solids content of reactor 1 solids which were below 50 percent. In contrast, during the experiment shown in Figure 3, the VSS in reactor 1 was always higher than 50 percent. Thus, the degree of autodigestion (if at all validly measured by VSS) could play a role in the matter of sludge compatibility.

Figures 4, 6, and 7 show results for experiments aimed at studying effects of degree of digestion on the effluent quality and the stability of the system. When the sludge in reactor 3 (Figure 4) was not fed with any fresh sludge five days before the shock load, the effluent suspended solids leakage was very high at 158 mg/l with high turbidity in the clarifier, and this effect receded only very slowly; whereas in Figures 6 and 7, the application of recycle solids was for only 12 and 14 hours. This was, of course, after allowing the cells to be starved of any fresh sludge for 30 and 35 days, respectively. In both cases, the recycle supernatant contained substantially higher amounts of soluble COD--in excess of 500 mg/l. The

recycle supernatant also contained quite large concentrations of NH_4-N and NO_3-N. The increase in the NH_4-N, NO_3-N, and COD concentrations were due mainly to the high amount of digestion the cells had undergone during the long detention times in reactor 3. It is important to note here that the digester cells undergo an accelerated phase of autodigestion periodically, during which time large amounts of cells lyse, leading to heavy foaming and a resultant increase in the concentrations of nutrients into the supernatant. These accelerated digestion phases were not limited to reactor 3 cells which were held without addition of new excess sludge. Even the addition of excess sludge regularly did not prevent the occurrence of periods of accelerated digestion and cell lysis, resulting in lower percentages of volatile organic solids; that is, "well digested" sludge would not appear to be an ideal characteristic. The O_2 uptake activity of such sludge was very low--around 2 to 3 mg/l/hr. Although the sludge was low in activity, the removal of substrate from solution was accomplished in all of these cases rather effectively without transient disturbance. The only problem was sludge rising in the clarifier and leakage of effluent suspended solids over the weir of the clarifier. Another cause for concern is that after the transient disruption had subsided, there was a persistence of high suspended solids concentrations due to predominance changes favoring filamentous forms and loss of protozoa. These fluctuations in the population not only caused the leakage of suspended solids, but soluble substrate also leaked through the effluent in larger quantities, i.e., S_e (as COD) was somewhat higher in the new steady state.

In order to reduce the adverse impact of reactor 3 cells, the

sludge in reactor 3 was treated with different amounts of cell hydrolysate at different dosing periods. Figure 8 was one such experiment used to study whether any improvement could be obtained if the reactor 3 biological solids were treated occasionally with 1000 mg/l COD of hydrolysate. In this case, the cells were so treated for a period of five days, and after a gap of nearly two weeks with no feed they were fed with 250 mg/l of hydrolysate three days before the sludge was used for recycle. The hydrolysate increased the endogenous oxygen uptake of the cells, and this activity dropped to the original levels slowly after the curtailment of the addition of hydrolysate. The transition in sludge caused only minor disturbance in suspended solids in the clarifier effluent. Similar results were obtained when the hydrolysate was regularly fed at slug doses of 1000 mg/l (Figure 9) and with a regular daily feeding of 100 mg/l COD (Figure 10). In all cases, the addition of hydrolysate did not guarantee good effluent quality. However, the response was better in cases wherein higher concentrations of hydrolysate (1000 mg/l) were added. The recycle in all cases contained high concentrations of soluble COD released from cells and also contained substantial concentrations of NH_4-N and NO_3-N. In all cases, the cells removed soluble COD from solution without significant disturbance. The addition of hydrolysate did not prevent the cells from undergoing periodic accelerated autodigestion and accompanying foaming. While a comprehensive study in this aspect of sludge preparation was not intended in this study, continuing work along these lines may provide feasible procedures for maintaining high sludge digestion rate and high biochemical ecological compatibility with the activated sludge.

An interesting aspect in this phase was that the activated sludge

pilot plant did not exhibit any transient disturbance when the recycle sludge introduced was not obtained from the aerobic digester (reactor 3). The sludge in this experiment (shown in Figure 5) was taken from the bottom of the secondary clarifier of the activated sludge wastewater treatment plant in Ponca City, Oklahoma. This experiment provides an indication that biological solids from a different source (undigested) may be useful on occasions if the external sludge populations are compatible with cells in a particular treatment plant. However, much experimentation is needed to determine cell or ecological compatibility before any external souce of cells could be used.

