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The biodegradability of aqueous film-forming foams (AFFF) used for fire fighting was evaluated in laboratory-scale activated sludge and trickling filter reactors at the Air Force Weapons Laboratory (AFWL). Three AFFFs were evaluated: "Light Water" FC-200 from 3M Company; Aerowater 3 percent from National Foam Company; and Aerowater 6 percent, also from National Foam Company. Concentrations not to exceed 100 mg/l of AFFF influent to the biological treatment process could be satisfactorily treated without affecting the performance of the process and with apparent detoxification of the AFFF. More detailed bioassay tests are required. Adsorption of AFFFs onto activated carbon is practical with removals varying from 75 to 100 percent, depending on the AFFF.

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AFWL-TR-73-279

TREATABILITY OF AQUEOUS FILM-FORMING FOAMS USED FOR FIRE FIGHTING

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TECHNICAL REPORT NO. AFWL-TR-73-279

Final Report for Period June 1972 through August 1973

/C

FOREWORD

The research was prepared under Program Element 63723F, Project 683M.

Inclusive dates of research were June 1972 through August 1973. The report was submitted 26 November 1973 by the Air Force Weapons Laboratory Project Officer, Lieutenant Ronald H. Kroop (DEE).

This technical report has been reviewed and is approved.

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ABSTRACT

(Distribution Limitation Statement A)

The biodegradability of aqueous film-forming foams (AFFF) used for fire fighting was evaluated in laboratory-scale activated sludge and trickling filter reactors at the Air Force Weapons Laboratory (AFWL). Three AFFFs were evaluated: "Light Water" FC-200 from 3M Company; Aerowater 3 percent from National Foam Company; and Aerowater 6 percent, also from National Foam Company. Concentrations not to exceed 100 mg/l of AFFF influent to the biological treatment process could be satisfactorily treated without affecting the performance of the process and with apparent detoxification of the AFFF. More detailed bioassay tests are required. Adsorption of AFFFs onto activated carbon is practical with removals varying from 75 to 100 percent, depending on the AFFF.

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ABBREVIATIONS AND SYMBOLS

AFFF	aqueous film-forming foam
COD	chemical oxygen demand
COD_T	total chemical oxygen demand
COD_F	filtrate chemical oxygen demand
BOD	biochemical oxygen demand
BOD_5	5-day biochemical oxygen demand
SS	suspended solids
MLSS	mixed liquor suspended solids
SVI	sludge volume index

SECTION I

INTRODUCTION

I. BACKGROUND

Aqueous film-forming foams (AFFF), MIL-F-24385, are fire-fighting agents for use on fuel and oil-type fires. Aqueous film-forming foams are concentrates and are, therefore, diluted prior to use. The specified dilution is 6 percent AFFF and 94 percent fresh or sea water. Aqueous film-forming foams have or are currently replacing the protein-type foams as the primary fire-fighting agent at most Air Force installations.

The Military Specification for AFFFs, MIL-F-24385, is a performance specification and, therefore, the composition of the products will vary to some extent. Basically, the AFFFs are fluorocarbon surfactants with foam stabilizers (Ref. 1). The fluorocarbon surfactant is likely to be a sulfonate compound such as sodium fluorocarbon sulfonate where the sulfonate group is soluble in water and the fluorocarbon group soluble in the fuel or oil. The fluorocarbon group is generally in the 8- to 10-carbon chain length. The foam stabilizer is likely to be a polyethylene glycol or glycol ether derivative (Ref. 2).

Three specific AFFFs were investigated by the Air Force Weapons Laboratory (AFWL) to determine the treatability and hazards of disposing of AFFFs. These were Light Water FC-200 manufactured by 3M Company, St Paul, Minnesota, and Aerowater 6 percent and Aerowater 3 percent manufactured by National Foam Company, West Chester, Pennsylvania. FC-200 is on the Qualified Products List (QPL) of the Military Specification, and Aerowater 6 percent is being considered at the time of this report. Aerowater 3 percent cannot satisfy the requirements of the Military Specification; however, hangar deluge systems may use a 3 percent AFFF instead of the 6 percent. FC-200 concentrate has a chemical oxygen demand (COD) of 710,000 mg/l and a pH of 7.4. Aerowater 6 percent concentrate has a COD of 456,000 mg/l and a pH of 7.6. Aerowater 3 percent concentrate has a COD of 495,000 mg/l and a pH of 8.0.

2. PURPOSE OF STUDY

The original purpose of this effort was to solve the specific problem of disposing of AFFFs from the "Crash Rescue Fire-Fighting Training Smoke-Abatement System" at Hill AFB, Utah. Basically, the smoke-abatement system consists of water-spray injection just above the burning fuel. For the system at Hill AFB the water injected into the fire would be collected, retained, and recirculated. Retention would be accomplished in an earthen reservoir. There was concern that the AFFFs used in the fire-fighting training would be solubilized in the spray injection water and through recirculation of this water, the AFFF concentration would increase to the point where the spray injection water would have a detrimental effect on the fire. Therefore, to prevent the AFFF concentration from "building up" in the recirculated water, an attempt was made to determine if microbial growth could be achieved in the reservoir when AFFFs represented the only source of organic matter for the microorganisms (the required nutrients added). If the microorganisms could use the AFFFs as a source of organic matter, the AFFF concentration might be kept low enough to prevent build-up problems.

During the Second Annual Environmental Workshop hosted by the Air Force Weapons Laboratory (AFWL), numerous major Air Command environmental coordinators expressed concern for disposing of AFFFs after use, whether in a real fire or in a training situation. This, coupled with concern voiced by Hq USAF/PRE about the disposal of large volumes of AFFF from proposed warehouse and hangar deluge systems, led AFWL to expand the effort to investigate the disposal of AFFFs in a more general situation. Of prime importance was the determination of the feasibility and the limitations of using existing biological waste treatment processes for achieving biodegradation and detoxification of the AFFFs. Also investigated was the use of activated carbon adsorption with the intent to employ a simple adsorption column at fire-training sites which are remotely located and unable to tie into a sanitary sewer. This would become an integral part of a smoke-abatement system. After treatment with activated carbon, water could then be directly discharged onto the land, into a water course, or possibly recycled into the water source of the smoke-abatement system.

SECTION II

LITERATURE REVIEW

The Environmental Health Laboratory at Kelly AFB, Texas, conducted an investigation on the biodegradability and toxicity of Light Water FC-199 (Ref. 3). On a macroscopic basis FC-199 is different from FC-200 in that the pH of FC-199 concentrate is in the range of 4.5. FC-200 was developed to eliminate the corrosive properties of FC-199.

Lefebre (Ref. 3) demonstrated a toxic effect to microorganisms, as measured by oxygen uptake rates, at an FC-199 concentration of 2500 ppm. Laboratory-scale continuous-flow activated-sludge reactors were operated on a mixture of synthetic sewage and varying concentrations of FC-199. At 250 ppm of FC-199 in the influents and a 12-hour detention time, COD and BOD_5 removals were 91 and 96 percent, respectively. At 500 ppm FC-199, detention time 6 hours, COD and BOD_5 removals were 90 and 96 percent, respectively. At 500 ppm there was significant inhibition of nitrification (Ref. 3).

Systematic bioassays were conducted on untreated FC-199 using fathead minnows. It was determined that the 96-hour LC_{50} (concentration at which 50 percent of the test fish are killed in 96 hours of exposure) was 398 ppm. Further, it was demonstrated that fathead minnows were able to survive during 8 days of testing in the clarified activated sludge reactor effluent when the FC-199 concentration was 250 ppm (Ref. 3).

The 3M Company has conducted some investigations into the disposal of Light Water FC-200, the AFFF product that they now manufacture. They have operated laboratory-scale continuous-flow activated-sludge reactors in which FC-200 was the only source of organic matter available to the microorganisms. At an FC-200 concentration of 250 ppm (COD = 175 mg/l), COD removal averaged 85 percent. At concentrations above 250 ppm, COD removal efficiency decreased. The source of microorganisms for the 3M Company laboratory-scale experiments was from their industrial wastewater-treatment plant activated-sludge reactor which has been receiving wastewater for years from the manufacturing of Light Water and other halogenated hydrocarbons (Ref. 4).

The 3M Company has also evaluated nonbiological methods of disposal. Oxidation with ozone, adsorption with activated carbon, foam fractionation, and incineration were investigated. Ozone oxidation and foam fractionation did not prove to be feasible. Incineration would be applicable only if the AFFF concentration were maintained fairly high, i.e., in the range of 1 to 6 percent. Activated carbon adsorption proved to be quite effective for dilute solutions of AFFF (Ref. 4).

Static bioassays have been conducted by the 3M Company on FC-200 using fathead minnows. It was demonstrated that both before and after biological wastewater treatment, the 96-hour LC_{50} was 80 ppm of FC-200 (Ref. 4).

SECTION III

MATERIALS AND METHODS

1. SCREENING EXPERIMENTS

The initial tests conducted on the three AFFFs consisted of 15-day biochemical oxygen demand (BOD) experiments using the static dilution technique. Biochemical oxygen demand tests for FC-200 were accomplished with both unacclimated and acclimated seed at an FC-200 dilution of 2/100,000. Aerowater 3 percent and Aerowater 6 percent concentrations were evaluated with unacclimated seed at a dilution of 1/100,000.

2. OXIDATION POND EXPERIMENTS

Four laboratory-scale oxidation ponds were operated at different organic loadings using Light Water FC-199 as the only source of organic matter available to the microorganisms. FC-199 was used because FC-200 had not yet been introduced at the time of the oxidation pond experiments. The oxidation ponds consisted of stainless steel water baths 18 inches (0.456 m) wide, 36 inches (0.912 m) long, and operated at a water depth of 10 inches (0.254 m). This yielded a liquid volume of 105 liters. The oxidation ponds were operated outdoors in direct sunlight during the months of May and June 1972. Originally, the oxidation ponds were filled with 103 liters of tap water and 2 liters of seed taken from the oxidation ponds on Kirtland AFB, New Mexico.

The primary purpose of the oxidation pond experiments was to simulate the loadings on the recirculation reservoir of the "Crash Rescue Fire-Fighting Training Smoke-Abatement System" at Hill AFB, Utah. To simulate the training operation which would be 3 to 5 days per month and several fires per day, Light Water was added to the four oxidation ponds in different amounts and at different time frequencies. Oxidation pond 1 (OP1) received 44 ml of Light Water concentrate initially to yield a 0.042 percent solution and a COD of 294 mg/l. For OP1 this was repeated every fifth day to simulate a fixed level of training every 5 days. The 44 ml was added in 4- to 11-ml aliquota every 2 hours for an 8-hour period. OP2 received 44 ml, repeated every tenth day. OP3 and OP4 received three times the amount of Light Water (132 ml) as did OP1 and OP2. This yielded an initial COD of 882 mg/l. Light water was added to OP3 every

fifth day and to OP4 every tenth day. Ammonium nitrate and a phosphorous solution was added each time to maintain a COD:N:P ratio of 100:5:2. Evaporation losses were made up daily, and samples were then taken for COD and suspended solids determinations.

3. ACTIVATED SLUDGE EXPERIMENTS

Activated sludge experiments were conducted for each AFFF, using laboratory-scale continuous-flow completely mixed reactors with separate upflow clarification (figure 1). The reactor volume was 8 liters, and the clarifier volume was 3 liters. Retention time in the reactor was 4 hours, taking into account a 25 percent return sludge flow rate. Reactor 1 was the control and received only synthetic wastewater, simulating domestic sewage. The synthetic wastewater consisted of a protein source, nonfat dry milk, and a carbohydrate source (common sugar). The nonfat dry milk represented 220 mg/l of COD, as did the sugar. Ammonium chloride, NH_4Cl, or ammonium sulfate, $(NH_4)_2SO_4$, was added to yield 40 mg/l of NH_3N. A mixture of monobasic and dibasic potassium phosphate, KH_2PO_4 and K_2HPO_4, was added to yield 20 mg/l of P. Reactor 2

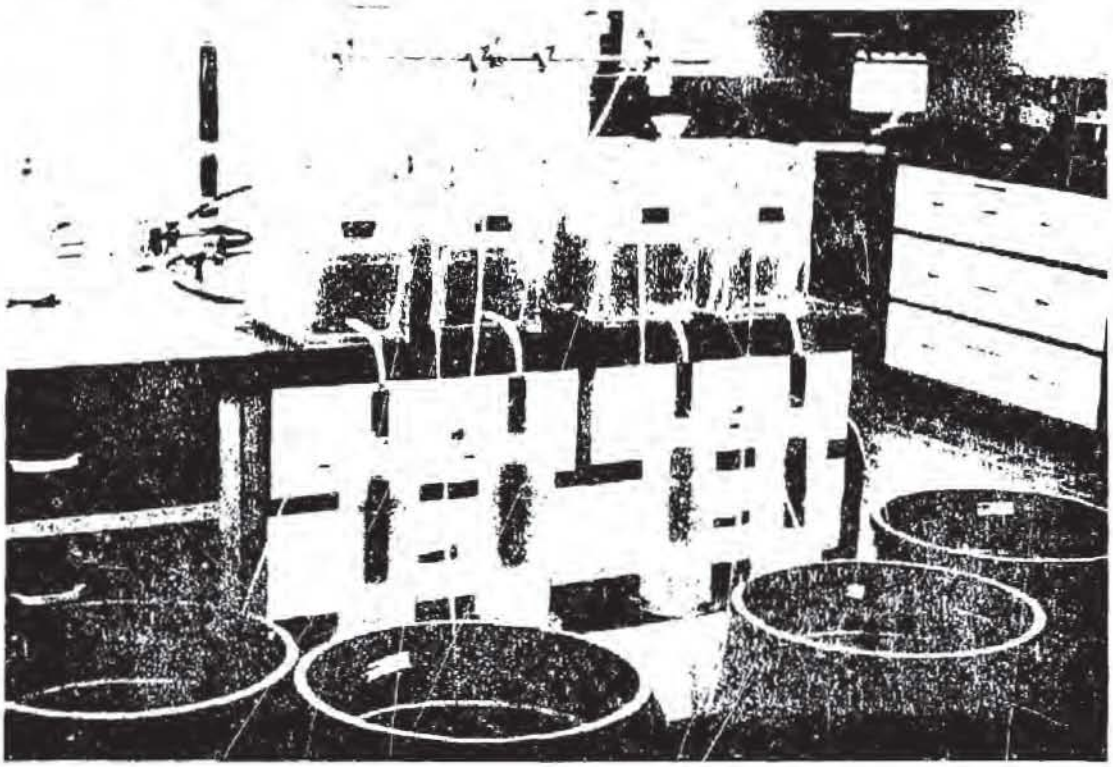

Figure 1. Activated Sludge Systems

received the synthetic wastewater and varying concentrations of FC-200. Reactor 3 received synthetic wastewater and Aerowater 3 percent. Reactor 4 received synthetic wastewater and Aerowater 6 percent. The last three reactors were brought to a steady-state condition with the synthetic wastewater before dosing with the AFFF.

Three separate activated sludge tests were conducted. Test 1 consisted of operating the four reactors until significant degradation in effluent quality occurred. Test 2 was conducted only on FC-200 and Aerowater 3 percent because the concentrations of each that yielded poor effluent quality in test 1 appeared too low. Therefore, the purpose of test 2 was to verify the results of test 1. It should be noted that near the end of test 2 reactor 4 was restarted on the synthetic wastewater and Aerowater 6 percent solely to provide an effluent for the toxicity experiments. Test 3 consisted of "slug loading" reactor 2 with 200 mg/l of FC-200 and reactor 4 with 200 mg/l of Aerowater 6 percent to determine the adverse effects, if any, on unacclimated microorganisms. This was done after the reactors were drained, reseeded, and brought to steady state on just the synthetic wastewater.

The AFFF concentration was increased in steps in each reactor for tests 1 and 2 (table I). It was originally intended to increase the AFFF concentration every 3 days; however, after observing the performance of the units, the frequency of increasing the AFFF concentration became variable, depending on the effluent quality. It should be noted that the influent wastewater was made during the late afternoon. Therefore increases in AFFF concentration were first reflected in the next morning's samples.

The performance of each reactor and the effluent quality was judged by analysis for mixed liquor suspended solids (MLSS), sludge volume index (SVI), total effluent COD, filtrate effluent COD, and effluent suspended solids (see analytical procedure for methods of analysis). Mixed liquor suspended solids (MLSS) and SVI were determined once a day in the morning. An attempt was made to maintain the MLSS concentration between 2000 to 3000 mg/l. Effluent samples were taken from a reservoir which contained 24 hours of flow and, therefore, represented composited samples.

Table I

AFFF CONCENTRATIONS IN ACTIVATED SLUDGE EXPERIMENTS

	AFFF concentration (mg/l)		
Day	FC-200	Aerowater 3 percent	Aerowater 6 percent
		Test 1	
1- 4	0	0	0
5- 7	10	10	10
8-11	25	25	25
12-13	50	50	50
14-23	80	80[1]	80
24-26	80[2]		120
27-32			150
33-37			210
38-53			250
		Test 2	
1- 4	0	0	
5- 8	10	10	
9-11	20	20	
12-19	50	50	
20-25	80	80	
26-32	120	120	
33-39	160	160	
40-44	200	200	
45-52	250	250	
53-59	320	320	0[4]
60-66	320[3]	400	75,[5] 125[6]
67-70		600	200[7]
		Test 3	
1- 8	200		200
9-11	0		200

[1]Day 18 reactor shutdown.
[2]Day 26 reactor shutdown.
[3]Day 62 reactor shutdown.
[4]Reactor started; being brought to steady state.
[5]Reactor begins 75 ppm AFFF on day 63.
[6]Reactor begins 125 ppm AFFF on day 66.
[7]Reactor begins 200 ppm AFFF on day 69.

4. TRICKLING FILTER EXPERIMENTS

A laboratory-scale trickling filter (figure 2) was operated to determine the adverse effects that FC-200 and Aerowater 6 percent would have on the performance of the trickling filter process. The trickling filters consisted of two columns operated independently (in parallel). Both contained 5.5 feet (1.680 m) of polypropylene plastic media (Kock Flexirings* 5/8 inch (0.0175 m) 105 ft^2/ft^3 (348 m^2/m^3)). As illustrated in figure 2, samples could be taken at depths of 18 inches (0.456 m), 36 inches (0.912 m), and 66 inches (1.815 m, full depth). This final discharge entered a small clarification and recirculation basin which was flushed with tap water every 2 to 4 days to remove sloughed biological solids.

Both columns were brought to steady state on the synthetic wastewater as described in the activated sludge experiments. Then column A (the column on the left) received varying concentrations of FC-200, and column B received Aerowater 6 percent. The concentrations received versus time are shown in table II.

Two tests were conducted for the FC-200 and the Aerowater 6 percent. Test 1 was without recycle at a hydraulic loading of 200 gpd/ft^2 (8150 l/day/m^2), and test 2 was with a one-to-one recycle at a hydraulic loading of 200 gpd/ft^2, i.e., 100 gpd/ft^2 of influent and 100 gpd/ft^2 of recycled effluent. Between tests 1 and 2 the trickling filters received only synthetic wastewater for a period of 9 days.

Samples were taken from the two sampling ports of each column and from the final discharge. These samples were grab samples taken in the morning, with COD being the only parameter analyzed. Because the samples contained varying amounts of settleable solids, the samples were allowed to settle, and the supernatent was used for COD analysis.

5. ADSORPTION EXPERIMENTS

Both batch and continuous-flow activated-carbon adsorption experiments were conducted using Calgon Filtersorb 400 granular activated carbon. Only Aerowater 6 percent and FC-200 were evaluated. Solutions were made up to contain approximately 2000 mg/l of each AFFF. It was believed that this would represent

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*Registered trademark.

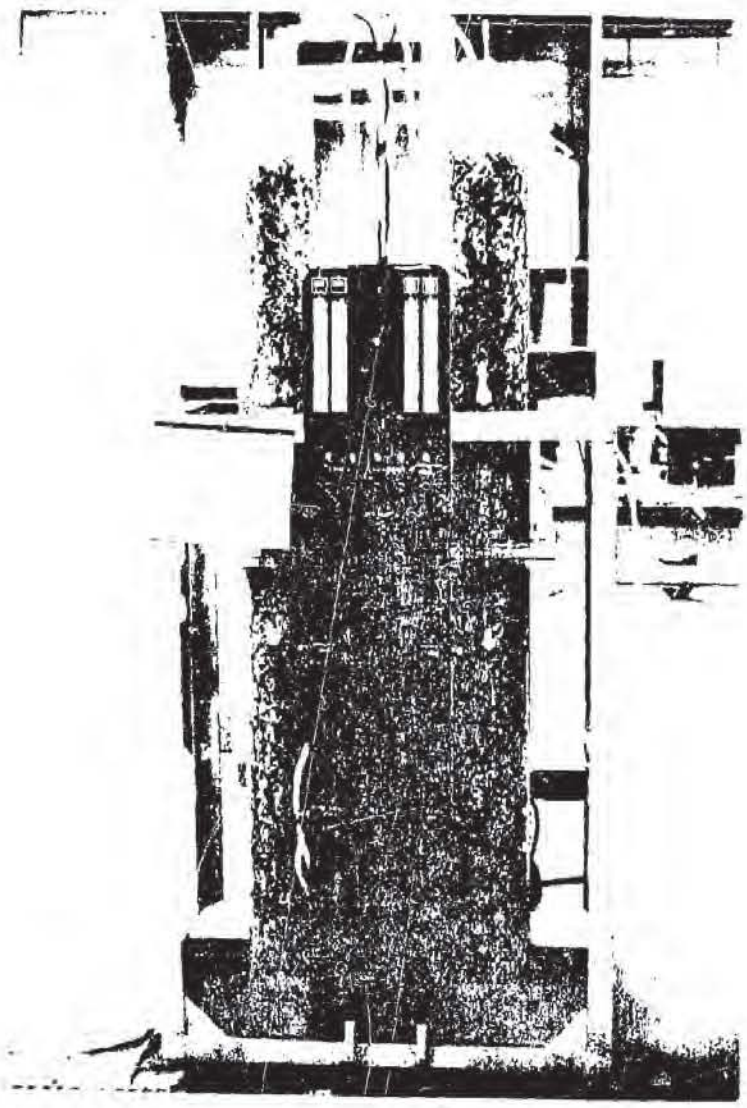

Figure 2. Trickling Filter System

Table II

AFFF CONCENTRATIONS IN TRICKLING FILTER EXPERIMENTS

Day	AFFF concentration (mg/l) FC-200	Aerowater 6 percent
	Test 1, No recycle	
1- 2	0	0
3- 6	25	25
7-11	50	50
12-16	80	80
17-20	120	120
21-35	160	160
	Test 2, One-to-one recycle	
1	0	0
2- 8	25	25
9-14	50	50
15-21	80	80
22-29	120	120
30-37	160	160
38-45	200	200
46-50	250	250
51-54	300	300

an expected discharge of AFFF from a fire-training facility employing a water spray injection system for smoke abatement. For the batch tests, 4 liters of each AFFF solution were made. To 2 liters of each AFFF solution, 20 mls of JP-4 jet fuel were added, shaken, and allowed to separate. The purpose of adding JP-4 was to determine if certain compounds in the AFFF were preferentially soluble in JP-4 and would thereby be extracted from the aqueous phase. The effect of this extraction, if any, on the adsorption of the AFFF was determined by conducting batch adsorption tests on both the untreated (no JP-4) solutions and the aqueous phase of the JP-4-treated solutions. Five hundred ml erlenmeyer flasks were used, each containing 200 mls of solution and varying amounts of pulverized (-200 mesh) activated carbon. Five flasks were used for each solution, containing 0.1, 0.4, 0.8, 1.2, and 2.0 grams of activated carbon, weighed to four decimal places. The flasks were agitated for 1 hour on a gyratery shaker at 22°C, after which the activated carbon was removed by vacuum filtration, using GFC filter paper.

