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MICROBIAL TREATABILITY OF AQUEOUS FILM FORMING FOAM (AFFF) WITH A CHEMOSTAT AND A ROTATING BIOLOGICAL CONTACTOR

The University of Oklahoma PH.D. 1982

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MICROBIAL TREATABILITY OF AQUEOUS FILM FORMING FOAM (AFFF) WITH A CHEMOSTAT AND A ROTATING BIOLOGICAL CONTACTOR

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

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BY

SUSAN ELIZABETH LANDON-ARNOLD

Norman, Oklahoma

1982

MICROBIAL TREATABILITY OF AQUEOUS FILM FORMING FOAM (AFFF)

WITH A CHEMOSTAT AND A ROTATING BIOLOGICAL CONTACTOR

APPROVED BY

DISSERTATION COMMITTEE

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CHAPTER I

AQUEOUS FILM FORMING FOAM (AFFF)

The threat of damage and death due to shipboard and land-based fires is an ever present menace to Naval personnel.

> More than 1,000 shipboard fires have been reported to the Naval Safety Center since 1969. Major losses during this period have included the 1975 USS KENNEDY/USS BELKNAP collision and fire ($213M, 8 dead); 1972 USS NEWPORT NEWS ($6.5M, 21 dead); 1973 USS FORCE (total loss); 1973 USS KITTYHAWK ($1M, 6 dead); 1972 USS FORRESTAL ($20M); 1967 USS ENTERPRISE ($5M, 27 dead); and USS ORISKANY ($10M, 43 dead). The Naval Safety Center reported 106 accidents involving property damage from fires in machinery spaces aboard surface ships. The costs totaled $5.8M and 36 dead (Bass, 1980).

Training of skilled firefighting personnel has become a priority with the Navy. The technology employed in the equipment and chemicals used in firefighting has steadily advanced. Many firefighting formulations have been evaluated for efficiency and safety. Most shipboard fires are due to ignited fuel and fuel spillage. Because fuel floats on water, the use of water on a fuel fire would spread flaming fuel. However, by generating and applying a foam, a fuel fire would be smothered into extinguishment. Protein foam and detergent-based foams accomplish this. Foams such as these spread over a fire and also prevent the escape of volatile vapors. However, these foams are fragile and the foam blanket is easily broken by firefighters as they walk and drag

hoses through the just extinguished area. This could result in reflash and burn back due to escaping volatile gases which would ignite. Injury to firefighting personnel can occur (3M, 1978).

Development of an aqueous film forming foam (AFFF), or "light water" as it was originally called, occurred in the mid-1960s. Since that time it has almost completely replaced protein and detergent foams. AFFF extinguishes fires faster than protein and/or detergent foams, so less firefighting agent is used in training exercises and actual fires. It has the advantage of producing a more rugged vapor sealing foam (Taylor, 1977). This is accomplished via an aqueous solution which drains from the foam bubbles and forms a film. This film, floating on the water surface, suppresses volatile vapors. AFFF possesses the ability to reform the film around any object that may disturb or break the film (i.e., a foot or hose). This "self-healing" property prevents reflash. AFFF will also spread across nonignited areas, preventing possible ignition. This is a property desirable for situations where there is limited or no access, such as a storm sewer. Also, due to AFFF's low surface tension, it is highly successful for treating fires involving rubber materials and Class A material. Table 1 shows a comparison of agent usage and relative cost (3M, 1978).

AFFF is a proprietary product, so the exact chemical composition is unknown to the lay person. However, according to an early U.S. patent (#3,258,423), the general composition is a fluorine-containing alphatic surfactant, a fluorine-free surfactant, polyoxyethylene glycol, and water (3M, 1971). As can be seen in Appendix A, AFFF is manufactured to fit specific functional requirements and not a specific chemical composition (U.S. Department of Defense, 1977), which can vary.

Table 1. Extinguishment Comparison of Firefighting Foams[a,b]

Item	Detergent Foam	Protein Foam	AFFF
Preburn, sec	40	40	40
Flow rate, gpm	180	100	100
Extinguishment, sec	120	130	40
Solution used (concentrate & H_2O), gal	360	217	67
Concentrate cost (approx), $	72.00	58.50	40.80

[a]Adapted from original table. Minnesota Mining and Manufacturing Company (1978). Fire Protection Systems, 3M Center, St. Paul.

[b]Tests were conducted on a 1,000-ft^2 area containing 400 gal of JP-5 fuel ignited.

One of the earliest AFFF formulations was FC 199, which was manufactured by 3M. It was considered undesirable due to the acidic nature of the compound. Since then, many AFFF formulations have been used (Table 2), the most current being FC 780.

The Navy has used AFFF on shipboard and in firefighting training exercises since the 1940s. All firefighting equipment installed on ships must be tested using AFFF semi-annually. When a ship is in unrestricted waters, testing can be done and wastewater discharged directly into the aquatic environment. When testing is done on the ship in port, the AFFF-laden wastewater cannot be discharged into the harbor because AFFF may pose a toxicity problem to the marine ecosystem (Taylor, 1977). Therefore, AFFF-laden wastewater is collected and stored in containers, such as drums, tanks, sludge barges, and closed-bottom donuts, or discharged into bilge (Bass, 1980). The collected waste must

Table 2. Comparison of Various Parameters of Aqueous Film Forming Foam (AFFF)

Parameter	3M Light Water			National Foam Systems			Ansul Co.
	FC 199	FC 200	FC 206	FC 780	AOW3	AOW6	K74-100
pH	4.6	7.6	7.8	7.5-8.5	7.8	7.9	7.9
Specific Gravity	1.02	0.989	1.020	1.010	1.062	1.031	1.015
COD, mg/l	550,000	730,000	500,000	450,000	500,000	350,000	210,000
TOC, mg/l		235,000	117,000	110,000	130,000	100,000	44,000
BOD_u, mg/l	303,000	450,000	411,000	330,000	354,000	300,000	159,000
BOD_5, mg/l	6,660	9,000	26,715	20,000	15,930	13,500	54,060
% H_2O		59	70	75	72	72	92
% Butyl Carbitol	1	39	27	20	10	10	

then be stored until appropriate disposal measures can be taken. Table 3 lists the estimated yearly quantity of AFFF generated aboard ships in port (Taylor, 1977). However, 90% of AFFF waste generated at Naval installations occurs in ten locations: San Diego, CA; Long Beach, CA; Alameda, CA; Honolulu, HI; Philadelphia, PA; Mayport, FL; Charleston, SC; Norfolk, VA; and Bremerton, WA (Taylor, 1977).

Table 3. Estimated Yearly Quantity of AFFF Generated Aboard Ships in Port Based Upon 90 Gal (0.34 m^3) of 6% Mixture Per Test Once Every Three Years and CY75 Shipyard Generation Estimates[a]

U.S. Navy Port Listing	Rank[b]	Estimated Gal (m^3) of 6% AFFF Generated		Estimated Total Gal (m^3) of AFFF Concentrate Discharged Per Year
		Port	Shipyard	
Alameda, CA	10	660 (2.47)		40 (0.15)
Baltimore, MD		120 (0.45)		7.2 (0.03)
Bayonne, NJ		120 (0.45)		7.2 (0.03)
Bronx, NY		120 (0.45)		7.2 (0.03)[c]
Bremerton, WA	9	540 (2.02)	400 (1.51)	56.4 (0.21)[c]
Brooklyn, NY		120 (0.45)		7.2 (0.03)[d]
Charleston, SC	3	3,690 (13.84)	225 (0.85)	221.4 (0.84)[d]
Concord, CA		240 (0.90)		14 (0.05)
Groton, CT		30 (0.11)		1.8 (0.01)
Fall River, MA		60 (0.22)		3.6 (0.02)
Galveston, TX		120 (0.45)		7.2 (0.03)
Pensacola, FL		180 (0.67)		11 (0.04)
Portland, ME		120 (0.45)		7.2 (0.03)
Little Creek, VA	7	1,950 (7.31)		117.0 (0.44)[d]
Long Beach, CA	8	1,560 (5.85)	1,100 (4.16)	93.6 (0.35)[d]
Mayport, FL	6	2,640 (9.90)		158.4 (0.60)
New London, CT		180 (0.67)		10.8 (0.04)
New Orleans, LA		120 (0.45)		7.2 (0.03)
New York, NY		240 (0.91)		14 (0.05)
Newport, RI		540 (2.04)		32 (0.12)[d]
Norfolk, VA	2	7,770 (29.41)	8,000 (30.28)	466.2 (1.76)[d]
Panama City, FL		60 (0.23)		3.6 (0.01)[d]
Pearl Harbor, HI	4	3,360 (12.72)		201.6 (0.76)[d]
Perth Amboy, NJ		120 (0.45)		7.2 (0.03)[c]
Philadelphia, PA	5	1,260 (4.77)	1,500 (5.68)	165.6 (0.63)[c]
Portland, OR		300 (1.14)		16 (0.07)

continued

Table 3. Continued

U.S. Navy Port Listing	Rank[b]	Estimated Gal (m^3) of 6% AFFF Generated		Estimated Total Gal (m^3) of AFFF Concentrate Discharged Per Year
		Port	Shipyard	
Portsmouth, NH	1	60 (0.23)		3.6 (0.02)
Tampa, FL		120 (0.45)		7.2 (0.03)
San Diego, CA		9,480 (35.88)		568.8 (2.12)
San Francisco, CA		540 (2.04)		32 (0.12)
Seattle, WA		360 (1.36)		22 (0.08)
St. Petersburg, FL		120 (0.45)		7.2 (0.03)
Tacoma, WA		180 (0.68)		11 (0.04)

[a]Adapted from original table. D. W. Taylor (1977) in Discharging aqueous film forming foam to harbor waters during tests of machinery space firefighting foam systems aboard U.S. Navy ships, Naval Ship Research and Development Center for Naval Sea Systems Command.

[b]Ranked by estimated quantity of AFFF generated per year during testing.

[c]Includes AFFF generated by shipyard tests; no alternate disposal procedure.

[d]Excludes AFFF generated by shipyard tests; alternate disposal procedure practiced.

The Navy has a total of 176 firefighting training facilities (Chan, 1978b). These firefighting facilities use from 20 to 125 gallons per week of AFFF concentrate. Each firefighting exercise may generate 2,000 to 50,000 gallons of AFFF-containing wastewater (Bass, 1980). In summary, the Navy as a whole produces 125 million gallons of AFFF-containing wastewater yearly, which is approximately one-half of the total amount of wastewater produced within the Department of Defense (Chan, 1978a).

Wastewater containing AFFF poses a disposal problem. In 1972, the Federal Water Pollution Control Act (FWPCA-PL92-500) set milestones, two of which were: (1) the elimination of pollutants into navigable

water by 1985, and (2) the prohibition of the discharge of toxic pollutants in toxic amounts (Bass, 1980). The National Pollutant Discharge Elimination System (NPDES) permit requirements have been established in association with the Environmental Protection Agency (EPA). Discharges, by the Navy, to local waters and wastewater treatment facilities must meet permit requirements with respect to oil concentration, and it is expected that standards will be set concerning AFFF-laden wastewater since AFFF has proven toxic to aquatic environments (Bass, 1980). How toxic AFFF is to the actual aquatic environment is unknown. However, the toxicity of AFFF to aquatic marine organisms has been studied since the early 1970s. Research by LeFebvre and Inman (1974) noted that in studies using Pimephales promelas (fathead minnows), FC 199 had a 96-hour LC_{50} of 398 mg $liter^{-1}$, oxygen uptake of certain activated sludge microorganisms was inhibited at 2,500 mg $liter^{-1}$, and nitrification was inhibited at 500 mg $liter^{-1}$. 3M (1975) presented information concerning their product, FC-203, and its effect on the following: P. promelas/static 96-hour LC_{50} of 1,900 mg $liter^{-1}$, Salmo gairdneri (rainbow trout)/static 96-hour LC_{50} of 1,300 mg $liter^{-1}$, Daphnia magna (water flea)/static 48-hour LC_{50} of 5,850 mg $liter^{-1}$, Gammarus faseratus (Scud)/static 48-hour LC_{50} of 1,100 mg $liter^{-1}$, Chlorella pyrenaides, and Phormidum unundalum, no growth at dilutions less than 1:1000. In 1976 (3M, 1976) and 1979 (3M, 1979), 3M presented similar information about FC 206 (i.e., P. promelas/continuous flow 96-hour LC_{50} of 3,000 mg $liter^{-1}$ and a static 96-hour LC_{50} of 1,500 mg $liter^{-1}$, S. gairdneri/static 96-hour LC_{50} of 1,800 mg $liter^{-1}$, D. magna/static 48-hour LC_{50} of 5,850 mg $liter^{-1}$, G. faseratus/static 48-hour LC_{50} of 5,170 mg $liter^{-1}$, Palaemontetes

vulgares (grass shrimp)/static 96-hour LC_{50} of 280 mg liter^{-1}, and Crossostrea virginica (Atlantic oyster larvae)/static 96-hour LC_{50} of >100 and <240 mg liter^{-1}. This formulation of AFFF appeared to have a lessened toxicity effect against chosen indicator species. The most recent data, presented by Laughlin, Guard, Heckly, Quay, and Coleman (1980), concerning Rhithropanopeus harrisii (mud crab larvae) stated that AFFF was acutely toxic, causing 100% mortality of the larvae within 24 hours, with 1% FC 206 (i.e., 10,000 mg liter^{-1}). Actual firefighting school wastewater was tested and found to cause 100% mortality of Crassostrea virginica (eastern oyster) embryos when diluted 1:100 (E.G.&G. Bionomics, 1978). If wastewater contains 3% AFFF, which is a Naval Civil Engineering Laboratory estimate, then a dilution of 1:100 would be 3,000 ppm volume to volume or 600 mg liter^{-1} COD. These experimental data show toxicity to a variety of freshwater and marine organisms. The effect of chronic exposure to AFFF on aquatic life is not known. Possible bioaccumulation in plants and animals could occur and not be recognized for a long period of time.

A standard test employed in firefighting training is field exercises involving extinguishment using a 6% solution of AFFF on large oil fires which are burned on the surface of water pools or pans. Because appreciable amounts of residual AFFF foam inhibits reignition of test oil fires, a complete purge of the oil layer after each fire, either by skimming the burn tank or by dumping the entire tank contents, takes place (Engineering Science Inc., 1976). Wastewater generated thusly contains fuel oil, gasoline, AFFF, PKP (if used), and miscellaneous

combustion products. Since discharge to the aquatic environment without some sort of treatment is not a possibility, release to a sanitation system may be a means of handling such waste.

It has been noted since the onset of AFFF usage that the BOD (biochemical oxygen demand) is very high, approximately 85% of the COD (chemical oxygen demand), indicating the ability for AFFF to be theoretically 85% oxidized biochemically. Prior to 1972, the 3M Company (Kroop and Martin, 1974) pursued this possibility by conducting experimentation on a lab scale: continuous flow, activated sludge reactor. FC 200 was the only source of organic carbon available to the unit. Their inoculum was from an activated sludge plant used in the treatment of industrial waste, which included "light water" waste. At an organic loading of 175 mg liter^{-1} COD, 85% removal occurred; however, a load greater than this caused a sharp decrease in the removal efficiency. An interesting note here was that both influent (i.e., untreated) and effluent (i.e., treated) wastewater exhibited a 96-hour LC_{50} of 8 mg liter^{-1}. This insinuates that toxicity of the AFFF was not a function of the components removed or else an equally toxic product was created as a result of treatment.

Table 4 lists the major research concerning biological treatment of AFFF since 1972. Kroop and Martin (1974) conducted work on laboratory scale: oxidation ponds, trickling filter, and a continuous-flow, completely mixed, activated sludge reactor. Of the three, the lab-scale activated sludge reactor gave the most positive result, though contradictory to previous results obtained by the 3M Company. They used a synthetic sewage containing protein, dry milk and sucrose to achieve a

Table 4. Summary of Research on the Biological Treatment of AFFF

Researcher	Year	Treatment	Concentration		AFFF Type	% Removal	Comments
			ppm V/V	mg/l COD			
3M Co.	prior to 1972	lab-scale activated sludge	250	175	FC 200	85	No greater than 250 V/V or % removal decreases
Kroop and Martin	1973	lab-scale activated sludge		<50	FC 200	--	Reactor upset due to foaming at 50 mg/l COD
Le Febvre and Inman	1974	lab-scale activated sludge	200-220		FC 206	95-99[a]	Reactor upset due to foaming
Fink	1978	actual site activated sludge		<150	FC 206	--	Reactor upset due to foaming; bulking organisms selected for & caused problems
Chian et al.	1980	lab-scale anaerobic activated carbon filter		440-1,334	FC 206	50	Saw decrease in foaming properties; greater degradation when effluent aerated & sent to aerobic lagoon

[a]Glucose and peptone were part of the synthetic sewage so AFFF was only 40% of all carbon added. These values are for total COD removal.

steady state within the reactor. The synthetic sewage was spiked with 50 mg liter^{-1} of AFFF. However, this amount of AFFF created foam which resulted in loss of solids and an upset of the system. They concluded that "it would be very difficult to acclimate a biological culture to degrade AFFFs when they represented the only source of organic matter." As a result of this research, it was suggested that releasing AFFF to a domestic treatment plant must be done at a controlled rate of ≤50 mg liter^{-1} initially, building up to a maximum discharge of 100 mg liter^{-1}. LeFebvre and Fink also pursued research with an activated sludge system: LeFebvre (1974) with a lab-scale model; and Fink (1978) testing an actual site operation. Both efforts showed a maximum of 150 mg liter^{-1} COD of AFFF able to be handled by these systems due to the foaming action, which forced solids over the sides of the reactors. Fink also documented an increase in bulking sludge, often associated with high organic loadings, along with noticeable solids carry over due to foaming in the aeration basin and in a lack of settling in the clarifier. The suggested concentration, by these studies, for disposal, was 75 mg liter^{-1} COD of either FC 20C or Ansul.[1]

Metabolic studies utilizing a Warburg respirometer and activated sludge organisms showed that after a period of acclimation there was no inhibition of oxygen uptake up to 100,000 µl liter^{-1} of AFFF, where the synthetic sewage medium contained additional carbon in the form of glucose, peptone, and urea (LeFebvre and Inman, 1974). These data indicate that sludge organisms were tolerant of AFFF concentrations greater than 60,000 µl liter^{-1} used in field exercises.

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[1]Since 1976, only 3M-produced AFFFs and ANSUL, a product of the Ansul Co., are on the qualified products list as having met MIL-SPEC-F-24385-A (U.S. Department of Defense, 1977).

Chian, Suidan, Cross, Shah, and Ghosh (1980), using an anaerobic-activated carbon filter, found they could acquire a 50% reduction in COD at concentrations of FC 206 from 333 mg liter^{-1} to 1,000 mg liter^{-1} TOC (total organic carbon). Further reduction, up to 85%, was accomplished when the filter effluent was aerated and fed to an aerobic lagoon. Chan (1978a) reported on actual firefighting school wastewater treated by a UNOX (pure oxygen activated sludge) process. He stated that the UNOX process "would effectively treat firefighting school wastewater with a 1:50 to 1:300 dilution" (with sewage) when the "biomass" was acclimitized with a gradual increase in the feeding of wastewater. Assuming a maximum 6% or 60,000 µl liter^{-1} concentration of AFFF in the wastewater, then these dilutions could be interpreted as 1,200 to 200 mg liter^{-1} COD. In general, all of the studies discussed present data that reflect on the ability of AFFF to be biodegraded and the tolerance of sewage organisms to AFFF.

Based on data such as those summarized in Table 4, the Naval Environmental Protection Support Service has set the level of AFFF to be released to treatment plants (Table 5) and the maximum concentration of AFFF allowable for direct discharge to streams (Table 6). A maximum target AFFF concentration of 200 µl liter^{-1} has been selected to minimize foaming in the municipal sewage system (Taylor, 1977). Table 7 shows the capabilities for treating AFFF discharge to sanitary sewer system at the 10 major Naval facilities already mentioned. These plants can handle the 200 µl liter^{-1} AFFF limit. A problem arises in achieving the 200 µl liter^{-1} level for discharge. Some physical removal techniques have been tried (i.e., alum flocculation, air flotation, etc.) (Chan,

1978a), but to date have not been effective. The solution thus far is storage of firefighting wastewater and a "bleeding-off" into sewer systems in the amounts necessary to achieve authorized concentrations.

Table 5. Comparison of Concentrations of AFFF in Synthetic Sewage Amenable to Biological Treatment[a]

Manufacturer's AFFF Concentrate Label	Gallons Per Million Gallons of Secondary STP Flow	
	Recommended for Treatment, $\mu l\ liter^{-1}$ (ppm)	Maximum to Sewage Treatment Plant, $\mu l\ liter^{-1}$ (ppm)
FC-199	25	250
FC-200	10	10
FC-206	20	200
Ansul-K74-100	25	250

[a]Taken from D. W. Taylor (1977), Discharging aqueous film forming foam to harbor waters during tests of machinery space firefighting foam systems aboard U.S. Navy ships, Naval Ship Research and Development Center for Naval Sea Systems Command.

Table 6. Recommended Maximum Concentration of AFFF for Direct Discharge to Stream[a]

AFFF Concentrate	Maximum Concentration, $\mu l\ liter^{-1}$ (ppm)
FC-199	20
FC-200	5
FC-206	54
K74-100	55

[a]Taken from D. W. Taylor (1977), Discharging aqueous film forming foam to harbor waters during tests of machinery space firefighting foam systems aboard U.S. Navy ships, Naval Ship Research and Development Center for Naval Sea Systems Command.

Table 7. Treatment Capabilities for AFFF at Major Naval Port Facilities[a]

Naval Port Facility		Plant Name	Type	Operating Daily Flow in Millions, gal (m^3)	Tank Truck Pumpout Rate for 200 µl liter^{-1} Port Facility Discharge, gpm (l/m)	Sewage Treatment Plant Influent AFFF Concentration with 200 µl liter^{-1} Port Facility Discharge (µl liter^{-1})
Location	Approximate Daily Flow in Millions, gal (m^3)					
San Diego, CA: Naval Station, North Island, Point Loma	1.0 (0.004) 1.5 (0.006) 0.2 (0.001)	City of San Diego Metropolitan Sewage Treatment Plant, Point Loma	Primary	100 (0.378)	0.14 (0.53) 0.21 (0.79) 0.03 (0.10)	2.0
Norfolk, VA	4.0 (0.015)	Hampton Roads Sanitary District, Army Base Plant	Primary (E.1979)	16 (0.060)	0.56 (2.1)	50
Charleston, SC	1.4 (0.005)	North Charleston Sewer District Plant	Primary (E.1980)[b]	11 (0.042)	0.19 (0.74)	25
Pearl Harbor, HI	5.5 (0.021)	Fort Kamehameha Tri-Services Treatment Plant	Secondary	5.5 (0.021)	0.76 (2.89)	200
Philadelphia, PA	1.0 (0.004)	City of Philadelphia South East Water Pollution Control Plant	Primary (E.1980)	136 (0.515)	0.14 (0.53)	1.4
Mayport, FL	0.6 (0.002)	Mayport Naval Station Treatment Plant	Secondary	0.6 (0.002)	0.08 (0.32)	200
Little Creek, VA	1.0 (0.004)	Hampton Roads Sanitary District, Elizabeth River Plant	Secondary	16 (0.060)	0.14 (0.53)	12
Long Beach, CA	1.0 (0.004)	Port of Long Beach, City of Los Angeles, Terminal Island Treatment Plant	Secondary	11 (0.042)	0.14 (0.53)	18
Bremerton, WA	0.6 (0.002)	Charleston Treatment Plant	Primary (E.1980)[b]	6 (0.023)	0.08 (0.32)	20
Alameda, CA	1.1 (0.004)	East Bay Municipal Utilities District Treatment Plant	Primary (E.1977)	80 (0.303)	0.15 (0.58)	2.8

[a]Taken from D. W. Taylor (1977), Discharging aqueous film forming foam to harbor waters during tests of machinery space firefighting foam systems aboard U.S. Navy ships, Naval Ship Research and Development Center for Naval Sea Systems Command.

[b]Estimated completion date of secondary treatment plant.

Characteristically, the fate of AFFF in treatment processes has been followed utilizing standard water analysis methods. These methods are: methylene blue active substance (MBAS) for determining surfactant amounts, fluorine ion sensing probes for measuring total amounts of fluorine, COD for measuring the amount of chemically oxidized carbon, BOD for measuring the amount of biochemically oxidized carbon, and TOC for measuring the amount of total organic carbon present. However, these have not been adequate in measuring AFFF when it is in combination with other carbon sources, as seen in firefighting school wastewater. Plus they have not been diagnostic for determining which of the components of AFFF have been removed with respect to a treatment process. In 1978 the Navy supported a major research effort to develop standard analytical procedures for measuring AFFF (Chan, 1978b). Through this effort, FC-206 and ANSUL were analyzed via the gross parameters just listed as well as by electrochemical organic content (EOC) (Davenport, 1978), analyzing gas chromatography (G.C.) (Guard, Propper, and Ng, 1978), infrared spectroscopy (IR) (Guard et al., 1978; Woodman, 1980), ultraviolet spectroscopy (UV), nuclear magnetic resonance (NMR), thin layer chromatography (TLC) and high performance liquid chromatography (HPLC) (Guard et al., 1978). Electrochemical organic content had not been developed suitably as a technique at that point and so was unavailable for usage. Gas chromatography was significant in identifying the diethylene glycol monobutyl ether fraction but little else. Nuclear magnetic resonance resolved only one distinct peak, IR identified something containing a nitrile, and UV gave an absorbance spectrum of 310 to

220 nm, with a maximum absorbance at 255 nm. Of all the parameters investigated, TLC and HPLC showed the most promise. Utilizing a reverse phase C-18 column and a solvent gradient composed of acetonitrite and water, Bass (unpublished) was able to isolate a 6-peak fingerprint for FC-206 on an HPLC. Identification and toxicity of the different components on the fingerprint have not, as yet, been identified nor quantitated. However, it is possible that by following such a fingerprint, different components of AFFF may be tracked with regard to removal and biotransformation.

In summary, AFFF is the most effective firefighting foam developed thus far, and no suitable substitute has been found or formulated. The problem faced by the Navy is one of disposal. AFFF may be released to commercial and domestic sewage treatment plants in concentrations no greater than 250 mg liter^{-1}. The Navy has to find some method of pretreating firefighting wastewater to achieve this level, since the holding facilities available are rapidly filling with wastewater. Firefighting exercises must then be suspended until wastewater is bled into the sewers, achieving the appropriate concentrations, and room is made for more AFFF-containing wastewater in the holding containers. The object of this research was to define the capabilities of sewage organisms to utilize FC 780, the current form of 3M's AFFF, as a carbon source and then to determine the ability of a rotating biological contractor (RBC) to treat synthetic wastewater containing AFFF and at what concentration, if any, would foaming pose a processing problem.

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CHAPTER II

FEASIBILITY OF ENRICHMENT FOR AFFF-UTILIZING ORGANISMS: THE CHEMOSTAT

Introduction

The continuous culture of microorganisms is a fundamental method for growing cultures that corresponds much better than batch culture to the dynamic interactions seen in the natural environment (Dean, 1976). In a continuous culture, growth occurs at a constant rate and in a constant environment. A fresh supply of nutrients is added while medium is simultaneously withdrawn from the culture; thus culture volume is constant (Gerhardt, 1981). Factors, such as pH, nutrient concentration, products of metabolism, and oxygen concentration, that will change during the "growth cycle" of a batch culture are more constant in a continuous culture (Herbert, Ellsworth, and Telling, 1956). This, theoretically, would allow continuous exponential growth (Gerhardt, 1981). Also, these individual parameters can be controlled independently by the experimenter if needed (Herbert, Ellsworth, and Telling, 1956).

The continuous culture techniques are important in the study of mixed cultures. Mixtures of organisms always produce a more stable result (in fermentations) than single, pure cultures (McKinney, 1962). According to Bungay and Bungay (1968), a continuous flow system would allow the mixed culture being studied to reach a steady state condition

or else stay within a narrow range of fluctuation with regard to growth rate and cell age due to wash out. This is in contrast to "batch cultures which undergo drastic and simultaneous changes in substrate concentrations, product accumulation, pH and dissolved oxygen" (Bungay and Bungay, 1968).

Historically, the idea of studying mixed cultures began about 85 years ago with work by Winogradsky and Beijerenck on interactions of soil organisms (Brown, Ellwood, and Hunter, 1978). Since then, researchers have tried to define interactions with known and unknown mixed cultures in continuous culture systems (Bungay and Bungay, 1968). Nurmiko looked at different strains of lactic acid bacteria and their interactions. Schaumburg and Kush (1966) showed that Escherichia coli was responsible for maintaining anaerobiasis for a culture of Methanobacillus omelianski. Azuma (1961) noted a synergistic ability between Rhodopseudomonas capsulatus and Azotobacter vinelandii with respect to nitrogen fixation. Working with undefined mixed culture continuous flow systems, Cassell, Sulger, and Lamb (1966) and Chian and Mateles (1966) commented on the oscillation of populations and cell concentration rather than the succession seen in batch culture, Schlegal and Jannasch (1967) noted that high dilution rates would favor attached organisms because free swimming organisms would be washed out. Cooke and Ludzak (1958) studied the effects of predators (i.e., fungi) that preyed upon rotifers in sewage mixed populations and noted a relationship between the decrease in fungi and a decrease in the bacteria necessary for nitrile removal.[1] Studies such as these indicate the significance of studying organisms in mixed rather than isolated continuous culture.

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[1]The decrease in the fungal predator caused an increase in the rotifer that preyed upon the nitrile-removing bacteria.

An apparatus commonly used for such studies of mixed culture is the chemostat. The chemostat offers the advantage of acquiring high population densities at low substrate concentration. This, then, would mimic the natural environment (Veldkamp and Jannasch, 1972). The chemostat has been especially useful in enrichment studies. When the population of a desirable organism is low, then some enrichment is necessary. Enrichment usually means increasing the population size by altering the environment. Research has indicated that the continuous culture of a chemostat can be used to select for organisms unlikely to predominate in a batch system (Brown et al., 1978). A mathematical justification for the chemostat as an enrichment system is given by Brown et al. (1978). He states that in a chemostat, the specific growth rate (μ) of a microbial population depends on the concentration of the growth limiting nutrient per substrate (S) present. Monod (Brown et al., 1978) described this relationship as

$$\mu = \mu m \frac{S}{K_s + S} \qquad (1)$$

where μm is the growth rate produced at saturating values of S, and K_s is a saturation constant numerically equal to the concentration of S at 1/2 μm. K_s is a measure of the affinity of the organism for S and is in the order of mg liter^{-1} for carbohydrates and μg liter^{-1} for amino acids.

In a chemostat one nutrient in the influent is maintained at a low concentration. S is fixed by the dilution rate (D) caused by the influent and thus controls μ. μ is maintained at values below μm, which is fixed by D (Brown et al., 1978). When D is greater than μm, "washout" will occur (Herbert et al., 1956).

The system is very selective, and in a mixed population competing for one S, the outcome will be determined by the μ to S relationship of the organisms involved. Figure 1 depicts a system where organism A has a higher μm and K_s than organism B. Here, organism A will outgrow B at any value of μ. Therefore, A will predominate in batch or chemostat culture. However, if the system seen in Figure 2 is used, then the μ to S of organisms A and C cross. This means that at high μ, A will outgrow C, and at low μ, C will outgrow A. So, in a batch system, A will always predominate due to its higher μm, but in a chemostat, the results of competition depend on D, and by using low dilution rates it is possible to enrich for the low K_s, low μm organisms of type C, which never predominate in batch culture experiments (Brown et al., 1978).

According to Brown et al. (1978), Jannasch (1965) was one of the first to use continuous culture enrichment and noted three advantages.

(1) No succession of species occurred and if there was no wall growth or interaction then the predominance of one species increased with time.
(2) The growth advantages of the successful competitor are not dependent on substrate specificity but on the particular growth parameters of the organism and the cultural conditions provided. If these parameters are known and stable then enrichment is reproducible.
(3) Enrichments may be carried out in the presence of extremely low concentrations of the limiting nutrient and therefore at low population densities (Brown et al., 1978).

Other researchers have used chemostat enrichments successfully for isolation of hydrocarbon degraders, oral cavity organisms, and organisms possessing uptake/reduction systems for nitrate (Brown et al., 1978).

In this phase of the research presented, enrichment for AFFF metabolizing organisms was accomplished utilizing a chemostat. It was the purpose of the chemostat study to decide the feasibility of enrichment

for AFFF metabolizing organisms in an aerobic, continuous flow reactor and to determine the environmental growth parameters necessary. These results were to be applied in the second phase of the research project dealing with the Rotating Biological Contactor (RBC).

Materials and Methods

Physical Setup

A diagram and photograph of the chemostat physical setup is given in Figures 3 and 4. Influent was sterilized in a 2-liter reservoir and put on line aseptically. The flow rate of sterile medium into the reaction vessel was 1 ml min^{-1}. The reaction vessel was a 4-liter aspirator bottle (Kimax), which was continuously agitated via a stir bar/stir motor arrangement (Corning Hot Plate Stirrer, PC-351). Aeration was accomplished via filtered air (Acropore 0.45-μm filter) bubbled into the bottom of the reaction vessel. A constant volume of 2 liters was maintained within the reaction vessel by a siphon overflow tube into a waste receptacle which was replaced and autoclaved when full. Samples were taken by suction-draw from the sampling port.

Inoculum

The inoculum or seed for the startup of the chemostat was 0.05 gram each of the following: dried bacteria culture (Horizon Ecology Company) for degrading fats, oils, and greases (#245-40); for hydrocarbon degradation in freshwater (#245-60); and 5 ml of activated sludge from the Buenaventura County Water Treatment Plant.

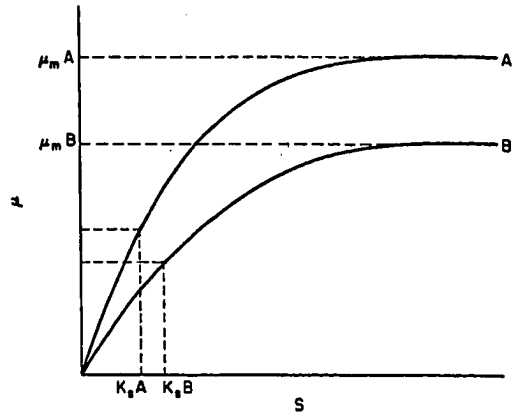


Figure 1. The relationship between μ and S. Organism A will outgrow organism B at all growth rates, in both batch and continuous cultures.[1]

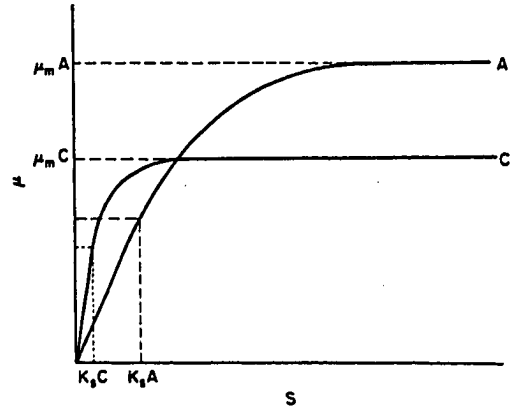
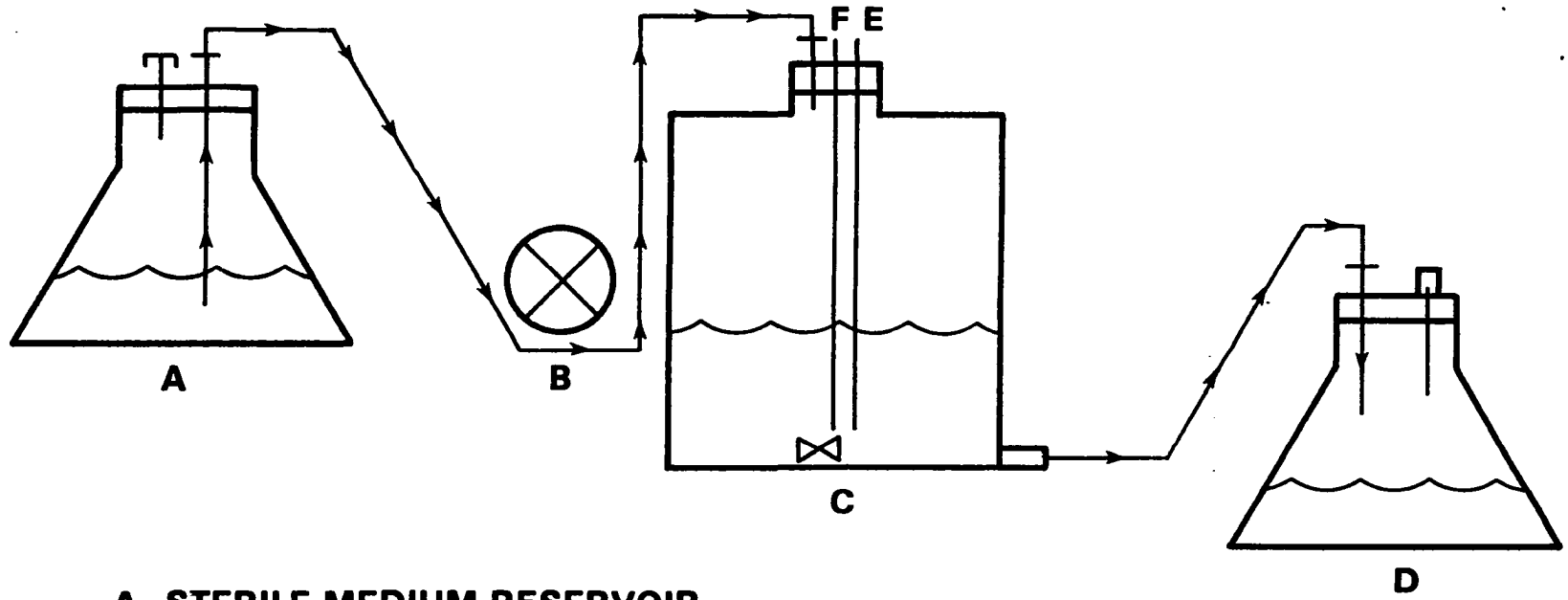


Figure 2. The relationship between μ and S. Organism A will outgrow organism C at high growth rates. C will outgrow A only in continuous culture at low dilution rates.[1]

[1]Taken from Brown, C. M., D. C. Ellwood, and J. R. Hunter. 1978. Enrichments in a chemostat. In D. W. Lovelock, Techniques for the study of mixed populations. Academic Press, New York, pp 214-215.



