

219-6641A

AN EXPERIMENTAL STUDY OF THE ACTIVATED, SLUDGE PROCESS  
UNDER STEADY STATE, AND DYNAMIC CONDITIONS

by

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A MASTER'S THESIS

submitted in partial fulfillment of the  
requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1973

Approved by:



Major Professor

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## CHAPTER I. INTRODUCTION

### 1. General Considerations

The disposal of waste water became a necessity as soon as humans began to live in organized communities. The development of industries and the installation of water closets early in the nineteenth century led to the development of drainage systems for the removal of offensive waste both from the industries and from the houses (1). Biological waste treatment processes were developed to treat these waste streams. The development of the activated sludge process enabled large quantities of organic wastes to be treated at reasonable costs.

The activated sludge process may be defined as a system in which flocculated biological growths are continuously circulated and contacted with organic waste in the presence of oxygen. The oxygen is usually supplied from air bubbles injected into the sludge-liquid mass under turbulent conditions. The process involves an aeration step followed by a solid-liquid separation step from which the separated sludge is recycled back for admixture with the waste. A portion of this sludge is removed for further treatment and disposal (2).

The conventional activated sludge process has long been successfully applied to the treatment of domestic sewage. A diagram of the process is shown in Figure 1 (3). The step aeration process is a modification of the conventional activated sludge process. Figure 2 shows the flow diagram of this process (3). The flow of sewage is introduced to

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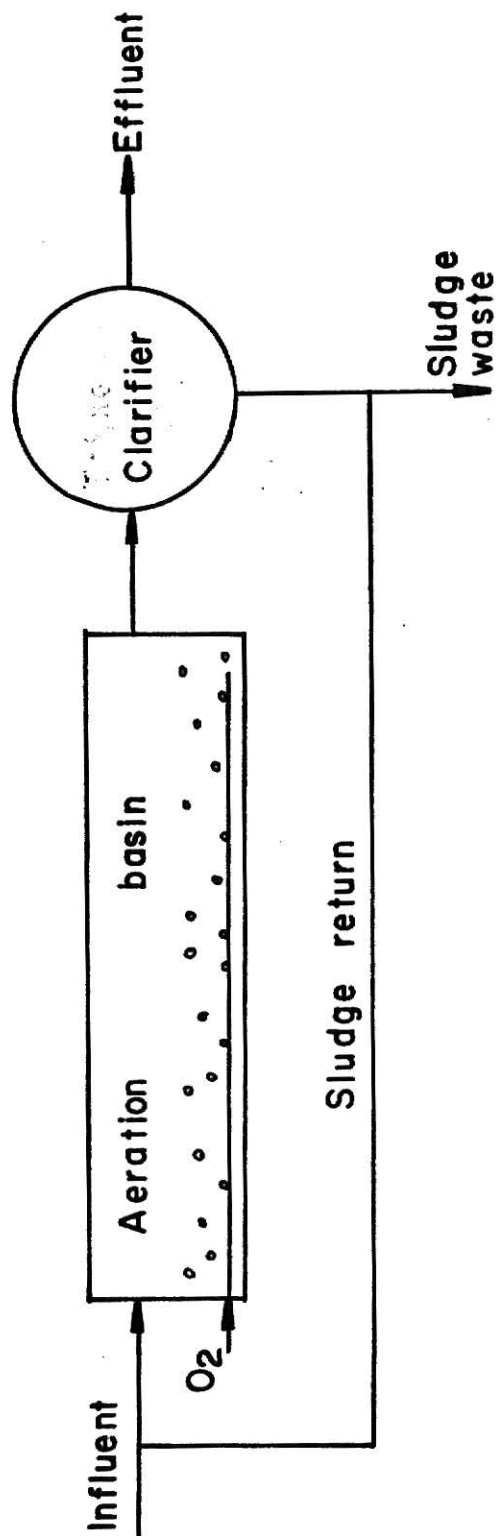


Fig. 1 . Flow diagram of conventional activated sludge process.

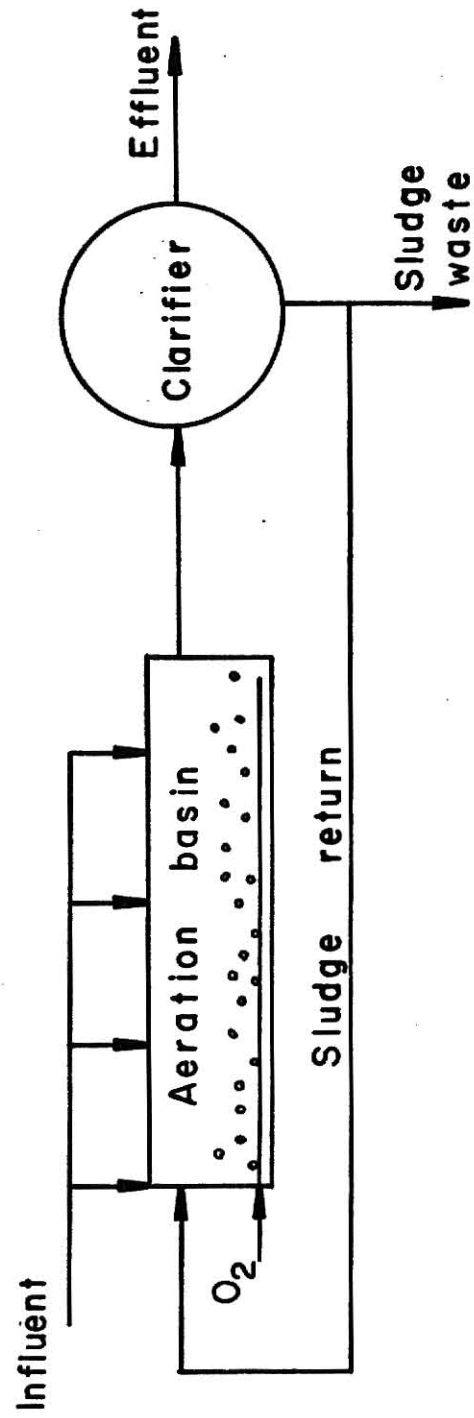


Fig. 2. Flow diagram of step aeration process.

the system at several different points, equal distances apart, along the aeration basin. As a result accelerated growth and oxidation are not confined to one end of the basin as in the conventional process but, instead, takes place over most of the basin. The difference between the oxygen demand patterns of the conventional process and the step aeration process is illustrated in Figure 3 (3).

In the first part of this work, an experimental study was carried out to optimize the step aeration activated sludge process using evolutionary operation techniques (4). One purpose of this work was to demonstrate how the techniques in evolutionary operation can be applied to the experimental optimization of step aeration activated sludge processes.

In the second part of this work, the transient behavior of a completely mixed activated sludge process was investigated experimentally. A better understanding of the dynamic behavior of activated sludge processes was the primary goal of this work. Knowledge of the dynamic behavior is needed to understand the effects of transient loadings and the appropriate control action needed for maximizing effluent quality.

## 2. References

- (1) Bartlett, R. E., Waste Water Treatment, pp. 1-9, Applied Science Publishers Ltd., London, England, 1971.
- (2) Eckenfelder, W. W., Jr., and D. J. O'Connor, Biological Waste Treatment, 2nd Impression, pp. 7-9, Pergamon Press, 1964.

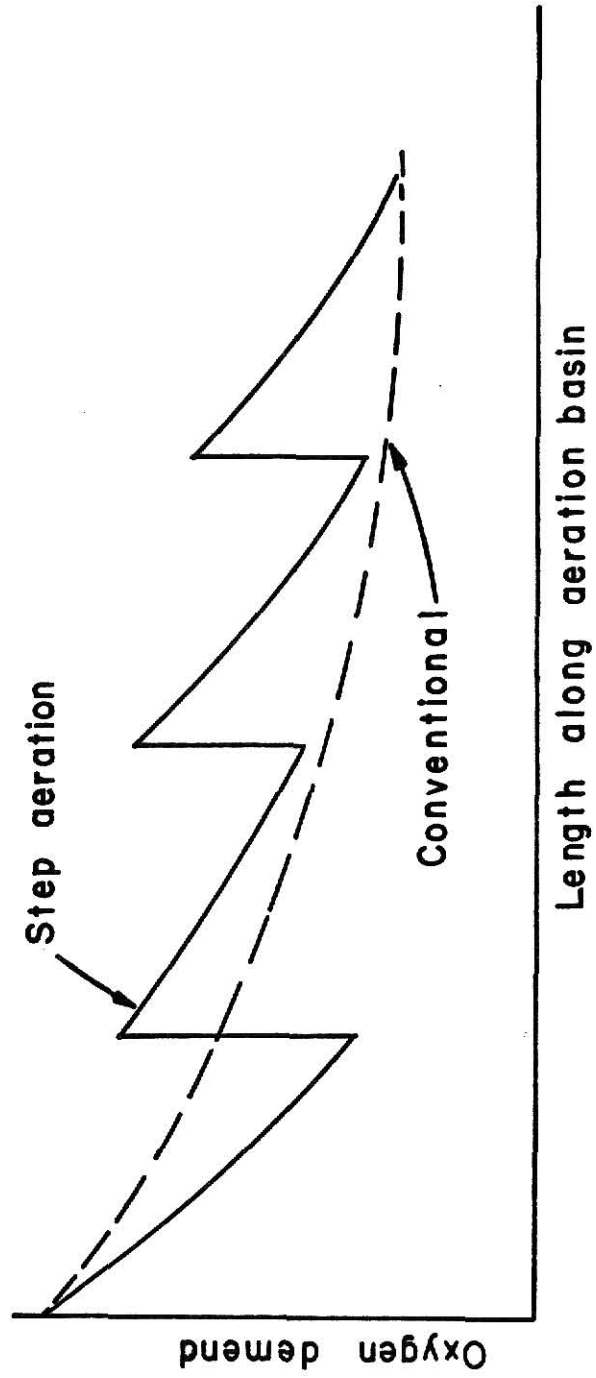


Fig. 3 . Comparison of oxygen demands exerted in the conventional and step aeration processes.

- (3) Rich, L. G., Unit Processes of Sanitary Engineering, pp. 38-46, John Wiley & Sons, Inc., New York, 1963.
- (4) Box, G. E. P. and N. R. Draper, Evolutionary Operation, John Wiley & Sons, Inc., New York, 1969.

## CHAPTER II. STEADY STATE EXPERIMENTAL OPTIMIZATION OF A STEP AERATION WASTE TREATMENT PROCESS

### 1. Introduction

In the past 30 years much progress has been made in developing biological waste treatment systems. The step aeration waste treatment process, in which the influent is introduced at several locations, was first described by Gould (1, 2) in 1942. A flow diagram of the step aeration process (3) is shown in Figure 2 of Chapter I.

Gould (1, 2) reported in 1942 that he provided the step aeration design on the Tallmans Island Activated Sludge Plant of New York City. Gould (1) has described the design of step aeration units as follows: "These tanks incorporate a principle, original, it is believed, with the author, whereby the sewage can be introduced in regulated amounts at multiple points throughout the course of the flow of the returned activated sludge through the tank."

In 1942 McKee and Fair (4) conducted a laboratory investigation of the effects of load distribution on the activated sludge process and concluded:

- 1) Load distribution appears to provide a workable modification of the activated sludge process by maintaining oxygen demand at a more uniform level than the conventional method of operation, producing an indigenous activated sludge process with good purifying capacity and settling properties, discharging a good

effluent without increasing the air consumption, and effecting a saving in tank volume.

- 2) Load distribution seems to render operation of aeration units flexible, making it possible to adjust the character of the sludge produced to the needs of the sewage treated, aiding in the control of bulking and blanket rising, and reducing the shock of sudden discharges of industrial or otherwise objectionable wastes.
- 3) Load distribution requires no special equipment, is readily incorporated in conventional tanks by the provision of sewage inlets and transverse baffles, and gives promise of increasing the capacity of overloaded aeration units by more effective use of available tank volumes.
- 4) Preaeration of sewage and reaeration of returned sludge, too, appear to be of importance in equalizing the oxygen demand of activated sludge units.
- 5) Installation in aeration units of an adequate number of baffles is essential to the control of longitudinal mixing and short-circuiting that will otherwise prevail.

Matsumoto and Onuma (5) investigated a step aeration process using both theoretical and experimental approaches. They compared their experimental results with their models and found reasonably good agreement; they did not optimize the process.

Polonscik et al. (6) investigated the theoretical optimi-

zation of a step aeration activated sludge process with three completely mixed tanks connected in series. In 1968 the step aeration biological waste treatment system was investigated theoretically in detail by Erickson et al. (7, 8, 9). Although much effort has been devoted to theoretical optimization studies of step aeration waste treatment systems, little experimental work has been done to verify these theoretical results or experimentally develop an optimum step aeration process.

Evolutionary operation (EVOP), as originally presented by G. E. P. Box in 1957 (10), is now an accepted means of improving the performance of industrial processes. The basic philosophy of EVOP is that a process should be run not merely to make the end product, but also to generate useful information on how to improve the process (11). EVOP has been successfully utilized in many factories in the U. S. A. and Europe (12). However, no report has been found in utilizing EVOP to improve or optimize biological waste treatment systems. This work is an effort to examine the applicability of EVOP in biological waste treatment system optimization. This chapter presents some results obtained using EVOP in an experimental investigation of a two-tank step aeration biological waste treatment system with recycle.

## 2. Materials and Methods

### A. Equipment

The schematic diagram of the experimental apparatus is



shown in Figure 4. The system consisted mainly of two 2-liter aeration tanks, a 6-liter sedimentation tank and a 300-ml homogenizing chamber. The aeration tank was made of plexiglass with a thickness of 0.5 inches. The aeration sparger consists of three divided air-stones in each aeration tank. Stainless steel heating and cooling coils in the aeration tanks were connected to a temperature-controlled waterbath (Forma waterbath, refrigerated, by Forma Scientific, Inc., Menietta, Ohio) with which the circulating water could be controlled at a desired temperature. A circulation pump continuously pumped water through the coils. On the top of each aeration tank there was a level-controlling device which was primarily designed for adjusting the desired working volume of the aeration tanks. The sedimentation tank was made by modifying a 6-liter erlenmeyer flask.

There were six pumps (Sigma motor pump, type AL-4-E-40, by Sigma Motor, Inc., Middleport, New York) in the system: two for incoming waste, one for pumping sludge suspension from the first tank to the second tank, one for waste sludge disposal, and one for pumping sludge from the homogenizing tank to the first tank. There was a magnetic stirrer (S/P Deluxe Mixer, S 8220, by Scientific Products, Evanston, Illinois) beneath the homogenizing chamber and a teflon-coated magnetic bar in the homogenizing chamber for the agitation of the active sludge. The air was pumped by an air compressor through a humidifier, which was designed so that the air passed through water. The air flow was then divided into two

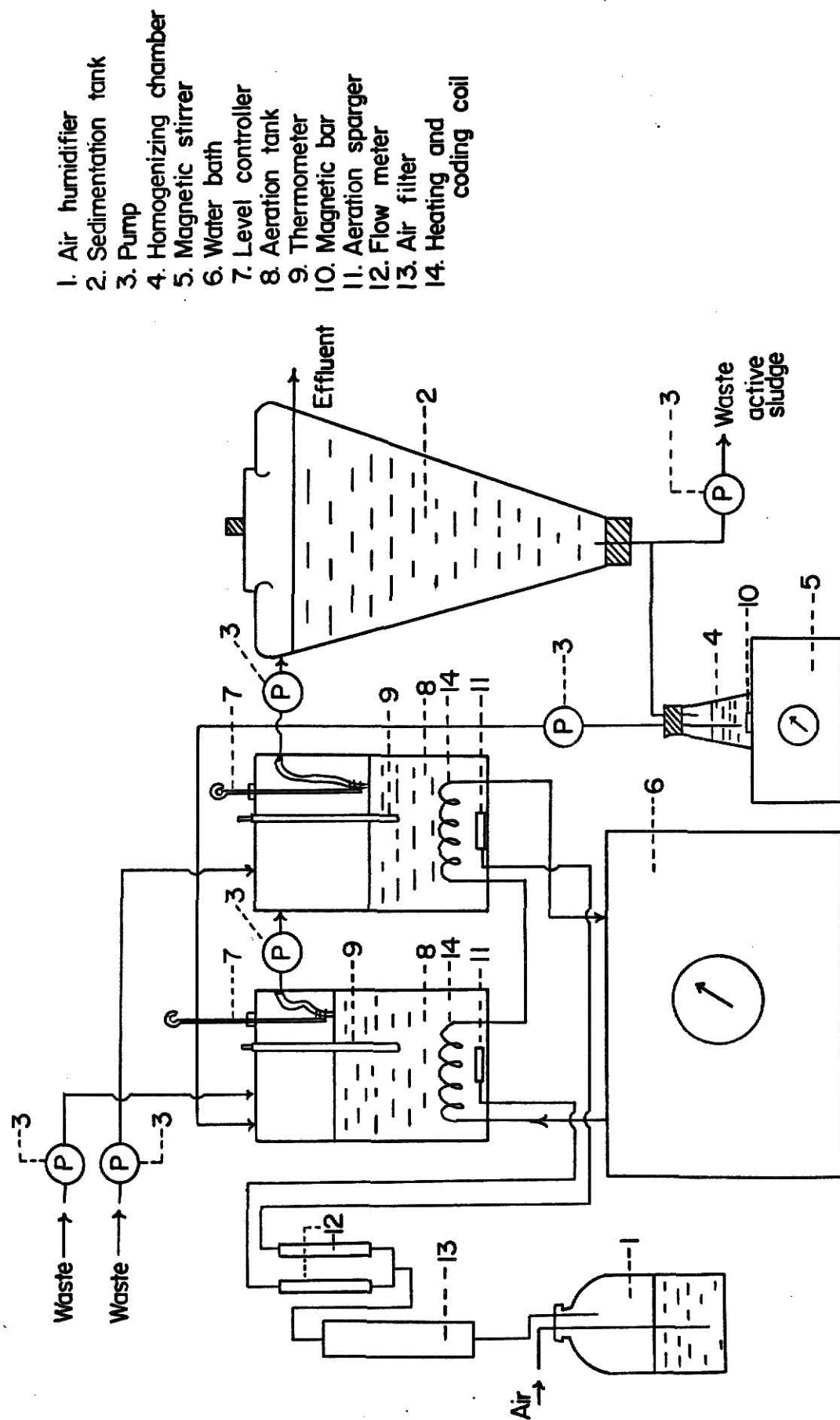


Fig. 4. Schematic diagram of experimental apparatus for step aeration waste treatment system.

streams with each stream connected to a flow meter and a sparger in one of the aeration tanks.