Continuous-flow experiments were conducted for the 2000-mg/l solutions (not treated with JP-4) of Aerowater 6 percent and FC-200. Small columns were used to achieve breakthrough in a reasonable time frame. The columns used were 1.25 inches (0.318 m) inside diameter and contained 24 inches (0.61 m) of activated carbon. The flow of 23.8 ml/min was set to yield an empty-bed contact time of 20 minutes. The flow was downflow with the discharge restricted to maintain a 2- to 3-inch liquid level above the activated carbon. Sampling ports were provided at 6 and 15 inches of activated carbon depth. Samples were taken periodically for analysis of COD.

6. TOXICITY EXPERIMENTS

To ascertain the detoxification, if any, that the biological wastewater treatment processes were achieving on the AFFFs, rainbow trout (4 to 6 inches in length (0.103 to 0.153 m)) were exposed to the activated sludge effluents (clarified effluent) from each reactor that, at the time, was receiving 200 mg/l of each AFFF. The trout were also exposed to the secondary effluent from the control. In addition, trout were exposed to each of the influents, i.e., synthetic wastewater and 200 mg/l AFFF, and to distilled water plus 200 mg/l AFFF. Four trout were added to each container having approximately 4 liters of liquid. The liquid was maintained at 10°C in an incubator and was aerated to maintain a dissolved oxygen concentration of 6 to 7 mg/l. During the test period (4 days), the liquid was changed once every 24 hours.

7. ANALYTICAL PROCEDURE

Chemical analyses were conducted on collected samples for determination of the desired compound (contaminant), thereby permitting evaluation of the treatment process performance. Chemical oxygen demands were determined in accordance with Standard Methods for the Examination of Water and Wastewater (Ref. 5). Both the standard and dilute technique were used as appropriate. Filtrate COD was determined on samples after filtering through GFC filter paper in accordance with Standard Methods.... For the activated sludge effluents, the effluent suspended solids and filtrate COD were determined from filtering of the same sample. For MLSS and SVI, 100 mls were drawn from the reactor, placed in a 100-ml graduated cylinder, and allowed to settle for 30 minutes, at which time the volume of settled solids was read. The 100 mls were then filtered through GFC filter paper for determineation of the MLSS. The SVI was then calculated from equation (1)

$$SVI = \text{mls of settled solids} \times 10{,}000/\text{MLSS} \qquad (1)$$

Free fluoride was analyzed for in the activated sludge effluents to determine if the fluorocarbon compound was being biologically metabolized, yielding free fluoride. This analysis was conducted using both the SPADNS method and the free ion electrode method described in reference 5.

Several attempts were made to develop a method of analysis for determining the fate of the fluorocarbon fraction of the AFFF. The first attempt was to measure the absorbance of infrared light energy for the fluorocarbon bond in the infrared region of 7.5- to 10-micron wavelength. Several concentrations of pure AFFF in distilled water were scanned in this wavelength region. IR-Tran cells of various cell thicknesses were used. In the concentration range of interest for the AFFFs, 1 to 300 mg/l, the strong absorb nce of the water in the 7.5- to 10-micron wavelength made this technique impractical.

Since extraction of the fluorocarbon fraction from the aqueous phase into a solvent could not be quantified without having the pure fluorocarbon compound by itself, i.e., no method to determine extraction efficiency, an attempt was made to evaporate the sample, then take it up in a polar or nonpolar solvent. The solvents used were benzene, chloroform, carbon tetrachloride, iopropyl ether, hexane, and methanol. Fifty mls of sample were evaporated at 103°C in 100-ml test tubes, then 50 ml of solvent was added and agitated on a vortex

mixer. The degree of resolubilization was determined visually. Aerowater 3 percent was the only AFFF that could be completely resolubilized, and this was in benzene. This was true even after 48 hours. However, the background adsorbance from benzene was too strong in the 7.5- to 10-micron wavelength. Thus, this technique was also ineffective for pure solutions.

The 3M Company developed a gas chromatographic technique for analysis of FC-200. However, "ghosting*" was a serious problem and made this method of analysis impractical. Further, it was learned from the 3M Company that the gas chromatographic method was for determination of the foam stabilizer fraction and not the fluorocarbon fraction.

*Ghosting is subsequent elution of the organic compound when the next sample is injected.

SECTION IV

RESULTS

1. SCREENING EXPERIMENTS

The screening experiments consisted of determining the biological oxygen demand (BOD) uptake over a 15-day period. FC-200 was evaluated using both acclimated and unacclimated seed. The acclimated seed was obtained from the activated sludge reactor receiving FC-200. The two Aerowater AFFFs were only evaluated using unacclimated seed. The results of these experiments are detailed in figures 3 through 5. For FC-200 it is seen that the acclimated seed demonstrated a slightly increased rate of oxygen uptake but not a higher overall total uptake. The 5-day BOD for the concentrated FC-200 is approximately 70,000 mg/l with the ultimate BOD (assuming this to occur at the 15-day point) of approximately 360,000 mg/l. The BOD_5 of Aerowater 3 percent concentrate was approximately 75,000 mg/l with a BOD_{ult} of 315,000 mg/l. Aerowater 6 percent concentrate had a BOD_5 of 40,000 mg/l with the ultimate BOD in excess of 280,000 mg/l.

Because of the tremendous dilution required (2/100,000 and 1/100,000) to determine BODs by the static dilution technique, the "typical" first order curve did not result. This is not to say that the data are invalidated but rather points out the limitation of BOD analysis. The significance to be drawn from the BOD tests performed is that at least some of the compounds in the AFFFs are available for biological metabolism, and further untreated AFFFs discharged into a watercourse would exert a very high oxygen demand.

2. OXIDATION POND EXPERIMENTS

As described in section III, four oxidation ponds were operated to simulate the AFFF loadings on the recirculation reservoir of the "Crash Rescue Fire-Fighting Training Smoke-Abatement System" at Hill AFB, Utah. In a more general sense, the results of the oxidation pond experiments could be related to any oxidation or holding pond where AFFFs represented the only source of organic matter available to the microorganisms. The COD reductions achieved in oxidation ponds (OP) 1 and 2 are shown in figure 6. Reductions from OP3 and OP4 are shown in figure 7. Reiterating, OP1 was loaded with 0.042 percent FC-199

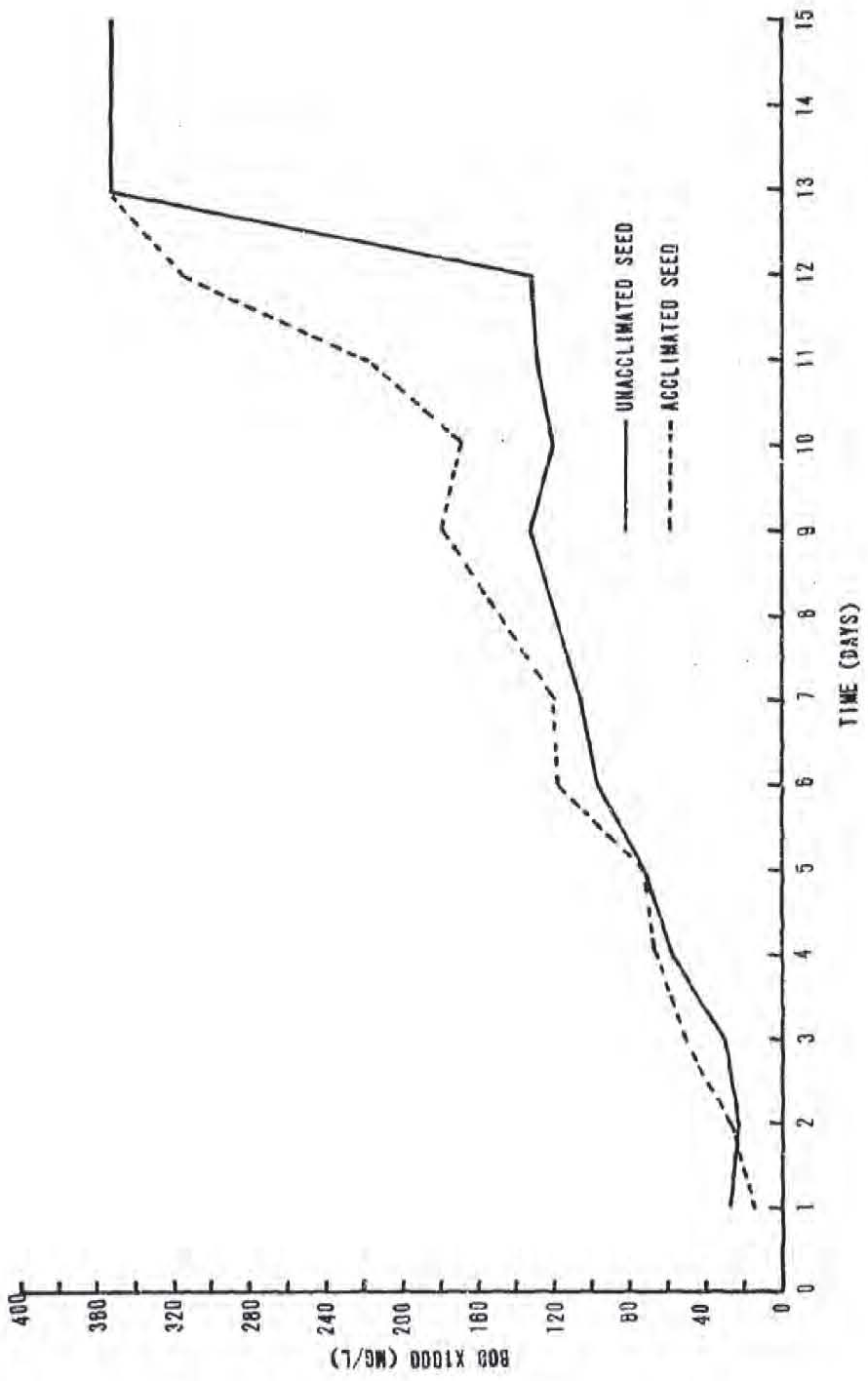

Figure 3. BOD Curve, FC-200

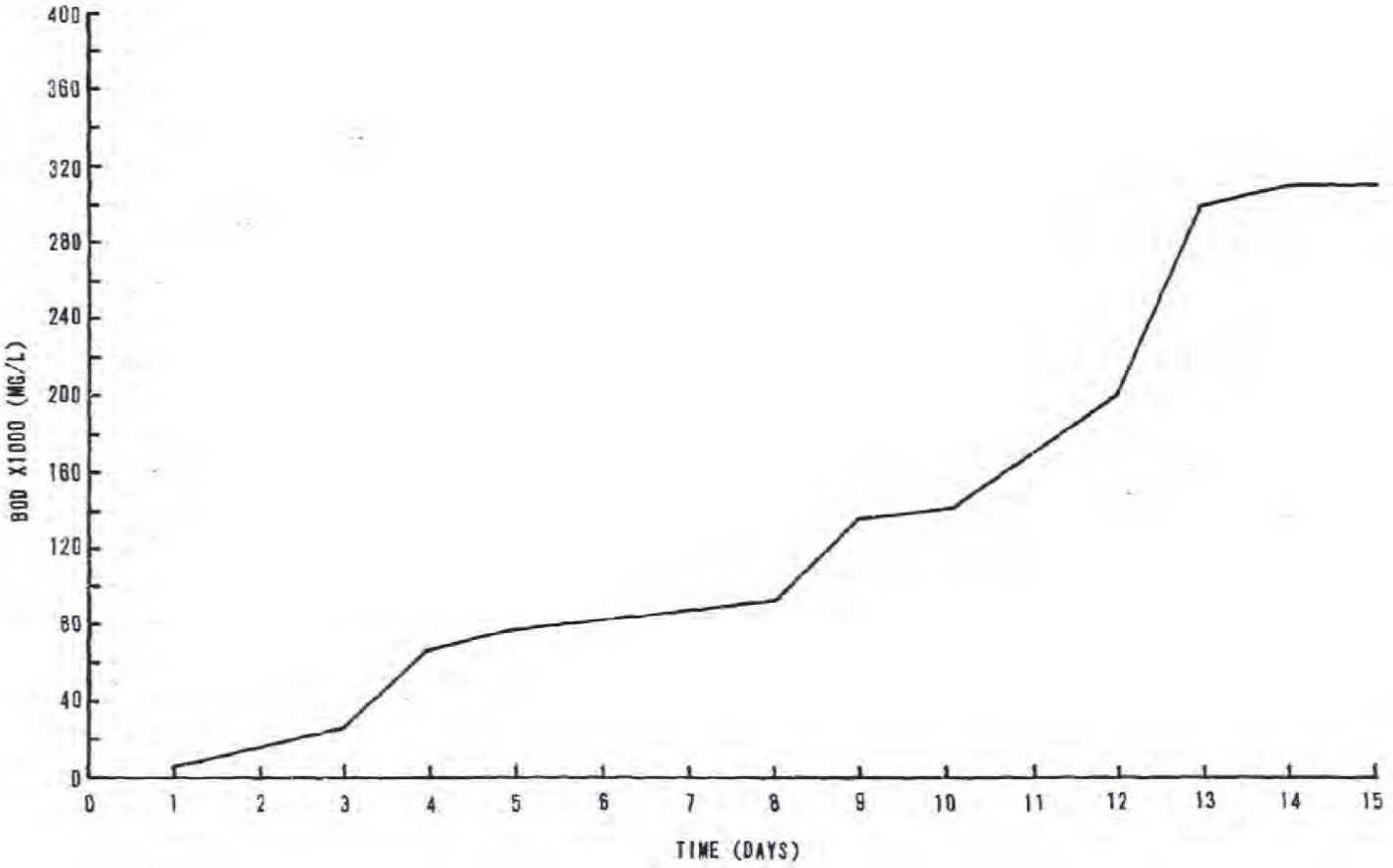

Figure 4. BOD Curve, Aerowater 3 Percent

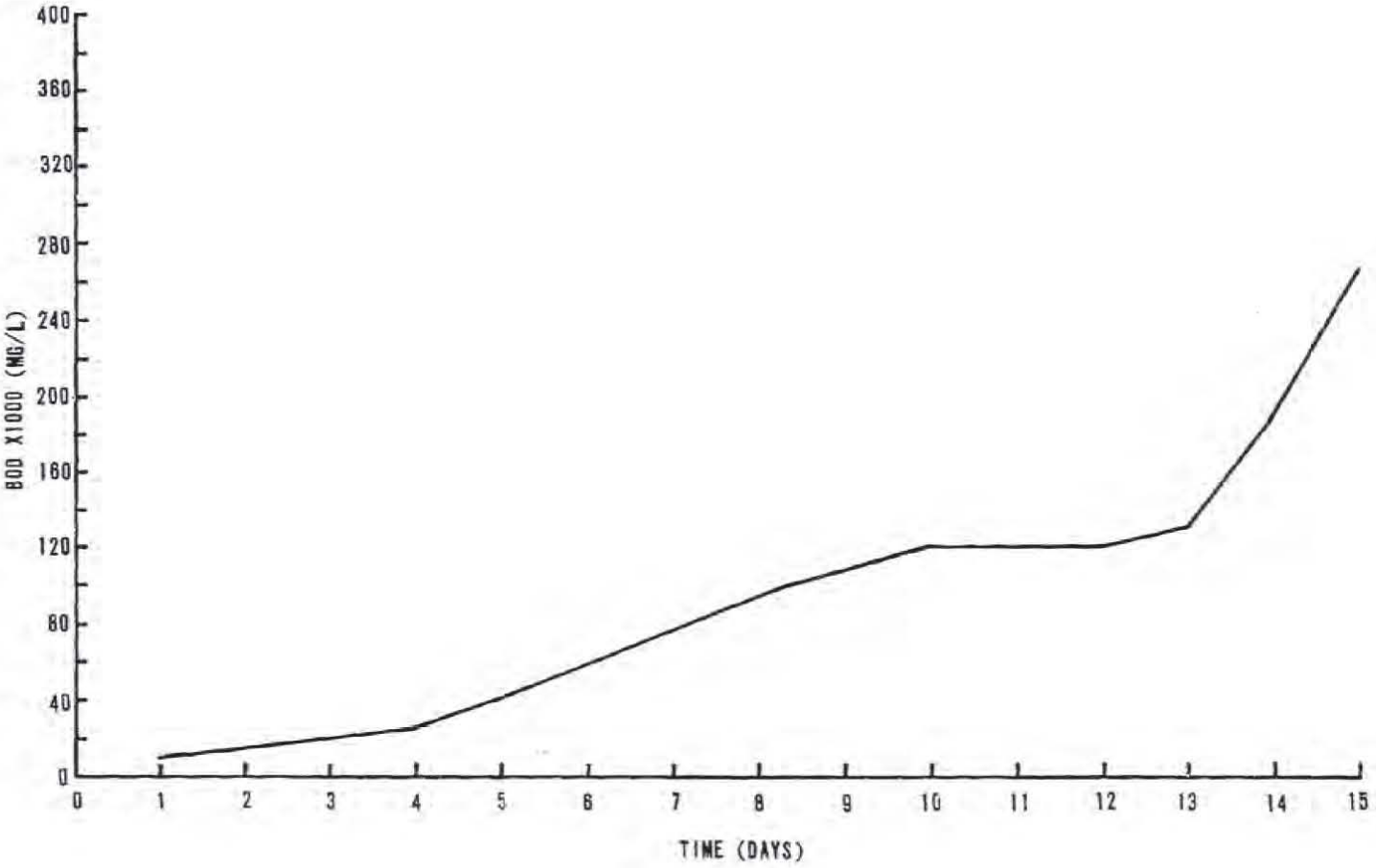

Figure 5. BOD Curve, Aerowater 6 Percent

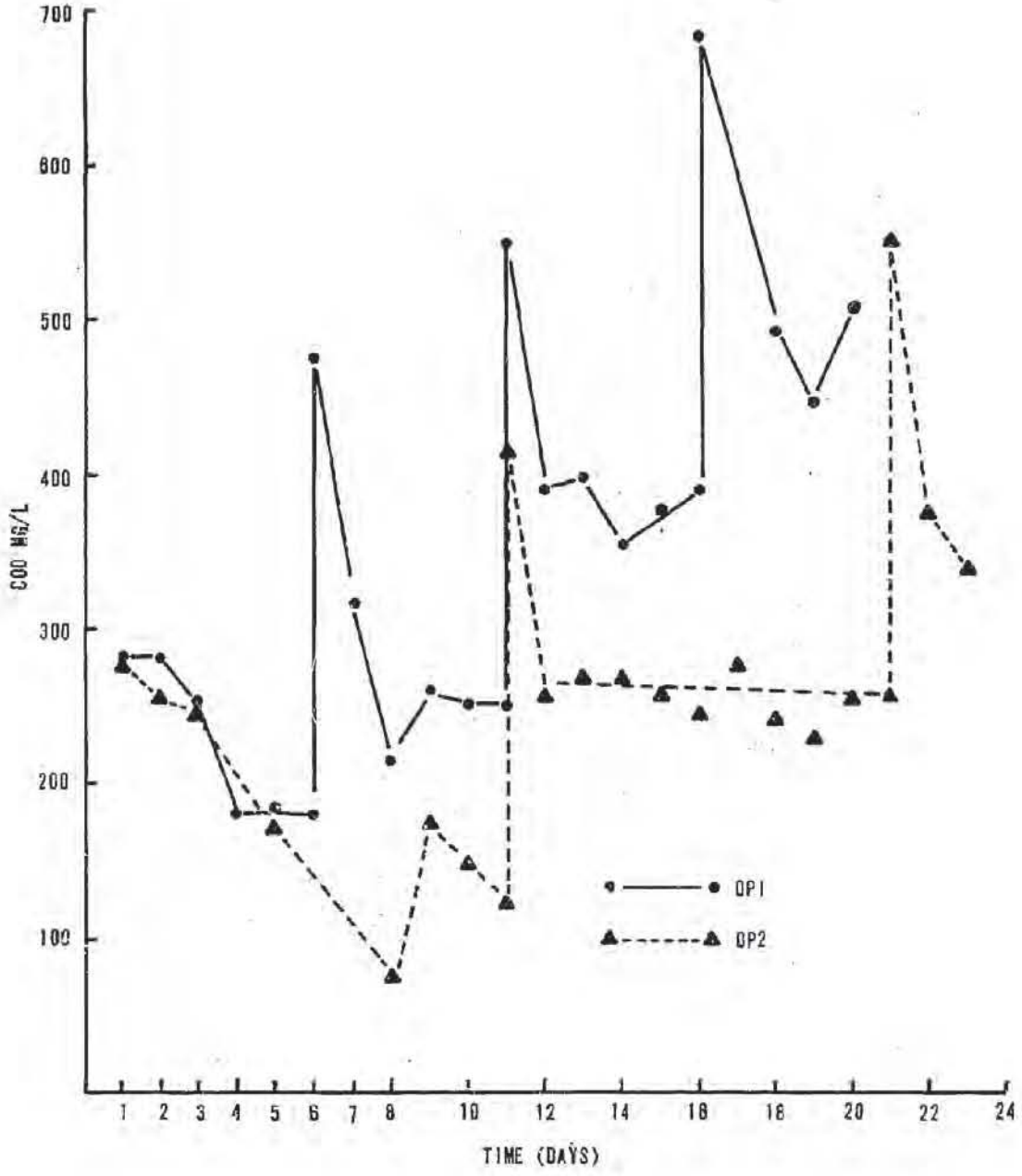

Figure 6. Oxidation Ponds 1 and 2, FC-199

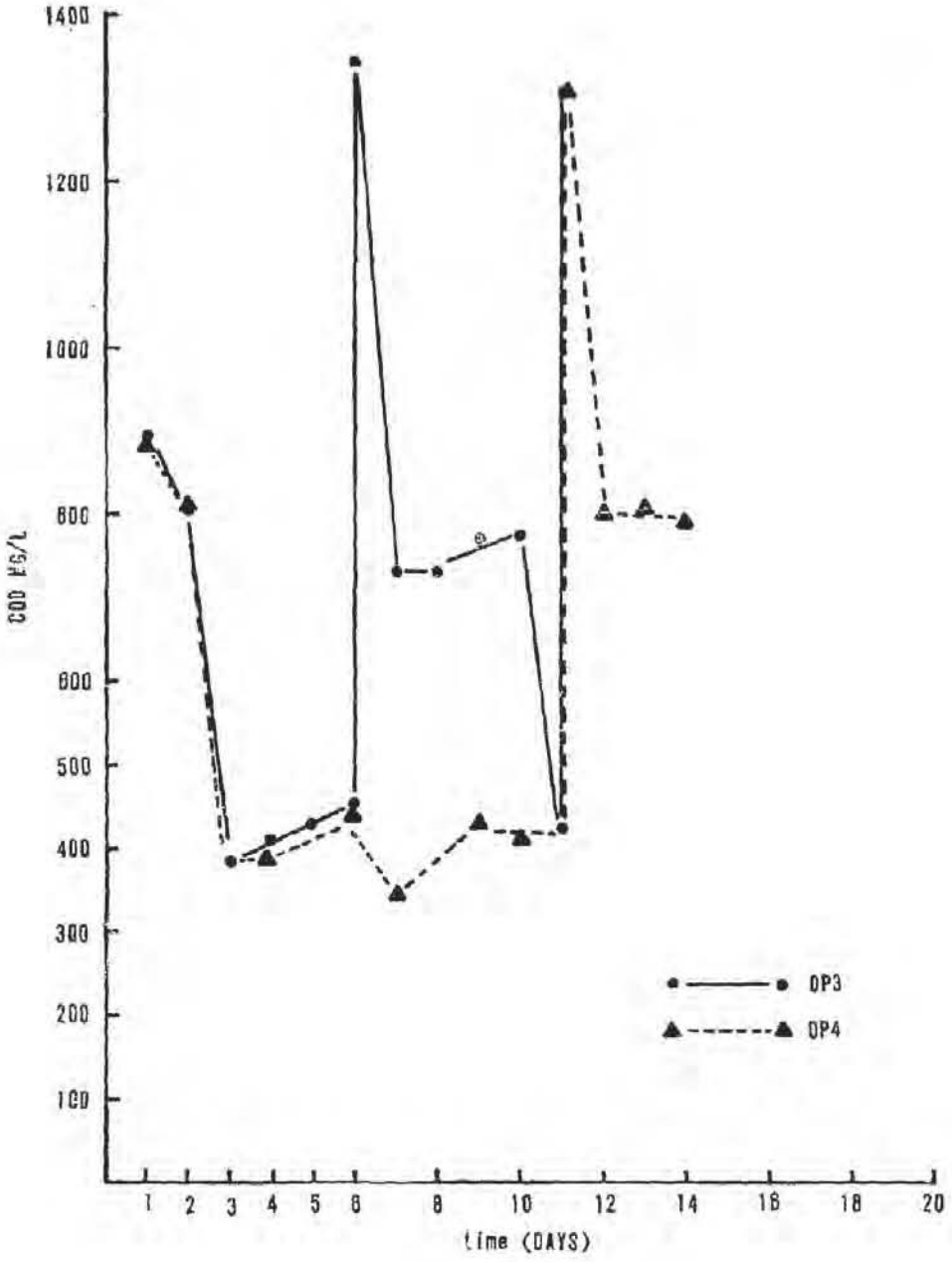

Figure 7. Oxidation Ponds 3 and 4, FC-199

every fifth day (initial COD - 294 mg/l) and OP2 every 10th day. Oxidation pond 3 was loaded with 0.136 percent FC-199 every fifth day (initial COD - 882 mg/l) and OP4 was loaded every 10th day. The results demonstrated a COD reduction occurring after dosing with FC-199 with most of the reduction occurring in the first 2 days after dosing. However, it is seen that there is a general build-up of some substance that is chemically but not biologically oxidizable. This COD reduction is not consistent with the concentration of suspended solids (taken to be biological solids) in the oxidation pond which did not increase with the decreasing COD, but rather followed no ascertainable pattern, varying in concentration between 10 and 70 mg/l for each of the oxidation ponds. If one assumes cell yields of 0.5 mg/l of biological oxidation of domestic wastewater to apply for the oxidation ponds, then biological solids concentrations in excess of 150 mg/l should have been observed.