The first phase experiments generally show that reactor 3 biological solids may not be used indiscriminately as a ready source of cells during shock loads, as these cells themselves can cause an appreciable transient deterioration in effluent quality and predicting their performance in this regard is a problem. Simply providing periodic "spiking" with cell hydrolysate does not appear to be a procedure which provides for an unstressed transition of the system. However, more research on this possible mode of control seems warranted. One possible enhanced operational mode is the semi-regular feeding of the aerobic digester, as commonly practiced in the field.

In the second phase, reactor 3 was operated as a semi-continuously fed reactor, and this mode of operation helped control and stabilize the sludge population. Heavy foaming of the sludge indicative of surges of autodigestion was reduced; the supernatant did not contain large amounts of carbon sources and NH_4-N and NO_3-N. The use of reactor 3 cells regularly for recycle provided effluent clarity without any large disturbances in the effluent quality. However, during the

operation of this phase, reactor 3 sludge concentration was kept the same as the recycle solids concentration (i.e., at 8000 mg/l). This is a rather low concentration for an aerobic digester. The amount of sludge was about three liters, but this volume remained fairly steady during this phase of the study, i.e., excess sludge did not build up in the system.

This mode of operation was fairly successful with feed of 500 mg/l glucose as carbon and energy source, X_R = 8000 mg/l, and α = 0.25, and it was tested as to the stability of effluent quality by increasing the influent substrate concentration 3-fold to 1500 mg/l glucose. This increase brought about a rapid rise in the reactor mixed liquor biological solids and the excess sludge rapidly increased the volume of reactor 3 sludge to 10.6 liters, the concentration of which was still maintained at 8000 mg/l. During this time, the effluent quality deteriorated to unreasonable levels, due mainly to dispersed growth and subsequent heavy leakages of effluent suspended solids even though the effluent soluble COD levels were unreasonably low. Effluent solids concentrations gradually returned to the original level after the influent substrate concentration was returned to 500 mg/l. The activated sludge pilot plant was kept in this state for some time until pseudo steady state was achieved. It is significant to note that while the system attained a steady state with respect to $\bar{X}$ and the effluent parameters, the large volume which had built up in reactor 3 during the shock load decreased gradually from 10.6 liters to 6.6 liters in about 32 days. The second 3-fold quantitative increase in the influent substrate concentration was accompanied by addition of 100 mg/l of coagulant, calcium oxide. But the effluent quality deteriorated rapidly to a maximum

solids leakage level above 300 mg/l. Since it was felt that the addition of CaO did not improve the conditions of the effluent solids leakage, its addition was stopped. This decision led to a further deterioration in the effluent solids leakage to X_e values greater than 800 mg/l. When a decision was made to let the recycle solids concentration increase in reactor 3, X_R soon reached 14,000 mg/l, and there was a gradual decrease in the effluent solids leakage coupled with a reduction in the amount of turbidity in the effluent. A summary of the above sequence of results described in phase 3 is provided in Table V. It seems apparent from these results that the lower unit feeding level (F/M) helps stabilize the system. To further investigate this aspect, it was decided to allow the maximum concentration that prevailed in reactor 3 to be used as the recycle biological solids concentration. Reactor 3 was allowed to settle by gravity for four hours. The concentration after decanting the supernatant was 18,700 mg/l. When this amount was recycled (with the feed remaining at 1500 mg/l glucose) the effluent quality was comparable or better (Figure 14) than the effluent quality shown in Figure 11, when the S_i was 500 mg/l and X_R was maintained steady at 8000 mg/l. Since it was impossible to remove cells from the bottom of the clarifier without also drawing some supernatant, it is apparent that the cells settled to a concentration somewhat higher than the recycle concentration. The concentration of biological solids in reactor 3 and thereby in the recycle remained reasonably constant and an overall net increase in the cells in the total system was not apparent. Also, it was observed that between 40 to 60 percent of the feed NH_4-N concentration leaked into the effluent and that the degree of nitrification was low. The total VSS concentration in reactor 1 and in

