EFFECT OF HIGH ORGANIC LOADING ON THE
RBC WASTEWATER TREATMENT PROCESS

By

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Dedicated to the memory of my husband,

Hussein El-Gindi

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CHAPTER I

INTRODUCTION

With the growth of societies and the development of technology, the pollution of natural waters has become a very large and important problem.

Biological treatment processes are a major technology for wastewater treatment, especially for municipal wastewater treatment. In this respect, they form a very important factor in controlling water pollution and thus creating cleaner, healthier and a more joyful environment.

RBC's are a relatively new biological wastewater treatment process compared to other processes such as activated sludge and trickling filters. Once an RBC is built there are very few operating parameters which can be adjusted to control its performance. Therefore, it is very important in the design and operation of RBC's that the parameters which control the performance be studied and defined carefully. One of the most important parameters in designing an RBC system is the applied organic load.

The purpose of this study was to determine the effect of high organic loadings on the organic removal rates and on the overall performance of a rotating biological contactor.

CHAPTER II

LITERATURE REVIEW

2.1. The RBC Process Description

Rotating biological contactors (RBC's) are aerobic, continuous flow, fixed-film reactors. In general, their performance and utility are similar to that of biological towers. The major objective of an RBC is to remove the soluble organic matter by converting it to insoluble microbial cells which can be removed by sedimentation. Therefore, RBC's can be used as a major means of treatment for both municipal and industrial wastewaters. They are not limited to low flow applications. Some plants have been built in the U.S.A. with capacities exceeding 30 MGD (large pulp and paper mill, in Minnesota) [1].

An RBC, in its simplest form, consists of closely spaced, parallel circular discs of high density polyethelene, attached perpendicular to a horizontal shaft. The entire assembly is placed into a tank with the shaft mounted so that about forty percent of the media area is submerged in the wastewater. The biomass film which grows on the media and the rotation of the discs are the two mechanisms responsible for the removal of wastewater substrate and aeration of the system. Also, the continuous rotation of the media through the wastewater provides a constant shear force which causes continual sloughing of the biofilm, and that maintains a more or less constant film thickness [1]. The microbial population depends upon the type of wastewater being treated and the position of each disc in the reactor. In general, the population usually consists of more filamentous and fewer slim-forming organisms. Therefore, the sloughed solids are relatively dense with good settling characteristics [3]. Antonie [1] has mentioned that due to the high sludge solids content obtained with the rotating disc process, sludge thickening before treatment and disposal is not necessary. RBC's are divided into stages. The substrate removal in the first stage is much greater than the other stages [1,5]. Antonie [1] demonstrated that relatively little treatment occurred in the fourth stage. However, the final two stages performed moderate nitrification.

One of the RBC's advantages is that the biomass is passing through the wastewater and that insures adequate wetting of all organisms at any flowrate [2]. RBC's do not need solid recycling [1]. They require low operating and maintenance costs along with power consumption [1]. The process is easy to operate and noiseless [4]. RBC's have a better shock load response and great ability to handle wide fluctuations in hydraulic and organic loadings [1, 5, 10].

2.2 RBC Performance and Scale Up

Although the biological mechanisms of wastewater treatment for RBC and activated sludge are the same, there are some differences relative to fixed bed growth versus fluidized bed growth systems [6].

There are many design parameters affecting an RBC performance such as organic loading, flow rate, rotational disc speed, detention time, disc surface area, wastewater temperature, submerged disc depth and number of stages. According to EPA, design manual for RBC, temperatures lower than 55°F may affect the organic removal efficiency. However, in some highly loaded RBC systems, lower wastewater temperatures do not always result in decreased carbonaceus removal rates, but may enhance removals. This phenomenon may be attributed to increasing DO saturation values with decreasing temperature, which promote increased oxygen transfer and possible reduction of the sulfide oxidizing organisms [12]. Some of those parameters control the oxygen transfer characteristics. Kima [7] related the oxygen transfer coefficient (KL_a) in RBC process to the rotational velocity, the disc size, and the space between the discs. Antonie [1] suggested that the optimum disc velocity is 2 rpm. However, all these parameters have been standardized to optimize the process design and operation [6]. The minimum submerged disc depth is forty percent. The typical full scale mechanical drive RBC disc diameters range from 10 to 12 feet. The typical rotation speed is 1.6 rpm or a peripheral velocity of about 60 fpm [6]. Due to standardizing of these parameters, each RBC has its own standard oxygen transfer capabilities [6]. Therefore, the flow rate and the organic concentration of the wastewater are the major factors to be controlled to meet the oxygen transfer capabilities and the required substrate removal rate and efficiency for each design. Antonie [1] considered the flow rate as the major controlling factor for substrate removal. He concluded that the BOD removal was 85 percent at a hydraulic loading of 2.8 gpd/ft^2 and the removal was 95 percent at a hydraulic loading of 0.5 gpd/ft^2. Clark [8] suggested a design hydraulic loading rate of 1.5 gpd/ft^2. The most recent concept is the concept of the total organic load. Stover and Kincannon [6] reported that the amount of organics removed by the system is the same at the same loading rate regardless of whether the loadings are accomplished by a low flow rate at a high organic concentration or a high flow rate at a low organic concentration. The concept of combining the two concepts of the hydraulic loading and the substrate concentration has many advantages. One of the advantages of this concept is its capability to predict the efficiency of the substrate removal at any loading condition, irrespective of zero, first or second order kinetics. By plotting the total loading applied versus the loading points or conditions, the points at which zero order kinetics occur can be defined. These points indicate that the system changes from biochemical reaction limiting process to an oxygen transfer limiting process [6]. In this study, the results obtained from different RBC's with different diameters and treating different wastewaters has been investigated. The treatment capabilities for both the pilot RBC (1.5 ft diameter) and the full scale RBC were the same up to 1.0 lb BOD/day/1000 ft^2 at a load higher than 1.5 lb BOD/day/1000 ft^2, a significant difference between the treatment capabilities started to appear. By applying Monod Kinetics, the maximum BOD removal rates could be observed. At these points the system becomes oxygen limited for these loading conditions. Also, this study showed that the major factor in the design of an RBC system is the applied loading to the first stage(s) to meet the oxygen transfer capabilities of the system. The recommended loading for the first stage(s) of a full scale RBC ranges from 1.0 to 1.5 lbs BOD/day/1000 ft^2 in order to avoid any oxygen transfer problem and it must not exceed 2.5 lbs BODs/day/100 ft^2 [6, 13]. Orwin [10] reported that the RBC unit had an 82 percent removal at organic loads of 3.0 lbs BOD/day/1000 ft^2, and that the removal efficiency started to decrease at higher organic loadings, depending on both hydraulic detention time and influent BOD concentration.

According to EPA [12], the safe and conservative first stage(s) loading limit for designing a mechanically driven RBC system is 2.5 lb soluble BOD_5/day/1000 ft^2 or 6 lb total BOD_5/day/1000 ft^2. An overloaded RBC can result in bulk liquid DO depletion which causes sulfate reduction and/or anaerobic decomposition products which produce an additional oxygen demand from the media side. When sulfide is present, either in the influent wastewater or by its production deep within the biofilm, sulfide oxidizing organisms such as Beggiatoa can frequently grow on the biofilm surface. They compete with hetrotrophic organisms for oxygen and space on RBC media surface. They reduce sulfate to sulfide and then reoxidize it to elemental sulfur. For each mole of sulfate to be reoxidized and deposited as elemental sulfur; 1.5 moles of O_2 are needed. Beggiatoa predominance can result in an increase in the concentration of biomass while causing a substantial reduction in the organic removal. In extreme cases, a progressive Beggiatoa takeover of the entire system causing significant deterioration of effluent quality. Also EPA [12] reported that in the absence of a biological sulfide problems and/or excessive anaerobic metabolism, the organically overloaded RBC may be operated at the maximum substrate removal rate possible. The removal rate is controlled only by oxygen transfer into the biofilm.

2.3 Colorless Sulfur Bacteria

It is a chemotrophic aerobic bacteria that oxidizes sulfur. It is often called colorless sulfur bacteria to distinguish it from the sulfur oxidizing photosynthetic bacteria. It has a great variety of metabolic capabilities and an important role in the sulfur cycle. It includes four genera, Thiobacillus, Thiodendron, Beggiatoa, and Sulfolobus [14].

Beggiatoa occurs widely in lake, pond, and river muds, in sulfur springs, in sewage-polluted streams, and in marine habitats which are rich in hydrogen sulfide [15]. It is a genus of the family Beggiatoaceae [16]. It is a filamentous organisms that can grow as a chemolithotrophic autotroph but is classified as a mixotroph because it grows better in the presence of acetate [14]. It grows in the form of unattached long, colorless, cylindrical trichomes that range in length from 80 μm to 1,500 μm. The diameter of a trichome ranges from 1 to 2.5 μm. It deposits sulfur granules within the cells when grown in the presence of H_2S. Cross walls are not easily seen, due to the deposition of sulfur granules. It does not have flagella. The entire trichome moves by gliding over a solid surface at a velocity of about 4 μm/sec. It is a non-pigmented structure. The question of autotrophy in Beggiatoa is yet not clarified. It grows readily as a heterotroph on a number of dilute organic media continuing 0.05 to 0.2 percent yeast extract, peptone or beef extract. It is non-fastidious, since it can use inorganic nitrogen sources, such as ammonium salts. Also, most strains show no vitamin requirement. Some amino acids such as aspartic acid and glutamic acid can act as both carbon and nitrogen sources. Acetate and hydrogen sulfide (H_2S) greatly stimulate the growth. Acetate can be used as a sole carbon source. Hydrogen sulfide has a stimulatory effect on growth even in the presence of organic matter. Moreover, some strains require H_2S for growth in the presence of acetate and mineral salts. The optimum pH for growth is about 7 and the optimum temperature range is from 25 to 30°C [15]. It may form mates with a slightly yellowish white appearance due to deposition of internal sulfur globules [17]. When Beggiatoa exists in an RBC unit, it reduces the sulfate (SO_4^2) to sulfide. Relative proportions of H^-S and H_2S existing in equilibrium are pH dependent. At pH 7.0, 50 percent will exist as H^- S and 50 percent as H_2S. Then sulfide is reoxidized to elemental sulfur. For each mole of sulfate to be reduced to sulfide and reoxidized to sulfur, 1.5 moles of O_2 are required [12].

CHAPTER III

MATERIALS AND METHODS

3.1 The RBC Unit

The pilot plant laboratory-scale RBC employed in this study was a 3.25 feet long, 8.97 liters capacity. It consisted of a tank made of plexiglass divided into five stages separated by baffles with holes in the bottom of each baffle to allow flow from one stage to the next. The first stage consisted of eight rotating discs and each of the other four stages consisted of four rotating discs for a total of twenty-four discs for the whole unit. Each disc was approximately six inches in diameter and 1/8 inch thick. The total disc surface area was 9.42 square feet for the entire unit. Three small styrofoam paddles were placed between every two discs to create sufficient turbulence condition for complete mixing of the wastewater and to keep the mixed liquor solids in suspense. A 1/20 horsepower electric speed reducer motor was used to rotate the discs at a speed of approximately 8 rpm. Forty percent of the surface of the discs was submerged into the liquor.

The wastewater was placed in a tank with a capacity of approximately twenty-five liters. The wastewater was pumped into the first stage by using a 1/4 horsepower motor driven controlled volume pump. From the first stage the wastewater flowed through the next stages and out to the effluent inlet, where it was collected in a twenty-five liter capacity tank and discharged to a sanitary sewer.

A hydraulic loading of 8 ml/min. which equals 0.32 gpd/ft^2, was applied to all loading conditions.

3.2 Synthetic Waste

The synthetic waste used in this experiment was composed of glucose ($C_6H_{12}O_6$)) as the carbon source and as growth limiting factor with nutrients and buffer. Sodium bicarbonate was used as a buffer to keep the pH always around 7.0. The wastewater was prepared daily by mixing the concentrated waste with a specific amount of tapwater in order to achieve the desired organic concentration. The composition of the wastewater for feeding 100 mg/l glucose is shown in Table I.

TABLE I

COMPOSITION OF FEED FOR 100 mg/l GLUCOSE AS SUBSTRATE

Constituent	Concentration (mg/l)
glucose	100 mg/l
NH_4Cl	30 mg/l
H_3PO_4	4 mg/l
$MgSO_4 \cdot 7H_2O$	10 mg/l
$FeCl_3 \cdot 6H_2O$	0.1 mg/l
$CaCl_2$	1 mg/l
$MnSO_4 \cdot H_2O$	1 mg/l

3.3 Operating and Sampling Procedures

The RBC unit was seeded with about 9 liters of primary effluent from the Stillwater municipal sewage treatment plant, and was run as a batch process for three days until some growth started on the discs. Then, the unit was operated as a continuous flow process by pumping the wastewater to it.

The study was done by using six different organic loadings. For each loading condition the system was run as a continuous flow unit for about six to seven days to reach equilibrium before samples were collected. Once the system reached equilibrium, samples were collected every other day.

Six samples were collected in each sampling period. The first sample was taken at the influent line. The other five samples were collected at the end of each of the following stages starting with the last stage. The samples were filtered directly after sampling procedure.

The analytical tests performed during this study were uninhibited soluble BOD and inhibited soluble BOD. The inhibited BOD tests were applied during the second and third loading conditions for the samples which were taken from third, fourth and fifth stages to inhibit nitrification. HACH inhibitor consisted of 2-Chloro-6 (trichloromethyl) pyridine, coated on an inert substrate, was used during this study. The BOD tests were run immediately after collecting the samples.

3.4 BOD Test

Biochemical oxygen demand (BOD) was used to analyze the organic concentration of the wastewater and the effluent from each stage. All the tests were run according to the procedure described in Standard Methods for the Examination of Water and Wastewater [17].

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Performance and Operating Conditions of the RBC Unit

In this study six different total organic loadings were used. A constant hydraulic loading of 11.5 L/day (0.32 gpd/ft^2) was used for the entire study. The different organic loadings were achieved by changing the concentration of the influent substrate. The organic concentration used were 400, 800, 1200, 2000, 2500, 4000 mg/l $sBOD_5$. These organic concentrations yielded a total organic loadings of 1, 2, 3, 5.4, 6.7, 10.8 lb $sBOD_5$/day/1000 ft^2. According to the data obtained from this study, these six loading conditions can be divided into three categories. Each category has a common performance data and operating conditions. The first category includes the first two loads (1, 2 lb $sBOD_5$/day/1000 ft^2). The second category includes the third and fourth loads (3, 5.4 lb $sBOD_5$/day/1000 ft^2) and the third category includes the fifth and sixth loads (6.7, 10.8 lb sBOD/day/1000 ft^2). The performance of the unit during the entire study was based on $sBOD_5$ removal capability of the unit. The columns representing the time in all the following tables indicate the running time for the BOD tests. Inhibited $sBOD_5$ tests were run during the second and third loads for the third, fourth and fifth stages.