The COD reduction achieved coupled with the lack of appreciable biological growth led to the assumption that some of the compounds in FC-199 were undergoing photochemical oxidation. Therefore, a fifth oxidation pond was set up but not seeded. The initial COD in this oxidation pond was 296 mg/l. Within the experimental error of the analysis, the COD concentration did not change over a 10-day period. Thus, it was concluded that photochemical oxidation was not the cause of the COD reduction. This leaves unanswered the reason for the observed COD reduction without appreciable biological growth.

3. ACTIVATED SLUDGE EXPERIMENTS

a. Test 1

The data collected for test 1 are listed in table III and are graphically represented in figures 8 through 11. The data show that none of the reactors were achieving proper settling characteristics as measured by sludge volume index and/or effluent suspended solids. This led to occasional use of alum (aluminum sulfate) and/or a cationic polyelectrolyte. Control of MLSS between 2000 to 3000 mg/l was attempted, but much of the time the reactors were outside of this concentration range. The control performance was more erratic than that desired. However, in general, COD removal was in the range of 85 to 90 percent for total effluent COD and consistently in excess of 90 percent removal for filtrate COD.

Table III

ACTIVATED SLUDGE ANALYSES, TEST 1

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
				Control			
1	500	24	24	<10	788	800	
2		44	48	<10	1086		
3		133	71	<10	1294	470	
4	440	55	16	48	1645	480	
5	445	95	103	26	2325	400	
6		82	38	34	2640	363	
7	466	62	25	14	2274	370	
8		24	25	16	2420	334	
9	457	150	34	18	2536		
10	474	68	41	18	2240	313	
11		53	37	25	2693	215	
12		73	49	21	2569	237	
13	434	57	41	15	2384	252	
14		43	31	<10	2262	252	
15		48	28	12	2652	294	
16		64	60	23	1079	639	
17		150	35	70	909	1023	Adding 20 mg/l alum
18		43	20	14	1217	559	
19		46	23	12	1146	785	Discontinue alum
20		58	35	12	1290	450	
21		16	20	15	1343	707	
22		89	24	37	2383	411	
23	351	101	40	11	2860	339	
24		15	16	10	3625	270	
25		25	23	12	3375	190	
26		34	25	<10	4056	160	
27		17	22	<10	3364	214	
28		24	7	<10	2356	293	
29		8	14	<10	1958	460	
30		74	18	17	2114	426	
31		51	22	38	2319	328	

Table III (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
32		66	31	23	2208	290	
33		35	26	<10	2490	246	
34		40	36	41	2675	202	
35		32	53	43	2686	279	
36		72	14	50	2420	289	
37	351	58	15	44	2396	221	
38		40	27	10	2571	307	
39	454	33	33	20	2430	407	
40		50	21	34	1189	580	
41		74	33	14	1083	553	
42	No sample						
43		53	15	14	1464	410	
44		19	17	13	1453	475	Begin 1 mg/l polyelct. 10 mg/l alum
45		182	36	123	1823	521	
46		124	23	114	1444	270	
47		75	18	27	1478	420	
48		89	32	21	1295	386	
49	345	73	38	14	1602	393	
50		59	19	13	1945	396	
51		92	80				
52		87	67	45	2146	261	
				FC-200			
1		81	40	40	774		
2		59	24	10	609		
3		67	86	12	1232	450	
4		59	31	15	1123	490	
5	445	82	40	<10	2240	402	First sample 10 mg/l FC-200
6		90	41	<10	2599	380	
7	404	88	33	13	2516	378	
8		60	38	27	1742	419	First sample 25 mg/l FC-200
9	468	120	73	45	1430		

Table III (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
10	474	155	51	91	914	492	First sample 50 mg/l FC-200
11		122	66	71	795	755	Adding 10 mg/l alum
12		219	93	105	403	695	Adding 20 mg/l alum
13	426	117	73	23	734	926	
14		83	59	16	690	1377	
15		171	60	77	565	1664	First sample 80 mg/l
16		100	72	49	661	1362	
17		77	73	<10	979	981	
18		83	58	18	526	760	
19		---	54	<10	939	958	
20		69	65	<10	1108	560	
21		48	52	<10	1015	887	
22		121	65	44	925	1081	
23		186	61	40	1394	710	
24		149	46	35	1477	670	
25		70	35	26	1288	776	
26		33	32	17	1565	633	
				Aerowater 3 Percent			
1		57	32	16	766	980	
2		48	28	15	421		
3		223	102	<10	1277	220	
4		55	35	18	1199	233	
5	450	198	155	61	2198	237	First sample 10 mg/l 3 percent
6		91	36	<10	2020	356	
7	428	62	25	16	3298	258	
8		48	57	26	2772	238	First sample 25 mg/l 3 percent
9	453	85	54	19	2856		
10	468	131	31	25	2591	208	First sample 50 mg/l 3 percent
11		91	44	33	2687	261	
12		93	53	35	2836	310	

Table III (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
13	481	105	93	37	3680	226	
14		39	31	10	3371	267	First sample 80 mg/l
15		187	44	90	3500	274	
16		300	68	108	2153	246	
17		340	62	393	1889	529	
18		130	38	65	326	552	
				Aerowater 6 Percent			
1		73	49	22	501	860	
2		63	55	14	848		
3		180	43	11	1166	450	
4		47	27	12	1184	439	
5	450	77	64	15	2063	339	First sample 10 mg/l 6 percent
6		55	37	31	1300	484	
7	436	59	30	<10	2010	393	
8		44	44	<10	1277	297	First sample 25 mg/l 6 percent
9	485	73	51	15	687		
10	440	55	31	<10	1420	317	First sample 50 mg/l 6 percent
11		67	44	19	1055	351	
12		73	53	19	1998	385	
13	473	65	45	10	1823	521	First sample 80 mg/l 6 percent
14		71	47	<10	2400	417	
15		108	52	40	2434	403	
16		72	56	19	1610	602	
17		88	85	19	2494	401	
18		110	54	43	1469	640	
19		54	50	54	1448	663	
20		69	54	<10	3172	246	
21		40	40	12	2730	231	
22		49	28	<10	3684	166	
23	424	57	50	<10	2776	180	First sample 120 mg/l

Table III (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
24		45	48	14	3144	305	
25		117	26	32	3365	285	
26		96	65	27	2848	337	
27		73	40	26	3007	326	
28		56	25	29	2854	347	First sample 150 mg/l 6 percent
29		---	48	28	2955	332	
30		68	33	24	2112	459	
31		146	38	82	1914	381	
32		98	42	48	1988	342	
33		43	49	13	1226	285	
34		75	24	40	1600	150	First sample 210 mg/l 6 percent
35		66	33	98	1554	129	
36		59	40	12	1498	207	
37		48	37	10	1962	398	
38	529	89	54	33	2462	223	First sample 250 mg/l 6 percent
39	546	72	57	17	3052	193	
40		70	48	21	2877	247	
41		127	101	---	1636	410	
42		262	211	---	---	---	
43		172	114	33	2380	315	
44		105	80	76	2670	135	
45		162	94	31	1675	567	
46		367	134	147	938	597	
47		277	169	64	755	464	
48		230	153	47	728	1278	
49	456	278	110	95	911	1021	
50		182	112	61	1157	484	
51		158	118	---	---	---	
52		95	89	118	756	529	

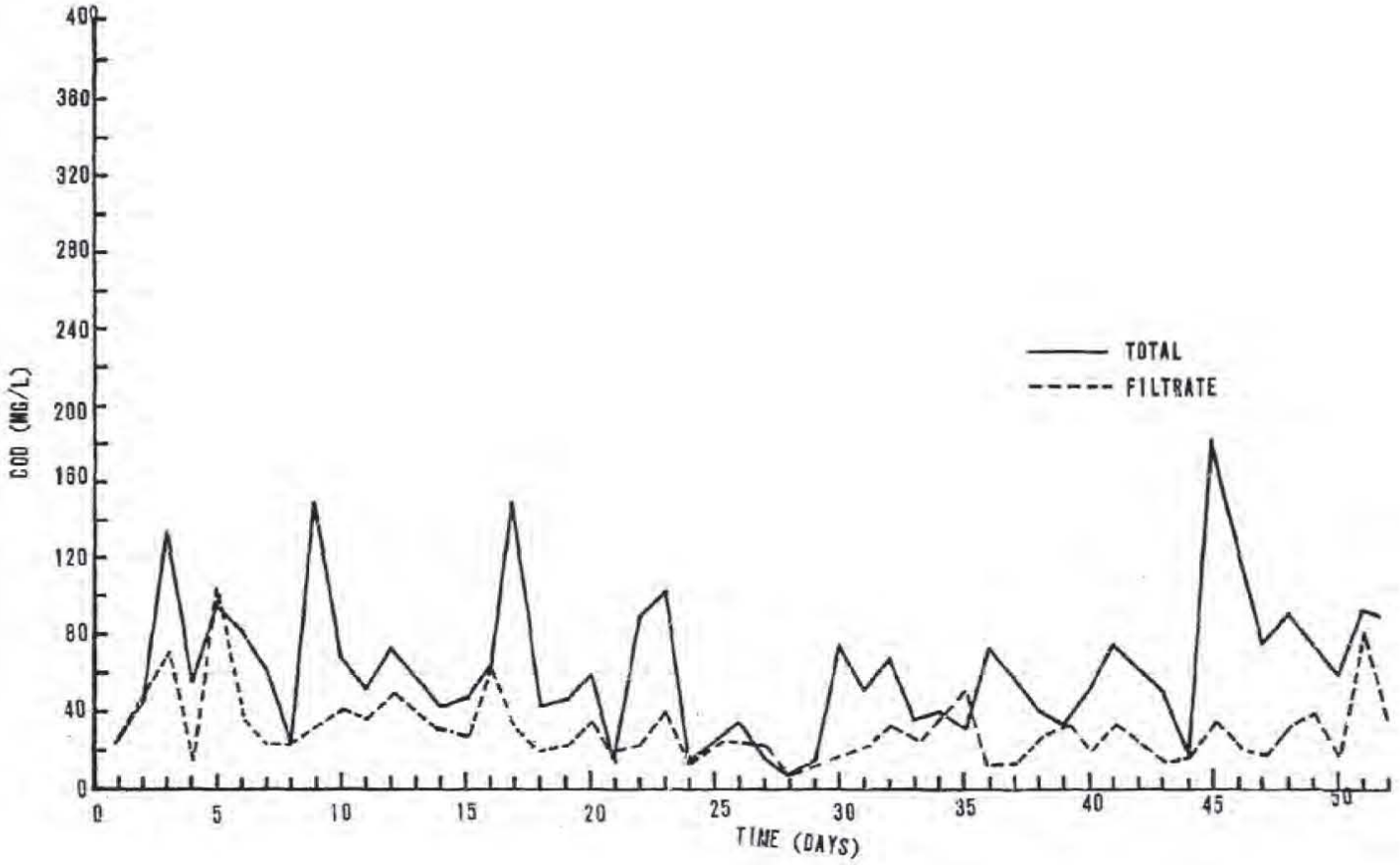

Figure 8. Test 1, Activated Sludge Effluent COD Control

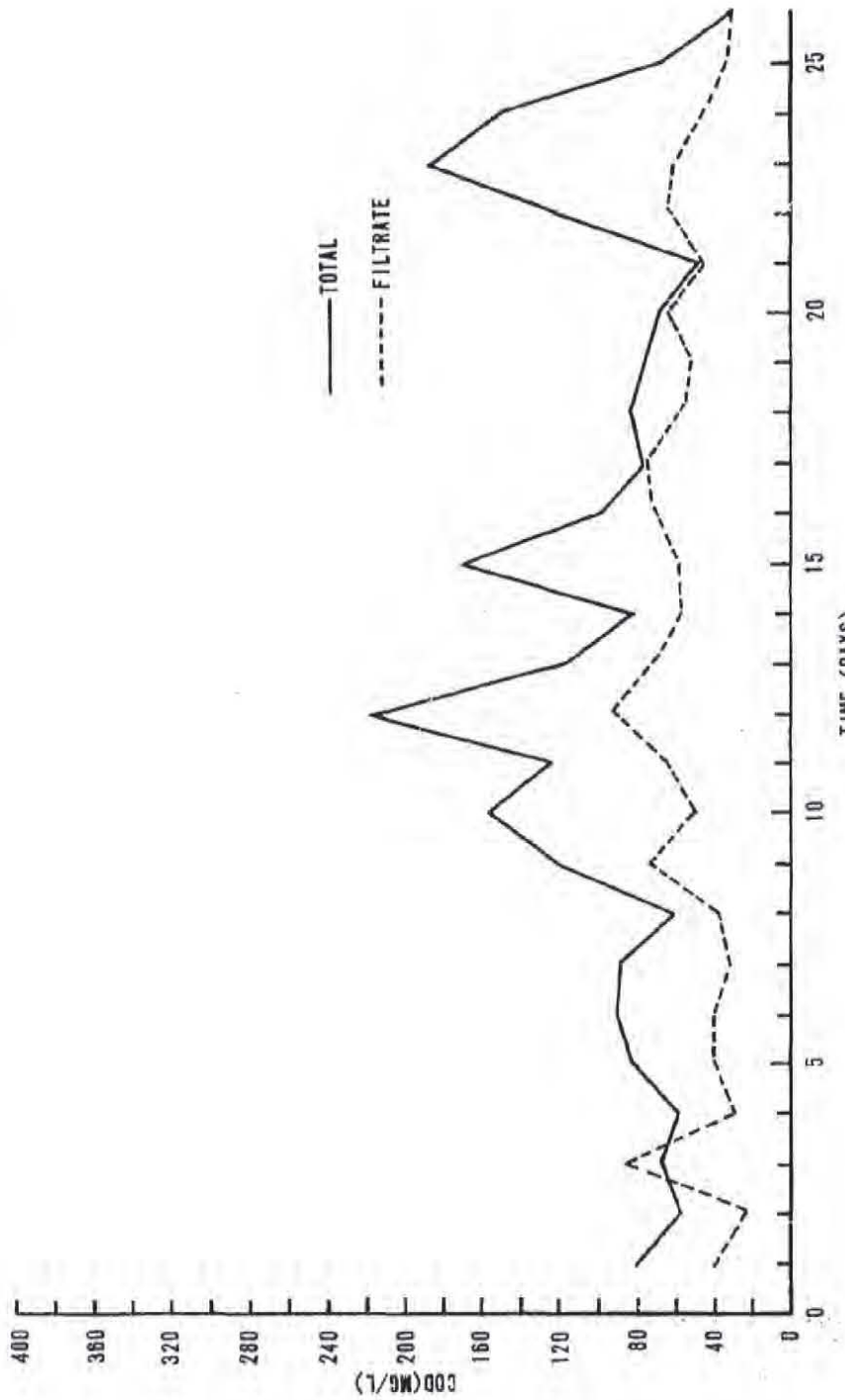

Figure 9. Test 1, Activated Sludge Effluent COD, FC-200

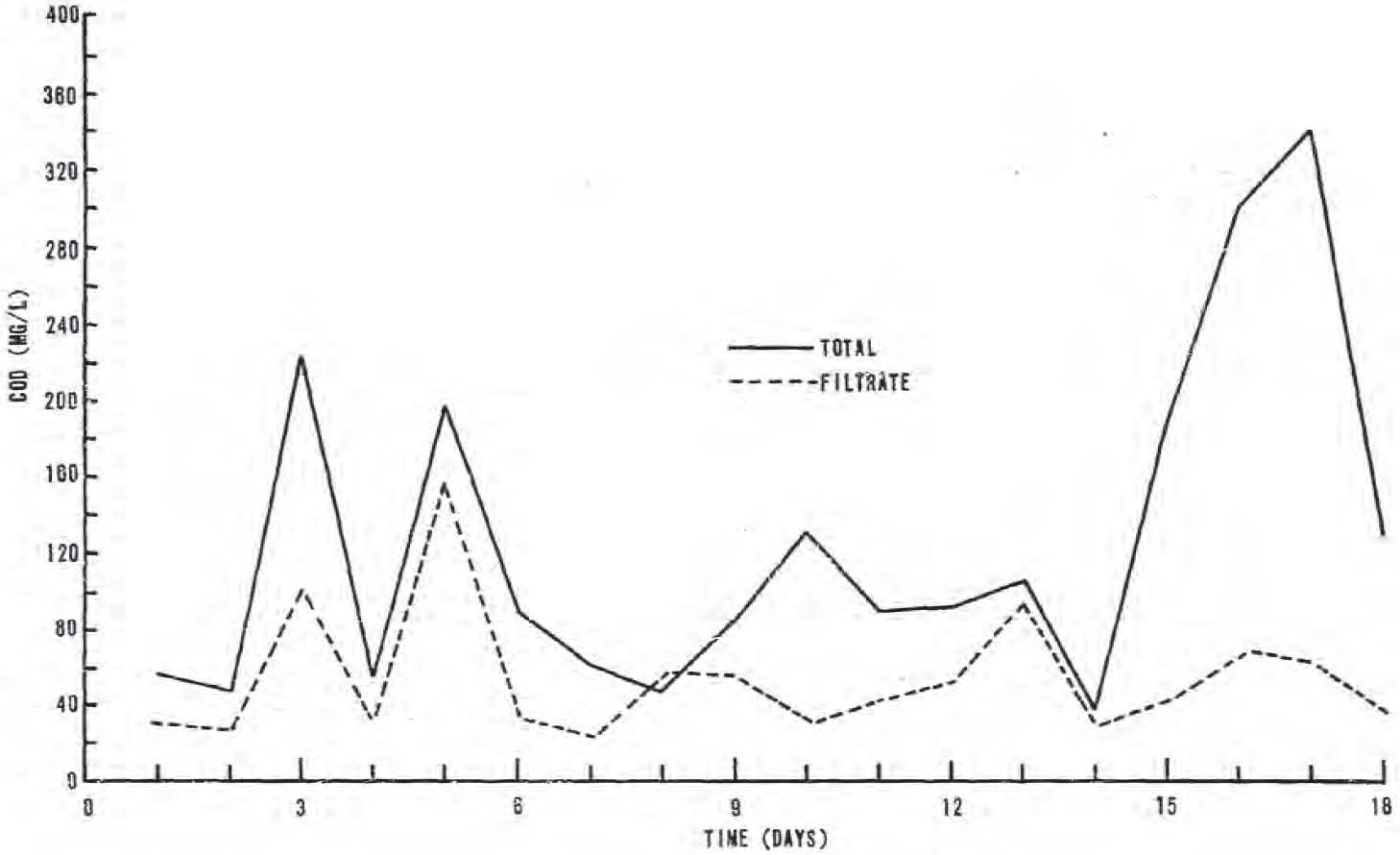

Figure 10. Test 1, Activated Sludge Effluent COD, Aerowater 3 Percent

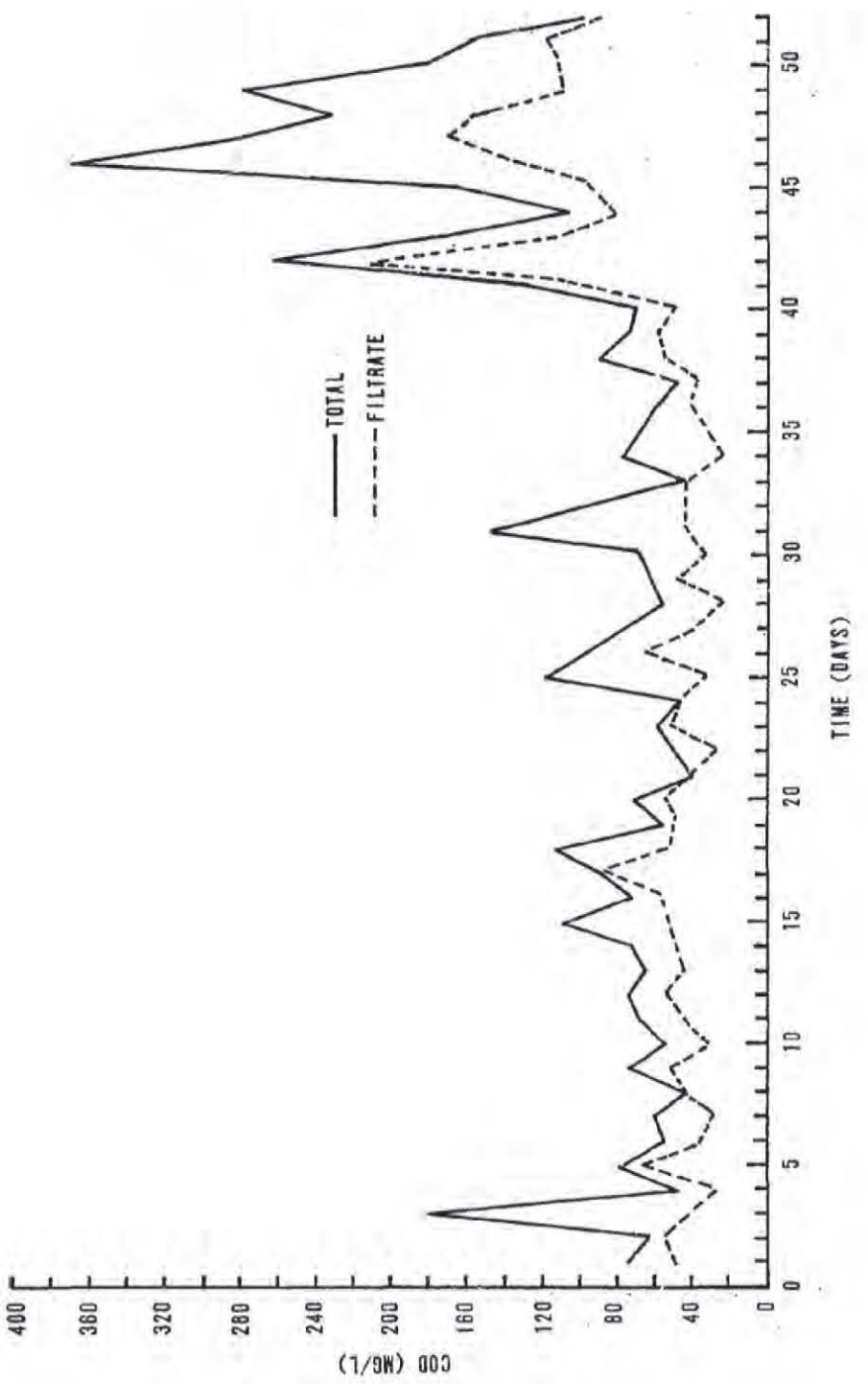

Figure 11. Test 1, Activated Sludge Effluent COD, Aerowater 6 Percent

For reactor 2 table III and figure 9 show that at the time the FC-200 concentration was increased to 50 mg/l, day 10, the MLSS decreased drastically, and the SVI increased roughly twofold. The use of alum to control this condition was only marginally successful. Effluent COD concentrations increased to unacceptable values. Although the FC-200 concentration was increased to 80 mg/l, it was clear that the activated sludge reactor performance had been upset at 50 mg/l of FC-200.