TABLE V

TABLE SHOWING INFLUENCE OF UNIT FEEDING RATIO, F/M, ON EFFLUENT QUALITY IN ACTIVATED SLUDGE

No.	F/M Ratio	Glucose Feed Conc. S_i (mg/l)	Effluent Soluble COD, S_e (mg/l)	Effluent Suspended Solids, X_e (mg/l)	Effluent Total COD S_e (mg/l)	Remarks
1	0.33	500	35	31	61	Steady state operation from 9/20/78. Recycle sludge regularly made up from reactor 3. X_R maintained at 8000 mg/l
2	0.31	500	31	28	67	Steady state operation same as above; X_R = 8000 mg/l from 12/14/78 to 12/20/78
3	0.69	1500	43	181	265	Steady state data after activated sludge pilot plant was shock loaded with 3-fold increase in feed from 500 mg/l to 1500 mg/l; X_R = 8000 mg/l from 12/24/78 to 1/18/79
4	0.31	500	27	32	62	Steady state data after feed concentration was reduced from 1500 mg/l to 500 mg/l, but maintaining X_R concentration at 8000 mg/l from 12/27/78 to 2/15/79
5	0.66	1500	46	678	731	Average values after activated sludge pilot plant was again shock loaded with a 3-fold increase in feed from 500 mg/l to 1500 mg/l; X_R = 8000 mg/l from 3/3/79 to 3/14/79
6	0.32	1500	31	21	48	Average values after keeping feed concentration same (1500 mg/l). Recycle sludge concentration X_R was allowed to go up freely. From 4/5/79 to 4/30/79; average X_R = 18,759 mg/l

reactor 3, 74.30 and 77.29 percent, respectively, was rather high. The batch growth studies performed show that μ_{max} and K_s and Y_{t_B} are also comparable when the seed was taken from these two reactors. When the seed was taken from reactor 1, $\mu_{max} = 0.3729\ hr^{-1}$, $K_s = 939$ mg/l, and $Y_{t_B} = 0.632$; for reactor 3, seed $\mu_{max} = 0.3636\ hr^{-1}$, $K_s = 818$ mg/l, and $Y_{t_B} = 0.632$. The lag periods in these two experiments were also reasonably close (between five to eight hours for both reactor 1 and reactor 3 cells) compared to the whole data where the lag period on an average for all data for both reactors was 8 to 10 hours and 12 to 13.5 hours, the larger figure being that for reactor 3. The endogenous O_2 uptake was markedly different at 7 mg/g/hr for reactor 1, and 1.0 mg/g/hr for reactor 3. This change in the operation (i.e., essentially extended aeration but with external recycle) allowed the operator to utilize the available cells to the maximum advantage, i.e., to slow down the specific growth rate. Higher concentrations of recycle biological solids seemed to provide for less dispersed growth as well as the least amount of excess sludge being produced. The reactor 3 filtrate COD was very low compared to the feed substrate concentration. The results indicate that the low COD of reactor 3 filtrate was obtained during all experiments conducted with semi-continuous operation of reactor 3 as part of the flow sheet of the process, i.e., as the source of X_R. The activated sludge process as operated at present in the field may not be suited for treatment of high influent substrate concentration, but a change in operation with the use of reactor 3 (aerobically digesting sludge) as a source of high X_R levels may enhance the capability of the system. The larger mass of cells tends to deter rapid changes in the predominating species and may keep the kinetic

constants reasonably stable. Also, the availability of higher amounts of (non-filamentous) sludge would reduce the possibility of filaments occurring in the system. A relatively important objective may be the maintenance of stable but lower sludge growth rates in reactor 2 under transient influent substrate feeding levels (F/M ratio). This objective may be accomplished by varying the X_R concentrations to keep the unit feeding ratio (F/M) at desired levels. This is illustrated in Figure 21, which shows that the net specific growth rate, μ_n, is proportional to the unit feeding ratio, F/M. μ_n can be reasonably controlled by controlling the F/M ratio. Thus, provision of a ready source of excess sludge affords the operator control of net specific growth rate, μ_n, by altering the recycle sludge concentration, X_R, to an optimum level. This aspect was also supported by Cashion et al. (35) in their studies. According to the authors, meaningful F/M control can be achieved only when provision is made for the external storage of biological solids, and without provision for external storage of biological solids, the benefits accrued would be negligible. The apparent influence of recycle sludge concentration, X_R, over net specific growth rate is demonstrated in Figure 22, which shows that at constant influent substrate loading level (500 mg/l glucose) increasing the recycle sludge concentration, X_R would reduce the net specific growth rate. Thus, provision of a separate reactor in the system for the storage of excess sludge will give the operator greater control over the activated sludge process. The operator can control the net specific growth rate, thereby effluent quality, in the system at all times by providing an optimum concentration recycle sludge, X_R, to control the F/M ratio which in turn exerts a dampening influence on changes in net specific

Figure 21. Plot Showing the Influence of Unit Feeding Ratio (F/M) on net Specific Growth Rate Using Glucose as Carbon and Energy Source, at a Constant Recycle Flow Ratio $\alpha = 0.25$

Data points were obtained from the PhD theses of Srinivasaraghavan, Saleh, Manickam, and the author.