The results of the first category are shown in Figures 1, 2, 3, 4,

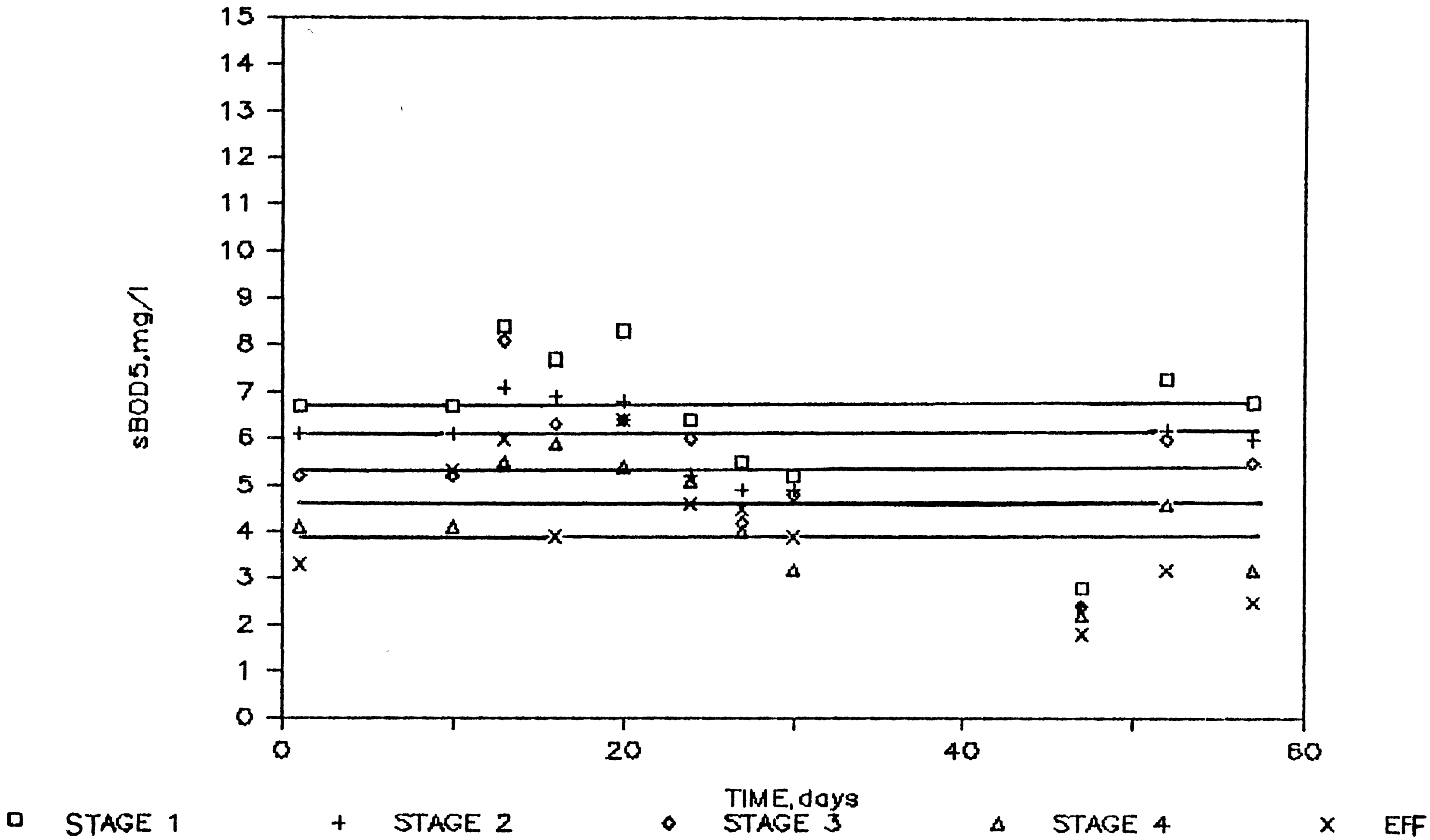

Figure 1. $sBOD_5$ Removal vs. Time for the First Organic Loading Condition (1 lb $sBOD_5$/day/1000 ft^2)

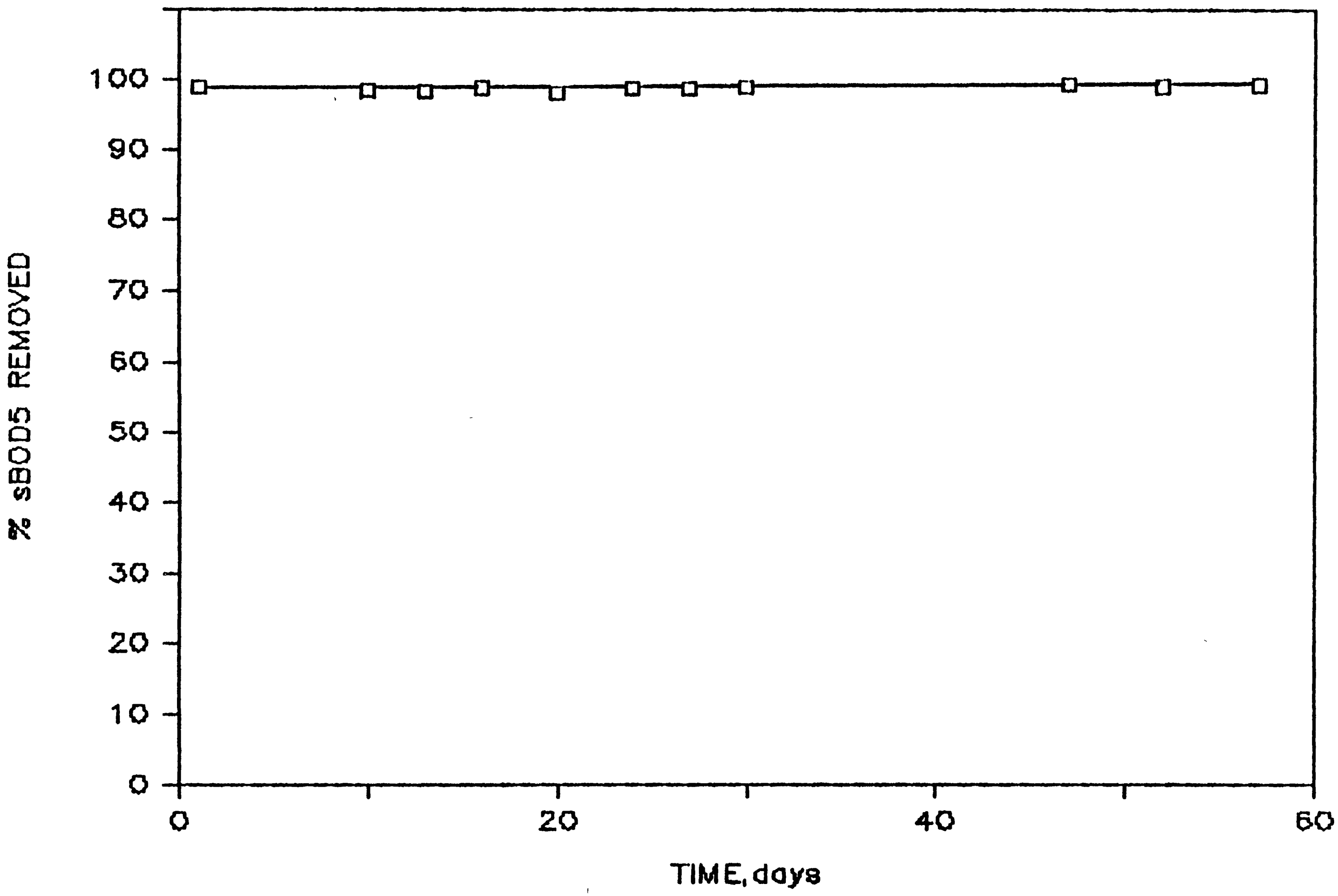

Figure 2. Efficiency of Treatment vs. Time for the First Organic Loading Condition (1 lb $sBOD_5$/day/1000 ft^2)

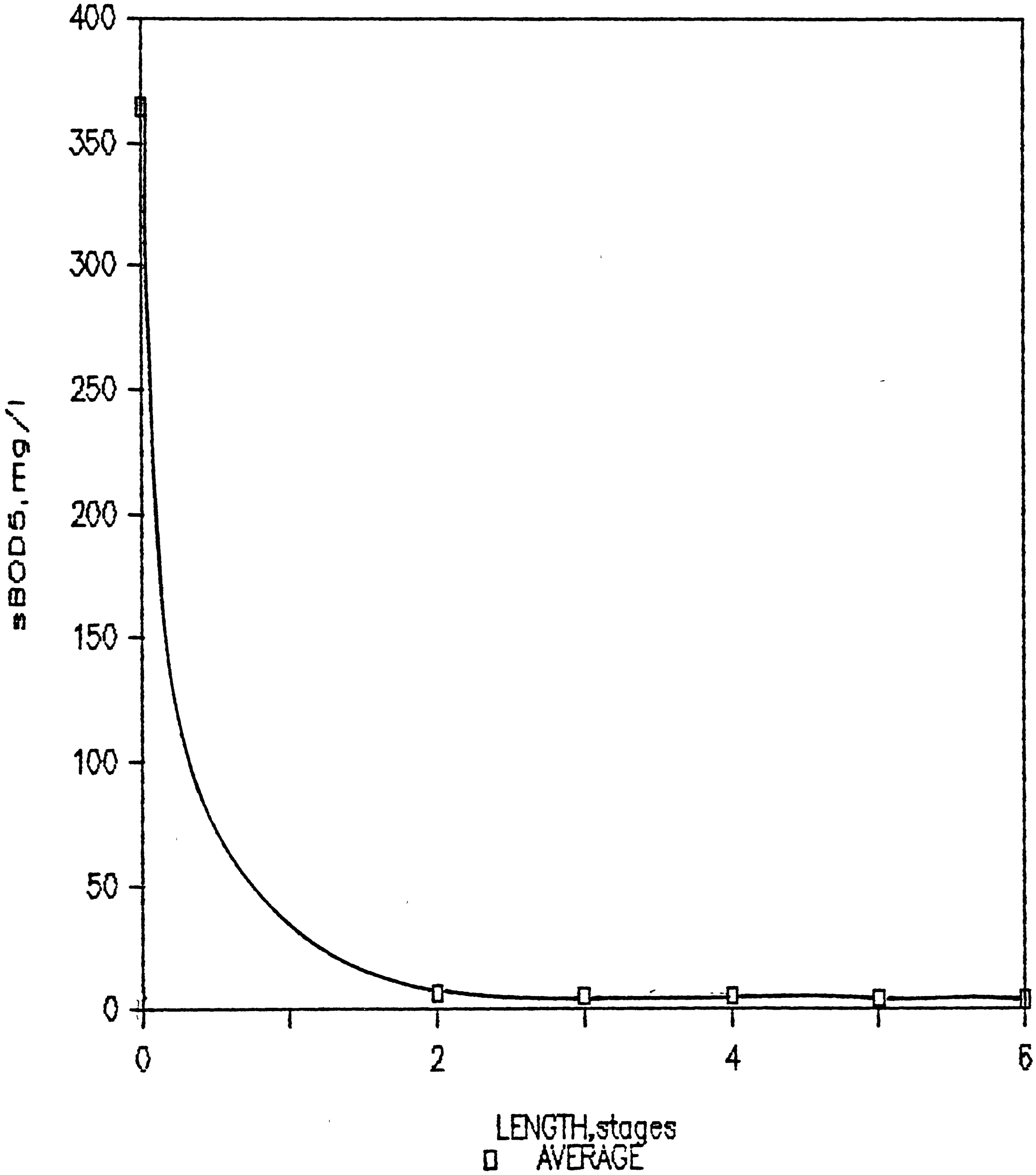

Figure 3. $sBOD_5$ Remaining vs. Stages for the First Organic Loading Condition (1 lb $sBOD_5$/day/1000 ft^2)

TABLE II

INFLUENT CONCENTRATION, REMAINING $sBOD_5$ FOR EACH STAGE AS mg/l AND THE BOD REMOVAL EFFICIENCY FOR THE FIRST LOADING CONDITION

DISK DIA = 6 INCHES AREA PER STAGE = 1.57sf TOTAL AREA = 9.42sf

LOAD NO.	FLOW l/day	INF	BOD, mg/l STAGE 1	STAGE 2	STAGE 3	STAGE 4	EFF	DAYS	% of removal
I	11.52	346.00	6.70	6.10	5.20	4.10	3.30	1.00	99.05
	11.52	391.00	6.70	6.10	5.20	4.10	5.30	10.00	98.64
	11.52	374.00	8.40	7.10	8.10	5.50	6.00	13.00	98.40
	11.52	354.00	7.70	6.90	6.30	5.90	3.90	16.00	98.90
	11.52	345.00	8.30	6.80	6.40	5.40	6.40	20.00	98.14
	11.52	364.00	6.40	5.20	6.00	5.10	4.60	24.00	98.74
	11.52	374.00	5.50	4.90	4.20	4.00	4.50	27.00	98.80
	11.52	386.00	5.20	4.90	4.80	3.20	3.90	30.00	98.99
	11.52	340.00	2.80	2.40	2.40	2.20	1.80	47.00	99.47
	11.52	377.00	7.30	6.20	6.00	4.60	3.20	52.00	99.15
	11.52	358.00	6.80	6.00	5.50	3.20	2.50	57.00	99.30
Ave.	11.52	364.50	6.53	6.70	5.50	4.30	4.10		98.88

TABLE III

APPLIED ORGANIC LOADINGS AND REMOVED $sBOD_5$ AS LBS/DAY/1000 FT^2 OF EACH STAGE FOR THE FIRST LOADING CONDITION

lb/day/1000ft sq.									
STAGE 1		STAGE 2		STAGE 3		STAGE 4		STAGE 5	
$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$
2.77	2.74	1.86	1.83	1.40	1.37	1.12	1.10	0.93	0.92
3.13	3.11	2.11	2.07	1.58	1.56	1.26	1.25	1.05	1.04
2.99	2.95	2.01	1.97	1.51	1.48	1.21	1.18	1.01	0.99
2.83	2.80	1.91	1.87	1.43	1.40	1.14	1.12	0.95	0.94
2.76	2.72	1.86	1.81	1.39	1.37	1.12	1.09	0.93	0.91
2.91	2.89	1.96	1.93	1.47	1.45	1.18	1.16	0.98	0.97
2.99	2.98	2.01	1.99	1.51	1.49	1.21	1.20	1.01	1.00
3.09	3.08	2.08	2.05	1.56	1.54	1.25	1.23	1.04	1.03
2.72	2.72	1.83	1.82	1.37	1.36	1.10	1.09	0.92	0.91
3.02	2.99	2.03	1.99	1.52	1.50	1.22	1.20	1.02	1.00
2.87	2.84	1.93	1.89	1.45	1.42	1.16	1.14	0.96	0.96
2.92	2.89	1.96	1.93	1.47	1.45	1.18	1.16	0.98	0.97

5 and 6 and Tables II, III, IV and V. The performance of the RBC based on BOD removal as a function of time is shown in Figures 1, 2, 4 and 5. The performance of the RBC based on BOD removal as a function of stages is shown in Figures 3 and 6.

Figures 1 and 2 show that the removal efficiency for the first total organic load (1.0 lb $sBOD_5$/day/1000 ft^2) is almost constant with time. The plots which represent the BOD removal versus time for the stages and the removal efficiency versus time are almost horizontal lines. The effluent BOD ranges from 1.8 mg/l to 6.0 mg/l. The treatment efficiency ranges from 98.1 to 99.5 percent. Figure 3 shows that the greatest BOD removal was accomplished by the first stage. An average of 98 percent of the substrate was removed in the first stage (2.9 lbs $sBOD_5$/day/1000 ft^2).

As shown in Figures 4 and 5, the removal efficiency for the second organic load (2.0 lb $sBOD_5$/day/1000 ft^2) is almost constant with the time. The plots which represents the BOD removal versus time for the stages and the removal efficiency versus time are almost horizontal lines. The effluent BOD ranges from 0.5 to 3.1 mg/l. The treatment efficiency ranges form 99.6 to 99.9 percent. Figure 6 indicates that the major BOD removal occurred in the first stage (about 6 lb $sBOD_5$/day/1000 ft^2).

The operating conditions for this category were very good. The system was free of any problem of odor or clogging. The biomass film was about 1/4 inch thick with a dark white color in the first stage, which got thinner and darker in the following stages.

The results of the second category, which includes total organic loadings of 3 and 5.4 lb $sBOD_5$/day 1000 ft^2 are shown in Figures 7-15

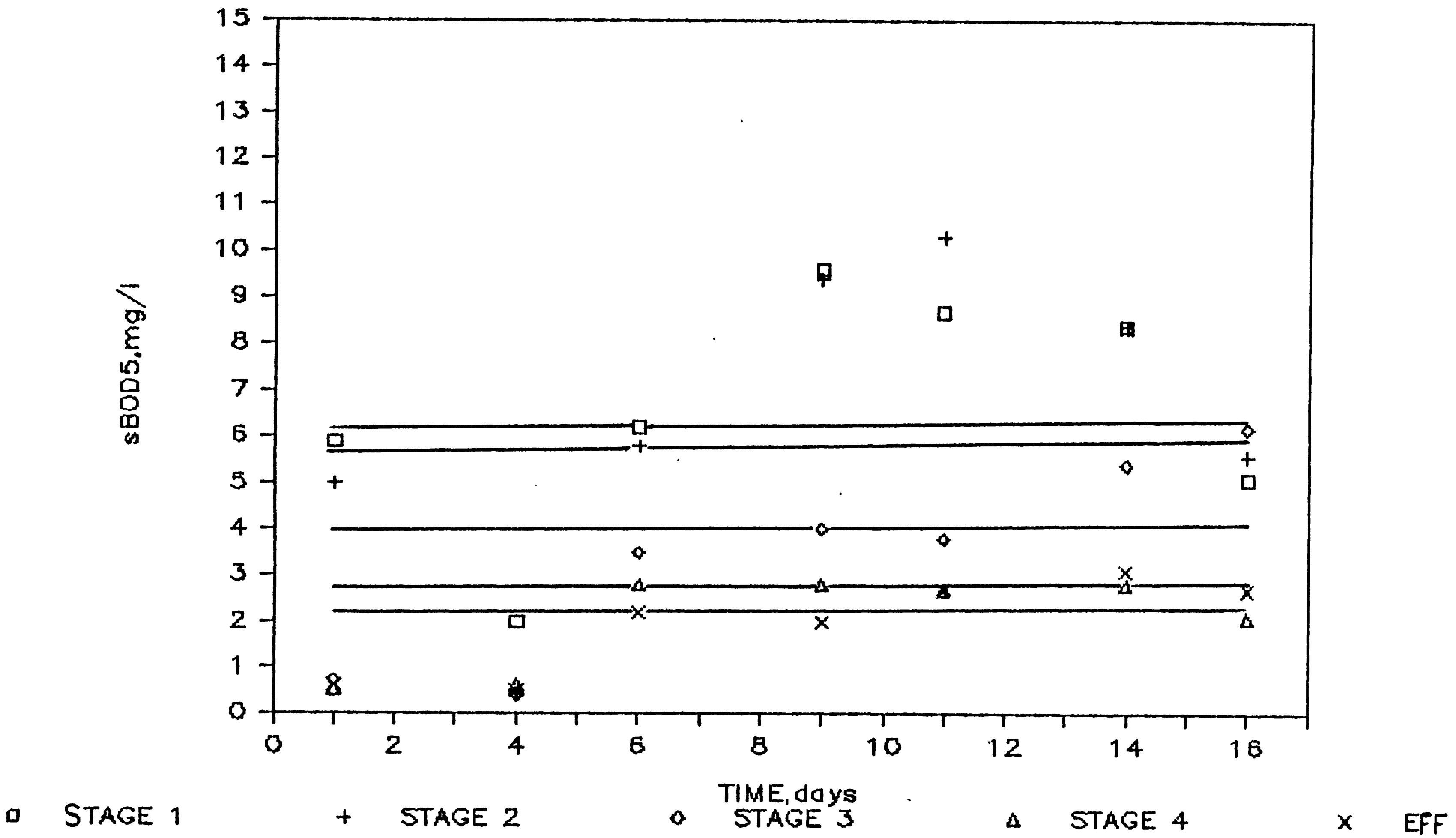

Figure 4. $sBOD_5$ Removal vs. Time for the Second Organic Loading Condition (2 lbs $sBOD_5$/day/1000 ft^2)