A -STERILE MEDIUM RESERVOIR

B -PERISTALTIC PUMP

C -REACTION VESSEL

D -WASTE

E -SAMPLE PORT

F -AERATION

Figure 3. Chemostat.

Figure 4. Chemostat: a. Sterile influent; b. Peristaltic pump; c. Reaction vessel; and c. Effluent (waste).

Media

Bushnell Haas Broth (Difco) was used as a minimal salts medium to which specific amounts of known carbon could be added. The carbon used in this experiment was D-Glucose (Difco) and/or the aqueous film forming foam designated FC-780 (3M). This then comprised the sterile influent.

Growth Conditions

The chemostat experiment was conducted at ambient temperature, under mild aeration and agitation. pH was monitored but no attempt at adjustment was made.

Procedure

System startup was as follows. The reaction vessel containing 2 liters of sterile Bushnell Haas Broth (BHB), 0.05% glucose, and 0.5% FC-780 was seeded with the inoculum and allowed to grow as a batch system. After 48 hours and an increase to 0.60 optical density, sterile influent containing 0.05% glucose and 0.5% FC-780 was put on line. On day 8, the influent was changed to contain 0.5% FC-780 (approximately 2,000 mg liter^{-1} COD) as the only carbon source. Samples from influent and effluent concurrently were taken three times a week and analyzed as follows:

A. Optical Density. Utilizing the sterile influent as a standard or blank, optical density of the effluent was determined at 460 nm, utilizing a Beckman Spectronic 88.

B. pH. The pH of the influent and the effluent were determined immediately after sample withdrawal using an Orion Research Model 701A/Digital Ionalyzer.

C. Biochemical Oxygen Demand (BOD). The 5-day soluble BOD determination was used as outlined in Section 507 in Standard Methods (American Public Health Association, 1976), utilizing an Orion Research Model 701A/Digital Ionalyzer and Model 97-08-00 O_2 electrode.

D. Chemical Oxygen Demand (COD). COD was performed according to the method outlined in Section 508 of Standard Methods (American Public Health Association, 1976) and modified by Technicon (Technicon Inst. Corp., 1976).

E. Total Organic Carbon (TOC). A variation on the procedure given in Section 505 of Standard Methods (American Public Health Association, 1976) was used. The variation, the acid sparge technique, was performed with the Beckman 915B TOC analyzer, and is outlined in the operation manual (Beckman Inst., 1979). All samples used for TOC, COD, and/or BOD determination were filtered prior to analysis through a series of graded membrane filters (i.e., 5 μm, 1.2 μm, 0.8 μm, and 0.45 μm (Gelman)). Each filter was washed prior to use with 30 ml of double deionized water to remove any organic wetting agent on the filter.

F. Microorganism Identification. Bacterial and fungal populations were identified and enumerated utilizing Nalgene Nutrient Pad Kits of the following media: Standard TTC - for total counts; Azide - for enterococci and fecal

streptococcus; Wort - for fungi, filamentous and nonfilamentous; Weman - for slime-forming mesophilic bacteria (e.g., Lueconostoc mesenteroides).

Results and Discussion

The results of BOD, COD, and TOC testing are presented in Figures 5, 6, and 7, respectively. From these figures it can be seen that the early influent values were erratic. However, after day 27, the system was in homeostasis with regard to the influent. Effluent values dropped to a low of approximately 200 mg liter^{-1} COD, 180 mg liter^{-1} BOD, and 100 mg liter^{-1} TOC, and these levels were maintained for several days.

The data in Figure 8 depicts the percent removal or conversion from influent to effluent with respect to COD, BOD, and TOC. Approximately 70% COD removal, 80% BOD removal, and 60% TOC removal were consistently observed from day 35 onward to day 67. From day 64 until shutdown of the chemostat on day 87, percent removal dropped to approximately 45% COD, 50% BOD, and 40% TOC. This was in part correlated with a pH rise in the reaction vessel to a pH of 7.1 or greater (Figure 9). The microbial populations observed in the chemostat changed drastically with the increase in pH. That is, a greater number of yeast and slime-forming bacteria were noted. No effort was made to readjust the pH of the chemostat and so percent removal in all three dropped to a level of 40% to 50%.

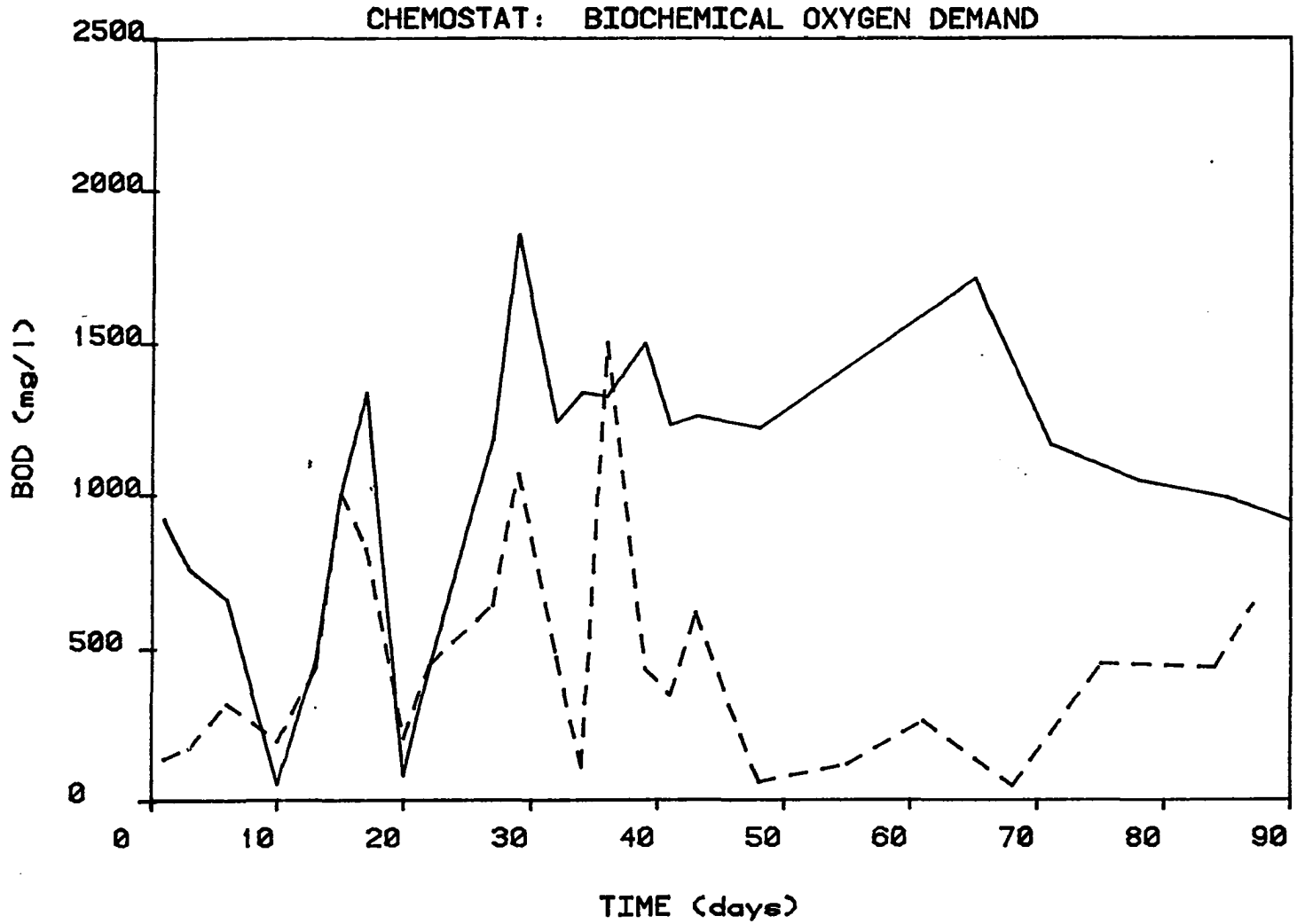


Figure 5. BOD values as a function of time. Influent———, effluent— — —.

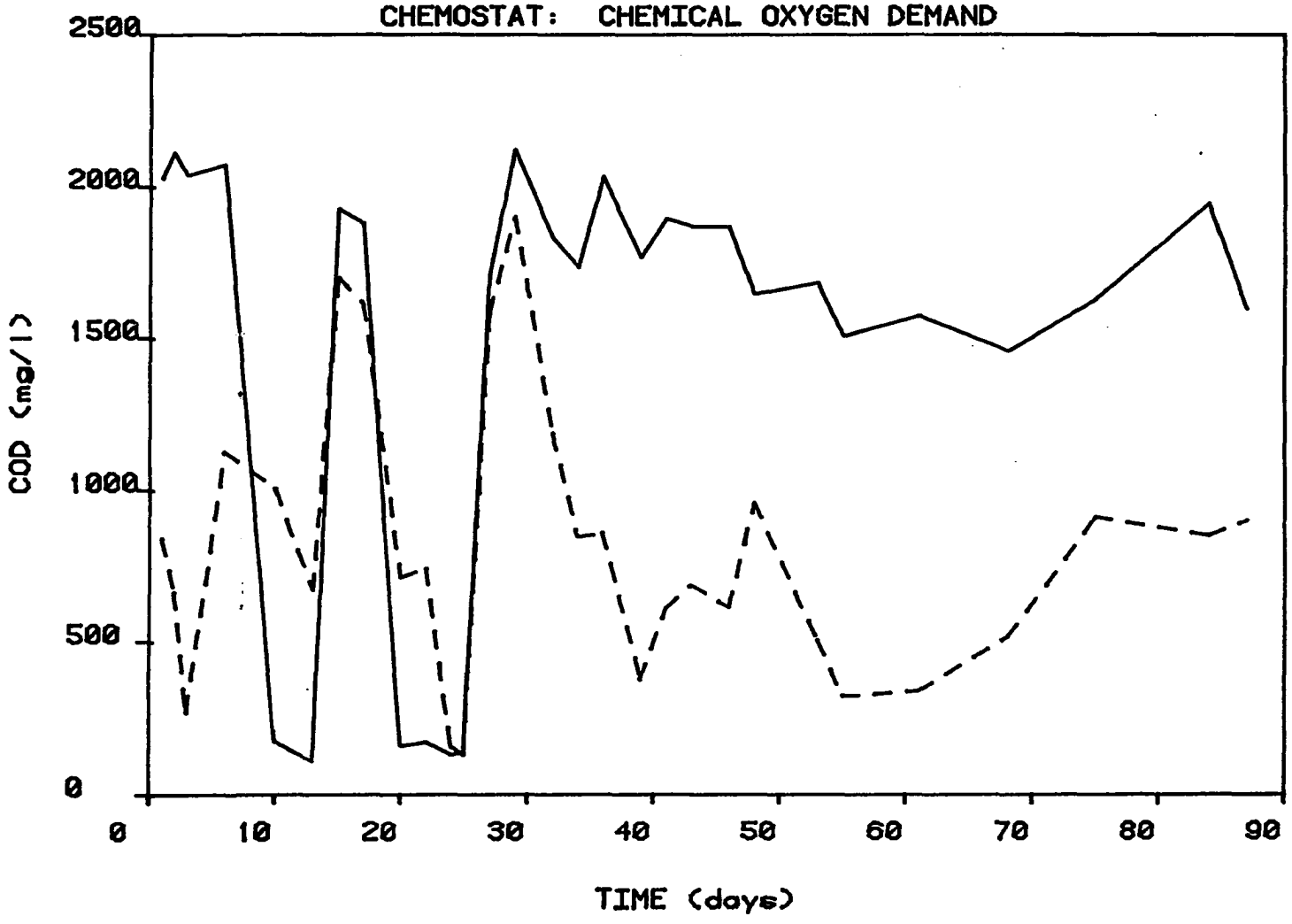


Figure 6. COD values as a function of time. Influent———, effluent— — —.

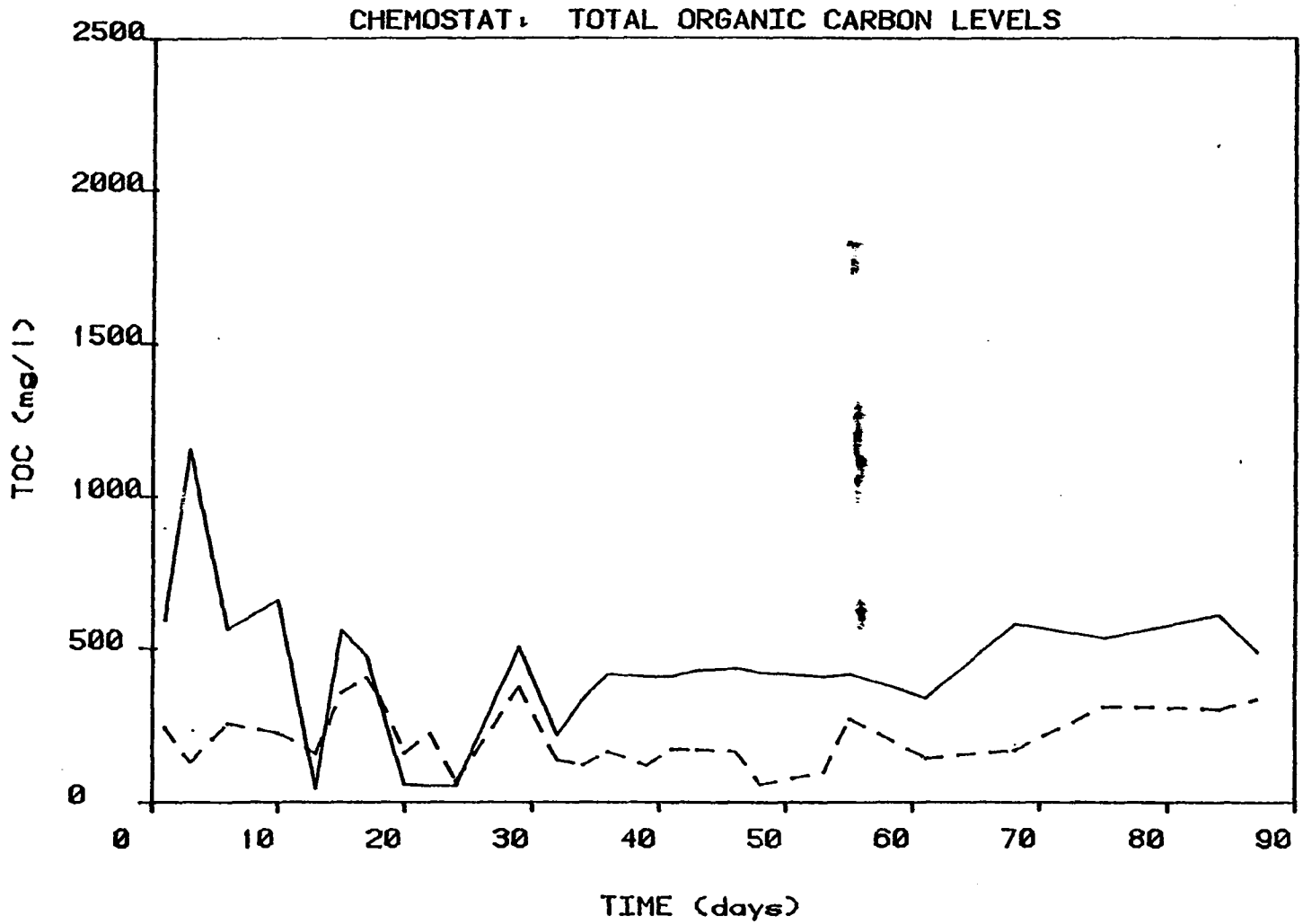


Figure 7. TOC values as a function of time. Influent———, effluent— — —.

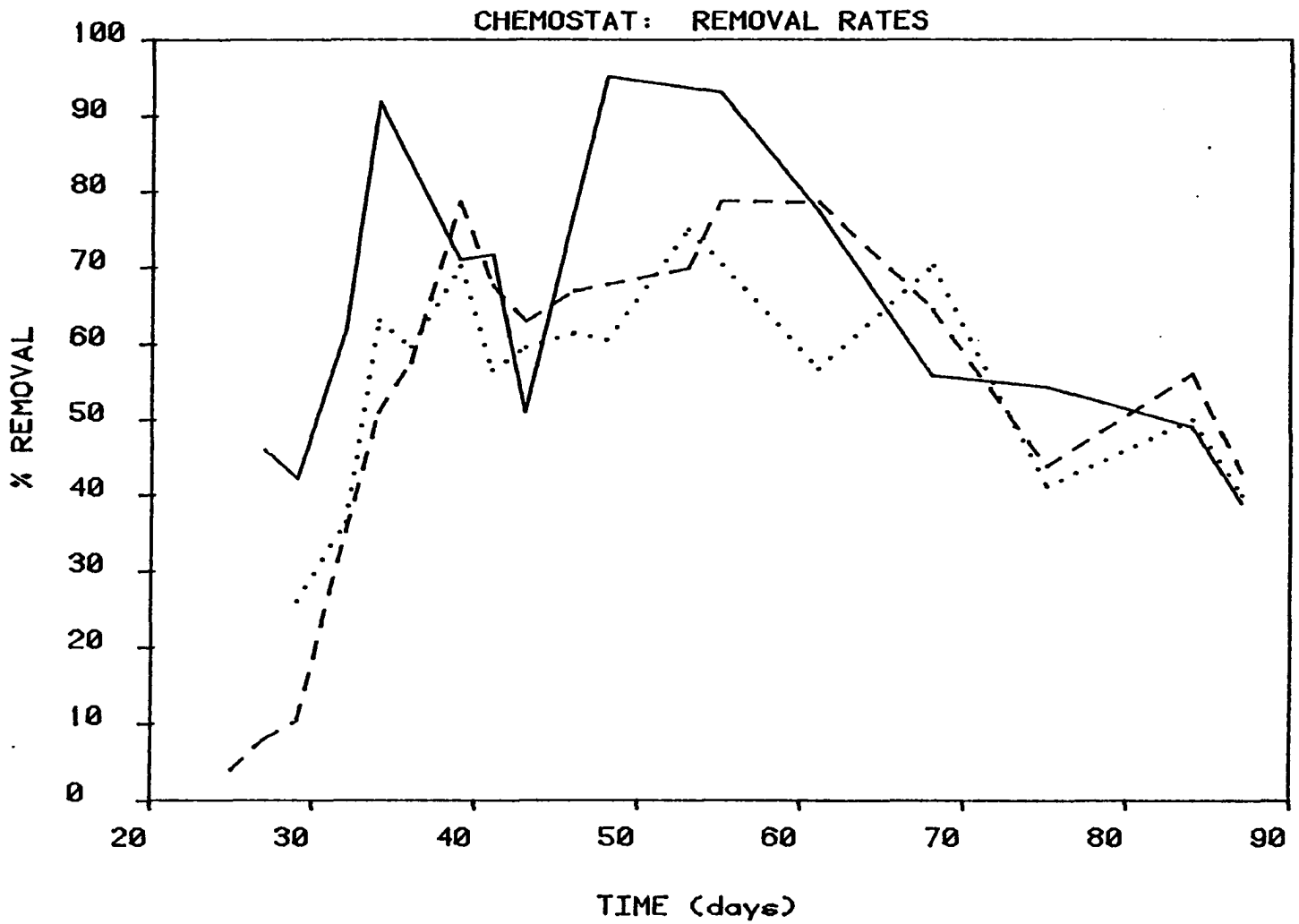


Figure 8. The percent removal of BOD——, COD — — — and TOC ..... are given as a function of time.

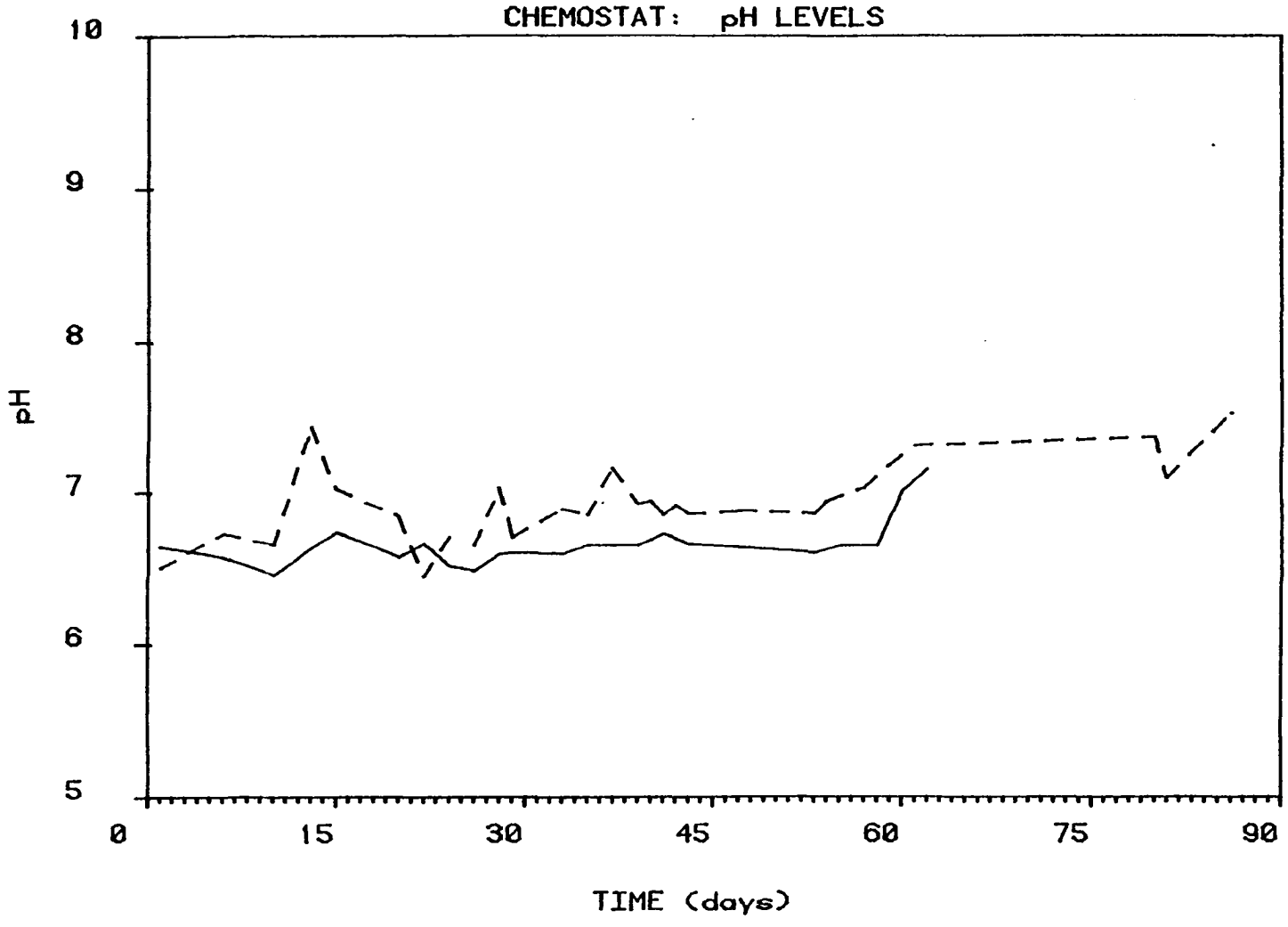


Figure 9. pH values as a function of time. Influent ———, effluent— — —.

As seen in Figure 8, the percent (%) conversion values exhibited some variance. This is partially due to technical errors and machine failure. Equipment failure occurred, and no new influent entered the reactor vessel for 12 to 16 hours. This resulted in microbial back contamination from the reactor vessel into the influent reservoir, which resulted in an increase in pH and a decrease in available carbon in the influent and thus a lower TOC, COD, and BOD conversion measurement. It also should be mentioned that plate counts were performed infrequently and were more for qualitative determination of different microbial populations.

A multiple regression analysis was run on data starting with day 27 through the end of the experiment. This was done to determine the effect of treatment, by the chemostat, on the removal of AFFF as determined by COD, BOD, and TOC decreases. Statistics from this analysis are given in Appendix C and are summarized in Table 8. From the data in Table 8, it can be seen that treatment by the chemostat was significant in changing the dependent variables: BOD, COD, and TOC levels. The negative value of the regression coefficient is indicative of an inverse relationship. Exposure to the chemostat lowered the levels of the dependent variables. Time, measured in days duration of the experiment, was not significant. This can be explained by the fact that organisms had already adapted to, or had been enriched by, the AFFF by day 27. Therefore, no significant alteration in utilization appeared with respect to time after this point.

Table 8. Summary of the Results of a Multiple Regression Analysis for the Chemostat Data

Independent Variable	Dependent Variable								
	BOD			COD			TOC		
	Regression Coefficient[a]	t[b]	r^2[c]	Regression Coefficient	t	r^2	Regression Coefficient	t	r^2
Treatment	-918.71	-7.07	0.792	-974.75	-5.79	0.694	-228.56	-7.49	0.823
Time (days)	-7.77	-1.97	0.792	-6.71	-1.26	0.694	0.76	0.74	0.823
pH	361.95	9.84	0.792	415.09	8.33	0.694	91.03	10.18	0.823

[a]The parameter value (x) for which one (1) unit value changes of the independent variable will cause x unit value change in the dependent variable. Ex: One pH unit increase would result in a 361.95 BOD unit increase.

[b]The critical t, calculated with 95% confidence, are: BOD, 2.06; COD, 2.04; TOC, 2.05. If t is greater than or equal to the critical t, then this value is considered significant.

[c]The coefficient of determination.

The fact that pH had an effect on the change in the dependent variables is obvious. An increase of 0.1 pH unit would cause an increase of 41.5 mg liter^{-1} COD, resulting in less efficient removal. Correlating this fact to microbial population changes observed, it was decided for future experimentation to adjust the pH of the RBC to 7.00.

From the chemostat data, one can see that enrichment for mixed microbial populations that were able to utilize FC-780 as their sole source of supplemented carbon was possible. The data from the chemostat also indicated that it was possible to change an influent containing 1,200 to 1,500 mg liter^{-1} COD of FC-780 into an effluent containing approximately 200 mg liter^{-1} COD. The next step in this research effort was to adapt and expand the knowledge obtained for use with the RBC.

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CHAPTER III

ROTATING BIOLOGICAL CONTACTOR

History

The Rotating Biological Contactor (RBC) process is a technique where "biologically active masses" grow on a "series of discs that slowly rotate" (Smith and Bandy, 1980). The rotation exposes the attached biomass to substrate-rich wastewater and atmospheric oxygen. The substrate is converted to new biomass and soluble and gaseous metabolic by-products. Under ideal conditions, the soluble substrate is 100% removed from the wastewater (Friedman, Robbins, Woods, and Wauford, 1979).

The first documented use of an RBC was in the early 1900s, when Wiegard (1900) in Germany tried using wooden discs and Doman (1929) in the United States used metal discs (Huang and Bates, 1980). Both of these attempts proved impractical due to deterioration. Also, few communities were interested in secondary treatment at that time (Dallaire, 1979). The technique was resurrected in the 1950s by researchers at Stuttgart University in West Germany. There, experiments were conducted with flat, plastic (polystyrene) discs. This was the foundation for work done in 1959 when J. Conrad Sengelin started to manufacture 2- and 3-meter-diameter polystyrene discs in West Germany, and 1960, when the first commercial installation went on stream. However, these early

commercial RBC units were not cost competitive with respect to installation and startup when compared with activated sludge processes. So, after 1960, the development of the RBC process stopped in Europe (Dallaire, 1979).

Between 1960 and 1965, Allis-Chalmers Company in the U.S. pursued developmental research on the RBC process. They termed the process a Two-Phase Contactor (TPC), denoting the two phases of media that the disc contacted (i.e., air and liquid). However, as the media rotated, it acted as a support for biological growth, and the descriptive name of Rotating Biological Contactor was coined (Welch, 1968). Five years later, in 1970, they sold the technology they had developed to Autotrol of Milwaukee, Wis. At this time the process still was not cost effective. In 1972, Autotrol developed a more compact disc, with more surface area per volume. With this development the process became competitive (Dallaire, 1979).

According to Smith and Bandy (1980), there are over 700 RBC installations in Europe. In the U.S., Chesner and Ianonne (1980) listed 263 municipal and 58 industrial RBC installations, and Smith and Bandy (1980) cited 300 additional U.S. sites being planned.

Description of the Process

By definition, the RBC is an aerobic, continuous flow, wastewater treatment system. As already mentioned, the RBC biologically changes the organic component of wastewater into biomass and metabolic by-products. Usually, a secondary clarifier is then used to separate the biomass - generated. In the process, wastewater flows into the RBC tank, which contains a series of high-density discs attached to a horizontal shaft

(Banerji, 1980). The discs are usually made of a low density, rigid material such as aluminum, polyethylene, plexiglass, or polystyrene (Smith and Bandy, 1980). The discs are 40% submerged in wastewater and are rotated continually by mechanical or air-driven systems. As a result, a film of wastewater is carried by the disc into the air, where oxygen can be transferred across the film surface (Figure 10). The organic component of this oxygenated film of wastewater is then utilized by the attached biomass. Excess dissolved oxygen is mixed with the contents of the wastewater flowing through the tank (the liquor), resulting in aeration. Suspended biomass cultures (floc) in the mixed liquor tank are aerated and contribute to the treatment (Banerji, 1980).

Groups of discs segregated by baffling are termed stages. The flow of wastewater can be parallel or perpendicular to the discs' faces. The microbial population within each stage is dependent on the hydraulic and organic loading conditions of the wastewater. In a system where the wastewater flow is perpendicular to disc face, heavy growth and substantial carbonaceous removal usually occurs in the first stage. These both decrease in successive stages. The amount of biomass on the discs is also controlled by the shearing forces exerted by the rotation of the discs. As a result, sloughing of the biomass occurs and prevents bridging and clogging between discs. The mixing action of the rotating discs keep the sloughed solids in suspension until they are removed from the RBC tank and can be separated by gravity in the secondary clarifier (Banerji, 1980). A more complete description of the RBC, process operation, and maintenance for the RBC are given in Appendix D, which contains excerpts from volume 1 of the Operation of Wastewater Treatment Plants.

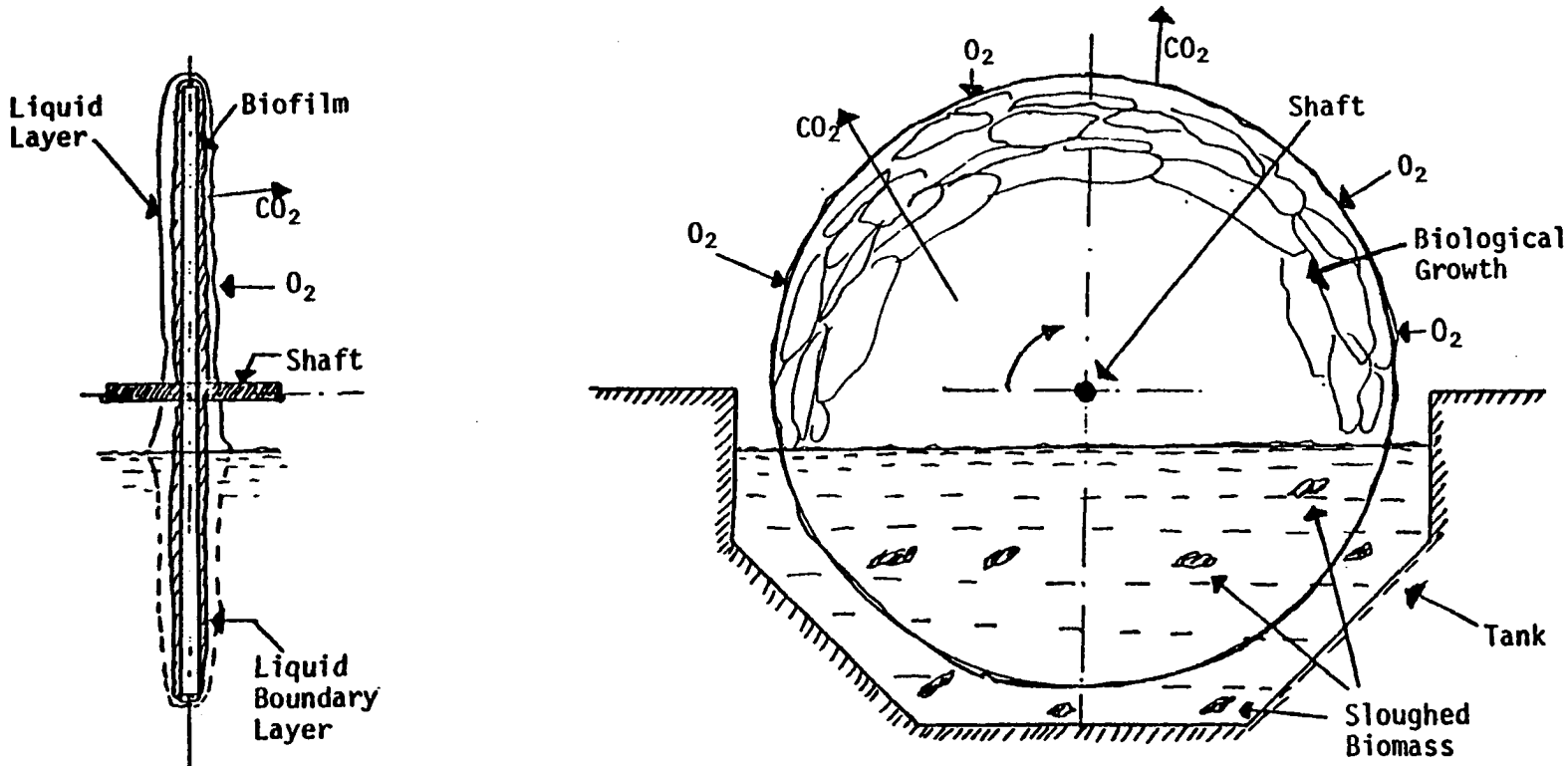


Figure 10. Rotating biological contactor disc. Reproduced from original figure. S. K. Banerji (1980). "ASCE water pollution management task committee report on rotating biological contactor for secondary treatment," in Proceedings of the National Symposium/Workshop on RBC Technology, p. 32.

Microbiology of the RBC

Biologically, the RBC has often been compared to percolating or biological filters. This comparison is true when examining the discs. However, the biology of the suspended floc within each stage would be more similar to that of activated sludge. It is necessary, then, to review the general microbial populations in both processes and of wastewater in general.

The organisms prominent in various wastewater treatment processes have been studied by many researchers. Generally, bacteria are predominant, unless the pH is less than 6.5, at which point fungi become the predominant organism (McKinney, 1962). Pseudomonas sp. are one of the most common bacteria found in wastewater. According to McKinney (1962), Pseudomonas can metabolize almost every type of organic matter and survive in almost every environment. It should be considered the prime bacterial genus responsible for degradation of organic material of sanitary significance. Of almost equal importance and frequency are Alcaligenes sp. and Flavobacterium sp. (McKinney, 1962; Pike, 1975).

The enumeration and isolation of bacteria is difficult when working with biological treatment processes. Standard axenic methods for dealing with bacteria must be modified or disregarded. Before total viable counts can be made, homogenization must be used to release individual bacteria from flocs. However, such techniques result in cell damage, cell death, and erroneous viable counts (Pike, 1975). Also, no single medium can be relied upon to support growth of all fastidious organisms found in the treatment processes. Direct microscopic counts of sewage bacteria are usually in error. This is attributed to difficulty in discerning bacterial cells from suspended debris (Pike, 1975).

According to Pike (1975), the traditional approach to identification of bacterial populations has three drawbacks: (1) many isolates have to be examined, (2) important but minority classes may not be isolated, and (3) the results can only be qualitative or partially quantitative. Table 9 lists the principle bacterial genera found in activated sludge processes, percolating filters, and oxidation lagoons. Several of these genera are filamentous.