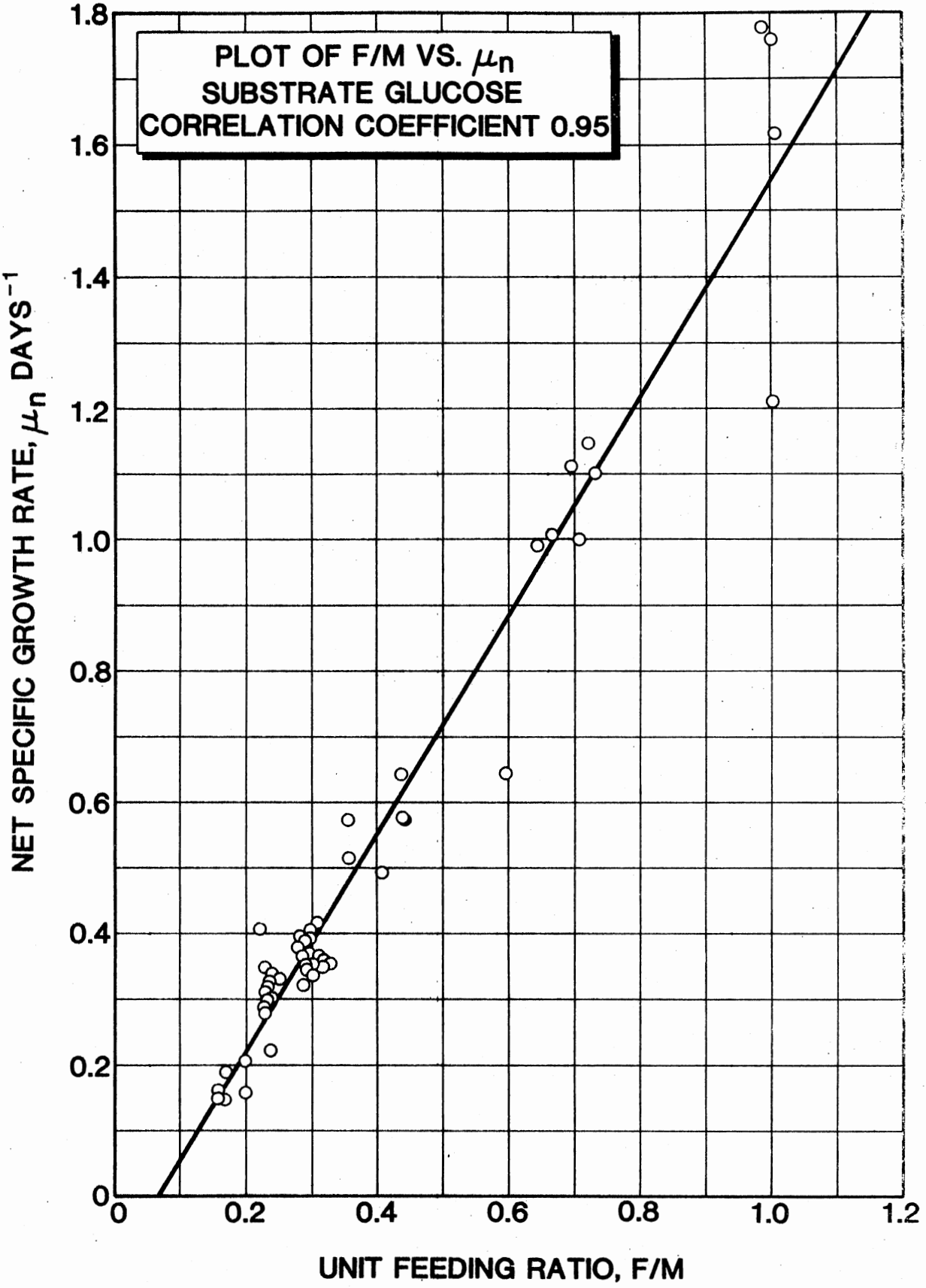
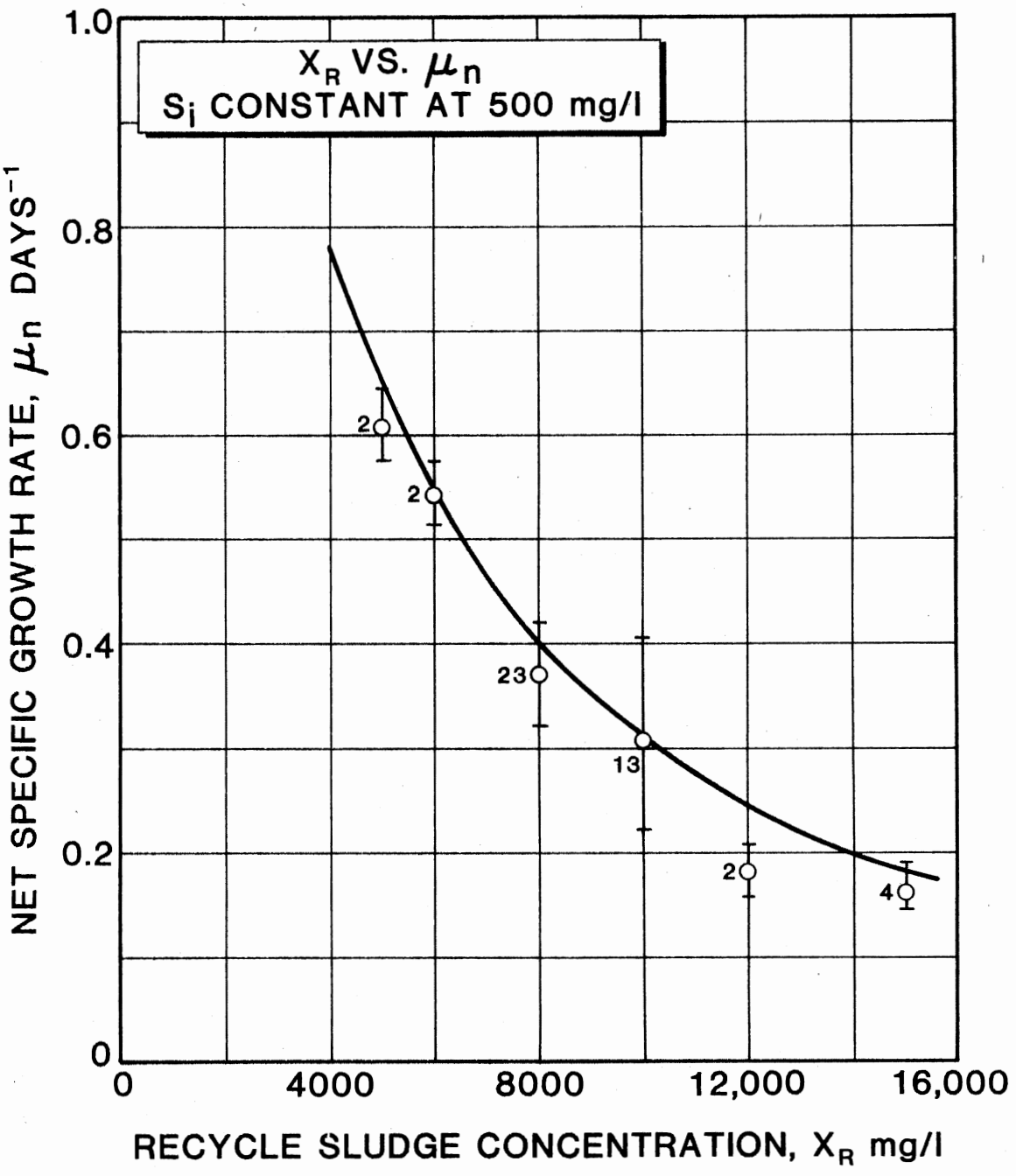