The temperature of the culture was controlled at  $25 \pm 0.5^{\circ}\text{C}$  and the pH of the original synthetic waste at  $7.2 \pm 0.15$ . The airflow rate to the aeration tanks was maintained at 2.0 VVM (volume of air per volume of culture per minute). This high aeration rate was maintained in order to supply enough oxygen for biological oxidation and also to provide sufficiently vigorous agitation in the aeration tanks.

The dissolved oxygen concentration was maintained above 2 mg/l which is higher than the critical oxygen requirement of the microorganisms in the sludge.

#### B. Synthetic waste

The composition of the glucose-limiting medium is shown in Table 1. The pH of the culture was controlled at  $6.8 \pm 0.35$  by the buffer action of the components in the medium.

#### C. Seed culture

Original seed culture was obtained from the municipal sewage treatment plant at Manhattan, Kansas. Two hundred milliliters of original seed from the primary clarifier were added to 800 ml of synthetic medium with 3-fold concentration in a glass jar and aerated moderately. The culture was refreshed every day by discarding 80% of the culture solution from the jar and replenishing with fresh medium. After three days, the seed culture was used as the inoculum to the continuous flow experimental system.

Table 1. Composition of synthetic waste.

Constituents	Concentration, mg/l
Glucose, $C_6H_{12}O_6$	1000.0
Ammonium sulfate, $(NH_4)_2SO_4$	500.0
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	100.0
Ferric chloride, $FeCl_3 \cdot 6H_2O$	0.5
Calcium chloride, $CaCl_2$	7.5
Manganese sulfate, $MnSO_4 \cdot H_2O$	10.0
Potassium phosphate, mono-basic, $KH_2PO_4$	527.0
Potassium phosphate, di-basic, $K_2HPO_4$	1070.0

#### D. Analytical procedures

The cell concentration in terms of mixed liquor suspended solids (MLSS), organic concentration in terms of chemical oxygen demand (COD) and pH were measured. MLSS was determined by the gravimetric method (13). Gravimetric measurements were conducted directly by weighing the dried suspended, non-volatile solids retained upon filtration of the sample through Millipore membrane filters with a pore size of 0.45  $\mu$ . The filtrate collected was used for dissolved COD analysis. For determination of the effluent total COD the sample from the effluent of the sedimentation tank was collected and analyzed by the dichromate method without filtering. The dichromate method, which is described in detail in "Standard Methods for the Examination of Water and Wastewater" (13), was employed for COD determination. The pH was measured by using an Accumet pH meter (Fisher Scientific Co., Pittsburgh, Pennsylvania).

#### 3. Design of the Experiment

Evolutionary operation (EVOP), a statistical method for process improvement, as described by Box and Draper (10) was employed in designing each experiment. Specifically the  $2^2$  factorial design technique was adopted. This procedure involves the use of a search pattern as shown in Figure 5 for a two variable search.

As this EVOP design proceeds, there will exist the current best-known conditions at any given stage. At the

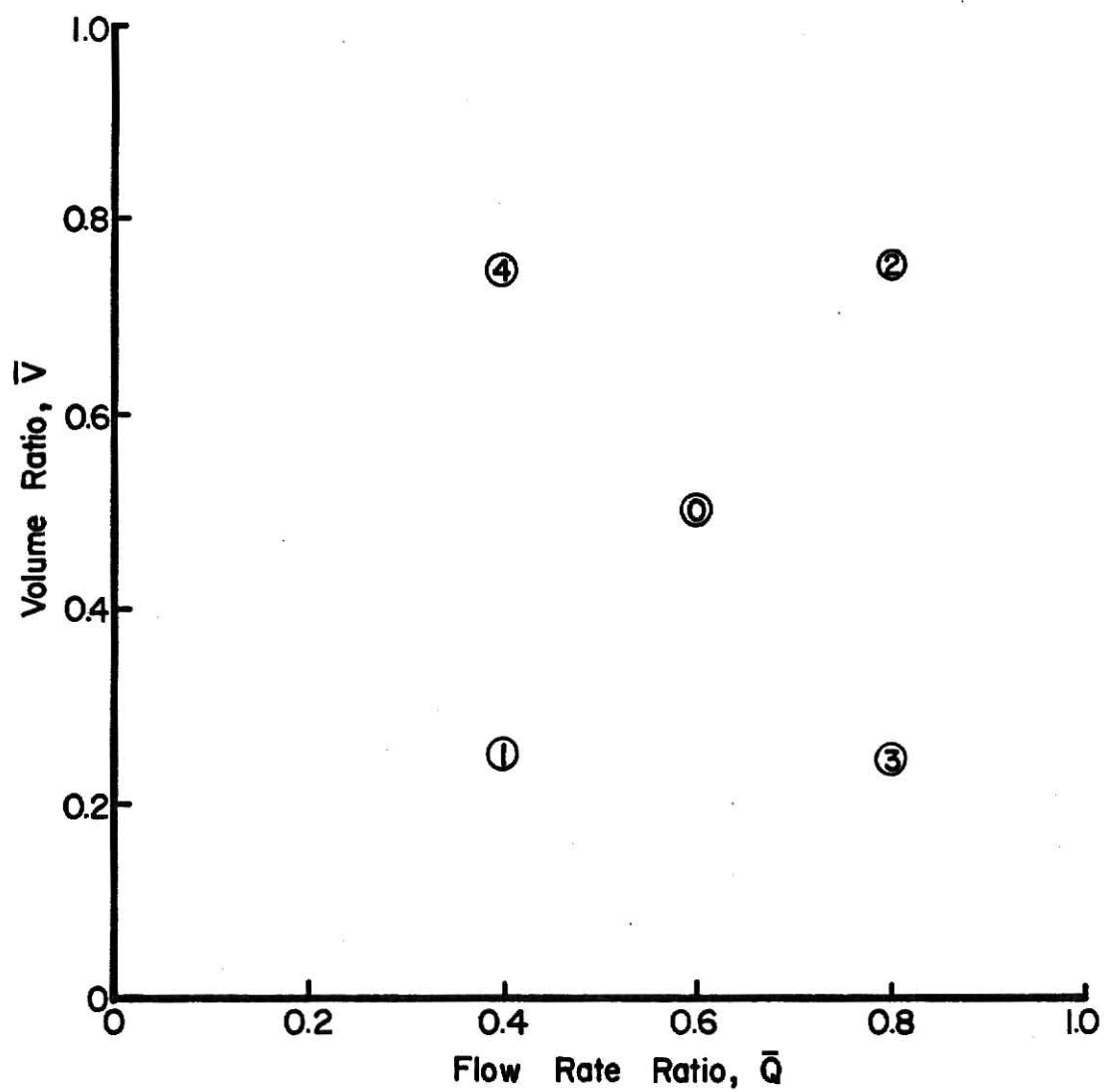


Fig. 5. Search pattern employed in evolutionary operation.

beginning of the operation these conditions will be those given by the previous theoretical optimization studies, but as improvements are incorporated the current best-known conditions may change. As a matter of fact, if the current best-known point is at the corner of the current search pattern, for example, one of the points 1, 2, 3, and 4 in Figure 5, the next search pattern will be arranged so that the prior current best-known point is at the center of the new search pattern, i.e. 0 in Figure 5. If the current best-known conditions are at the center of the search pattern, the next search pattern will be set by shrinking the range of operating conditions keeping the prior current best-known point at the center. This procedure will go on until eventually a satisfactory optimal operating condition of a process is reached.

In this study the ratio of the inlet flow rates into the two tanks and the ratio of the volumes of the two tanks as defined below were chosen as decision variables.

The volume ratio was defined as

$$\text{volume ratio of 1st tank} = \bar{V} = \frac{V_1}{V_1 + V_2} \quad (1)$$

$$\text{volume ratio of 2nd tank} = 1 - \bar{V} \quad (2)$$

where

$V_1$  = working volume of 1st tank.

$V_2$  = working volume of 2nd tank.

The inlet flow rate ratio was defined as

$$\text{flow rate ratio of 1st tank} = \bar{Q} = \frac{Q_1}{Q_1 + Q_2} \quad (3)$$

$$\text{flow rate ratio of 2nd tank} = 1 - \bar{Q} \quad (4)$$

where

$Q_1$  = influent flow rate of the waste to the 1st tank.

$Q_2$  = influent flow rate of the waste to the 2nd tank.

The total COD in the effluent from the sedimentation tank was the objective function to be minimized. The inlet flow rate ratio and the volume ratio of the two tanks were varied according to the search procedures developed for a two-variable EVOP program.

The total working volume ( $V_1 + V_2$ ) and total inlet flow rate ( $Q_1 + Q_2$ ) were set at 2.4 liters and 25 ml/min, respectively. These values were selected in order to have operating conditions in which changes in  $\bar{Q}$  and  $\bar{V}$  had an appreciable effect on system performance. Smaller organic loading closer to that used in large scale plants could have been selected; however, more experiments would have probably been required to obtain statistically significant results.

The calculation formula for the 2 standard error (S. E.) limits for averages, effects with 2 S. E. limits and estimated standard deviations are shown in Appendix I. These formulae were primarily used for setting up the EVOP information board as suggested by Box and Draper (10).



#### 4. Operating Procedures

In starting a continuous culture experiment a batch culture was initiated by inoculating the seed culture into the two aeration tanks with an inoculum of 10% on a volume basis. After approximately 5 hours of batch cultivation the continuous flow was started.

The flow rates of waste and air coming into the tanks were adjusted initially to the desired values. The sludge recycle rate was set at 30% of the total inlet synthetic waste flow rate. The flow rate at which sludge was wasted was fixed at 20% of the total inlet synthetic waste flow rate.

The experiment for each operating condition lasted about one week. Shifting from one operating condition to another was carried out by adjusting to the new operating condition without stopping the continuous culture.

Samples were collected and analyzed daily. The aeration tanks were brushed once a day to reduce the error caused by microorganisms sticking to the walls of the tanks.

#### 5. Results and Discussion

Three series of experiments each involving five runs according to the pattern shown in Figure 5, were carried out. These three series of experiments corresponded to cycle 1 and cycle 2 of phase 1 and cycle 1 of phase 2 (see Appendix I for definitions of run, cycle, and phase as used in EVOP). In phase 1, the volume ratio ranged from 0.25 to

0.75 and the flow rate ratio ranged from 0.40 to 0.80. Two cycles were carried out at the five operating conditions established for phase 1. In phase 2, the volume ratio ranged from 0.35 to 0.65 and the flow rate ratio from 0.50 to 0.70.

At each operating condition four data points including those from the second day through the fifth day were used for computing the average steady state values for each run. The data from the first day were not used in calculating the average value because of their transient nature.

The experimental results from the first cycle of phase 1 are shown in Table 2. The results show that the COD removal based on the second tank dissolved COD was as high as 96.64% when the operating condition consisted of a volume ratio of 0.50 and a flow rate ratio of 0.60. The highest total COD removal, 75.93%, was found under the same operating condition.

In cycle 1, phase 1, the best operating condition appears to be in the region where 50% of the volume was allocated to each tank and where 60% of the influent was fed to the first tank. The poorest operating condition appears to be where 75% of the volume was allocated to the first tank and 40% of the influent was allocated to the first tank. The COD removal rate based on the second tank dissolved COD was only 86.77%. Since 60% of the influent must be treated in 25% of the volume in this case, poor operating behavior was to be expected.

Table 2. Performance of treatment system for cycle 1, phase 1.

Operating condition	$\bar{V} = 0.25$ $Q = 0.40$	$\bar{V} = 0.75$ $Q = 0.80$	$\bar{V} = 0.25$ $Q = 0.80$	$\bar{V} = 0.75$ $Q = 0.40$	$\bar{V} = 0.50$ $Q = 0.60$
Total COD in original medium (g/l)	1.07	1.07	1.06	1.08	1.09
pH in original medium	7.25	7.26	7.26	7.32	7.20
MLSS in effluent (g/l)	0.188	0.140	0.150	0.206	0.173
pH in effluent	6.72	6.67	6.65	6.67	6.77
MLSS in 2nd tank (g/l)	0.878	0.773	0.585	0.653	0.768
pH in 2nd tank	6.84	6.74	6.70	6.71	6.83
COD removal based on 2nd tank dissolved COD (%)	95.22	95.22	92.54	86.77	96.64
Total COD removal (%)	70.40	73.39	69.35	55.42	75.93
pH in recycle stream	6.65	6.63	6.60	6.60	6.71

The standard EVOF information board for cycle 1, phase 1, is shown in Table 3. Three items were taken into account, namely, the total COD removal, the dry weight in the effluent and the COD removal based on the second tank dissolved COD. Among these, the total COD removal was the objective function which was to be maximized, while the other two were included here for information. The statistical results in this Table were computed according to the formulae given by Box and Draper (10). These are briefly summarized in Appendix I.

In Table 3, a response surface covering the points 0, 1, 2, 3, and 4 is formed according to the search pattern as shown in Figure 5. This surface shows that point 0 has the highest total COD removal and point 4 has the lowest value. The influence of variables are expressed by the effects with 2 S. E. (standard error) limits. There are four kinds of effects which have been taken into account, namely,  $\bar{Q}$ ,  $\bar{V}$ ,  $\bar{Q} \times \bar{V}$  and change in mean. To thoroughly understand these five effects it is advisable to examine the calculation formulae as shown in Appendix I. The effect  $\bar{Q}$  has a value of  $8.46 \pm 4.44$  which implies that increasing  $\bar{Q}$  will improve the process as long as only  $\bar{Q}$  is considered. Similarly, a value of  $-5.47 \pm 4.44$  is given for the effect of  $\bar{V}$ , which means that an increase in  $\bar{V}$  will be unfavorable for the total COD removal. As for the effect of interaction,  $\bar{Q} \times \bar{V}$ , the value of  $9.51 \pm 4.44$  shows that the maximum point for total COD removal may be in the direction 1-0-2 according to the

Table 3. EVOP information board for cycle 1, phase 1.

	Total COD Removal	MLSS in Effluent	COD Removal Based on 2nd Tank Diss. COD
Requirement	Maximize	Low	High
Process averages	$\bar{V}$ 55.42    73.39 75.93 70.40    69.35 $\bar{Q}$	$\bar{V}$ 0.206    0.140 0.173 0.188    0.150 $\bar{Q}$	$\bar{V}$ 86.77    95.22 96.64 95.22    92.54 $\bar{Q}$
2 S. E. limits for averages	$\pm 4.44$	$\pm 0.138$	$\pm 1.84$
Effects with 2 S. E. limits	Phase mean	0.171	93.27
	$\bar{Q}$	$-0.052 \pm 0.138$	$2.89 \pm 1.84$
	$\bar{V}$	$0.004 \pm 0.138$	$-2.89 \pm 1.84$
	$\bar{Q} \times \bar{V}$	$-0.014 \pm 0.138$	$5.57 \pm 1.84$
Estimated standard deviations	Change in mean	$-0.002 \pm 0.124$	$-3.37 \pm 1.65$
	2.22	0.069	0.92

search pattern.

The experiments of cycle 2, phase 1, were similar to those of cycle 1, phase 1; however, the order in which the operating conditions were changed among the five positions was different. In the experiments of cycle 1, phase 1, the order (see Figure 5) 1, 2, 3, 4, 0 was used while in cycle 2, phase 1, the order was 2, 4, 0, 1, 3. The results of the experiments of cycle 2, phase 1, are shown in Table 4. Comparison of Table 2 and 4 shows that the results are similar. Based on the objective function of per cent total COD removal, the relative ranking of the five operating conditions remains unchanged. It appears that the experiments are fairly reproducible; however results from cycle 2, phase 1, are slightly lower in some cases than those in cycle 1, phase 1. This may be due to a change of population of micro-organisms in the system or experimental error.

The information board for cycle 2, phase 1, was constructed based on the results obtained from cycle 1, phase 1, and cycle 2, phase 1. Table 5 shows the information board following cycle 2, phase 1. In this Table the process averages were computed by averaging the results from these two cycles. In the total COD removal column the effects of  $\bar{Q}$ ,  $\bar{V}$ ,  $\bar{Q} \times \bar{V}$  and change in mean are very similar to those in Table 3; however, the 2 S. E. limits are smaller in Table 5, because  $n$  increased from 1 to 2 (see Table A-1 in Appendix I).

In the results discussed above the center point operating condition (0) with a volume ratio of 0.50 and a flow

Table 4. Performance of treatment system for cycle 2, phase 1.