The performance of reactor 3, in which Aerowater 3 percent was used, yielded higher effluent CODs than either the control or the other two reactors up to the time (day 14) the concentration was increased to 80 mg/l. The total effluent COD increased drastically then, primarily because of effluent suspended solids. At day 16 the MLSS began to decrease rapidly, and the reactor was shut down on day 18.

Reactor 4 (Aerowater 6 percent) performance was reasonably consistent and acceptable (see table III and figure 11), although effluent CODs were somewhat higher than that of the control, until the concentration reached 250 mg/l. Shortly after the Aerowater 6 percent concentration was increased to 250 mg/l (day 38), the effluent COD, total and filtrate, increased significantly, the MLSS decreased, and the SVI increased appreciably at this time. It thus appeared that the activated sludge process could not tolerate 250 mg/l of Aerowater 6 percent.

b. Test 2

The results for test 2 are presented in table IV and figures 12 through 15. The primary purpose of test 2 (as stated in section III) was to determine if, in fact, the limiting concentrations of FC-200 and Aerowater 3 percent were valid. It is noted that during test 2, the performance of the reactors with respect to settlability and acceptable MLSS concentrations, effluent CODs, total and to some extent filtrate, were sporadic for the control. There were some mechanical difficulties encountered--the sludge recycle would stop during the night because of the geometry of the sludge hopper causing a clear zone with no sludge. This was corrected for the most part by keeping the volume of sludge in the bottom of the clarifier to a minimum.

The performance of reactor 2 (FC-200, table IV and figure 13) was unsteady during the initial dosing of FC-200, days 4 through 13, but was relatively satisfactory thereafter until day 37 when effluent quality began to

Table IV

ACTIVATED SLUDGE ANALYSES, TEST 2

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
1		69		Control			
1		69	30	26	2123	57	
2		54	38	21	2366	42	
3		52	32	22	2084	48	
4		41	25	<10	2453	45	
5		53	45	16	2557	43	
6	429	61	52	<10	2349	64	
7		71	49	<10	2009	50	
8		44	39	31	1840	54	
9	417	128	101	<10	1834	55	Solids concentration in clarifier
10	386	61	44	18	2353	47	No recycle or sludge
11	402	43	30	<10	1846	54	
12		70	33	38	2866	63	
13	394	218	162	61	3432	52	No sludge recycle
14		63	31	<10	3476	40	
15	No data						
16		46	44	13	3269	58	
17		84	35	42	2945	63	
18		184	39	36	2808	64	No sludge recycle
19		44	41	52	2999	63	
20	402	185	32	45	2866	59	No sludge recycle
21		86	24	15	2764	61	
22		37	35	87	2073	58	
23		62	35	30	2575	43	
24	422	145	40	35	2398	67	
25	414	72	52	17	2148	61	
26		39	34	14	2672	60	
27		36	34	<10	2972	47	
28	409	94	64	16	3710	43	
29		73	63	24	2658	56	
30		48	43	34	2237	63	

Table IV (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
31		26	21	29	3306	51	
32	382	30	28	53	3034	53	
33		27	20	<10	3217	50	
34		22	19	<10	3426	50	
35		25	25	12	4017	42	
36		24	21	17	3682	43	
37		28	27	35	4169	41	
38		42	30	13	2010	55	Upset; broken line
39	417	39	26	17	1968	61	
40		35	31	25	2148	56	
41		42	35	12	2105	57	
42		62	32	23	2396	71	
43		38	26	15	1819	71	
44	361	31	36	<10	2491	80	
45		37	33	21	1850	76	
46		87	---	23	2021	89	
47		168	42	27	1840	109	
48		50	27	11	1680	101	
49		47	35	23	1673	90	
50		45	37	<10	2451	78	
51		46	30	19	2271	88	
52	404	90	30	34	2204	109	
53	456	16	12	<10	2289	100	
54		30	30	12	2607	84	
55		29	37	<10	2213	90	
56		32	30	12	2015	84	
57		34	48	<10	2254	80	
58		64	70	<10	2216	81	
59	445	57	56	<10	3121	61	
60		44	58	10	3541	56	
61		41	27	<10	3580	50	
62		56	30	12	3733	54	
63		54	49	16	3997	50	

Table IV (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
64	454	112	117	18	3820	47	
65		65	37	22	3916	51	
66	461	52	47	26	3795	50	
67				11	3897	44	
68	414	44	36	14	4319	46	
69				26	3042	49	
				FC-200			
1		34	32	13	1491	67	
2		50	32	39	1770	51	
3		51	33	19	1814	50	
4	345	62	32	32	2083	67	First sample 10 mg/l FC-200
5		44	32	29	2351	51	
6	444	52	39	<10	2698	41	
7		184	66	122	2038	54	
8		153	47	27	2279	57	
9	474	111	94	<10	2260	62	First sample 20 mg/l FC-200
10	339	68	46	24	2100	67	
11	402	43	30	<10	1846	54	
12		104	58	31	1861	56	First sample 50 mg/l FC-200
13		215	162	35	1700	65	
14	375	53	43	20	2111	62	
15	No data						
16		79	45	55	2584	58	
17		71	47	36	2146	65	
18		84	26	44	1756	68	
19		49	44	54	1560	64	
20	480	54	50	92	1231	73	First sample 80 mg/l FC-200
21		56	45	22	1618	68	
22		114	36	81	1354	66	

Table IV (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
23		40	38	51	1635	27	
24	484	35	27	14	2500	60	
25	471	79	61	20	2430	62	
26		89	36	28	3139	54	First sample 120 mg/l FC-200
27		45	45	11	3100	45	
28	504	61	53	22	3625	50	
29		98	56	24	3266	55	
30		43	43	35	4160	48	
31		61	45	31	4414	41	
32	546	44	39	30	4654	39	First sample 160 mg/l FC-200
33		59	42	10	4175	50	
34		90	41	53	3520	55	
35		58	54	18	3374	50	
36		49	45	19	3386	53	
37		41	39	32	3612	53	
38		48	39	25	3982	50	
39	551	76	67	15	3406	59	First sample 200 mg/l FC-200
40		98	84	33	3808	32	
41		108	108	13	3758	67	
42		139	118	117	3674	63	
43		134	63	63	3209	65	
44	615	72	67	<10	3749	53	First sample 260 mg/l FC-200
45		---	---	44	3470	52	
46		60	50	20	2558	63	
47		139	139	17	2549	59	
48		40	39	<10	2211	59	
49		43	43	23	1872	69	
50	No data; reactor overflowed						
51	No data; reactor overflowed						
52	645	98	71	10	835	96	First sample 320 mg/l
53	537	170	95	25	1414	78	

Table IV (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
54		173	97	39	902	499	
55		180	78	58	962	343	
56		165	77	46	1257	684	
57		86	34	60	2227	292	
58		191	66	46	1433	188	
59	671	176	109	70	1559	603	
60		158	86	83	1474	468	
61		158	110	39	1149	305	
				Aerowater 3 Percent			
1		84	55	37	1509	60	
2		53	37	31	1431	49	
3		33	27	10	1522	53	
4	418	30	25	<10	1825	49	First sample 10 mg/l 3 percent
5		52	41	14	2098	43	
6	421	52	48	<10	2305	52	
7		111	71	32	2013	50	
8		84	57	21	2412	54	First sample 20 mg/l 3 percent
9	472	182	89	<10	2062	49	
10	449	77	41	33	1706	41	
11	425	46	43	<10	1649	67	
12		75	43	24	1904	74	First sample 50 mg/l 3 percent
13	394	261	152	65	1258	70	
14		46	41	86	1615	124	
15	No data						
16		47	47	10	1575	70	
17		54	43	12	1592	85	
18		68	43	19	1761	85	
19		44	44	23	1810	88	
20	457	77	46	36	1522	72	First sample 80 mg/l
21		140	47	112	1662	90	
22		37	36	57	1434	77	

Table IV (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
23		46	29	32	1792	51	
24	465	69	32	43	2310	71	
25	457	76	58	22	2540	71	
26		60	40	33	3330	60	First sample 120 mg/l 3 percent
27		47	42	<10	3166	58	
28	465	91	63	22	3720	48	
29		78	56	23	2847	60	
30		38	33	39	3682	52	
31		51	43	37	3232	56	
32	515	41	35	---	3736	51	First sample 160 mg/l 3 percent
33		44	27	13	3441	55	
34		37	37	<10	3779	53	
35		36	37	13	3880	46	
36		49	41	28	3609	53	
37		45	46	19	3867	52	
38		66	48	15	3626	50	
39	528	57	47	24	3770	53	First sample 200 mg/l 3 percent
40		66	50	35	3974	58	
41		71	56	22	3637	52	
42		77	49	40	3940	53	
43		47	36	13	4048	52	
44	486	54	57	10	4519	51	First sample 260 mg/l 3 percent
45		54	66	15	3896	54	
46		62	22	22	4374	50	
47		101	56	31	4272	56	
48		43	39	<10	4474	51	
49		61	46	14	4556	55	
50		63	55	<10	4949	51	
51		62	45	<10	5418	42	
52	562	63	63	<10	5230	52	First sample 320 mg/l 3 percent
53	458	65	62	<10	6027	50	

Table IV (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
54		58	67	18	5857	51	
55		112	65	11	5830	45	
56		106	73	13	4709	42	
57		75	74	<10	5172	43	
58		103	93	11	5152	37	
59	634	152	105	23	2490	40	First sample* 400 mg/l 3 percent
60		140	100	49	2858	35	
61		121	82	36	2867	35	
62		122	79	37	3374	36	
63		90	92	152	2977	34	
64	530	110	98	21	3456	32	
65		93	90	20	4061	30	
66	722	102	69	35	4026	35	First sample 600 mg/l 3 percent
67		---	---	38	3664	27	
68	659	304	77	100	2654	30	
69		412	98	147	---	---	

*Foaming causing bacteria to wash out of reactor

Aerowater 6 Percent

1		---	---	---	3051	187	
2		69	49	35	3565	79	
3		48	19	15	3506	80	
4		61	30	31	3451	72	First sample 75 mg/l 6 percent
5		46	51	11	4048	67	
6		155	89	19	4227	62	
7	510	69	50	13	4485	65	First sample 125 mg/l 6 percent
8		41	31	15	4094	66	
9		---	---	<10	3994	60	
10		53	58	13	4636	58	First sample 200 mg/l 6 percent

Table IV (cont'd)

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
11		---	---	29	4590	61	
12		61	58	<10	3190	72	
13		39	40	17	2712	92	

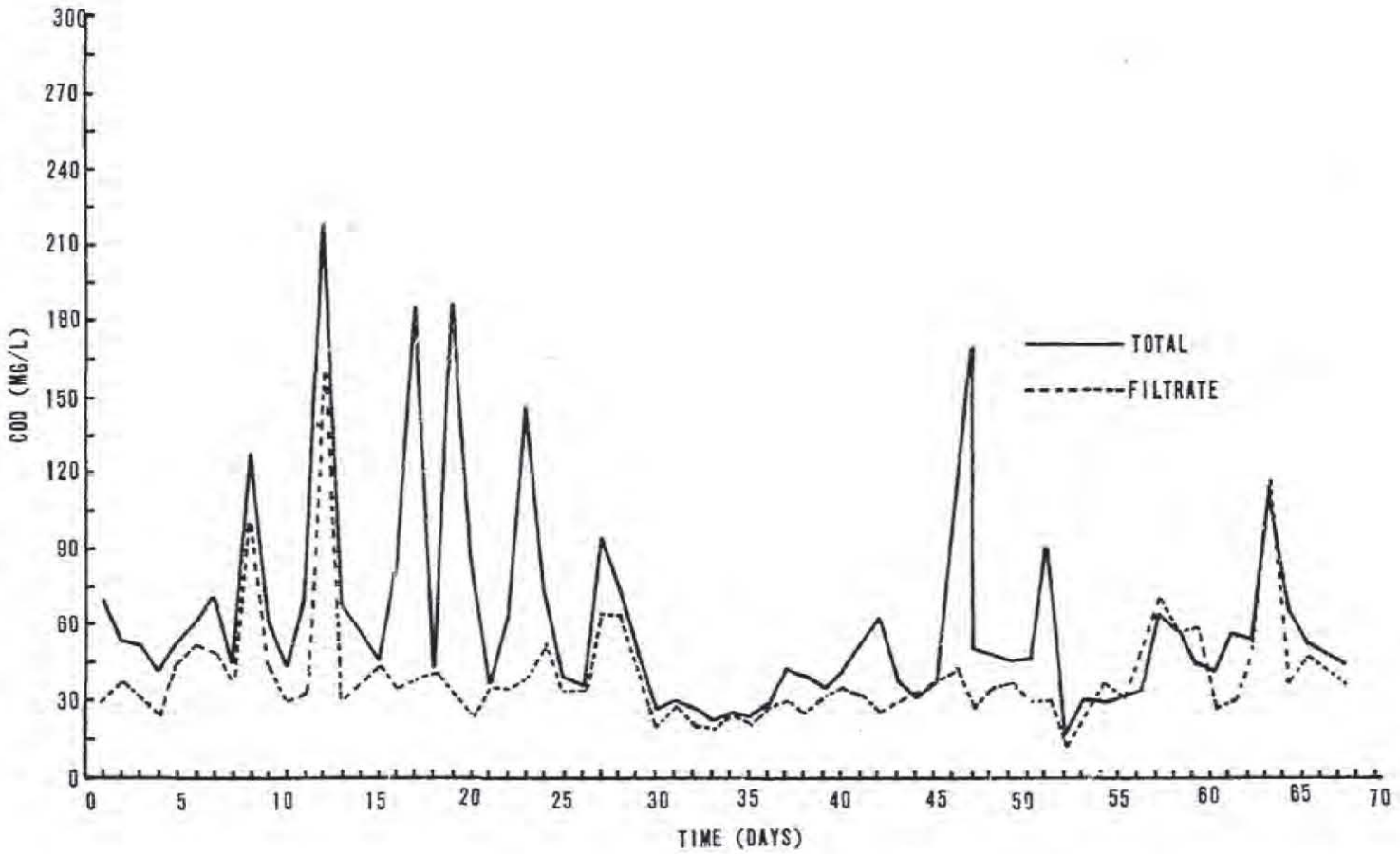

Figure 12. Test 2, Activated Sludge Effluent COD Control

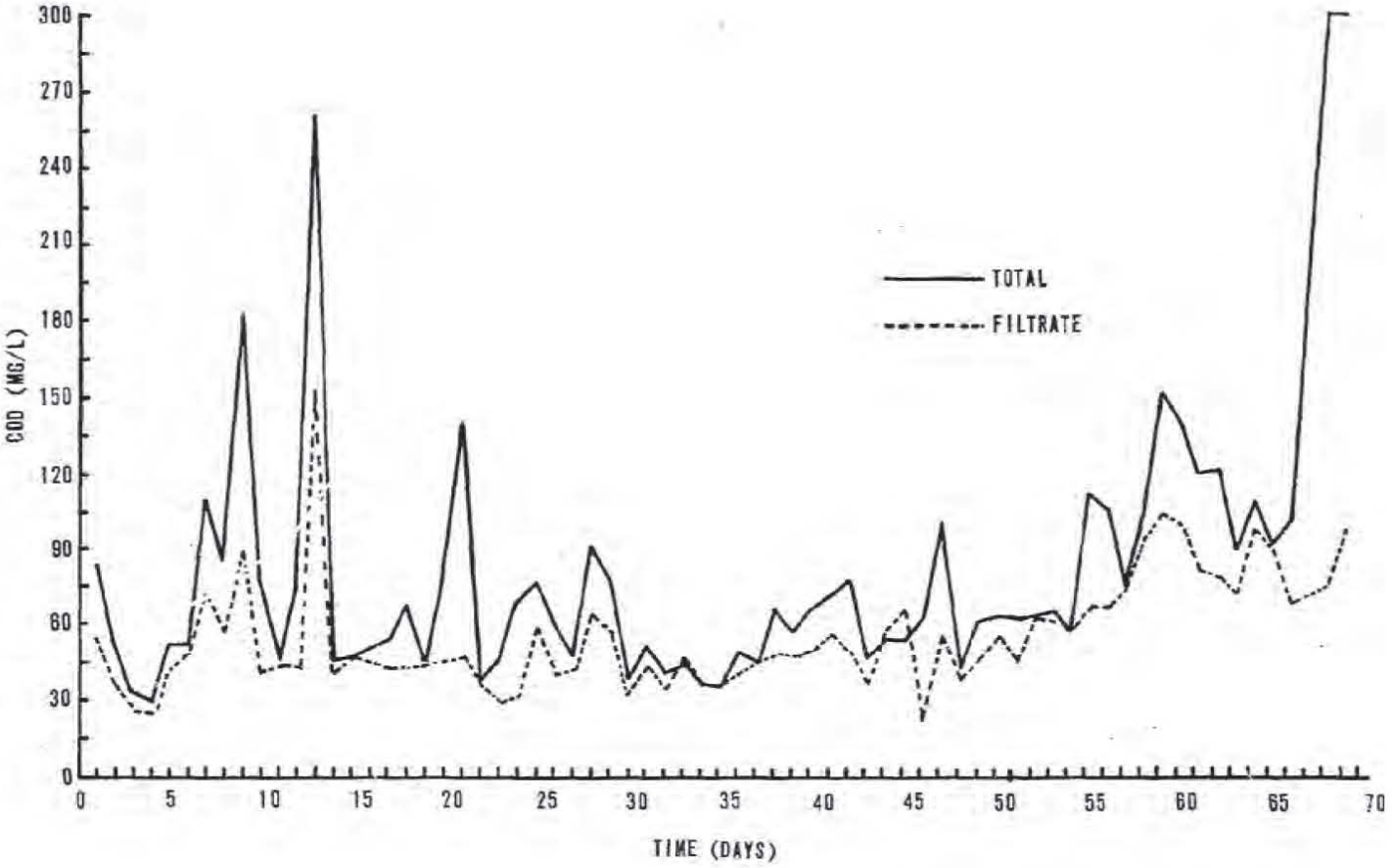

Figure 13. Test 2, Activated Sludge Effluent COD, FC-200

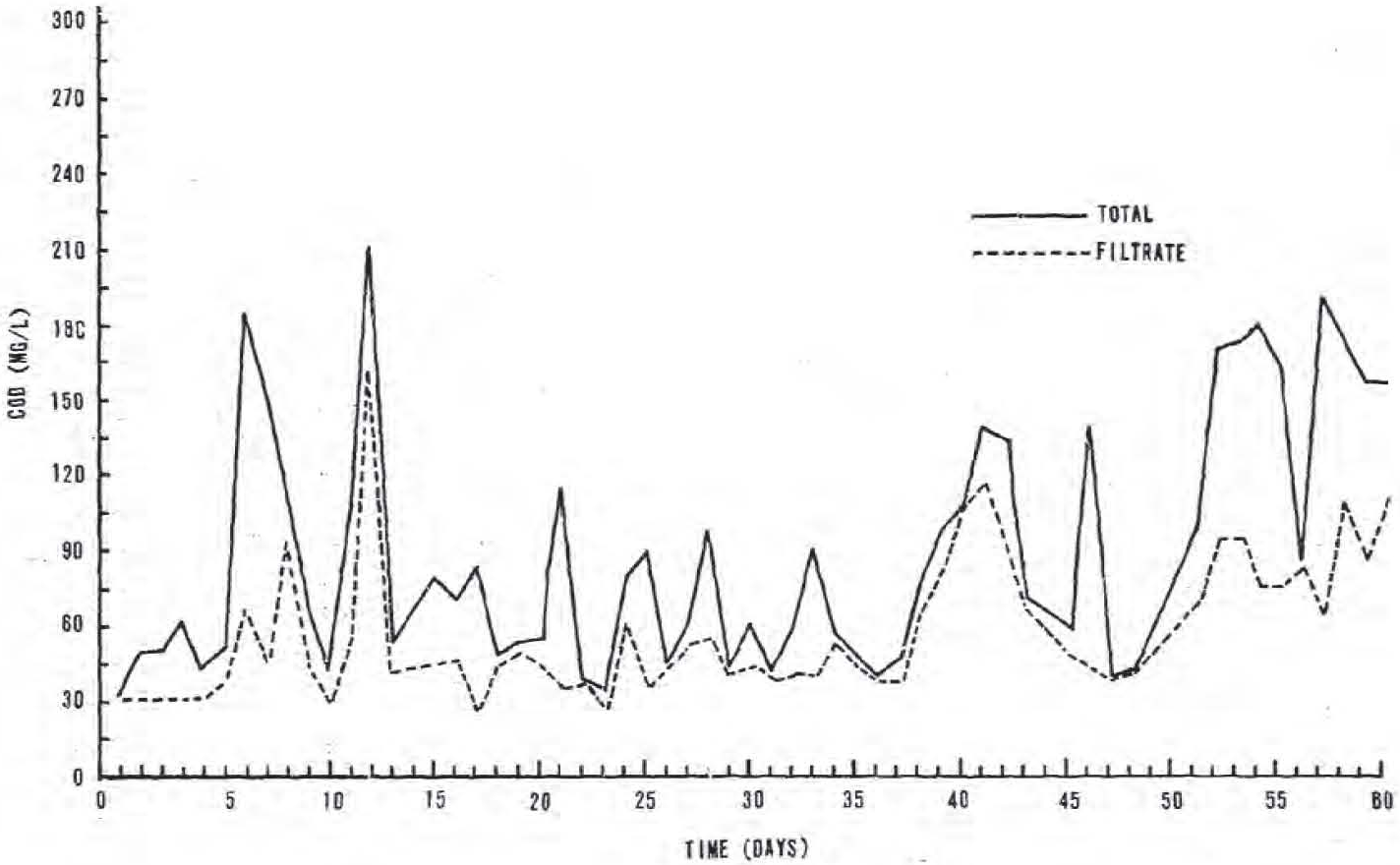

Figure 14. Test 2, Activated Sludge Effluent COD, Aerowater 3 Percent

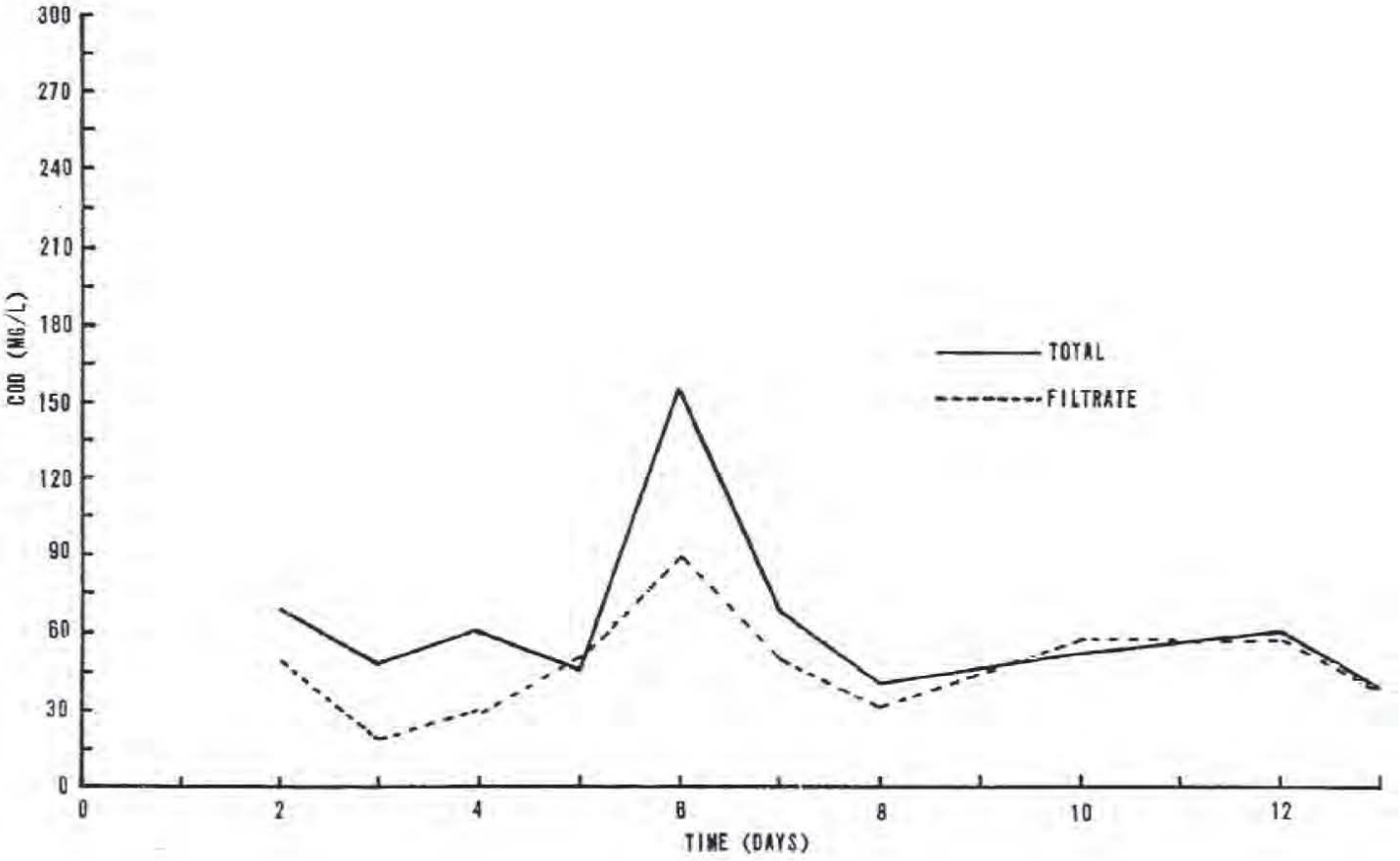

Figure 15. Test 2, Activated Sludge Effluent COD, Aerowater 6 Percent

degrade. This is several days after the reactor had been receiving 160 mg/l of FC-200. On days 50 and 51 the overflow line from the reactor to the clarifier plugged during the night. The reactor spilled over and washed out much of the MLSS. From that point on the reactor was unable to recover, and the effluent quality degraded seriously.