Table 9. Principle Genera Which Have Been Recorded in Taxonomic Studies of Biological Treatment Processes[1]

Activated Sludge	Biological Filters	Oxidation Lagoons
Pseudomonas	Pseudomonas	Pseudomonas
Comamonas	Myxobacterium	Thiopedia
Lophomonas	Cytophaga	Thicapsa
Zoogloea	Zoogloea	Thiospirillum
Sphaerotilus	Sphaerotilus	Merismopedia
Azotobacter	Paracolobactrum	Azotobacter
Chromobacterium	Chromobacterium	Chromatium
Achromobacter	Achromobacter	Achromobacter
Flavobacterium	Flavobacterium	Flavobacterium
Coli-aerogenes bacteria	Escherichia	Escherichia
Alcaligenes	Alcaligenes	Alcaligenes
Nocardia	Nocardia	Seratia
Staphylococcus	Streptococcus (faecalis)	Streptococcus (faecalis)
Bacillus	Bacillus	Bacillus
Arthrobacter	Sarcinae	Sarcinae
Micrococcus		Micrococcus
coryneform bacteria		
Mycobacterium		
Bdellovibrio		

[1]Taken from E. B. Pike (1975). "Aerobic bacteria," in C. E. Curds and H. A. Hawkes, Ecological Aspects of Used-Water Treatment. San Francisco, Calif., Academic Press.

Filamentous bacteria and fungi play a useful part in the construction of floc particles. Kinner (unpublished) researched filamentous growth on RBC discs and found that Sphaerotilus was the major filamentous organism in healthy disc growth. Other researchers have reported that filamentous organisms are the primary organism responsible for adherence of "zoogleal slime" to RBC discs (Banerji, 1980; Corpe, 1978; Kinner and Bishop, 1980). However, an overabundance of these organisms can result in large, loose floc particles that are "of such bulk and fluffiness" that it will not settle. Such flock will not separate into sludge and supernatant layers when quiescent, resulting in a condition known as "bulking sludge." The result of bulking sludge is biomass loss in the overflow or effluent from a clarifier (Gaudy and Gaudy, 1980). Bulking sludge has been associated with a decrease in carbonaceous removal.

There are seven groups of filamentous organisms, as described by Eikelboom (1975). They are:

Group I: Sheath forming gram negative organisms

Group II: Sheath forming gram positive organisms

Group III: Cyanophyceae type

Group IV: Tiny curled filaments

Group V: Short, straight, multicellular bacteria

Group VI: Organisms possessing gliding motility

Group VII: Miscellaneous

Specific filamentous genera found in activated sludge processes are: Thiothrix, Taxothrix, Vitreoscilla (Farguhar and Boyle, 1971), Sphaerotilus (Chudoba, Ottova, and Madera, 1973; Eikelboom, 1975; Farguhar and Boyle, 1971), Beggiatoa (Banerji, 1980; Eikelboom, 1975), Leucothrix (Chudoba

et al., 1973; Eikelboom, 1975), Bacillus and Geotrichum (Eikelboom, 1975). The organisms most often associated with bulking are Leucothrix, Sphaerotilus, Bacillus, Beggiatoa, and Geotrichum (Eikelboom, 1975; Sykes, Rozich, and Tiefert, 1979). An increase of these bulking organisms is related to several environmental parameters. Pike (1975) related bulking to low sludge age in activated sludge. Low dissolved oxygen (DO) in completely mixed systems tends to promote growth of Sphaerotilus natans (Palm, Jenkins, and Parker, 1980), and a DO greater than 2 mg liter^{-1} is necessary to prevent bulking from S. natans. It is often recommended that hydrogen peroxide be added to influent to act as an oxygen source to prevent bulking organism growth (Schwartz, Popowchak, and Becker, 1980). Organic loading is a factor in the enrichment of bulking organisms. Chudoba et al. (1973) said that the concentration of Leucothrix and Sphaerotilus in activated sludge depended on organic loading and mixing. They found that complete mixing led to excessive growth of filamentous organisms. This finding was concurred by Hautmeyer, van den Eynde, Polf, and Verachtert (1980). They reported that continuously fed activated sludge systems developed highly filamentous bulking sludge whereas intermittently fed processes developed sludge with good settling characteristics.

The occurrence of fungi in waste treatment processes has been recorded most often on percolating filters. They are considered undesirable as the predominant member due to potential blocking of the filter by fungal mats. The most common fungi associated with the film of filters are: Sepodonium sp., Subbaromyces splendens, Ascoidea rubescens, Fusarium aquaeductuum, Geotrichum candidum, and Trichosporon

cutaneum (Tomlinson and Williams, 1975). Fungi are not normally found as dominant organisms in activated sludge processes (Tomlinson and Williams, 1975). Farguar and Boyle (1971) did report on fungi which were part of the bulking organisms found in activated sludge plants. When bacteria are inhibited, for example by sudden discharge of acid plating wastes, fungi such as G. candidum will grow in abundance (Hawkes, 1963). Such bulking sludge may be very effective in removing organic waste, but they do not settle well and will consequently impair effluent quality (Tomlinson and Williams, 1975). Some treatment processes have experienced growth of predacious fungi. It is unknown yet what the effect of such fungi are on the protozoan and metazoan populations. Cooke and Ludzak (1958) did report that a decrease in predacious fungi caused an increase in rotifers, which then overgrazed nitrile-removing bacteria causing a decrease in nitrile removal.

Protozoa were orginally throught to be harmful to wastewater processes, but it is now known that protozoa help keep the excess bacterial populations down (McKinney, 1962).

> Waste treatment facilities are an ideal feeding ground for protozoa, and protozoa perform an important function in clarifying the effluent by ingesting bacteria that remain in suspension without sedimentation. Attached protozoa also aid settling by increasing the weight of sludge particles (Gaudy and Gaudy, 1980).

Curds and Fey (1969) proved the role of protozoa in clarification. They studied six protozoa-free, activated sludge plants. The effluent from these plants was turbid and of poor quality. When ciliates were introduced into three of these systems, they reported a dramatic decrease in turbidity. They reported that E. coli had a 16-hour half-life in

protozoan-free activated sludge and a 18-hour half-life when protozoa were added. There are two ways in which protozoa could cause improved effluent quality: either by flocculation or predation. Protozoa in pure culture are able to flocculate suspended particles and bacteria, often by secretion of a mucus-like polysaccharide or mucin. However, it is more likely that the major role of ciliated protozoa in aerobic used-water treatment is the removal of dispersed bacteria by predation (Curds and Hawkes, 1975).

With respect to protozoa in wastewater, the following can be said. Mastigophora are never found in large numbers except in polluted waters. Phytoflagellates must compete with the bacteria for soluble substrate, but with less success. Zooflagellates use bacteria for food, but not as efficiently as free-swimming ciliates (McKinney, 1962). Generally, sludge is said to be in poor condition when there are few ciliates and many flagellates present. In good sludge, ciliates predominate, and effluent quality is at its best when ciliate populations consist predominantly of peritrichs (Sykes and Skinner, 1971). Free-swimming ciliates are proportional, in population, to the number of bacteria. If bacterial populations decrease, then the free-swimming ciliates decrease in number because there is not enough food to support their tremendous energy expenditure. Peritrichia will then be the predominant ciliate group (McKinney, 1962). All the peritrichous species found in activated sludge are sessile types. They attach, usually via a stalk, to the sludge floc and draw food to them by rapidly moving cilia. Their low energy demand allows them to survive at very low bacterial populations (McKinney, 1962; Sykes and Skinner, 1971). Sarcodina also

feed upon bacteria and may even ingest flocculated bacteria. In summary, Sykes and Skinner (1971) state that (1) all the most important protozoa are ciliates, (2) all but one (Trachelophyllum pusillum) are known to feed on bacteria, and (3) most of the important protozoa are either sessile or crawl over the surface of sludge flocs.

McKinney (1962) states that when Peritrichia populations decrease, the Rotifera populations increase. The appearance of Rotifera is indicative of 95% to 100% purification of sewage in activated sludge. Rotifers break up floc particles, provide nuclei for further flock formation, and clear effluents by removing suspended nonflocculated bacteria. Secretion, by rotifers, of mucus-bound fecal pellets contributes to floc formation. Rotifers are often seen late in the development of the biological community due to reduced grazing competition from protozoa as floc particle size becomes too large to be handled by protozoa (Doohan, 1975).

In addition to Rotifera, other metazoan populations can be found in wastewater systems. Nematoda have been found in almost all aerobic wastewater treatment processes, although population densities may vary. They are greatly significant in the film of percolating filters and RBC discs (Schiemer, 1975). Free-living nematodes in wastewater are not indicative of faecal pollution. They usually originate from the soil via land runoff, fresh vegetable washings, etc. Those that feed on bacteria thrive in wastewater treatment processes (American Public Health Association, 1976). Schiemer (1975) lists three positive functions of nematodes in wastewater: (1) control of bacterial growth and density by grazing, (2) metabolic decomposition of organic material, and (3) the recycle of energy-rich substances, such as excretion products, faeces, and dead body tissue.

Arachnids, in particular three astigmatids (mites), have been associated with percolating filters. These are: Histiogaster carpio, Histiostoma feroniarum, and Rhizoglyphus echinopus. They feed mainly on liquids rich in microorganisms or on plant material, and thus form part of the "scouring group" of organisms on filters. Film removal is their primary role (Baker, 1975). Other metazoans associated with wastewater biological treatment processes are the Annelida, Insecta, Crustacea, and Mollusca (Curds and Hawkes, 1975).

The microbiology of the RBC, like the process itself, is still a neophyte with regard to the study of the organisms present. Kornegay and Andrews (1967) measured the disc biofilm thickness and related this to efficiency of organic removal. Antonie and Welch (1969) were two of the first researchers to actually identify organisms associated with the RBC biomass. They identified the filamentous organisms Geotrichum candidum and Bacillus cereus as most important, and Zoogloea filependula, Pseudomonas denitrificans, Aerobacter aerogenes, and Escherichia coli as most predominant. Torpey, Huekelkeon, Kaplan, and Epstein (1971) reported on the succession of organisms in an RBC. They first saw "zoogleal" bacteria and and Sphaerotilus followed by free-swimming protozoa, stalked protozoa, rotifers, and nematodes. Hoag and Hovey (1980) compared the fauna of a four-stage lab-scale RBC to that of a four-stage full-scale RBC. In both, they saw the following distribution of organisms. The first stage was dominated by filamentous bacteria, with free-swimming ciliates as the primary predators. In the second stage, bacteria and peritrichs were dominant. In the third and fourth stages, rotifers and Sarcodina were the predominant organisms seen. Ouyang (1980) also studied the variation of predominant organisms within successive stages

and reported that the first stage contained Sphaerotilus, Zoogloea, and other filamentous organisms, stage two contained Zoothamnia and rotifers, and stages three and four contained Rototoria and Podophrya. Similar results were presented by Pescod and Nair (1972) and Khan and Ramon (1980).

> The predominant organisms including Sphaerotilus and zoogleal bacteria are present on all discs. Besides these two important kinds, the diversity and abundance of free-swimming protozoa (Paramecium, Cyclidium, Ocomonas, Oxytrichia, and Euglena) are present in the first few stages. The growth of rotifers (Epiphanes and Proales), stalked ciliates (Vorticella), nematodes (Ethmolaimus), and a loop forming fungus (Athrobotrys) together with algae (Coelastrum, Chlorella, Fragilarie and Pinnularia) take place in the last few stages only when organic loading is low but high enough to support microbial growth. The quickly developed biofilm at the earlier stages of the RBC system is much thicker than bacterial slime produced on the later discs.
>
> The mechanisms of attached growth in a RBC treatment system is described as the filamentous organisms (Sphaerotilus, Geotrichum, Bacillus) actually serving a sort of skeltal system on which other microorganisms are able to attach. The thickness of biofilm is substantially reduced in each stage as a result of significant reduction in filamentous populations, and that is caused by the marked change of carbonenergy level in wastewater after passing it through each stage. Both Pseudomonas denitrificans and Beggiatoa alba are also present in the RBC system indicating that there are the involvements of nitrogen and sulphur transfers inherent in the systems (Banerji, 1980).

Jones, Roth, and Sanders (1969) used an electron microscope to study attachment of organisms to discs. They said that attachment was due to extracellular material produced by the organisms.

When organic loading to the RBC is too high, anoxia or anaerobiosis can occur (Bracewell, Jenkins, and Cameron, 1980; Chesner and Iannone, 1980; Hitdlebaugh and Miller, 1980; McGan and Sullivan, 1980; Smith and Bandy, 1980; Srinwaraghavan, Reh, and Canaday, 1980). The predominance of Beggiatoa has been linked to RBC biofilm growth when

loading rates are excessive or available oxygen is reduced (Banerji, 1980; Charackles and Trulear, 1980; Clark, Moseng, and Asano, 1978; Kinner and Bishop, 1980; Sudo, Okada, and Moie, 1977; Pretorius, 1971; Zobell, 1943). Labeled as a nuisance organism which hinders or degrades process performance, Beggiatoa appears on the disc as a whitish, filamentous mixotroph, oxidizing sulfide under aerobic or microaerobic conditions (Buchanan and Gibbons, 1974; Chesner and Iannone, 1980; Zobell, 1943). Desulfovibrio, a sulfide-producing organism, is often seen in anoxic situations, under Beggiatoa growth. According to Corpe (1978), these two organisms live symbiotically.

> At the onset of anoxia the lower strata organisms would successfully shift to alternative electron acceptors as a function of free energy (i.e., $O_2 \rightarrow NO^{-3}/NO_2 \rightarrow Fe^{3+} \rightarrow SO_4^{2-}$). Production and diffusion of sulfide towards the overlying aerobic zone would promote Beggiatoa which would employ sulfides and oxygen as electron donor and acceptor.

Alleman, Veil, and Canaday (1980) observed the relationship between Beggiatoa and Desulfovibrio with the scanning electron microscope. They concurred with Corpe, in that the outer layer would be aerobic and the inner layer anaerobic due to the hinderance of oxygen diffusion by the thickness of the biofilm. This, accompanied by sulfate reduction and fermentation reactions, would facilitate the growth of heterotrophic sulfate-reducing bacteria such as Desulfovibrio (Gaudy and Gaudy, 1980; Buchanan and Gibbons, 1974).

In the RBC a certain amount of filamentous growth is desirable to provide a backbone matrix for additional bacterial attachment (Banerji, 1980). Filamentous organisms may capture and retain organic solids for degradation by nonfilamentous species. However, a predominance of filamentous organisms, such as Sphaerotilus, Geotrichum, and Beggiatoa, has been related to poor overall efficiency of the RBC process.

RBC Literature Review

The RBC has traditionally been used for the removal of organic carbon from wastewater. Later its usage was expanded to encompass nitrification and denitrification. One of the earliest applications of the RBC in the U.S. was by Welch (1968). Working with an experimental unit for Allis-Chalmers, he was able to acquire 12.8 kg/m^3 d (800 lb/ 1,000 ft^3 d) removal of COD from concentrated wastewater. Torpey et al. (1971) worked with a ten-stage aluminum disked RBC and reported 92% BOD removal from a 124-mg $liter^{-1}$ influent within 5 months. Nitrification, as indicated by a drop in ammonia-nitrogen (NH_3-N) from 14.2 to 5.7 mg and a rise in nitrate from 0.0 to 10.4 mg $liter^{-1}$, also occurred. Antonie (1974) found good BOD removal with a full-scale RBC and reported up to 3.9 grams NH_3-N could also be removed.

Various parameters have been studied and varied to see what factors contribute to maximizing the efficiency of the RBC. Antonie (1970) varied flows and found that a retention time of 60 minutes in his system gave good COD removal, but that a retention time of 30 minutes or less lowered the COD removal. Antonie (1974) also found that low temperatures reduced the efficiency of actual RBC units and that covering the discs prevented seasonal problems. He also noted that sludge age, which is exceptionally long, is not a factor in the efficiency of the RBC.

Rotational speed of the discs has been studied by several researchers. A high rotational speed is desirable to increase dissolved oxygen levels, yet undesirable with regard to shearing force exerted on the biomass. Chittenden and Wells (1971) worked with an aerobic lagoon

effluent containing 225 mg liter^{-1} BOD. They were able to attain an overall BOD reduction of 83.2%; however, if the rotational speed was lowered, poor BOD removal and anoxia resulted. Pescod and Nair (1972) mentioned that a velocity (tip speed) of 5 cm sec^{-1} should be maintained, but Friedman et al. (1979) referred to early velocities set at 0.3 m sec^{-1} and said that the "advantage in increasing rotational speed is in higher organic loadings." However, Huang and Bates (1980) mentioned that although rotational speed would increase possible oxygen transfer, the rotational speed could not be increased indefinitely without increased power requirements and hydraulic shearing forces. They suggested replacing air with pure oxygen under pressure. They reported increased settleability and biomass production under these conditions. However, the increase in biomass caused bridging and may have resulted in decreased organic removal.

Many researchers noted that the variables already mentioned were dependent on the organic loading of the system. Stover and Kincannon (1976) experimentally determined that at least 90% COD removal would occur as long as the organic load to an RBC was kept at 6.4 kg meter^{-1} d^{-1} (400 lb/1,000 ft d) or less. Reh (1977), Lagrese (1978), and Sullivan (1978) all concluded that the design of the RBC should be based on soluble BOD_5 (Smith and Bandy, 1980), and Clark et al. (1978) found that BOD removal was a function of hydraulic loading. However, Poon, Choo, and Mikucki (1979) put the emphasis for design on organic loading or weight per unit time per volume. They stated that organic loading would take into account detention time and organic concentration.

The RBC process has been effectively applied to many types of wastewater such as dairy waste (Antonie and Welch, 1969), winery waste (LaBella, 1972), anaerobic effluents (Pretorius, 1971), highly saline domestic wastewater (Smith, Poon, and Miller, 1981), combined sewer overflows and storm infiltrations (Smith and Bandy, 1980), and munition wastes (Kitchens, Hyde, Purce, Jones, Wentsel, and Scot, 1980; Chesler and Eskelund, 1981; Smith, 1982; Smith and Green, 1982). It has also been used for removal of phosphorus and biological recarbonation (Noss and Miller, 1980), as an anaerobic treatment process (Pescod and Nair, 1972; Tait and Friedman, 1980; Smith, 1982), and in various municipal uses (Sack and Phillips, 1973; Griffith, Young, and Chien, 1978).

The advantages of the RBC are many, and are listed in Table 10. A comparative cost analysis by Clark et al. (1978) cites the following annual operating costs: $327,000.00 for modified activated sludge system, $698,000.00 for activated sludge with chemical additions, $383,000.00 for activated sludge with split flow filtrate, and $211,000.00 for RBC system. Pierce and Lundberg (1980) and Smith et al. (1981) equate the RBC, costwise, with single-stage activated sludge processes. However, Smith and Bandy (1980) point out that the economic advantage of the RBC is only true for small-capacity plants and is not proportional for large facilities.

The major disadvantages are few, and many are common to all biological systems (i.e., toxic materials and organic or hydraulic shock loads will cause decrease and some treatment deficiency, but not as much as in "suspended growth system" (Antonie, 1974; Smith and Bandy, 1980)). Specific disadvantages to the RBC are: (1) the RBC has been untested by

time (the oldest plant in the U.S. is only 7 years old) (Smith and Bandy, 1980); (2) an enclosure is necessary for areas where low temperatures are found (Antonie, 1974; Smith and Bandy, 1980); and (3) if scour velocity is too low, or if grit is present, suspended solids may accumulate in the reactor and result in foul odor and a fall in process efficiency (Smith and Bandy, 1980).

Table 10. The Advantages of the Rotating Biological Contactor (RBC) Over Other Biological Treatment Processes

Advantage	Reference
Handle shock loading	1,4
Handle nutrient-deficient waste	1
No failures due to washout or floating sludge	4
Low land requirement (500 ft^2/shaft)	1,4,5
Low capital cost	1
Simplicity of operation	1,4,5
Low maintenance	2,5
Low power consumption	2,5
High efficiency in oxygen transfer	4
Improved sludge settling	2,4,5
Nitrification	2
Flexibility	2
Greater response to transient loading	2,3
Ease of transporting and relocating	5
Can be retrofitted to existing treatment plants	5

References:

[1]Pescod and Nair (1972).

[2]Clark, Viessman, and Hammer (1978).

[3]Fibron (1979).

[4]Smith (1980).

[5]Smith, Poon, and Miller (1981).

Today, the RBC appears to be a stable and efficient biological process applicable to a wide variety of wastewaters. The RBC will fit well with trickling filter systems, which constitute approximately 95%

of the sewage treatment systems on military bases, and increased popularity in the use of RBCs on military bases is anticipated (Chan, unpublished). This, in part, is due to the success experienced by other researchers for using RBCs to treat various organic compounds, such as formaldehyde and formic acid as well as explosives RDX, HMX, and TNT in wastewaters generated by the military.

Many researchers have used bench-scale RBC plants for feasibility studies and scale-up determinations. The advantage of the bench-scale RBC versus larger pilot plants are: less chemicals required, less power to run, and more rapid conditioning to changing parameters (Chesler and Eskelund, 1980). A laboratory-scale RBC was used by Khan and Ramon (1980) to treat synthetic and domestic wastewater to size a pilot plant facility. Watt and Cahill (1980) used a five-stage, 0.25-meter-diameter disc system and were successful in using results for scaling up to a system containing 20,000 m^2 media area. Chesler and Eskelund (1980, 1981) used a small RBC system containing 2.28 m^2 of disc surface area and were able to do linear scale-up using pounds of BOD per square foot of disc surface area. The research presented here utilized a laboratory bench-scale RBC to determine (1) the technical feasibility of the RBC to handle AFFF-containing wastewater, and (2) the effect, if any, of AFFF on predominant biological populations within the RBC.

Materials and Methods

Physical Setup

A diagram and a photograph of the RBC physical setup are given in Figures 11 and 12, respectively. Influent was sterilized and aseptically added to a 20-liter reservoir (5-gallon bottle, Kimax). The

reservoir was then put on line aseptically. The initial flow rate of sterile influent into the aerobic RBC was 3.5 ml min^{-1} and was controlled by a peristaltic pump (Cole Parmer). The RBC was on loan from the U.S. Army Mobility Equipment Research and Development Command (USAMERDC), Ft. Belvoir, Va., and has been described in detail by them (Chesler and Eskelund, 1981). Basically, it was a five-chambered unit constructed of plexiglass. Each of the first four chambers contained six 1/4-inch- (0.6-cm-) thick plexiglass discs, 9-1/2 inches (24 cm) in diameter, mounted on a shaft 1/2 inch (1.27 cm) in diameter. One hundred and twelve (112) holes, 1/4 inch (0.6 cm) in diameter, were bored into each disc to aid in microbial attachment. The total disc area was 23.55 ft^2 (2.288 m^2). The last chamber was void of discs, acting as a 1-liter-capacity reservoir-clarifier. The total liquid capacity of the unit was 14.5 liters. The discs were rotated at 17.5 rpm, thus being equivalent to an edge velocity of 0.73 ft sec^{-1} (0.22 m sec^{-1}). An additional clarifier was added in the form of a modified Imhoff cone, which was used to visually measure the amount of sedimentation produced in a 24-hour period. Samples were taken from within all four stages, from the influent and, in the later period of the experiment, from the Imhoff cone/clarifier.

Inoculum

The seed for the startup of the RBC was 1 liter of activated sludge obtained from the Buenaventura County Water Treatment Plant, and was inoculated within 1 hour of acquisition.

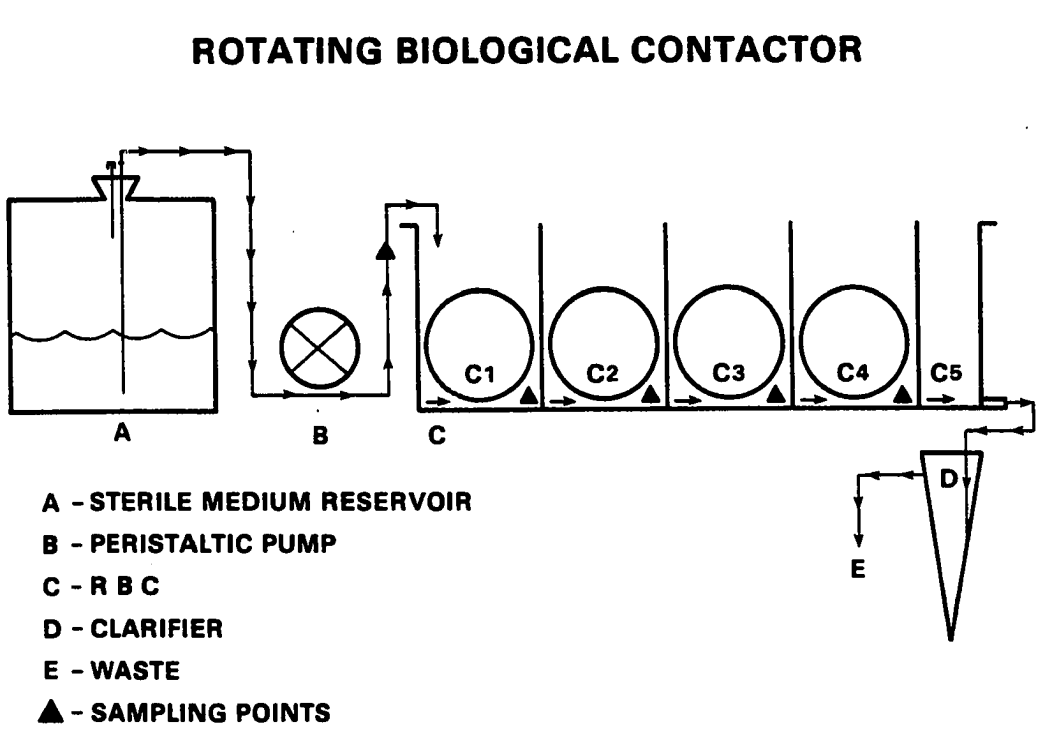


Figure 11. Diagram of rotating biological contactor setup.

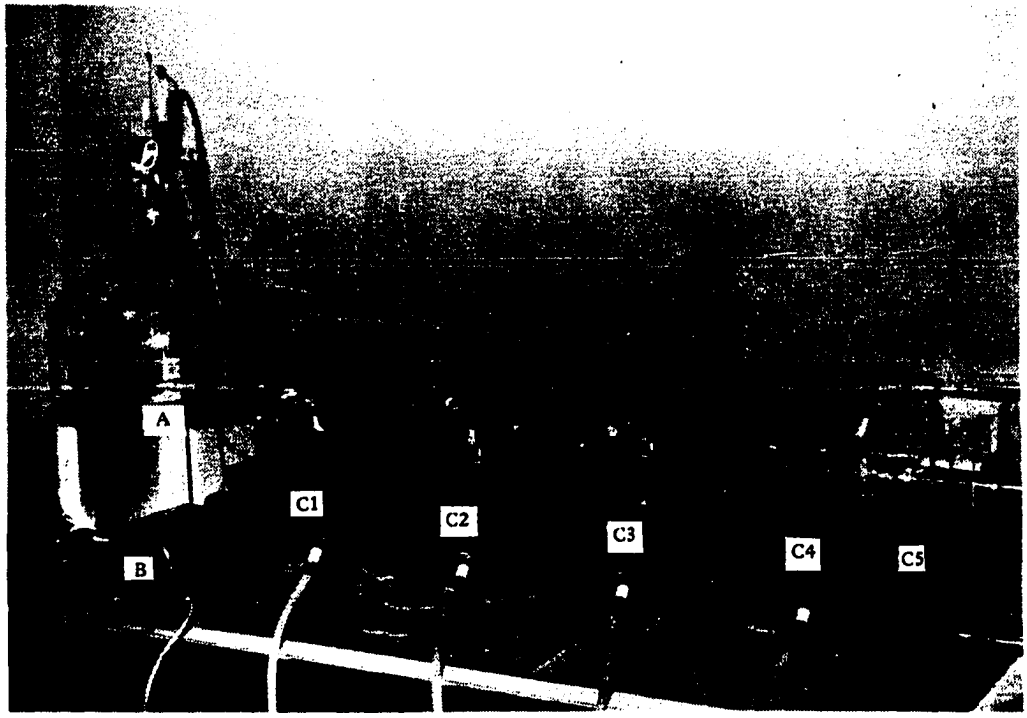


Figure 12. Bench-top rotating biological contactor.

Media

Bushnell Haas Broth (BHB) (Difco) was used. Varying concentrations of D-glucose, Nutrient Broth (Difco), and/or FC-780 were added as outlined in the procedure.

Growth Conditions

The RBC experiment was conducted at ambient temperature. Aeration was accomplished by the revolution of the discs through the wastewater. pH was monitored, and adjustments were made using 1N NaOH or 1N HCL when necessary.

Procedure

The system startup was as follows. The RBC was filled with 14.5 liters of BHB plus 0.1% glucose, inoculated with activated sludge, and allowed to run as a static system for 24 hours. Sterile influent containing 0.1% glucose was fed into the unit at a rate of 3.5 ml min^{-1} to achieve a hydraulic loading rate of 2.12 liters m^{-2} d^{-1} (0.052 gal/day/ft^2) and an organic loading rate of 0.788 kg/m^3 d (0.049 lb/day/ft^3). After 2 days it was determined that this mode of addition of the carbon source was inadequate to maximize colonization of the discs, and so glucose and/or nutrient broth was added to each stage once daily to a total concentration of 0.1% carbon. On day 29, FC-780 was added to the influent at a concentration of 100 mg $liter^{-1}$ in terms of COD. The concentration of FC-780 was gradually increased until a level of 1,000 mg $liter^{-1}$ COD was achieved on day 64. By day 78, the only carbon source added to the RBC was AFFF, via the influent, in the amount of 1,000 mg $liter^{-1}$ COD. This was equal to an organic loading of 0.742 kg m^{-3} d^{-1} (0.046 lb/day/ft^3). A concentration of 8,000 mg $liter^{-1}$ COD

was gradually reached by day 144 and maintained until the conclusion of the experiment on day 160. The final hydraulic and organic loading rates were 4.24 liters m^{-2} d^{-1} (0.104 gal/day/ft^3) and 11.789 kg m^{-3} d^{-1} (0.736 lb/day/ft^3), respectively. Flow rate was increased to 7.0 ml min^{-1} on day 115 and maintained throughout the remainder of the experiment. Samples were taken three times per week. BOD, COD, TOC, turbidity of the clarifier, and pH analyses were performed as described in Chapter II. Other parameters measured were:

A. Temperature. Readings were taken three times per week utilizing a Wahl digital heat-prober thermometer. The thermometer was placed directly into each of the four stages of the RBC.

B. Microorganism Identification. Bacterial and fungal populations were identified and enumerated utilizing: Nalgene Nutrient Pad Kits -- TTC and Wort, Bio Stix and Myco Stix test strips (Ames Company) and/or Total Count Water Tester (Millipore Corp). Microscopic qualitative observations were photographically recorded every 14 days to visually monitor changes in predominant populations. Observations were taken from glass microscope slides that were suspended for 14 days within each stage, scrapings off of actual discs, and wet mounts of suspended floc within each stage. Isolation of AFFF utilizing bacteria was accomplished as follows. Samples from the discs or the mixed liquor were streaked onto Bushell Haas Agar (Difco) containing 0.1% AFFF. After 7 to 10 days incubation

at ambient temperature, isolated colonies were picked and restreaked for isolation. This was repeated a third time to assure culture purity. Organisms were then identified to genus and species when possible.

C. Chromatographic Separation. Separation and quantification of different components within the influent and effluents were accomplished with the use of a high performance liquid chromatograph (Series 700, Waters Associates). A reverse phase C^{18} column (Waters Associates) was used as the stationary phase. The mobile phase consisted of a water and acetonitrile gradient (Bass, unpublished) given in Table 11. Chromatograms obtained from samples of BHB plus various concentrations of AFFF were compared with chromatograms of filtered, double deionized water (Figure 13). Peaks specific to AFFF were determined. AFFF eluted into two peaks: one eluting at approximately 0.66 minute and one eluting around 5.3 minutes after injection. Quantification of peak areas was performed internally by the machine. The quantity within peak 0.66 minute was significantly less than the quantity of substance eluting at 5.3 minutes.

D. Dissolved Oxygen. After day 108, dissolved oxygen (DO) readings were taken within each stage of the RBC utilizing an Orion oxygen electrode (Model 97-08).

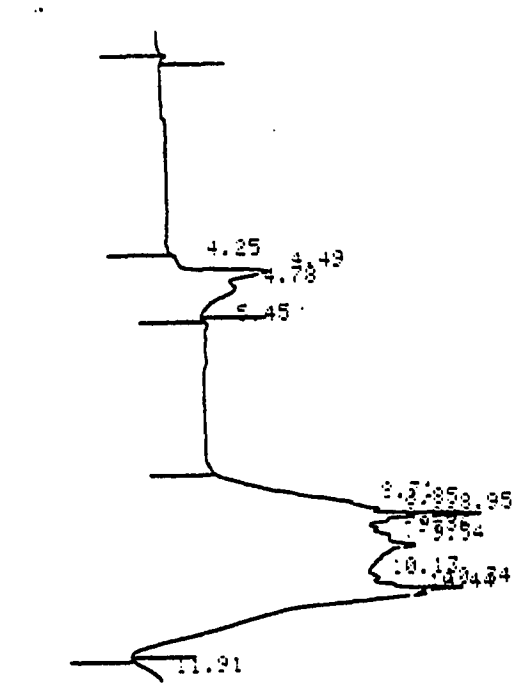
Table 11. HPLC Mobile Phase Gradient Used for Separation of AFFF-Containing Wastewater

Time (min)	Flow ($ml\ min^{-1}$)	% Acetonitrile	% Water
Initial	3.00	0	100
3.00	5.00	0	100
5.00	5.00	18	82
7.00	5.00	18	82
8.00	5.00	100	0
9.00	5.00	100	0
10.00	5.00	0	100
12.00	3.00	0	100

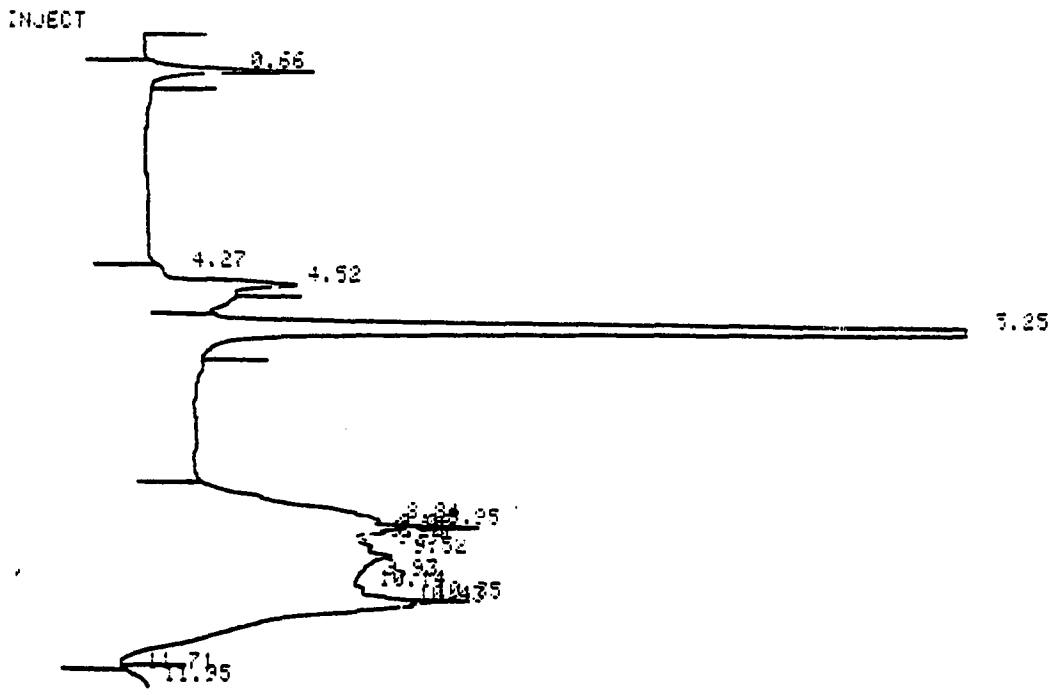
E. Sludge Sedimentation. Fifty milliliters of the mixed liquor from each stage was pipetted into a 50-ml conical centrifuge tube (VWR Scientific Inc., cat. no. 21008-500). After 30 minutes, the amount of gravity-settled solids was visually measured. The amount of settled solids in the clarifier was recorded after 24 hours of quiescence.

F. Foaming. A shake test for the foaming properties of residual AFFF in effluent was conducted on day 85. In the shake test 50 ml of the sample was placed in a ground glass stoppered 100-ml graduated cylinder. The sample was shaken vigorously for 30 seconds and allowed to settle for 5 minutes. Foam height was recorded and equated to linear alkylbenzene sulfonate as described by Chian (1978).

G. Ammonia Nitrogen. NH_3-N determination was performed according to the phenate method outlined in section 418 of Standard Methods (American Public Health Association, 1976) as modified by Technicon (Technicon Instrument Corporation, 1976).



a.



b.

Figure 13. High Performance Liquid Chromatography (HPLC) chromatograms for water (a) and AFFF (b) subjected to an acetonitrile and water gradient as described in the text.

H. Phosphate. Orthophosphate determination was performed according to the procedure outlined in section 425 of Standard Methods (American Public Health Association, 1976) and modified by Technicon (Technicon Instrument Corporation, 1976).