Operating condition	$\bar{V} = 0.25$ $Q = 0.40$	$\bar{V} = 0.75$ $Q = 0.80$	$\bar{V} = 0.25$ $Q = 0.80$	$\bar{V} = 0.75$ $Q = 0.40$	$\bar{V} = 0.50$ $Q = 0.60$
Total COD in original medium (g/l)	1.05	1.05	1.04	1.05	1.05
pH in original medium	7.22	7.22	7.31	7.10	7.26
MLSS in effluent (g/l)	0.145	0.285	0.150	0.323	0.203
pH in effluent	6.67	6.63	6.69	6.53	6.73
MLSS in 2nd tank (g/l)	0.738	0.783	0.455	0.593	0.688
pH in 2nd tank	6.71	6.64	6.79	6.63	6.78
COD removal based on 2nd tank dissolved COD (%)	96.07	95.29	95.57	87.30	96.33
Total COD removal (%)	68.79	69.80	67.42	56.96	71.47
pH in recycle stream	6.53	6.50	6.46	6.54	6.56

Table 5. Information board for cycle 2, phase 1.

	Total COD Removal	MLSS in Effluent	COD Removal Based on 2nd Tank Diss. COD
Requirement	Maximize	Low	High
Process averages	<div><div><div>56.1971.59</div><div>73.70</div><div>69.5968.38</div></div><div><math>\bar{V}</math></div></div> <div><math>\bar{Q}</math></div>	<div><div><div>0.2650.213</div><div>0.188</div><div>0.1670.150</div></div><div><math>\bar{V}</math></div></div> <div><math>\bar{Q}</math></div>	<div><div><div>87.0395.26</div><div>96.49</div><div>95.6594.56</div></div><div><math>\bar{V}</math></div></div> <div><math>\bar{Q}</math></div>
2 S. E. limits for averages	$\pm 3.11$	$\pm 0.098$	$\pm 1.30$
Phase mean	67.89	0.197	93.80
Effects with	$\bar{Q}$	$-0.034 \pm 0.098$	$3.57 \pm 1.30$
2 S.E. limits	$\bar{V}$	$0.081 \pm 0.098$	$-3.96 \pm 1.30$
	$\bar{Q} \times \bar{V}$	$-0.018 \pm 0.098$	$4.66 \pm 1.30$
Change in mean	$-5.81 \pm 2.78$	$0.009 \pm 0.087$	$-2.69 \pm 1.16$
Estimated standard deviations	2.22	0.069	0.918



rate ratio of 0.60 gave the highest total COD removal for both cycles of phase 1. In the information board, the change in mean compares the center point with the average of the other four points. The negative value in Table 5 of  $-5.81 \pm 2.78$  indicates that the center point is significantly better than the average of the other four points. Based on this result, a decision was made to retain this center point and to decrease the range of the search such that the volume ratio ranged from 0.35 to 0.65 and the flow rate ratio ranged from 0.50 to 0.70.

The values of operating ranges used and experimental results for cycle 1, phase 2, are shown in Table 6. Table 6 shows that the highest total COD removal is obtained with a volume ratio of 0.50 and a flow rate ratio of 0.60. The corresponding EVOP information board is shown in Table 7. The total COD removal column in this table indicates that the effect of  $\bar{Q}$  has a value of  $4.54 \pm 4.56$  which is not as significant statistically as the value of  $7.09 \pm 3.11$  in Table 5. From this result, the possibility of moving the search pattern in the direction of larger values in  $\bar{Q}$  is suggested; however the effect is of the same magnitude as the 2 S. E. limits. The effects for  $\bar{V}$  and  $\bar{Q} \times \bar{V}$  are small compared to their 2 S. E. limits. The best operating condition is at position  $\underline{Q}$  with volume ratio 0.50 and flow rate ratio 0.60. The effect for change in mean is  $-8.10 \pm 4.08$  which indicates that the result obtained at the center point ( $\underline{Q}$ ) is significantly higher than the average of the other four points. The oper-

Table 6. Performance of treatment system for cycle 1, phase 2.

Operating condition	$\bar{V} = 0.35$ $Q = 0.50$	$\bar{V} = 0.65$ $Q = 0.70$	$\bar{V} = 0.35$ $Q = 0.70$	$\bar{V} = 0.65$ $Q = 0.50$	$\bar{V} = 0.50$ $Q = 0.60$
Total COD in original medium (g/l)	1.03	1.06	1.08	1.06	1.05
pH in original medium	7.19	7.11	7.15	7.13	7.18
MLSS in effluent (g/l)	0.160	0.097	0.093	0.263	0.078
pH in effluent	6.53	6.55	6.55	6.64	6.59
MLSS in 2nd tank (g/l)	0.610	0.570	0.443	0.690	0.710
pH in 2nd tank	6.62	6.58	6.58	6.79	6.65
COD removal based on 2nd tank dissolved COD (%)	96.27	95.96	95.67	90.59	95.95
Total COD removal (%)	69.74	74.36	73.95	69.48	82.00
pH in recycle stream	6.53	6.50	6.46	6.54	6.56

Table 7. EVOP information board for cycle 1, phase 2.

Requirement	Total COD Removal	MLSS in Effluent	COD Removal Based on 2nd Tank Diss. COD	
			Low	High
Process Averages	$\bar{V}$ 69.48    74.36 $\bar{Q}$ 82.00 69.74    73.95	$\bar{V}$ 0.263    0.097 $\bar{Q}$ 0.078 0.160    0.093	$\bar{V}$ 90.59    95.96 $\bar{Q}$ 95.95 96.27    95.67	
2 S. E. limits for averages	$\pm 4.56$	$\pm 0.112$	$\pm 0.69$	
Effects with 2 S.E. limits	Phase mean		94.88	
	$\bar{Q}$		0.138	
	$\bar{V}$		$-0.120 \pm 0.112$	
	$\bar{Q} \times \bar{V}$		$0.053 \pm 0.112$	
	Change in mean		$-0.049 \pm 0.112$	
Estimated standard deviations	2.28	0.056	$0.060 \pm 0.100$	0.346

ating condition at a volume ratio of 0.50 and a flow rate ratio of 0.60 is significantly better than the other four operating conditions.

The search was terminated after cycle 1, phase 2, because the best result was at the center point and the value there was significantly better than the values at any of the other four points. The search could have been continued by decreasing the size of the pattern further; however, because of population shifts and other variations in operation which are difficult to control, further refinement did not appear justified.

The results presented in this work indicate that optimum operation involved using two tanks of about equal volume. These experimental results were found to be qualitatively in agreement with the theoretical results presented by Erickson et al. in 1968 (8, 9). The optimum results presented by Erickson et al. (8) depend on the value of the saturation constant,  $K_s$ , in the kinetic model. Chiu et al. (14, 15) have evaluated  $K_s$  using the same synthetic waste and the same source of organisms. The result from continuous culture experiments was 26.5 mg/liter, with batch culture experiments giving some smaller and some larger values of  $K_s$ . Since the initial synthetic waste contained about 1050 mg/liter COD, the dimensionless value,  $K_1 = K_s/S_0$ , is about 0.026. Figures 12 and 13 of Reference 7 show that the experimental results of  $\bar{V} = 0.50$  and  $\bar{Q} = 0.60$  are in reasonable agreement with the optimal results obtained using mathematical

models.

These results indicate that EVOP can be useful in experimentally optimizing a biological waste treatment system. Since this technique is designed to provide useful information when experimental error is present, it is ideal for biological waste treatment. Since most waste treatment plants must handle all of the waste fed to them, gradual changes in quantity and concentration of the waste often occur as population increases and new commercial activities and industries are added to the system. Thus, there is often a need to find a new optimal operating condition because of changes in influent conditions. EVOP can be continuously employed to search for improved operating conditions if the results justify the experimental effort. Often the needed information is collected regularly and little additional effort is required to employ the results advantageously.

## 6. Conclusions

If the total volume and total influent waste flow rate are fixed in a two-stage step aeration waste treatment system with recycle, the volume ratio and the inlet flow rate ratio have a significant influence upon the treatment efficiency of the waste treatment system. Using EVOP to experimentally find the best operating condition, the volume ratio of 0.50 and the inlet flow rate ratio of 0.60 gave the best results. A total COD removal of about 82% was found under this operating condition.

The EVOP method appears to be useful in experimentally optimizing the operation of a biological waste treatment system.

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### CHAPTER III. DYNAMIC BEHAVIOR OF A COMPLETE MIXING ACTIVATED SLUDGE SYSTEM

#### 1. Introduction

Currently, biological waste treatment processes seem to provide the most economical and most widely used solution for removing soluble and colloidal organic components from industrial and municipal wastewaters.

Transient loadings of organic concentration and flow rate frequently occur in the majority of waste treatment plants in operation today. For this reason, considerable attention has been given recently to the studies of the transitional characteristics of continuously cultured systems subject to changes in the influent conditions. Many investigators studied the transient responses of continuous biological systems without continuous feedback of activated sludge using either laboratory-scale units or computer simulation (see for example, References 1, 2, 3, 4, 5, 6, and 7). Many of their contributions are reviewed by Fan et al. (8) and Gaudy and Gaudy (9). However, the number of available reports on transient responses of the waste treatment process with sludge recycle is rather limited.

In 1970, Adams and Eckenfelder (10) studied the response of the activated sludge system to organic transient loadings. They used a laboratory-scale activated sludge unit. Their unit was constructed of plexiglass and combined both aeration chamber and settling compartment into a single unit, separated

by an adjustable baffle. An internal recycling system was provided for the return of the activated sludge; no control and measurement of the recycle flow rate were possible and no activated sludge wasting line was installed. Employing a synthetic substrate, they found that, the activated sludge system can tolerate applied transients, up to three times the normal loading for 12 hours per day, for several days without showing any significant increase of effluent soluble organic matter.

In 1971 Ott and Bogan (11) reported on their theoretical investigation of activated sludge dynamics. They used an analog computer to simulate the dynamics of an activated sludge system with recycle. In their equations the recycle sludge concentration was related to the sludge concentration in the aeration tank by means of a final clarifier sludge compaction ratio without considering the dynamics of the final clarifier. They found that control of the input flow rate and the input BOD (Biochemical Oxygen Demand) appeared to provide the most effective means of regulating process performance.

Lee and Andrews (12) conducted a theoretical analysis of the dynamics and control of a multi-stage activated sludge process. They developed a dynamic model of the process including both a biological reactor and a clarifier for computer simulation. They superimposed a sinusoidal perturbation to the influent of the system and observed the responses of the underflow sludge concentration, sludge blanket depth and effluent concentration with different clarifier depths



and recycle ratios. They found that a dynamic input to the system would significantly affect the performance of the process and indicated that in a dynamic flow system the sludge-loading might be controlled properly by varying the recycle ratio or changing the pattern of inflow to the aeration tank.

Terajima et al. (13) investigated the dynamics of an activated sludge process with sludge recycle and wasting. They experimentally observed the response of the system to natural temperature changes. They also briefly investigated the response to a step change in influent COD loading from 0.125 to 0.25 kg COD/kg MLSS/day. They found that such a change in the COD loading gave rise to poor sedimentation within a week or so.

ATP (Adenosine Triphosphate) is a high-energy compound which is present in microorganisms, plants and animals. ATP is the carrier of chemical energy from the energy yielding catabolic pathways to the synthetic reactions which do not occur spontaneously and can proceed only if chemical energy is applied.

In 1970 Patterson et al. (14) reported that the ATP pool was found to reflect the toxicity of pH and a heavy metal (Mercury) to activated sludge cultures and appeared appropriate as an estimator of toxic stress on microbial systems. Using both laboratory and field studies they also demonstrated that the ATP pool responded rapidly to changes in the metabolic activity of activated sludge. They indicated that the ATP

measurement was more appropriate and desirable than biomass as a parameter in controlling a biological waste treatment process.

Brezonik and Patterson (15) concluded in 1971 that ATP is a specific measure of sludge activity and the ATP content per cell was affected by substrate loading. They also indicated that ATP measurement could be used to estimate viable biomass in the sludge.

In 1971 Weddle and Jenkins (16) also reported that ATP measurements were proportional to the viable cell content in the activated sludge under steady-state conditions, and would be an appropriate parameter to reflect biomass at growth rates commonly encountered in activated sludge system operation.

Recently Chiu et al. (17) conducted a series of experiments with steady-state continuous and batch cultures and found that the dilution rate can significantly affect sludge activity and cellular ATP content. They indicated that the microbial populations in continuous systems operated at high dilution rates had a high metabolic activity and a low ATP pool, while those species predominating at low dilution rates had a low metabolic activity and a high ATP content. Their results also showed that ATP concentrations were generally proportional to biomass concentration.

The overall objective of this study was to observe and investigate the dynamic responses of a laboratory activated sludge system when subjected to step changes of influent

organic concentration, step changes of recycle flow rate and step changes of sludge wasting rate. A study of the transient responses of the ATP concentration in the biological waste treatment process under dynamic conditions was also undertaken.

## 2. Materials and Methods

### A. Equipment

The equipment consisted of a 3-liter aeration tank, a 6-liter sedimentation tank and a 600-ml homogenizing chamber. A schematic diagram of this equipment is shown in Figure 6.

The aeration tank was made of plexiglass with thickness 0.5 inches. The aeration sparger consisted of three divided air-stones in the aeration tank. The desired temperature in the aeration tank was controlled by connecting a stainless steel heating and cooling coil in the aeration tank to a temperature-controlled water bath (Forma waterbath, refrigerated, by Forma Scientific, Inc., Menietta, Ohio) with a circulating pump. This pump continuously pumped water through the coil.

The effluent from the aeration tank flowed by gravity to the sedimentation tank. The sedimentation tank was constructed by modifying a 6-liter erlenmeyer flask. Both the aeration tank and the sedimentation tank were allowed to overflow as shown in Figure 6.

The system contained three pumps (Sigma motor pump, type AL-4-E-40, by Sigma Motor, Inc., Middleport, New York): one for incoming waste, one for pumping activated sludge from

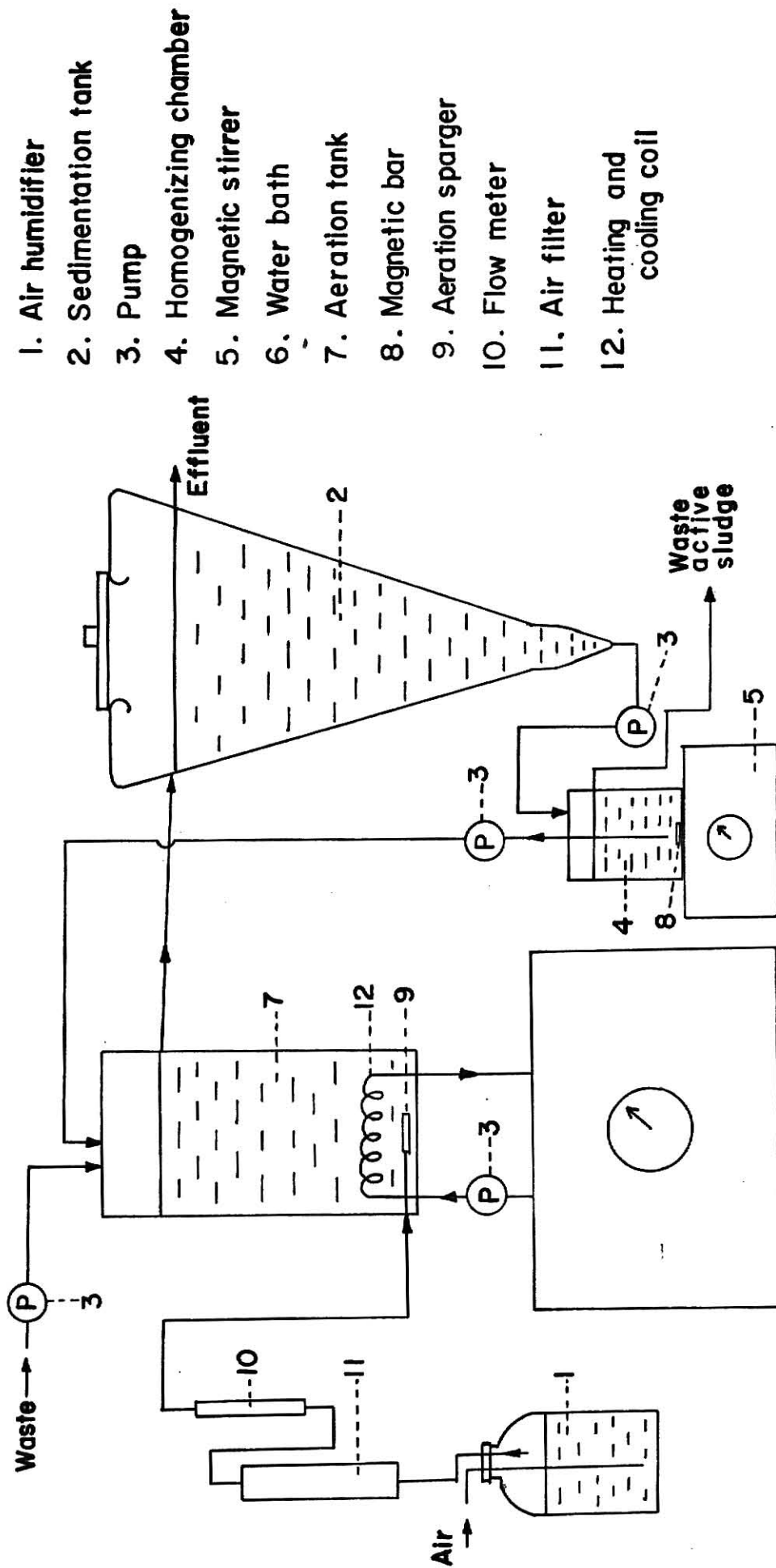


Fig. 6. Schematic diagram of experimental apparatus for investigation of activated sludge system dynamics.

the sedimentation tank to the homogenizing chamber and one for pumping activated sludge from the homogenizing chamber to the aeration tank. There was a magnetic stirrer (S/P Deluxe mixer, S-8200, by Scientific Products, Evanston, Illinois) beneath the homogenizing tank and a teflon-coated magnetic bar in the homogenizing tank for the agitation of the activated sludge.