The effect of Aerowater 3 percent on the activated sludge process for test 2 is shown in figure 14. Again, unsteady performance was observed during the dosing of low concentrations of Aerowater 3 percent on days 4 through 14. After day 14 performance evened out, with the exception of day 21 when the effluent contained a high concentration of effluent suspended solids. This appears to have been caused by the increase of the Aerowater 3 percent concentration to 80 mg/l. At about day 35 the total and filtrate effluent COD began to rise gradually, apparently in response to increasing concentrations of Aerowater 3 percent. On day 53 effluent quality degraded rapidly in response to the increase of Aerowater 3 percent concentration to 320 mg/l. This degradation in effluent quality would have occurred sooner except that the MLSS was allowed to rise to over 5000 mg/l.

As stated earlier, reactor 4 was restarted on Aerowater 6 percent primarily to obtain an effluent for the toxicity experiments which were conducted at 200 mg/l of AFFF. Even though the Aerowater 6 percent concentration was increased relatively faster than for the other AFFFs, effluent quality (with the exception of day 6) was consistent and acceptable when measured against the control.

c. Test 3

Recognizing that slug loads of AFFFs would occur at domestic wastewater treatment plants, an attempt was made to determine what impact would result from such undesirable occurrences. Unacclimated activated sludge reactors were slug loaded with 200 mg/l of FC-200 and Aerowater 6 percent, then increased in the case of Aerowater 6 percent to 400 mg/l. The results of these slug loadings are listed in table V and figure 16 for FC-200 and in figure 17 for Aerowater 6 percent.

For FC-200 it was observed that 200 mg/l led to large volumes of foam which encapsulated much of the MLSS, carrying them out of the reactor. Effluent COD increased dramatically on day 7 (FC-200 was added the evening of day 6) and though the effluent COD decreased sharply on day 8, the upset for day 7 was clearly unacceptable.

Table V

ACTIVATED SLUDGE ANALYSES, TEST 3, SLUG LOADING

Day	COD_{INF}	COD_T	COD_F	SS_{EFF}	MLSS	SVI	Remarks
				FC-200			
1		112	22	33	1552	64	
2		139	42	77	1692	236	
3	446	95	59	49	1892	476	
4		79	47	34	3120	212	
5	445	85	31	36	3604	72	
6		---	---	37	3526	65	
7	556	420	96	274	2478	77	First sample 200 mg/l FC-200
8		110	110	257	---	---	Uncontrollable foaming
				Aerowater 6 Percent			
1		61	58	<10	3190	72	At 200 mg/l 6 percent
2		39	40	17	2712	92	
3	535	31	31	<10	3481	126	
4		64	55	---	---	---	
5	646	175	71	51	3093	259	First sample 400 mg/l 6 percent
6		374	133	120	2755	334	
7		435	135	121	3204	179	
8	628	183	125	47	3779	233	
9		209	134	59	3724	207	
10		194	112	83	4093	230	
11		217	104	69	3995	235	

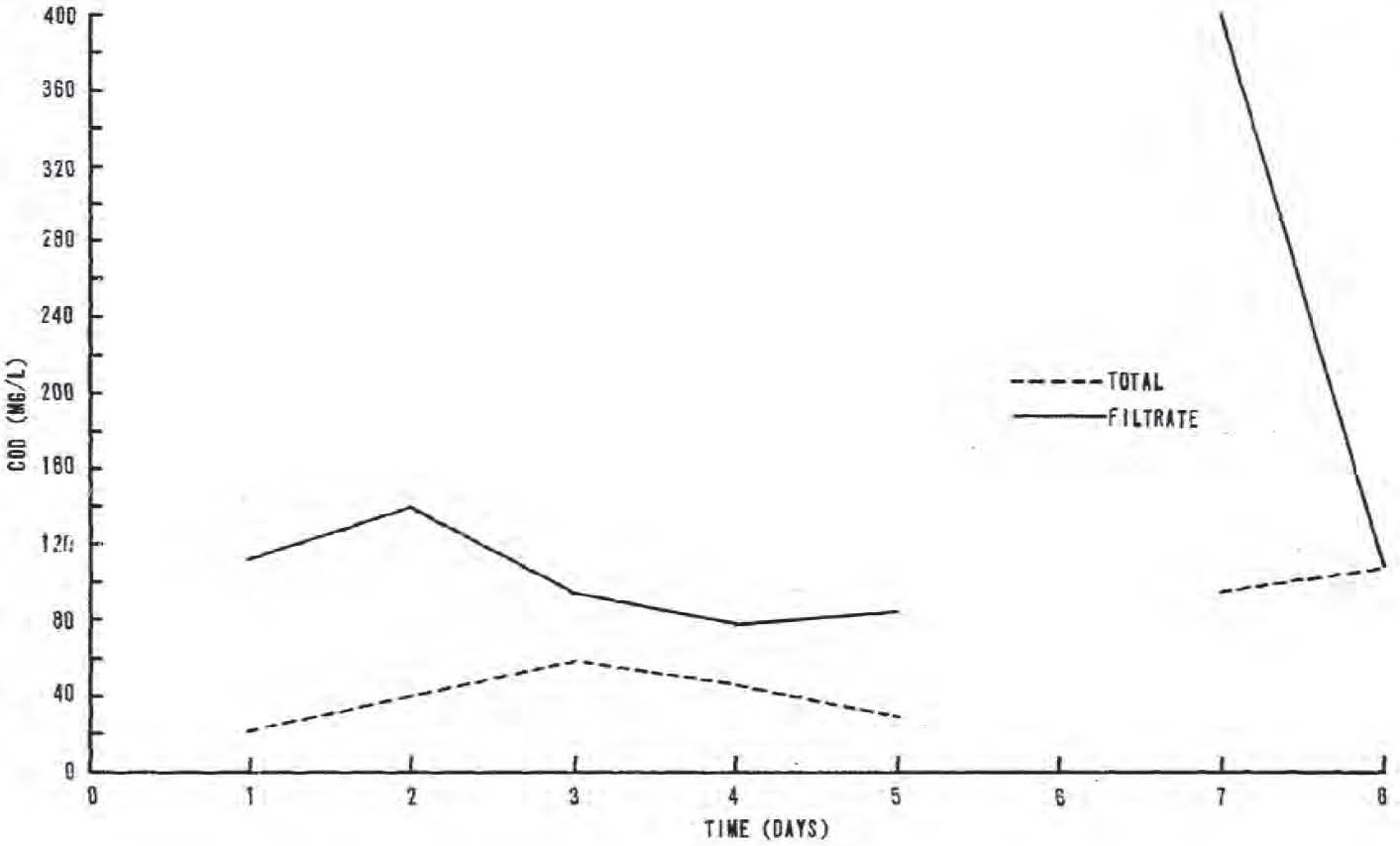

Figure 16. Test 3, Slug Loading, FC-200, Activated Sludge Effluent COD

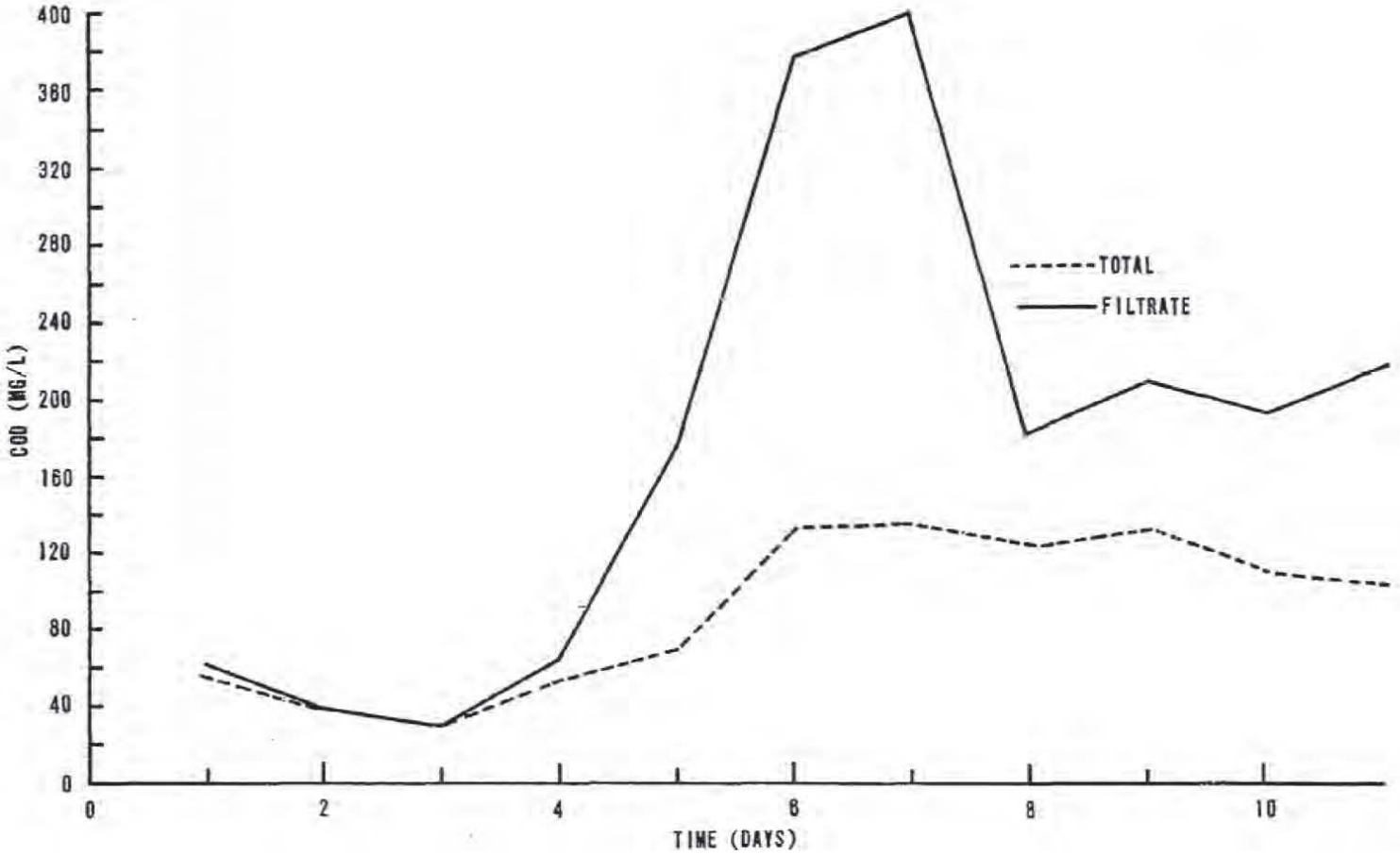

Figure 17. Test 3, Slug Loading, Aerowater 6 Percent, Activated Sludge Effluent COD

The slug load of 200 mg/l of Aerowater 6 percent did not appear to cause any drastic effects on the reactor performance, as shown in figure 17. Therefore, on day 4 the concentration was doubled, after which the total and filtrate effluent COD climbed rapidly, coupled with decreasing settlability. Thus, it appeared that the unacclimated reactor could tolerate a slug load of 200 mg/l but not 400 mg/l.

d. Summary of Activated Sludge Results

Summarizing the results of the activated sludge experiments, average percent COD removal and average effluent COD is plotted against influent AFFF concentration in figures 18 through 20. These figures were constructed by averaging the effluent COD values for a given influent AFFF and then connecting the lines between each point, thus permitting determination of where the effluent quality begins to decrease. Percent COD removal was plotted for both total and filtrate. Effluent COD was plotted for just the total. It must be remembered that increasing the AFFF concentration causes an increase in the influent COD (10 mg/l FC-200 $\cong$ 7 mg/l COD, 10 mg/l Aerowater 3 percent $\cong$ 5 mg/l COD, and 10 mg/l Aerowater 6 percent $\cong$ 4.5 mg/l COD). Therefore, even if the same percent COD removal was obtained after increasing the AFFF concentration, the effluent COD would be higher. For this reason a more practical value is placed on the effluent COD curves.

For FC-200 (figure 18) it is seen that percent COD removal tends to increase and effluent COD tends to decrease up to 160 mg/l. The percent removal increase can be explained by the increasing influent COD attributed to the FC-200. The effluent COD decrease can be attributed to either unsteady performance initially or possibly to an inhibiting effect of the FC-200 on the unacclimated microorganisms. Effluent COD takes a sharp rise between 160 to 200 mg/l; however, at 260 mg/l the effluent COD decreases significantly. Since these are averaged values, these phenomena are not readily explainable.

In figure 19 it is seen that for Aerowater 3 percent the percent COD removal, total and filtrate, shows a gradual decline above an influent concentration of 160 mg/l. However, between 400 and 600 mg/l the percent filtrate COD removal remained constant, while the percent total COD removal dropped significantly. This is explained by the increased effluent suspended solids concentration. For the effluent COD there is a decrease in concentration up to 120 mg/l influent Aerowater 3 percent which, like FC-200, is attributed to

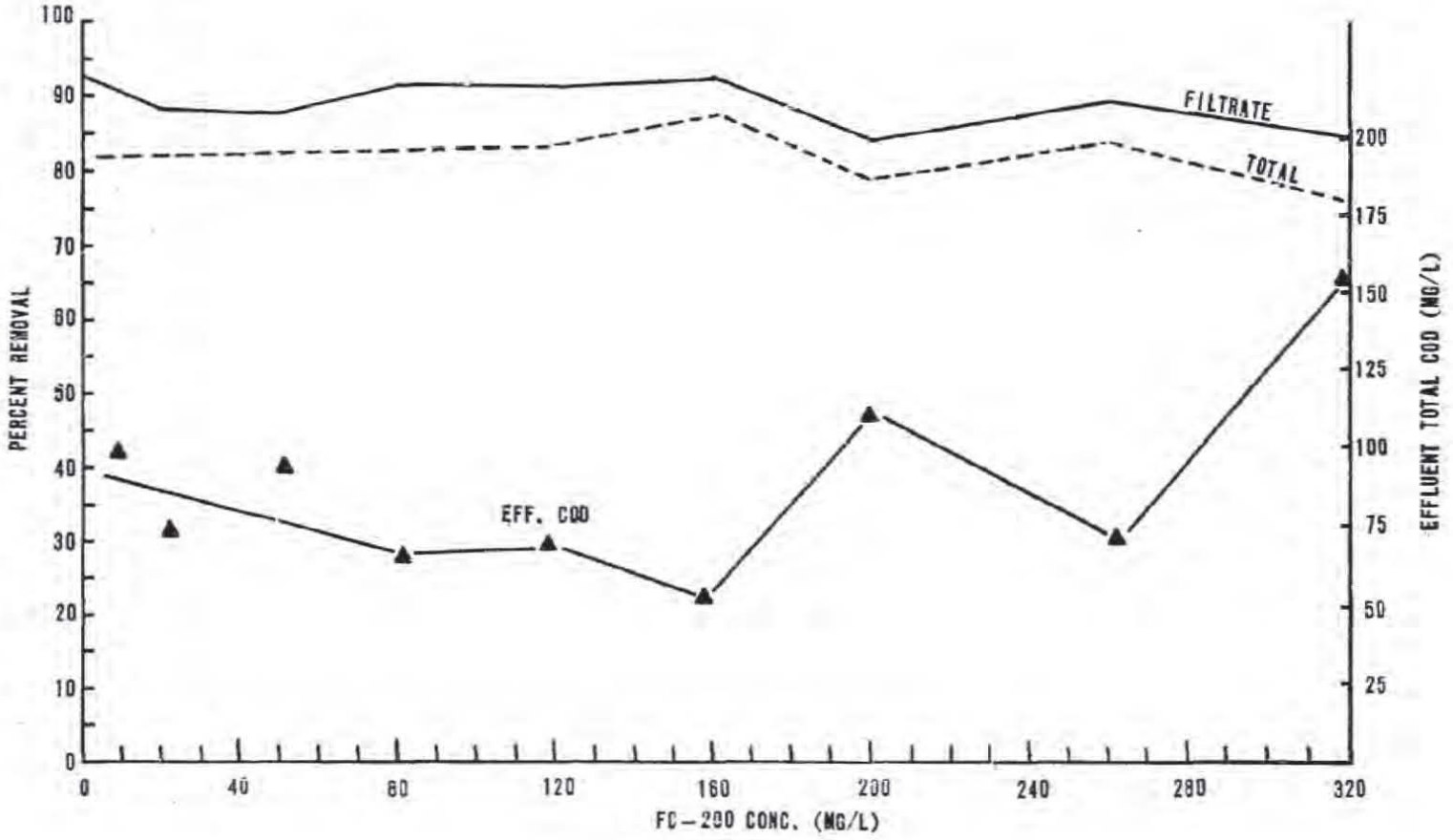

Figure 18. Percent COD Removal and Effluent COD versus Influent Concentration, Activated Sludge, FC-200

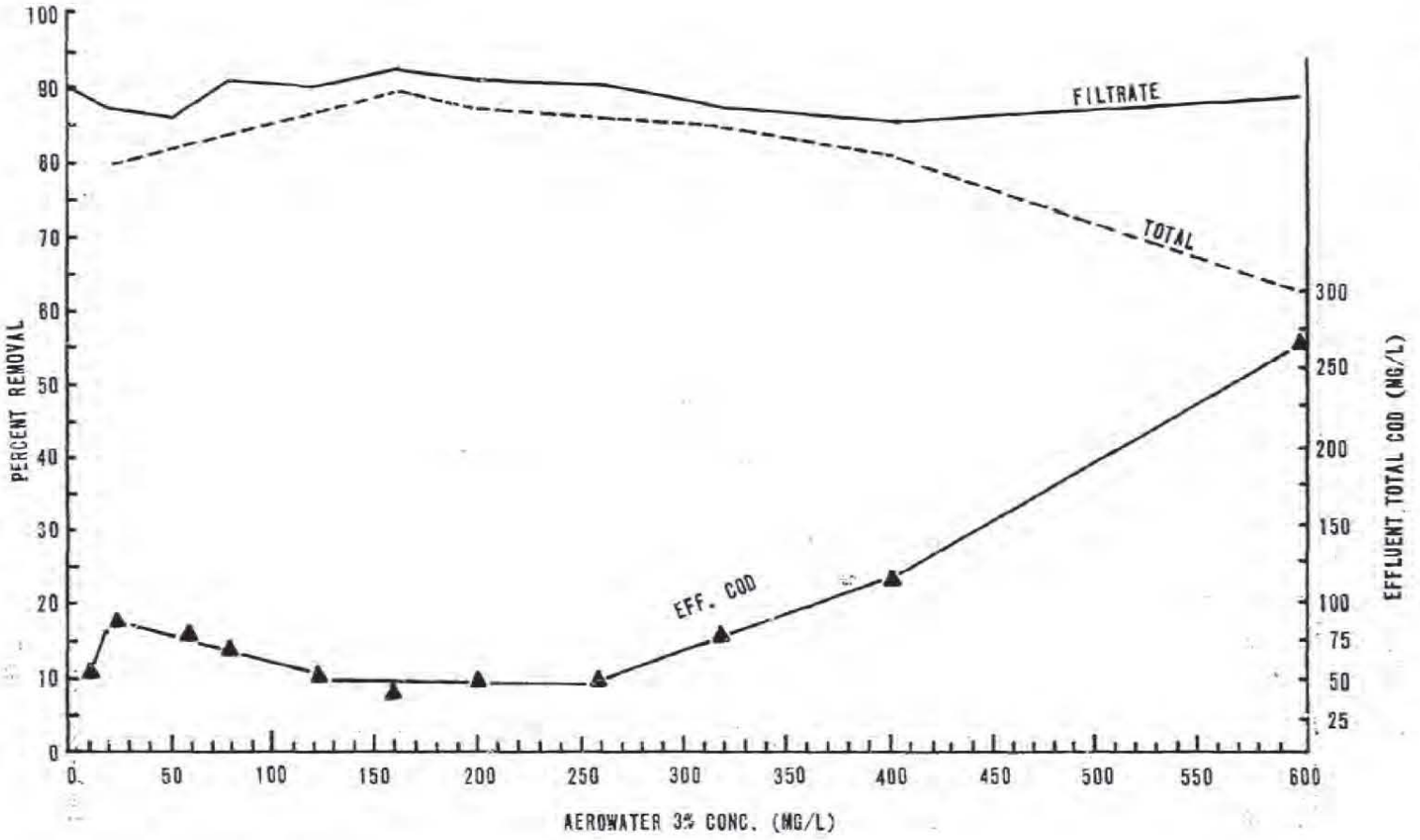

Figure 19. Percent COD Removal and Effluent COD versus Influent Concentration, Activated Sludge, Aerowater 3 Percent

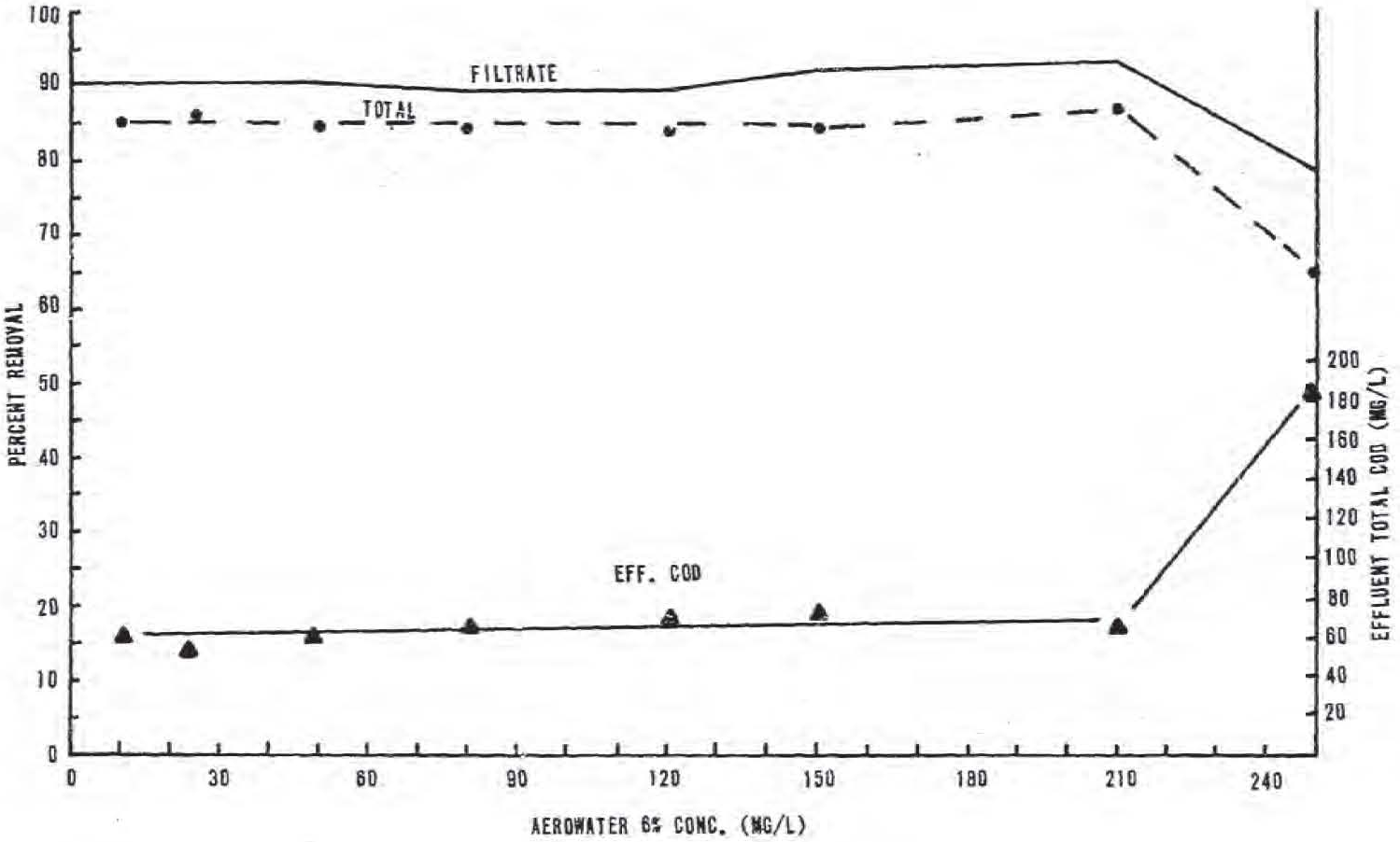

Figure 20. Percent COD Removal and Effluent COD versus Influent Concentration, Activated Sludge, Aerowater 6 Percent

either unsteady performance initially or an initial inhibiting effect. Above 250 mg/l the effluent COD increases to clearly unacceptable levels.