PLOT OF F/M VS. μ_n
SUBSTRATE GLUCOSE
CORRELATION COEFFICIENT 0.95
NET SPECIFIC GROWTH RATE, μ_n DAYS^{-1}
UNIT FEEDING RATIO, F/M
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

Figure 22. Data Showing the Influence of X_R on net Specific Growth Rate at a Constant Value of S_i at 500 mg/l and α = 0.25

Data points obtained from the PhD theses of Srinivasaraghavan, Saleh, Manickam, and the author.


X_R VS. μ_n
S_i CONSTANT AT 500 mg/l
NET SPECIFIC GROWTH RATE, μ_n DAYS^{-1}
1.0
0.8
0.6
0.4
0.2
0
0
4000
8000
12,000
16,000
RECYCLE SLUDGE CONCENTRATION, X_R mg/l
2
2
23
13
2
4

growth rate, μ_n.

Even though the overall sludge retention time was close to total oxidation, the individual sludge retention times in reactors 1 and 3 could also be adjusted by changing X_R to suit like changes in feed flow conditions. This type of operation may also be useful to study the effect of overall sludge retention time in the system on the hydraulic detention time need in reactor 1. A careful study in this area may yield economical dividends by reducing the capital costs of the treatment plants without sacrificing the treatment efficiency. One might be able by dealing with lower volumes of more concentrated sludge to take advantage of aerobic digestion and some of the advantages claimed for contact stabilization process.