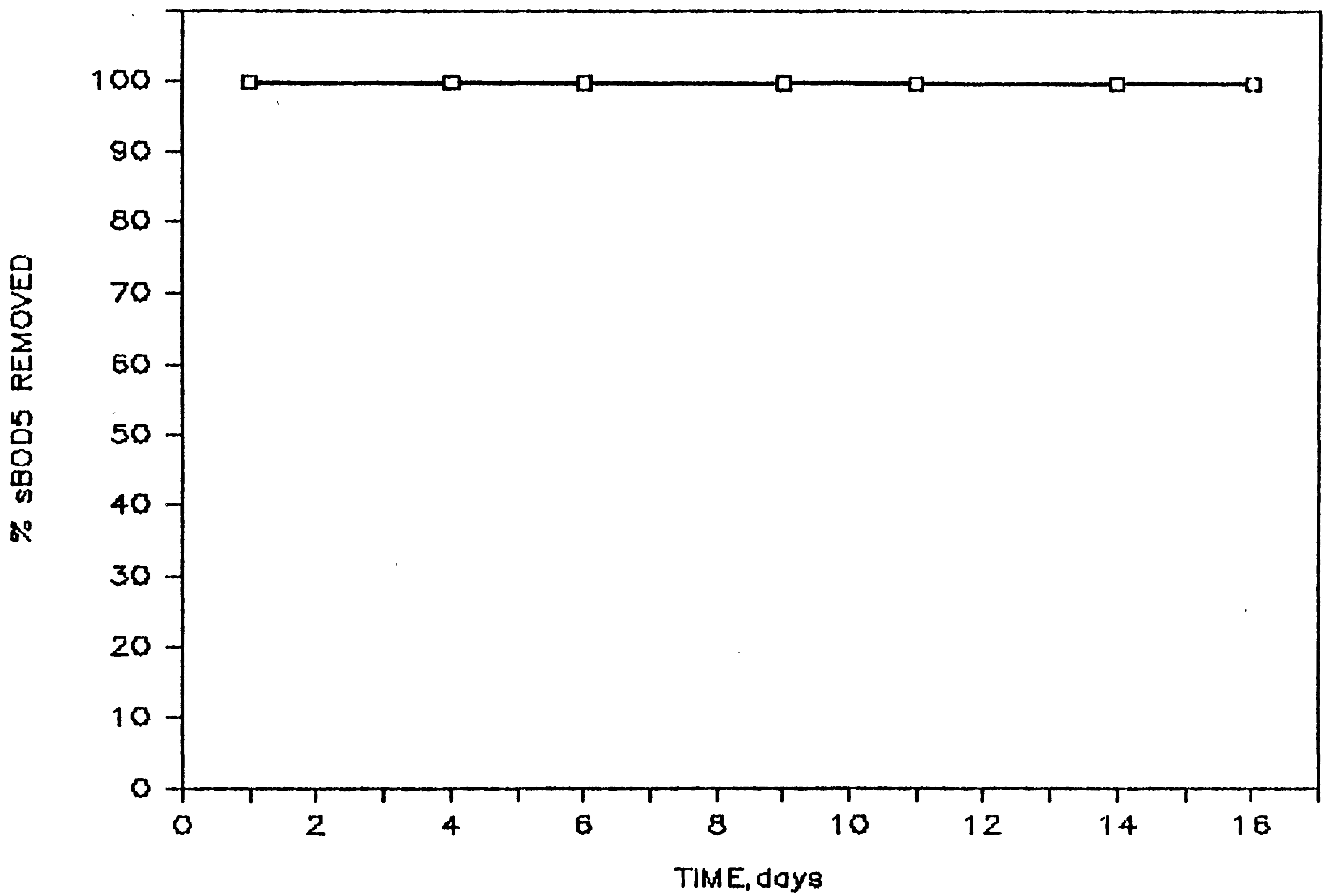

Figure 5. Efficiency of Treatment vs. Time for the Second Organic Loading Condition (2 lbs $sBOD_5$/day/1000 ft^2)

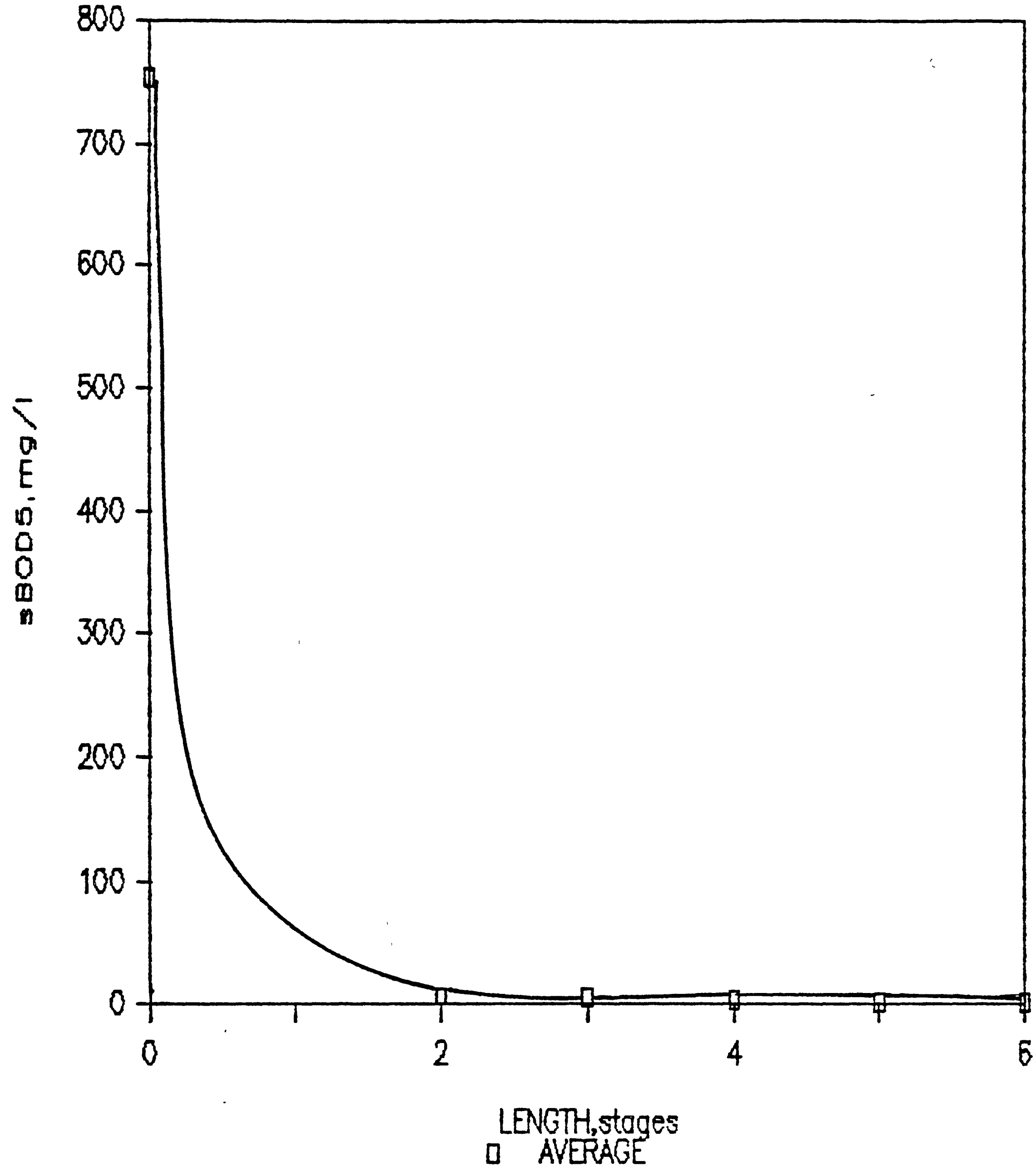

Figure 6. $sBOD_5$ Remaining vs. Stages for the Second Organic Loading Condition (2 lbs $sBOD_5$/day/1000 ft^2)

TABLE IV

INFLUENT CONCENTRATION, REMAINING $sBOD_5$ FOR EACH STAGE AS mg/l AND THE MOD REMOVAL EFFICIENCY FOR THE SECOND CONDITION

DISK DIA = 6 INCHES   AREA PER STAGE = 1.57sf   TOTAL AREA = 9.42sf

LOAD NO.	FLOW l/day	INF	BOD, mg/l STAGE 1	STAGE 2	STAGE 3	STAGE 4	EFF	DAYS	% of removal
II	11.52	728.00	5.90	5.00	0.70	0.50	0.60	1.00	99.92
	11.52	743.00	2.00	0.40	0.40	0.60	0.50	4.00	99.93
	11.52	776.00	6.20	5.80	3.50	2.80	2.20	6.00	99.72
	11.52	753.00	9.60	9.40	4.00	2.80	2.00	9.00	99.73
	11.52	762.00	8.70	10.30	3.80	2.70	2.70	11.00	99.65
	11.52	767.00	8.40	8.40	5.40	2.80	3.10	14.00	99.60
	11.52	748.00	5.10	5.60	6.20	2.10	2.70	16.00	99.64
Ave.	11.52	753.86	6.56	6.41	3.43	2.04	1.97		99.74

TABLE V

APPLIED ORGANIC LOADING AND REMOVED $sBOD_5$ AS LBS/DAY/1000 FT^2 OF EACH STAGE FOR THE SECOND LOADING CONDITION

lb/day/1000ft sq.									
STAGE 1		STAGE 2		STAGE 3		STAGE 4		STAGE 5	
$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$
5.83	5.84	3.92	3.89	2.94	2.92	2.35	2.35	1.96	1.96
5.95	5.99	4.00	3.99	3.00	3.00	2.40	2.40	2.00	2.00
6.21	6.22	4.18	4.15	3.14	3.11	2.51	2.50	2.09	2.08
6.03	6.01	4.06	4.00	3.04	3.00	2.43	2.42	2.03	2.02
6.10	6.09	4.11	4.06	3.08	3.04	2.46	2.45	2.05	2.05
6.14	6.13	4.13	4.09	3.10	3.07	2.48	2.46	2.07	2.06
5.99	6.00	4.03	4.00	3.02	3.00	2.42	2.40	2.01	2.01
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6.03	6.04	4.06	4.03	3.05	3.02	2.44	2.43	2.03	2.03

and Tables VI, VII, VIII and IX. The performance of the RBC unit based on the BOD removal versus the time for the third organic load (2.0 lb $sBOD^5$/day/1000 ft^2) is shown in Figure 7. It indicates that the BOD removal in the first stage was increasing with the time during the first 12 days of applying this load. The BOD leaving the first stage decreased to 13.7 mg/l, then it started to increase to reach 30.2 mg/l after 17 days. The curve of the effluent and the first stage versus the time are not parallel, see Figure 7. While the first stage BOD started to increase, the effluent BOD started to decrease. Figure 8 represents the BOD removal efficiency versus the time. It ranges from 98 percent to 99.7 percent and being almost constant. Figure 9 and 10 indicate the BOD removal as a function of the stages. They represent the average of the data collected before and after the deterioration, respectively. As shown in Figures 9 and 10 the BOD removal of the first stage decreased after the deterioration from 98.7 percent to 97.5 percent while the BOD removal of the last stage increased from 98.6 percent to 99 percent. The two curves indicate that the greatest BOD removal occurred in the first stage. An average of 98.3 percent of the BOD was removed in the first stage (9.1 lbs $sBOD_5$/day/1000 ft^2).

Figure 11 shows the BOD removal as a function of time for the fourth total organic load (5.4 lbs $sBOD_5$/day/1000 ft^2). It indicates that the BOD leaving the first stage decreased form 249.0 mg/l to 140.0 mg/l within 12 days of applying this load and 5 days from starting BOD tests. Then, a sudden and significant deterioration occurred in the system. The BOD jumped to 999.0 mg/l, then decreased to 408.0 mg/l, and increased again. As shown in Table VIII, the BOD leaving the first stage increased from 140. mg/l to 1108.0 mg/l within 2 days. Due to

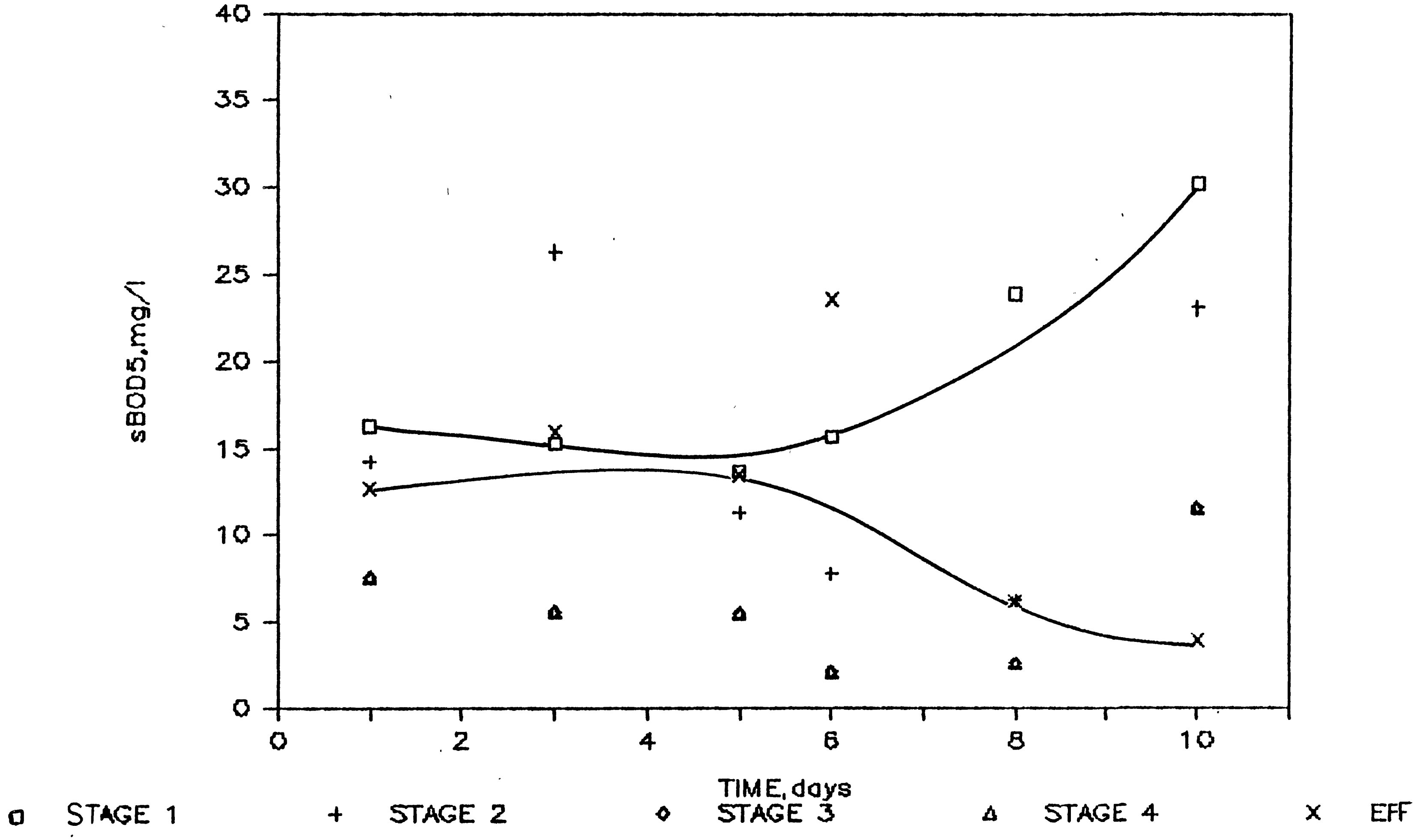

Figure 7. $sBOD_5$ Removal vs. Time for the Third Organic Loading Condition (3 lbs $sBOD_5$/day/1000 ft^2)