Summarizing the effects of Aerowater 6 percent on the activated sludge process, it is seen from figure 20 that total effluent COD increased quite gradually up to 210 mg/l, above which there was a sharp increase. This is reflected by the percent COD removal curves. Effluent CODs of 60 to 70 mg/l are as expected from a reasonably well-operated activated sludge plant.

4. TRICKLING FILTER EXPERIMENTS

a. Test 1

The data collected for test 1 are demonstrated in table VI and in figures 21 and 22. As stated in section III, test 1 was conducted with no recycle of the effluent. The hydraulic loading was 200 gpd/ft^2. Since both columns were receiving AFFFs and there were no additional columns available, a control was not run concurrently. However, just before the dosing of the AFFF, both columns A and B were achieving 75 to 85 percent COD removal when receiving synthetic wastewater. Samples were taken from the two sampling ports and the final discharge. These data are presented in table VI. Only the final discharge is presented in the figures to avoid cluttering of the illustrations. During Test 1, sloughing of the microorganisms was moderate and observed to be at a relatively constant rate. It is seen from table VI that, in general, for both FC-200 and Aerowater 6 percent, most of the COD removal occurred between sample port 2 and the final discharge. This is contrary to expected performance for standard trickling filters receiving domestic wastewater. This, coupled with the fact that the COD concentrations at sample ports 1 and 2 were frequently the same value with sample port 2 sometimes having higher COD than sample port 1, leads to the assumption that the samples taken at sample ports 1 and 2 were unrepresentative.

From figure 21 for FC-200 it is seen that the effluent CODs from the final discharge were quite erratic but do demonstrate an increasing effluent concentration with time (increasing FC-200 concentration). Essentially, the same observation is made for Aerowater 6 percent in that the effluent CODs were clearly unacceptable by the time 160 mg/l of AFFF was reached; the columns were converted back to receiving only synthetic wastewater on day 25.

Table VI

TRICKLING FILTER ANALYSES, TEST 1, NO RECYCLE

[COD (mg/l)]

Day	Influent	Port 1	Port 2	Final discharge	Remarks
			FC-200		
1		331	331	60	
2		411	359	103	First sample 25 mg/l FC-200
3		350	293	98	
4		208	216	74	
5		296	264	86	
6	373	271	240	95	First sample 50 mg/l FC-200
7		279	256	85	
8		238	234	83	
9		197	205	65	
10		165	213	88	
11		163	202	120	
12	368	182	253	96	First sample 80 mg/l FC-200
13		245	285	111	
14		310	278	94	
15		278	242	88	
16		248	240	106	First sample 120 mg/l FC-200
17		326	294	110	
18		397	413	113	
19		411	340	158	
20	550	387	308	133	First sample 160 mg/l FC-200
21		368	225	186	
22		400	354	300	
23		377	392	285	
24		226	365	201	
25		414	367	176	

Table VI (cont'd)

Day	Influent	Port 1	Port 2	Final discharge	Remarks
			Aerowater 6 Percent		
1		317	314	67	First sample 25 mg/l 6 percent
2		296	348	89	
3		386	337	81	
4		220	252	70	
5		216	304	62	
6	357	136	209	74	First sample 50 mg/l 6 percent
7		120	213	74	
8		155	202	100	
9		110	173	61	
10		189	193	54	
11		83	163	94	
12	364	150	174	152	First sample 80 mg/l 6 percent
13		91	202	146	
14		246	214	146	
15		111	206	122	
16		205	181	80	First sample 120 mg/l 6 percent
17		290	278	115	
18		294	270	95	
19		372	304	126	
20	484	332	324	117	First sample 160 mg/l 6 percent
21		298	306	134	
22		377	300	192	
23		338	269	177	
24		---	274	89	
25		348	270	109	

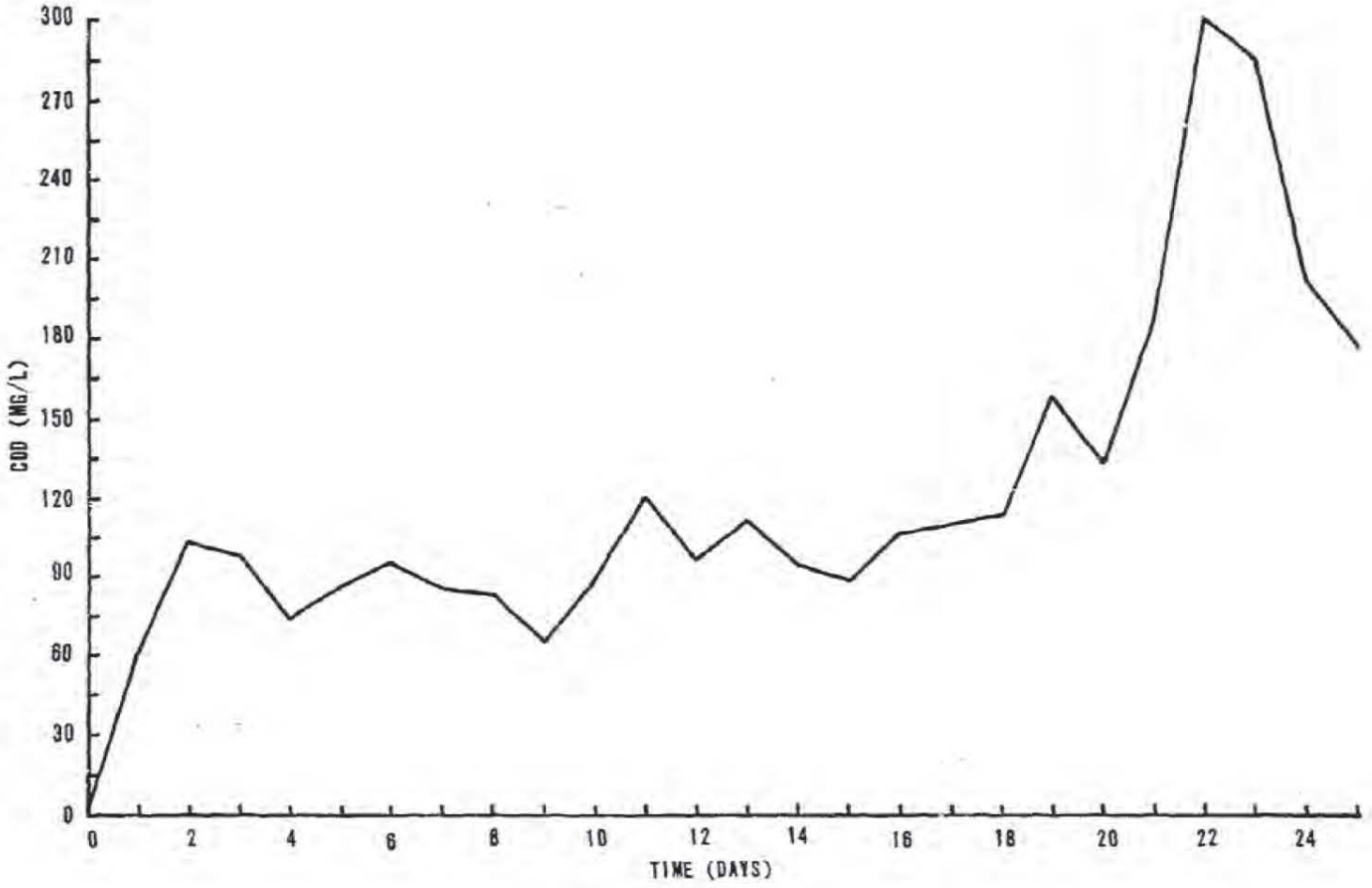

Figure 21. Trickling Filter Effluent COD (No Recycle), FC-200

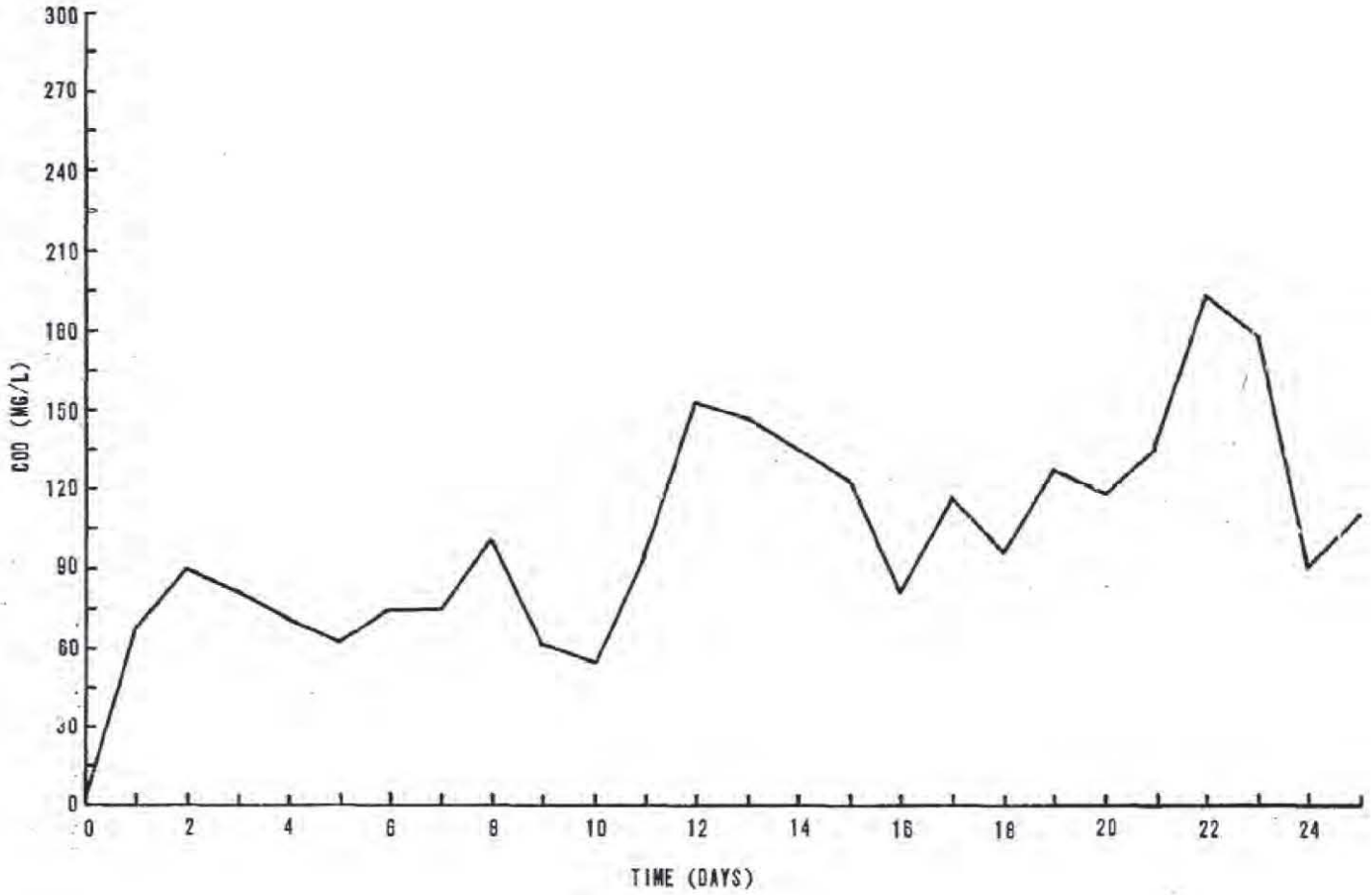

Figure 22. Trickling Filter Effluent COD (No Recycle), Aerowater 6 Percent

b. Test 2

Test 2 consisted of dosing the columns with equal volumes of influent and recycled effluent, i.e., one-to-one recycle. The recycle was taken from the collection basin to which the final discharge entered. As stated in section III, the hydraulic loading was 200 gpd/ft^2 (8150 l/day/m^2) of which 100 gpd/ft^2 was synthetic wastewater plus AFFF and 100 gpd/ft^2 was recycled effluent. After test 1, the columns were dosed with synthetic wastewater for 9 days, at which time it was considered acceptable to begin adding the FC-200 and Aerowater 6 percent. Table VII and figures 23 and 24 represent the results for test 2. It should be noted that the influent listed in table VII is that which was in the feed tank and not that which entered the top of the column. The COD concentration entering the top of the column at any time would equal the feed tank COD plus the recycled effluent COD divided by 2.

From figure 23 it is seen that for the trickling filter column receiving FC-200, no change in performance at the final discharge is observed up to about day 36, at which time the FC-200 concentration was increased to 200 mg/l. However, even up to this point the effluent COD was higher than expected and quite variable. Above 200 mg/l FC-200 effluent quality started to degrade beyond the already less than acceptable quality.

Recycling of effluent is a common practice in the operation of trickling filters to improve effluent quality. For the trickling filter loaded with FC-200, recycling the effluent did not improve performance but rather had some deleterious effects when the data is compared against test 1. However, there is insufficient data to determine if this occurrence is caused by the FC-200.

Figure 24 illustrates the performance of the trickling filter receiving Aerowater 6 percent during test 2. It can be seen that up to 300 mg/l of Aerowater 6 percent, influent to the trickling filter, there was no observed degradation of effluent quality. When compared against the data of test 1 (figure 22), it is seen that recycle of the effluent, which in turn lowers the organic loading, permitted the achievement of higher AFFF loadings than without recycle, while still yielding acceptable effluent quality.

c. Summary of Trickling Filter Results

Summarizing the results of the two trickling filter tests, influent AFFF concentration is plotted against averaged percent COD removal and effluent COD concentration for both no recycle and one-to-one recycle. This is plotted

Table VII

TRICKLING FILTER ANALYSES, TEST 2, ONE-TO-ONE RECYCLE

[COD (mg/l)]

Day	Influent	Port 1	Port 2	Final discharge	Remarks
			FC-200		
1		234	191	127	
2		184	160	112	
3		244	220	124	
4		192	200	128	
5		288	264	144	
6		212	248	64	
7		236	216	78	
8		273	301	98	
9		301	294	123	
			Aerowater 6 Percent		
1		---	139	87	
2		96	76	52	
3		100	80	36	
4		80	72	36	
5		164	96	24	
6		156	64	---	
7		100	40	29	
8		203	210	78	
9		231	203	95	
			FC-200		
1	488	321	294	106	First sample 25 mg/l FC-200
2		369	282	121	
3		351	311	164	
4		319	295	129	
5		315	287	126	
6		344	328	147	
7		246	354	210	
8	484	329	298	---	First sample 50 mg/l FC-200

Table VII (cont'd)

Day	Influent	Port 1	Port 2	Final discharge	Remarks
9		341	333	286	
10		333	318	274	
11		372	348	288	
12		335	314	218	
13		242	222	165	
14		256	232	140	
15		320	304	240	First sample 80 mg/l FC-200
16		203	203	147	
17		271	283	195	
18		232	232	192	
19		292	240	224	
20		160	144	128	
21	524	240	176	192	First sample 120 mg/l FC-200
22		320	312	240	
23		202	165	133	
24	No data				
25		218	198	117	
26		292	276	196	
27		140	124	112	
28		176	152	116	
29	584	304	280	192	First sample 160 mg/l FC-200
30		384	360	256	
31		352	304	224	
32		372	368	272	
33		264	220	196	
34		240	232	200	
35		200	152	112	
36	559	269	281	225	
37	618	285	277	245	First sample 200 mg/l FC-200
38		457	394	378	
39		449	201	386	

Table VII (cont'd)

Day	Influent	Port 1	Port 2	Final discharge	Remarks
40		465	457	433	
41		394	386	337	
42		424	424	384	
43	592	424	416	380	
44		432	408	368	
45	587	272	224	192	First sample 250 mg/l FC-200
46		280	216	224	
47		237	213	213	
48		153	145	153	
49		269	277	237	
50	640	308	286	271	First sample 300 mg/l FC-200
51		401	318	303	
52		320	288	268	
53		336	272	216	
54		337	305	265	
			Aerowater 6 Percent		
1	464	194	194	119	First sample 25 mg/l 6 percent
2		---	143	113	
3		223	179	83	
4		147	128	61	
5		150	134	36	
6		214	176	58	
7		103	56	52	
8	468	198	135	75	First sample 50 mg/l 6 percent
9		222	123	87	
10		230	171	75	
11		233	170	83	
12		210	125	133	
13		210	97	113	
14		132	88	32	

Table VII (cont'd)

Day	Influent	Port 1	Port 2	Final discharge	Remarks
15	480	256	176	88	First sample 80 mg/l 6 percent
16		139	84	52	
17		187	120	84	
18		192	84	84	
19		180	120	52	
20		120	88	60	
21	504	272	148	68	First sample 120 mg/l 6 percent
22		120	112	64	
23		---	85	36	
24	No data				
25		80	61	---	
26		244	160	104	
27		200	104	52	
28		156	72	56	
29	528	200	128	96	First sample 160 mg/l 6 percent
30		192	144	104	
31		88	80	64	
32		---	136	56	
33		96	64	32	
34		208	120	40	
35		136	88	64	
36	474	132	48	40	
37	545	165	68	28	First sample 200 mg/l 6 percent
38		236	142	79	
39		465	134	118	
40		442	94	79	
41		187	122	57	
42		240	176	72	
43	560	240	160	96	
44		244	160	96	
45	540	104	136	72	First sample 250 mg/l 6 percent

Table VII (cont'd)

Day	Influent	Port 1	Port 2	Final discharge	Remarks
46		240	160	72	
47		253	173	108	
48		100	64	48	
49		153	76	48	
50	584	211	218	143	First sample 300 mg/l 6 percent
51		303	198	131	
52		240	136	96	
53		225	169	80	
54		273	213	---	