This aspect was studied briefly in phase 5 of the thesis in which the activated sludge unit was operated first as a total oxidation system with constant X_R at 10,000 mg/l, S_i = 500 mg/l, with the hydraulic detention time at 16 hours and 12 hours instead of the 24 hours generally employed. The excess sludge was kept in reactor 2 at a constant 10,000 mg/l concentration. This operation yeilded good results in terms of effluent quality and relatively steady state conditions in terms of the reactor 2 volume. Initially, the results showed that on average, 23 percent of the recycle sludge remained as excess sludge in reactor 2 when the hydraulic detention time was 16 hours; i.e., a 33 percent reduction in hydraulic detention time increased the reactor 2 volume by 23 percent. In terms of reactor 1 volume, this amounted to an increased aeration volume of 5.75 percent (23 x 0.25); that is, by providing 5.75 percent of reactor 1 volume elsewhere to keep the excess sludge, a 33 percent reduction in the hydraulic detention volume could

be achieved. Similarly, when the hydraulic detention time in reactor 1 was 12 hours, the excess sludge retained in reactor 2 above the X_R = 10,000 mg/l requirement was 17 percent of recycle volume.

An interesting result to be noted in this discussion was that the cells from reactor 1 and reactor 3 showed different lag periods in batch growth studies. These lag periods in the individual flasks are tabulated for each experiment in Table VI. Considering all initial substrate concentration levels, the lag periods for reactor 1 seed was between 8.7 hours and 10.20 hours, whereas the lag time for reactor 3 seed varied from 11.1 hours to 13.5 hours. The fact that there is a longer lag for reactor 3 cells compared to reactor 1 cells gives some indication that the recycle cells may need a longer period of adjustment upon entry to reactor 1 than cells recycled in the usual manner. Whether some alteration in predictive model construction would be needed because of the lag times or because of differences in lag time for cells in different parts of the system is not determinable at present, but the results do indicate some future consideration of this aspect may be in order.

Table VII provides the summary biokinetic constants determined from the batch growth data. The maximum specific growth rate, μ_{max}, the saturation constant, K_s, and the batch yield are tabulated. These data show that on the average, the K_s value was somewhat higher for reactor 3 cells and the μ_{max} and Y_{t_B} values were lower compared to reactor 1 values. Whether these differences in the biokinetic constants can be related to lag times in, say, predictive or mechanistic ways is not clear and more data on the effects that aging may have on relative values of the kinetic parameters is needed.

TABLE VI

STATISTICAL ANALYSIS OF INITIAL LAG PERIODS FOR BATCH GROWTH STUDIES PERFORMED BY TAKING SEED FROM BOTH REACTOR 1 AND REACTOR 3 STUDIES*

Initial Range	S_i	1000	800	600	400	200	100
Seed from Reactor 1	N	20	19	20	17	14	7
	Mean	8.7 hrs	8.68	9.41	9.44	9.96	9.79
	S.D.	3.78	3.48	3.54	4.33	6.23	5.52
	C.V.	43.44	40.09	37.61	45.86	62.55	56.38
Seed from Reactor 3	N	25	24	22	23	18	11
	Mean	12.34 hrs	13.54	12.30	12.76	11.44	12.86
	S.D.	5.42	5.67	5.65	6.01	6.59	7.04
	C.V.	43.92	41.87	45.93	47.10	57.60	54.74

*Lag time in hours.

TABLE VII

STATISTICAL ANALYSIS OF KINETIC CONSTANTS OBTAINED FROM BATCH GROWTH STUDIES PERFORMED BY TAKING SEED FROM BOTH REACTOR 1 AND REACTOR 3

	Reactor 1			Reactor 3		
	μ_{max}	K_s	Y_{t_B}	μ_{max}	K_s	Y_{t_B}
N	22	22	22	27	27	26
Mean	0.47	441.36	0.63	0.41	576	0.58
S.D.	0.36	555.76	0.07	0.20	1019.17	0.09
C.V.	76.59	125.91	11.11	48.78	176.93	15.51

CHAPTER VI

CONCLUSIONS

1. Introduction of aerobic digester sludge into a growth environment does not assure a successful response automatically in terms of effluent quality.

2. Addition of sludge hydrolysate to the aerobic digester before introducing the digester sludge into the activated sludge recycle did not always guarantee good effluent quality, but does show some improvement.