At the end of the 160-day RBC experiment, and effort was made to determine the amount of AFFF lost to mechanical foaming. The bench-top unit was drained and cleaned. Double deionized water containing 0.5, 1.0, 1.5, or 2.0% AFFF flowed through the RBC for 24-hour periods. At the end of each 24 hours, COD, TOC, BOD, HPLC analysis, and total colony counts were performed on sampling sites. Sampling sites were the influent bottle, each of the four stages, and the clarifier.

Results and Discussion

At initial start-up, 0.2% glucose was added via the influent to stage 1 of the RBC at a flow rate of 4 ml min^{-1}. This proved to be too high of a concentration of glucose in that the pH of the RBC rapidly became acidic and was thought to endanger the not yet well established microbial population. Therefore, the concentration of added carbon, in the form of glucose, was dropped to 0.1%. However, the majority of this carbon (97%) was used in stages 1 and 2, and stages 3 and 4 failed to exhibit growth on the discs. To achieve colonization of all the RBC discs, 0.1% carbon-source, in the form of a 10X concentrate, was added to each stage daily. This also stopped the recurring back contamination into the sterile influent reservoir, which now contained BHB only.

It was noted that the pH of the effluents daily dropped into the acidic range (6.0-6.9) and had to be chemically adjusted. After 3 days, nutrient broth was added in the form of a 10X concentrate, along with the 10X glucose, to result in a final concentration of 0.1% carbon. It was thought that whereas glucose was metabolized aerobically into acids, the nutrient broth would be metabolized with the resulting release of amino groups. This would help to raise the pH, and the protein itself would also act as an additional buffer. This provided adequate pH regulation early in the experiment unless a malfunction in the equipment or a laboratory error occurred which resulted in a decrease in the pH of one or more of the stages. After day 78, sterile HCl was added to the influent to compensate for the alkalinity resulting from AFFF utilization. If the influent was adjusted to a pH between 2.5 to 3, this was adequate to maintain a pH of approximately 7.0 in the RBC.

Temperature within the RBC stages fluctuated between 15°C and 22°C, with a mean temperature of 19.7°C over the 160-day experiment.

The results of total colony counts for bacteria and fungi are given in Figures 14 and 15. Results presented in these figures should be considered as approximate. The amount of floc contained in each sample varied because the regions sampled within each stage were not the same from sampling period to sampling period. The diluent containing the sample was vortexed vigorously; however, this was not adequate to homogenize the clumps of floc (Pike, 1975). The media used was not specific for total wastewater microorganism enumeration (Pike, 1975).

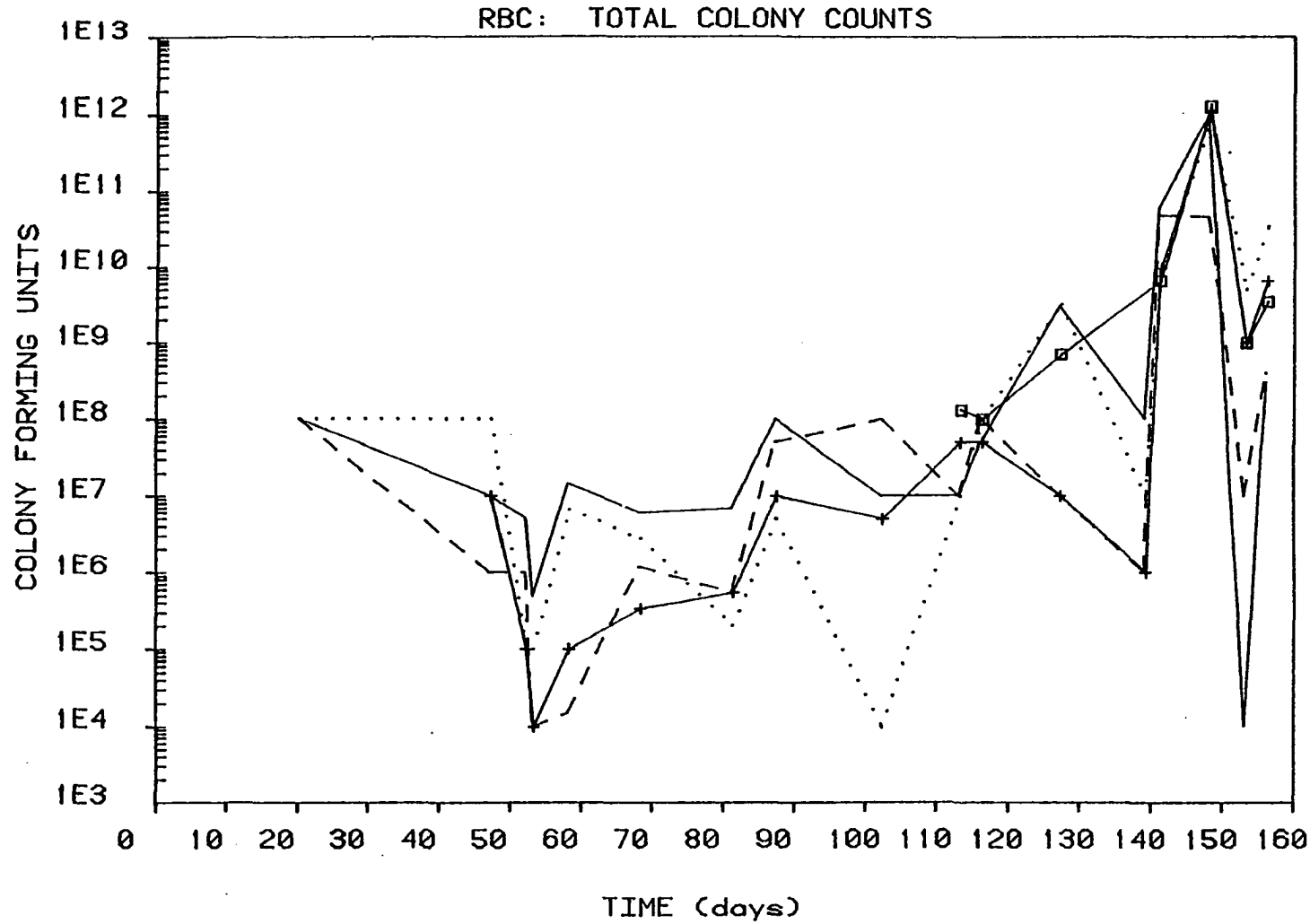


Figure 14. Total colony counts within each stage present as a function of time.
Stage 1, ———, Stage 2— — —, Stage · · · · ·, Stage 4 ⊟⊟⊟, Clarifier -/-/-/-/—.

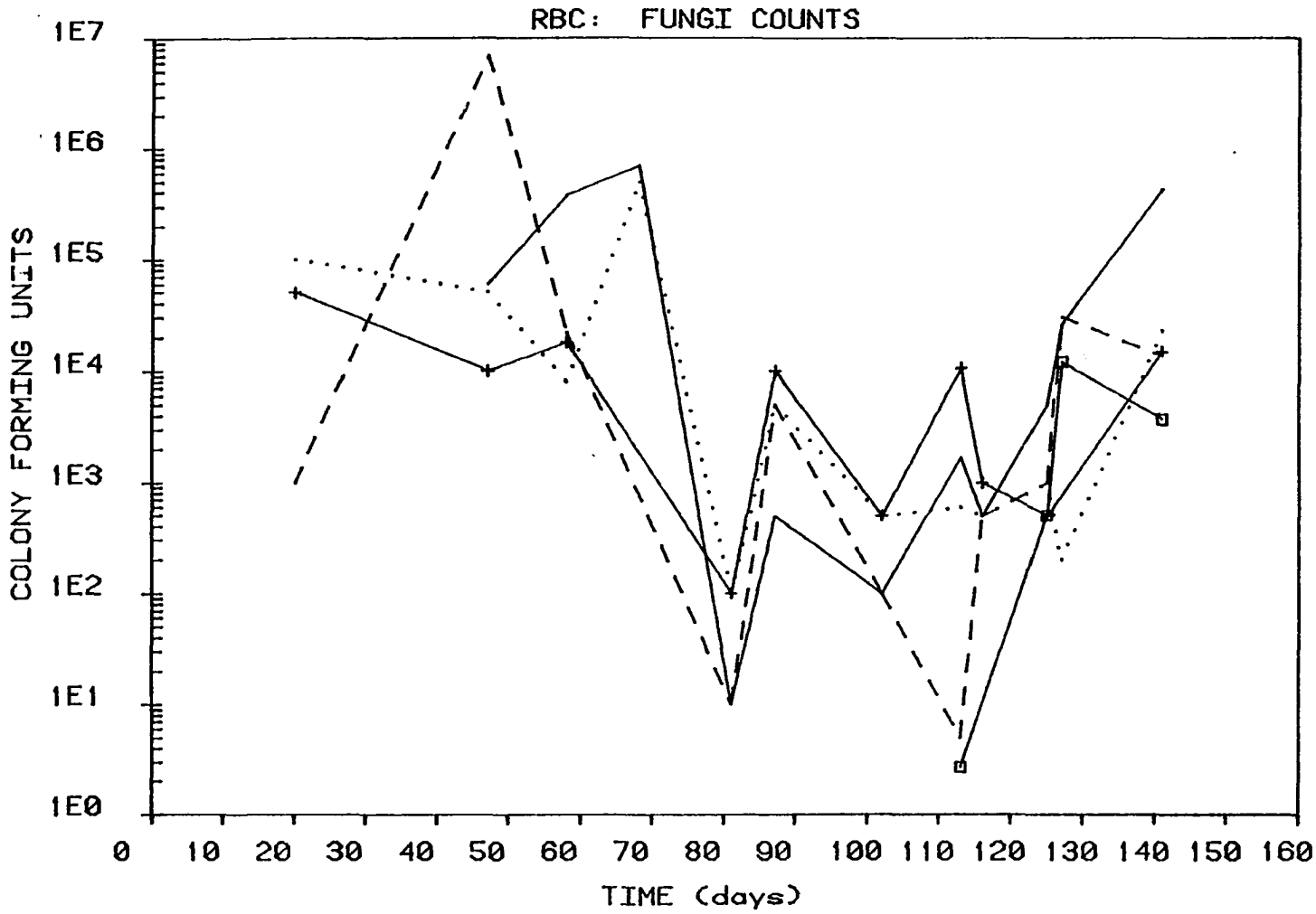


Figure 15. Total fungal colony counts within each stage presented as a function of time.
Stage 1———, Stage 2— — —, Stage 3 · · · · ·, Stage 4 ⊟⊟⊟, Clarifier ⁄ ⁄ ⁄.

From Figure 14 it can be seen that the relative number of bacterial colony forming units (cfu) increased with time. This correlated to the increasing concentration of AFFF entering through the synthetic wastewater. This increase in AFFF-correlated cfu was visually verified. Figures 16 through 26 show the microscopic and macroscopic appearance of the RBC with respect to AFFF concentrations and time. Table 12 categorizes the organisms seen into Monera, Algae, Fungi, Protozoa, and Metazoa. These categories are presented in relation to their appearance at various concentrations of AFFF.

Figure 16 shows the gross appearance of the RBC after 30 days. The biofilm on the discs appears relatively even from stage to stage, attributed to adding organic carbon to each stage individually. The texture of the brown biofilm was relatively dry. Sample organisms found adhering to the glass microscope slides suspended in each stage are given in Figure 17. The general composition of the adherent biomass was filamentous with ciliates, nematodes, rotifers, and numerous gram-staining bacteria (Table 12). The macroscopic appearance of the RBC unit handling 1,000 mg liter^{-1} COD (0.742 kg m^{-3} d^{-1} organic loading of AFFF) is shown in Figure 18. Low levels of foam began to accumulate. The discs still appeared even, with respect to the amount of growth present, because nutrient broth was added to each stage daily. The color and texture of the biomass was similar to that seen prior to AFFF addition. Microscopically, Figure 19 shows the general appearance of the biomass adherent to the suspended slides. Suctoria were the predominant protozoan at this time, and Rotiforia were conspicuously absent in stages 1 and 2 (Table 12). The gross appearance of the RBC at AFFF concentrations of

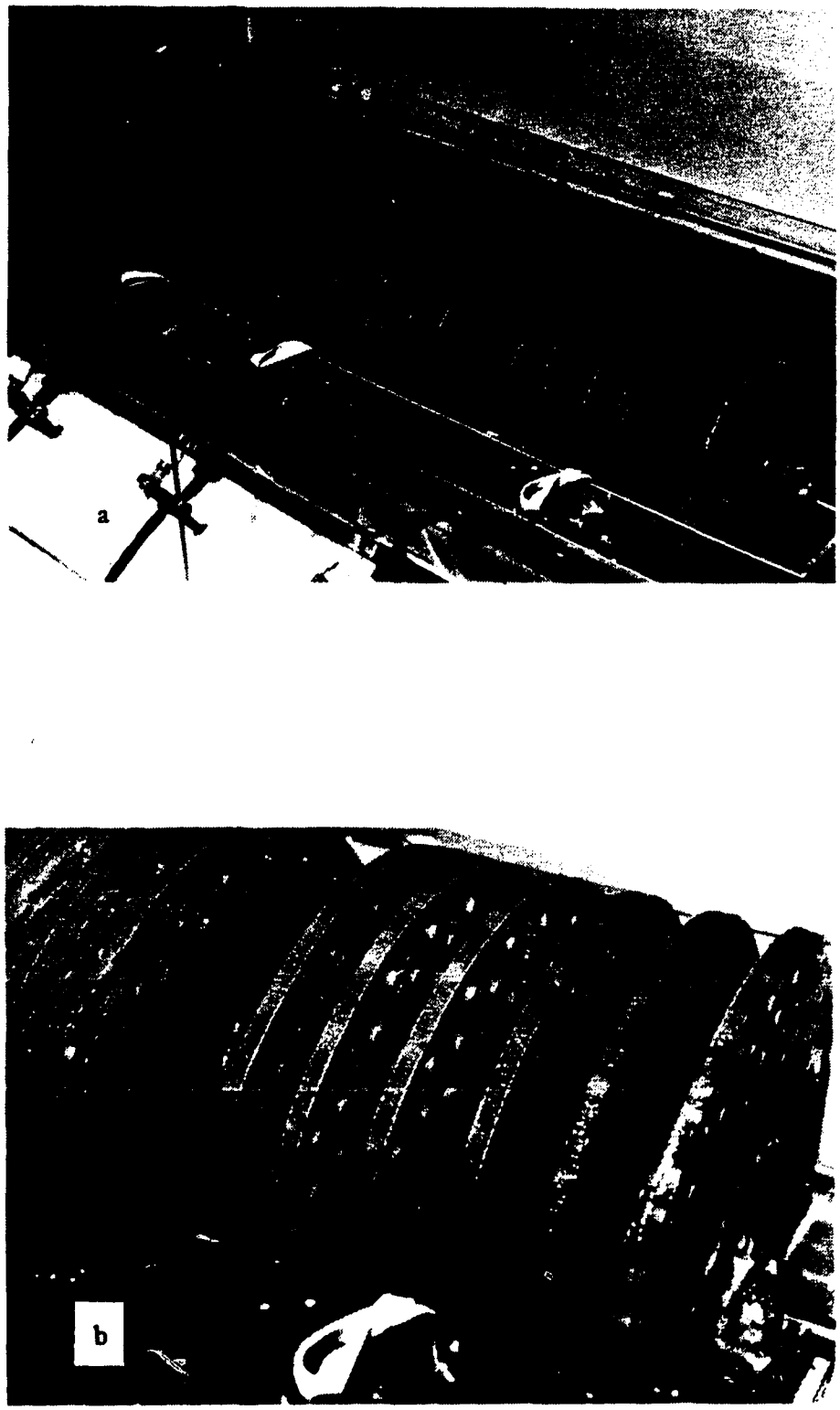


Figure 16. Rotating Biological Contactor after 30 days. Carbon source was glucose and/or nutrient broth added to each stage separately. a. Overview of all four stages; b. Close-up of disks in stage four showing texture and density of biofilm.

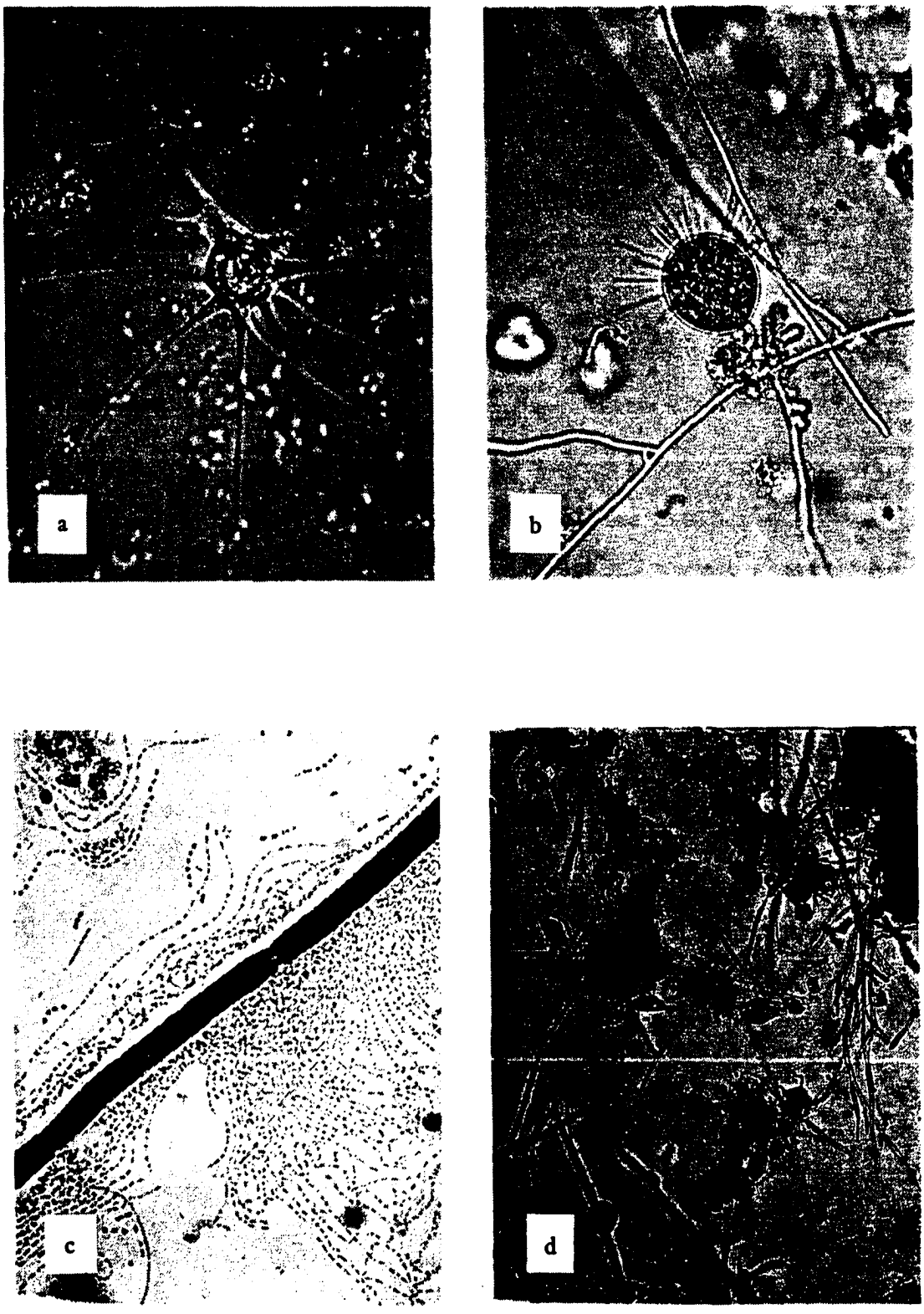


Figure 17. Representative RBC organisms seen adhering to suspended microscope slides. Carbon source was glucose and/or nutrient broth added to each stage separately. a. Amoeba radiosa (x800); b. Podophrya (x800); c. Filamentous bacteria (x2,000); d. Overview of adherent biofilm (x200).

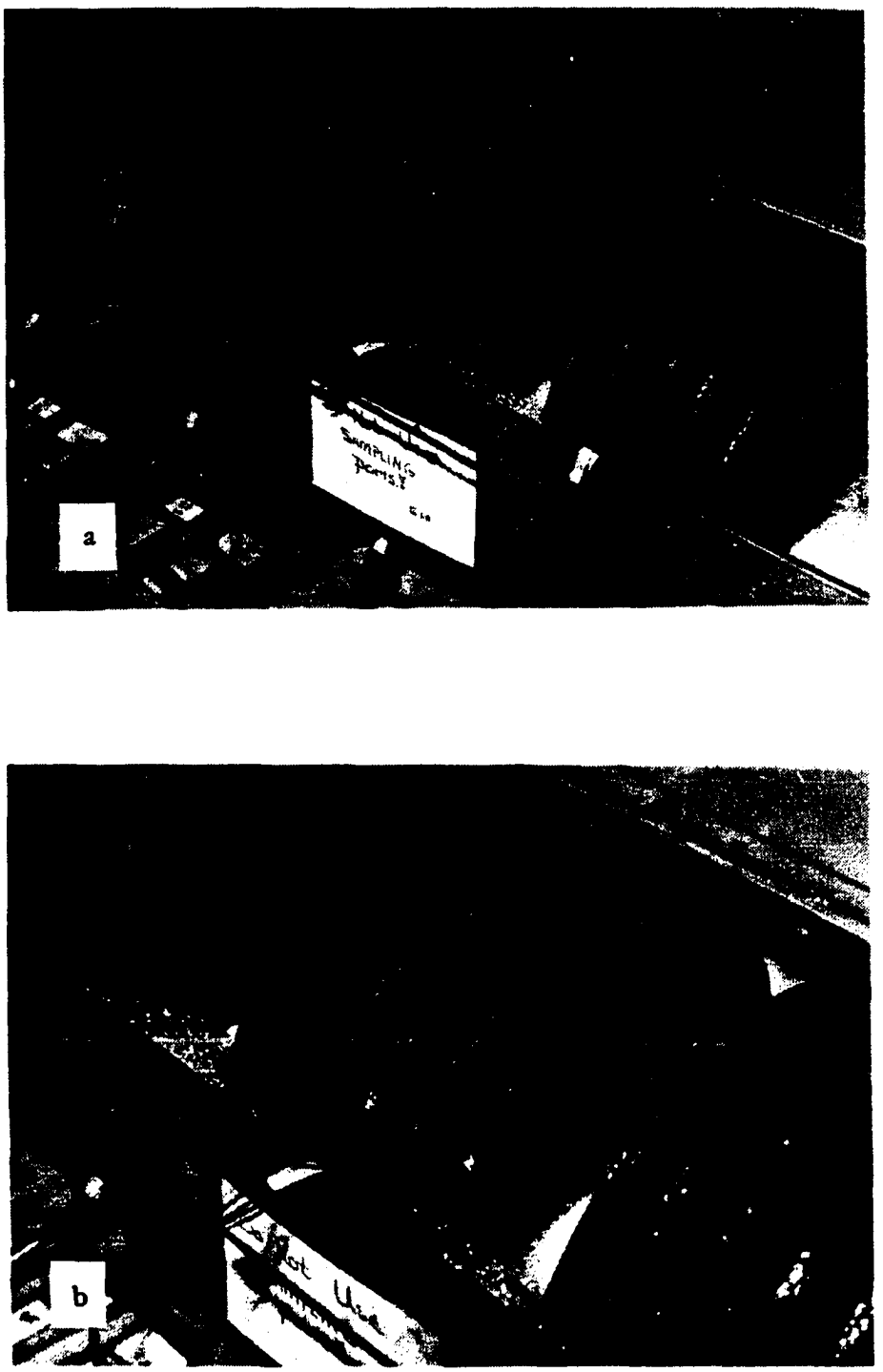


Figure 18. Appearance of RBC handling AFFF concentration of 1,000 mg liter^{-1} COD (0.742 kg m^{-3} d^{-1}). Glucose and/or nutrient broth added to each stage separately. a. Overview of all four stages; b. Close-up of disks in stage four showing texture and density of biofilm.

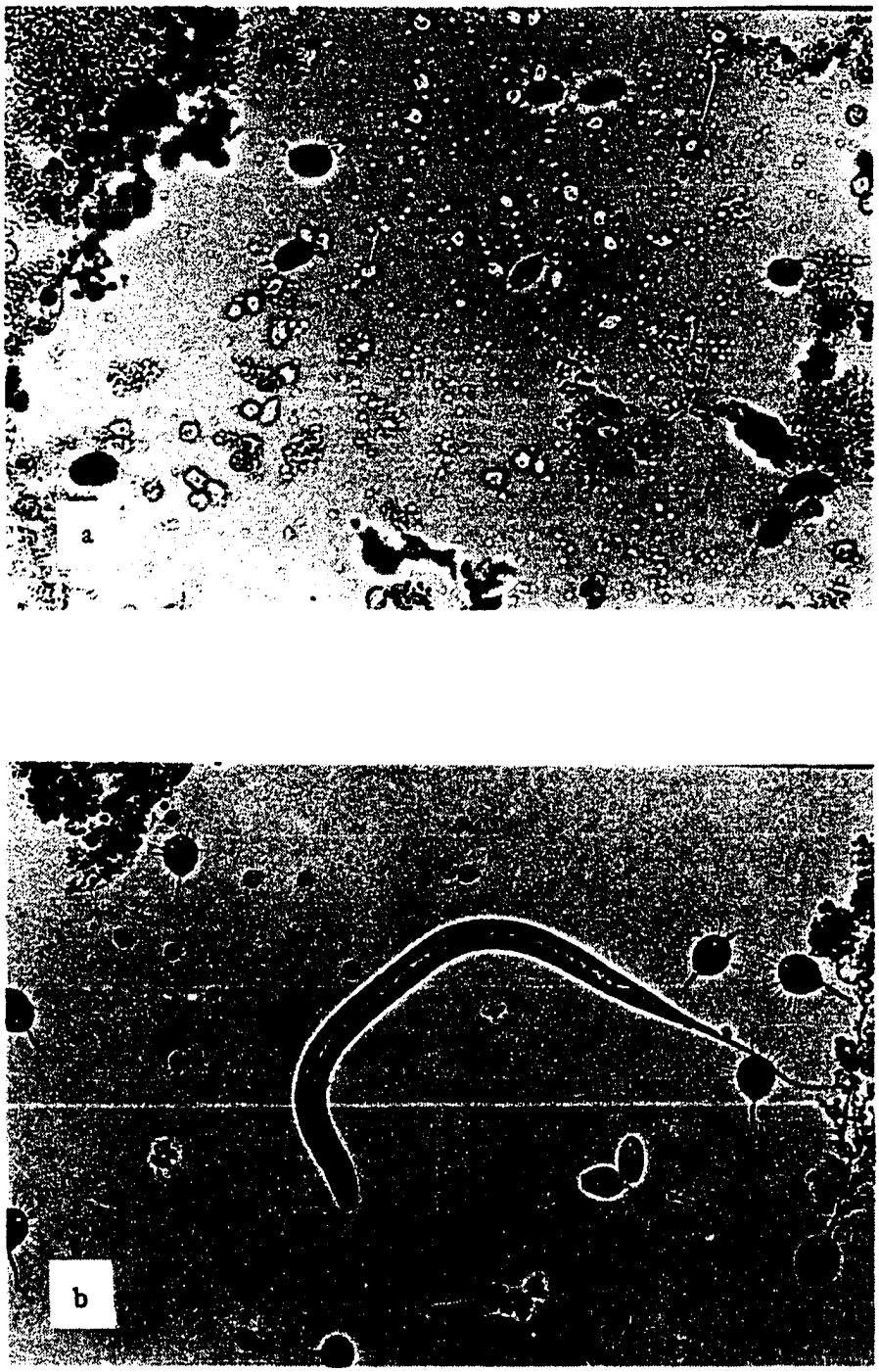


Figure 19. Representative RBC organisms adhering to suspended microscope slides. Carbon source was AFFF (1,000 mg liter^{-1} COD) and glucose or nutrient broth. a. Overview of adherent biofilm (x200); b. Nematode (x200). Note the prevalence of Suctoria.

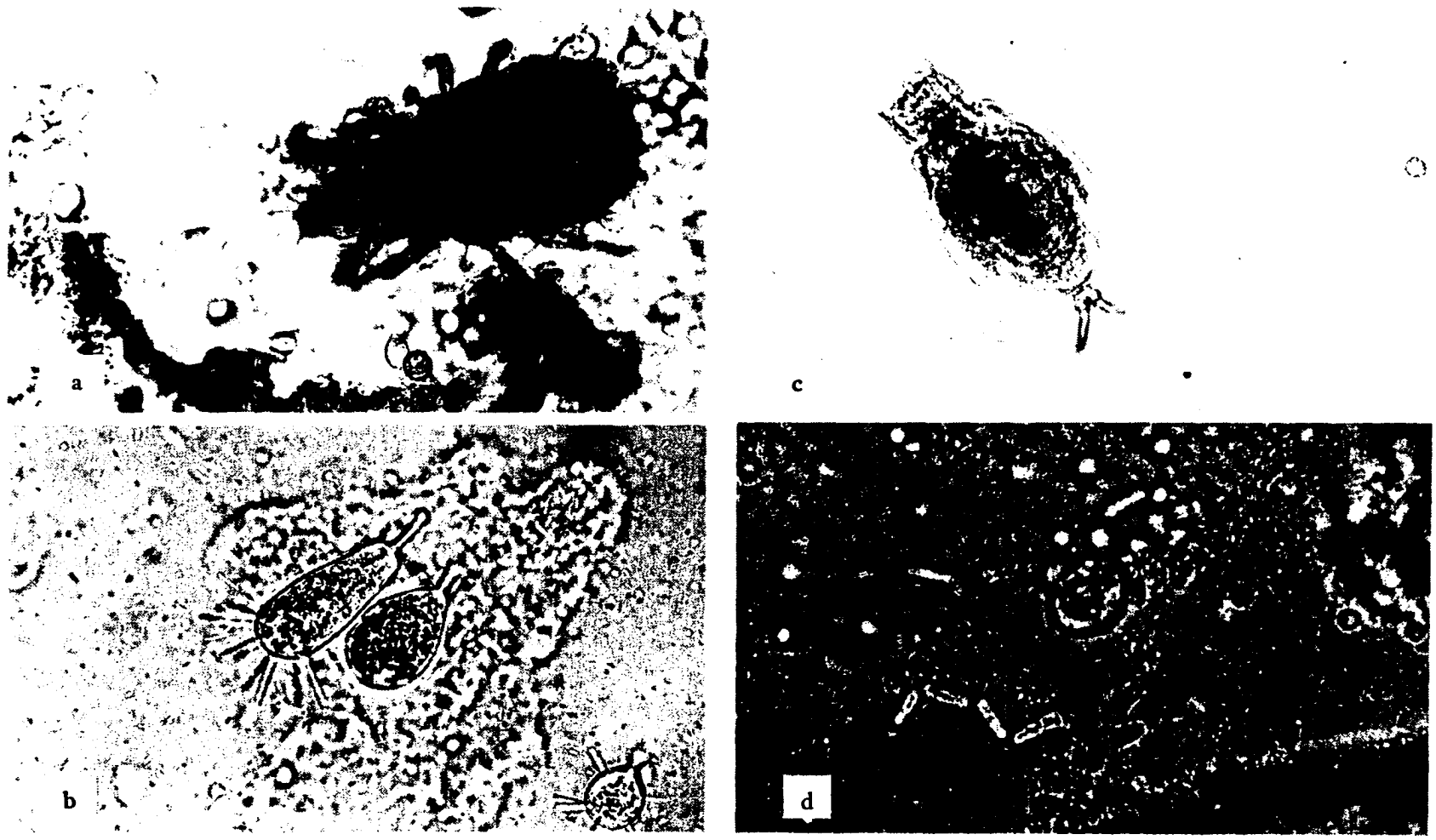


Figure 20. Representative RBC organisms adhering to suspended microscope slides. Carbon source was AFFF (2,000 mg liter^{-1} COD) added through the influent into stage one only. a. Histiostoma sp. (x200); b. Suctoria; c. Rotifera; d. Geotrichum sp. (x800).

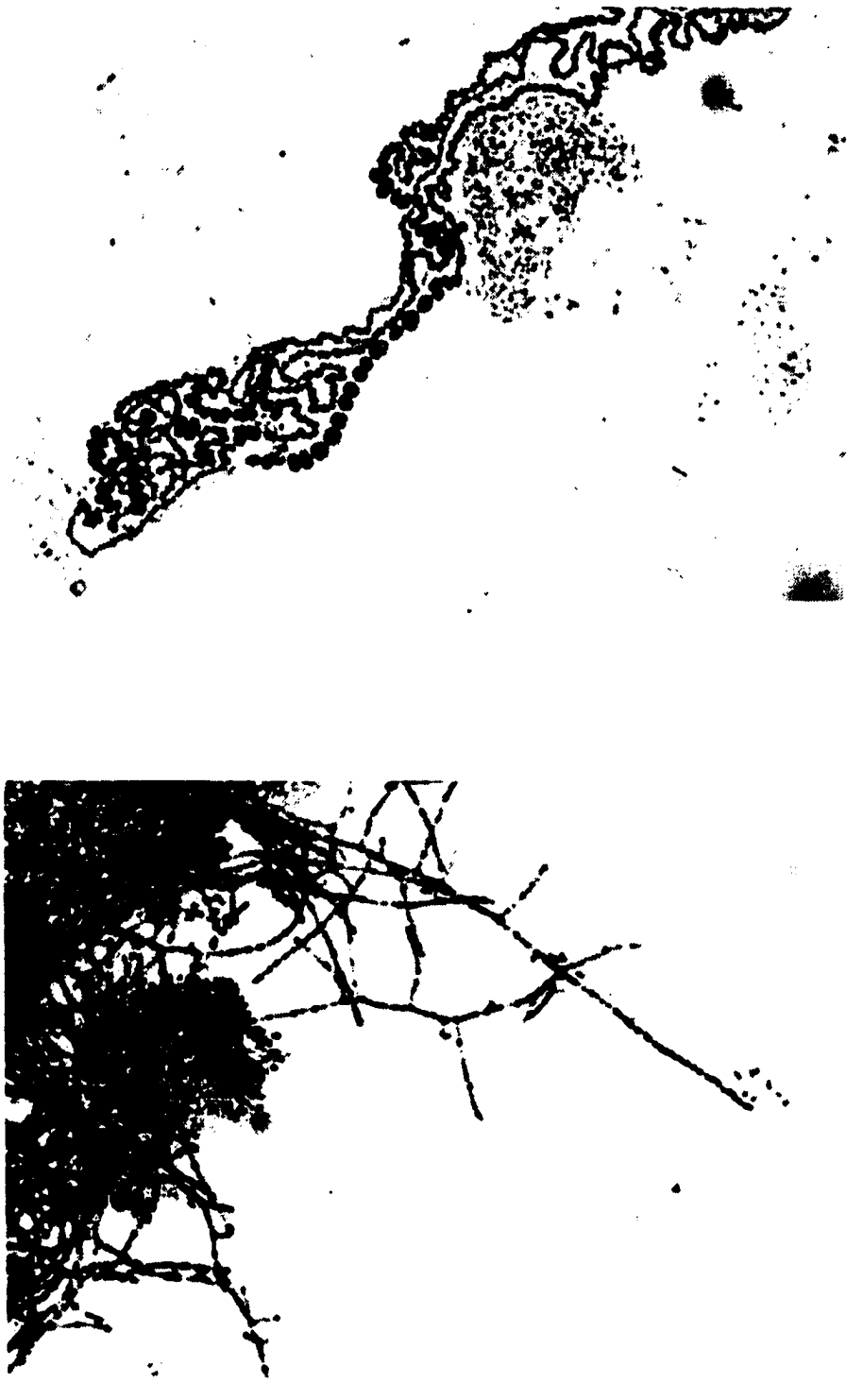


Figure 21. Typical filamentous organisms adhering to suspended microscopic slides. Carbon source was AFFF (2,000 mg liter^{-1} COD) added through the influent into stage one only (x2,000).