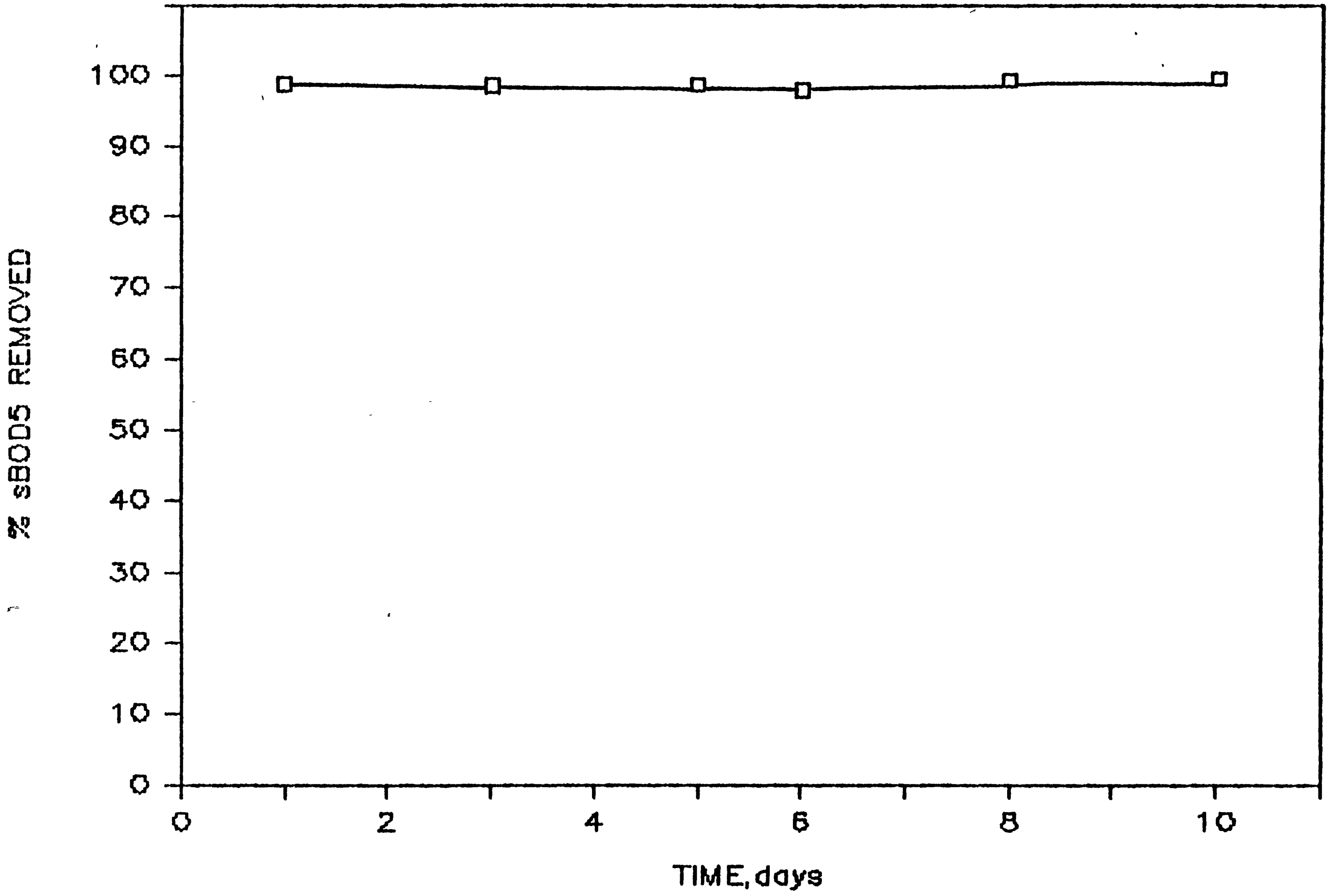

Figure 8. Efficiency of Treatment vs. Time for the Third Organic Loading Condition (3 lbs $sBOD_5$/day/1000 ft^2)

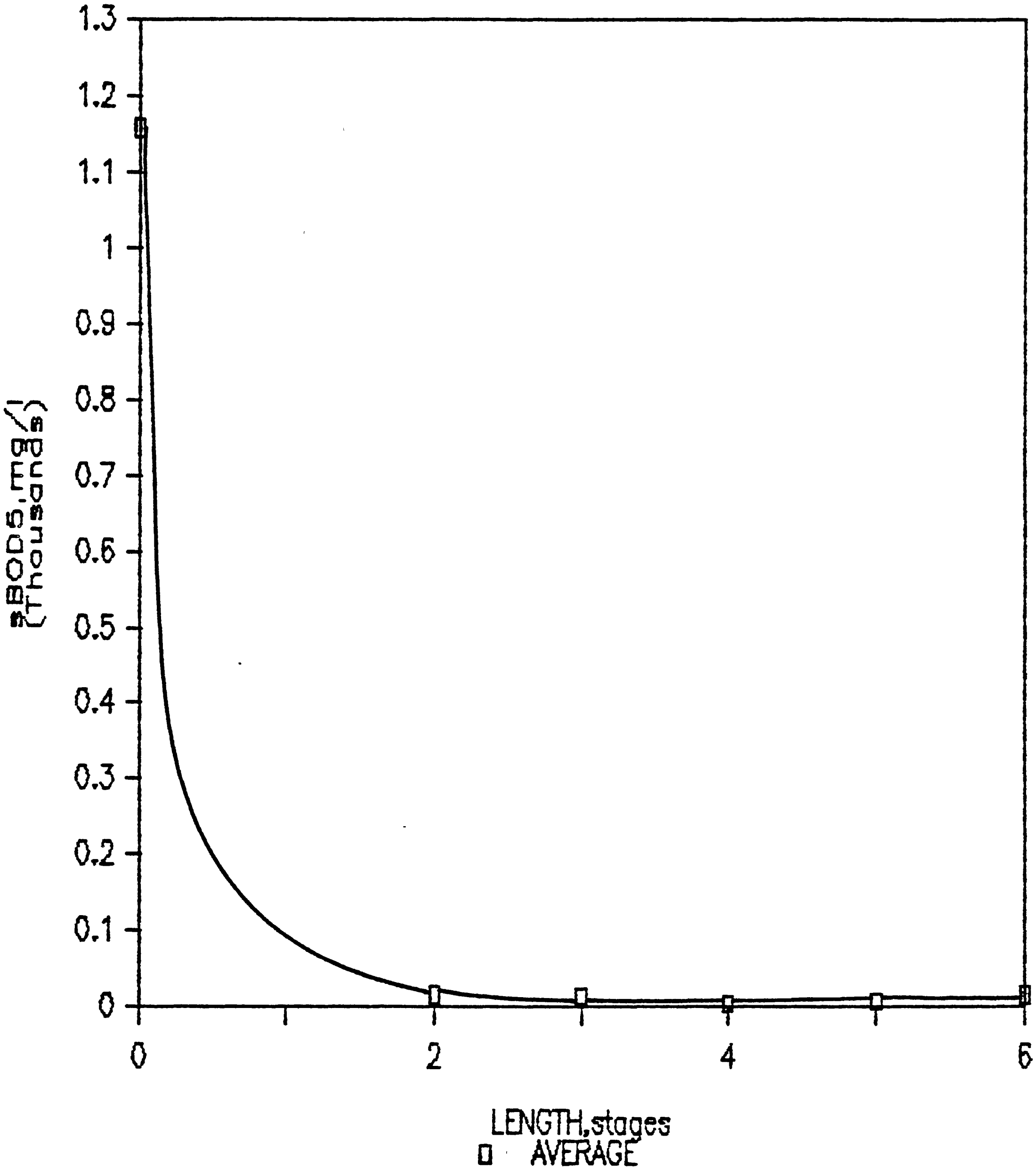

Figure 9. $sBOD_5$ Remaining vs. Stages for the Third Organic Loading Condition (3 lbs $sBOD_5$/day/1000 ft^2). Before the Deterioration

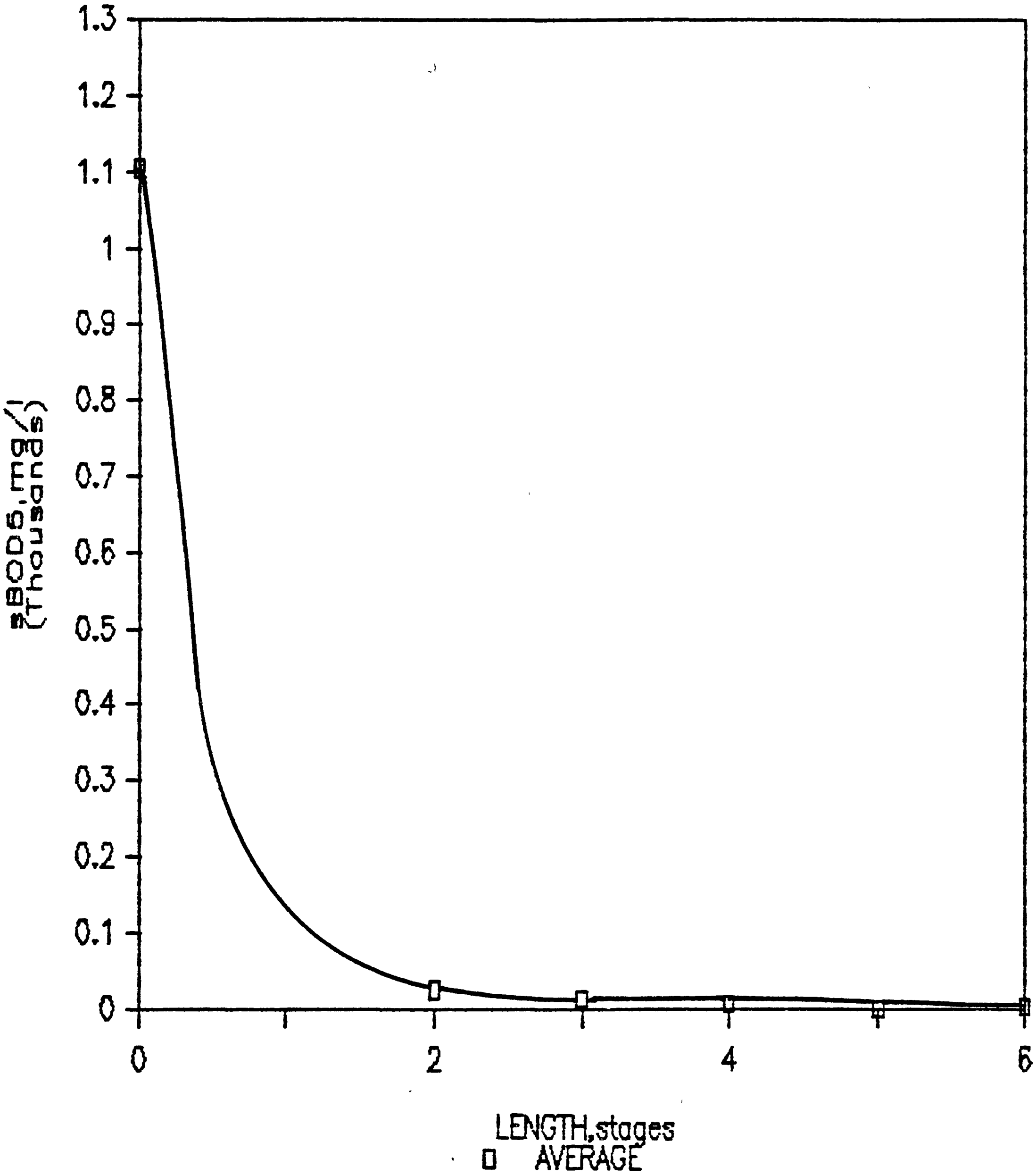

Figure 10. $sBOD_5$ Remaining vs. Stages for the Third Organic Loading Condition (3 lbs $sBOD_5$/day/1000 ft^2). During the Deterioration

TABLE VI

INFLUENT CONCENTRATION, REMAINING $sBOD_5$ FOR EACH STAGE AS mg/l AND THE BOD REMOVAL EFFICIENCY FOR THE THIRD LOADING CONDITION

DISK DIA = 6 INCHES   AREA PER STAGE = 1.57sf   TOTAL AREA = 9.42sf

LOAD NO.	FLOW l/day	INF	BOD, mg/l STAGE 1	STAGE 2	STAGE 3	STAGE 4	EFF	DAYS	% of removal
III	11.52	1152.00	16.30	14.30	7.60	7.00	12.70	1.00	98.90
	11.52	1196.00	15.30	26.30	5.60	5.20	16.00	3.00	98.66
	11.52	1088.00	13.70	11.30	5.50	5.90	13.50	5.00	98.76
	11.52	1193.00	15.70	7.80	2.10	12.80	23.60	6.00	98.02
	11.52	1063.00	23.90	6.30	2.60	1.20	6.20	8.00	99.42
	11.52	1146.00	30.20	23.10	11.60	1.40	3.90	10.00	99.66
Ave.	11.52	1139.67	19.18	14.85	5.83	5.58	12.65		98.89

TABLE VII

APPLIED ORGANIC LOADING AND REMOVED $sBOD_5$ AS LBS/DAY/1000 FT^2 OF EACH STAGE FOR THE THIRD LOADING CONDITION

lb/day/1000ft sq.									
STAGE 1		STAGE 2		STAGE 3		STAGE 4		STAGE 5	
FSi / A	F(Si-Se) / A	FSi / A	F(Si-Se) / A	FSi / A	F(Si-Se) / A	FSi / A	F(Si-Se) / A	FSi / A	F(Si-Se) / A
9.22	9.18	6.21	6.12	4.65	4.60	3.72	3.70	3.10	3.08
9.57	9.54	6.44	6.36	4.83	4.73	3.87	3.85	3.22	3.21
8.71	8.68	5.86	5.79	4.40	4.35	3.52	3.50	2.93	2.91
9.55	9.51	6.43	6.34	4.82	4.79	3.86	3.85	3.21	3.18
8.51	8.40	5.73	5.60	4.30	4.27	3.44	3.43	2.86	2.86
9.17	9.02	6.17	6.01	4.63	4.54	3.70	3.67	3.09	3.08
9.12	9.05	6.14	6.04	4.60	4.54	3.68	3.67	3.07	3.05

this unexpected BOD increase, the BOD for the last three stages could not be measured for the fourth through the sixth data. The three latter data are not included in any calculation or curves. They are shown in the table just to indicate this sudden deterioration of the treatment efficiency. As shown in Figure 11, the curve of the effluent is almost parallel to the curve of the first stage except for the last three data. While the first stage BOD started to increase, the effluent BOD started to decrease. Figure 12 indicates the efficiency of treatment as a function of time. It shows that the efficiency of treatment increased from 91 percent to 96.4 percent then it decreased suddenly to 52.3 percent after 19 days of applying this load and it started to increase again to reach 83.6 percent after 24 days. Figures 13-15 represent the BOD removal as a function of stages for the data collected before, during and after the deterioration. The three curves show that the greatest removal occurred in the first stages and a little treatment occurred in the next stages. An average of 90 percent of the BOD was removed in the first stage (14.4 lbs BOD_5/day/1000 ft^2) and 3.8 percent was removed in the next four stages, see Figure 13. An average of 45.4 percent of the BOD was removed in the first stage (6.72 lbs $sBOD_5$/day/1000 ft^2) and a very little treatment, almost zero, occurred in the next three stages, then 6.9 percent of the BOD was removed in the last stage, Figure 14. In Figure 15 the BOD removal increased again to 74.8 percent in the first stage and a very little removal occurred in the next three stages (2.4 percent removal); 4.7 percent of the BOD was removed in the last stage.

The problem in operating conditions started to appear in this category. The odor problem started to appear during applying the first

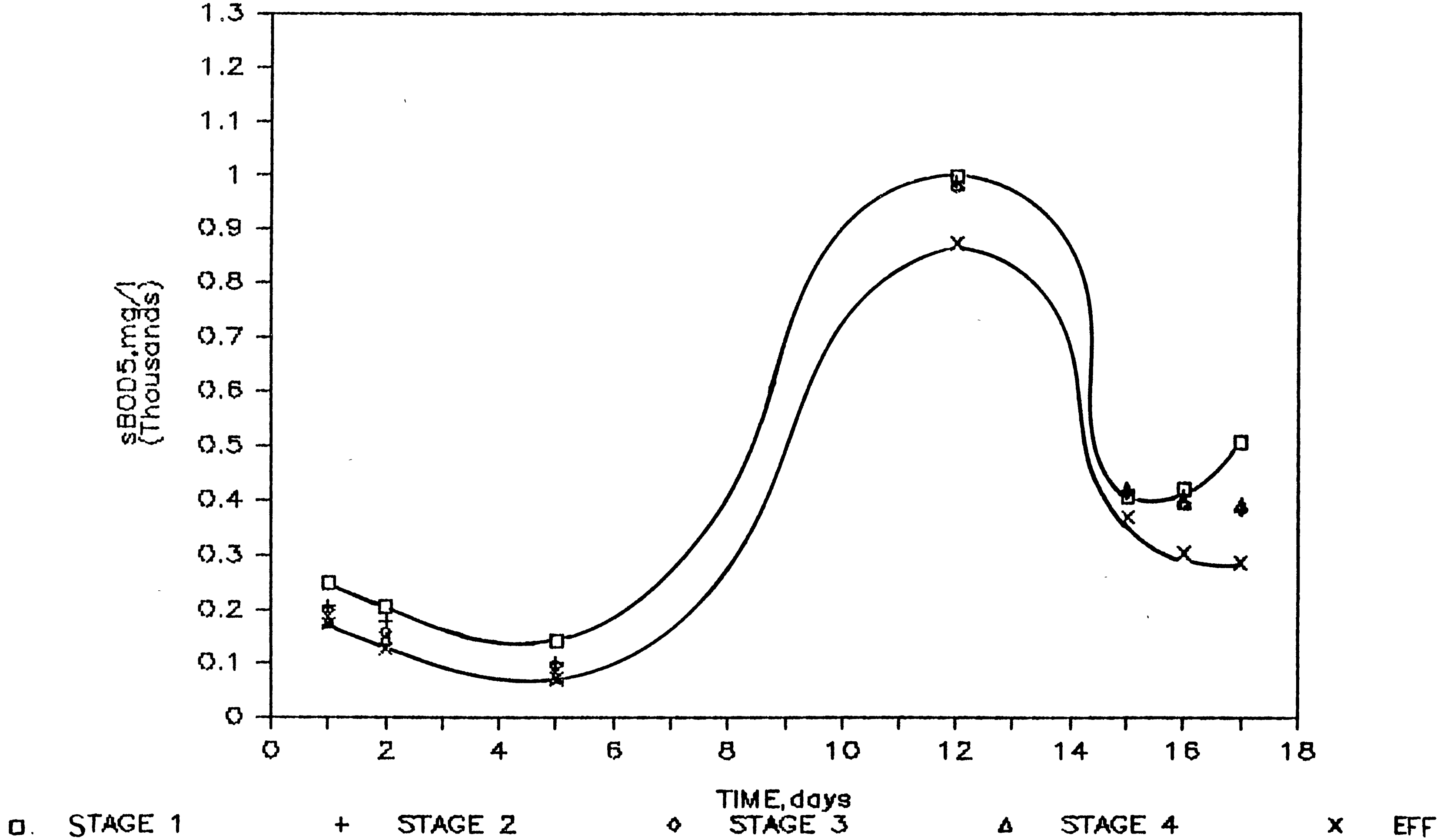

Figure 11. $sBOD_5$ Removal vs. Time for the Fourth Organic Loading Condition (5.4 lbs $sBOD_5$/day/1000 ft^2)