The air was pumped by an air compressor through a humidifier, an air filter, and a flow meter to the sparger in the aeration tank.

#### B. Synthetic waste

The composition of the glucose-limiting media is shown in Table 8. Three compositions were used, namely, 1.0-fold, 1.5-fold and 0.5-fold.

#### C. Seed culture

Original seed culture was obtained from the municipal sewage treatment plant at Manhattan, Kansas. Two hundred milliliters of original seed from the primary clarifier were added to 800 ml of synthetic medium with 3-fold concentration in a glass jar and aerated moderately.

The culture was refreshed every day by discarding 80% of the culture solution from the jar and replenishing with fresh medium. After three days the seed culture was used as the inoculum to the continuous flow experimental system.

#### D. Analytical procedures

During the continuous culture experiments the cell

Table 8. Composition of synthetic waste.

Constituents	Concentration, mg/l		
	0.5-fold	1.0-fold	1.5-fold
Glucose, $C_6H_{12}O_6$	500.0	1000.0	1500.0
Ammonium sulfate, $(NH_4)_2SO_4$	250.0	500.0	750.0
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	50.0	100.0	150.0
Ferric chloride, $FeCl_3 \cdot 6H_2O$	0.25	0.5	0.75
Calcium chloride, $CaCl_2$	3.25	7.5	10.75
Manganese sulfate, $MnSO_4 \cdot H_2O$	5.0	10.0	15.0
Potassium phosphate, mono-basic, $KH_2PO_4$	263.5	527.0	790.5
Potassium phosphate, di-basic, $K_2HPO_4$	535.0	1070.0	1605.0

concentration in terms of mixed liquor suspended solids (MLSS), organic concentration in terms of chemical oxygen demand (COD), and adenosine triphosphate (ATP) concentration were analyzed.

MLSS was determined by the gravimetric method (18). Gravimetric measurements were conducted directly by weighing the dried suspended, non-volatile solids retained from filtration of samples through Millipore membrane filters with membranes of pore size 0.45  $\mu$ . The filtrate collected herein was used for dissolved COD analysis. For determination of the effluent COD the sample from the clarifier effluent was collected and analyzed by the dichromate method without filtering through a Millipore membrane.

The dichromate method, which is described in detail in "Standard Methods for the Examination of Water and Wastewater" (18), was employed for all the COD determinations.

The ATP concentration was determined by use of a DuPont 760 Luminescence Biometer (E. I. DuPont de Nemours & Co., Wilmington, Delaware). To prepare a sample for ATP measurement, 10 ml of the sample from the aeration tank was first diluted to a desired concentration and mixed well using a blender mixer. Then one ml of this diluted mixed liquor was mixed well with one ml butanol for 10 seconds to lyse the cells. This was followed by an addition of 8 ml of octanol, vigorous shaking for 10 seconds, and centrifugation at 3,000 rpm for 3 minutes. Butanol was partitioned into the top octanol layer and ATP into the aqueous layer. Using a syringe,

a quantity of 0.01 ml of the extracted ATP solution was then injected into a cuvette in the Luminescence Biometer which contained luciferase and luciferin. A flash of light occurred directly in front of a photomultiplier tube which converted the light into an electrical signal. The signal passed to a memory circuit where the peak intensity is stored and then converted to a decimal count displayed on a digital counter. The decimal count when properly calibrated represents the concentration of ATP in the sample.

### 3. Operating Procedures

To start a continuous culture experiment a batch culture was initiated by inoculating the aeration tank with an inoculum of 10% seed culture on a volume basis. After approximately 5 hours of batch cultivation, continuous flow was started.

The working volumes of the aeration tank and the sedimentation tank were fixed at 2 and 5 liters respectively. The working volume of the homogenizing chamber was maintained at 400 ml. The temperature of the culture was controlled at  $25 \pm 0.5^{\circ}\text{C}$ ; while the pH of the culture was controlled at  $6.8 \pm 0.35$  by the buffering action of the components in the synthetic waste.

The air flow rate to the aeration tank was maintained at 2.0 VVM (volume of air per volume of culture per minute). This substantially higher aeration rate was employed in order not only to supply sufficient dissolved oxygen but also to



maintain sufficiently vigorous mixing in the aeration tank. The dissolved oxygen concentration under this aeration rate was maintained above 2 mg/l. This was assumed to be higher than the critical oxygen requirement of the microorganisms in the activated sludge.

The continuous culture was initially operated under the following nominal condition:

Influent COD concentration: 1000 mg/l.

Influent flow rate: 25 ml/min.

Recycle flow rate: 10 ml/min.

Sludge wasting flow rate: 2.5 ml/min.

After the system had been operated continuously for 5 days under the nominal condition upon which a steady state was established, one of the following six different kinds of step changes was introduced;

- 1) step increase in the influent organic concentration.
- 2) step decrease in the influent organic concentration.
- 3) step increase in the recycle flow rate.
- 4) step decrease in the recycle flow rate.
- 5) step increase in the active sludge wasting flow rate.
- 6) step decrease in the active sludge wasting flow rate.

After each dynamic run the system was adjusted back to the nominal operating condition for 5 days before a new step change was applied.

The flow rates of influent waste, recycle activated sludge and sludge wasting were checked once a day to see if the desired pumping rates were maintained. The pumping rates

usually deviated less than  $\pm 5\%$  from day to day. With each calibration, the pumping rates were adjusted back to the desired values.

#### 4. Results and Discussion

##### A. Response of the system to a step increase in the influent organic concentration

In this experiment the step size of 500 mg/l was selected. After the system had been running at the nominal condition (see Operation Procedures) for 5 days the influent glucose concentration was increased from 1000 mg/l to 1500 mg/l. The actual measured step change in this experiment was from 1016 mg/l to 1528 mg/l of COD concentration. The results of this experiment are shown in Figure 7.

The dissolved COD in the aeration tank, the effluent COD, and the ATP concentration in the aeration tank changed significantly in the first thirty minutes following the step change. The effluent COD (the effluent from the sedimentation tank) increased from 150 to a peak value of 300 mg/l within 0.5 hours after the step change. Then it slowly decreased to 130 mg/l; this required about 10 hours. It increased to about 165 mg/l at the time of 36 hours after the step change and then decreased to 142 mg/l at 47 hours. It is doubtful that this large initial increase of effluent COD could have been caused by the increased cell production which resulted from the increased influent organic concentration because the response was very rapid. A change in the physiological state of the organisms entering the clarifier may have resulted

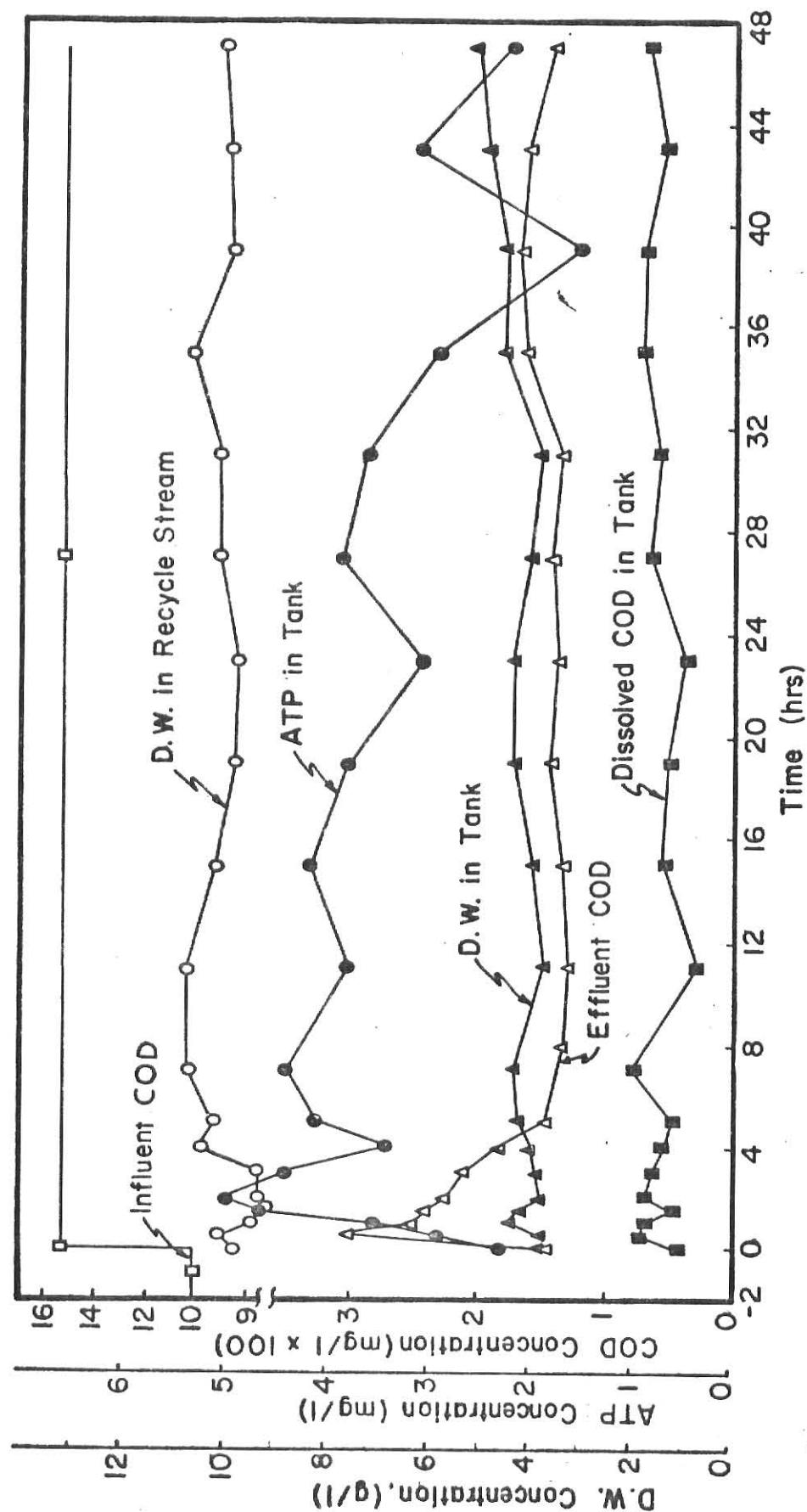


Fig. 7. Response of the system to a step increase in influent COD concentration from 1016 mg/l to 1528 mg/l (D.W. refers to dry weight or MLSS).

from the sudden increase in the influent substrate concentration. The change in the clarification efficiency is also indicated by other results in Figure 7. For example, the recycle sludge concentration decreased during the first several hours of the experiment. Practically speaking, this change in the effluent COD had a significant effect on the efficiency of the treatment process.

The dry weight concentration in the recycle stream fluctuated in the initial 5 hours after the step change. It decreased in response to the initial increase in effluent COD, but then it increased as clarifier performance improved. It increased from an initial value of 9.7 g/l to 10.7 g/l after 7 hours. It dropped slowly to 9.8 g/l at 23 hours, and then fluctuated between 9.8 g/l and 10.7 g/l for the remainder of the experiment. Comparison between the initial and final values shows that the recycle cell concentration increased only about 3% because of the step change.

The dry weight concentration of cells in the aeration tank increased from an initial value of 3.9 g/l to a final value of 5.0 g/l. Some increase was expected since more organic substrate was put into the system after the step change. However, the net increase was significantly larger than would be predicted from the increased cell production (500 mg/l of COD should yield about 300 mg/l of suspended solids). The magnitude of the initial dynamic response of the cell dry weight in the aeration tank was about 300 mg/l. The dynamic response was probably influenced by both the

increased organic load and the dynamics of the recycle cell concentration.

The dissolved COD concentration in the aeration tank increased initially and then decreased, perhaps in response to the increase in the cell concentration because it increased again as the cell concentration decreased. There was a net increase in the dissolved COD concentration of about 30 mg/l during the experiment.

Shilling (19) describes four different ways to estimate the time constant when a first order response is obtained following a step change. These four methods (19) are briefly described in Appendix II. The time constant is an important parameter since it is a measure of the response rate of a dynamic system.

The effluent COD response was analyzed and a time constant of 3.1 hours was found when the peak level of the effluent COD concentration was treated as the initial point. In other words, it took 3.1 hours for the effluent COD concentration to complete 63.2% of its response.

The response of the ATP concentration in the aeration tank was remarkable. The ATP concentration in the aeration tank increased from 1.85 to 5.0 mg/l within 2 hours after the step change. Then, it decreased with considerable fluctuation. A plot of ATP/MLSS versus time was also constructed (see Figure 8). The dissolved COD is also plotted in Figure 8 because the ATP concentration appears to be affected by the dissolved COD concentration. The step increase in the organic

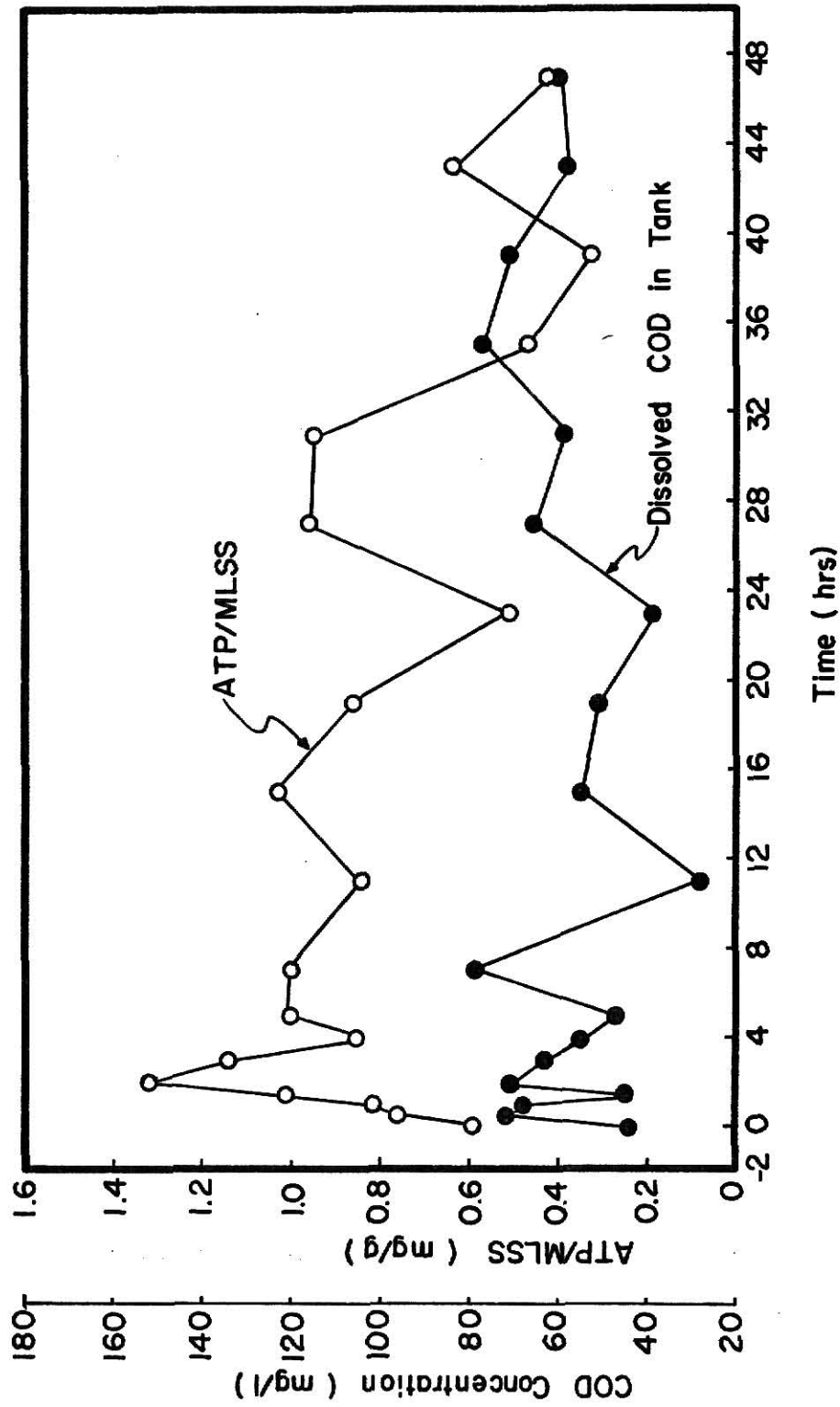


Fig. 8. Response of ATP/MLSS and dissolved COD in aeration tank to a step increase in influent COD concentration from 1016 mg/l to 1528 mg/l.

substrate concentration appears to have caused the cells to build a larger ATP pool. After the cells adapted to the new nutritional condition, they did not appear to require as much energy; thus, the ATP pool eventually dropped to a new level.

Chiu et al. (17) found that in a continuous mixed culture system the ATP/MLSS value decreased as the dilution rate was increased. Such a change could often be associated with population shifts. The increase in the influent COD concentration basically corresponds to an increase in the dilution rate (both increase the cell's food supply). Figure 8 shows that the ATP/MLSS decreased from an initial value of 0.59 mg/g to a final value of 0.43 mg/g which is in agreement with Chiu's observation. Figure 8 shows that the dissolved COD in the aeration tank increased which is also in agreement with Chiu's results.