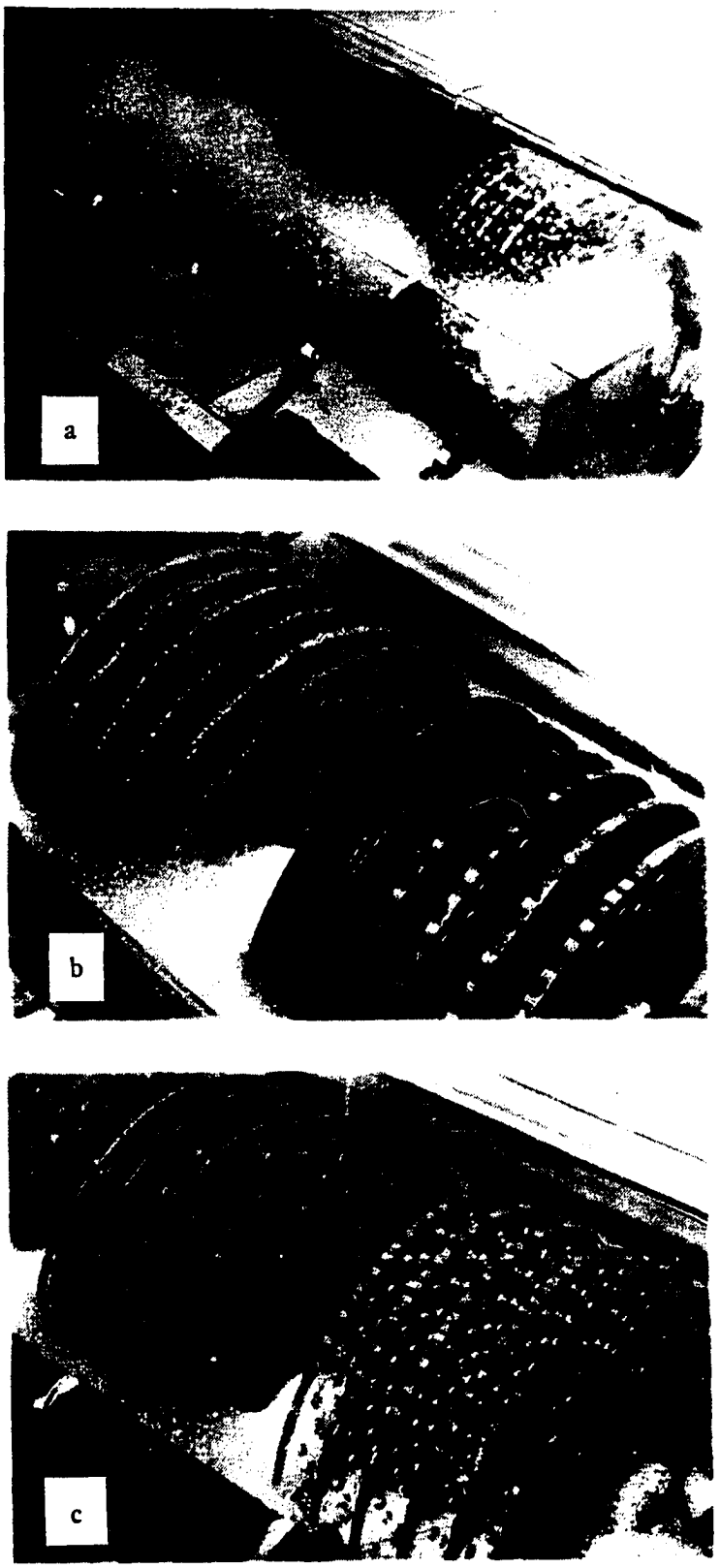


Figure 22. Appearance of RBC handling AFFF concentration of 4,000 to 6,000 mg liter^{-1} COD (3 kg to 8.8 kg m^{-3} d^{-1}) added by influent into stage one. Note the appearance of foam in all stages. a. Overview of all four stages; b. Stages one and two: stage one shows light color and change in biofilm texture; c. Stages three and four: stage four showing little biofilm attacked.

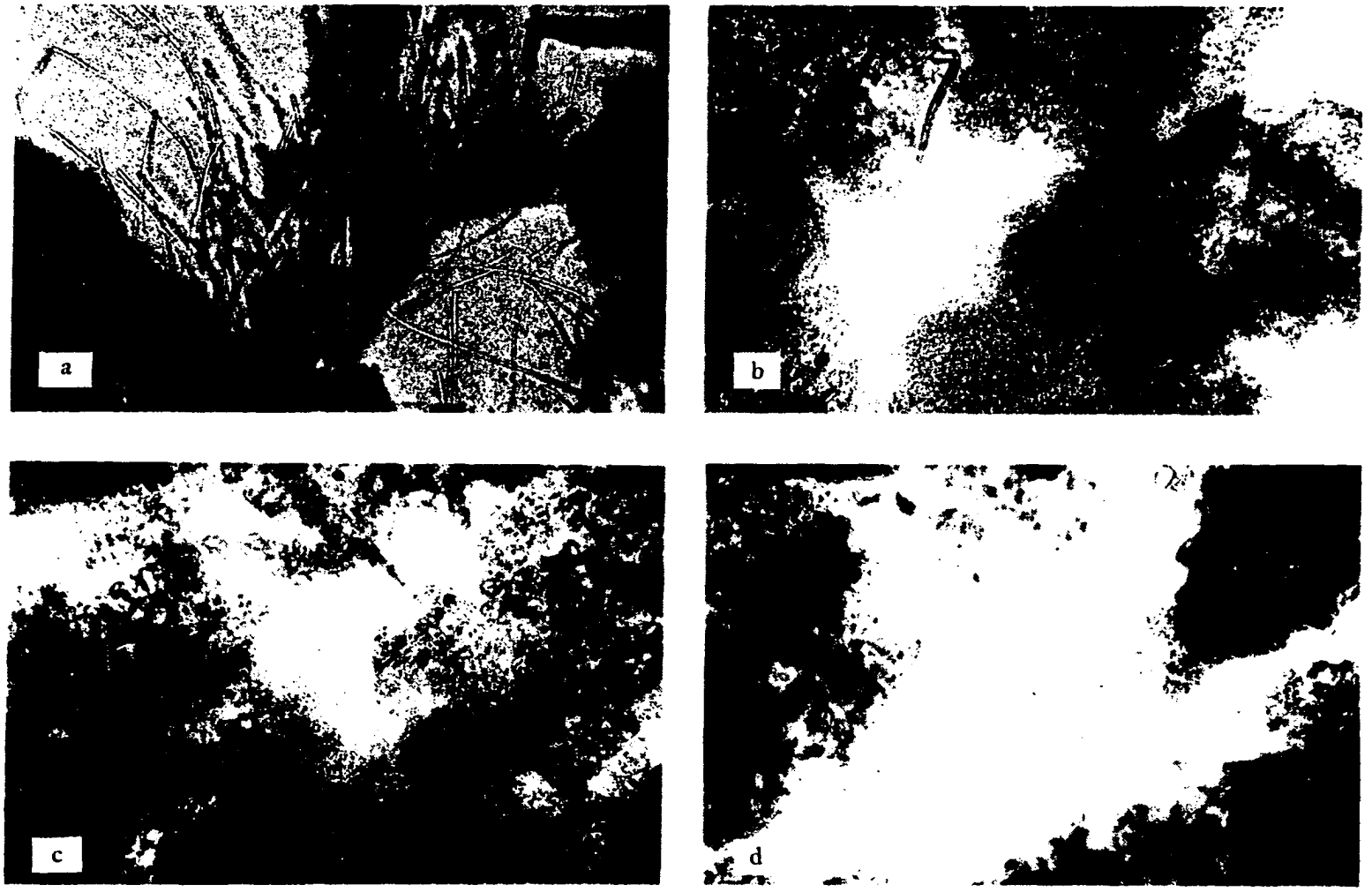


Figure 23. Representative RBC organisms scraped off of disks. Carbon source was 6,000 mg liter^{-1} COD
a. Stage one; b. Stage two; c. Stage three; d. Stage four (x200).

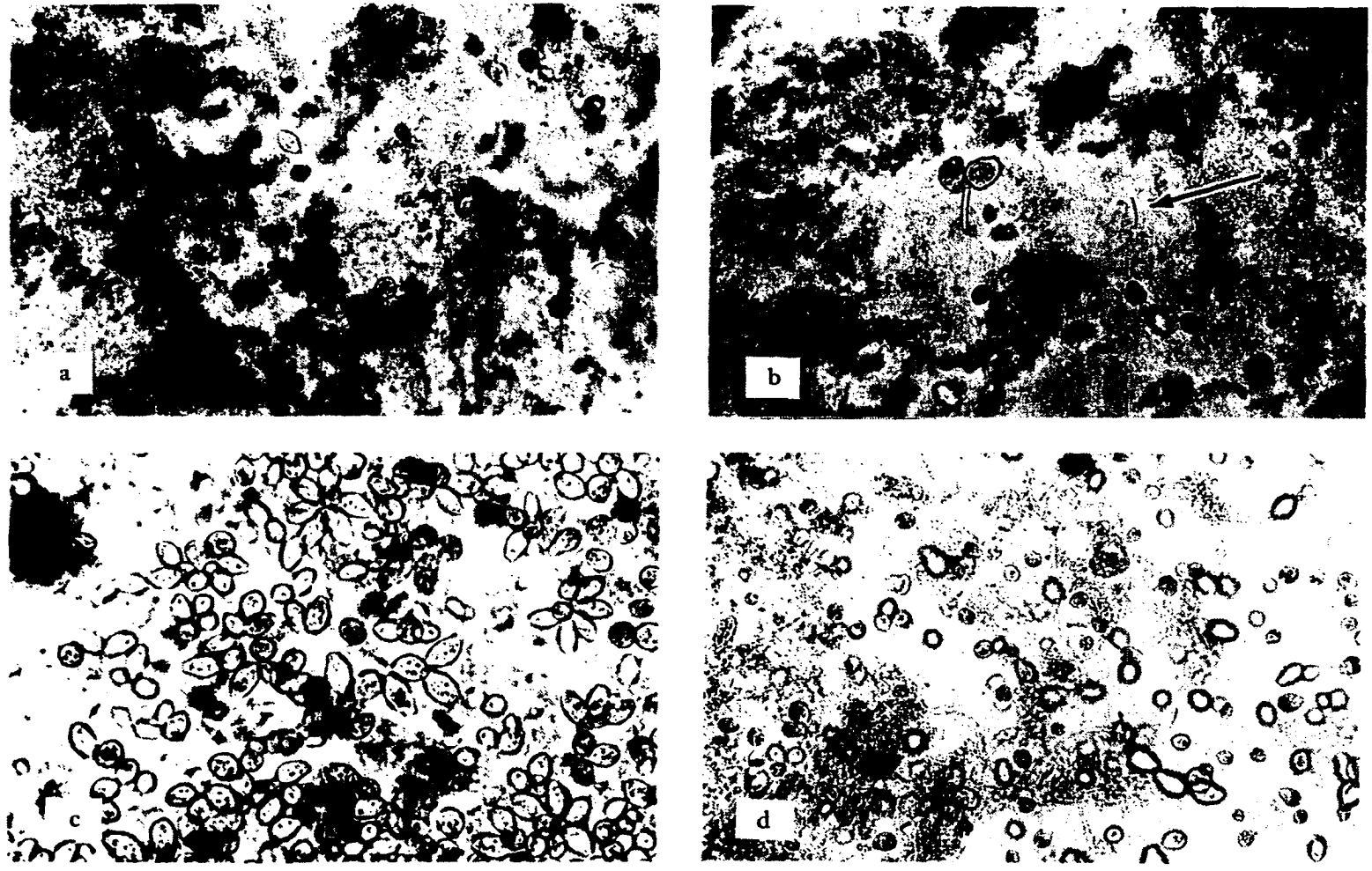


Figure 24. Representative organisms in suspended floc. Carbon source was 6000 mg liter $^{-1}$ COD.
a. Stage 1; b. Stage 2, arrow pointing to Fusarium spore; c. Stage 3; d. Stage 4 (200x).

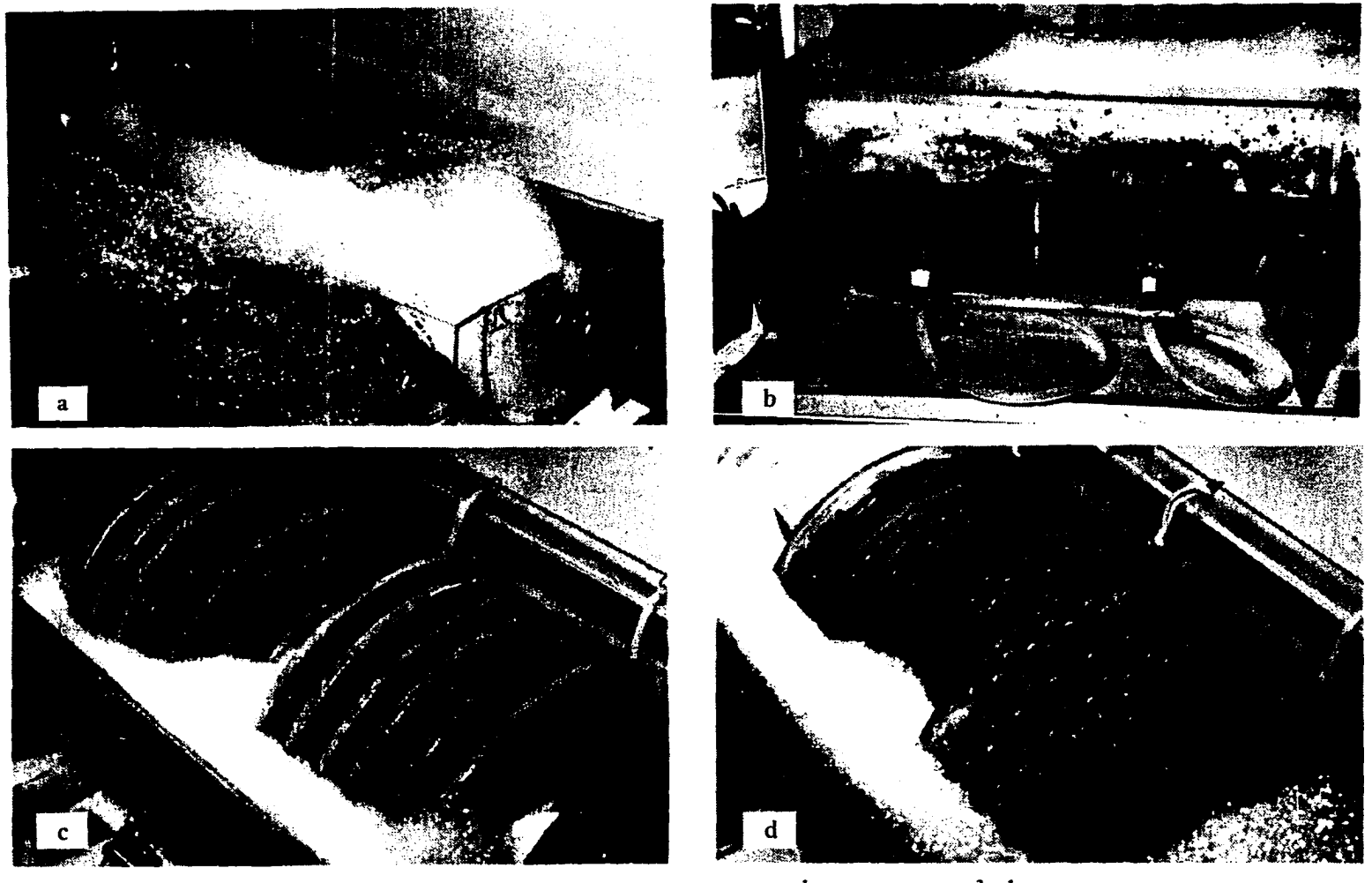


Figure 25. Appearance of RBC treating AFFF concentration of 8,000 mg liter^{-1} COD (11.8 kg m^{-3}d^{-1}). a. Overview of unit. Note the immense amount of foam produced; b. Side view of stages one and two, dark precipitate thought to be H_2S production; c. Stages one and two, note light color and texture of biofilm; d. Stages three and four.

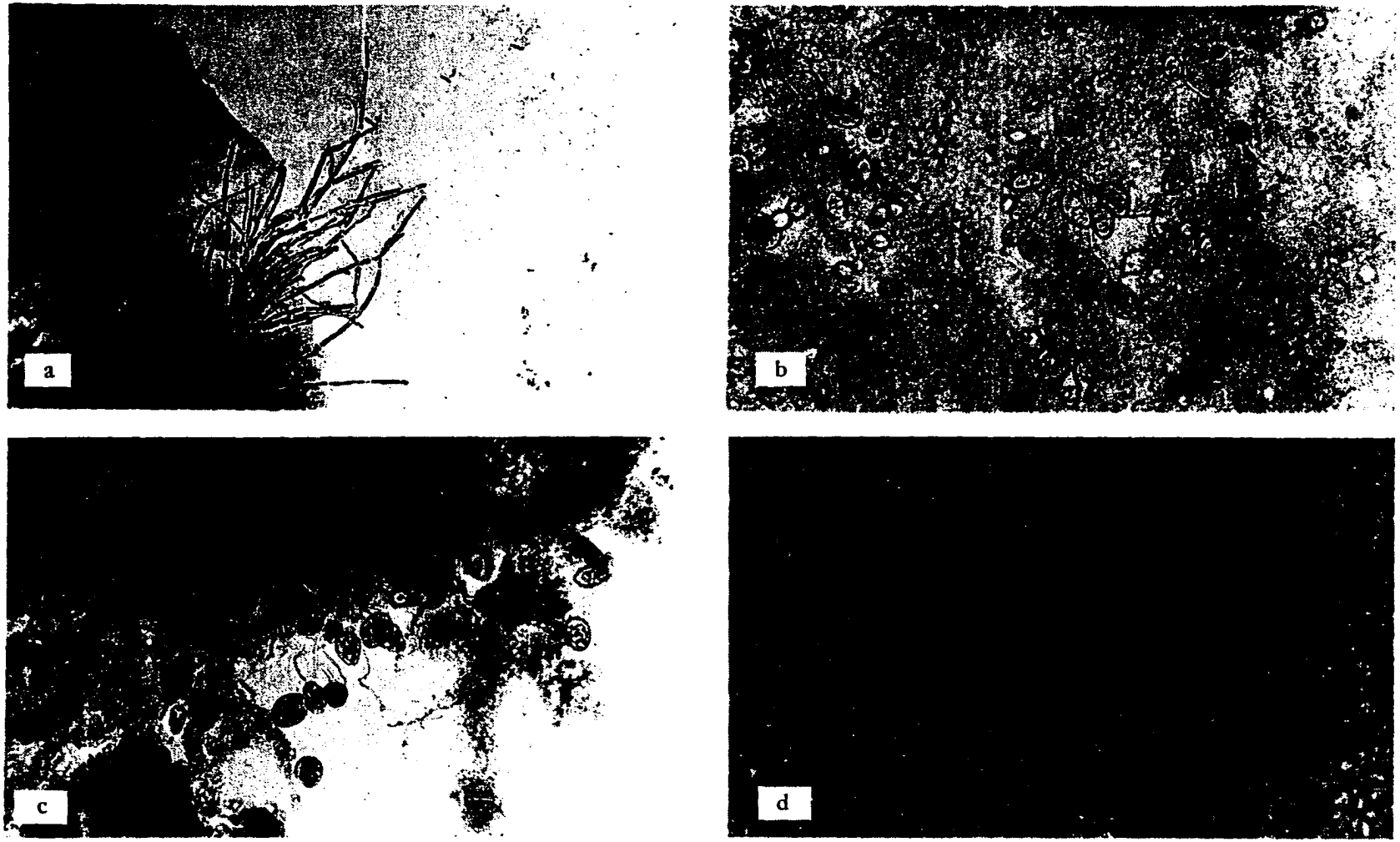


Figure 26. Representative RBC organisms adhering to suspended microscope slides. Carbon source was AFFF (8,000 mg liter^{-1} COD). a. Stage one; b. Stage two; c. Stage three; and d. Stage four.

2,000 mg liter^{-1} COD (1.484 kg m^{-3} d^{-1} organic loading) was similar to that seen with 1,000 mg liter^{-1} of AFFF (Figure 18). Some changes were seen in the microscopic population (Figure 20). The most noticeable changes were the relative absence of Sarcodina, the appearance of Arachnida, and a noticeable increase in the filamentous adherent bacteria (Figure 21). On day 78, the unit received AFFF as the sole carbon source and this was added via the influent. This had a dramatic effect on the gross appearance of the RBC. The first two stages maintained a relatively similar amount of growth compared to that previously seen. However, stage 3 exhibited much less growth, and stage 4 was extremely sparse. This situation can be seen in Figure 22. Here, the concentration of AFFF is 4,000 mg liter^{-1} (2.969 kg m^{-3} d^{-1} organic loading). Foam, at this concentration, posed a problem in that the increased density induced additional drag on the discs, slowing the rotational speed. This was compensated for by increasing the variable drive on the motor. It was noted that the biofilm on the discs in stage 1 was a lighter color than previously seen. The DO of stage 1 dropped to less than 1 mg liter^{-1} and it was assumed that the filamentous organisms seen on the discs were Beggiatoa sp. At 6,000 mg liter^{-1} COD (8.842 kg m^{-3} d^{-1} organic loading), the DO of stage 1 remained at 1 mg liter^{-1} and the biomass became dirty white in color. On microscopic examination, wet mounts of biomass from the discs in stage 1 showed heavy bacteria growth, dominated by Spirochetes, interspersed among filamentous growth (Figure 23). Even stage 4 showed an overabundance of bacteria compared to previous microscopic examinations. Examination of suspended floc within each stage showed more organismal diversity than the disc scrapings.

Floc was extremely heavy in all stages (Figure 24). This was confirmed by the observance of increased sludge sedimentation in each stage (Appendix A) around day 140. By the time an AFFF level of 8,000 mg liter^{-1} COD (11.789 kg m^{-3} d^{-1} organic load) was reached, the appearance of the RBC discs was obliterated by the amount of foam generated (Figure 25a). When the foam was cleared away, it was observed that the discs in stages 1 and 2 were dirty white in color (Figure 25c) and upon examination, heavily filamentous possibly by Beggiatoa sp (Table 12) (Buchanan and Gibbons, 1974; Chesner and Iannone, 1980; Zobell, 1943). Black, hydrogen sulfide precipitate, probably due to Desulfovibrio, was apparent through the sides of stages 1 and 2 (Figure 25b). This would correlate with the fact that the DO was often 1 mg liter^{-1} or less (Table 13). Low DO concentrations are conducive to Desulfovibrio growth (Chesner and Iannone, 1980). The biofilm on the discs in stages 3 and 4 was less dense and browner in color. The DO in these stages was 6 to 8 mg liter^{-1}. Suspended slide observations are presented photographically in Figure 26. Mastigophora were prevalent and were indicative of poor effluent quality. After one retention time of 8,000 mg liter^{-1} COD, the number of total cfu decreased in stages 1 and 2 (Figure 14) and the DO level elevated (Table 13). It is not known what happened here, possibly the high organic load caused die off of aerobic organisms or else a major sloughing occurred causing a decrease in the number of organisms in stages 1 and 2. Either would result in less metabolism and less use of DO.

Table 12. Organisms Present in RBC at Progressively Increasing Loads of AFFF

AFFF Organic Loading (kg/m^3 d)	AFFF (mg/l)	RBC Stage	Monera															Algae	Fungi		Protozoa					Metazoa		
			Gram Positive							Gram Negative																		
			Coccus	Streptococcus	Tetrad	Sarcinae	Bacillus	Streptobacillus	Sheathed	Coccus	Streptococcus	Bacillus	Coccobacillus	Streptobacillus	Sheathed	Spirochete	Spirillus		Filamentous	Yeast	Mastigophora	Sarcodina	Holotrichia/ Spirotrichia	Peritrichia	Suctoria	Rotifers	Nematodes	Arachnids
0.00	0	1	X	X	X	X	X	X		X	X		X						X		X	X	X	X	X	X	X	
		2	X	X	X	X	X	X		X	X		X						X		X	X	X	X	X	X	X	
		3	X	X	X	X	X	X		X	X		X						X		X	X	X	X	X	X	X	
		4	X	X	X	X	X	X		X	X		X						X		X	X	X	X	X	X	X	
0.148	200	1				X	X			X		X	X									X	X	X	X	X		
		2	X		X	X			X	X		X	X						X			X		X		X	X	
		3	X	X	X	X	X		X			X	X						X			X	X	X		X	X	
		4	X	X	X							X	X						X			X	X	[X]		X	X	
0.742	1,000	1	[X]	[X]	[X]	[X]	[X]	[X]	[X]		X	X	X			X		X			X	X	X	X	[X]		X	
		2							X			X	X					X	X			X	X	X	[X]		X	
		3	X	X			X		X									X	X					X	X	X		
		4	[X]			[X]	[X]					[X]	[X]					X	X	X	X	X	X	[X]		X	X	
1.484	2,000	1	X	X		X	X			X		X	X	X				X	X	X	X		X	X	X		X	X
		2	X		X		X		X			X	X						X				X	X	X	X	X	
		3					X	X	X			X							X					X	X		X	
		4						X				X		X					X				X	X	X	X	X	
2.969	4,000	1					X		X			X	X	X	X			X	X				X	X		X	X	X
		2	X				X	X	X			X	X	X					X	X	X			X			X	
		3					X	X	X			X	X	X	X					X	X			X		X	X	
		4										X	X	X	X								X	X		X		
5.894	4,000	1	X				X	X				X	X	X		X	X		X				X	X	X	X	X	
		2	X		X		X		X			X	X					X					[X]	X		X	[X]	X
		3	X	X			X	X	X			X		X		X					X				X			
		4	X	X			X	X	X			X		X					X		X				X			
8.842	6,000	1						X						X		[X]			X		X							
		2							X			X	X						X		X			X			X	
		3					X	X				X	X		X						X			X			X	
		4	X	X						X	X	X	X								[X]			X	X		X	
11.789	8,000	1					X	X	X			X	X								X			X			X	
		2	X				X	X	X			X	X						X		X			X			X	X
		3					X	X	X			X	X	X	X			X			X		[X]	X				X
		4	d	d	d	d	d	d	d	d	d	d	d	d	d	d		X	X		X		X	X		X	X	

[X] = predominant organism
d = data not available.

Table 13. Dissolved Oxygen (DO) as a Function of AFFF Concentration and Time

Day	AFFF Concentration (mg liter^{-1})	Organic Load (kg m^{-3} d^{-1})	Dissolved Oxygen (mg liter^{-1})			
			Stage 1	Stage 2	Stage 3	Stage 4
111	4,000	2.969	2.9	7.2	9.3	9.5
113			7.6	8.3	9.1	9.1
114			6.3	7.1	8.8	9.1
115			3.9	4.7	7.0	7.0
116		5.890	1.1	1.3	6.8	8.4
117			5.7	6.7	8.1	7.9
118			3.2	5.3	8.8	9.1
119			1.1	2.9	8.8	9.1
120			1.8	4.6	7.6	7.7
121			2.3	5.5	8.8	8.9
122			3.5	4.4	8.3	8.5
125			1.4	6.0	8.0	7.8
127			1.9	1.9	8.6	8.3
128			0.5	4.4	8.4	8.9
129			2.2	4.5	7.9	7.8
131			2.9	7.3	8.6	8.9
134			0.8	1.5	9.5	10.0
135			4.6	6.7	8.1	8.7
136			1.0	6.0	7.6	7.8
139	6,000	8.872	1.0	4.6	6.5	6.7
141			1.0	4.3	8.0	8.4
143			1.2	4.6	9.0	9.4
148	8,000	11.789	4.0	4.0	4.4	6.4
155			9.8	7.2	1.0	2.7
156			5.5	2.0	1.0	1.8

High organic loading correlated to a decrease in the amount of clarifier sedimentation with an increase in clarifier turbidity (Figures 27 and 28). The turbidity exhibited a marked increase around day 120. Here, the concentration of AFFF was 400 mg liter^{-1} COD and the flow rate was 3.5 ml min^{-1}. Flow was increased to 7 ml min^{-1}, thus increasing the scour velocity resulting in a settled solids increase into the clarifier.

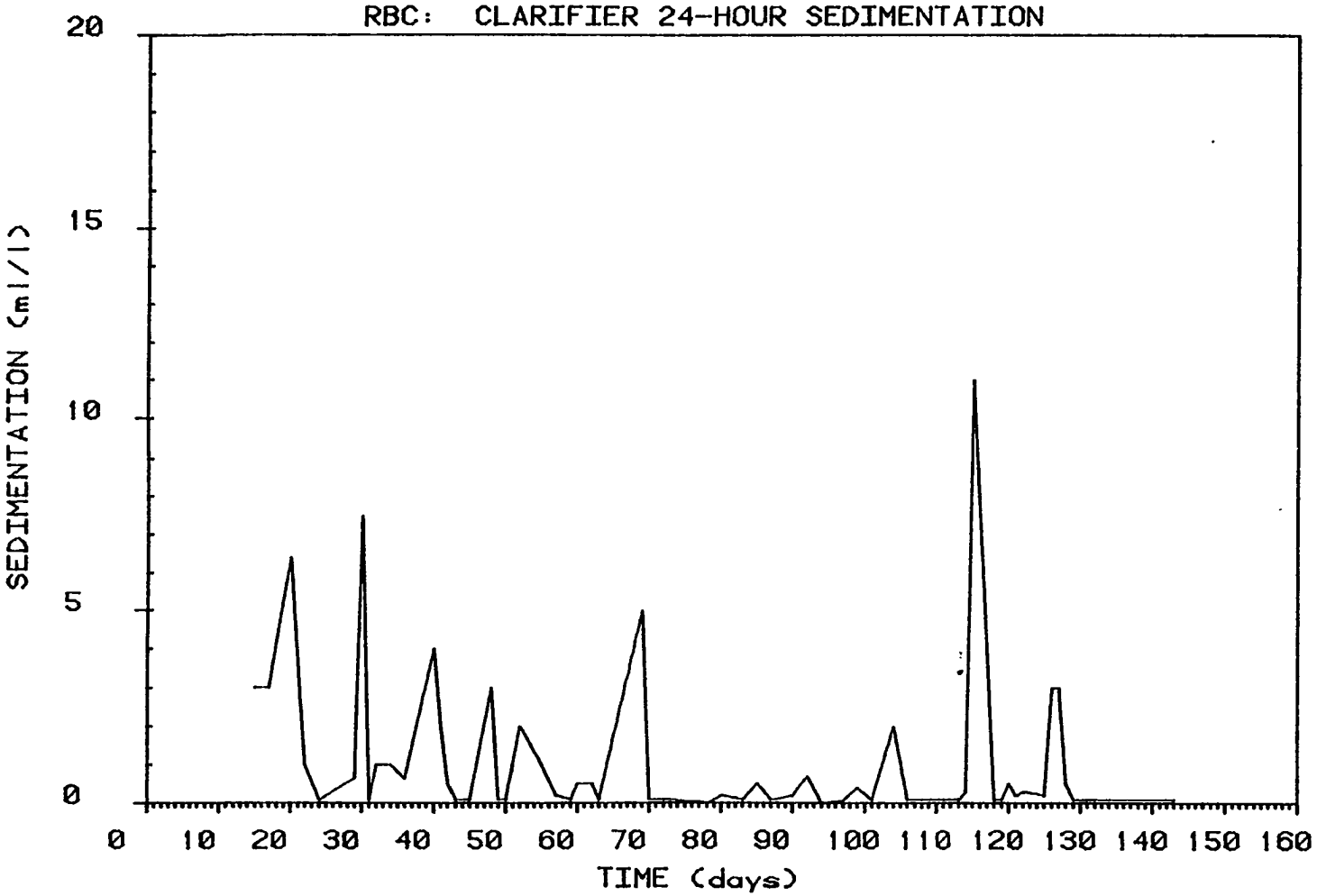


Figure 27. Sedimentation of solids within the clarifier. Values presented are milliliters per liter produced in a 24-hour period.

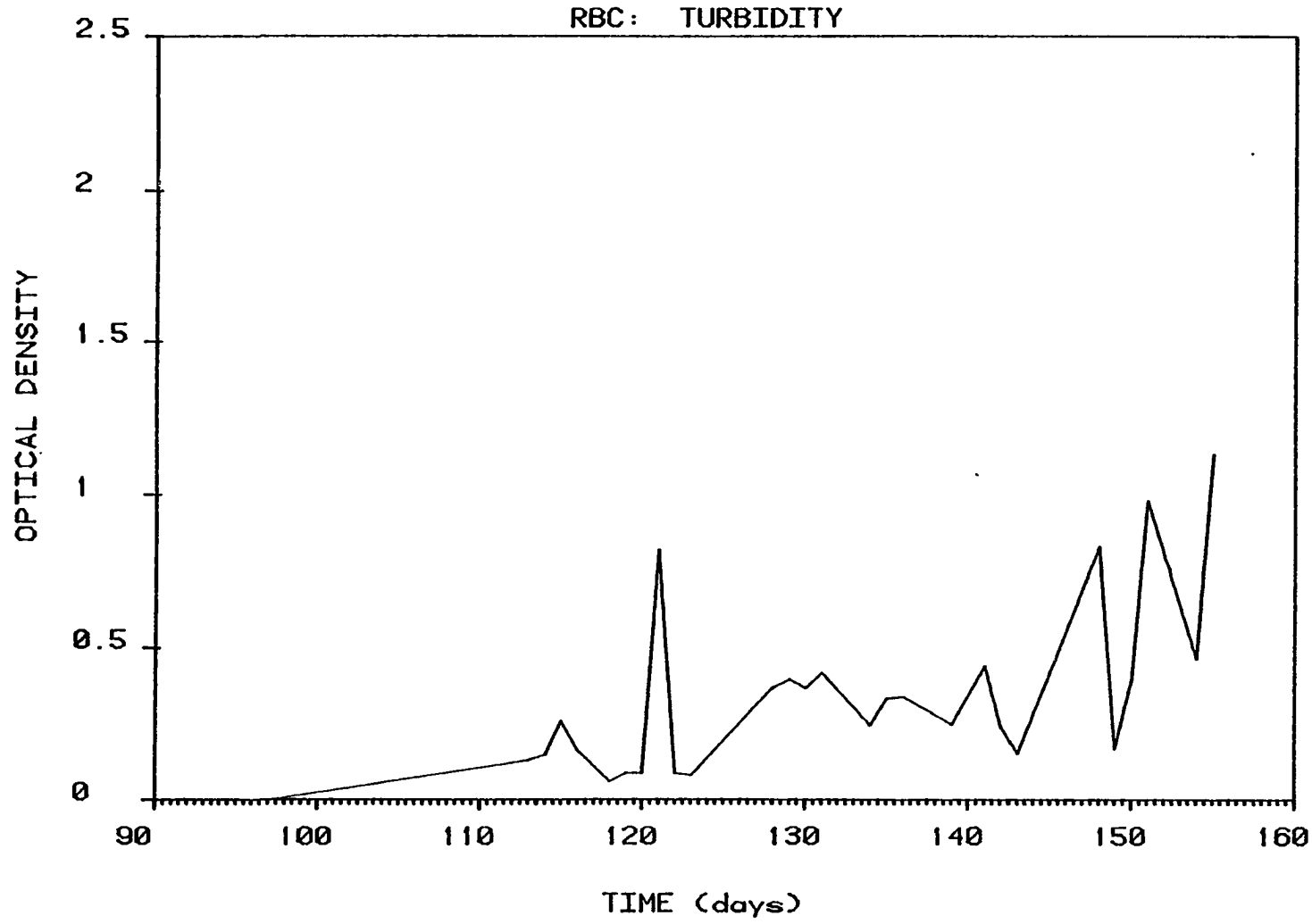


Figure 28. Clarifier turbidity measured as optical density. Samples were taken after 24-hour intervals.

The turbidity in the clarifier then decreased once again, possibly due to introduction of ciliates via the scoured sludge. As AFFF concentrations approached 6,000 to 8,000 mg liter^{-1} COD, the turbidity slowly increased. Microscopic observations were not done on the clarifier, but observations conducted on the RBC showed an increase in the mastagophoran population and a decrease in rotifers. Initially, efficiency remained high, but a correlated drop in carbonaceous removal occurred by the end of the experiment.

A list of organisms that were identified, at least to genus, is given in Table 14. Identification for all the organisms except those isolated on BHA containing 1% AFFF was via morphological characteristics (Curds and Hawkes, 1975; Martin, 1968; Needham and Needham, 1972; Ward, 1918). The organisms isolated on BHA with AFFF were identified according to morphological and biochemical characteristics as described in Bergey's Manual (Buchanon and Gibbons, 1974). Pseudomonas has been a prominent organism in the treatment of industrial wastes such as kepone (Orndorff and Colwell, 1980) and munition wastes (Kitchens, 1980). Alcaligenes species have been known to degrade mono and dichlorophenols (Yordy and Alexander, 1980). Both of these organisms were isolated frequently on media containing only AFFF as a carbon source.

The amount of ammonia nitrogen and orthophosphate were related to COD values to determine the carbon-to-nitrogen-to-phosphorus ratios (C:N:P). These ratios are listed according to their corresponding AFFF organic loading and are given in Table 15. Chan (unpublished) states that a normal ratio of C:N:P in treatment plants is 100:5:1. The C:N:P ratios presented in Table 15 were suitable to sustain luxuriant growth.