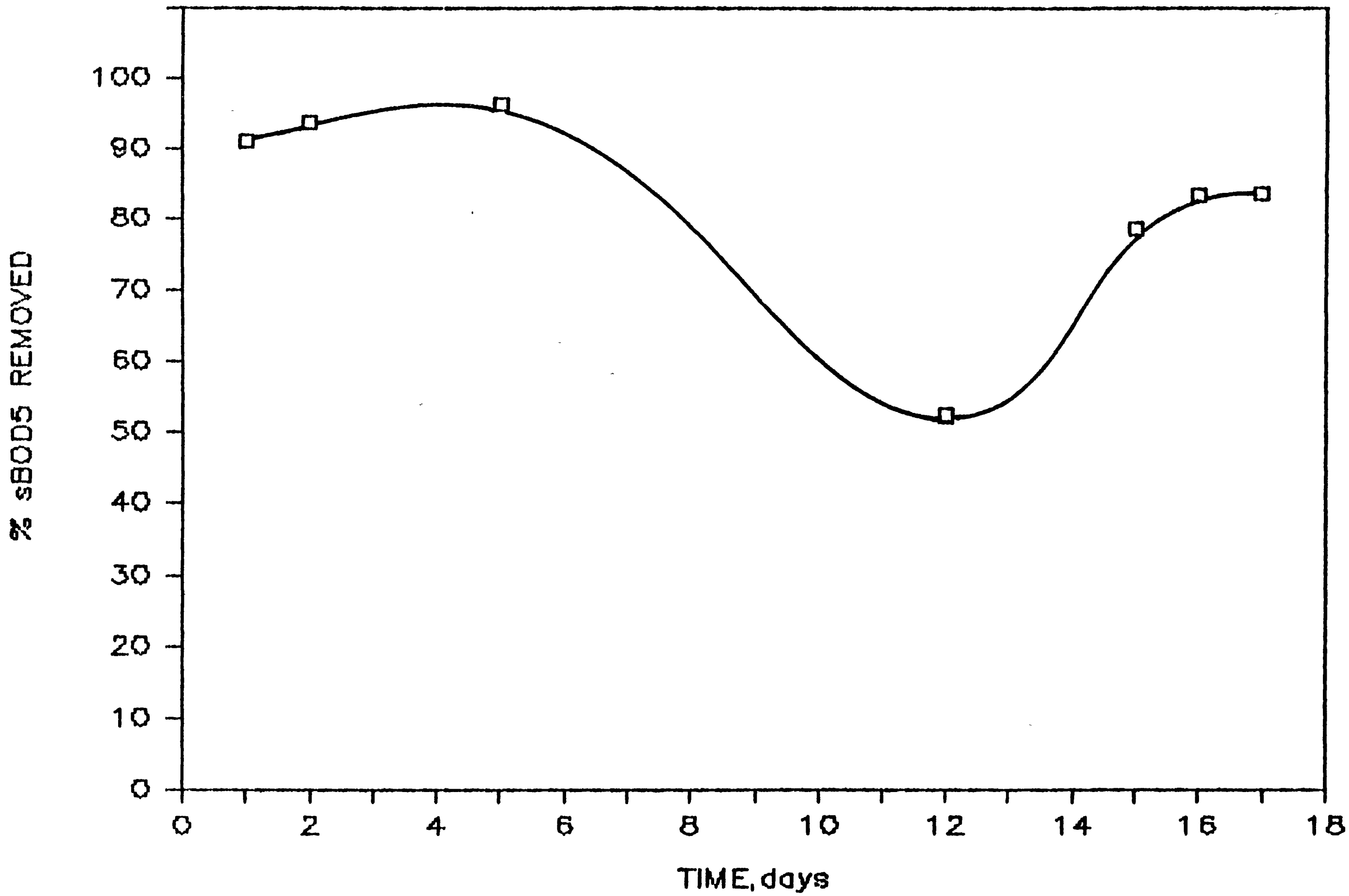

Figure 12. Efficiency of Treatment vs. Time for the Fourth Organic Loading Condition (5.4 lbs $sBOD_5$/day/1000 ft^2)

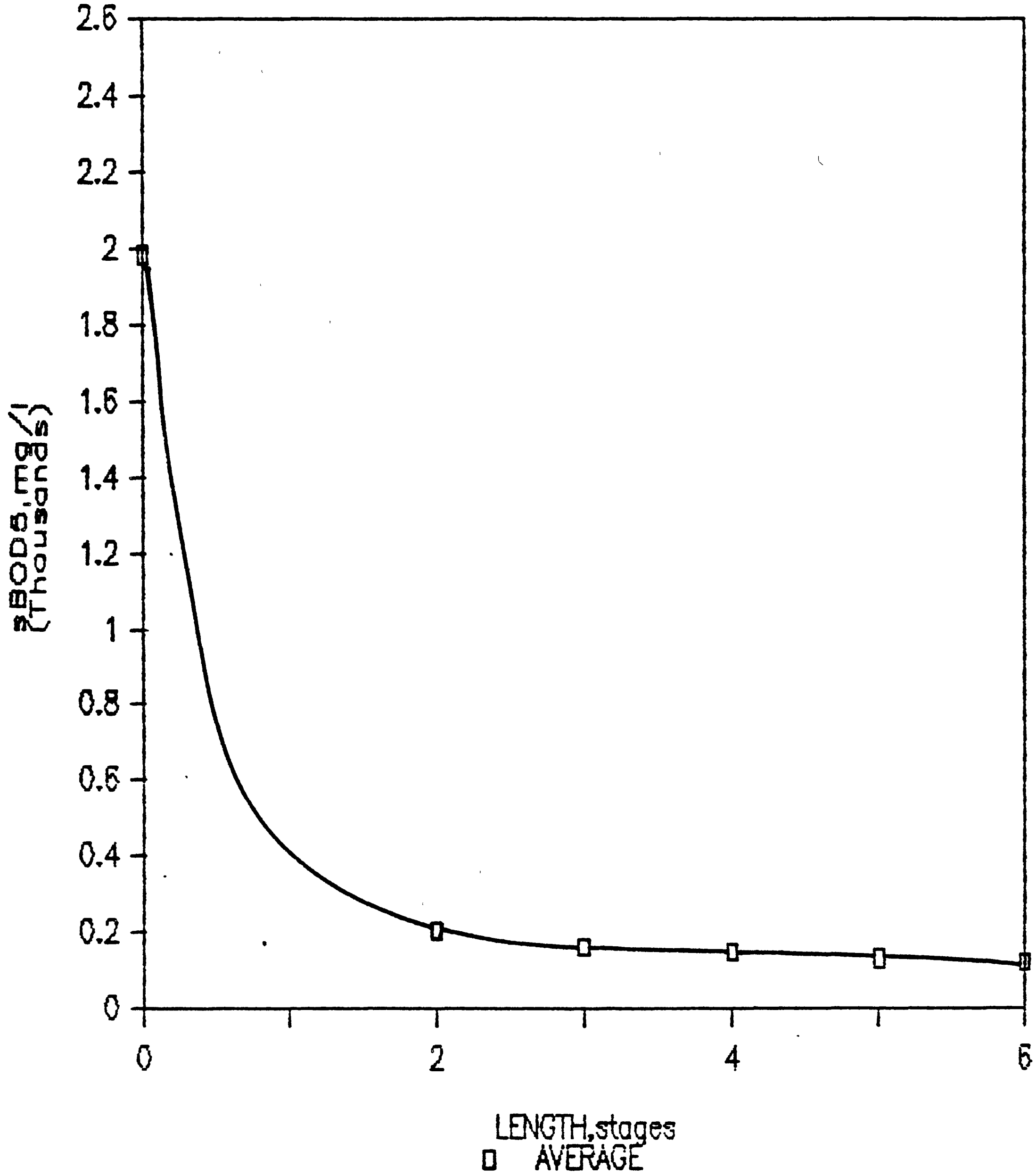

Figure 13. $sBOD_5$ Remaining vs. Stages for the Fourth Organic Loading Condition (5.4 lbs $sBOD_5$/day/1000 ft^2). Before the Deterioration

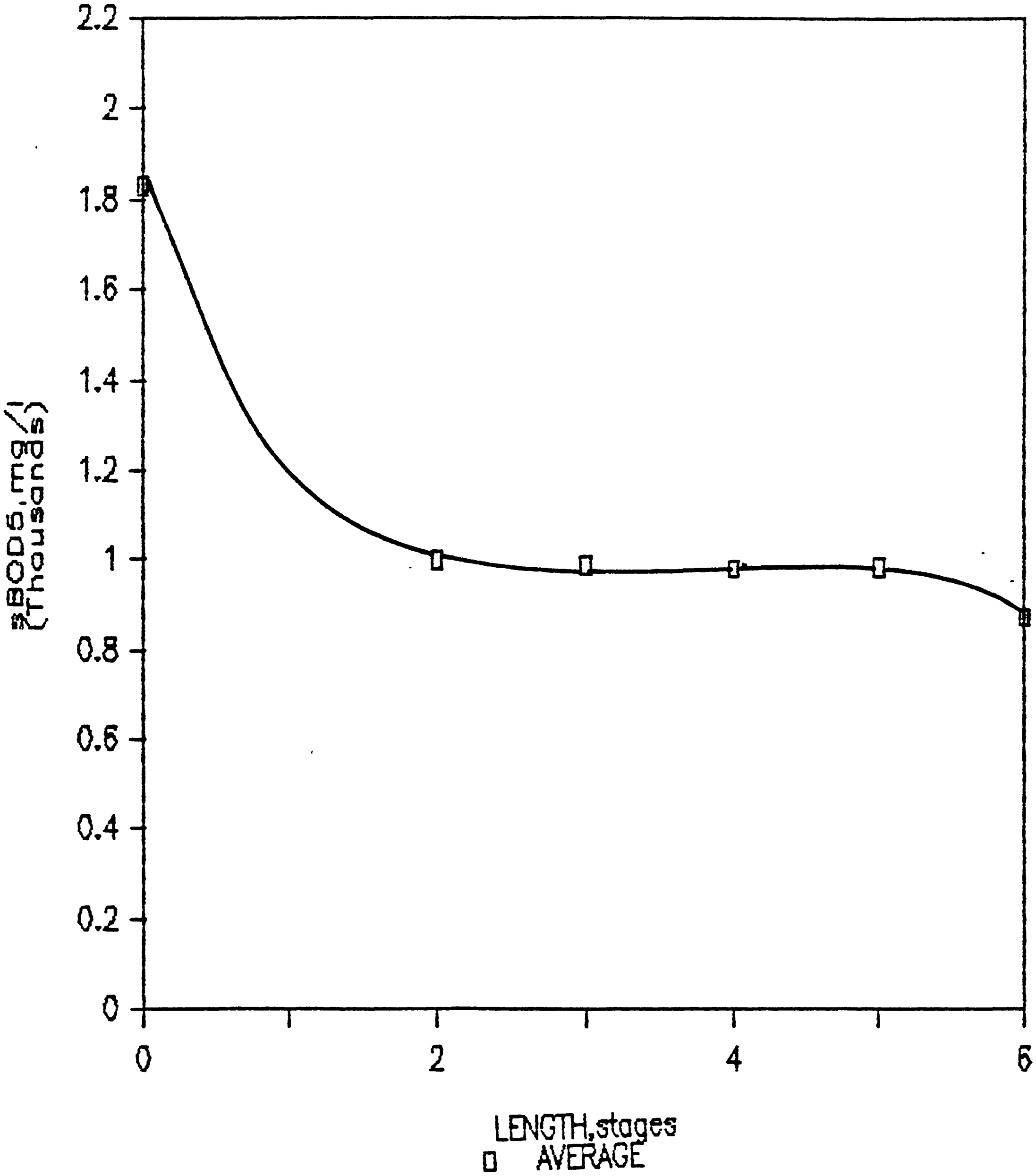

Figure 14. $sBOD_5$ Remaining vs. Stages for the Fourth Organic Loading Condition (5.4 lbs $sBOD_5$/day/1000 ft^2). During the Deterioration

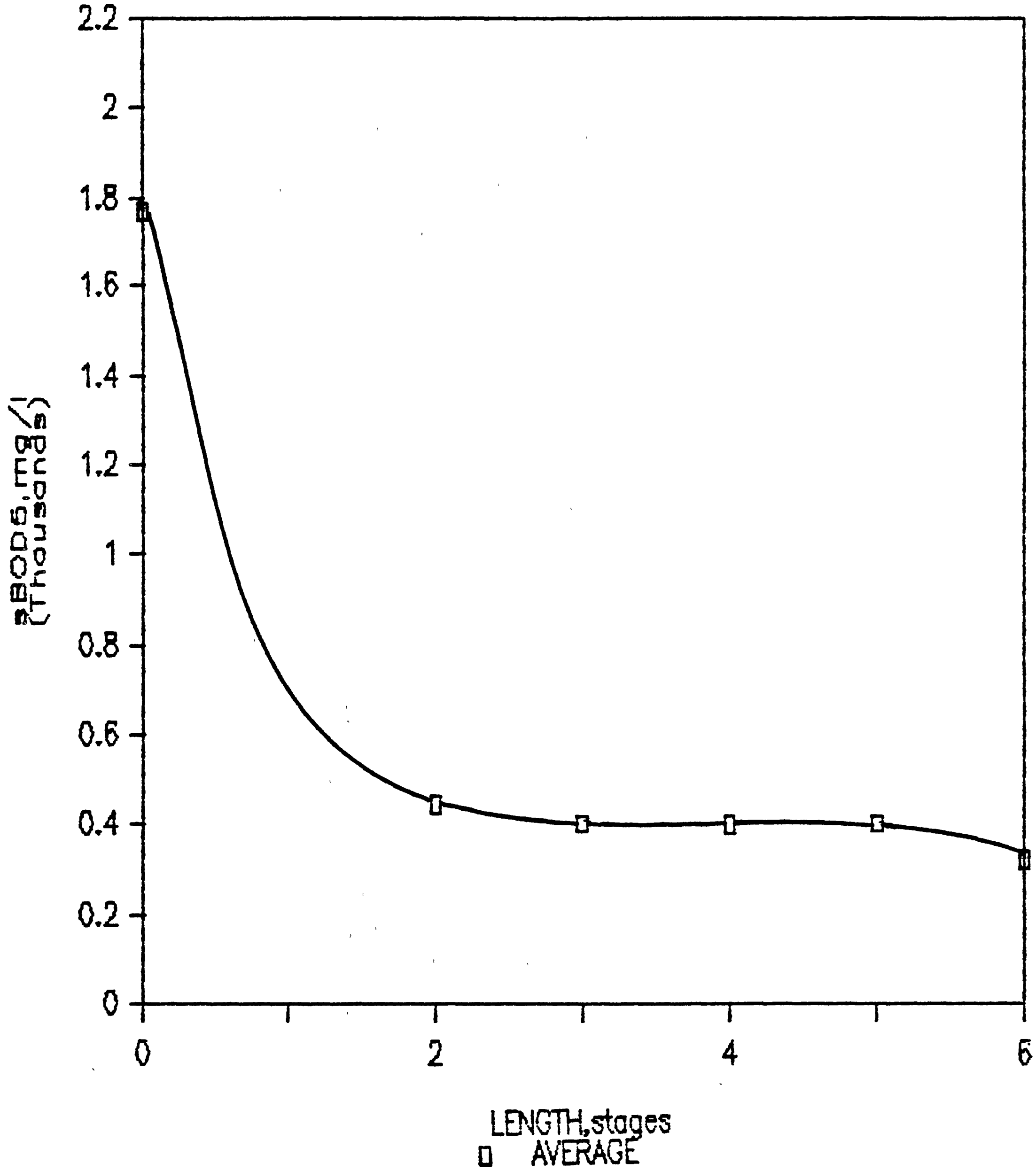

Figure 15. $sBOD_5$ Remaining vs. Stages for the Fourth Organic Loading Condition (5.4 lbs $sBOD_5$/day/1000 ft^2). After the Deterioration

TABLE VIII

INFLUENT CONCENTRATION, REMAINING $sBOD_5$ FOR EACH STAGE AS mg/l AND THE BOD REMOVAL EFFICIENCY FOR THE FOURTH LOADING CONDITION