During the first 31 hours the variation in ATP/MLSS and the variation in the dissolved COD appear to be directly related; however, after 31 hours a change in the relationship appears to take place. This may be due to a population shift.

From the result of this experiment one can realize that an increase in the influent waste concentration can significantly affect the treatment efficiency. In most waste treatment plants, variations in the influent waste concentration frequently occur. The effect of these variations on process performance can be significant.

## B. Response of the system to a step decrease in the influent organic concentration

The results of this experiment are shown in Figure 9. The influent COD concentration was reduced from 1070 mg/l to 535 mg/l.

As shown in Figure 9, the cell dry weight in the recycle stream gradually decreased from an initial value of 6.5 g/l to 3.4 g/l after 37 hours. The step decrease in the influent COD concentration resulted in a reduced rate of cell production and a decrease in the cell concentration. The analysis shows that the time constant of this step response was about 19.3 hours.

The dry weight concentration in the aeration tank also decreased slowly from 2.9 g/l at the starting time to about 1.6 g/l after 29 hours. The response of the dry weight concentration had a time constant of about 17.5 hours. This is slightly smaller than that of the dry weight concentration in the recycle stream. This difference may be due to the fact that the cell mean residence time is smaller in the aeration tank than in the sedimentation tank and homogenizer.

The cell mean residence time for the system was evaluated from available and estimated information. Using a value of 10 grams of cells in the clarifier, concentrations of 2.8 g/l in the aeration tank and 6.4 g/l in the homogenizer with working volumes of 2.0 and 0.4 liters respectively, and a sludge wasting rate of 0.96 grams cells per hour ( $0.15 \text{ l/hr} \times 6.4 \text{ g/l}$ ), a cell mean residence time of 19 hours was obtained.



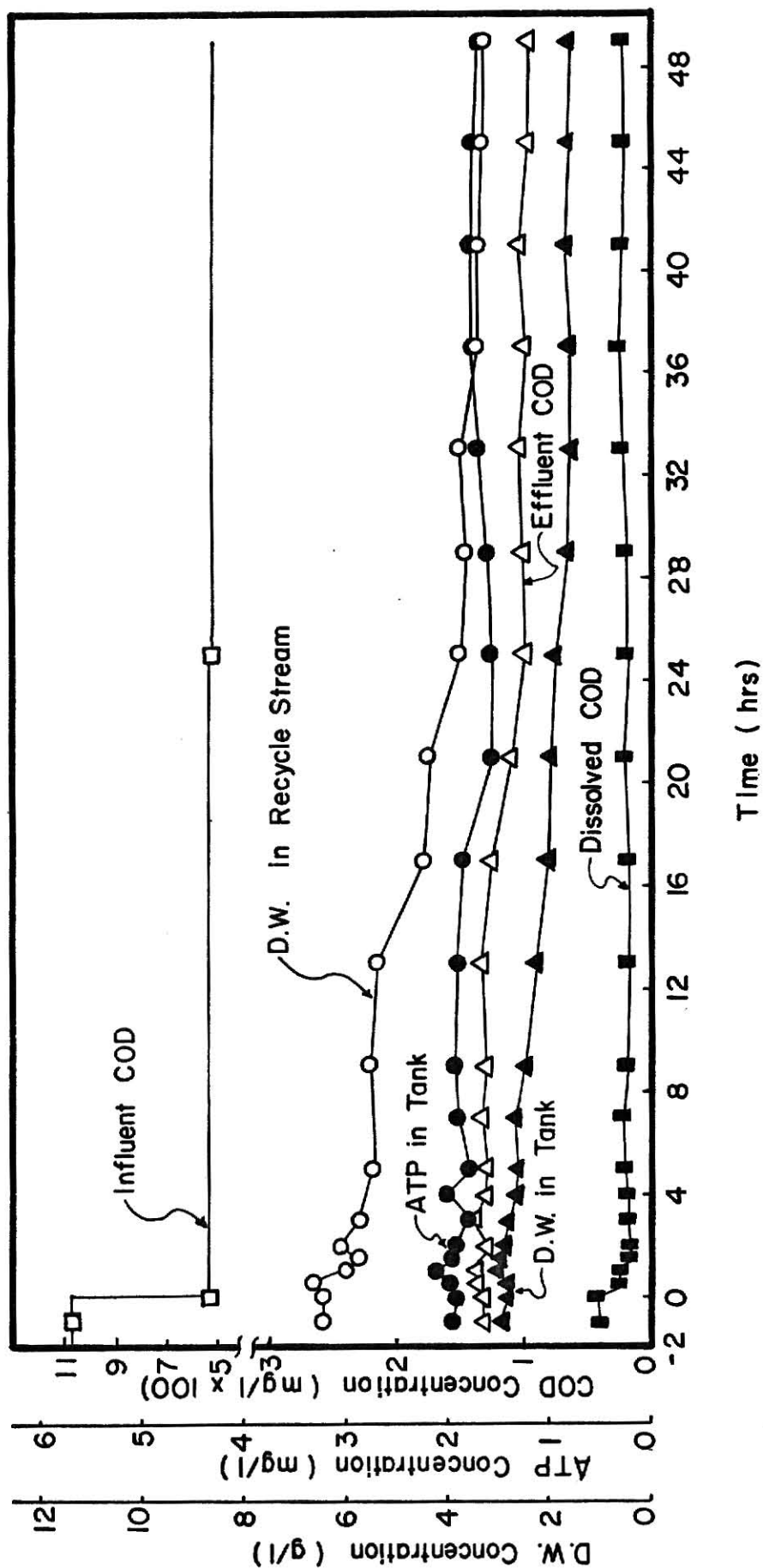


Fig. 9. Response of the system to a step decrease in influent COD concentration from 1070 mg/l to 526 mg/l.

This cell mean residence time is of the same order of magnitude as the time constants of the dry weight concentration in the recycle stream and the dry weight concentration in the aeration tank.

The dissolved COD concentration in the aeration tank decreased from 42 mg/l at the starting time to about 18 mg/l after 2 hours. The time constant for the response of the dissolved COD in the aeration tank has a value of 0.75 hours. This small time constant indicates that it takes a much shorter period of time for the dissolved COD in the aeration tank to respond to the step change in influent COD.

The fluid mean residence time in the aeration tank was calculated to be 0.95 hours. This demonstrated that the time constant of the dissolved COD in the aeration tank was closely related to the fluid mean residence time in the aeration tank.

The effluent COD fluctuated some initially. The step change resulted in a decrease from the initial value of 132 mg/l to a final value of 100 mg/l. This change occurred in the time period from 13 hours to 25 hours.

The ATP concentration in the aeration tank decreased slowly from an initial value of 1.9 mg/l to a final value of 1.7 mg/l. Comparison of this result to the result in A showed that the response of the ATP concentration in the aeration tank to a step decrease in the influent COD concentration was more stable than that to a step increase in the influent COD concentration.

The ATP/MLSS and the dissolved COD in the aeration tank were plotted versus time as shown in Figure 10. In response to the step decrease in the influent COD concentration, the ATP/MLSS increased slowly from an initial value of 0.67 mg/g to 1.0 mg/g after 29 hours, while the dissolved COD decreased. These results are again in agreement with that of Chiu et al. (17) since a step decrease in the influent COD concentration and a decrease in the dilution rate of the system both result in a reduced flow of substrate into the system.

#### C. Response of the system to a step increase in the recycle flow rate

This experiment and the next one deal with the response of the treatment system to step changes in the recycle flow rate. In this experiment the system was initially maintained at the nominal condition (see Operating Procedures) for 5 days. To start the dynamic experiment, the recycle flow rate was changed from 10 ml/min to 15 ml/min; that is, from 40% to 60% of the influent flow rate. The response of the system to this step change is shown in Figure 11.

The dry weight concentration in the recycle stream was relatively constant during the experiment. It decreased from 7.7 g/l to 7.3 g/l in the initial 3 hours and other small fluctuations were observed. The higher flow rate to the clarifier and the higher recycle rate did not significantly alter the recycle sludge concentration.

The dry weight concentration in the aeration tank increased from 3.2 g/l to 4.0 g/l during the first 1.5 hours,

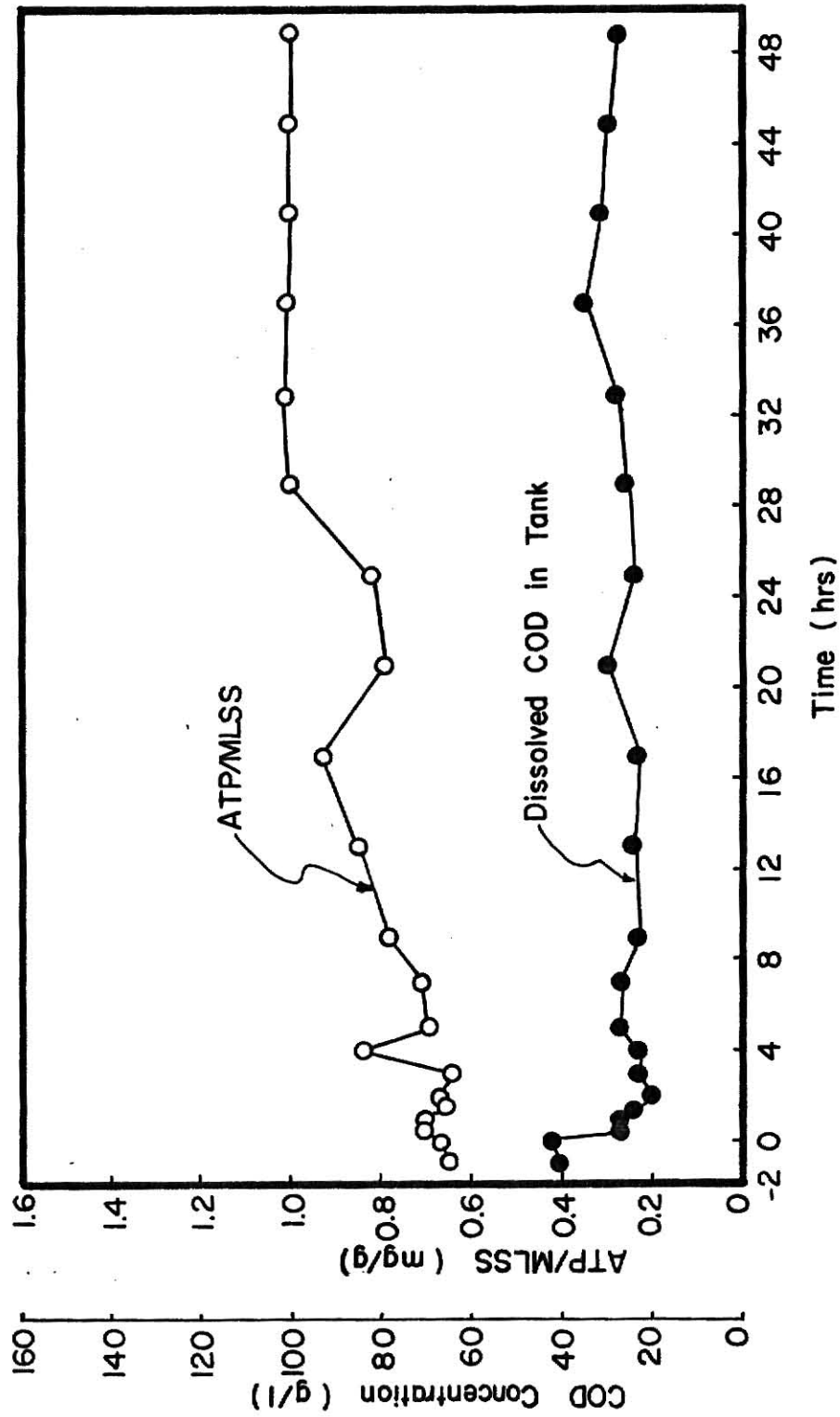


Fig. 10. Response of ATP/MLSS and dissolved COD in aeration tank to a step decrease in influent COD concentration from 1070 mg/l to 526 mg/l.

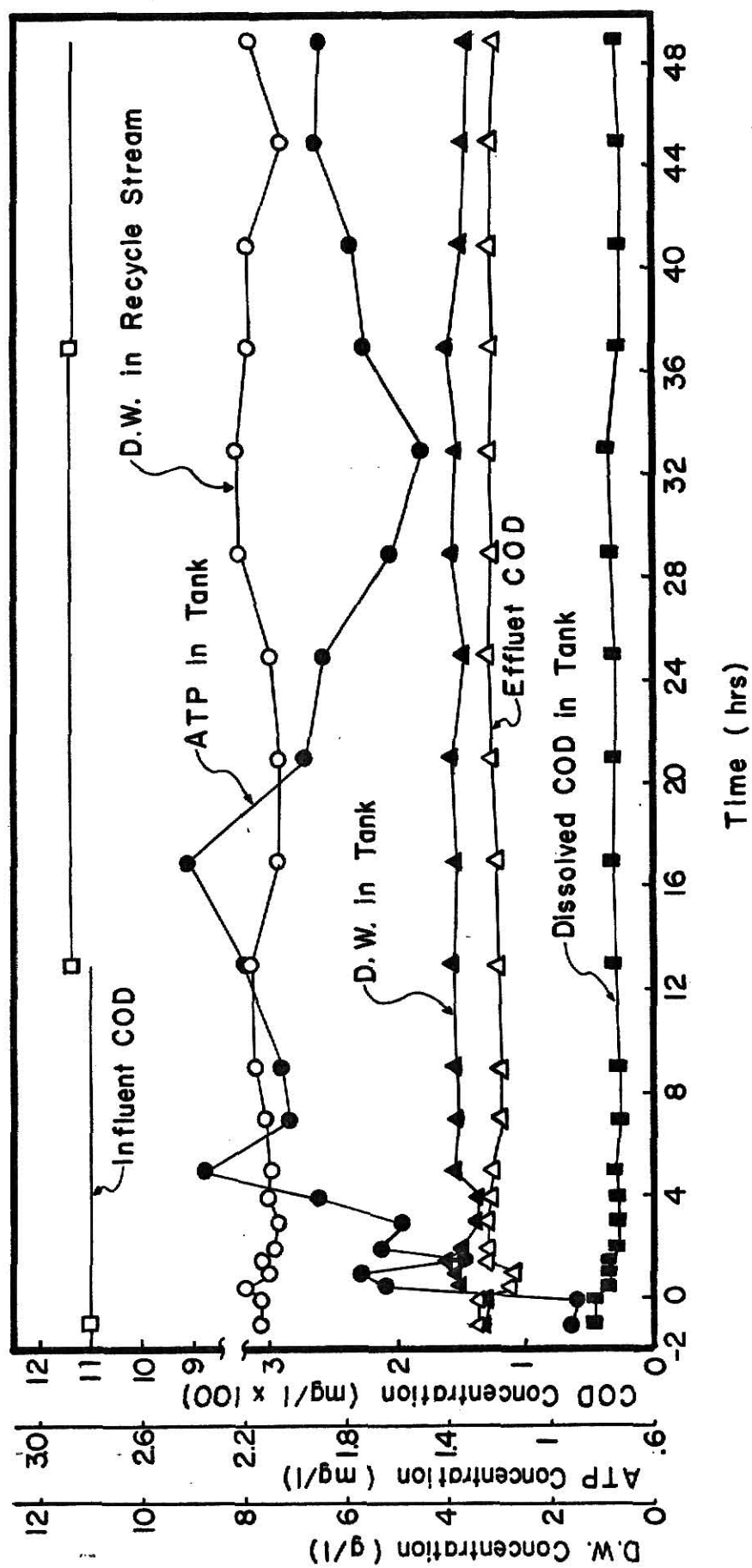


Fig. 11. Response of the system to a step increase in recycle flow rate from 10 ml/min to 15 ml/min.

then decreased to 3.5 g/l at 3 hours, and finally it increased to about 3.8 g/l at about 5 hours after introduction of the step change; it remained fairly steady thereafter. The time constant of the initial increase of this response was evaluated to be 0.4 hours.

The net increase in the cell concentration in the aeration tank was due to the increase in the recycle flow rate which transferred additional cells to the aeration tank.

The dissolved COD concentration in the aeration tank decreased from 45 mg/l to 30 mg/l in the first two hours and remained near this level throughout the rest of this experiment. The time constant for this response was 0.97 hours which is slightly larger than the aeration tank mean residence time of 0.83 hours.

The effluent COD concentration decreased from 135 mg/l to 110 mg/l in the first hour. This can be attributed to the lowering of the sludge blanket in the clarifier which improved clarification. However, as the sludge loading on the clarifier increased, the effluent concentration also increased. After about 2 hours the effluent COD concentration had increased to about 125 mg/l. Comparing this to the initial steady state value of 135 mg/l, it can be seen that the increase in the recycle flow rate led to an improvement in process performance. This improvement can be attributed to the additional substrate consumption which occurs in the aeration tank.

The ATP concentration in the aeration tank increased significantly from 0.9 to 2.3 mg/l during the initial 5 hours after the step change. It fluctuated during the next 16 hours, and then decreased to 1.5 mg/l at 33 hours after the step change was made. Finally it increased slowly to 1.09 mg/l at the end of the experiment.

Figure 12 shows a plot of the ATP/MLSS and the dissolved COD in the aeration tank versus time. The ATP/MLSS increased while the dissolved COD decreased in response to the step change. Since the substrate must be divided among a larger number of cells after the step change, this response is in agreement with that of Chiu et al. (17).