Table 14. Identified Genera From RBC Treating Wastewater Containing 1,000 to 8,000 mg liter^{-1} AFFF (as COD)

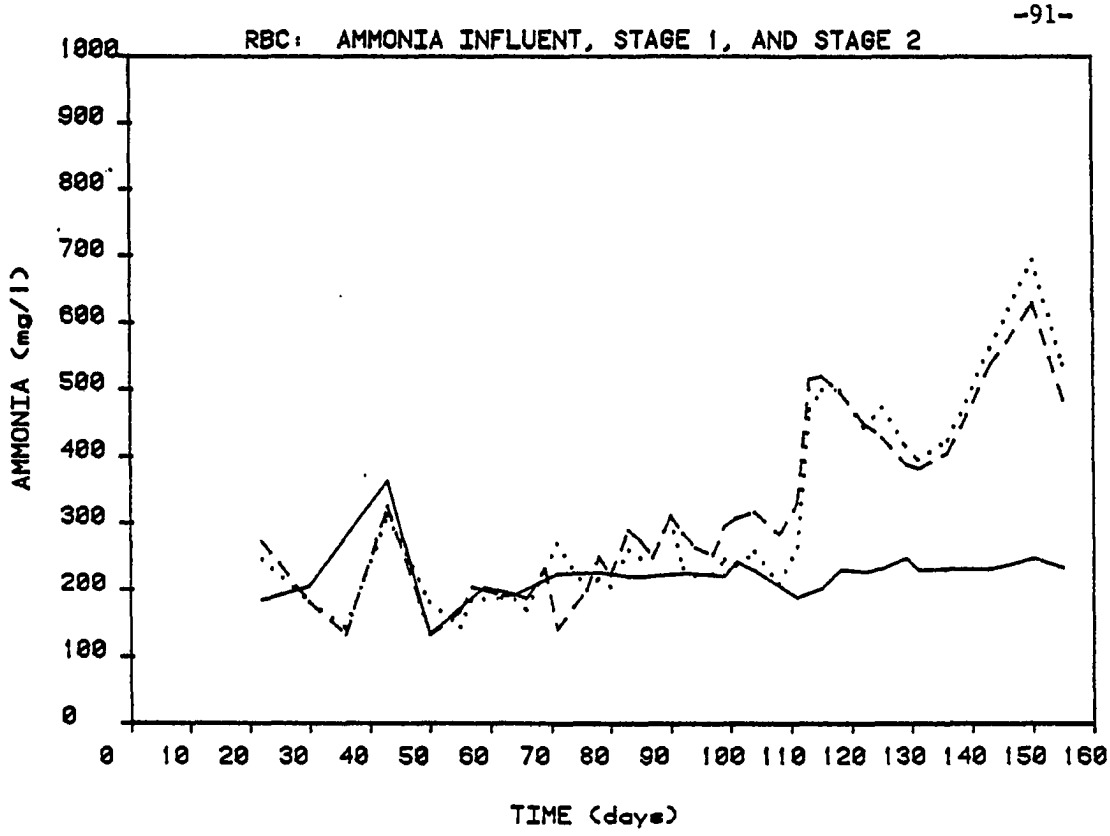
AFFF Utilizing	High Organic Loading
Monera	
Alcaligenes faecalis	*Sphaerotilus* sp
Flavobacterium sp	*Beggiatoa* sp
Pseudomonas fluoreseens	*Desulfovibrio* sp
Pseudomonas aeruginosa	
Pseudomonas putida	
Fungi	
Aspergillus sp	
Fusarium sp	
Rhizopus sp	
Geortrichum sp	
Protozoa	
Amoeba radiosa	
Argella sp	
Difflugia sp	
Paramecia sp	
Tetrahymina sp	
Stentor sp	
Vorticella sp	
Opercularia sp	
Oxytricha sp	
Lionotus sp	
Podophrya sp	
Ephilota sp	
Euploites	
Metazoa	
Rotifora	
Philodina sp	
Lecane sp	
Euchlanus sp	
Arachnida	
Rhizoglyphus echnopus	
Histiostoma feroniarum	

Table 15. The Organic Loading of AFFF and the Related Carbon-to-Nitrogen-to-Phosphorus (C:N:P) Ratio

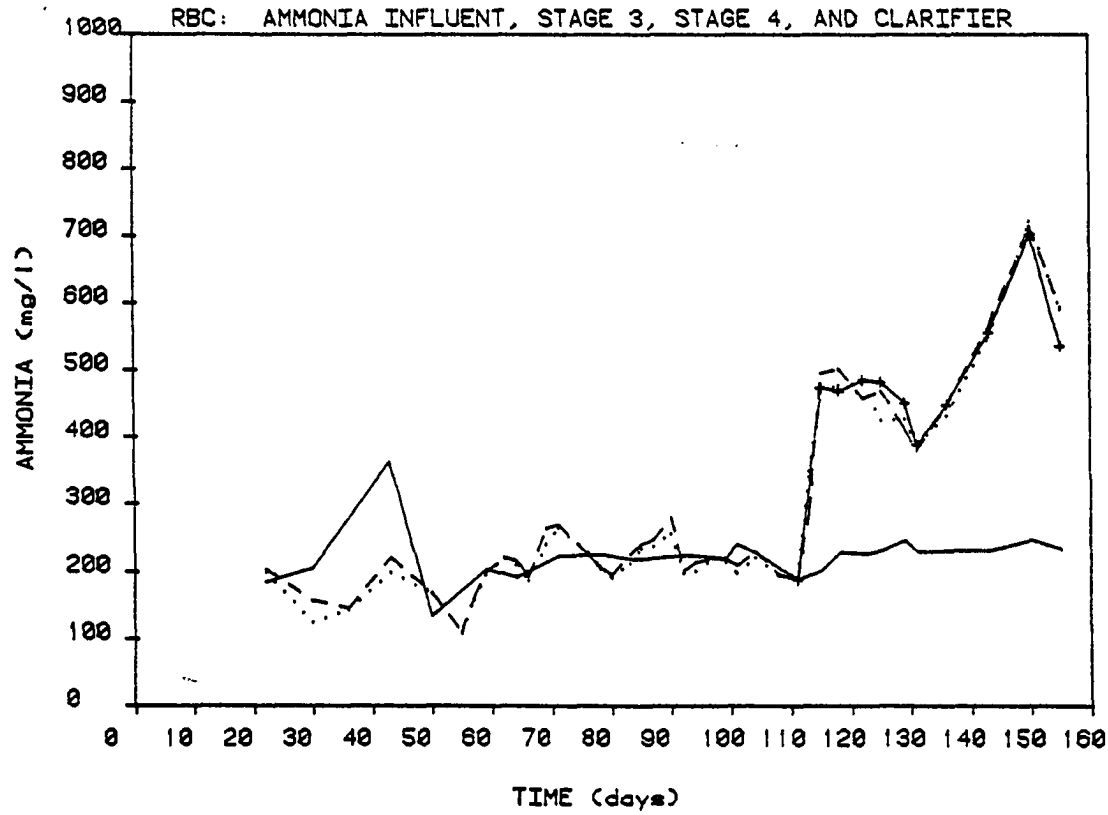
Organic Loading (kg m^{-3} d^{-1})	C:N:P	AFFF (mg $liter^{-1}$ COD)
0.742	5:1:5	1,000
2.947	10:1:5	2,000
4.453	20:1:5	4,000
5.894	16:1:5	4,000
8.842	26:1:5	6,000
11.789	35:1:5	8,000

Phosphate and ammonia nitrogen were added in the form of BHB in the amounts suggested by the manufacturer. It is possible that these amounts could be lowered with equally good growth and less cost as a result.

Also, ammonia levels were observed to see if a decrease, indicating nitrification, would occur. A significant decrease in ammonia never occured; in fact, a significant increase occurred around day 120 (Figure 29). This occurred when the concentration of AFFF was approximately 4,000 mg $liter^{-1}$ COD (organic load of 5,894 kg m^{-3} d^{-1}). At this high of a loading, Nitrosomonas and Nitrobacter would not be competitive. Nitrosomonas is inhibited by 30 mg $liter^{-1}$ free ammonia (Ford, Churchwell, and Ketchteck, 1980). It is probable that the increase in ammonia was due to cell death and the decomposition of cellular proteins and/or metabolic proteinacious by-product degradation. These would increase as cell population density increased. Bacterial cell population density would increase, to a point, as organic loading increased.



(a) Influent ——, stage 1 – – –, stage 2 · · · · ·.

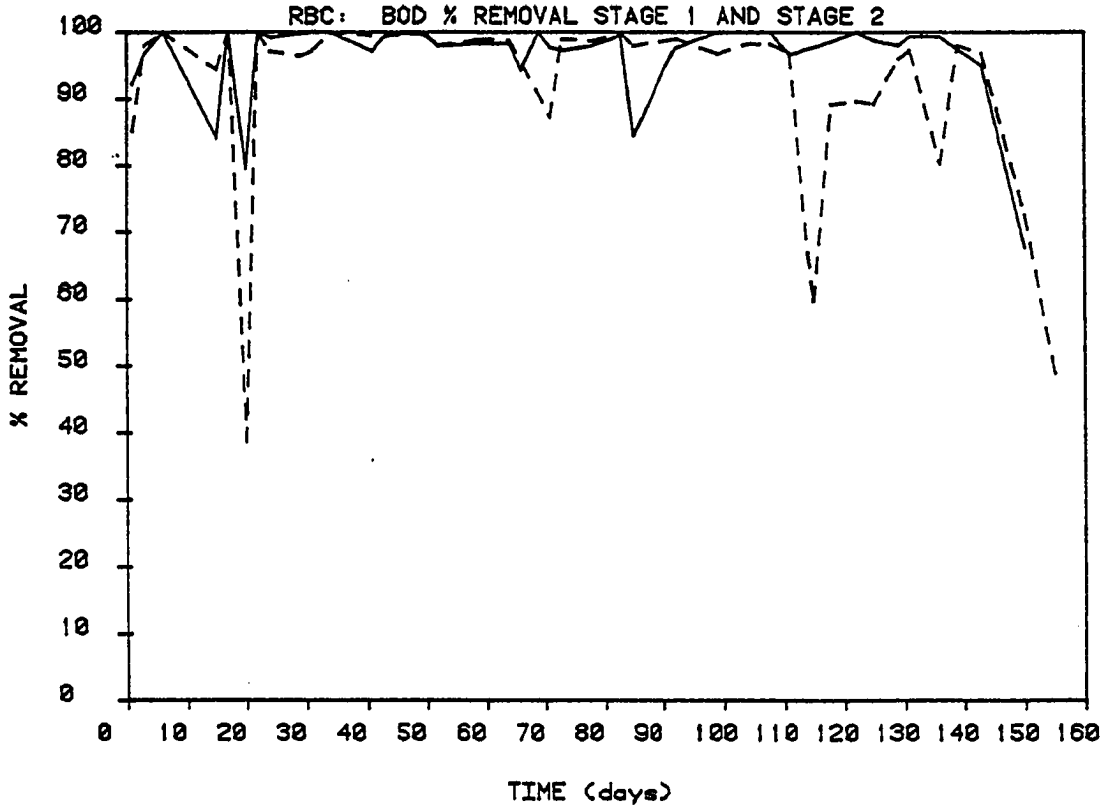


(b) Influent——, stage 3 – – –, stage 4 · · · ·, clarifier–//–.

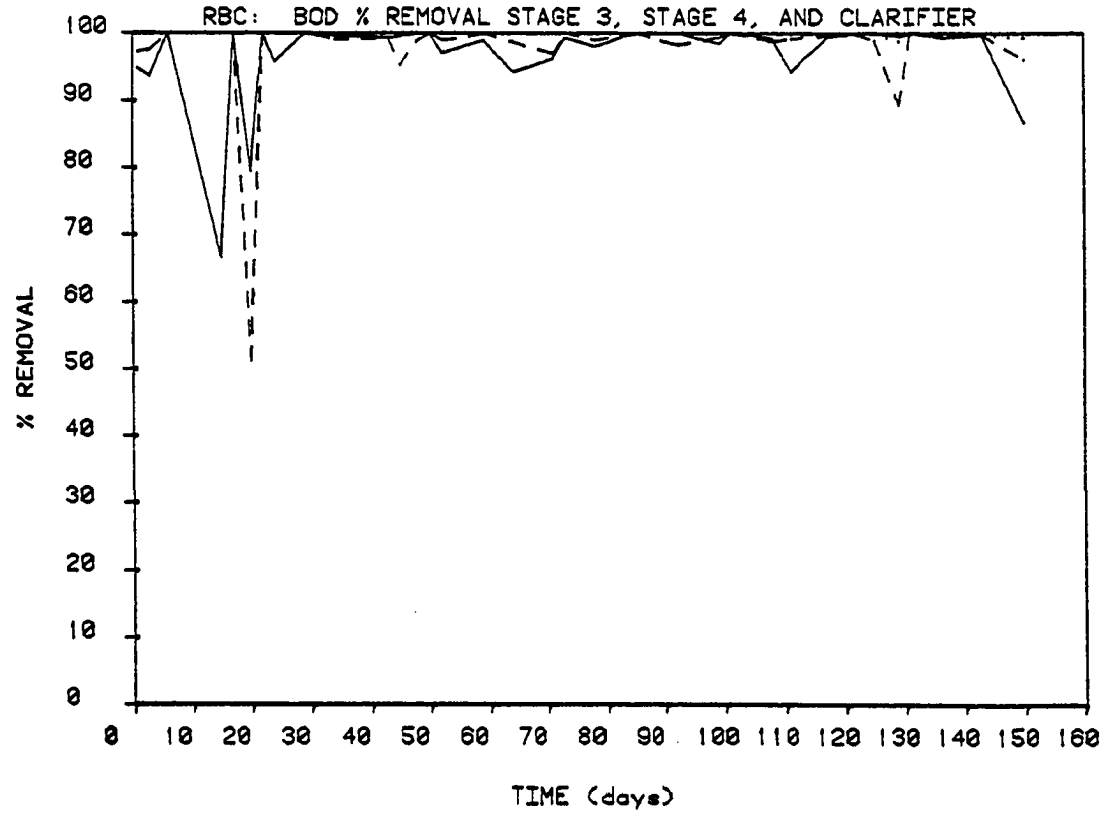
Figure 29. Ammonia concentration presented as a function of time.

A shake test was conducted on day 85. The amount of foam measured decreased by 70% with treatment (i.e., a decrease from 59 μg ml^{-1} LAS to 19 μg ml^{-1} LAS). This indicated that the foaming capabilities (i.e., the surfactants) were being degraded by the microorganisms.

The results of BOD, COD, TOC, and HPLC determination for AFFF concentration with respect to time and treatment are given in Appendix E. Only one of the HPLC peaks, peak 5.3, decreased as a result of treatment by the RBC. Peak 0.66 did not decrease, and at times appeared to increase after RBC treatment. It was later determined that a metabolite resulting from RBC treatment of the AFFF-laden synthetic wastewater eluted very close to peak 0.66. At times the two peaks were not resolved separately, and this appeared as an increase in peak 0.66. It is not known, as yet, what the identity is of 0.66. Whatever the components, peak 0.66 did not change as a result of RBC treatment, and all data referred to as HPLC will be concerning the components eluting in peak 5.3. The resultant reductions in BOD, COD, TOC, and HPLC 5.25 (peak 5.25) are presented in Figures 30 through 33. In these figures, percent removal is shown with respect to time given in days. After 30 days of continuous operation, an apparent steady state condition was achieved within the RBC, in terms of COD, TOC, and BOD removal. Ninety-seven percent removal was achieved in all three parameters measured until day 113, when the organic loading was increased to 4,000 mg AFFF $liter^{-1}$ AFFF COD and stage 1 dropped to 15% removal. However, overall COD removal by the unit was 78%, as seen in the data from stage 4. At this time the flow rate was increased to 7 ml min^{-1}, and the unit recovered rapidly. Ninety percent COD removal was seen by day 117, and 97% removal was again achieved by day 129. BOD

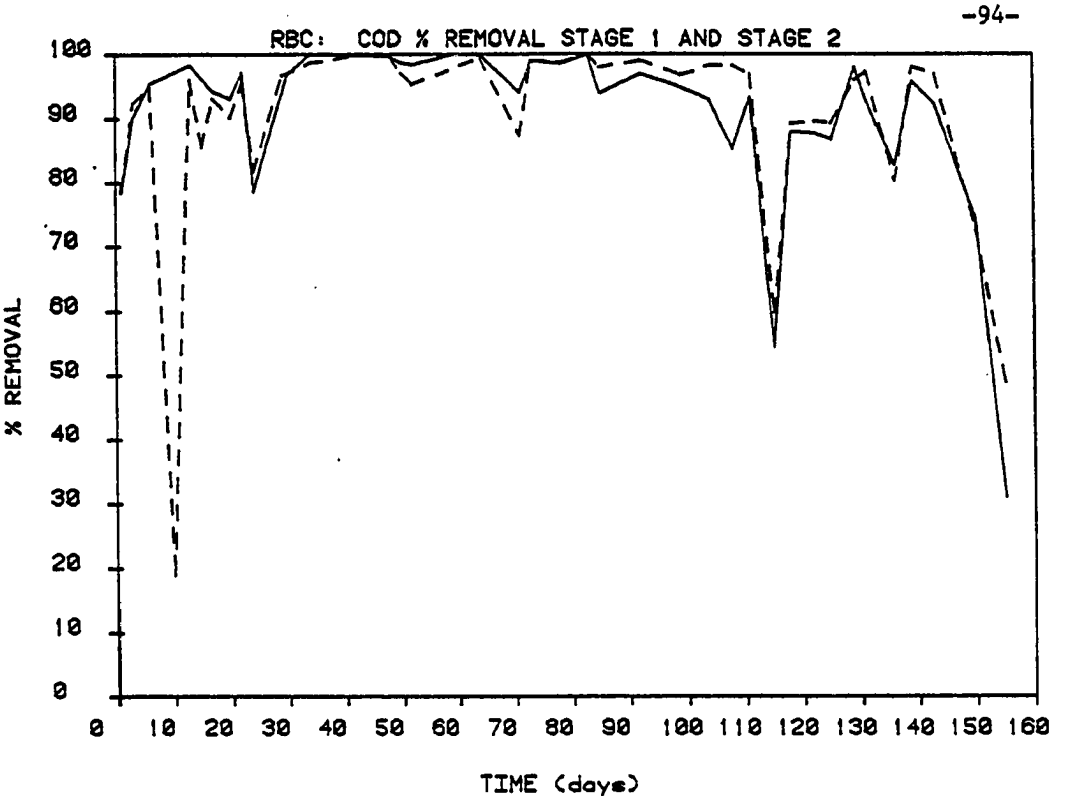


(a) Stage 1 ——, stage 2 – – –.

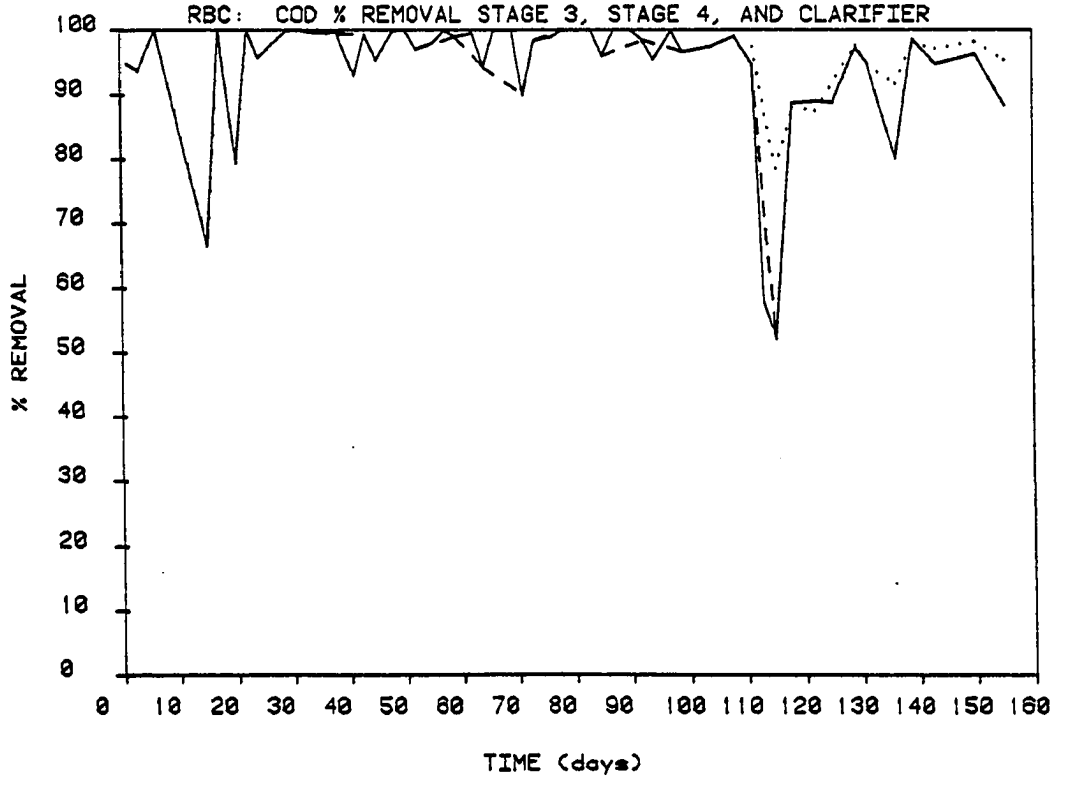


(b) Stage 3 ——, stage 4 – – –, clarifier • • • •.

Figure 30. Biochemical oxygen demand (BOD) removal presented as a function of time.

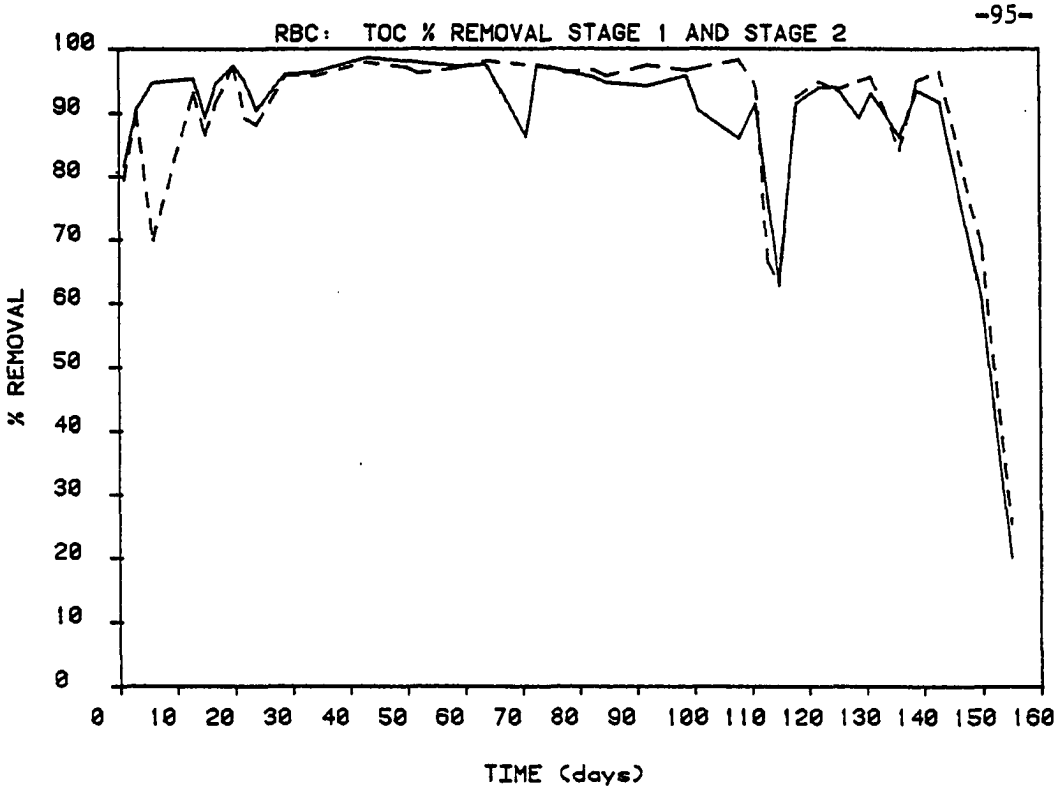


(a) Stage 1 ———, stage 2 – – –.

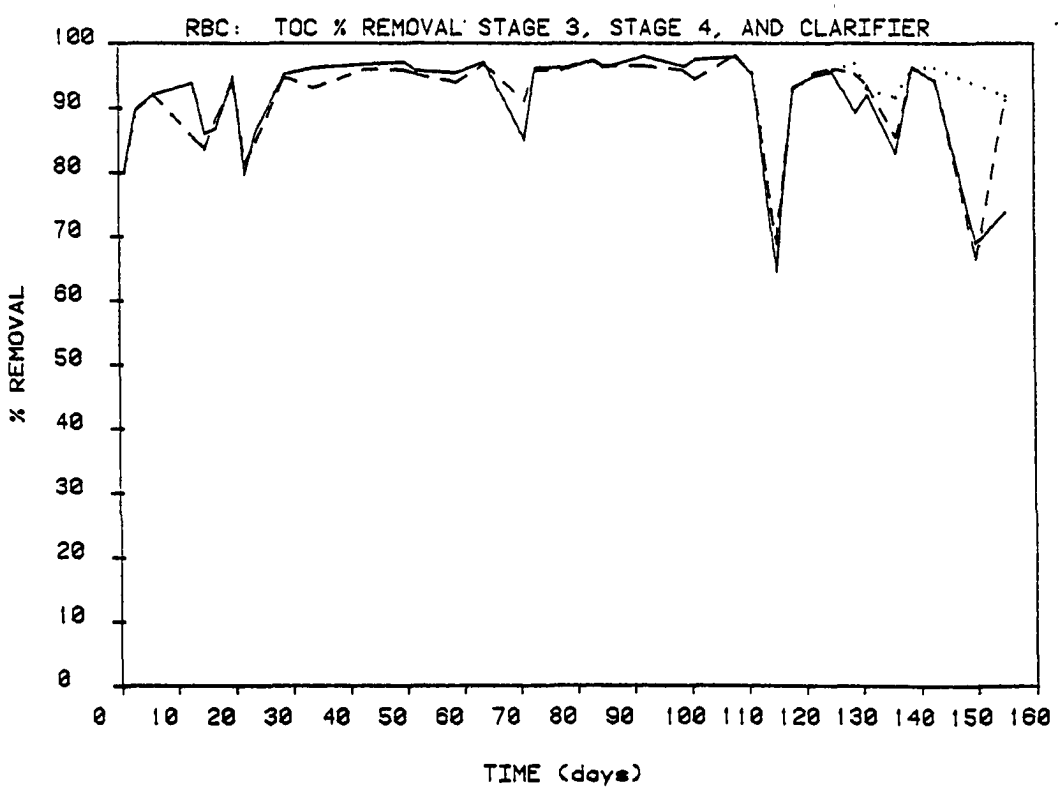


(b) Stage 3 ———, stage 4 – – –, clarifier • • • • •.

Figure 31. Chemical oxygen demand (COD) removal presented as a function of time.

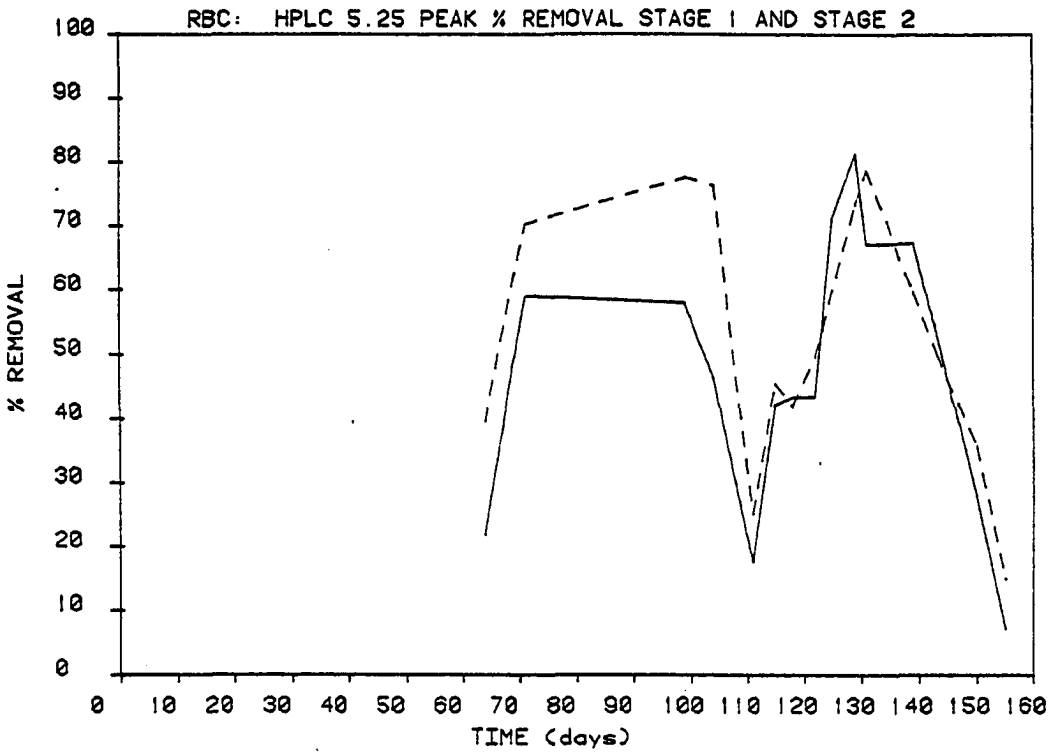


(a) Stage 1 ———, stage 2 — — —.

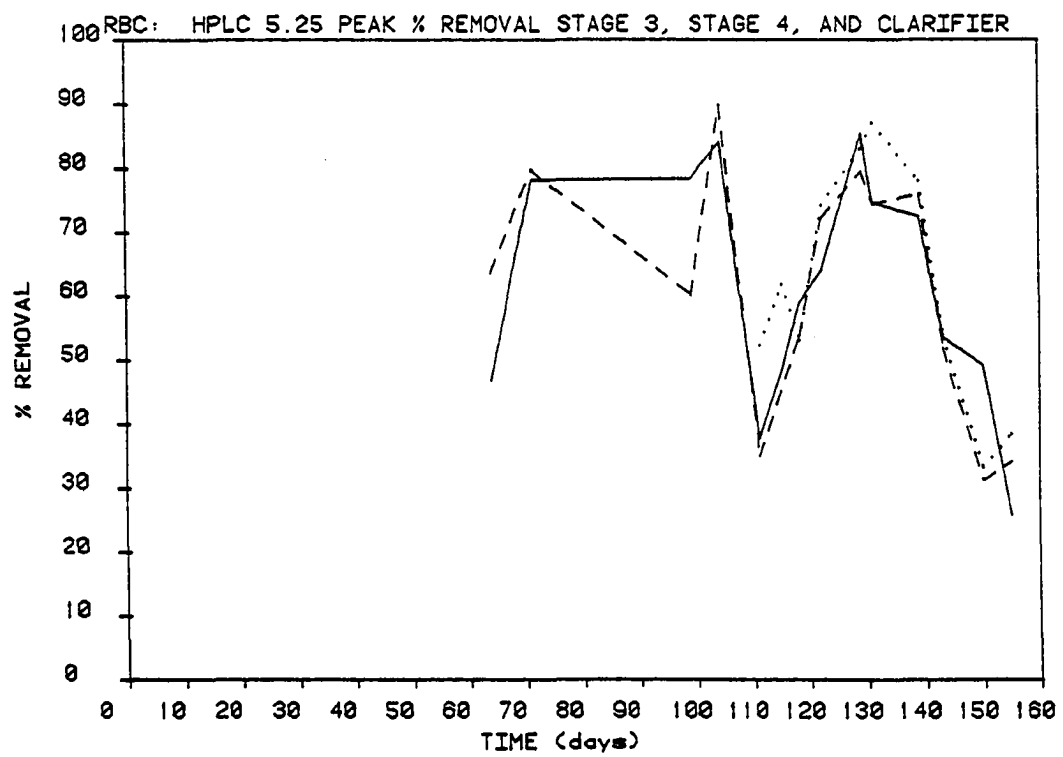


(b) Stage 3 ———, stage 4 — — —, clarifier . . . .

Figure 32. Total organic carbon (TOC) removal presented as a function of time.



(a) Stage 1 ——— , stage 2– – – .



(b) Stage 3———, stage 4– – –, clarifier . . . . .

Figure 33. High performance liquid chromatography (HPLC) peak 5.25 removal presented as a function of time.

removal did not indicate any problem with the increase in organic (AFFF) loading, and TOC followed the pattern seen with the COD data. Discernible HPLC peaks, specific for AFFF, were not seen until day 85. Previous to this, the peaks were masked by interference as a result of absorbance by the nutrient broth. HPLC data also decreased proportionally less when organic loading increased. However, the recovery of the unit was indicated by a return of 90% removal in HPLC peak by day 129. After day 145, the concentration of AFFF gradually increased to 8,000 mg liter^{-1} COD (11.8 kg m^{-3} d^{-1}). The removal in stages 1 and 2 dropped to 25% for COD, 50% for TOC and HPLC, and 70% for BOD. However, the overall efficiency of the unit, as indicated by stage 4 and the clarifier (stage 5), was 85% COD removal, 90% TOC removal, 50% HPLC removal, and 95% BOD removal.

As seen in Figure 34, exposure of the RBC to FC-780 began on day 35 with the addition of 0.025% FC-780, or 100 mg liter^{-1} in terms of COD. By day 60, 1,000 mg liter^{-1} COD of FC-780 was being fed. Simultaneously, the amount of nutrient broth, which was the only other carbon source after day 52, was lowered to a level of approximately 500 mg liter^{-1} COD. This level of carbon was maintained until day 80. The conversion rate at that time was 98% COD, 96% BOD, and 94% TOC. After this time until the completion of the experiment, the level of AFFF was equal to the total carbon found in the influent.

The data were divided as follows for statistical analysis. First, the data were analyzed as a whole (i.e., days 1 to 160). Second, the data were divided into three sections: section 1 (day 1 through day 113, going from no AFFF to 4,000 mg liter^{-1} COD), section 2 (day 114

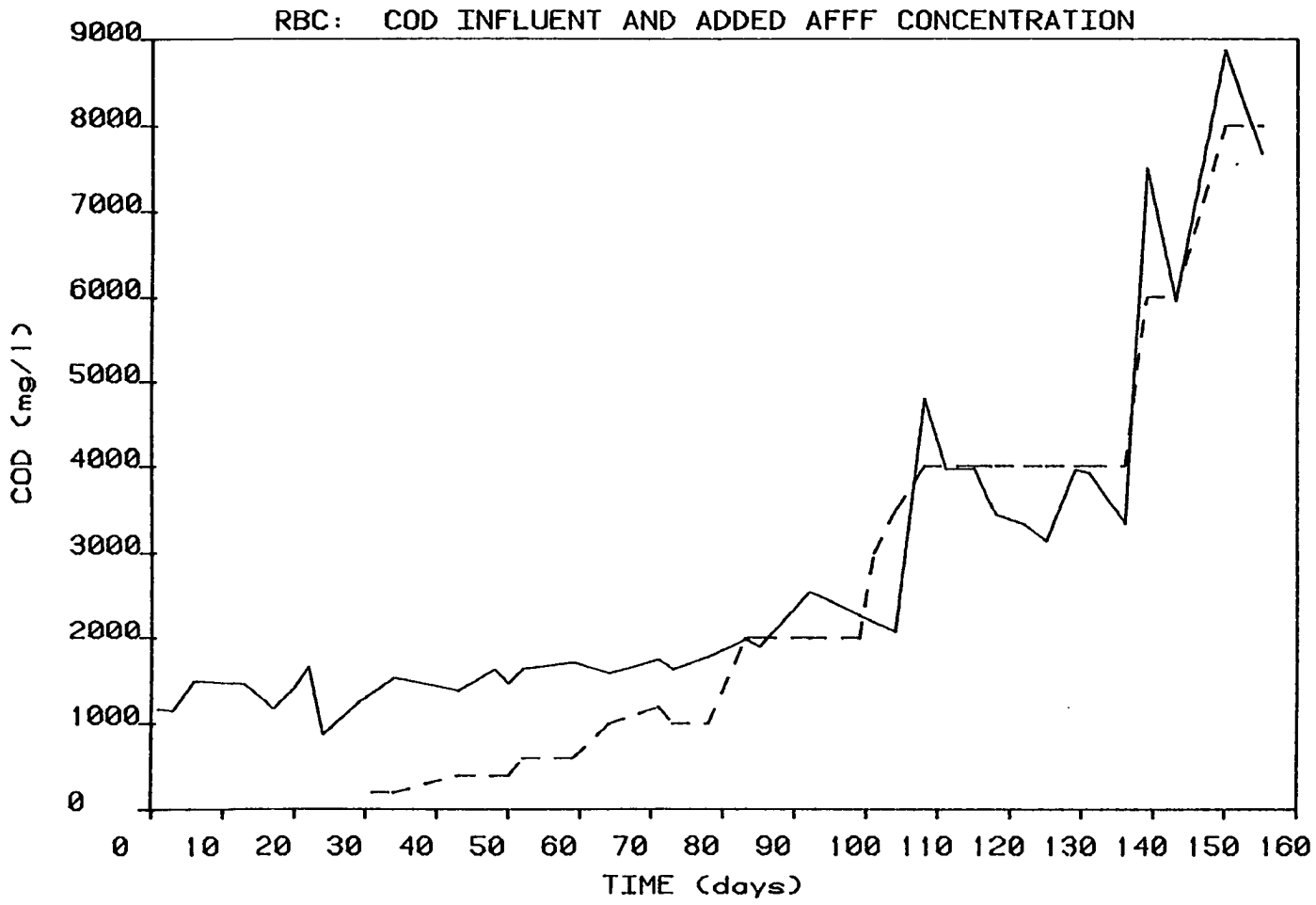


Figure 34. Daily concentration of AFFF as expressed in COD. Actual COD measured,———. Theoretical COD value calculated from the percent of AFFF added to the influent,— — —.

to day 140, no change in AFFF concentration, but a two-fold change in hydraulic load), and section 3 (day 114 to day 160, AFFF concentration increased beyond 4,000 mg liter^{-1} COD and above the 6.4 kg m^{-1} d^{-1} COD recommended to attain 90% removal) (Stover and Kincannon, 1976). A one-way, completely randomized analysis of variance was conducted on each division or section with respect to COD, BOD, TOC, or HPLC. The results are given in Table 16. The calculated F values for each test are given. Values larger than the calculated F are indicative of a significant variation between treatment and nontreatment with the RBC. The Bartlett's test of homogeneous variance indicated no violation of the homogeneity assumption of ANOVA. The significance levels show low probability of error within the test. This is true for all the analytical parameters except the data concerning HPLC peak 0.66. Here the F value is very low in all sections, indicating low removal of this peak as previously mentioned. The remaining four parameters confirm the ability of the RBC to treat AFFF-laden wastewater. It is interesting to note that although efficiency of removal by the unit dropped when treating 8,000 mg liter^{-1} AFFF, the significance of treatment is still very high as can be seen from the F values in section 4.