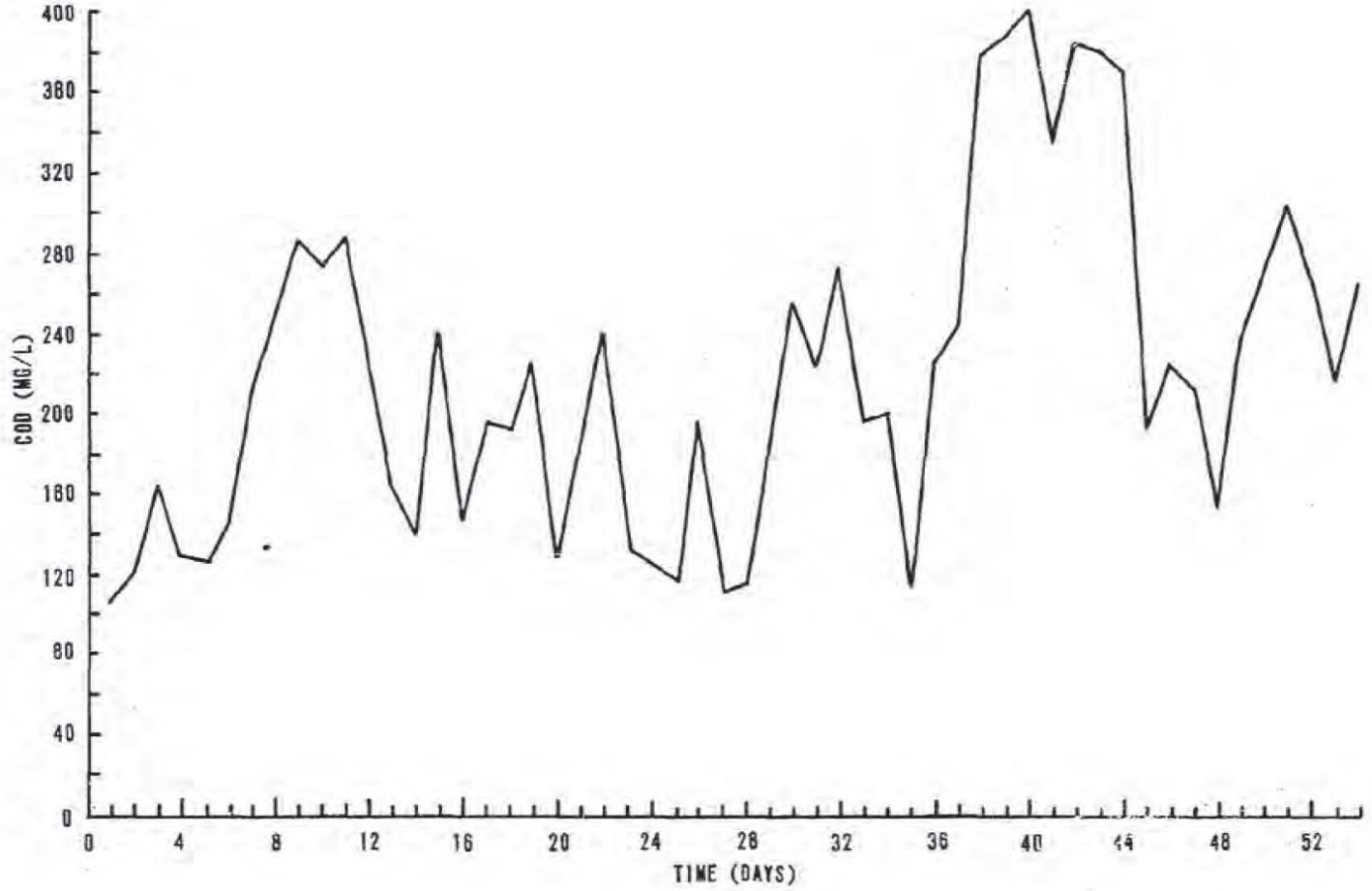

Figure 23. Trickling Filter Effluent COD (One-to-One Recycle), FC-200

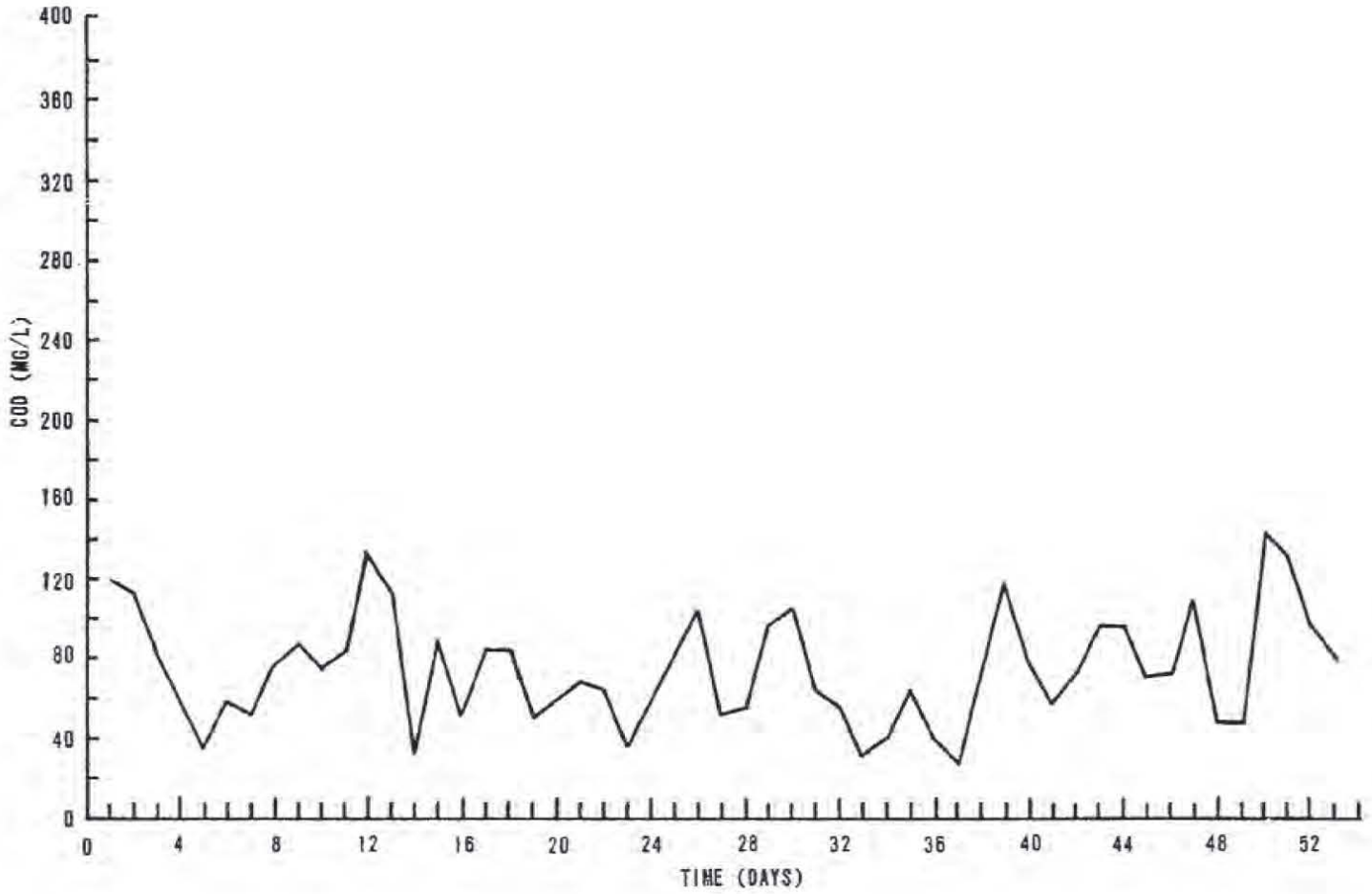

Figure 24. Trickling Filter Effluent COD (One-to-One Recycle), Aerowater 6 Percent

in figure 25 for FC-200 and in figure 26 for Aerowater 6 percent. It must be remembered that increasing AFFF concentrations results in increasing influent COD concentrations and thus affects percent COD removal. For FC-200, as was stated earlier, performance was better with no recycle than with the one-to-one recycle. Percent COD removals and effluent COD concentrations were less than acceptable for all concentrations of FC-200 in both tests. The FC-200 concentration above which the effluent quality starts to degrade beyond a baseline effluent quality (baseline not necessarily taken to be acceptable) appears to be 120 mg/l for both no recycle and one-to-one recycle.

The impact of Aerowater 6 percent on effluent quality is seen in figure 26. It was observed that above 50 mg/l of Aerowater 6 percent, with no recycle, there was a significant increase of effluent COD. On the other hand, for one-to-one recycle, the effluent COD remained nearly constant and of acceptable quality up to 250 mg/l of Aerowater 6 percent.

Why, in the case of FC-200, effluent quality would suffer from recycling of a portion of the effluent and improve in the case of Aerowater 6 percent is not readily explainable. This is a significant observation, but unfortunately, ther are insufficient data to say that this occurrence is a result of the AFFF. It would be difficult to reason that recycling of the effluent containing treated or partially treated FC-200 would cause a decrease in effluent quality from that of no recycle. This is especially true since the overall mass of FC-200 entering the trickling filter from the feed solution during one-to-one recycle is one half of that during no recycle.

5. TOXICITY EXPERIMENTS

The results of the toxicity experiments are given in table VIII. From this table it is seen that for Aerowater 3 percent and Aerowater 6 percent all the rainbow trout were able to survive for 96 hours in the activated sludge effluent. However, for the FC-200 on the first test, all four trout had died within 24 hours. When the test was repeated, two trout died within 48 hours and the remaining two in the next 24 hours. Further, all the trout exposed to the influents and the distilled water containing untreated AFFFs died within 96 hours. That the trout would die in distilled water is not immediately explainable. Potential explanation for this occurrence is the sensitivity of the trout to the change in mineral content of water to which they were acclimated.

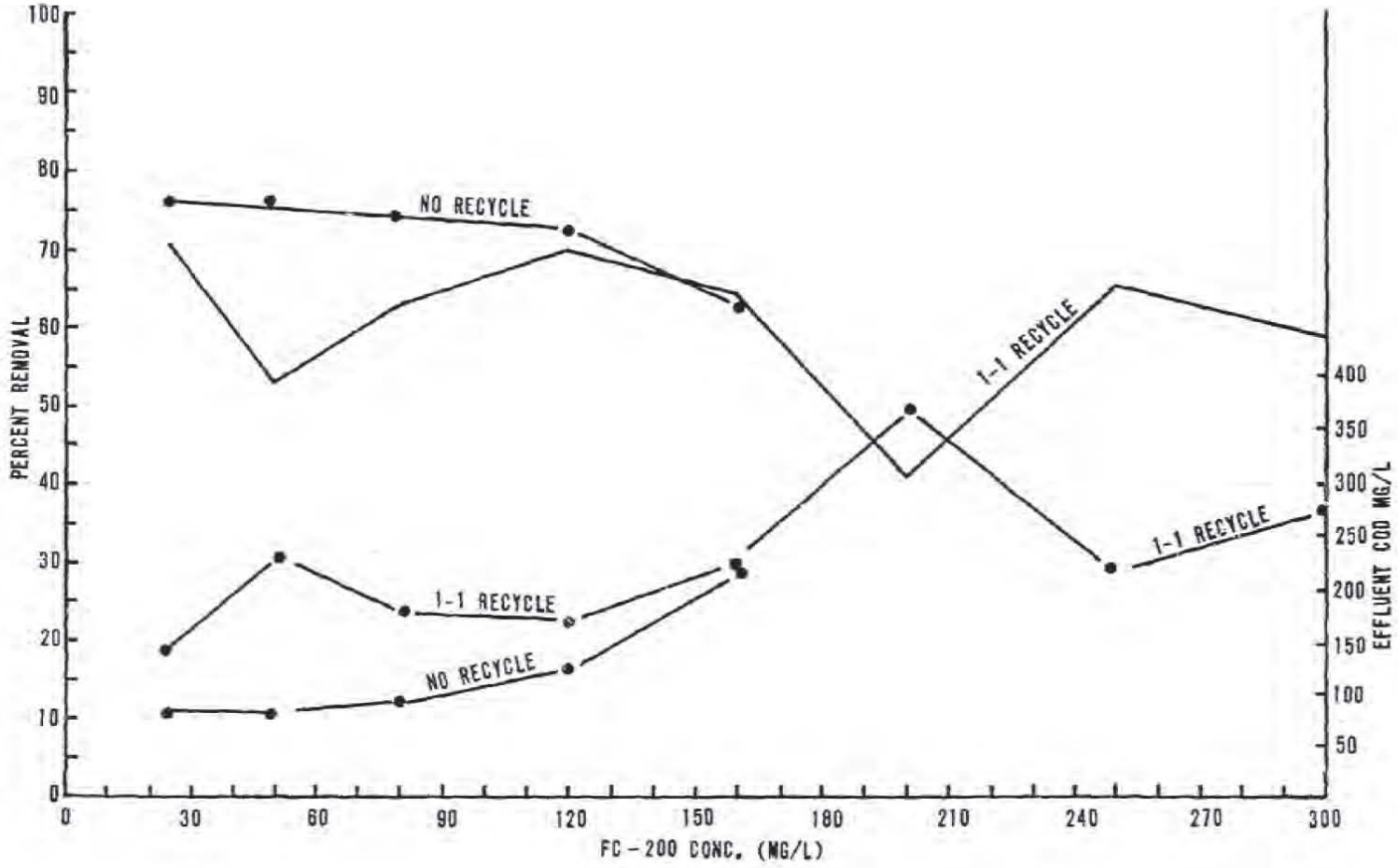

Figure 25. Percent COD Removal and Effluent COD versus Influent FC-200 Concentration, Trickling Filter

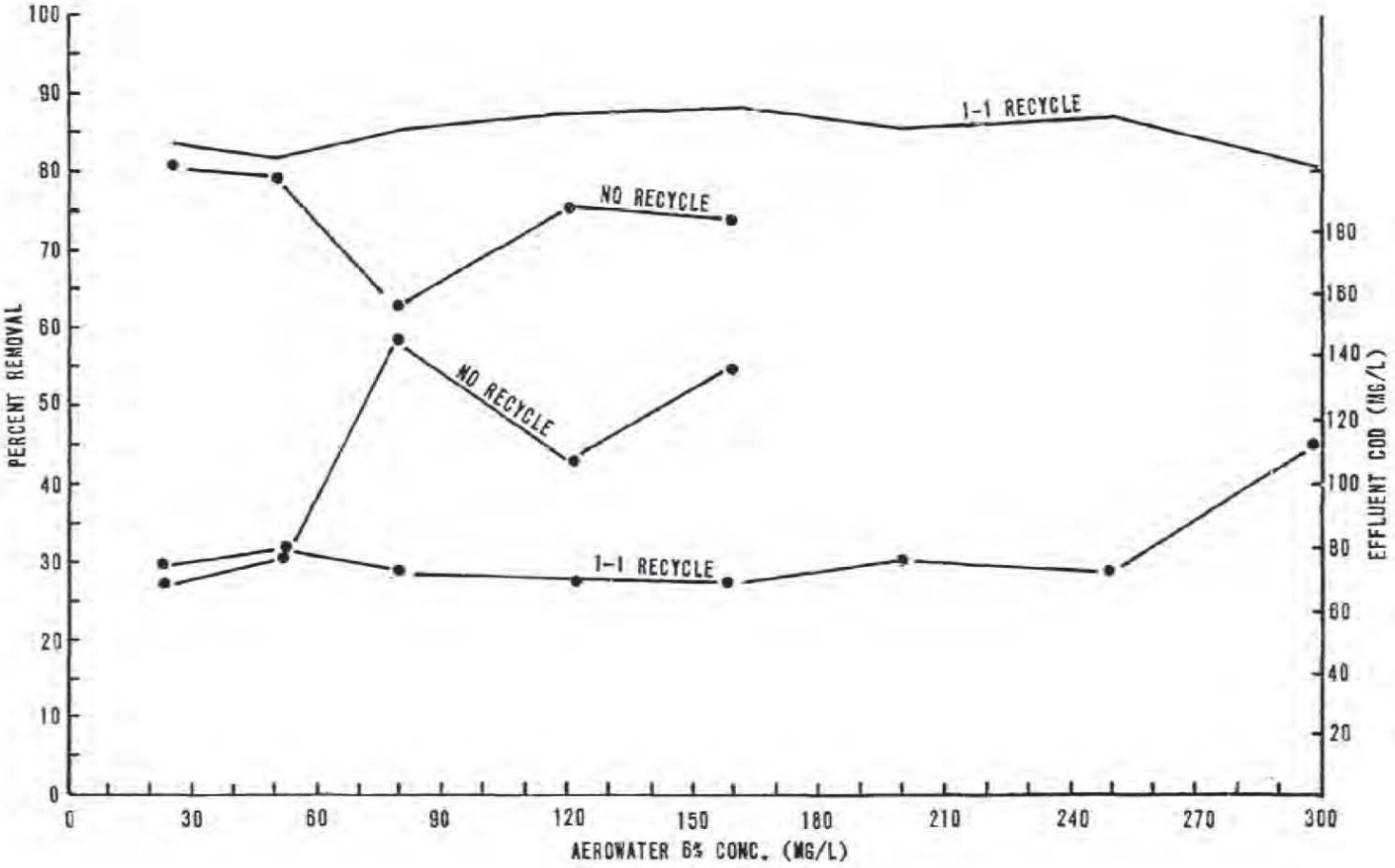

Figure 26. Percent COD Removal and Effluent COD versus Influent Aerowater 6 Percent Concentration, Trickling Filter

Table VIII

TOXICITY OF AFFF TO RAINBOW TROUT*

Condition	Time 24 hr	48 hr	72 hr	96 hr
Effluent control	0	0	0	0
Effluent Aerowater 3 percent	0	0	0	0
Effluent Aerowater 6 percent	0	0	0	0
Effluent FC-200	4	---	---	---
Effluent FC-200 (repeat)	1	2	4	---
Influent control (synthetic wastewater)	2	2	4	---
Influent Aerowater 3 percent	1	4	---	---
Influent Aerowater 6 percent	1	4	---	---
Influent FC-200	1	4	---	---
Distilled water	1	2	2	4
Distilled water and Aerowater 3 percent	1	1	2	4
Distilled water and Aerowater 6 percent	1	2	4	---
Distilled water and FC-200	2	2	4	---

*Starting with four trout per tank, number given is the cumulative number dead.

The data show that there is definite detoxification occurring by biological treatment for Aerowater 3 percent and Aerowater 6 percent. For FC-200 biological treatment does not appear to offer significant detoxification. However, one must be cautioned not to accept this as conclusive data since it represents only one test at one AFFF concentration. Further, the concentration of AFFF used is higher than that recommended (see Conclusions, section VI) for discharge into a sanitary sewer.

6. ADSORPTION EXPERIMENTS

The 2000-mg/l solutions of FC-200 and Aerowater 6 percent yielded CODs as indicated below (the average of triplicate analysis):

FC-200	1500 mg/l
FC-200 after JP-4	1433 mg/l
Aerowater 6 percent	944 mg/l
Aerowater 6 percent after JP-4	992 mg/l

JP-4 added to distilled water (20 ml in 2 liters), then separated, yielded a COD of approximately 100 mg/l in the aqueous phase. This indicates that some of the compounds in JP-4 are at least slightly soluble in water. Coupling this fact with the COD data for the four solutions reveals that there was a decrease in COD of the FC-200 solution that was contacted with JP-4, although approximately 100 mg/l of COD was added from the JP-4. This indicates that a significant fraction of FC-200 is extracted into the JP-4 phase. This fraction is estimated to be approximately

$$\frac{1500 + 100 - 1433}{1500 + 100} = 10 \text{ percent}$$

Conversely for Aerowater 6 percent there is a 48-mg/l increase in COD after contact with JP-4. This indicates that a much smaller fraction of Aerowater 6 percent is taken up in the JP-4 phase.

The results of the batch adsorption experiments are given in figures 27 through 30. The notation used is X = wt of COD adsorbed = initial COD concentration C_0 - final COD concentration C_F x volume, M = wt of activated carbon

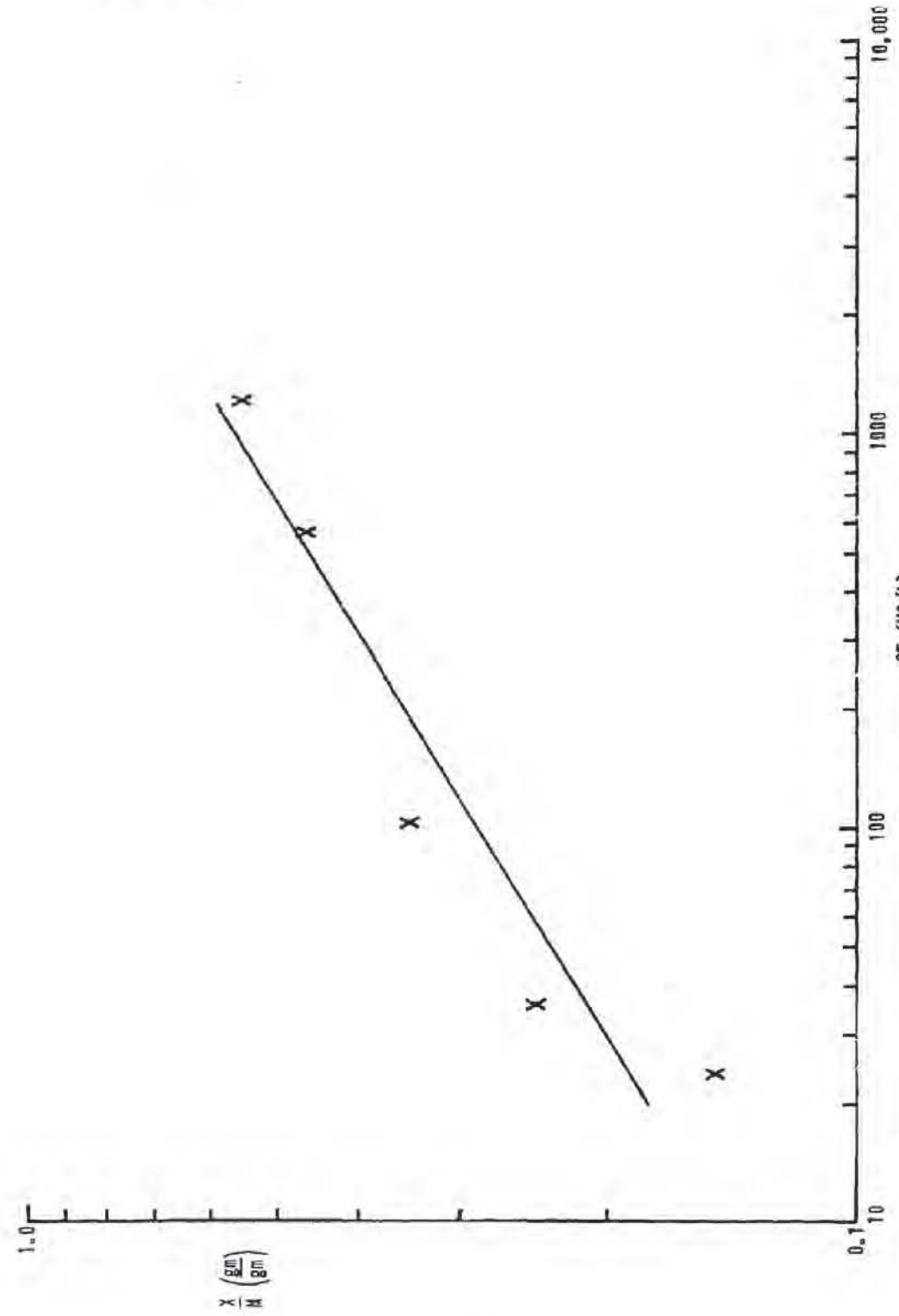

Figure 27. Batch Adsorption Isotherm, FC-200 (No JP-4)

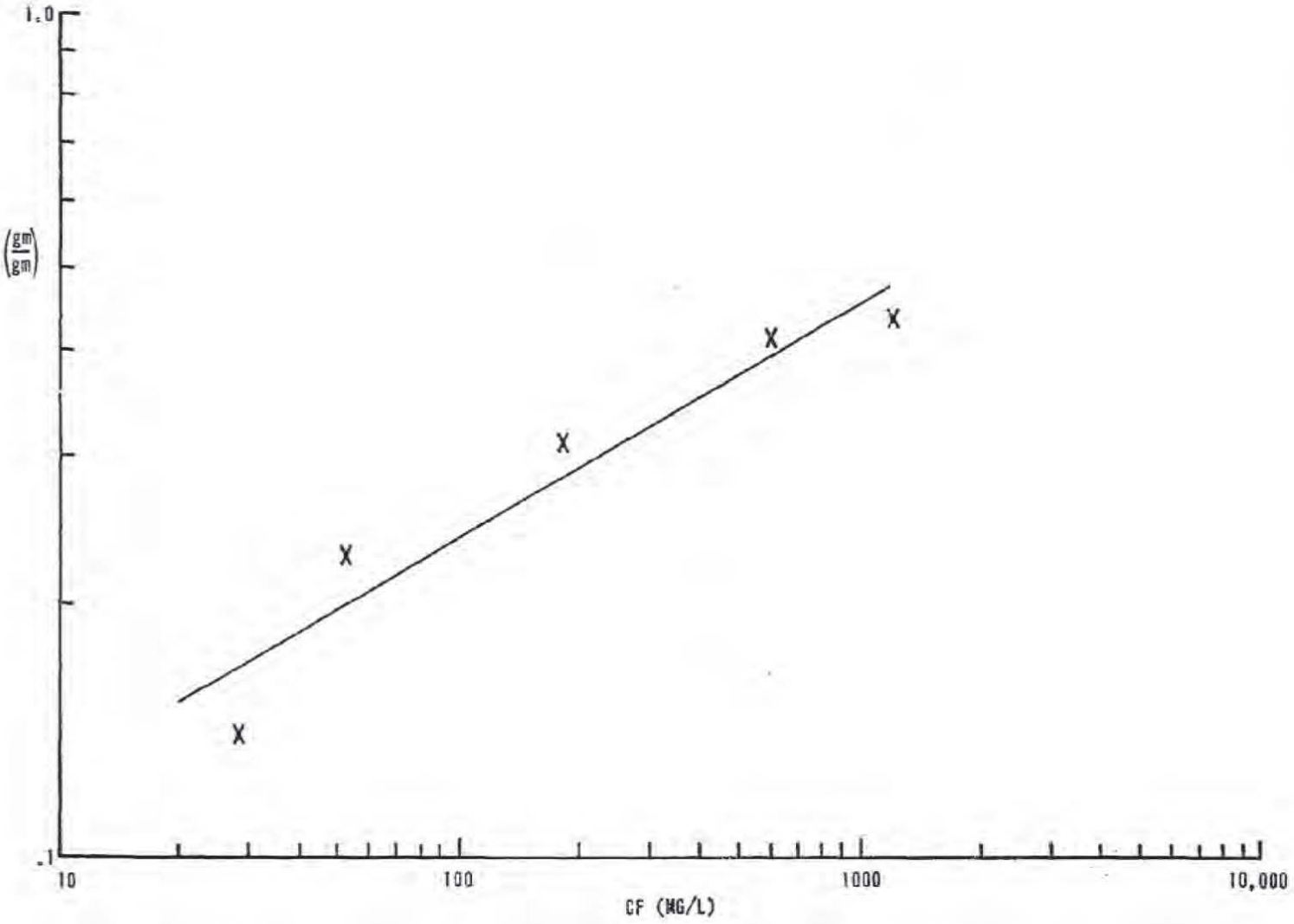

Figure 28. Batch Adsorption Isotherm, FC-200 (After JP-4 Extraction)