#### D. Response of the system to a step decrease in the recycle flow rate

In this experiment a step change in the recycle flow rate from 10 ml/min to 5 ml/min was carried out. This corresponded to a change from 40% to 20% of the influent flow rate. The results of this experiment are shown in Figure 13.

The dry weight concentration in the recycle stream appeared to fluctuate around 7.8 g/l throughout the experiment. The dry weight concentration in the aeration tank decreased from 4.1 g/l at the starting time to 3.4 g/l after 3 hours of operation, but it increased to 3.7 g/l at about 8 hours after the step change was made. It remained fairly steady thereafter. This decrease in the dry weight concentration in the aeration tank resulted because of the

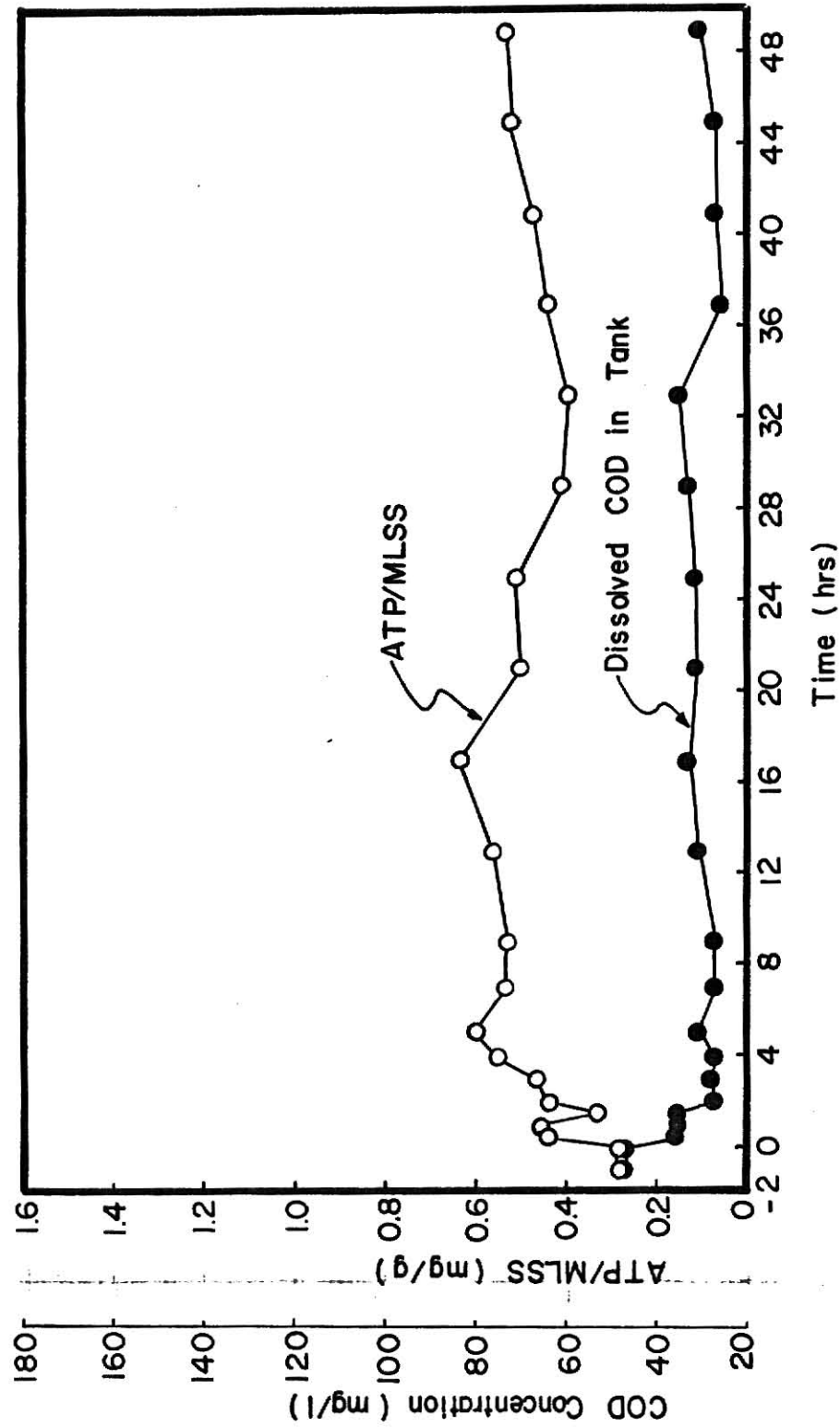


Fig. 12. Response of ATP/MLSS and dissolved COD in aeration tank to a step increase in recycle flow rate from 10 ml/min to 15 ml/min.



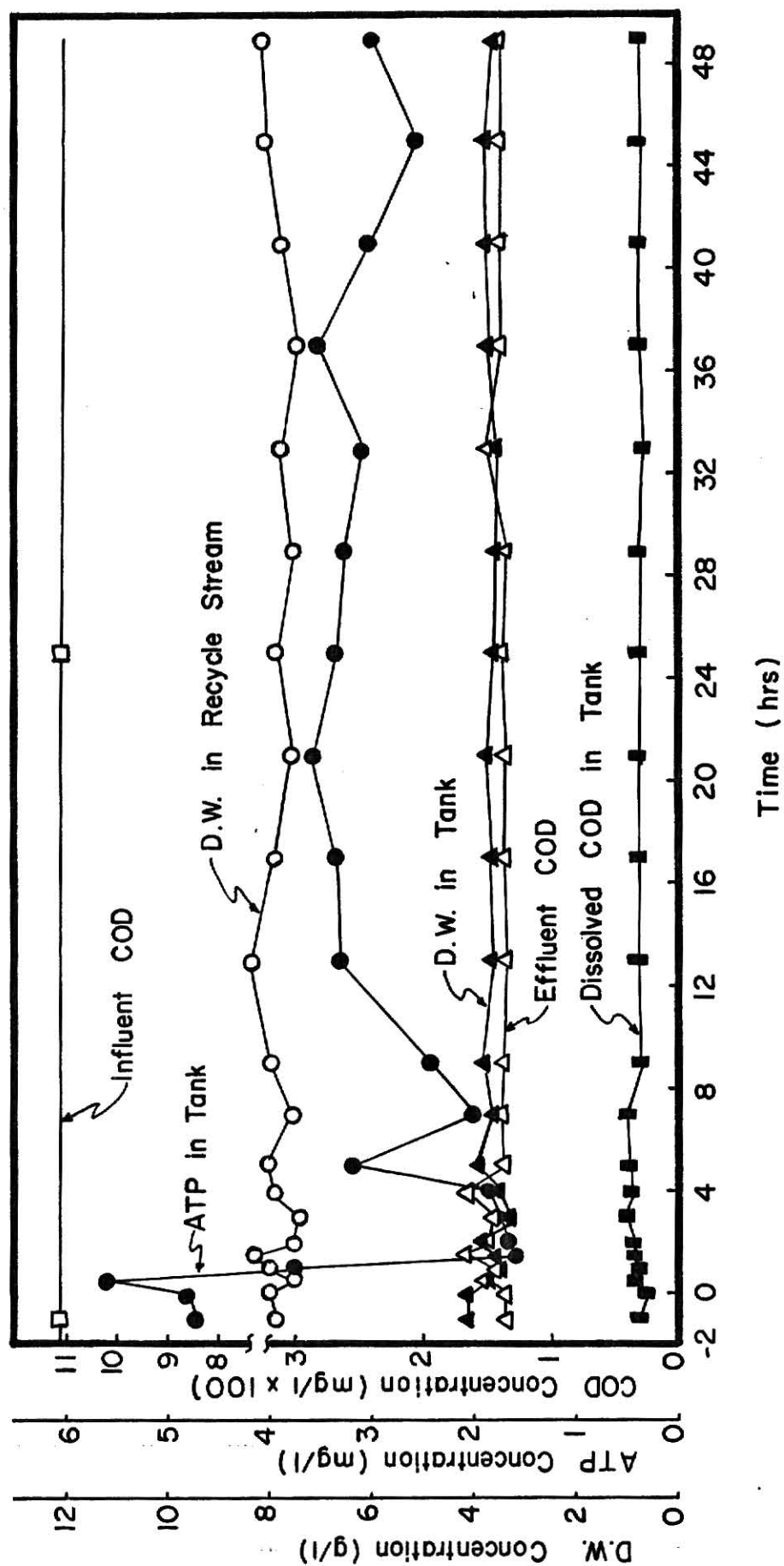


Fig. 13. Response of the system to a step decrease in recycle flow rate from 10 ml/min to 5 ml/min.

decrease of the recycle flow rate. A larger decrease than that observed here was predicted by making a mass balance around the aeration tank. Some change in the sedimentation of cells in the aeration tank may have resulted because of the decrease in the flow rate. The time constant was evaluated to be 0.7 hours which is smaller than the aeration tank mean residence time of 1.1 hours. This may be again attributed to the change in the sedimentation of cells in the aeration tank.

The dissolved COD concentration in the aeration tank increased from 25 mg/l to 40 mg/l in the first hour, and then it decreased to about 31 mg/l at 9 hours. It remained at this level throughout the remainder of this experiment. The time constant of this response had a value of 0.8 hours. The increase in the dissolved COD concentration in the aeration tank was primarily due to the decrease in the cell concentration in the aeration tank.

The decrease in the recycle flow rate also resulted in an increase in the effluent COD from the initial value of 135 mg/l to about 160 mg/l at 4 hours after the step change. It decreased to about 140 mg/l at 5 hours and remained near this value till the end of the experiment.

The ATP concentration in the aeration tank started at a value of 4.7 mg/l and increased to 5.6 mg/l after 1 hour, but it then decreased sharply to 1.6 mg/l at 1.5 hours. Later the ATP concentration increased slowly to a level of about 3.3 mg/l at 13 hours. It remained relatively constant

from 13 hours to 37 hours and then decreased.

Figure 14 shows a plot of the ATP/MLSS and the dissolved COD in the aeration tank versus time. When the initial and final values were compared, it was found that the ATP/MLSS decreased from 1.17 to 0.8 mg/g and the dissolved COD in the aeration tank increased from 25 to 31 mg/l. This response is in agreement with that of Chiu et al. (17) since the cell concentration decreased after the step change.

#### E. Response of the system to a step increase in the sludge wasting flow rate

This experiment and the next were designed to investigate the responses of the system when subjected to changes the sludge wasting flow rate. A step increase in the sludge wasting flow rate resulted in a decrease in the cell concentration and vice versa.

In this experiment a step change in the sludge wasting rate from 2.5 ml/min to 5.0 ml/min was arranged; this corresponded to an increase from 10% to 20% in the influent flow rate. The results are shown in Figure 15.

As shown in Figure 15, the dry weight concentration in the recycle stream decreased continuously from 7.1 g/l to about 3 g/l within 29 hours after the step change. It remained fairly stable in the rest of the experiment. This decrease in the dry weight concentration in the recycle stream undoubtedly was due to the increase in the sludge wasting rate. The time constant of this response was evaluated using the

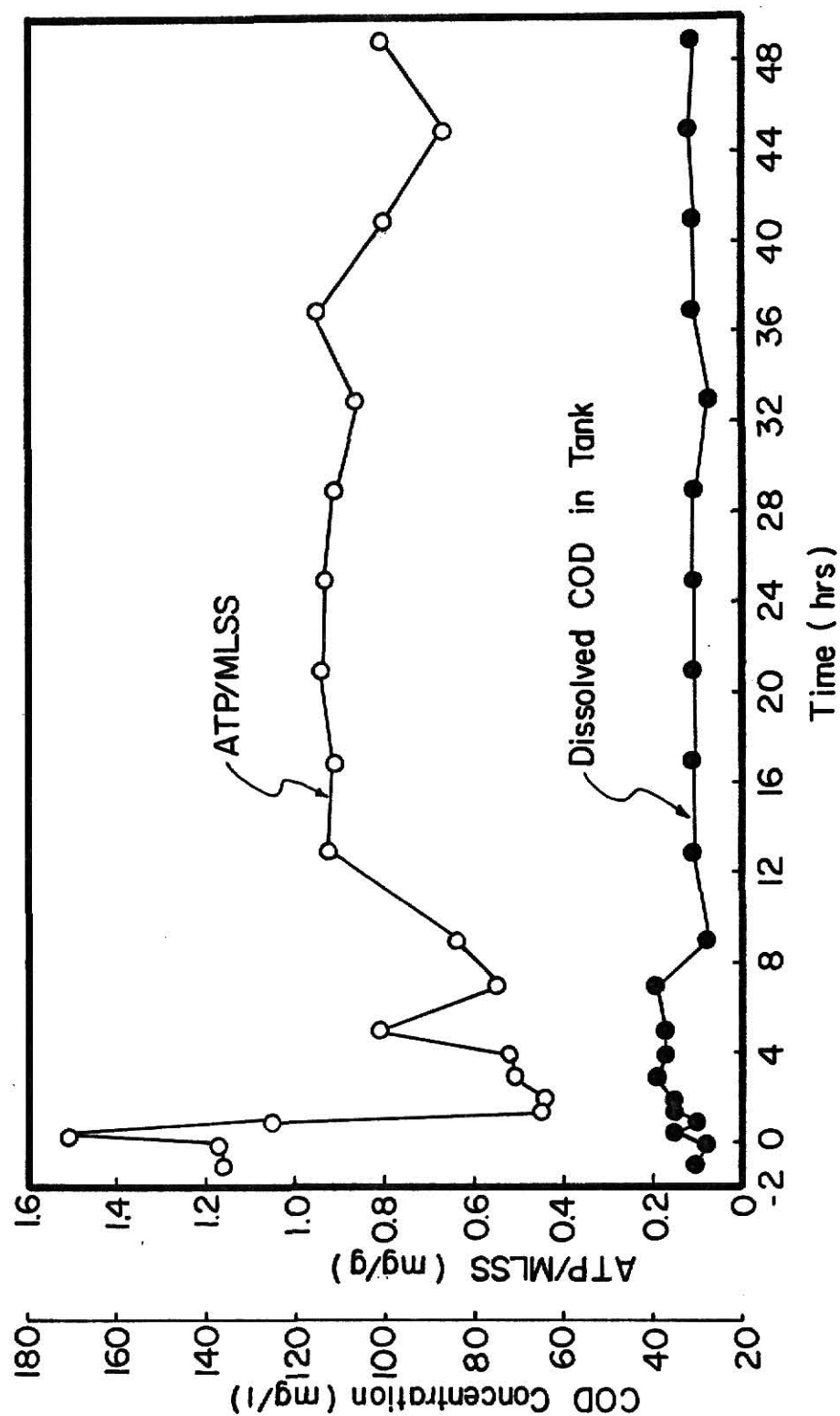


Fig. 14. Response of ATP/MLSS and dissolved COD in aeration tank to a step decrease in recycle flow rate from 10 ml/min to 5 ml/min.

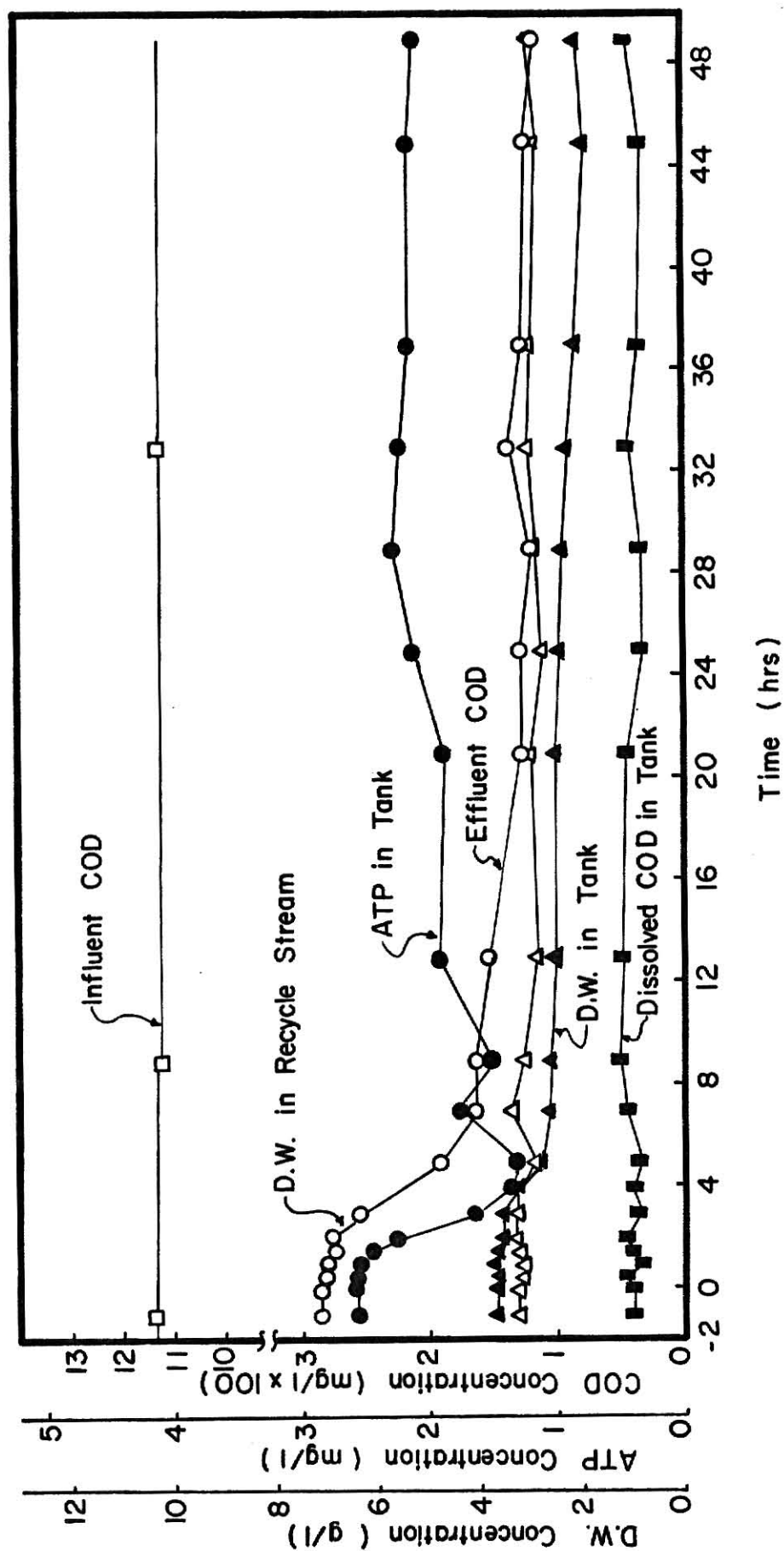


Fig. 15. Response of the system to a step increase in wasting flow rate from 2.5 ml/min to 5 ml/min.

four methods described in Appendix II. The time constant of this response was 9 hours.