Many researchers have used mathematical models for estimating carbonaceous removal capacity of RBC systems. Wu, Smith, and Hung (1980) developed a model from multiple regression analyses run on data obtained from the literature. They assumed that the fraction of carbonaceous material, measured as BOD in the influent, is directly proportional to flow and inversely proportional to the influent BOD concentration, disk rotational speed, effective disk surface area, and wastewater

Table 18. Data From Testing to Determine Mechanical Removal of AFFF by Foam Generation

Organic Loading (kg/m^3 d)	AFFF Concentration (%)	Sample Site	Total Bacterial cfu	Total Fungal cfu	COD	COD % Removal	BOD	BOD % Removal	TOC	TOC % Removal
2.947	0.5	influent			1,423	--	867	--	1,117	--
		stage 1			1,452	0	1,395	0	1,511	0
		stage 2	d	d	1,472	0	1,131	0	1,467	0
		stage 3			1,585	0	1,254	0	1,500	0
		stage 4			1,754	0	1,090	0	910	0
		clarifier			1,318	0	1,199	0	1,001	0
5.894	1.0	influent			3,811	--	2,220	--	1,693	--
		stage 1	$>1 \times 10^6$	>300	2,410	24	2,298	0	1,297	23
		stage 2	$>1 \times 10^6$	>300	2,156	32	1,299	42	1,344	21
		stage 3	$>1 \times 10^6$	>300	1,908	40	2,124	4	1,275	25
		stage 4	$>1 \times 10^6$	>300	2,054	35	1,878	15	1,270	25
		clarifier	≦100	>300	1,764	45	1,356	39	--	--
8.842	1.5	influent	$>1 \times 10$		4,662				2,247	--
		stage 1	$>1 \times 10^7$		3,617	22			1,207	46
		stage 2	$>1 \times 10^7$	d	3,466	26	d	d	1,038	54
		stage 3	$>1 \times 10^7$		3,617	22			933	59
		stage 4	$>1 \times 10^7$		3,440	27			971	57
		clarifier	$>1 \times 10^7$		3,251	30			948	58
11.789	2.0	influent	1×10^6		5,670	--			2,254	--
		stage 1	1×10^6	4×10^4	5,822	0			1,603	29
		stage 2	1×10^6	4×10^5	5,721	0			1,512	33
		stage 3	1×10^6	2×10^3	5,117	9.8	d	d	1,512	33
		stage 4	1×10^6	2×10^4	5,972	0			1,421	37
		clarifier	$>3 \times 10^4$	4×10^4	5,519	2.7			1,648	27

d = data not available

temperature. However, the data they used indicated that disk rotational speed, liquid retention time, and submerged disk depth were not major controlling factors in the RBC system. They used the equation

$$\log F = \beta\, a \log L_o + b \log T + r \log q \qquad (2)$$

where F = fraction of influent loading remaining in the effluent

B = log K/N

K = treatability constant of waste material (day^{-1})

N = number of stages

L_o = influent concentration of waste material (mg $liter^{-1}$ BOD)

T = temperature of waste material

q = hydraulic loading rate

a,b,r = partial regression coefficients

The expression of the equation derived from their data and Equation 2 was

$$F = 7.55\, q^{0.5579}\ L_o^{0.6837}\ T^{0.2477} \qquad (3)$$

This equation indicated that the influent concentration was the most significant variable, when not in excess of 355 mg $liter^{-1}$.

A similar analysis was performed on data presented here. The independent variables were temperature (T), hydraulic loading (q), and concentration of AFFF (L_o). Since pH was adjusted and held relatively constant, it was not used as a variable. The dependent variables used to indicate the quantity of carbonaceous material were BOD, COD, TOC, and HPLC. Of these dependent variables, only COD produced barely acceptable r^2 values when subjected to a multiple linear regression analysis. The results of these analyses are given in Table 17. Neither

temperature nor hydraulic loading proved to be significant, so the regression was repeated without them and a final expression derived for the data from the RBC studied here. It is

$$F = -2.2204\ L_o^{0.9927} \quad (4)$$

where F is the remaining COD in the effluent. Although this would appear to be a simplistic expression, it is reasonable when one considers that the temperature did not vary greatly, the hydraulic loding changed only once, and then in correlation to an increase in organic loading, and all other environmental factors were dependent to the organic loading.

Table 17. Regression Analysis of RBC Variables

Variable	AFFF Concentration	Hydraulic Loading	Temperature
Regression Coefficient	1.6934	0.5268	-0.4181
t Test	1.4626	1.7667	-0.1382
$r^2 = 0.6508$, $\beta = 0.4903$, DF = 23, $t_{0.95} = 2.07$			
Regression Coefficient	0.6197	1.3671	
t Test	2.3524	1.6917	
$r^2 = 0.6680$, $\beta = -1.2598$, DF = 27, $t_{0.95} = 2.05$			
Regression Coefficient	0.9927		
t Test	6.6535		
$r^2 = 0.6300$, $\beta = -2.2209$, DF = 27, $t_{0.95} = 2.05$			

The Foaming test, as described in the Materials and Methods section, was conducted to determine what fraction, if any, of AFFF entering the RBC unit was removed as a result of the mechanical production of foam rather than the bioremoval. The results are given in

Table 18. From this table it can be seen that no decrease in AFFF occurred within 24 hours at 2,000 mg liter^{-1} COD. After 24 hours at 4,000 mg liter^{-1} COD and 24 hours at 6,000 mg liter^{-1} COD (72 hours continuous operation), a significant decrease in AFFF levels was seen. It cannot be said, however, that this decrease was due to mechanical action. Total colony counts taken at the same time showed significant growth of bacteria and fungi. Since the test could not be run aseptically, the amount of AFFF removed by foam generation was not determined.

Summary

From the data presented here it has been determined that the RBC is a viable alternative for treating AFFF-laden wastewater. The unit was able to treat up to 4,000 mg liter^{-1} COD with a reduction to less than 100 mg liter^{-1} COD or 200 ppm volume-to-volume. This is well within the standards for discharge to municipal treatment facilities. The unit could handle concentrations of 8,000 mg liter^{-1} COD and lower the COD level to approximately 200 mg liter^{-1} COD. It is possible that with a longer retention time or with recirculation and additional aeration of influent the RBC could lower such high concentrations further.

AFFF proved to be nontoxic to sewage-type microorganisms of the RBC. This was valid even up to 8,000 mg liter^{-1}. However, high organic loads did cause a decrease in dissolved oxygen, which in turn selected for anaerobic or microaerophilic "bulking type" organisms. Although these organisms are associated with inefficient removal, no long-lasting decrease in efficiency was observed in this study up to 6,000 mg liter^{-1} COD, and no correlation between predominant populations and AFFF removal efficiency can be made for organic loadings below 11 kg m^{-1} d^{-1}.

Table 16. One-Way Completely Randomized Analysis of Variance Versus Bartlett's Variance

Analytical Form		Calculated F	One-Way Analysis		Bartlett's Variance	
			F	Significance	F	Significance
Day 0-160	COD	3.26	34.039	0.000	2,268.000	0.000
	BOD	3.70	127.683	0.000	1,157.143	0.000
	TOC	3.26	66.701	0.000	2,268.000	0.000
	HPLC	4.18	0.641	0.670	607.615	0.001
	$HPLC_{5.3}^{.66}$	3.82	6.098	0.001	632.344	0.000
Day 0-113	COD	3.11	37.829	0.000	87,268.089	0.000
0-4,000 mg $liter^{-1}$	BOD	3.11	76.032	0.000	27,348.021	0.000
HL: 0-3 kg m^{-3} d^{-1}	TOC	3.11	61.598	0.000	25,775.815	0.000
	HPLC	3.37	1.270	0.289	3,203.609	0.000
	$HPLC_{5.3}^{.66}$	3.37	3.200	0.012	4,707.243	0.000
Day 114-160	COD	3.34	23.953	0.000	4,628.571	0.000
4,000 mg $liter^{-1}$	BOD	3.46	88.740	0.000	2,579.825	0.000
HL: 3-6 kg m^{-3} d^{-1}	TOC	3.34	30.022	0.000	4,303.257	0.000
	HPLC	3.72	0.612	0.691	719.407	0.000
	$HPLC_{5.3}^{.66}$	3.70	3.960	0.007	811.834	0.013
Day 114-160	COD	3.14	84.167	0.000	1,151.741	0.000
4,000-8,000 mg $liter^{-1}$	BOD	3.17	114.967	0.000	1,122.016	0.000
HL: 6-12 kg m^{-3} d^{-1}	TOC	3.17	153.026	0.000	22,510.331	0.000
	HPLC	d	d	d	d	d
	$HPLC_{5.3}^{.66}$	d	d	d	d	d

HL = hydraulic loading

d = insufficient data

The HPLC, as a tool, may not be applicable in the identification and quantification of AFFF in firefighting school wastewater. Additional components in the wastewater, such as jet fuel, may mask the AFFF peaks.

Finally, the following comments are offered with regard to design scale-up:

1. Foam generation is a problem. Many RBCs have only one rotational speed. Drag exerted by the foam would slow down the rotation of the disks. This, in turn, would cause a decrease in DO, which would select for the bulking, less efficient organisms. Foam generation, then, would not only increase stress on the mechanical apparatus, it would also result in potential removal efficiency. An antifoaming agent could be used. However, antifoaming agents are expensive and would decrease the cost effectiveness of the process. Serendipitously, it was discovered that a moderately fine spray of water caused foam dissipation. Possibly, a misting apparatus could be incorporated into the design of RBCs treating AFFF wastewater.

2. The decrease in DO due to high organic loading can be partially compensated for by preaerating the influent and increasing the scour velocity. An increase in scour velocity by recirculation would lower the amount of settled, free floc in each stage and thus lower the metabolic oxygen demand.

3. The derived math expression for the small RCB may not be extensive enough to be applicable to scale-up. However, Chesler and Eskelund (1981) used organic loading successfully as the sole parameter

necessary for scale-up. Future engineering research should be conducted to determine if T and q are significant on a more standardized pilot plant. Such research is in progress, and preliminary data are presented in Appendix F.

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APPENDIX A

GENERAL DESCRIPTION OF U.S. PATENT #3,772,195
3M COMPANY (1973)

The patent describes a composition that:

> ... will form tough, durable, rapidly-forming and spreading films on the surface of hydrocarbon liquids comprising, in combination a water soluble fluoroaliphatic surfactant and a water-soluble synthetic imputrescible hydrocarbon-congruous organic fluorine-free surfactant and water. The films formed by these compositions are especially effective in suppressing the vaporization of hydrocarbon liquids into the air and are, therefore, useful for extinguishing liquid hydrocarbon fires.

The chemical is intended to be supplied as a concentrate, diluted to a 6% solution, and mixed with large quantities of vaporized propellant or air. A foam stabilizer, exemplified by high molecular weight polyethylene glycol, or freeze-resistant components, may be added. The overall composition should be compatible with solid fire extinguishing agents such as powdered potassium bicarbonate (commonly referred to as purple K powder)*.

The fluoroaliphatic surfactant described here is a molecule that contains a fluoroaliphatic radical and a water solubilizing group, represented in the patent as R_fQmZ. R_f is a fluorinated saturated monovalent, nonaromatic radical containing from 3 to 20 carbon atoms in which the carbon atoms of the chain are substituted only by fluorine, chlorine, or hydrogen atoms with no more than one hydrogen or chlorine atom for every two carbon atoms, and in which a divalent oxygen or trivalent nitrogen atom, bonded only to carbon atoms, can be present in

*PKP is an effective firefighting agent for oil fires when the oil is in spray form and burning in space.

the skeletal chain. Qm, where m is an integer from 0 to 2, is a multivalent linking group comprising alkyline, aryline, sulfonamido, alkylene, and carbonamido alkylene radicals. Z is a water soluble polar group comprising anionic, cationic, nonionic, and ampholytic radicals.

The structure of the surfactant is not critical; rather it is a balance of the combination of fluoroaliphatic, radical, and water solubilizing groups to create solubility in water at 25°C that is important.

Fluorochemical compounds have been used to form barrier films for evaporative suppression of gasoline, and that such films would establish and maintain a continuous barrier even when disturbed or moved. Films comprised of water and specific fluorochemicals produce a film on fuel surfaces which will reduce the rate of evaporation and thus ignition becomes difficult.

To function effectively as a film-spreading agent, a surface tension of less than 23 dynes/cm should be present in aqueous solutions of a concentration of 0.25% or less. "If the fluoroaliphatic surfactant is too soluble in hydrocarbon liquid, it will be extracted too rapidly from aqueous film to provide sufficient durable coverage." That is to say, the film will collapse too rapidly. This requires 20% by weight carbon bonded fluorine in the surfactant. The film-forming ability of the fluorochemical surfactant is enhanced by the addition of a water soluble, fluorine-free surfactant. The film promoting fluorine-free surfactant must not combine with the fluorine containing surfactant to form an inactive product. It should be water soluble to about 0.02% by weight in water at 25°C, hydrocarbon-congruous, that is soluble in the hydrocarbon phase, imputrescible and capable of being diluted by 94%.

APPENDIX B

MATERIAL SAFETY DATA SHEET, PUBLISHED BY 3M COMPANY,
CONCERNING HAZARDS OF FC-206A (AFFF)

MATERIAL SAFETY DATA SHEET

Form 16693 C PWD

3M
3M Center
St. Paul, Minnesota 55144
(612) 733-1110

DUNS NO.: 00-617-3082

Chemical Family: Fire Control Agent

Trade Name: FC-206A LIGHT WATER Brand Aqueous Film Forming Foam

3M I. D. Number: 98-0211-0737-4 (5 gallon unit)

Commercial Chemicals Division

1. INGREDIENTS	CAS. #	%	TLV® (unit)
Butyl Carbitol	112-34-5	20	Not Established
Water	7732-18-5	75	
Fluoroalkyl Surfactants		<5	Not Established
Synthetic Detergents		<5	Not Established

2. PHYSICAL DATA

Boiling Point	Initial	212°F	Solubility in Water	Miscible
Vapor Pressure			Specific Gravity (H_2O=1)	1.01
Vapor Density (Air = 1)			Percent Volatile	94
Evaporation Rate (B.A. 1)		<1	pH	7.5-8.5

Appearance and Odor: Clear, amber colored liquid.

3. FIRE AND EXPLOSION HAZARD DATA

Flash Point (Test Method): None

Flammable Limits: LEL - UEL -

Extinguishing Media: FC-206A is a fire extinguishing agent.

Special Fire Fighting Procedures

None

Unusual Fire and Explosion Hazards: Toxic by-products including HF may be formed.

4. ENVIRONMENTAL INFORMATION

Spill Response

Collect spilled material. Wash residue to a wastewater treatment system.

Recommended Disposal

Bleed to a wastewater treatment system in accordance with local regulations. Keeping the concentration below 10 mg/l will eliminate foaming in activated sludge aeration basins.

Environmental Data

Chemical Oxygen Demand (COD) - 0.45 g/g
Biochemical Oxygen Demand (BOD_5) - 0.02 g/g, (BOD_{20}) - 0.33 g/g
96-Hr. LC_{50}, Fathead Minnow (Pimephales promelas) - >3.0 g/l (continuous flow)
Acute Inhibitory Effect on Activated Respiration Rate - None at 1000 mg FC-206A per Liter

Threshold Limit Values listed above are current to 1979. Because they are reviewed yearly by ACGIH and subject to change (usually to a lower value) it is necessary for the user of this Material Safety Data Sheet to maintain a list of revised TLV's and update the sheet periodically.

TRADE NAME: FC-206A LIGHT WATER Brand Aqueous Film Forming Foam

5. HEALTH HAZARD DATA

Eye Contact Undiluted FC-206A is mildly irritating to the eyes upon direct contact. A 6% FC-206A solution is non-irritating ocularly. Persons having eye contact with the undiluted product would be expected to experience slight transient irritation.

Skin Contact Undiluted FC-206A is minimally irritating dermally. Diluted FC-206A is non-irritating dermally. The dermal LD_{50} for butyl carbitol (rabbit) is 4 g/kg. Avoid prolonged or repeated contact with skin.

Inhalation Inhalation studies on butyl carbitol indicate there is little hazard from acute exposure to high concentrations of vapor. Prolonged or repeated inhalation of vapors should be restricted.

Ingestion The acute oral LD_{50} (rat) for FC-206A is greater than 5 g/kg. FC-206A is considered practically non-toxic orally.

Suggested First Aid

EYE CONTACT: Flush eyes with plenty of water. Call a physician.
SKIN CONTACT: Wash affected area with soap and water.
INHALATION: Remove person to fresh air.
INGESTION: Do not induce vomiting. Call a physician.

6. REACTIVITY DATA

STABILITY	☐ Unstable ☒ Stable	Conditions to Avoid
INCOMPATABILITY		Materials to Avoid
HAZARDOUS POLYMERIZATION	☐ May Occur ☒ May Not Occur	Conditions to Avoid

Hazardous Decomposition Products

Thermal decomposition may produce toxic materials including HF.

7. SPECIAL PROTECTION INFORMATION

Eye Protection
Safety Glasses

Skin Protection
Rubber Gloves desired.

Ventilation
General ventilation is adequate.

Respiratory and Special Protection
None Required

Other Protection

8. PRECAUTIONARY INFORMATION

Avoid eye contact. Avoid prolonged or repeated skin contact. Store between 35°F to 120°F.

9. DEPARTMENT OF TRANSPORTATION

DOT Proper Shipping Name	DOT Hazard Class
Not Applicable	Not Applicable

Issue Date	Supersedes
Sept. 1980	7/78

The information on this Data Sheet represents our current data and best opinion as to the proper use in handling of this product under normal conditions. Any use of the product which is not in conformance with this Data Sheet or which involves using the product in combination with any other product or any process is the responsibility of the user.

APPENDIX C

MULTIPLE REGRESSION ANALYSIS OF CHEMOSTAT DATA

CHEMOSTAT III

MULTIPLE REGRESSION

ANOVA AND REGRESSION

Filename: CHEM03

Dependent Variable: BOD

SOURCE	SS	MS	df	F	PR > F
Regression	8.47E+006	2.82E+006	3.0000	32.9892	5.14E-009
Residual	2.23E+006	8.56E+004	26.0000		
Total	1.07E+007				

R-square: 0.7919 Rbar-square: 0.7765

Root of Residual MS: 292.5937

PARAMETER	ESTIMATE	STANDARD ERROR	t	PR > ABS(t)
Intercept	-4.0472			
b 1 TREATME	-918.7063	129.8684	-7.0741	1.64E-007
b 2 DAY	-7.7728	3.9415	-1.9720	0.0593
b 3 PH	361.9457	36.7739	9.8425	2.95E-010

Mean of dependent variable: 724.9433

Standard deviation of dependent variable: 607.3859

Value of Durbin-Watson statistic 2.5357

CHEMOSTAT III

MULTIPLE REGRESSION

ANOVA AND REGRESSION

Filename: CHEM03

Dependent Variable: COD

SOURCE	SS	MS	df	F	PR > F
Regression	1.32E+007	4.42E+006	3.0000	24.2003	2.29E-008
Residual	5.84E+006	1.82E+005	32.0000		
Total	1.91E+007				

R-square: 0.6941 Rbar-square: 0.6755

Root of Residual MS: 427.1643

PARAMETER	ESTIMATE	STANDARD ERROR	t	PR > ABS(t)
Intercept	-5.4871			
b 1 TREATME	-974.3536	168.1968	-5.7929	1.98E-006
b 2 DAY	-6.7099	5.3440	-1.2556	0.2184
b 3 PH	415.0924	49.8150	8.3327	1.61E-009

Mean of dependent variable: 1001.8653

Standard deviation of dependent variable: 738.4631

Value of Durbin-Watson statistic: 1.1429

CHEMOSTAT III

MULTIPLE REGRESSION

ANOVA AND REGRESSION

Filename: CHEM03

Dependent Variable: TOC

SOURCE	SS	MS	df	F	PR > f
Regression	6.73E+005	2.24E+005	3.0000	43.3013	1.20E-010
Residual	1.45E+005	5180.7676	28.0000		
Total	8.18E+005				

R-square: 0.8227 Rbar-square: 0.8104

Root of Residual MS: 71.9775

PARAMETER	ESTIMATE	STANDARD ERROR	t	PR > ABS(t)
Intercept	1.5117			
b 1 TREATME	-228.5642	30.5091	-7.4917	3.69E-008
b 2 DAY	0.7552	1.0214	0.7394	0.4658
b 3 PH	91.0293	8.9417	10.1804	6.48E-011

Mean of dependent variable: 236.1906

Standard deviation of dependent variable: 162.4473

Value of Durbin-Watson statistic: 2.5230

APPENDIX D

EXCERPTS FROM CHAPTER 7, VOLUME 1, OF OPERATION OF WASTEWATER TREATMENT PLANTS -- A FIELD STUDY TRAINING PROGRAM

(2nd edition, published by U.S. Environmental Protection Agency, Office of Water Program Operations, Municipal Permits and Operations Division, 1980)

GLOSSARY

Chapter 7. ROTATING BIOLOGICAL CONTACTORS

BIODEGRADABLE BIODEGRADABLE

Organic matter that can be broken down by bacteria to more stable forms which will not create a nuisance or give off foul odors.

COMPOSITE (PROPORTIONAL) SAMPLE COMPOSITE (PROPORTIONAL) SAMPLE

A composite sample is a collection of individual samples obtained at regular intervals, usually every one or two hours during a 24-hour time span. Each individual sample is combined with the others in proportion to the flow when the sample was collected. The resulting mixture (composite sample) forms a representative sample and is analyzed to determine the average conditions during the sampling period.

GRAP SAMPLE GRAB SAMPLE

A single sample of wastewater taken at neither a set time nor flow.

INHIBITORY SUBSTANCES INHIBITORY SUBSTANCES

Materials that kill or restrict the ability of organisms to treat wastes.

MPN MPN

MPN is the Most Probable Number of coliform-group organisms per unit volume. Expressed as a density or population of organisms per 100 ml.

NEUTRALIZATION NEUTRALIZATION

Addition of an acid or alkali (base) to a liquid to cause the pH of the liquid to move towards a neutral pH of 7.0.

NITRIFICATION NITRIFICATION

A process in which bacteria change the ammonia and organic nitrogen in wastewater into oxidized nitrogen (usually nitrate). The second-stage BOD is sometimes referred to as the "nitrification stage" (first-stage BOD is called the "carbonaceous stage").

PYROMETER PYROMETER

An apparatus used to measure high temperatures.

SOLUBLE BOD SOLUBLE BOD

Soluble BOD is the BOD of water that has been filtered in the standard suspended solids test.

SUPERNATANT SUPERNATANT

Liquid removed from settled sludge. Supernatant commonly refers to the liquid between the sludge on the bottom and the scum on the surface of an anaerobic digester. This liquid is usually returned to the influent wet well or to the primary clarifier.

CHAPTER 7. ROTATING BIOLOGICAL CONTACTORS

7.0 DESCRIPTION OF ROTATING BIOLOGICAL CONTACTORS

Rotating biological contactors (RBC) are a secondary biological treatment process (Figure 7.1*) for domestic and *BIODEGRADABLE*[1] industrial wastes. Biological contactors have a rotating "shaft" surrounded by plastic discs called the "media." The shaft and media are called the "drum" (Figures 7.2 and 7.3). A biological slime grows on the media when conditions are suitable. This process is very similar to a trickling filter where the biological slime grows on rock or other media and settled wastewater (primary clarifier effluent) is applied over the media. With rotating biological contactors, the biological slime grows on the surface of the plastic-disc media. The slime is rotated into the settled wastewater and then into the atmosphere to provide oxygen for the organisms (Fig. 7.2). The wastewater being treated usually flows parallel to the rotating shaft, but may flow perpendicular to the shaft as it flows from stage-to-stage or tank-to-tank.

The plastic-disc media are made of high-density plastic circular sheets usually 12 feet (3.6 m) in diameter. These sheets are bonded and assembled onto horizontal shafts up to 25 feet (7.5 m) in length. Spacing between the sheets provides the hollow (void) space for distribution of wastewater and air (Figures 7.3 and 7.4).

The rotating biological contactor process uses several plastic media drums. Concrete or coated steel tanks usually hold the wastewater being treated. The media rotate while approximately 40 percent of the media surface is immersed in the wastewater (Fig. 7.4). As the drum rotates, the media pick up a thin layer of wastewater which flows over the biological slimes on the discs. Organisms living in the slimes use organic matter from the wastewater for food and dissolved oxygen from the air, thus removing wastes from the water being treated. As the attached slimes pass through the wastewater, some of the slimes are sloughed from the media as the media rotates downward into the wastewater being treated. The effluent with the sloughed slimes flows to the secondary clarifier where the slimes are removed from the effluent by settling. Figure 7.5 shows the location of a rotating biological contactor process in a wastewater treatment plant. The process is located in the same position as the trickling filter or activated sludge aeration basin. Usually the process operates on a "once-through" scheme, with no recycling of effluent or sludge, which makes it a simple process to operate.

The major parts of the process are listed in Table 7.1 along with their purposes. The concrete or steel tanks are commonly shaped to conform to the general shape of the media. This shape eliminates dead spots where solids could settle out and cause odors and septic conditions. These tanks may be divided into four bays (stages) with either concrete walls or removable baffles, depending on the design.

The rotating biological contactor process is usually divided into four different stages (Fig. 7.6). Each stage is separated by a removable baffle, concrete wall or cross-tank bulkhead. Wastewater flow commonly is parallel to the shaft. Each bulkhead or baffle has an underwater orifice or hole to permit flow from one stage to the next. Each section of media between bulkheads acts as a separate stage of treatment.

Staging is used in order to maximize the effectiveness of a given amount of media surface area. Organisms on the first-stage media are exposed to high levels of BOD and reduce the BOD at a high rate. As the BOD levels decrease from stage to stage, the rate at which the organisms can remove BOD decreases.

Treatment plants requiring four or more shafts of media usually are arranged so that each shaft serves as an individual stage of treatment. The shafts are arranged so the flow is perpendicular to the shafts (Fig. 7.6, Layout No. 3). Plants with fewer than four shafts are usually arranged with the flow parallel to the shaft (Fig. 7.6, Layout No. 1).

Rotating biological contactors are covered for several reasons which depend on climatic conditions:

1. Protect biological slime growths from freezing;
2. Prevent intense rains from washing off some of the slime growths;
3. Stop exposure of media to direct sunlight to prevent growth of algae;
4. Avoid exposure of media to sunlight which may cause the media to become brittle; and
5. Provide protection for operators from sun, rain or wind while maintaining equipment.

---

[1] *Biodegradable (BUY-o-dee-GRADE-able). Organic matter that can be broken down by bacteria to more stable forms which will not create a nuisance or give off foul odors.*

* Note: The figures contained in the original publication have been deleted from these excerpts.

TABLE 7.1 PURPOSE OF PARTS OF A ROTATING BIOLOGICAL CONTACTOR

Part	Purpose
1. Concrete or Steel Tank Divided into Bays (Sections) by Baffles (Bulkheads)	Tank. Holds the wastewater being treated and allows the wastewater to come in contact with the organisms on the discs.
	Bays and baffles. Prevent short-circuiting of wastewater.
2. Orifice or Weir Located in Baffle	Controls flow from one stage to the next stage or from one bay to the next bay.
3. Rotating Media	Provide support for organisms. Rotation provides food (from wastewater being treated) and air for organisms.
4. Cover over Contactor	Protects organisms from severe fluctuations in the weather, especially freezing. Also contains odors.
5. Drive Assembly	Rotates the media.
6. Influent Lines with Valves	Influent lines. Transport wastewater to be treated to the rotating biological contactor.
	Influent valves. Regulate influent to contactor and also to isolate contactor for maintenance.
7. Effluent Lines with Valves	Effluent lines. Convey treated wastewater from the contactor to the secondary clarifier.
	Effluent valves. Regulate effluent from the contactor and also isolate contactor for maintenance.
8. Underdrains	Allow for removal of solids which may settle out in tank.

Fiber glass covers in the shape of the media are easily removed for maintenance. In some areas, the rotating biological contactors are covered by a building. In other areas only a roof is placed over the media for protection against sunlight. The type of cover depends on climatic conditions.

Two types of drive assemblies are used to rotate the shafts supporting the media:

1. Motor with chain drive (Fig. 7.7), and

2. Air drive (Fig. 7.8).

The first type of drive assembly consists of a motor, belt drive, gear or speed reducer, and chain drive. The other drive unit consists of plastic cups attached to the outside of the media (Fig. 7.8). A small air header below the edge of the media releases air into the cups. The air in the cups creates a buoyant force which then makes the shaft turn. With either type of drive assembly, the main shaft is supported by two main bearings.

Individual units are usually provided with influent and effluent line valving to allow isolation for maintenance reasons. Usually the units are not shut down during the low flow conditions because power consumption is minimal and as the flows decrease, the percent of BOD removal increases.

7.1 PROCESS OPERATION

Performance by rotating biological contactors is affected by hydraulic loadings and temperatures below 55°F (13°C). Plants have been designed to treat flows ranging from 18,000 gpd to 50 MGD. Typical operating and performance characteristics are as follows:

Characteristic	Range
HYDRAULIC LOADING[2]	
BOD Removal	1.5 to 6 gpd/sq ft
Nitrogen Removal	1.5 to 1.8 gpd/sq ft
ORGANIC LOADING[2]	
SOLUBLE BOD[3]	3 to 5 lbs BOD/day/1000 sq ft
BOD Removal	80 to 95 percent
Effluent Total BOD	15 to 30mg/L
Effluent Soluble BOD	7 to 15 mg/L
Effluent NH_3-N	1 to 10 mg/L
Effluent NO_3-N	2 to 7 mg/L

See Section 7.5, "Loading Calculations," for procedures showing how to calculate the hydraulic and organic loadings on rotating biological contactors.

Advantages of rotating biological contactors over trickling filters include the elimination of the rotating distributor with its problems, the elimination of the problems cause by ponding on the media, and filter flies. More efficient use of the media is achieved due to the even or uniform rotation of the media into the wastewater being treated. A limitation of the process, as compared with trickling filters, is the lack of flexibility due to the absence of provisions for recirculation; however, in most installations recirculation is not needed.

7.10 Pretreatment Requirements

Rotating biological contactors are usually preceded by pretreatment consisting of screening, grit removal, and primary settling. Grit and large organic matter, if not removed, can settle beneath the drums and form sludge deposits which reduce the effective tank volume, produce septic conditions, scrape the slimes from the media, and possibly stall the unit.

Some rotating biological contactor plants have aerated flow equalization tanks instead of primary clarifiers ahead of the contactors. Flow equalization tanks may be installed to equalize or balance highly fluctuating flows and to allow for the dilution of strong wastes and neutralization of highly acidic or alkaline wastes. These equalization tanks are capable of reducing or eliminating shock loads.

7.11 Start-Up

Prior to plant start-up, become familiar with and understand the contents of the plant O & M manual. If you have any questions, be sure to ask the design engineer or the manufacturer's representative. Both of these persons should instruct the operator on the proper operation of the plant and maintenance of the equipment.

7.110 Pre-Start Checks for New Equipment

Before starting any equipment or allowing any wastewater to enter the treatment process, check the following items:

1. *TIGHTNESS*

Inspect the following for tightness in accordance with manufacturer's recommendations.

a. Anchor bolts
b. Mounting studs
c. Bearing caps
Check any torque limitations.
d. Locking collars
e. Jacking screws

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[2] *Hydraulic and organic loadings depend on influent flow, influent soluble BOD, effluent BOD, temperature and surface area of plastic media. Manufacturers provide charts converting flow to hydraulic and organic loadings for their media.*

[3] *Soluble BOD. Soluble BOD is the BOD of water that has been filtered in the standard suspended solids test.*

f. Roller chain
   Be sure chain is properly aligned.
g. Media
   Unbalanced media may cause slippage.
h. Belts
   Use matched sets on multiple-belt drives.

2. *LUBRICATION*

Be sure the following have been properly lubricated with proper lubricants in accordance with manufacturer's recommendations.

a. Mainshaft bearings
b. Roller chain
c. Speed reducer

3. *CLEARANCES*

a. Between media and tank wall.
b. Between media and baffles or cover support beams.
c. Between chain casing and media.
d. Between roller chain, sprockets and chain casing.

4. *SAFETY*

Be sure safety guards are properly installed over chains and other moving parts.

7.111 Procedure for Starting Unit

Actual start-up procedures for a new unit should be in your plant O & M manual and provided by the manufacturer. A typical starting procedure is outlined below.

1. Switch on power, allow shaft to rotate one turn, turn off the power, lock out and tag switch. Inspect and correct if necessary during this revolution:
   a. Movement of chain casing.
   b. Unusual noises.
   c. Direction of media rotation.
      Where wastewater flow is parallel to the rotating media shaft, the direction of rotation is not critical. If the wastewater flow is perpendicular to the rotating media shaft, the media should be moving through the wastewater against the direction of flow (see Figure 7.6, p. 209).

2. Switch on power and allow shaft to rotate for 15 minutes. Inspect the following:
   a. Chain-drive sprocket alignment.
   b. Noises in bearings, chain drives and drive package.
   c. Motor amperage. Compare with nameplate value.
   d. Temperature of mainshaft bearing (by hand) and drive-package pillow block. If too hot for the hand, use a *PYROMETER*[4] or thermometer. Temperature should not exceed 200°F (93°C).
   e. Tightness of shaft bearing-cap bolts. Tighten to manufacturer's recommended torque.
   f. Determine number of revolutions per minute for drum and record for future reference.

3. Open inlet valve and allow wastewater to fill the tank (all four stages if in one tank). Open the outlet valve to allow water to flow through the tank. Turn on power and make inspections listed in steps 1 and 2 again while drum is rotating. Shut off power, lock out and tag switch to make any corrections.

4. Check the relationship between the clarifier inlet and the rotating biological contactor outlet for hydraulic balance. This means that you want to be sure that the tank containing the biological contactor will not overflow and cause stripping of the biomass.

5. See Section 7.20 for break-in maintenance instructions which start after eight hours of operation.

Development of biological slimes can be encouraged by regulating the flow rate and strength of the wastewater applied to nearly constant levels by the use of recirculation if available. Maintaining building temperatures at 65°F (18°C) or higher will help. The best rotating speed is one which will shear off growth at a rate which will provide a constant "hungry and reproductive" film of microorganisms exposed to the wastewater being treated.

Allow one to two weeks for an even growth of biological slimes (biomass) to develop on the surface of the media with normal strength wastewater. After start-up, a slimy growth (biomass) will appear. During the first week, excessive sloughing will occur naturally. This sloughing is normal and the sloughed material is soon replaced with a fairly uniform, shaggy brown-to-gray appearing biomass with very few or no bare spots.

Follow the same start-up procedures whether a plant is starting at less than design flow or at full-design flow. Start-up during cold weather takes longer because the organisms in the slime growth (biomass) are not as active and require more time to grow and reproduce.

7.12 Operation

Rotating biological contactor treatment plants are not difficult to operate and produce a good effluent provided the operator properly and regularly performs the duties of inspecting the equipment, testing the influent and effluent, observing the media, maintaining the equipment and taking corrective action when necessary.

7.120 Inspecting Equipment

This treatment process has relatively few moving parts. There is a drive train to rotate the shaft and there are bearings upon which the shaft rotates. Neither the media nor the shaft require maintenance. Check the following items when inspecting equipment:

1. Feel outer housing of shaft bearing to see if it is running hot. Use a pyrometer or thermometer if temperature is too hot for your hand. If temperature exceeds 200°F (93°C), the bearings may need to be replaced. Also check for proper lubrication and be sure the shaft is properly aligned. The longer the shaft, the more critical the alignment.
2. Listen for unusual noises in motor bearings. Locate cause of unusual noises and correct.
3. Feel motors to determine if they are running hot. If hot, determine cause and correct.
4. Look around drive train and shaft bearing for oil spills. If oil is visible, check oil levels in the speed reducers and chain drive system. Also look for damaged or wornout gaskets or seals.
5. Inspect chain drive for alignment and tightness.
6. Inspect belts for proper tension.
7. Be sure all guards over moving parts and equipment are in place and properly installed.
8. Clean up any spills, messes or debris.

[4] *Pyrometer (pie-ROM-uh-ter). An apparatus used to measure high temperatures.*

7.121 Testing Influent and Effluent

Wastewater analysis is required to monitor overall plant and process performance. Because there are few process control functions to be performed, only a minimal analysis is required to monitor and report daily performance. To determine if the rotating biological contactors are operating properly, you should measure (1) BOD, (2) suspended solids, (3) pH and (4) dissolved oxygen (DO). Performance is best monitored by analysis of a 24-hour *COMPOSITE SAMPLE*[5] for BOD and suspended solids on a daily basis. DO and pH should be measured using *GRAB SAMPLES*[6] at specific times. Actual frequency of tests may depend on how often you need the results for plant control and also how often your NPDES permit requires you to sample and analyze the plant effluent.