DISK DIA = 6 INCHES   AREA PER STAGE = 1.57sf   TOTAL AREA = 9.42sf

LOAD NO.	FLOW l/day	BOD, mg/l INF	STAGE 1	STAGE 2	STAGE 3	STAGE 4	EFF	DAYS	% of removal
IV	11.52	1939.00	259.00	207.00	199.00	177.00	173.00	1.00	91.08
	11.52	2020.00	206.00	179.00	158.00	144.00	126.00	2.00	93.76
	11.52	1987.00	140.00	101.00	95.00	74.00	71.00	5.00	96.43
	11.52	1720.00	1108.00	1122.00	---	---	---	7.00	---
	11.52	1764.00	1043.00	1074.00	---	---	---	8.00	---
	11.52	2091.00	1032.00	1077.00	---	---	---	9.00	---
	11.52	1830.00	999.00	989.00	979.00	984.00	873.00	12.00	52.30
	11.52	1729.00	408.00	420.00	416.00	423.00	370.00	15.00	78.60
	11.52	1832.00	423.00	410.00	396.00	397.00	304.00	16.00	83.41
	11.52	1746.00	506.00	383.00	385.00	392.00	286.00	17.00	83.62

TABLE IX

APPLIED ORGANIC LOADING AND REMOVED $sBOD_5$ AS LBS/DAY/1000 FT^2 OF EACH STAGE FOR THE FOURTH LOADING CONDITION

lb/day/1000ft sq.									
STAGE 1		STAGE 2		STAGE 3		STAGE 4		STAGE 5	
FSi / A	F(Si-Se) / A	FSi / A	F(Si-Se) / A	FSi / A	F(Si-Se) / A	FSi / A	F(Si-Se) / A	FSi / A	F(Si-Se) / A
15.52	13.58	10.45	9.05	7.83	7.00	6.27	5.62	5.22	4.75
16.17	14.66	10.88	9.77	8.16	7.44	6.53	6.02	5.44	5.05
15.91	14.93	10.70	9.95	8.03	7.62	6.42	6.12	5.35	5.15
---	---	---	---	---	---	---	---	---	---
---	---	---	---	---	---	---	---	---	---
---	---	---	---	---	---	---	---	---	---
14.65	6.72	9.86	4.48	7.39	3.40	5.92	2.75	4.93	2.28
13.84	10.68	9.31	7.12	6.99	5.29	5.59	4.24	4.66	3.52
14.66	11.39	9.87	7.59	7.40	5.75	5.92	4.64	4.93	3.87
13.98	10.02	9.41	6.68	7.05	5.51	5.64	4.40	4.70	3.65

load and it became stronger during the second load. Clogging problem happened once during the second load. At the first load, the biomass film was about 1/2 inch thick with a white color, firm and attached to the media in the first stage, and it got thinner and darker in the next four stages. At the second load, the biomass film was thicker and darker and it was sloughing from the media and concentrating between discs causing clogging problems. A white filaments film grew around the discs and the interior surface of the tank. When the failure happened in the system the biomass film turned to a slightly yellowish-white color. Red and black worms were found in the system, too.

The results of the last category are shown in Figures 16-21 and Tables X, XI, XII and XIII. the performance of the unit based on BOD removal as a function of time is shown in Figures 16, 17, 19 and 20. The performance of the unit based on BOD removal as a function of stages is shown in Figures 18 and 21.

As shown in Figures 16 and 17, the treatment efficiency for the fifth total organic load (6.7 lbs $sBOD_5$/day/1000 ft^2) varied with time. the effluent BOD decreased from 882.0 mg/l to 633.0 mg/l within the first five days of collecting data, then it increased to 852.0 mg/l and decreased again to 733.0 mg/l. The curve of the effluent is almost parallel to the curve of the first stage, Figure 16. The percentage BOD removal ranged from 65.6 percent to 73.2 percent with an average of 69.5 percent. Figure 18 indicates that the major treatment occurred in the first stage. An average of 61.3 percent of the BOD was removed in the first stage (12.3 lbs $sBOD_5$/day/1000 ft^2), and a very little treatment occurred in the next three stages (3.4 percent removal); 4.6 percent of the substrate was removed in the last stage.

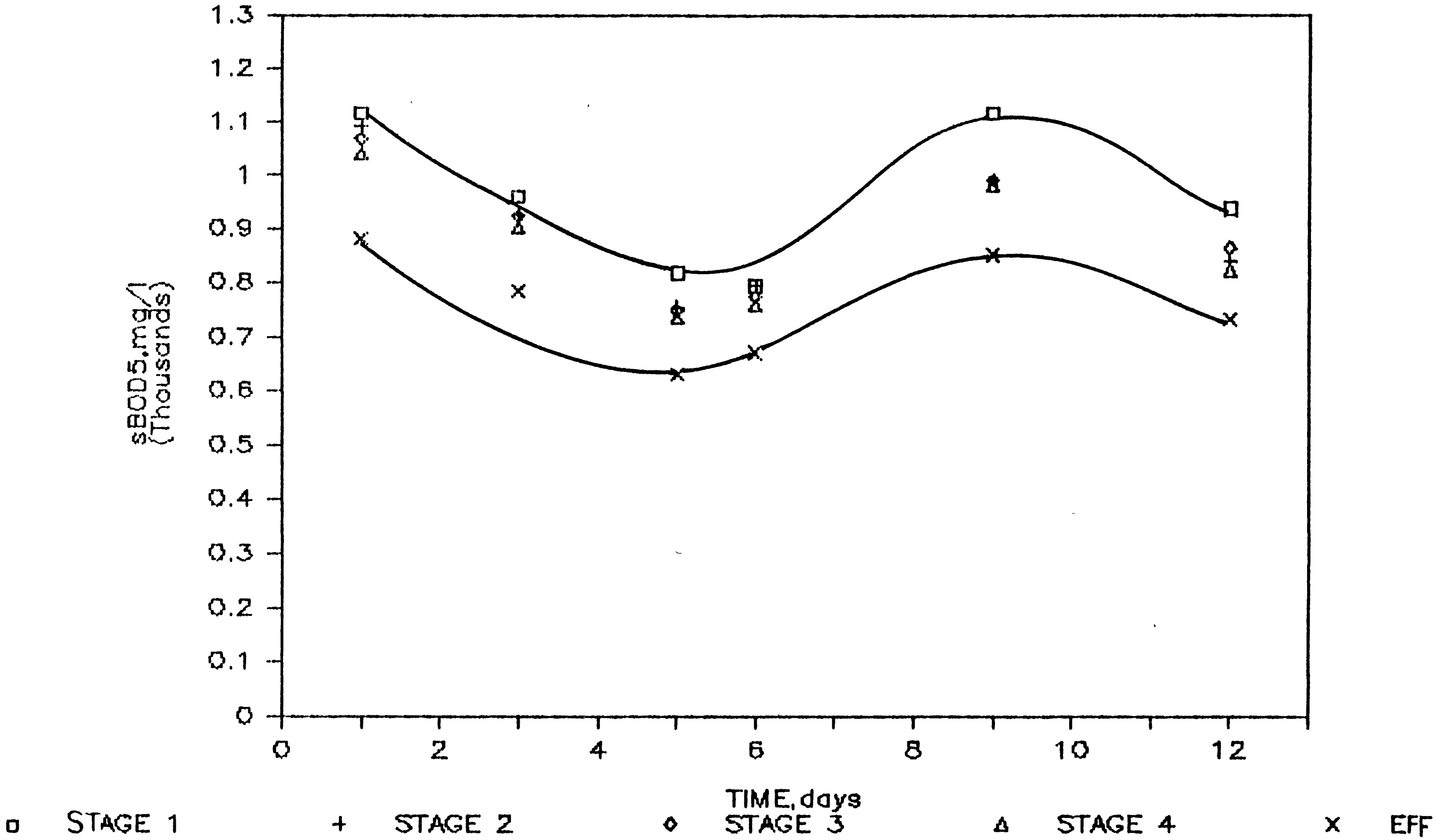

Figure 16. $sBOD_5$ Removal vs. Time for the Fifth Organic Loading Condition (6.7 lbs $sBOD_5$/day/1000 ft^2)

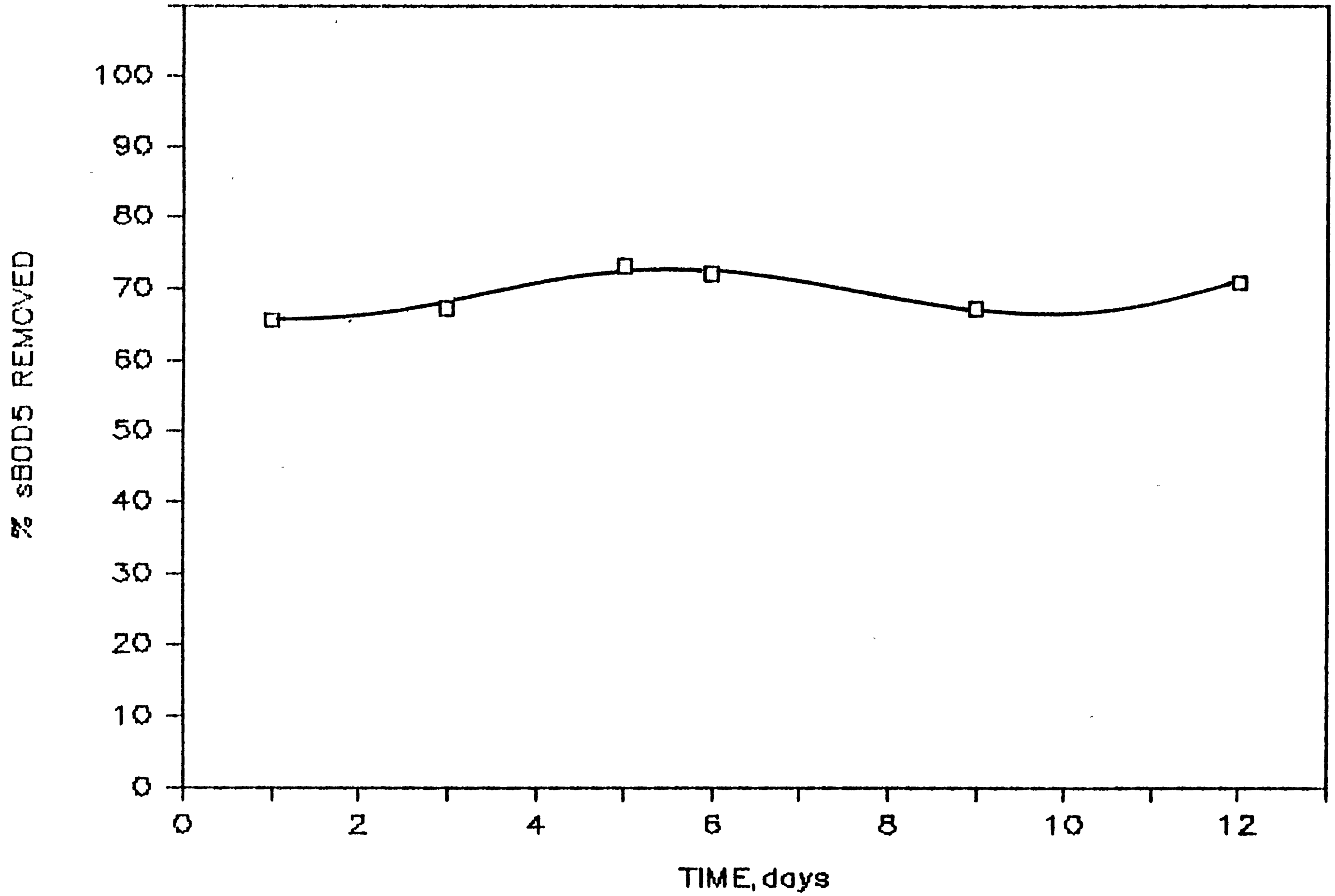

Figure 17. Efficiency of Treatment vs. Time for the Fifth Organic Loading Condition (6.7 lbs $sBOD_5$/day/1000 ft^2)

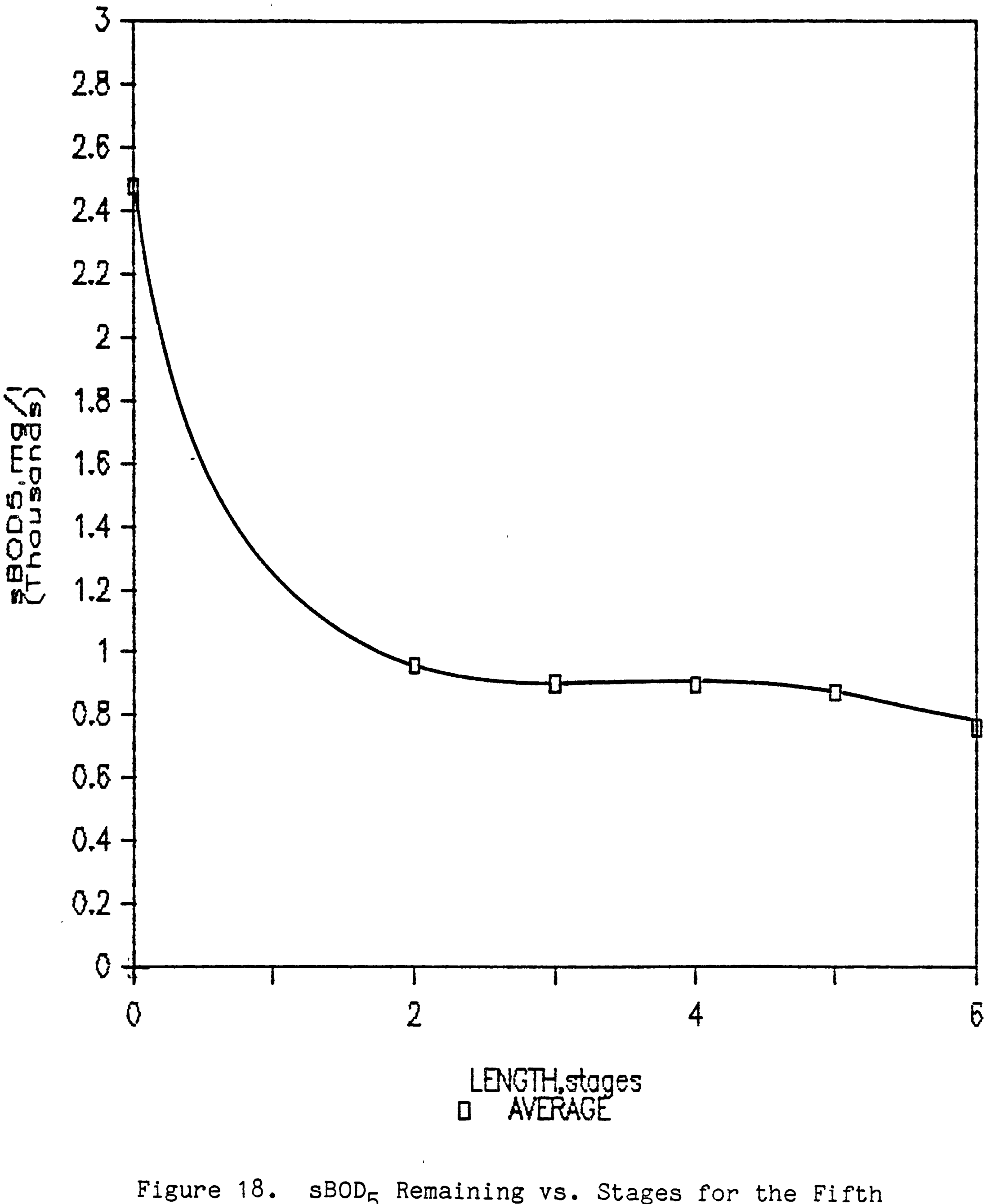

Figure 18. $sBOD_5$ Remaining vs. Stages for the Fifth Organic Loading Condition (6.7 lbs $sBOD_5$/day/1000 ft^2)

TABLE X

INFLUENT CONCENTRATION, REMAINING $sBOD_5$ FOR EACH STAGE AS mg/l AND THE BOD REMOVAL EFFICIENCY FOR THE FIFTH LOADING CONDITION

DISK DIA = 6 INCHES AREA PER STAGE = 1.57sf TOTAL AREA = 9.42sf

LOAD NO.	FLOW l/day	INF	STAGE 1	STAGE 2	BOD, mg/l STAGE 3	STAGE 4	EFF	DAYS	% of removal
V	11.52	2565.00	1116.00	1092.00	1068.00	1041.00	882.00	1.00	65.61
	11.52	2400.00	960.00	927.00	924.00	903.00	786.00	3.00	67.25
	11.52	2360.00	819.00	756.00	750.00	736.00	633.00	5.00	73.18
	11.52	2415.00	795.00	796.00	775.00	760.00	673.00	6.00	72.13
	11.52	2599.00	1116.00	990.00	990.00	980.00	852.00	9.00	67.22
	11.52	2522.00	938.00	840.00	865.00	823.00	733.00	12.00	70.94
Ave.	11.52	2476.83	957.33	900.17	895.33	873.83	759.83		69.32

TABLE XI

APPLIED ORGANIC LOADING AND REMOVED $sBOD_5$ AS LBS/DAY/1000 FT^2 OF EACH STAGE FOR THE FIFTH LOADING CONDITION

lb/day/1000ft sq.									
STAGE 1		STAGE 2		STAGE 3		STAGE 4		STAGE 5	
$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$	$\frac{FSi}{A}$	$\frac{F(Si-Se)}{A}$
20.53	11.71	13.82	7.81	10.36	5.95	8.29	4.84	6.91	4.11
19.21	11.64	12.93	7.76	9.70	5.95	7.76	4.77	6.46	4.03
18.89	12.45	12.71	8.30	9.54	6.48	7.63	5.20	6.36	4.37
19.33	13.09	13.01	8.73	9.76	6.54	7.81	5.30	6.51	4.46
20.80	11.98	14.00	7.99	10.50	6.50	8.40	5.20	7.00	4.36
20.19	12.80	13.59	8.53	10.19	6.80	8.15	5.36	6.79	4.58
19.83	12.28	13.34	8.19	10.01	6.37	8.01	5.11	6.67	4.32

Figures 19 and 20 indicate that the removal efficiency for the sixth total organic load (10.8 lbs $sBOD_5$/day/1000 ft^2) varied with time. And the curve of the first stage is not parallel to the curve of the effluent. The percentage BOD removal ranged from 55.1 percent to 61.2 percent with an average of 58.5 percent. Figure 21 shows that the major treatment occurred in the first stage. An average of 46.6 percent of the substrate was removed in the first stage (14.28 lbs $sBOD_5$/day/1000 ft^2), and 11.9 percent removal occurred in the next four stages.