The dry weight concentration in the aeration tank also decreased from 3.7 g/l at the starting time to about 0.9 g/l at 40 hours after the step change was made. The time constant of this response was also found to be 9 hours. This indicated that both the transient responses of dry weight concentration in the recycle stream and in the aeration tank were closely related. In addition, this experiment demonstrated that some control of the sludge concentration in the aeration tank can be obtained by controlling the sludge wasting rate.

The effluent COD concentration decreased from 130 mg/l at the initial steady state to about 120 mg/l at 13 hours after the step change. It remained fairly stable thereafter. This decrease in the effluent COD concentration was attributed to improved clarification. The increase of sludge wasting resulted in a decrease in the effluent flow rate and a decrease in the sludge concentration.

The ATP concentration in the aeration tank decreased sharply from 2.6 to 1.3 mg/l in the first 4 hours. It then recovered slowly to about 2.0 mg/l at 28 hours after introduction of the step change; then it kept fairly steady thereafter.

The ATP/MLSS and the dissolved COD in the aeration tank were plotted against time as shown in Figure 16. The ATP/MLSS decreased initially while the dissolved COD concentration

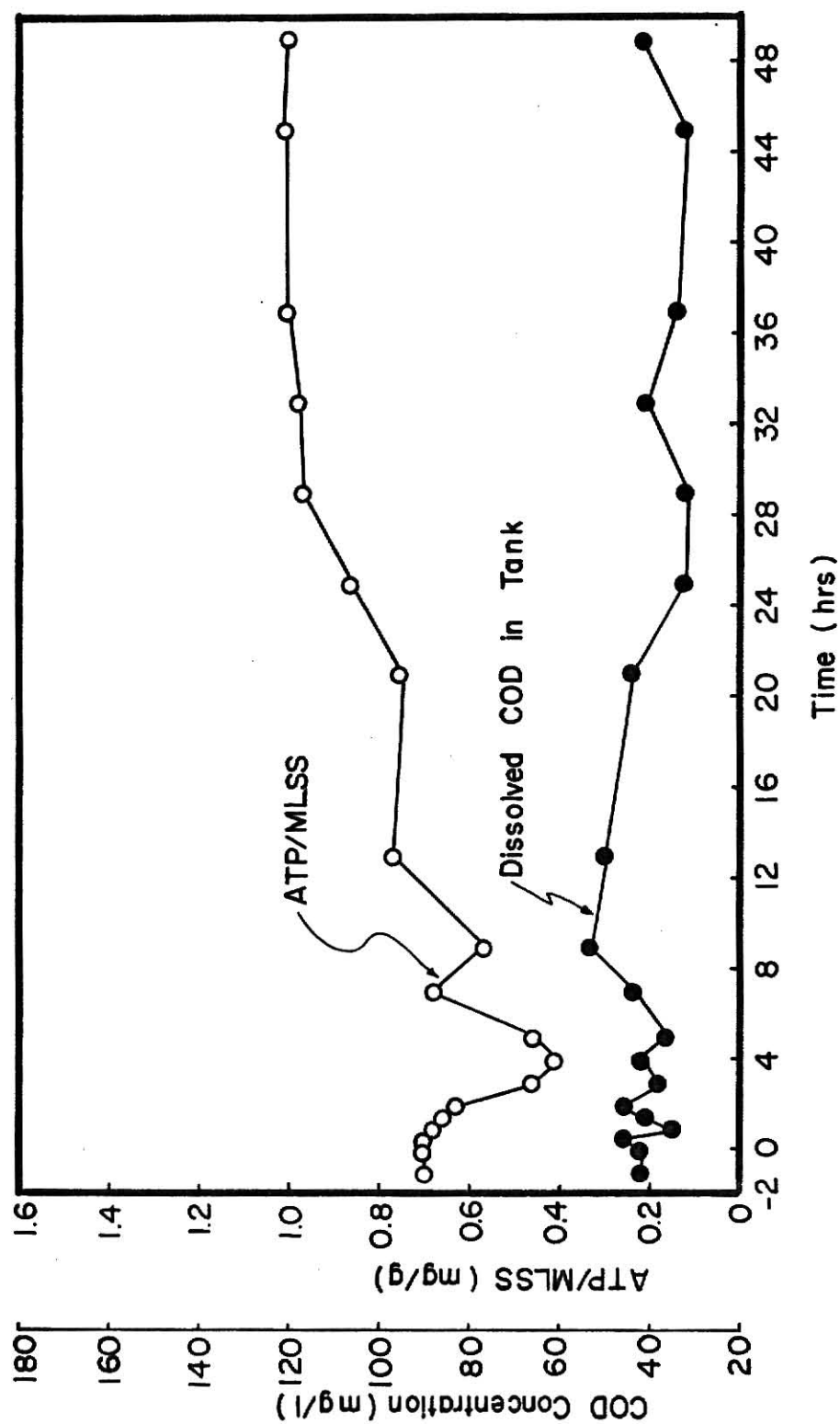


Fig. 16. Response of ATP/MLSS and dissolved COD in aeration tank to a step increase in wasting flow rate from 2.5 ml/min to 5 ml/min.

increased. This is again in agreement with the results of Chiu et al. (17). However, from 9 hours till the end of the experiment the ATP/MLSS increased and the dissolved COD in the aeration tank decreased. A cell population shift could explain these results. The higher wasting rate of sludge could have resulted in an increase in viability which would in turn show an increase in ATP/MLSS.

#### F. Response of the system to a step decrease in the sludge wasting flow rate

A step change from 2.5 to 0 ml/min of the sludge wasting flow rate was made in this experiment. In other words, at the starting time the sludge wasting flow rate was decreased from 10% of the influent flow rate to no wasting of activated sludge. Figure 17 shows the results of this experiment.

The dry weight concentration in the recycle stream increased continuously throughout the experiment from an initial steady state of 8.6 g/l to 13.4 g/l at the end of experiment. This resulted because no sludge was wasted. Using Method IV in Appendix II, the time constant of this response was evaluated and found to have a value of 41 hours; the terminal dry weight concentration was also estimated to be 15 g/l. From this time constant analysis and the results in Figure 17, it appears that the response to the step change was not complete when the experiment was terminated.

The dry weight concentration in the aeration tank also continuously increased from 3.5 g/l at the starting time to 4.7 g/l at the end of the experiment. The time constant



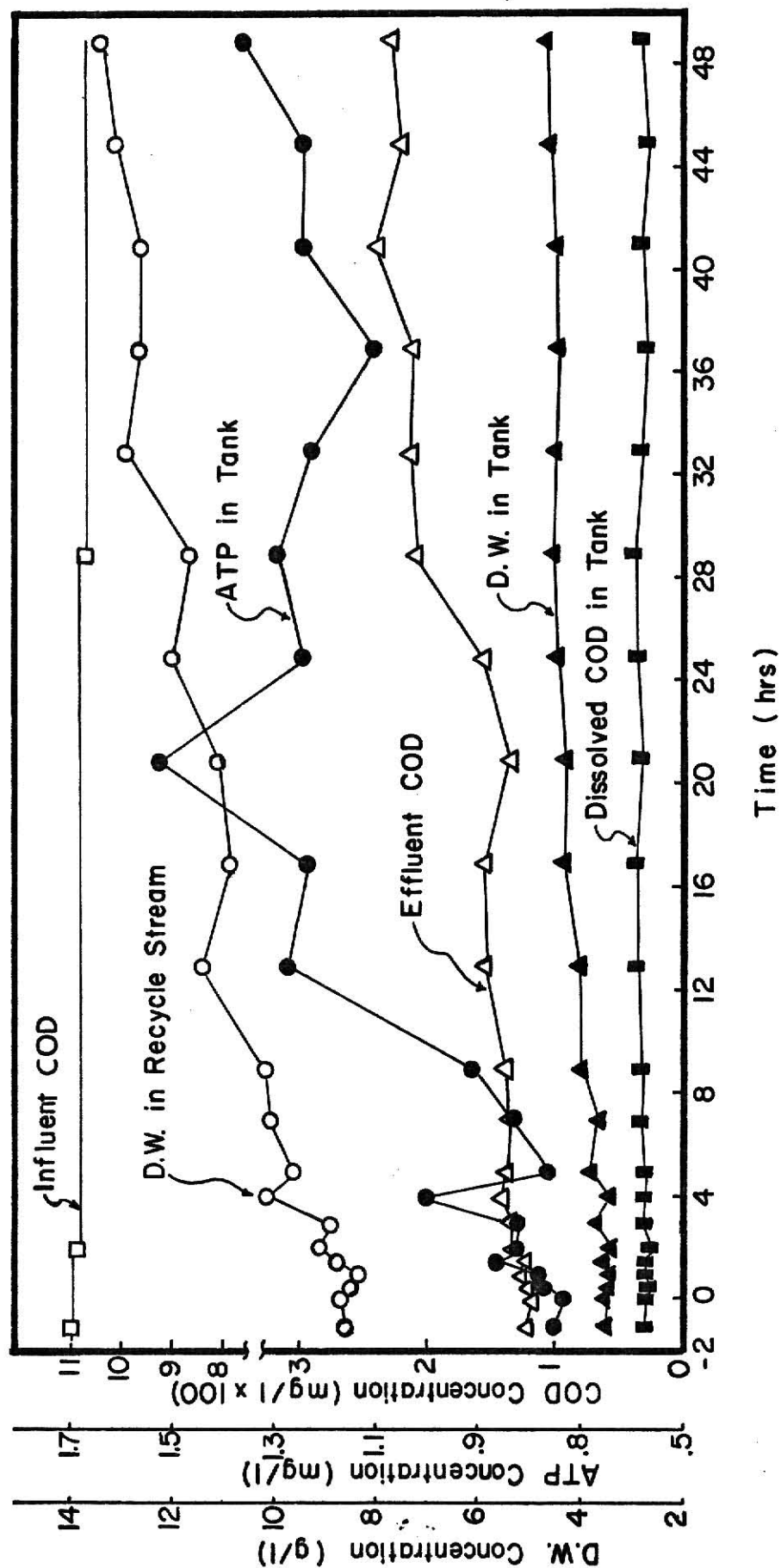


Fig. 17. Response of the system to a step decrease in wasting flow rate from 2.5 ml/min to 0 ml/min.

was evaluated to be 27 hours; while the terminal value of the dry weight concentration in the aeration tank was estimated to be about 5 g/l. The dry weight concentration in the aeration tank took a shorter period of time to respond to this step change compared to that of the dry weight concentration in the recycle stream.

The effluent COD concentration continuously increased from 120 mg/l to about 230 mg/l during the experiment. Using Method IV in Appendix II the time constant of this step response was estimated to be 45 hours and the terminal effluent COD concentration was also estimated to be about 290 mg/l. It appears that the responses of the effluent COD concentration and the dry weight concentration were directly related. The level of the sludge blanket increased in this experiment until the sludge losses in the effluent were sufficient to achieve a new steady state. The values of the time constants for effluent COD and the dry weight in the recycle stream are probably both related to the time required to achieve a new sludge blanket level in the clarifier.

The ATP/MLSS and the dissolved COD concentration in the aeration tank versus time were plotted as shown in Figure 18. The ATP/MLSS increased and the dissolved COD concentration in the aeration tank decreased during the first two hours; this is in agreement with the results of Chiu et al. (17). However, during the rest of the time period the ATP/MLSS increased slightly while the dissolved COD concentration also increased.

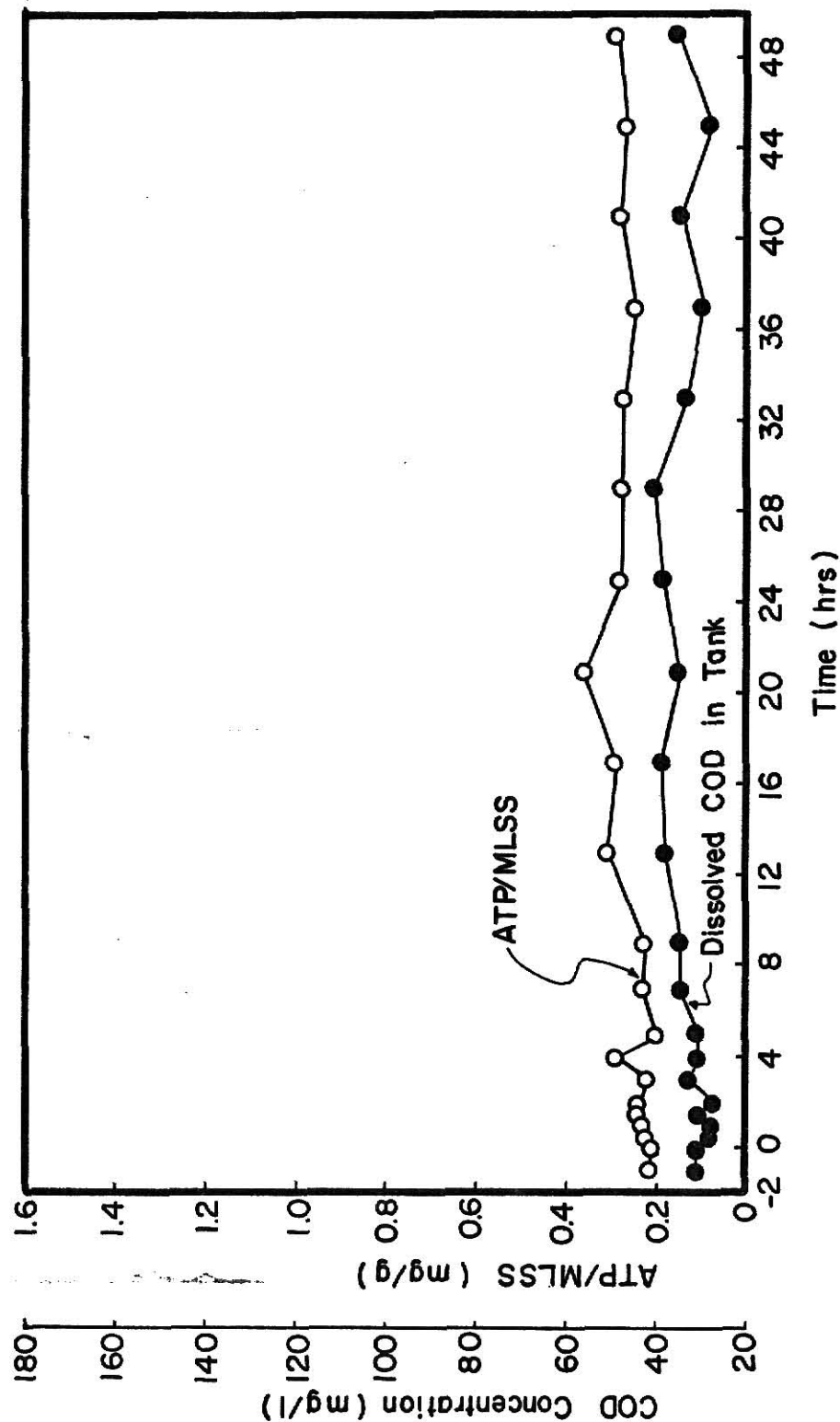


Fig. 18. Response of ATP/MLSS and dissolved COD in aeration tank to a step decrease in wasting flow rate from 2.5 ml/min to 0 ml/min.

#### G. Average ATP/MLSS values in the dynamic experiments

The average values of ATP/MLSS for the experiments conducted in this chapter were calculated. Table 9 shows these values for each dynamic experiment. The ATP/MLSS value of 0.26 mg/g in the last run was especially low compared to the other ATP/MLSS values. This could be partly attributed to the accumulation of non-viable material after long-term continuous operation which increased the ratio of non-viable to viable sludge. However, some shifts in dominant population may also be responsible for these changes.

The average ATP/MLSS values from runs A to E were close to those between dilution rates 0.4 and 0.6 of Chiu et al. (17).

### 5. Conclusions

Using a laboratory-scale biological waste treatment system with recycle and wasting of sludge, it was found that system performance changed appreciably when the system was subjected to step changes in the influent waste concentration, the recycle flow rate, or the sludge wasting rate.

Generally the responses to a step increase and a step decrease for the same kind of forcing were not symmetrical, especially in the response of the ATP concentration. Population shifts and differences in the mechanisms of metabolic adjustment may account for these differences.