3. The results indicate that use of biological solids from the bottom of the secondary clarifier of a different treatment plant for recycle purposes may be feasible.

4. The mode of operation in which the clarifier underflow was added to the aerobic digester regularly and the recycle solids were drawn from such digester improved the sludge compaction to greater than 20,000 mg/l for recycle needs and provided reasonably good effluent quality.

5. The mode of operation described in No. 4 reduced the possibility of occurrence of accelerated autodigestion in the aerobic digester and kept the supernatant COD in the aerobic digester at reasonable levels.

6. Provision of the aerobic digester in the process line seemed to reduce the occurrence of filamentous organisms predominating in the activated sludge process.

7. The results indicate that lower unit feeding level (F/M) ratio or maintenance of a slower specific growth rate (μ or μ_n) may enhance the effluent quality.

8. Hydraulic detention time in total oxidation activated sludge systems may be reduced by providing a recycle reactor.

9. Aerobic digestion of sludge seemed to increase the lag period in batch growth studies, but the maximum specific growth rate, μ_{max}, and batch yield coeffienct, Y_{t_B}, values decreased to 0.41 hr^{-1} and 0.58 for aerobically digested seed compared to 0.47 hr^{-1} and 0.63 for reactor 1 seed, whereas the saturation coefficient, K_s, showed an increase for aerobic digester cells from a value of 576 mg/l to 441 mg/l for reactor 1 cells.

CHAPTER VII

SUGGESTIONS FOR FUTURE WORK

1. Long-term studies are needed to investigate the feasibility of using the aerobic digester as a source of recycle solids.

2. There is need to study the feasibility of conducting aerobic digestion in two phases, i.e., using a short hydraulic detention time to "burn off" internal storage products of cells, followed by a longer detention time to effect maximum sludge reduction; also, there is need to determine if cells in the first stage can be used for recycle purposes.

3. There is need for more study of ecological factors, such as viruses, inhibition products, and predatory effects, etc., that affect the aerobic digestion process.

4. There is need to further study the feasibility of reducing hydraulic detention time by providing a separate recycle reactor.

5. Further study is needed on the feasibility of spiking the aerobic digester with hydrolyzed sludge to make it compatible for introduction into recycle.

6. There is need to study the effectiveness of F/M control during transient disturbances in terms of effluent quality.

7. There is need to further study the feasibility of using activated sludge from different treatment plants and possible activity parameters to understand the nature and compatibility of the sludge.

8. There is need to further study the effects of aging of biological solids on relative values of kinetic parameters.

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APPENDIX

SUMMARY DATA OF BATCH GROWTH STUDIES

TABLE VIII

VALUES OF BATCH GROWTH KINETIC CONSTANTS, μ_m, K_s, AND Y_{t_B} FOR UNIT 1 OBTAINED BY TAKING SEED FROM REACTOR 1 AND THE AEROBIC DIGESTER (REACTOR 3)

Date	μ_m hr^{-1}	K_s mg/l	Y_{t_B} mg/mg	μ_m hr^{-1}	K_s mg/l	Y_{t_B} mg/mg
1977	Reactor 1			Reactor 3		
3/6	0.44	275	0.628	0.318	190	0.5835
3/27	0.555	693	0.600	0.526	315	0.5926
4/10	0.487	185	0.68	0.432	274	0.56
4/30				0.494	128	0.58
5/15	0.56	145	0.62	0.43	162	0.56
6/7				0.289	40	
6/18	0.476	485	0.415	0.226	51	0.57
7/15	0.48	480	0.52	0.289	160	0.56
7/26	0.33	250	0.52	0.275	34	0.45
8/8	0 219	23	0.66	1.0	4400	0.61
8/21	0.162	65	0.728	0.259	168	0.684
8/30(29)	0.289	112	0.68	0.526	449	0.68
9/5	0.259	109	0.652	0.380	495	0.608
9/25				0.292	44	0.662
10/20	1.11	377	0.608	0.588	459	0.688
1978						
1/27				0.500	2550	0.396
2/6	0.222	783	0.62			
3/14				0.105	63	0.408
4/7				0.180	216	0.555
4/10	0.177	79	0.628			
4/26	0.329	211	0.632	0.173	156	0.544
5/11(12)	0.875	2625	0.6625	0.432	484	0.568
8/16	0.466	409	0.652	0.416	766	0.472
8/28	1.739	906	0.585	0.581	139	0.504
10/20				0.481	108	0.688
12/17	0.196	128	0.752	0.909	2745	0.632
1979						
1/17	0.204	96	0.664	0.232	29	0.516
2/6	0.459	435	0.652	0.317	124	0.712
4/3	0.3729	939	0.652	0.3636	818	0.632
N	22	22	22	27	27	27
$\bar{X}$	0.47	441.36	0.63	0.41	576	0.58
S	0.36	555.76	0.07	0.20	1019.17	0.09
1978	t = 16 hrs Unit 2-Reactor 1					
12/6	0.29	254	0.57			
12/10	0.31	159	0.658			
12/11	0.46	300	0.71			
1979	t = 12 hrs					
2/28	0.70	2040	0.572			