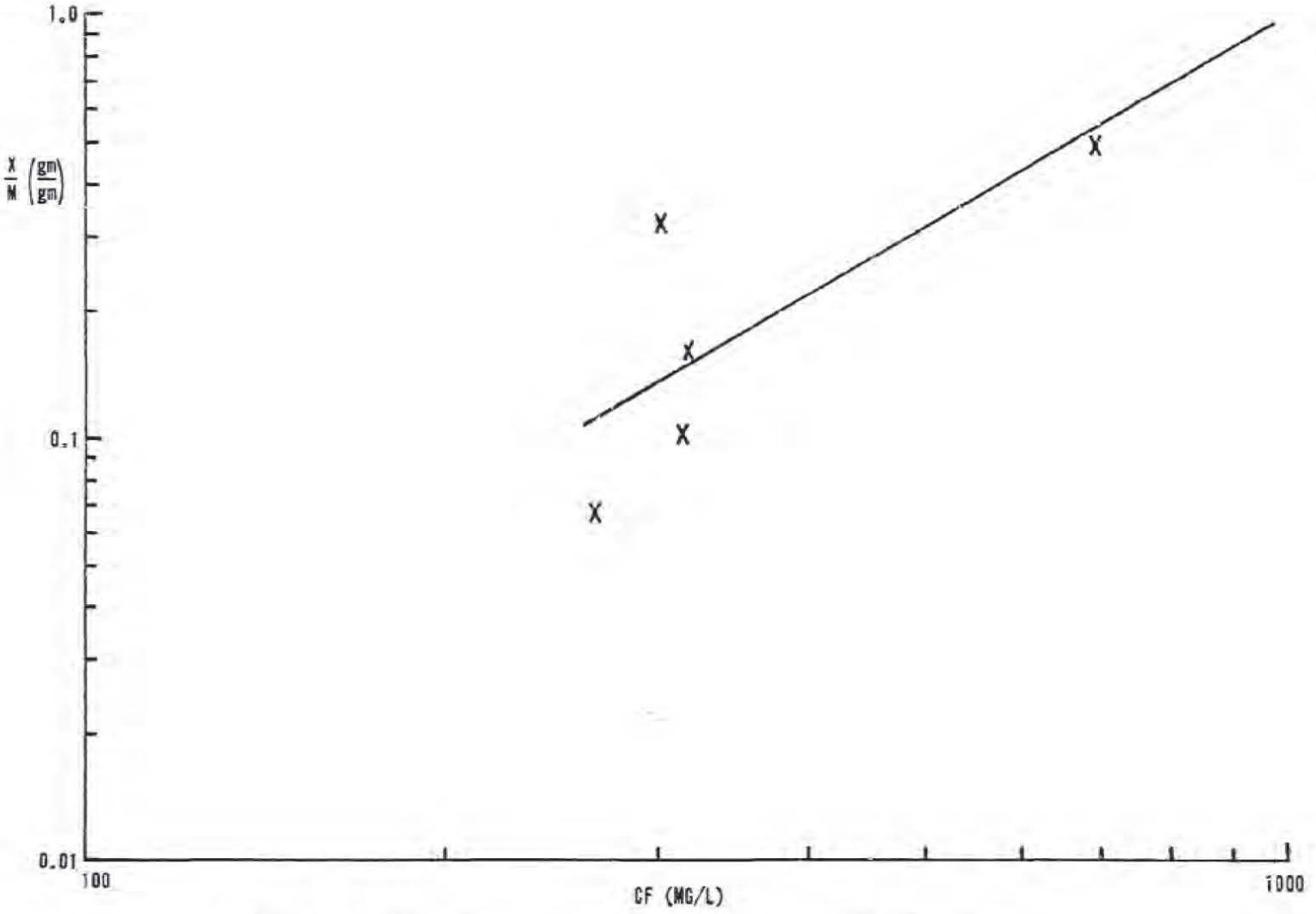

Figure 29. Batch Adsorption Isotherm, Aerowater 6 Percent (No JP-4)

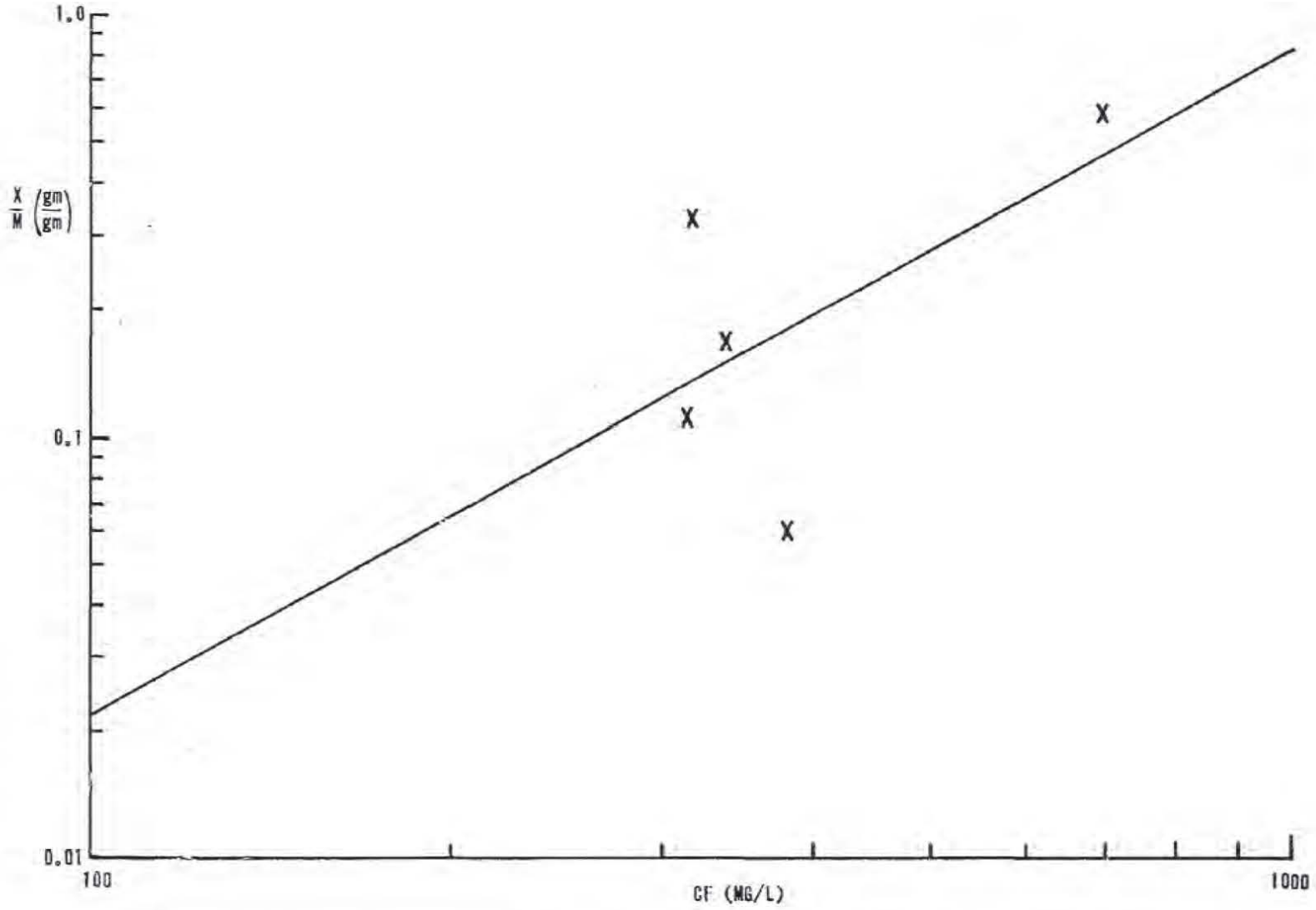

Figure 30. Batch Adsorption Isotherm, Aerowater 6 Percent (After JP-4 Extraction)

used, and C_F = final COD concentration = COD remaining in solution. X/M then becomes the carbon loading, also taken to be a good approximation of the adsorptive capacity.

Comparing figures 27 and 28, it is seen that the carbon loading is slightly lower for the FC-200 solution that was contacted with JP-4. X/M at C_F of 1500 mg/l = 0.6 for the FC-200 solution and equals 0.5 for the FC-200 solution contacted with JP-4. This difference is attributed to the presence of different organic compounds in the solution after JP-4 contact.

For Aerowater 6 percent one cannot make any comparisons because the batch adsorption data did not obey the Freundlich isotherm properties. A straight line is constructed through the data points in figures 29 and 30 using a least-squares fit. However, no validity is placed on this line. The data points do indicate the presence of a nonadsorbable component in the Aerowater 6 percent, comprising approximately 300 mg/l of COD. This is further substantiated in the continuous-flow experiments.

Assuming that some JP-4/water separator would be provided in a fire-training facility and therefore no JP-4 would contact the activated carbon, one can conclude from the batch data (at least for FC-200) that a somewhat reduced carbon loading (adsorptive capacity) will result from the interaction of the AFFF and the JP-4.

The results of the continuous-flow experiments are given in figure 31 for FC-200 and in figure 32 for Aerowater 6 percent. Only the pure solutions were used for the continuous-flow experiments. The breakthrough curves in figure 31 for the two sampling ports and the final discharge are very good with the slope of the breakthrough portion being relatively moderate. With respect to contact time until breakthrough, essentially all the FC-200 has been adsorbed by the time the water reaches the first sampling port (5 minutes contact time).

Being conservative and saying that the activated carbon is completely exhausted at the bottom of the breakthrough curve (approximately 360 minutes for port 1 and 1200 minutes for port 2), the adsorptive capacity for FC-200 is calculated to be 0.34 gm COD removed/gm of activated carbon. In terms of the FC-200, this is equivalent to 0.49 gm FC-200 removed/gm of activated carbon; or in terms of liquid volume, 0.48 ml FC-200 removed/gm of activated carbon (0.058 gal/lb). Expressed another way, for every gallon of FC-200 concentrate used, approximately 17 pounds of activated carbon would be required.

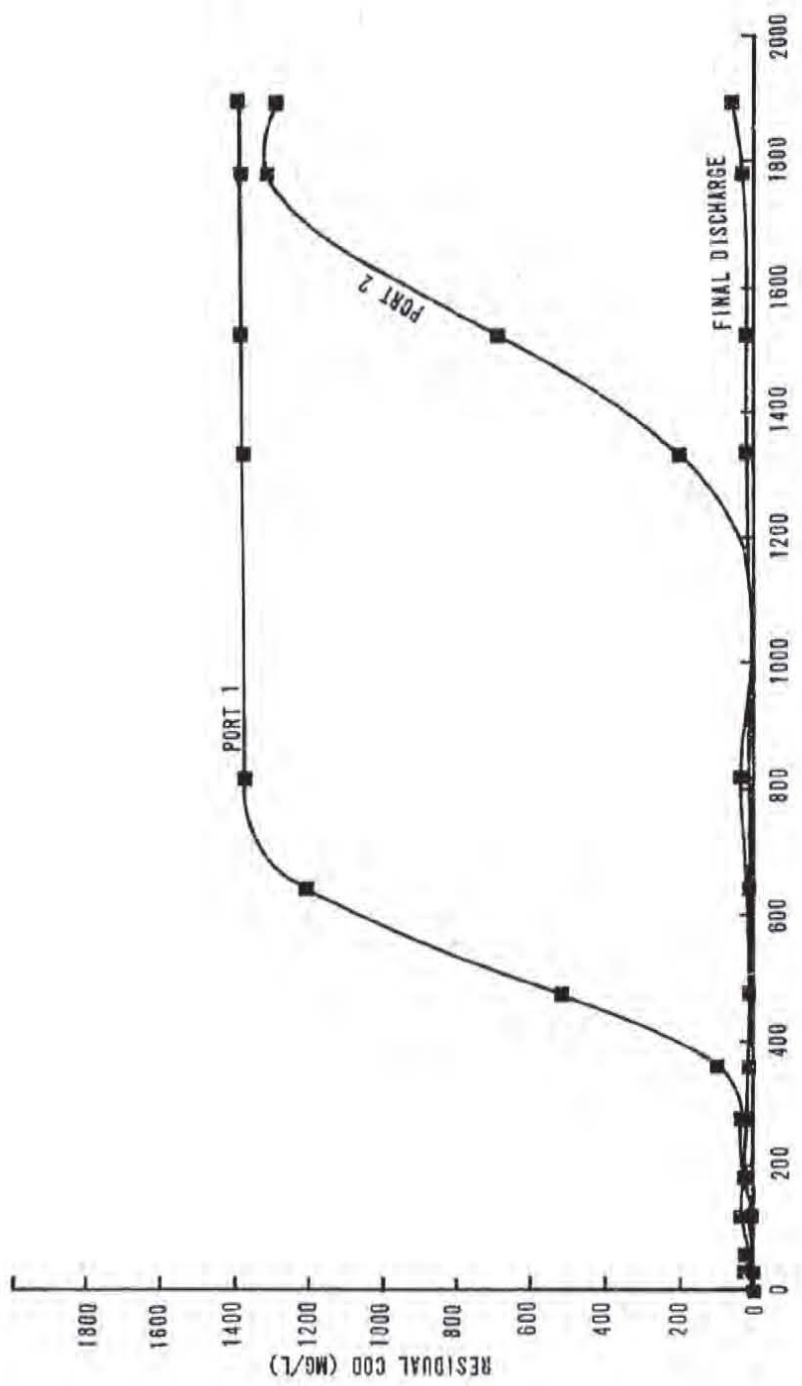

Figure 31. Breakthrough Curves, FC-200

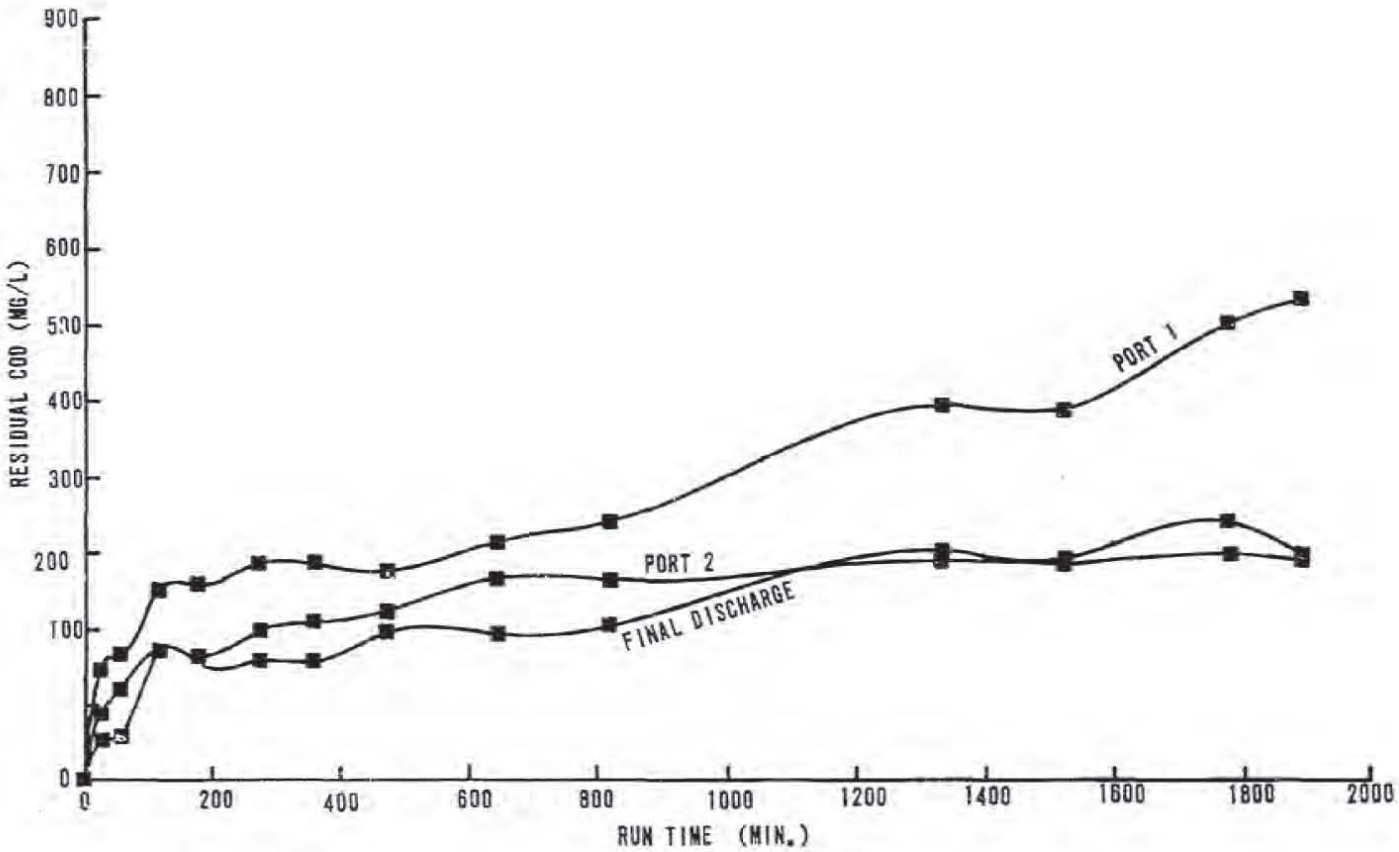

Figure 32. Breakthrough Curves, Aerowater 6 Percent

Recall that this is based on a conservative estimate of the adsorbed capacity and is for a 2000-mg/l solution of FC-200. If a more concentrated solution is processed, generally one can expect a higher adsorptive capacity since higher organic concentrations usually result in the activated carbon being relatively more saturated at exhaustion.

For Aerowater 6 percent it is seen in figure 32 that the breakthrough curves are not typical, and therefore it is not possible to calculate a realistic adsorptive capacity. This is due to a nonadsorbable fraction which accounts for 200 to 300 mg/l of COD. Therefore, virgin activated carbon is capable only of removing approximately 75 percent of the COD. A much longer contact time would further reduce the COD in the discharge, but not significantly, as evidenced by the difference in COD between the sampling ports at any given time. It is assumed that the nonadsorbable fraction is the foam stabilizer since this is likely to be a glycol compound which would be relatively polar and possibly of low molecular weight. Both properties would result in low affinity for being adsorbed or activated carbon. If this assumption is correct, the discharge of the water after activated carbon adsorption would likely be acceptable since glycol-type compounds are generally of low toxicity to aquatic life. On the other hand, the discharge at 200 to 300 mg/l of COD representing glycol compounds would pose a high oxygen demand since the glycol compounds are largely biodegradable.

SECTION V

DISCUSSION

1. BIODEGRADATION AND TOXICITY EXPERIMENTS

The results of the biodegradability experiments yielded much information as summarized below. First, it appears that it would be very difficult to acclimate a biological culture to degrade AFFFs when they represented the only source of organic matter. Second, the three AFFFs tested yielded for practical purposes the same degree of treatability when blended with a synthetic wastewater. Although the data tended to demonstrate that the biological waste treatment processes could assimilate higher concentrations of Aerowater 3 and 6 percent than FC-200, one would have to retest to verify this conclusively. Third, while AFFF dosages as high as 250 mg/l were capable of being treated, this was under laboratory conditions with a constant composition of influent wastewater; therefore a conservative maximum concentration of 80 to 100 mg/l is recommended. Since slug loading to unacclimated bacteria caused excessive foaming and impaired reactor performance, it appears obvious that bleeding in the AFFF at a controlled rate (not to exceed 50 mg/l initially and building up to 100 mg/l maximum) is a necessity. This would obviously require holding capabilities and some means of controlling the release to the sanitary sewer. Knowing the wastewater flow at the sewage treatment plant, one can easily calculate a release rate once the quantity of AFFF used is known.

Concerning the detoxification provided by biological waste treatment, the rudimentary experiments performed tend to indicate detoxification of Aerowater 3 percent and 6 percent, but not for FC-200. However, these experiments were too brief to draw a definite conclusion. It should be remembered that these toxicity experiments were conducted at influent AFFF concentrations of 200 mg/l; whereas it is recommended that the AFFF concentration not exceed 100 mg/l in the influent wastewater.

Since a good analytical method was not developed to follow the biodegradation, if any, of the AFFFs, one can only surmise what is happening to the major components, the fluorocarbon surfactant, and the foam stabilizer. The foam stabilizer, which is assumed to be some type of polyethylene glycol or glycol

ether, should be fairly biodegradable and should not pose any problems to either the treatment plant or the receiving stream. The fluorocarbon surfactant, on the other hand, is at best only partially biodegradable. The microorganisms can probably break down the fluorocarbon surfactant into smaller chain-length compounds and potentially oxidize the surfactant portion completely. The fraction of compound containing the fluorocarbon bonds will almost undoubtedly not oxidize. This was substantiated in the beginning of the activated sludge experiments where it was observed that no increase in free fluoride concentration was occurring in the treated effluent. It is possible that if the microorganisms were able to break the original compound to a compound containing only F, C, and H that the solubility in water would be significantly reduced so that it would tend to separate or be readily adsorbed onto a solid surface such as the microorganisms. How these assumptions and hypotheses fit in with detoxification of the AFFFs cannot be answered since the exact composition of each AFFF is not known.

2. ACTIVATED CARBON EXPERIMENTS

The results of the activated carbon adsorption experiments demonstrate a definite affinity of the AFFFs (particularly FC-200) for being adsorbed on activated carbon. Essentially, complete removal of the FC-200, as measured by COD, was achieved within 5 minutes of contact time. For the Aerowater 6 percent only partial removal (70 to 75 percent) of the COD was achieved. Increasing the contact time beyond 20 minutes would not yield appreciable increase in the COD removal. Why FC-200 was completely removed by activated carbon and the Aerowater 6 percent only partially removed is easily explained by the fact that they are different formulations and, although likely to be similar in composition, the differences in the compounds used readily account for adsorption of FC-200 and partial adsorption of Aerowater 6 percent.

The use of activated carbon for treating AFFFs would be preferred for the small-proficiency fire-training facilities where it is not feasible to tie into a sanitary sewer. Assuming a smoke-abatement system would be in use, all that would be required is a small holding facility to allow the JP-4 carryover to separate and a pump to lift the water to the top of an activated carbon column. The column can be constructed of any convenient plastic pipe. Plastic, PVC, polyethylene, etc., is necessary because granular activated carbon is very corrosive. It is envisioned that the column would be about 15 inches in diameter and about 10 feet in height. The actual size would have to be

determined for each fire-training facility. The top could be opened to the atmosphere for easy filling and withdrawal of the activated carbon. The bottom should be closed with the discharge regulated to keep the column flooded during operation. Since it is not expected to use more than a few hundred pounds of activated carbon per month, the exhausted activated carbon should be thrown away, accumulated in Remarketing and Distribution for potential resale, or mixed with coal (assuming coal is used on base for heating). By keeping a log on the number of gallons of FC-200 used, one can calculate the frequency of replacing the activated carbon by using the adsorptive capacity which conservatively, for FC-200, is 1 gallon FC-200 adsorbed per 17 pounds of activated carbon.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. Biodegradation of AFFFs when they represent the only source of organic matter is not practical.

2. Discharge of AFFFs into sanitary sewers where physically practical should be done, but at a controlled rate so as not to exceed 100 mg/l of AFFF influent to the biological treatment plant. It does not appear that either activated sludge or tricking filter processes offer an advance over the other. The discharge rate should be set initially so as not to exceed, say, 50 mg/l of AFFF influent to the biological treatment plant to permit time for acclimation of the microorganisms. Slug loading should definitely be avoided. If practical, it is recommended that the AFFF be continuously discharged, which would result in the lowest concentration in the domestic wastewater.

3. From the aspect of biological treatability one cannot conclude decisively that any of the three AFFFs tested is more amenable to biological treatment than the others. Rather it is concluded that all three can be satisfactorily discharged into a sanitary sewer when the AFFF concentration does not exceed 100 mg/l (see conclusion 4).

4. Detoxification (lack of acute toxicity) of the AFFFs by biological treatment at 200 mg/l of AFFF appears to be achieved for the Aerowater products but not for FC-200. However, because of the rudimentary techniques employed, this cannot be taken as a firm conclusion. Long-term and precise bioassay tests should be conducted on each AFFF.

5. For small fire-training facilities using water spray-injection smoke-abatement systems where it is impractical to tie into a sanitary sewer, activated carbon adsorption should be employed before discharging the water containing AFFF.

REFERENCES

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