The ATP/MLSS ratio was found to depend on the food to organism ratio in the aeration tank. When this ratio was

Table 9. Average ATP/MLSS values in the aeration tank of dynamic experiments.

Run	Average ATP/MLSS (mg ATP/g MLSS)
A	0.89
B	0.84
C	0.47
D	0.82
E	0.74
F	0.26

small, the ATP/MLSS was large. These results are in general agreement with those found by Chiu et al. (17). Because of variations of this type, the ATP concentration often did not have the same transient response as the MLSS. Thus, measurement of ATP will not generally give a good estimate of MLSS under transient conditions.

The time constant analysis showed that the dry weight time constants were directly related to the sludge mean residence time; as the sludge wasting rate increased, the value of the time constant decreased. The time constants of the dissolved COD variation in the aeration tank were much smaller than the time constants of the sludge dynamics. The dissolved COD time constants were found to be closely related to the fluid mean residence time in the aeration tank.

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## CHAPTER IV. CONCLUSIONS AND RECOMMENDATIONS

In a two-tank step aeration activated sludge waste treatment system with recycle and wasting of activated sludge, the volume ratio and the inlet flow rate ratio were found to have a significant influence upon the steady state performance of the treatment process. The optimum operating condition was determined by the EVOP technique. For the specific system employed, the optimum volume ratio was 0.50 and the optimum inlet flow rate ratio was 0.60 when the total volume, total influent waste flow rate, recycle flow rate and wasting flow rate were fixed. The total COD removal under this optimal condition was found to be approximately 82%.

The EVOP technique was found to be useful in experimentally optimizing the two-tank step aeration waste treatment system. Further investigation of this technique in larger waste treatment plants is needed to fully understand the value of this technique.

With a one-tank activated sludge system with recycle and wasting of sludge, significant changes in system performance were found when the system was subjected to step changes in the influent waste concentration, the recycle flow rate, or the sludge wasting rate. Generally the responses to a step increase and a step decrease for the same operating variable were not symmetrical, especially in the response of the ATP concentration in the aeration tank. The ATP/MLSS ratio was found to depend on the food to organism ratio in

the aeration tank. When this ratio was large, the ATP/MLSS was small, and when the food to organism ratio was small the ATP/MLSS was large. Because of variations of this type, the measurement of ATP will not generally give a good estimate of MLSS under transient conditions. It was found from the time constant analysis that the dry weight time constants were directly related to the sludge mean residence time; as the sludge wasting rate increased, the time constant decreased. The time constants of the dissolved COD in the aeration tank were much smaller than the sludge time constants. The dissolved COD time constants were found to be closely related to the fluid mean residence time in the aeration tank.

In addition to the step changes carried out here, changes in the influent flow rate and temperature should also be investigated. Further study of the dynamics of the clarifier is also needed. For example, the rapid change in effluent quality which followed the step change in influent waste concentration (see Fig. 7) needs to be investigated further. A good dynamic model of the clarifier is also needed.

Since the cell concentration in the aeration tank is directly related to the recycle flow rate and the sludge wasting rate, the cell concentration can be suitably controlled by changing recycle flow rate and sludge wasting rate. A study of how to change the recycle flow rate and the sludge wasting rate to best handle changes in influent loading is also needed.

## ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation and thanks to Dr. Larry E. Erickson and Dr. Liang-tseng Fan for their constant guidance, inspiration and enthusiasm during the entire course of this study.

The author's thanks are also due to the members of the waste treatment seminar group in the Department of Chemical Engineering at Kansas State University. Their discussions and suggestions improved the study immeasurably.

The author would like to thank Dr. Lawrence A. Schmid, for his presence on the advisory committee.

The author's special thanks are given to his wife, Yue-Feng, for her enthusiasm and unfailing encouragement during the entire study.

This work was made possible through the financial support of the Kansas Water Resources Research Institute, Manhattan, Kansas, and the Environmental Protection Agency. Financial support for some equipment was provided by the Department of Chemical Engineering and Engineering Experiment Station of Kansas State University.

APPENDIX I. The  $2^2$  Factorial EVOP Design

The EVOP technique was originally presented by Box in 1957. The details of this technique are described in Reference 10 of Chapter II.

In the  $2^2$  EVOP design two variables are examined (flow rate ratio and volume ratio in Chapter II, for example) at each of the points indicated by the numbering as shown in Figure A-1. A single performance at one of the five operating conditions is called a run while a performance of the complete set of operating conditions is called a cycle. The order of experiments within a cycle should be randomized. After several cycles, statistically significant results become available and a new phase or new set of operating conditions can be selected.

After  $n$  cycles, the effects and their standard errors for a  $2^2$  design can be computed according to Table A-1. The effects of flow rate ratio, volume ratio and interaction can be presented diagrammatically as shown in Figure A-2. From this diagram and Table A-1 the effect of a variable can be interpreted.

The sample standard deviation,  $s_j$  at point  $j$  is calculated from the positive root of the sample variance as follows:

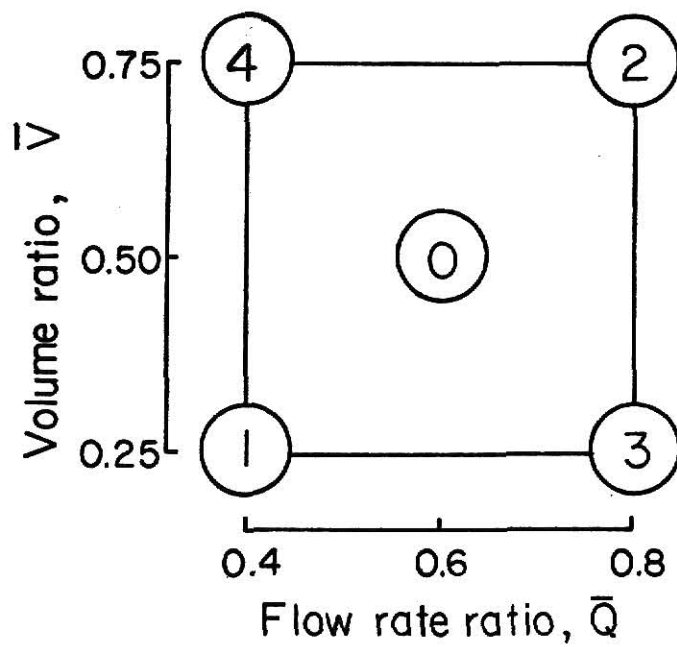


Fig. A-1. Sequence of the runs in a  $2^2$  EVOP design.

Table A-1. Computational formulae for the effects  
and standard errors for a  $2^2$  EVOP design.

Effect	Formula (Sequence Numbering)	Standard Error
Main effect of flow rate ratio ( $\bar{Q}$ )	$\frac{1}{2}(\bar{y}_2 + \bar{y}_3 - \bar{y}_4 - \bar{y}_1) *$	$\frac{s}{\sqrt{n}} **$
Main effect of volume ratio ( $\bar{V}$ )	$\frac{1}{2}(\bar{y}_2 + \bar{y}_4 - \bar{y}_3 - \bar{y}_1)$	$\frac{s}{\sqrt{n}}$
Interaction ( $\bar{Q} \times \bar{V}$ )	$\frac{1}{2}(\bar{y}_2 + \bar{y}_1 - \bar{y}_4 - \bar{y}_3)$	$\frac{s}{\sqrt{n}}$
Change in mean	$(\bar{y}_1 + \bar{y}_2 + \bar{y}_3 + \bar{y}_4 - 4\bar{y}_0)/5$	$0.89 \frac{s}{\sqrt{n}}$

\*  $\bar{y}_1, \bar{y}_2, \bar{y}_3, \bar{y}_4$  and  $\bar{y}_0$  = process averages from the n cycles  
for operating conditions 1, 2, 3, 4  
and 0, respectively.

\*\* s = sample standard deviation calculated from the positive  
root of the sample variance.

n = number of cycles performed.

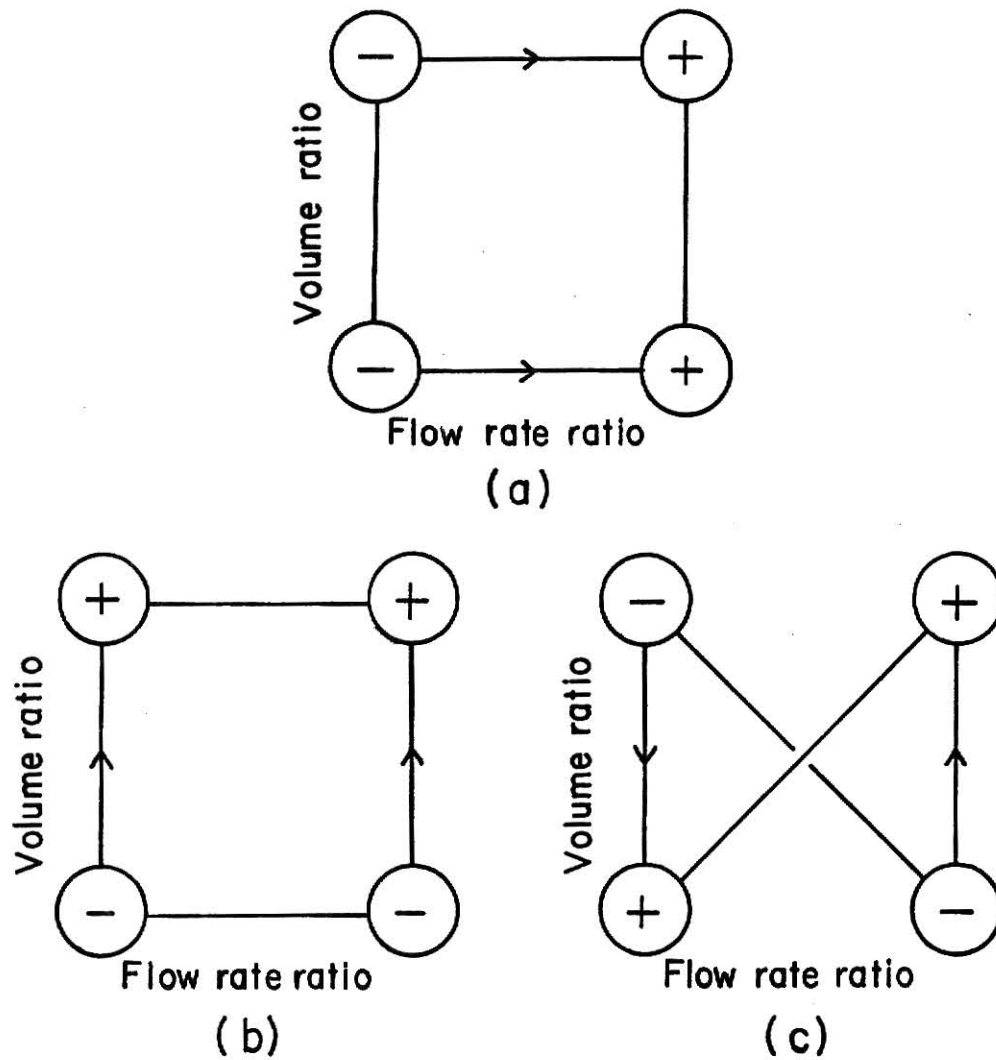


Fig. A-2. Diagrammatic representation of effects for  $2^2$  EVOP design: (a) flow rate ratio effect; (b) volume ratio effect; (c) interaction effect.

$$(s_j)^2 = \frac{\sum_{i=1}^N (\bar{y}_j - y_{ij})^2}{N - 1} \quad (1)$$

where

$s_j$  = sample standard deviation at point  $j$ .

$$\bar{y}_j = \left( \sum_{i=1}^N y_{ij} \right) / N$$

= average of the  $N$  observations at point  $j$ .

$y_{ij}$  = value of the  $i$ th observation at point  $j$ .

$N$  = number of observations.

One can estimate  $s$  from preliminary experiments before initiating the EVOP search pattern or by use of data obtained during EVOP experiments. In this work  $s$  was initially estimated using the four observations from four successive days, for each of the five operating conditions during phase 1, cycle 1; that is at point  $j$

$$(s_j)^2 = \frac{\sum_{i=1}^4 (y_j - y_{ij})^2}{3}, \quad j = 1, 2, 3, 4, 5. \quad (2)$$

where

$$y_j = \left( \sum_{i=1}^4 y_{ij} \right) / 5$$

$y_{ij}$  = observation on day  $i$  at point  $j$ .

$s_j$  = standard deviation at point  $j$ .

The average of the five values is

$$s = \frac{\sum_{j=1}^5 (s_j)}{5} \quad (3)$$



The estimation of  $s$  for phase 2 was slightly different from that of phase 1. First, the four standard deviations for the operating conditions 1, 2, 3 and 4 between cycle 1 and 2 of phase 1 were calculated by use of Equation (1): and the standard deviation for 0 was computed based on the three data at this operating condition from cycle 1 and 2 in phase 1 and cycle 1 in phase 2. Second, the average of these five standard deviations was taken as the standard deviation for cycle 1 in phase 2.

After the standard deviation is obtained the information in Table A-1 can be employed to evaluate the effects and 2 S. E. limits which are to be used in constructing the EVOP information board. An information board generally consists of the functions of interest (objective function and other reference functions), requirement, running averages, 2 S. E. limits, phase mean, effects with 2 S. E. limits and standard deviations for individual observations. The results of these calculations and the information boards are shown in Table 3, 5 and 7 in Chapter 2.

## APPENDIX II. Methods of Estimating the Time Constant for First Order Step Response

Shilling described four methods to evaluate the time constant for a first order response to a step forcing. The details of these four methods are described in Reference 19 of Chapter III.

If one defines the following variables:

$E$  : the variable one measures in the response.

$E_f$ : final value of  $E$ .

$E_o$ : initial value of  $E$ .

$t$  : time.

$T$  : time constant.

Then, for all first order systems a plot of  $E$  versus  $t$  will yield a response curve in a shape which depends on the function  $(1 - e^{-t/T})$ . The whole function can be written as

$$E = E_o + (E_f - E_o)(1 - e^{-t/T}) \quad (1)$$

When  $t/T = 1$ , the response is 63.2 percent complete. That is, when  $t = T$ , we have

$$E = E_o + 0.632(E_f - E_o) \quad (2)$$

In Method I,  $T$  is determined by finding the time required to reach 63.2% completion of the response.

A second way of computing  $T$  for a system from

experimental data is from the initial slope of the recorded response to a step forcing. Differentiating equation (1) yields

$$\frac{dE}{dt} = (E_f - E_o) \frac{e^{-t/T}}{T} \quad (3)$$

At  $t = 0$ ,  $(dE/dt) = (E_f - E_o)(1/T)$ . A line, tangent to the curve at  $t = 0$ , intersects  $E_f$  at  $t = T$ . This is Method II.

If we rearrange equation (1) and take logarithms of both sides we can obtain

$$\ln(E_f - E) = -\frac{t}{T} + \ln(E_f - E_o) \quad (4)$$

A plot of  $\ln(E_f - E)$  versus  $t$  should yield a straight line with a slope of  $-1/T$ . In Method III,  $T$  is evaluated using this slope.

Equation (1) can be rearranged to obtain

$$e^{-t/T} = \frac{E_f - E}{E_f - E_o} \quad (5)$$

If we substitute equation (5) into equation (3) we obtain

$$E = -T \left( \frac{dE}{dt} \right) + E_f \quad (6)$$

which is the basic equation used in Method IV.

A plot of  $E$  versus  $-(dE/dt)$  should yield a straight line with slope of  $T$ . The line will intersect  $(dE/dt) = 0$  at  $E = E_f$ . It should be noted that this last Method IV does not require that  $E_f$  be known. Instead we can estimate  $E_f$  using Method IV.

AN EXPERIMENTAL STUDY OF THE ACTIVATED SLUDGE PROCESS  
UNDER STEADY STATE AND DYNAMIC CONDITIONS

by

GEORGE CHAO-YI CHU

B. S., National Taiwan University, 1965

M. S. Massachusetts Institute of Technology, 1970

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the  
requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1973

## ABSTRACT

In the first part of this work, an experimental optimization of a step aeration activated sludge system was carried out using evolutionary operation (EVOP). A laboratory-scale two-tank step aeration activated sludge unit was designed and used in this study. The total volume, total influent waste flow rate, recycle flow rate and sludge wasting rate were fixed in this experimental search for the best operating condition which maximized per cent COD removal in the effluent. The volume ratio of 0.50 and the influent flow rate ratio of 0.60 which gave a total COD removal of about 82% were found to be the optimal values of the decision variables. Evolutionary operation was useful in experimentally optimizing the operation of a biological waste treatment system.

In the second part of this work, the transient behavior of a one-tank completely mixed activated sludge process was investigated experimentally. Step changes in the influent waste concentration, the recycle flow rate and the sludge wasting rate were used to disturb the system. The responses of this system to step increases and step decreases for each of the disturbances were investigated. In general, the responses were not symmetrical, especially in the response of the ATP concentration. The ATP/MLSS ratio was found to depend on the food to organism ratio in the aeration tank. When this ratio was large, the ATP/MLSS was small, and when the food to organism ratio was small the ATP/MLSS was large.

Because of variations of this type, the ATP concentration often did not have the same transient response as the MLSS. Thus, measurement of ATP will not generally give a good estimate of MLSS under transient conditions. Time constants were estimated from the experimental data. The dry weight time constants were related to the sludge mean residence time; as the sludge wasting rate increased, the time constant decreased. The time constants of the dissolved COD in the aeration tank were much smaller than the sludge time constants. This dissolved COD time constant was found to be closely related to the fluid mean residence time in the aeration tank.