μ_m = maximum specific growth rate
K_s = saturation coefficient
Y_{t_B} = batch yield coefficient

TABLE IX

VALUES OF INITIAL LAG PERIODS OBSERVED DURING BATCH GROWTH STUDIES FOR UNIT 1 TAKING SEED FROM REACTOR 1, USING GLUCOSE AS CARBON AND ENERGY SOURCE

	Initial Substrate Concentration											
Time	1000	800	750	600	500	450	400	300	250	200	150	100
1977						Hours						
3/6	5			5			8		8			7
3/27	0	2		3			3			3		
4/10	15	12		14	14		12			10		
4/30												
5/15	7.5	7.5		7.5			7.5			14		
6/7												
6/18	5	5	5		5			5		5		
7/15	16	11.5		11.5		17		11.5			12.5	
7/26	6.5	9		8.5		8		17.5			11	
8/8	9	9		12	9			9		9		
8/21	12	13.5		14.5	12			12		18		
8/30	14	14		13.5		14		13			13	
9/5	6.5	6.5		6.5		6.5		6.5			8.5	
9/25												
10/20	9	9		10.5		10.5		12.5			14	
1978												
1/27												
2/6												
3/14												
4/7												
4/10	4.5	4.5		8.0			8.5			10		10
4/26	7.5	7.5		7.5	5.5			5.5				
5/27												
5/11												
5/12	4	4		4				4		4		4
5/27												
8/16	5.0			9.0			4.5			2.5		7.5
8/28	7.5	9.0		10.25			11.5			13.5		14
10/20												
12/17	15	15		15.5			15			20		
1979												
1/17	10	10		11			16.5			20		20
2/6	8	8		6			8.5			5.5		
4/3	7.0	8.0		10.5			5.5			5.0		6.0
N	20	19		20	5		17.0	9		14		7
$\bar{X}$	8.7	8.68		9.41	9		9.44	10.20		9.96		9.79
$\bar{S}$	3.78	3.48		3.54	3.94		4.33	4.12		6.23		5.52

TABLE X

VALUES OF INITIAL LAG PERIODS DURING BATCH GROWTH STUDIES BY TAKING SEED FROM AEROBIC DIGESTER (REACTOR 3) USING GLUCOSE AS SUBSTRATE

	Initial Substrate Concentration								
Time	1000	800	600	500	400	300	200	150	100
1977					Hours				
3/6	5.5		6		8		4		4
3/27	13	15	11		11		11		
4/10	11	10	10	9	9		6		
4/30	2.5	2.5	0	0	2.5		1.5		
5/15	3.5	12.5	13.5		14.5		13.5		
6/7	21	11			13		16.5		
6/18	10	10.5		19		19.5	19.5		
7/15	16.5	19	16		12.5	18		14	
7/26	17	28			28.5	21.5		17.5	
8/18									
8/21	16.5	16.5	16.5	16.5		17.5			
8/30	17.5	17.5	17.5		15	17		17	
9/5	14.5	14	11		11	11		10	
9/25	13.5	13.5	13.5		13.5	17.5		13.5	
10/20	16.5	22.5	20		20.5	21			
1978									
2/6									
3/14	1	2	2		2		2		
4/7	10	10	10		10		10		
4/10									
4/26	15	15	15		15		11		
5/27									
5/11	22	11	8.5		11.5		10		
5/12									
5/27									
8/16	13	13	14		10		4.5		6
8/28	10	16.5	17		16.5		17		17.5
10/20	15	15	15		15		15		
12/17	15.5	18	19		15.5		16.5		
1979									
1/17	12.5	15	21		23.5		26.5		28
2/6	8	10.0	9		8		8		6
4/3	8	7	5		7.5		8		8
N	25	24	22		23		18		11
$\bar{X}$	12.34	13.54	12.30		12.76		11.14		12.86
S	5.42	5.67	5.65		6.01		8.59		7.04

VITA[2]

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