The operating conditions for this category were difficult. The odor problem was severe in both loads. The biomass film was thick with a dark white color. It sloughed fast from the disc surfaces and concentrated between discs causing a lot of clogging problems. A white filamentous film grew around the discs and the tank interior surface. Red and black worms were found in the system.

4.2 Kinetic Analyses

The kinetic analyses in this study was based upon the concept of the total organic loading. This concept was first introduced by Kincannon and stover in the early 1970's [6, 13]. In this concept, the specific substrate utilization rate is a function of the specific loading (FSi/A) as lbs $sBOD_5$ applied/day/1000 ft^2. Figure 22 represents the relationship of soluble BOD removed (lbs/day/1000 ft^2) as a function of soluble BOD applied (lbs/day/1000 ft^2). The specific loadings and specific substrate utilization rates were calculated by considering the influent substrate concentration, S_i, as the influent $sBOD_5$ to the entire stages. The effluent substrate concentration, S_e, was considered

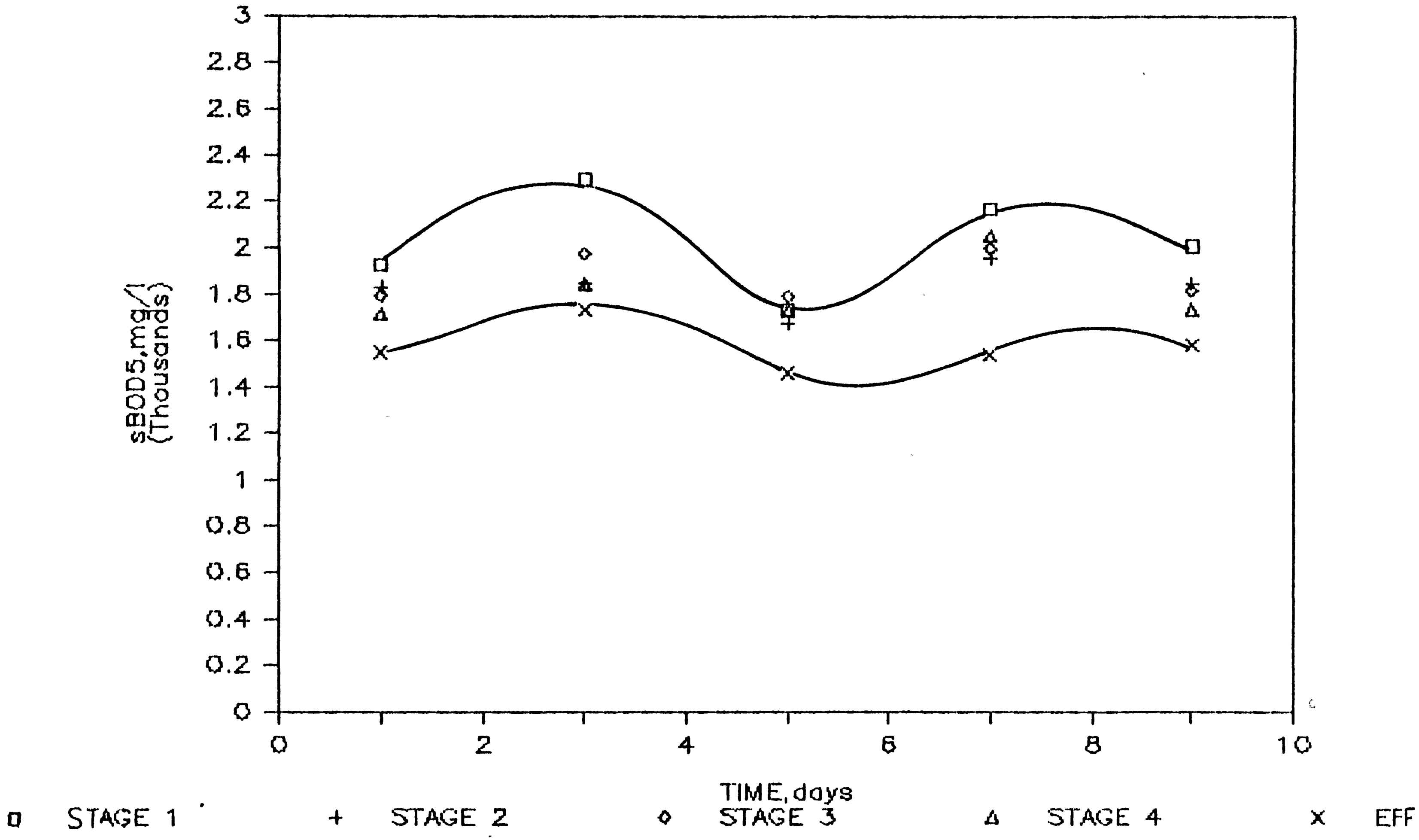

Figure 19. $sBOD_5$ Removal vs. Time for the Sixth Organic Loading Condition (10.8 lbs $sBOD_5$/day/1000 ft^2)

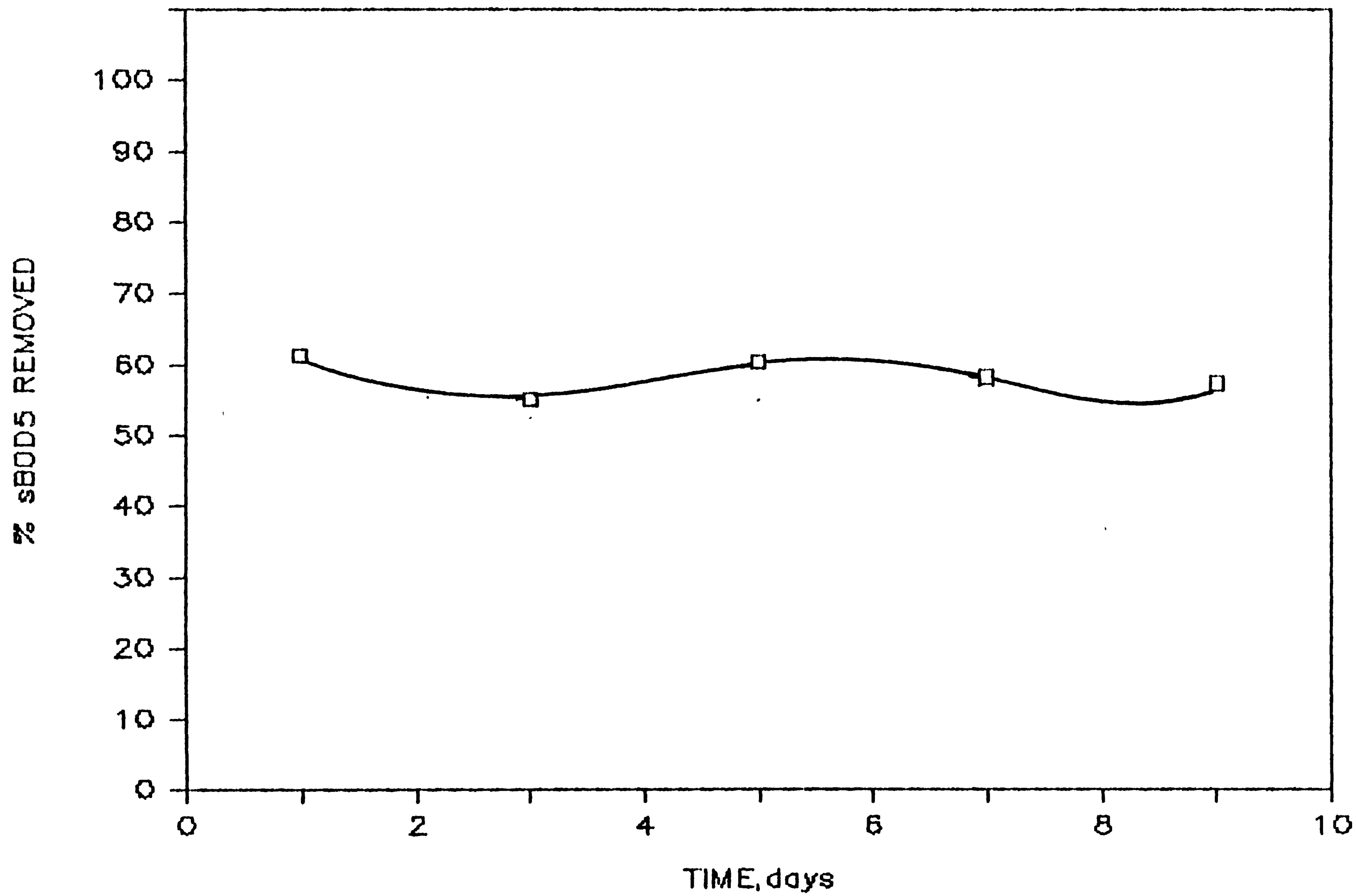

Figure 20. Efficiency of Treatment vs. Time for the Sixth Organic Loading Condition (10.8 lbs $sBOD_5$/day/1000 ft^2)

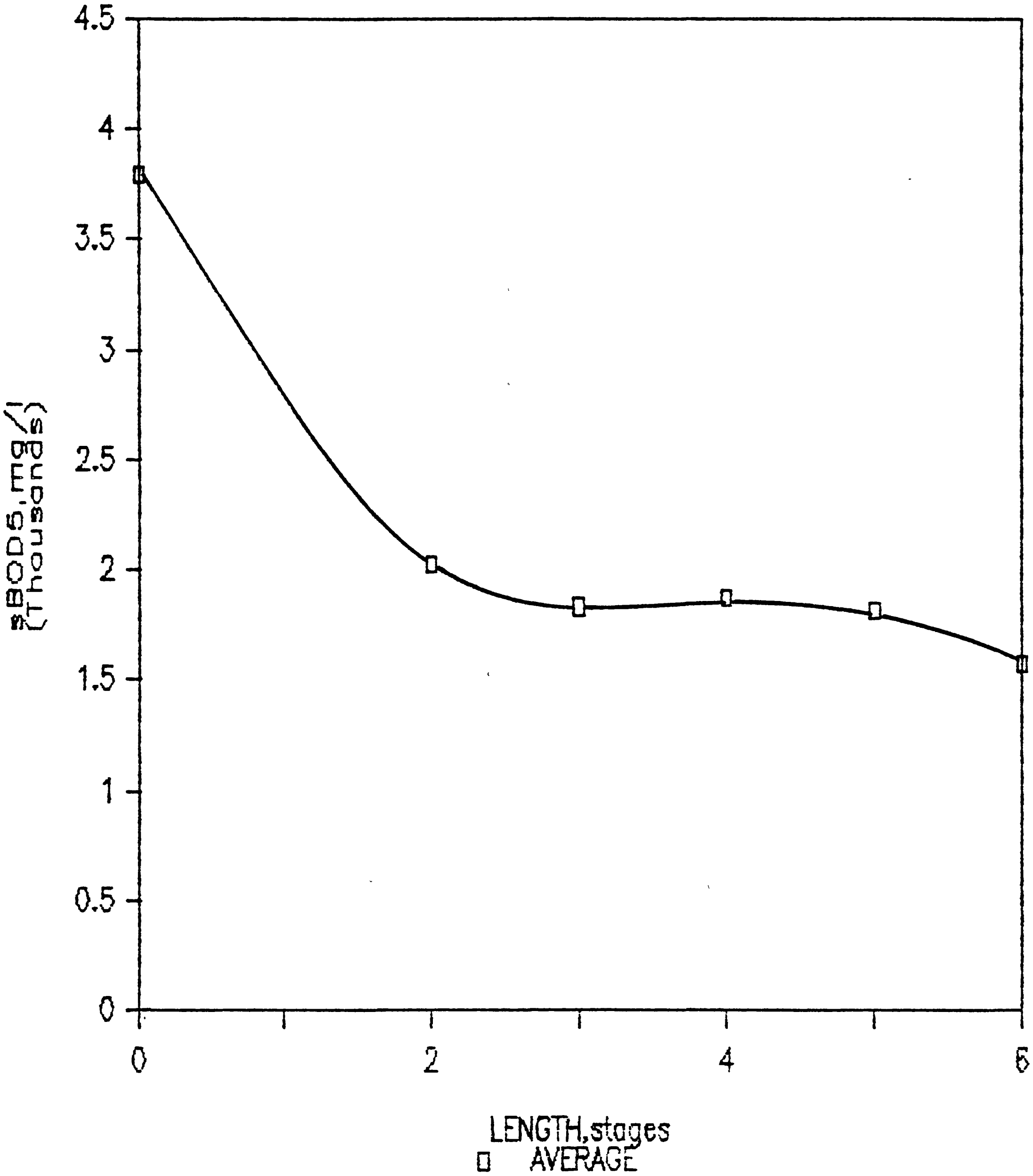

Figure 21. $sBOD_5$ Remaining vs. States for the Sixth Organic Loading Condition (10.8 lbs $sBOD_5$/day/1000 ft^2)

TABLE XII

INFLUENT CONCENTRATION, REMAINING $sBOD_5$ FOR EACH STAGE AS mg/l AND THE BOD REMOVAL EFFICIENCY FOR THE SIXTH LOADING CONDITION

DISK DIA = 6 INCHES AREA PER STAGE = 1.57sf TOTAL AREA = 9.42sf

LOAD NO.	FLOW l/day	INF	BOD, mg/l STAGE 1	STAGE 2	STAGE 3	STAGE 4	EFF	DAYS	% of removal
VI	11.52	4005.00	1926.00	1834.00	1799.00	1717.00	1554.00	1.00	61.20
	11.52	3865.00	2295.00	1847.00	1976.00	1847.00	1736.00	3.00	55.08
	11.52	3692.00	1736.00	1676.00	1794.00	1732.00	1463.00	5.00	60.37
	11.52	3696.00	2168.00	1959.00	1998.00	2052.00	1544.00	7.00	58.23
	11.52	3713.00	2008.00	1850.00	1820.00	1738.00	1584.00	9.00	57.34
Ave.	11.52	3794.20	2026.60	1833.20	1877.40	1817.20	1576.20		58.46

TABLE XIII

APPLIED ORGANIC LOADING AND REMOVED $sBOD_5$ AS LBS/DAY/1000 FT^2 OF EACH STAGE FOR THE SIXTH LOADING CONDITION

lb/day/1000ft sq.

STAGE 1		STAGE 2		STAGE 3		STAGE 4		STAGE 5	
FSi/A	F(Si-Se)/A	FSi/A	F(Si-Se)/A	FSi/A	F(Si-Se)/A	FSi/A	F(Si-Se)/A	FSi/A	F(Si-Se)/A
32.06	16.80	21.58	11.20	16.18	8.77	12.95	7.13	10.79	6.16
30.94	12.69	20.82	8.46	15.62	8.15	12.49	6.11	10.41	5.44
29.55	15.81	19.89	10.54	14.92	8.15	11.93	6.14	9.95	5.28
29.58	12.35	19.91	8.23	14.93	7.02	11.95	5.49	9.96	4.43
29.72	13.78	20.00	9.19	15.00	7.53	12.00	6.12	10.00	5.32
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30.37	14.28	20.44	9.52	15.33	7.92	12.26	6.20	10.22	5.33

as the effluent from any stage under consideration [13]. Figure 22 indicates that the removal capabilities of the RBC unit at these six different organic loads followed monomolecular kinetics and it can be fitted with a hyperbolic function similar to the "Monod equation" as described by Kincannon and Stover [6, 13]. This relationship can be shown as follows:

$$L_R = \frac{L_{R(max)} L_0}{k_s + L_0}$$

where: L_0 = Applied BOD loading in lbs BOD/day/1000 ft^2 (FS_i/A)

L_R = BOD removed in lbs BOD/day/1000 ft^2 $(F(S_i - S_e)/A)$

$L_{R(max)}$ = Maximum BOD removed in lbs BOD/day/1000 ft^2

k_s = Applied BOD loading rate at which the rate of BOD removal is one-half the maximum rate, or the saturation constant.

Figure 22 indicates that the amount of BOD removed increased as the amount of BOD applied increased until the breaking point of 6.0 to 6.5 Lbs BOD/day/1000 ft^2 where the amount of BOD removed per BOD applied started to significantly decrease. Beyond these loading conditions the removal capabilities of the unit decreased and the BOD removed approached a maximum value at a loading condition of 20 lbs BOD/day/1000 ft^2.

Figure 23 represents the reciprocal plot of $sBOD_5$ removed (lbs/day/1000 ft^2) versus $sBOD_5$ applied (lbs/day/1000 ft^2) for the averages of every stage at every applied load. by rearranging the previous equation as follows.

$$\frac{1}{L_R} = \frac{k_s}{L_{R(max)}} \cdot \frac{1}{L_0} + \frac{1}{L_{R(max)}}$$

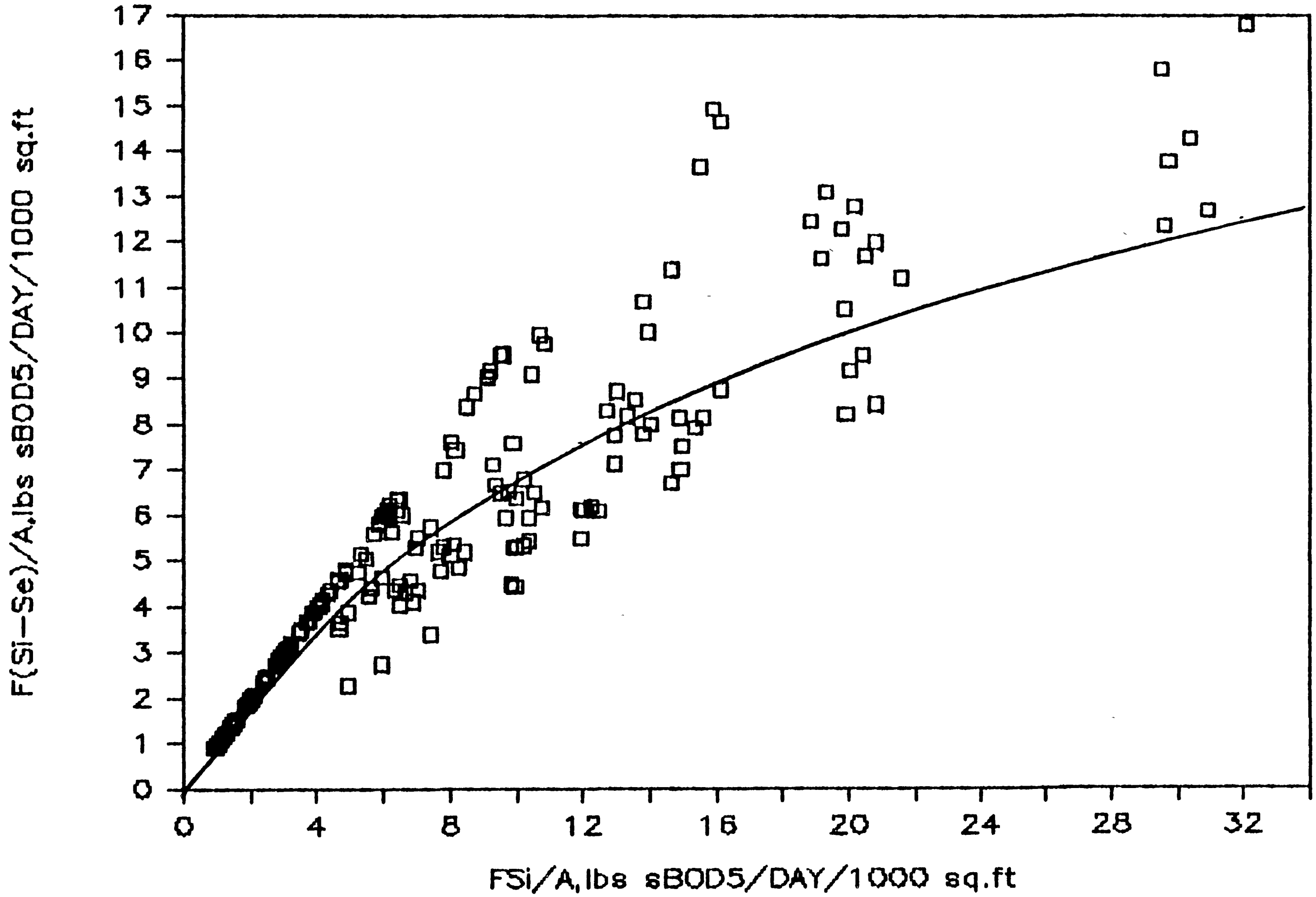

Figure 22. Specific Substrate Utilization Rate as a Function of Loading Rate.

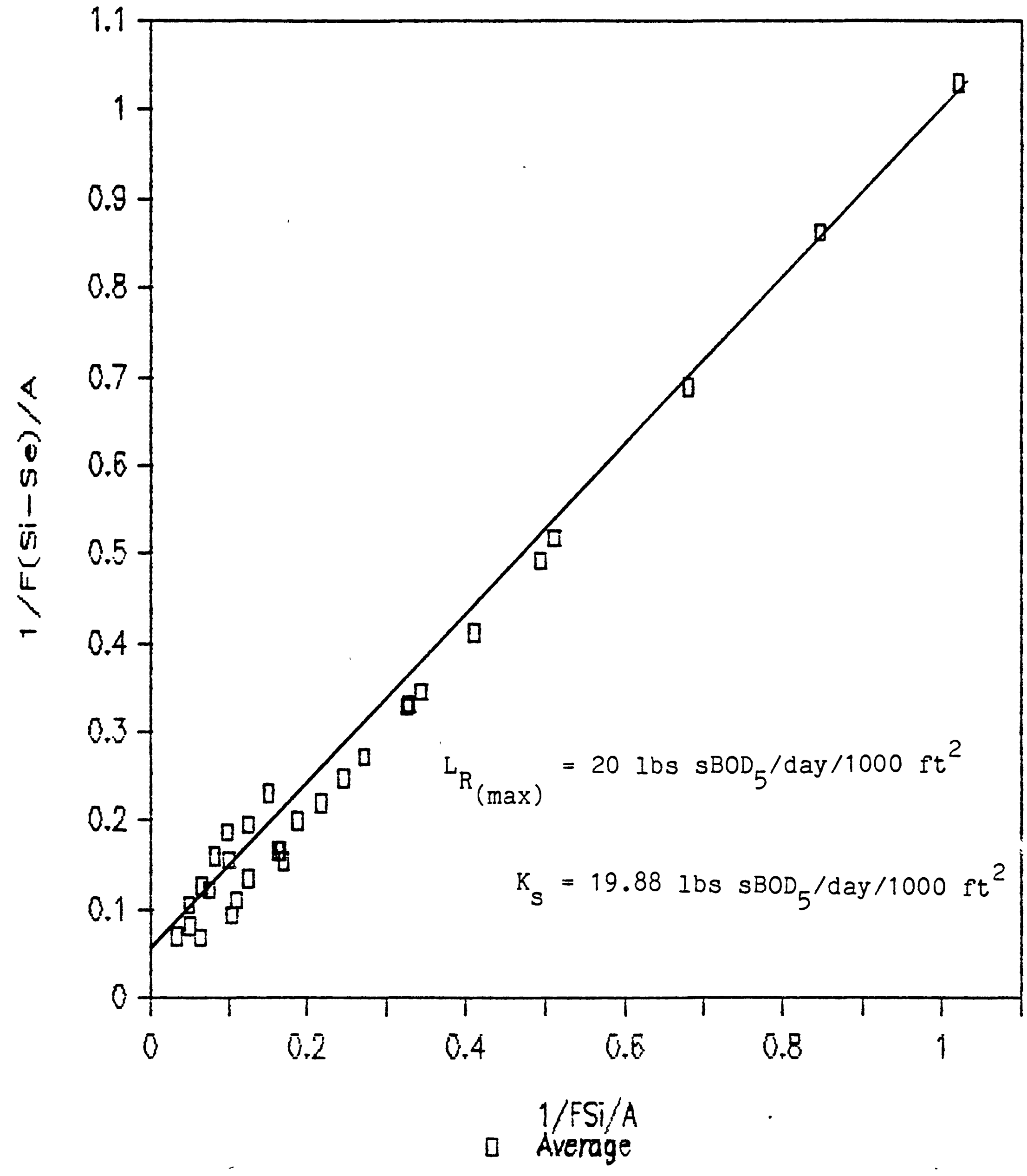

Figure 23. Reciprocal plot of $sBOD_5$ Removed (lb $sBOD_5$/day/1000 ft^2) vs. $sBOD_5$ Applied (lb/day/1000 ft^2)

$L_{R(max)}$ and K_s can be determined by the intercept and the slope of the curve in Figure 23. the maximum theoretical BOD removal rate $L_{R(max)}$ was 20 lbs $sBOD_5$/day/1000 ft^2 and k_s was 19.88 lbs $sBOD_5$/day/1000 ft^2.

CHAPTER V

SUMMARY OF RESULTS AND DISCUSSION

The performance of the unit based on BOD removal for the first category, which includes total organic loads of 1 and 2 lbs $sBOD_5$/day/1000 ft^2, was very good and stable. The efficiency of treatment was almost constant with time as shown in Figures 2 and 5, it was 98.9 percent for the first load and 99.5 percent for the second load. the major BOD removal was accomplished by the first stage (98 percent removal for the first load and 99 percent removal for the second load). The average BOD leaving the first stage for both loads was 6.5 mg/l. Due to this low organic concentration of the wastewater leaving the first stage, nitrification took place in the RBC. The biomass was dark due to the nitrification process. Inhibited $sBOD_5$ test was run during the second load to eliminate the nitrogenous BOD from the data obtained. Due to running inhibited $sBOD_5$ tests in the second load, the efficiency of treatment was higher for this load. Up to 2.9 lbs $sBOD_5$/day/1000 ft^2 was removed in the first stage for the first load and 6.0 lbs $sBOD_5$/day 1000 ft^2 for the second load. The operating conditions were good during this category. From these results, it can be concluded that the major treatment occurred in the first stage. Up to 6.0 lbs $sBOD_5$/day/1000 ft^2 was removed in the first stage. The operating condition was very good and the system was free of any odor or clogging problems. This means that the unit was free of any nuisance organisms such as Beggiatoa up to a total organic load of 2 lbs $sBOD_5$/day/1000 ft^2 and 6.0 lbs $sBOD_5$/day/1000 ft^2 organic load for the first stage.

The performance and the operating conditions of the unit for the second category which includes total organic loads of 3 and 5.4 lbs $sBOD_5$/day/1000 ft^2, started to change. During the first 12 days of applying the first load (3 lbs $sBOD_5$/day/1000 ft^2) the performance and the operating conditions were good. The efficiency of treatment was stable and ranging from 98.7 to 98.9 percent. The major treatment occurred in the first stage (98.3 percent removal). Then the treatment efficiency of the first stage started to deteriorate. As shown in Figure 7, the curves of the first stage and the effluent were not parallel, when the deterioration began in the first stage the effluent BOD began to decrease from an average of 14.9 mg/l to 3.9 mg/l. From these observations it seems that sulfide oxidizing organisms (Beggiatoa) began to grow only in the first stage but not in the other stages. Figure 7 and Table VI show that the effluent BOD was higher than the BOD of the fourth stage for the entire data of the third load. Also in some data the BOD decreased from stage to stage and then increased in one of the stages even that happened with the data obtained from inhibited BOD tests. No valid explanation is available for these changes. The odor problem began during this load but there was no clogging problems. During applying the second load in this category (5.4 lbs, $sBOD_5$/day/1000 ft^2), the performance and the operating conditions were changing very rapidly. During the first 12 days the performance was fairly good. The efficiency of treatment varied from 91 to 96.4 percent. Up to 14.4 lbs $sBOD_5$ was removed in the first stage (90 percent removal). then, when the sudden deterioration occurred, the treatment efficiency dropped to 52.3 percent; the odor and clogging problems became severe and the biomass turned to slightly yellowish-white color. A white filaments film grew around the discs and the tank surface. The treatment efficiency began to improve again to reach 83.6 percent, then it decreased again. Figure 11 shows that the curves of the first stage and the effluent were parallel except for the last three data where the effluent quality started to improve while the treatment efficiency of the first stage decreased.

From these observations, it can be concluded that during the third load (3 lbs $sBOD_5$/day/1000 ft^2) the Beggiatoa began to grow around the first stage and caused reduction in the organic removal only in this stage. by increasing the organic load to 5.4 lbs $sBOD_5$/day/1000 ft^2, the applied load to the first stage was about 15.0 lbs $sBOD_5$/day/1000 ft^2. This load seems to exceed the oxygen transfer capability of the system. Exceeding this capability resulted in the proliferation of sulfide oxidizing organisms (Beggiatoa) over the entire unit and caused overall process deterioration. The yellowish-white color appeared in the biomass after the deterioration was due to the sulfur deposited by Beggiatoa around the discs.

The performance of the unit during the third category which included total organic loads of 6.7 and 10.8 lbs $sBOD_5$/day/1000 ft^2, varied rapidly. The operating conditions were difficult. the efficiency of treatment during the fifth load (6.7 lbs $sBOD_5$/day/1000 ft^2) increased form 65.6 to 73.2 percent within 12 days then it started to decrease to 67.2 within 4 days. The BOD removal in the first stage was 61.3 percent. An average of 19.8 lbs sBOD/day/1000 ft^2 organic load was applied to this stage and just 12.3 lbs $sBOD_5$/day/1000 ft^2 was removed, while an average of 14.4 lbs $sBOD_5$/day/1000 ft^2 was removed in the first stage during the fourth load before the deterioration occurred. The efficiency of treatment during the sixth load (10.8 lbs $sBOD_5$/day/ 1000 ft^2) varied with time, too. It changed from 55.1 to 61.2 percent. The BOD removal in the first stage was 46.6 percent. An average of 30.4 lbs $sBOD_5$/day/1000 ft^2 was applied to the first stage during this organic load, only 14.3 lbs $sBOD_5$/day/1000 ft^2 were removed. The odor and the clogging problems were severe for the two loads. As observed during those tow loads, the Beggiatoa grew around the discs and the tank, but no sudden deterioration occurred. This may be because those two loads had been applied to the unit first before the fourth load (5.4 lbs $sBOD_5$/day/1000 ft^2) where the deterioration occurred, and that gave the Beggiatoa enough time to be predominate during the fourth load and to cause this sudden deterioration.

As shown in Figure 22 and the previous discussion that the amount of BOD removed increased as the amount of BOD applied increased up to 6.5 lbs $sBOD_5$/day/1000 ft^2, then the amount of BOD removed per BOD applied starting to decrease. Beyond these loading conditions, the removal capabilities of the unit decreased and the BOD removed approached a maximum value (12.5 lbs $sBOD_5$/day/1000 ft^2) at a loading condition of 20 lbs $sBOD_5$/day/1000 ft^2. At organic loading rates higher than 20 lbs $sBOD_5$/day/1000 ft^2, the removal capabilities of the unit started to become oxygen transfer limited instead of biochemical reaction rate limited. Figure 22 as shown before follows Monod equation as described by Kincannon and Stover [6, 13].

A theoretical maximum BOD removal rate ($L_{R(max)}$) of 20.0 lbs

$sBOD_5$/day/1000 ft^2 was found from Figure 23. However, the actual maximum removal rate of 14.4 lbs $sBOD_5$/day/1000 ft^2 occurred at an applied loading rate of 15.9 lbs $sBOD_5$/day/1000 ft^2. As mentioned before, the breaking point of 6.0 to 6.5 lbs $sBOD_5$/day/1000 $ft^2$and a maximum BOD removal rate of 12.5 lbs $sBOD_5$/day/1000 ft^2 were observed for this RBC unit and this type of wastewater. These rates seem to be higher than the rates obtained by Stover and Kincannon (1-1.5 lbs $sBOD_5$/day/1000 ft^2 and 2.5 lbs $sBOD_5$/day/1000 ft^2) by using a full scale RBC. This high removal rates are due to the small size of the discs (1/2 feet in diameter) and small diameter systems provide better oxygen transfer and higher removal rates at higher organic loadings compared to larger diameter systems [6].

CHAPTER VI

CONCLUSIONS

The following conclusions were drawn from the results of this work:

1. The major BOD removal occurs in the first stage of the unit for this type of wastewater. Approximately 98 percent of the total BOD removal occurred in this stage for the first three total organic loads (1, 2, 3, lbs $sBOD_5$/day/1000 ft^2). Ninety, 61.2 and 46.6 percent of the BOD removed in this stage for the last three total organic loads (5.4, 6.7, 10.8 lbs $sBOD_5$/day/1000 ft^2). The BOD removal was very little in the other four stages for the six organic loads.

2. Up to 6.0 lbs $sBOD_5$/day/1000 ft^2 was removed in the first stage and the unit was free from any nuisance organisms such as Beggiatoa, the operating conditions were very good and treatment efficiency was very stable.

3. At organic loadings higher than 6.0 lbs $sBOD_5$/day/1000 ft^2 applied to the first stage, Beggiatoa started to grow in the system and it caused deterioration in the first stage at a first stage organic loading rate of 9.0 lbs $sBOD_5$/day/1000 ft^2. A progressive Beggiatoa took over the entire system and caused severe and sudden deterioration of the effluent quality during the first stage organic loading rate of 15.0 lbs $sBOD_5$/day/1000 ft^2.

4. A maximum removal rate ($L_{R(max)}$) of 12.5 lbs $sBOD_5$/day/1000 ft^2 occurred at an applied loading rate of 20.0 lbs $sBOD_5$/day/1000 ft^2.

Beyond this loading rate, the unit became oxygen transfer limited.

5. The BOD removal rates were high during the six organic loading due to the small size of the disc (1/2 ft diameter) which provided better oxygen transfer and higher removal rates.

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