DISSOLVED OXYGEN

The DO in the wastewater being treated beneath the rotating media will vary from stage to stage. A plant designed to treat primary effluent for BOD- and suspended-solids removal will usually have 0.5 to 1.0 mg/L DO in the first stage. The DO level will increase to 1 to 3 mg/L in the fourth stage. A plant designed for *NITRIFICATION*[7] to convert ammonia and organic nitrogen compounds to nitrate will have four stages also. The difference between a RBC unit designed for BOD removal and one designed for nitrification is the design flow applied per square foot of media surface area. DO in the first stage of nitrification unit will be more than 1 mg/L DO and often as high as 2 to 3 mg/L. The DO in the fourth stage of a nitrification unit may be as high as 4 to 8 mg/L.

EFFLUENT VALUES

Typical BOD, suspended solids, and ammonia and nitrate effluent values for rotating biological contactors depend on NPDES permit requirements and design effluent values. As flows increase, effluent values increase because a greater flow is applied to each square foot of media while the time the wastewater is in contact with the slime growths is reduced. Also, the greater the levels of BOD, suspended solids and nitrogen in the influent, the greater the levels in the plant effluent. Figure 7.9 shows influent and effluent values for a rotating biological contactor. The influent and effluent data plotted are seven-day moving averages which smooth out daily fluctuations and reveal trends. Procedures for calculating moving averages are explained in Chapter 18, "Analysis and Presentation of Data."

If analysis of samples reveals a decrease in process efficiency, look for three possible causes:

1. Reduced wastewater temperatures,
2. Unusual variations in flow and/or organic loadings, and
3. High or low pH values (less than 6.5 or greater than 8.5).

Once the cause of the problem has been identified, possible solutions can be considered and the problem corrected.

TEMPERATURE

Wastewater temperatures below 55°F (13°C) will result in a reduction of biological activity and in a decrease in BOD or organic material removal. Not much can be done by the operator except to wait for the temperatures to increase again. Under severe conditions, provisions can be made to heat the building, the air inside the RBC unit cover, or the RBC unit influent.

Solar heat can be used effectively to maintain temperature in buildings and enclosures without drying out the biological slime growths. Ceilings should be kept low to effectively use available heat. If existing buildings have high ceilings, large vaned fans can be mounted on the ceilings to direct heat downward.

INFLUENT VARIATIONS

When large daily influent flow and/or organic (BOD) variations occur, a reduction in process efficiency is likely to result. Before corrective steps are taken, the exact extent of the problem and resulting change in process efficiency must be determined. In most cases, when the influent flow and/or organic peak loads are less than three times the daily average values during a 24-hour period, little decrease in process efficiency will result.

In treatment plants where the influent flow and/or organic loads exceed design values for a sustained period, the effluent BOD and suspended solids must be measured to determine if corrective action is required.

During periods of severe organic overload, the bulkhead or baffle between stages one and two may be removed. This procedure provides a larger amount of media surface area for the first stage of treatment. If the plant is continuously overloaded and the effluent violates the NPDES permit requirements, additional treatment units should be installed. A possible short-term solution to an overload problem might be the installation of facilities to recycle effluent; however, this would cause a greater increase of any hydraulic overload.

pH

Every wastewater has an optimum pH level for best treatability. Domestic wastewater pH varies between 6.5 and 8.5 and will have little effect on organic removal efficiency. If this range is exceeded at any time (due to industrial waste discharges for example), however, a decrease in efficiency is likely.

To adjust the pH towards 7.0, either pre-aerate the influent or add chemicals. If the pH is too low, add sodium bicarbonate or lime. If the pH is too high, add acetic acid. The amount of chemicals to be added depends on the characteristics of the water and can best be determined by adding chemicals to samples in the lab and measuring the change in pH.

When dealing with nitrification, pH and alkalinity are very critical. The pH should be kept as close as possible to a value of 8.4 when nitrifying. The alkalinity level in the raw wastewater should be maintained at a level at least 7.1 times the influent ammonia concentration to allow the reaction to go to completion without adversely affecting the microorganisms. Sodium bicarbonate can be used to increase both the alkalinity and pH.

Another item under pH variations could be the adding of

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[5] *Composite (Proportional) Sample (com-POZ-it). A composite sample is a collection of individual samples obtained at regular intervals, usually every one or two hours during a 24-hour time span. Each individual sample is combined with the others in proportion to the flow when the sample was collected. The resulting mixture (composite sample) forms a representative sample and is analyzed to determine the average conditions during the sampling period.*

[6] *Grab Sample. A single sample of wastewater taken at neither a set time nor flow.*

[7] *Nitrification (NYE-tri-fi-KAY-shun). A process in which bacteria change the ammonia and organic nitrogen in wastewater into oxidized nitrogen (usually nitrate). The second-stage BOD is sometimes referred to as the "nitrification stage" (first-stage BOD is called the "carbonaceous stage").*

SUPERNATANT[8] from a digester. The supernatant should be tested for pH and suspended solids. Without testing the supernatant, you will not know what kind of load you're placing on the rest of the plant. Sometimes it's best to drain supernatant at low flows to the plant. Caution should be taken to avoid overloading the process. If the supernatant pH is too low, supernatant could be drawn off during high flows when these flows can be used for dilution and *NEUTRALIZATION*.[9]

7.122 Observing the Media

Rotating biological contactors use bacteria and other living organisms growing on the media to treat wastes. Because of this, you can use your sight and smell to identify problems. The slime growth or biomass should have a brown-to-gray color, no algae present, a shaggy appearance with a fairly uniform coverage, and very few or no bare spots. The odor should not be offensive, and certainly there should be no sulfide (rotten egg) smells.

BLACK APPEARANCE

If the appearance becomes black and odors which are not normal do occur, this could be an indication of solids or BOD overloading. These conditions would probably be accompanied by low DO in the plant effluent. Compare previous influent suspended solids and BOD values with current test results to determine if there is an increase. To solve this problem, place another rotating biological contactor unit in service, if possible, or try to pre-aerate the influent to the RBC unit. Also review the operation of the primary clarifiers and sludge digesters to be sure they are not the source of the overload.

WHITE APPEARANCE

A white appearance on the disc surface also might be present during high loading conditions. This might be due to a type of bacteria which feeds on sulfur compounds. The overloading could result from industrial discharges containing sulfur compounds upon which certain sulfur-loving bacteria thrive and produce a white slime biomass. Corrective action consists of placing another RBC unit in service or trying to pre-aerate the influent to the unit. During periods of severe organic or sulfur overloading, remove the bulkhead or baffle between stages one and two.

Another cause of overloading may be sludge deposits which have been allowed to accumulate in the bottom of the bays. To remove these deposits, drain the bays, wash the sludge deposits out and return unit to service. Be sure the orifices in the baffles between the bays are clear.

SLOUGHING

If severe sloughing or loss of biomass occurs after the start-up period and process difficulty arises, the causes may be due to the influent wastewater containing toxic or *INHIBITORY SUBSTANCES*[10] that kill the organisms in the biomass or restrict their ability to treat wastes. To solve this problem, steps must be taken to eliminate the toxic substance even though this may be very difficult and costly. Biological processes will never operate properly as long as they attempt to treat toxic wastes. Until the toxic substance can be located and eliminated, loading peaks should be dampened (reduced) and a diluted uniform concentration of the toxic substance allowed to reach the media in order to minimize harm to the biological culture. While the corrections are made at the plant, dampening may be accomplished by regulating inflow to the plant. Be careful not to flood any homes or overflow any low manholes. Toxic wastes may be diluted using plant effluent (until it contains toxic material) or any other source of water supply.

Another problem which could cause loss of biomass is an unusual variation in flow and/or organic loading. In small communities one cause may be high flow during the day and near zero flow at night. During the day the biomass is receiving food and oxygen and starts growing; then the night flow reduces to near zero — available food is reduced and nearly stops. The biomass starts sloughing off again due to lack of food.

Possible solutions to sloughing of the biomass due to excessive variations in plant flow and/or organic loading include throttling peak conditions and recycling from the secondary clarifier or RBC effluent during low flows. Be very careful when throttling plant inflows that low elevation homes are not flooded or that manholes do not overflow. Usually RBC units do not have provisions for any recycling from the secondary clarifier. If low flows at night are creating operation problems due to lack of organic matter, a possible solution is the installation of a pump to recirculate water from the secondary clarifier. If recirculation is provided, try to maintain a hydraulic loading rate of greater than 1.0 to 1.5 gpd/sq ft. A flow equalization tank can be used to provide fairly continuous or even flows.

Possible rotating biological contactor process operational problems, causes and solutions are summarized in Table 7.2.

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[8] *Supernatant (sue-per-NAY-tent). Liquid removed from settled sludge. Supernatant commonly refers to the liquid between the sludge on the bottom and the scum on the surface of an anaerobic digester. This liquid is usually returned to the influent wet well or to the primary clarifier.*

[9] *Neutralization (new-trall-i-ZAY-shun). Addition of an acid or alkali (base) to a liquid to cause the pH of the liquid to move towards a neutral pH of 7.0.*

[10] *Inhibitory Substances. Materials that kill or restrict the ability of organisms to treat wastes.*

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[10] *Inhibitory Substances. Materials that kill or restrict the ability of organisms to treat wastes.*

7.13 Abnormal Operation

Abnormal operating conditions may develop under the following circumstances:

1. High or low flows,
2. High or low solids loading, and
3. Power outages.

When your plant must treat high or low flows or solids (organic) loads, abnormal conditions develop as the treatment efficiency drops. For solutions to these problems, refer to Section 7.12, "Operation," and Table 7.2. One advantage of RBC units is the fact that high flows usually do not wash the slime growths off the media; consequently the organisms are present and treating the wastewater during and after the high flows.

A power outage requires the operator to take certain precautions to protect the equipment and the slime growths while no power is available. If the power is off for less than four hours, nothing needs to be done. If the power outage lasts longer than four hours, the RBC shaft needs to be turned about one-quarter of a turn twice a day. Turning prevents all the slime growth from accumulating on the bottom portion of the plastic disc media. Before attempting to turn the shaft, lock out and tag the power in case the outage ends abruptly. To turn the shaft, *REMOVE THE BELT GUARD USING EXTREME CARE.* Turn the shaft by using the belts. *BE CAREFUL YOU DON'T CUT OFF YOUR FINGERS.* Place a wedge-shaped block between the belts and belt sprocket to hold the shaft and media in *the desired location. Actually, the shaft is very delicately* balanced and easy to rotate. Do not try to weld handles or brackets to the shaft to facilitate turning because this will throw the shaft off balance.

WARNING. If the shaft starts to roll back to its original position before you get the block properly inserted, do not try to stop the shaft. Let it roll back and stop. If you try to stop the shaft from rolling back, you could injure yourself and also damage the belts and sprockets.

Gently spray water on the slime growth that is not submerged frequently enough to keep the biomass moist whenever the drum is not rotating.

If the power outage lasts longer than 12 hours, more than normal sloughing will occur from the media when the unit is placed back in service. When the sloughing becomes excessive, increase the sludge-pumping rate from the secondary clarifier.

7.14 Shutdown and Restart

The rotating biological contactor may be stopped by turning off the power to the drive package. If the process is to be stopped for longer than four hours, follow the precautions listed in Section 7.13, "Abnormal Operation," when a power outage occurs. Do not allow one portion of the media to be submerged in the wastewater being treated for more than four hours. Occasionally spray the media not submerged to prevent the slime growth from drying out whenever the drum is not rotating.

If the tank holding the wastewater being treated must be drained, a portable sump pump may be used. A sump is usually located at the end of the unit by the motor. Pump the water either to the primary clarifier or to the inlet end of a RBC unit in operation. A trough running the full length of the tank allows the solids to be pumped out. While the tank is empty, inspect for cracks and any other damage and make necessary repairs.

Try to keep the slime growths moist to minimize sloughing *and a reduction in organism activity when the process starts* again. A loss in process efficiency can result if the slimes are washed off the media. *DO NOT WASH THE SLIME GROWTH OFF THE MEDIA* because you will be washing away the organisms that treat the wastewater. If the unit is to be out of service for longer than one day, the slimes may be washed off the media to prevent the development of odor problems.

Restart rotation by applying power to the drive unit. Before applying power, inspect the shaft and drive unit for possible interference from such items as tools or bulkheads. If slippage occurs from an unbalanced media, inspect and adjust alignment and tension.

7.2 MAINTENANCE

Rotating biological contactors have few moving parts and require minor amounts of preventive maintenance. Chain drives, belt drives, sprockets, rotating shafts and any other moving parts should be inspected and maintained in accordance with manufacturers' instructions or your plant's O & M manual. All exposed parts, bearing housing shaft ends and bolts should be painted or covered with a layer of grease to prevent rust damage. Motors, speed reducers and all other metal parts should be painted for protection.

Maintenance also includes the repair or replacement of broken parts. A preventive maintenance program that keeps equipment properly lubricated and adjusted to help reduce wear and breakage requires less time and money than a program that waits for breakdowns to occur before taking any action. The frequency of inspection and lubrication is usually provided by manufacturer's instructions and also may be found in the plan O & M manual. The following sections indicate a typical maintenance program for a rotating biological contactor treatment process. More detail can be found in a plant O & M manual.

7.20 Break-In Maintenance

AFTER 8 HOURS OF OPERATION

1. Recheck tightening torque of capscrews in all split-tapered bushings in the drive package.
2. Visually inspect hubs and capscrews for general condition and possibility of rubbing against an obstruction.
3. Inspect belt drive (drive package).

AFTER 24 HOURS OF OPERATION

1. Inspect all chain drives.

AFTER 40 HOURS OF OPERATION

1. Inspect all belt drives in drive packages.

AFTER 100 HOURS OF OPERATION

1. Change oil in speed reducer. Use manufacturer's recommended lubricants.

TABLE 7.2 POSSIBLE RBC OPERATIONAL PROBLEMS, CAUSES AND SOLUTIONS

Problem	Cause	Solution
1. Slime on media appears shaggy with a brown-to-gray color.	PROPER OPERATION	NO PROBLEM. NORMAL CONDITION.
2. Black slime	Solids and/or BOD overloading	a. Place another RBC unit in service if available. b. Pre-aerate RBC influent. c. For severe organic overloads, remove bulkhead or baffle between stages 1 and 2.
3. Rotten egg or other obnoxious odors	Solids and/or BOD overloading	See problem 2, solutions a, b and c above.
4. White slime	Bacteria which feed on sulfur compounds. Also, industrial discharges containing sulfur compounds may cause an overload.	See problem 2, solutions a, b and c above.
5. Sloughing or loss of slime (biomass)	(1) Toxic or inhibitory substances in influent.	a. Eliminate source of toxic or inhibitory substances. b. Reduce peaks of toxic or inhibitory substances by carefully regulating inflow to plant. c. Dilute influent using plant effluent or any other source of water.
	(2) Variation in flow and/or organic loading.	a. During low flow or loading periods, pump from secondary clarifier or RBC unit effluent to recycle water with food and DO through the RBC unit. b. During high flow or loading conditions, attempt to throttle plant inflow during peak periods. c. For severe organic overloads, remove bulkhead or baffle between stages 1 and 2.
6. Decrease in process efficiency	(1) Reduced wastewater temperature.	a. Heat air inside RBC unit cover or building. b. Heat influent to unit.
	(2) Unusual variatons in flow and/or organic loading.	See problem 5, cause (2), solutions a, b and c above.
	(3) Sustained flows or loads above design levels.	Install additional treatment units.
	(4) High or low pH values.	a. If the pH is too low, add an alkali (base) such as lime. b. If the pH is too high, add an acid such as acetic acid.
	(5) Improper rotation of media.	a. Inspect belt tension and adjust. b. Check air pressure and adjust.

2. Clean magnetic drain plug in speed reducer.
3. Check all capscrews in split-tapered bushings and setscrews in drive package output sprocket and bearing for tightness.
4. Inspect belt drive of drive package.

AFTER 3 WEEKS OF OPERATION

1. Change oil in chain casing. Be sure oil level is at or above the mark on the dipstick. Use manufacturer's recommended lubricants.

7.21 Preventive Maintenance Program

Interval	Procedure
Daily	1. Check for hot shaft and bearings. Replace bearings if temperature exceeds 200°F (93°C).
Daily	2. Listen for unusual noises in shaft and bearing. Identify cause of noise and correct if necessary.
Weekly	3. Grease the mainshaft bearings and drive bearings. Use manufacturer's recommended lubricants. Add grease slowly while shaft rotates. When grease begins to ooze from the housing, the bearings contain the correct amount of grease. Add six full strokes where bearings cannot be seen.
4 wk.	4. Inspect all chain drives.
4 wk.	5. Inspect mainshaft bearings and drive bearings.
4 wk.	6. Apply a generous coating of general purpose grease to mainshaft stub ends, mainshaft bearings and end collars.
3 mo.	7. Change oil in chain casing. Use manufacturer's recommended lubricants. Be sure oil level is at or above the mark on the dipstick.
3 mo.	8. Inspect belt drive.
6 mo.	9. Change oil in speed reducer. Use manufacturer's recommended lubricants.
6 mo.	10. Clean magnetic drain plug in speed reducer.
6 mo.	11. Purge the grease in the double-sealed shaft seals of the speed reducer by removing the plug located 180 degrees from the grease fitting on both the input and output seal cages. Pump grease into the seal cages and then replace the plug. Use manufacturer's recommended grease.
12 mo.	12. Grease motor bearings. Use manufacturer's recommended grease. To grease motor bearings, stop motor and remove drain plugs. Inject new grease with pressure gun until all old grease has been forced out of the bearing through the grease drain. Run motor until all excess grease has been expelled. This may require up to several hours running time for some motors. Replace drain plugs.

7.22 Housekeeping

Properly designed systems have sufficient turbulence so solids or sloughed slime growths should not settle out on the bottom of the bays. If grease balls appear on the water surface in the bays, they should be removed with a dip net or screen device.

If media comes apart, squeeze the two unbonded sections together with a pair of pliers. Take another pair of pliers and force a heated nail through the media. The heat from the nail will melt the plastic and make a plastic weld between the two sections of media.

7.23 Troubleshooting Guide

7.230 Roller Chain Drive

Trouble	Probable Cause	Corrective Action
1. Noisy Drive	1. Moving parts rub stationary parts.	1. Tighten and align casing and chain. Remove dirt or other interfering matter.
	2. Chain does not fit sprockets.	2. Replace with correct parts.
	3. Loose chain.	3. Maintain a taut chain at all times.
	4. Faulty lubrication..	4. Lubricate properly.
	5. Misalignment or improper assembly.	5. Correct alignment and assembly of the drive.
	6. Worn parts.	6. Replace worn chain or bearings. Reverse worn sprockets before replacing.
2. Rapid Wear	1. Faulty lubrication.	1. Lubricate properly.
	2. Loose or misaligned parts.	2. Align and tighten entire drive.
3. Chain Climbs Sprockets	1. Chain does not fit sprockets.	1. Replace chain or sprockets.
	2. Worn-out chain or worn sprockets.	2. Replace chain. Reverse or replace sprockets.
	3. Loose chain.	3. Tighten.
4. Stiff Chain	1. Faulty lubrication.	1. Lubricate properly.
	2. Rust or corrosion.	2. Clean and lubricate.
	3. Misalignment or improper assembly.	3. Correct alignment and assembly of the drive.
	4. Worn-out chain or worn sprockets.	4. Replace chain. Reverse or replace sprockets.
5. Broken Chain or Sprockets	1. Shock or overload.	1. Avoid shock and overload or isolate through couplings.
	2. Wrong size chain, or chain that does not fit sprockets.	2. Replace chain. Reverse or replace sprockets.
	3. Rust or corrosion.	3. Replace parts. Correct corrosive conditions.
	4. Misalignment.	4. Correct alignment.
	5. Interferences.	5. Make sure no solids interfere between chain and sprocket teeth. Loosen chain if necessary for proper clearance over sprocket teeth.

7.3 SAFETY

Any equipment with moving parts or electrical components should be considered a potential safety hazard. *ALWAYS SHUT OFF THE POWER TO UNIT, TAG THE SWITCH AND LOCK THE POWER SWITCH IN THE "OFF" POSITION BEFORE WORKING ON A UNIT.*

7.30 Slow-Moving Equipment

Slow-moving equipment does not appear dangerous. Unfortunately, moving parts such as the chain sprockets, chain, belt sprockets and belts can cause serious injury by tearing and/or crushing your hands or legs.

7.31 Wiring and Connections

Wiring and connections should be inspected regularly for potential hazards such as loose connections and bare wires. Again, always shut off, tag, and lock out the power switch before working on a unit.

7.32 Slippery Surfaces

Caution must be taken on slippery surfaces. Falls can result in serious injuries. Any spilled oil or grease must be cleaned up immediately. If covers over the media allow sufficient space for walkways, condensed moisture on surfaces will create slippery places. If the temperature of the air within the enclosure can be kept several degrees above the temperature of the wastewater, condensation is significantly reduced. This condensation cannot be avoided completely so walk carefully at all times.

7.33 Infections and Diseases

Precautions must be taken to prevent infections in cuts or open wounds and illnesses from waterborne diseases. After working on a unit, always wash your hands before smoking or eating. *GOOD PERSONAL HYGIENE MUST BE PRACTICED BY ALL OPERATORS AT ALL TIMES.*

7.4 REVIEW OF PLANS AND SPECIFICATIONS

When reviewing plans and specifications, be sure the following items are included in the design of rotating biological contactors.

1. Enclosure to protect biomass from freezing temperature. Enclosure constructed of suitable corrosion-resistant materials and has windows or louvered structures in sides for ventilation. Forced ventilation is not necessary.
2. Heating. A source of heat is helpful during winter operation to minimize the corrosion caused by condensation and to improve operator comfort. If the temperature of the air within the enclosure is kept several degrees above the temperature of the wastewater, condensation is significantly reduced. Ceilings should be kept low to effectively use available heat.

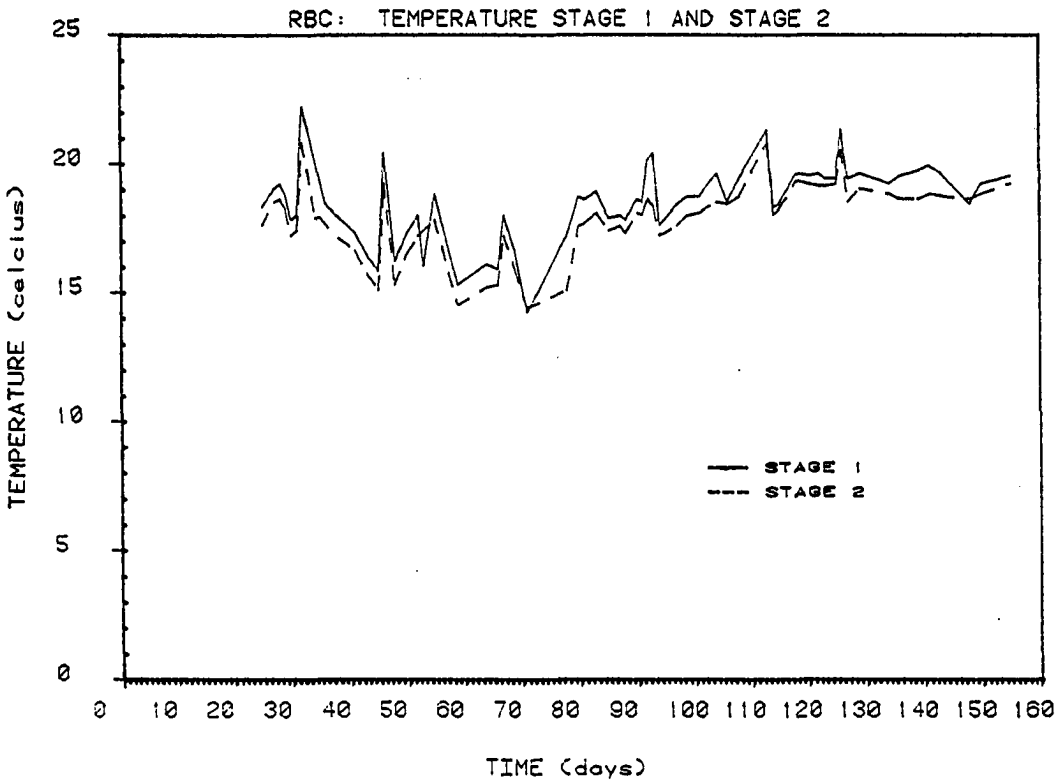
1 Belt Drive

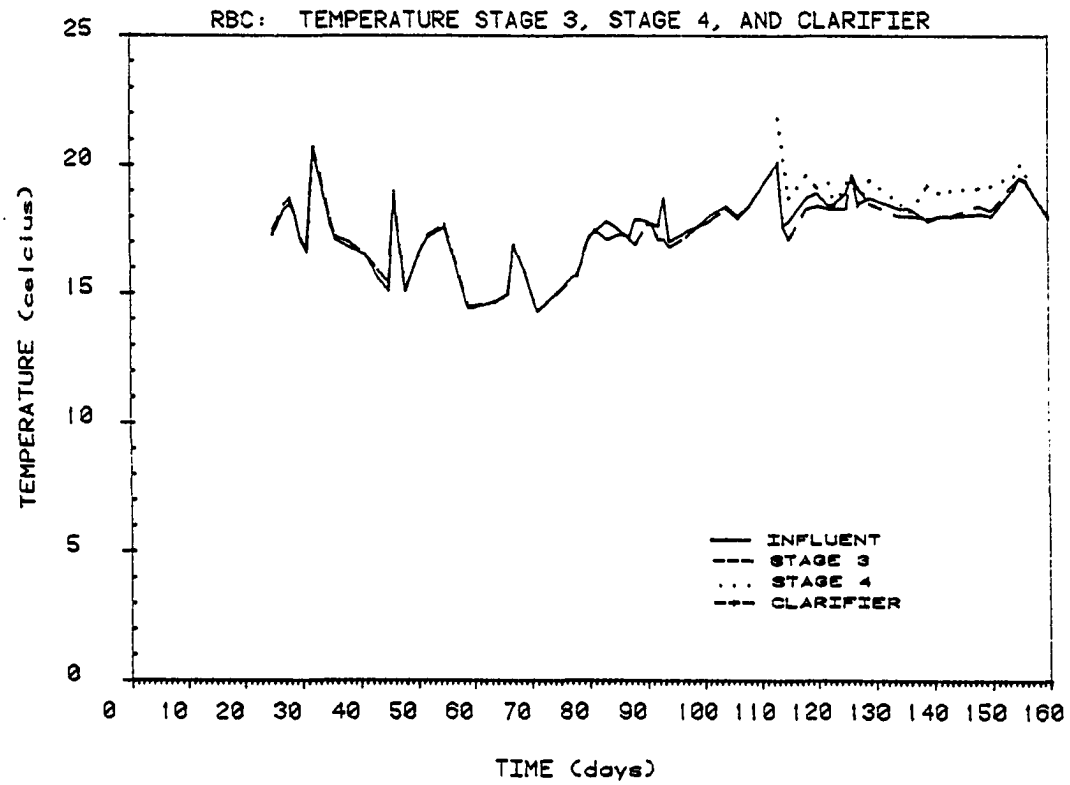
Trouble	Probable Cause	Corrective Action
Excessive edge wear	1. Misalignment or non-rigid centers.	1. Check alignment and/or reinforcement mounting.
	2. Bent flange.	2. Straighten flange.
Jacket wear on pressure-face side of belt tooth.*	Excessive overload and/or excessive belt tightness.	Reduce installation tension and/or increase drive load-carrying capacity.
Excessive jacket wear between belt teeth (exposed tension members)*	Excessive installation tension.	Reduce installation tension.
Cracks in Neoprene backing	Exposure to excessively low temp. (below −30°F or −35°C).	Eliminate low temperature condition or consult factory for proper belt construction.
Softening of Neoprene backing	Exposure to excessive heat (+200°F or 93°C) and/or oil.	Eliminate high temperature and oil condition or consult factory for proper belt construction.
Tensile or tooth shear failure.*	1. Small or sub-minimum diameter pulley.	1. Increase pulley diameter.
	2. Belt too narrow.	2. Increase belt width.
Excessive pulley tooth wear (on pressure-face and/or OD)*	1. Excessive overload and/or excessive belt tightness.	1. Reduce installation tension and/or increase drive load-carrying capacity.
	2. Insufficient hardness of pulley material.	2. Surface-harden pulley or use harder material.
Unmounting of flange	1. Incorrect flange installation.	1. Reinstall flange correctly.
	2. Misalignment.	2. Correct alignment.
Excessive drive noise	1. Misalignment.	1. Correct alignment.
	2. Excessive installation tension.	2. Reduce tension.
	3. Sub-minimum pulley diameter.	3. Increase pulley diameters.
Tooth shear*	1. Less than 6 teeth in mesh (TIM).	1. Increase TIM or use next smaller pitch.
	2. Excessive load.	2. Increase drive load-carrying capacity.
Apparent belt stretch	Reduction of center distance or non-rigid mounting.	Re-tension drive and/or reinforce mounting.
Cracks or premature wear at belt tooth root.*	Improper pulley groove top radius.	Regroove or install new pulley.
Tensile break	1. Excessive load.	1. Increase load-carrying capacity of drive.
	2. Sub-minimum pulley diameter.	2. Increase pulley diameters.

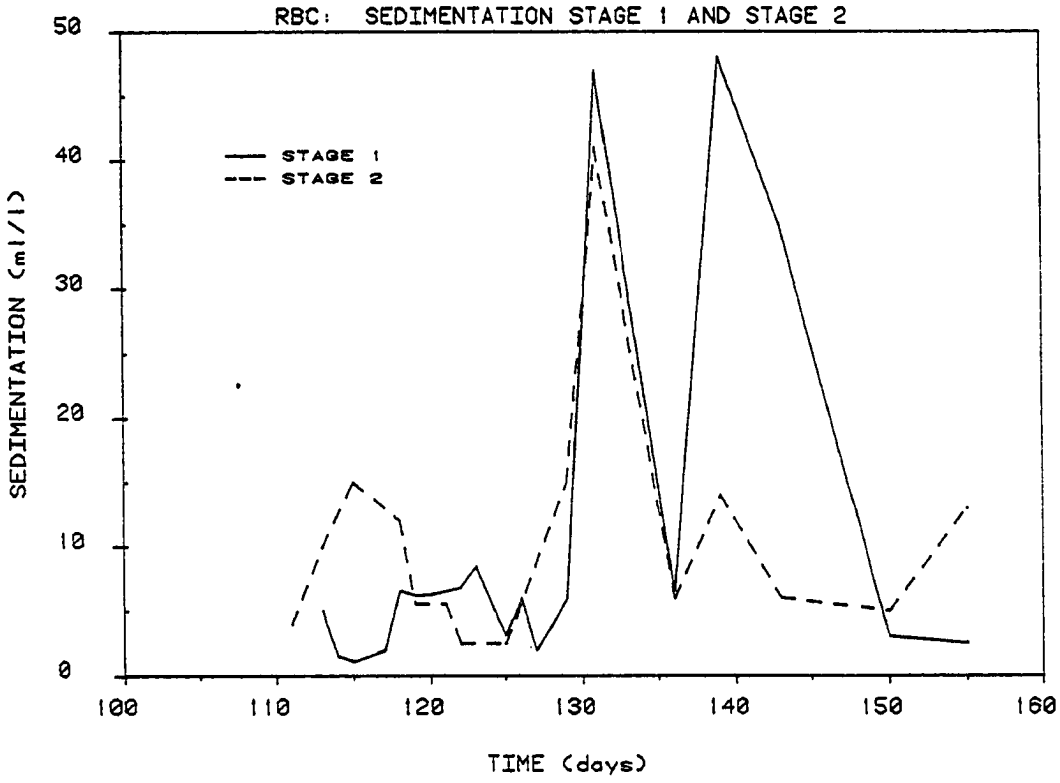
*Pertains to a timing belt system only.
†Recent systems use a V-belt drive.

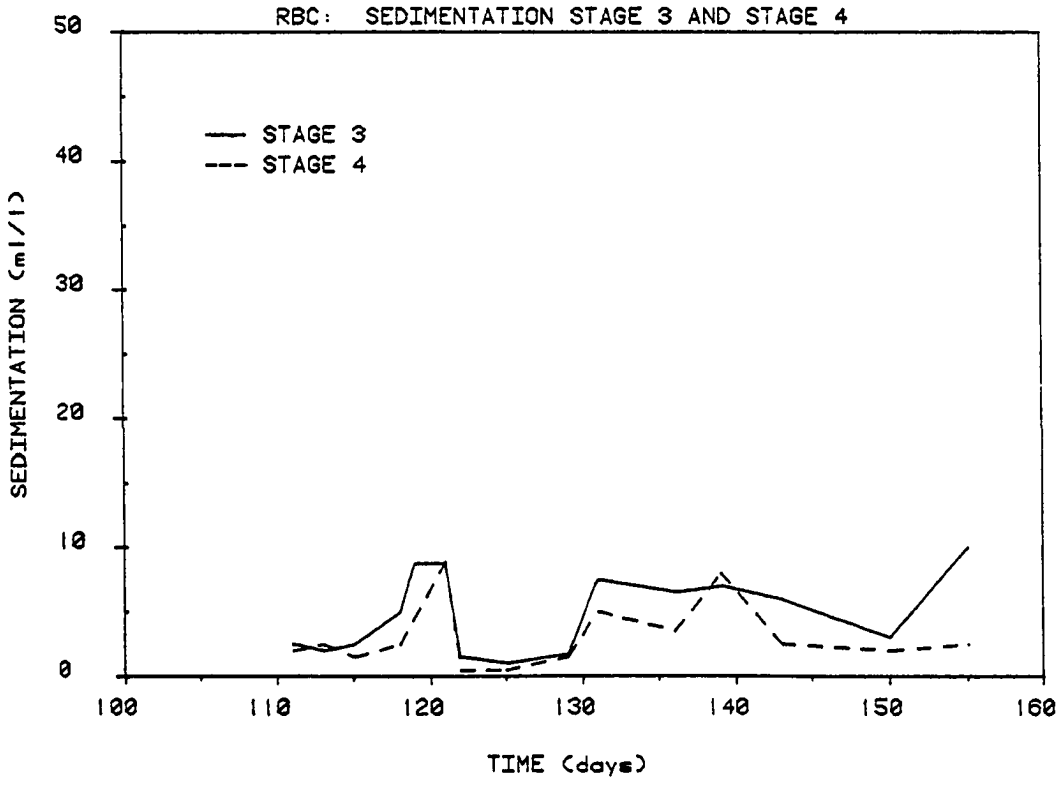
APPENDIX E

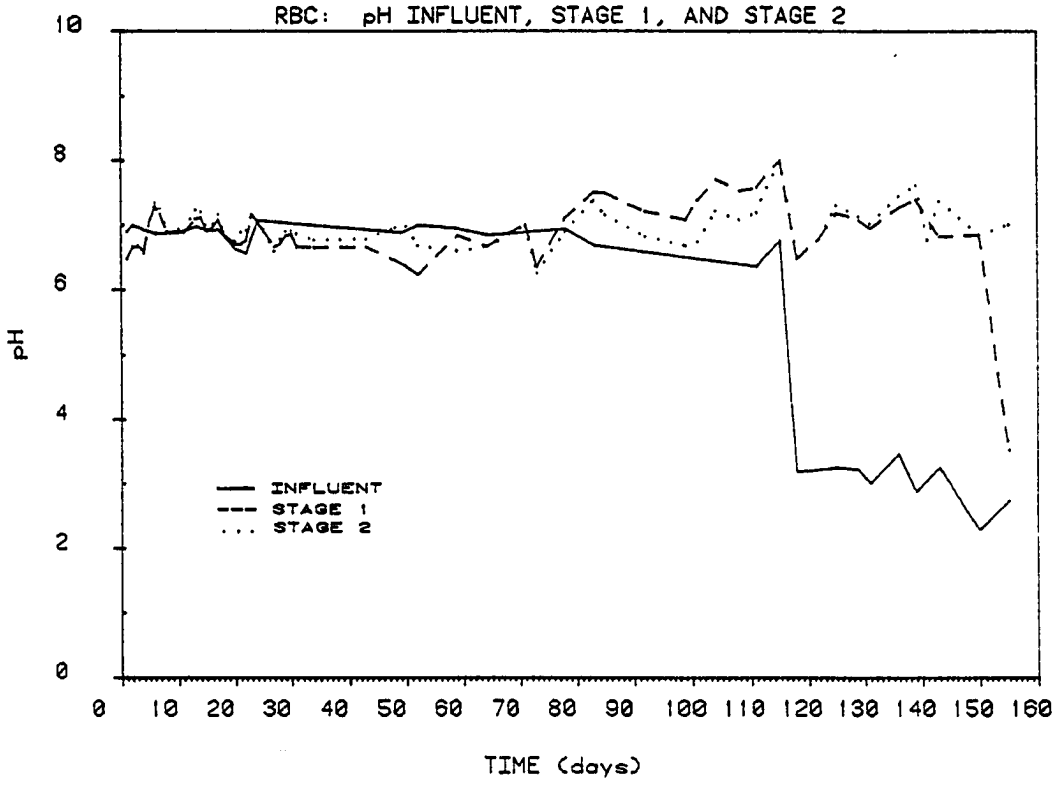
TIME SERIES ANALYSES FOR RBC TEST PARAMETERS

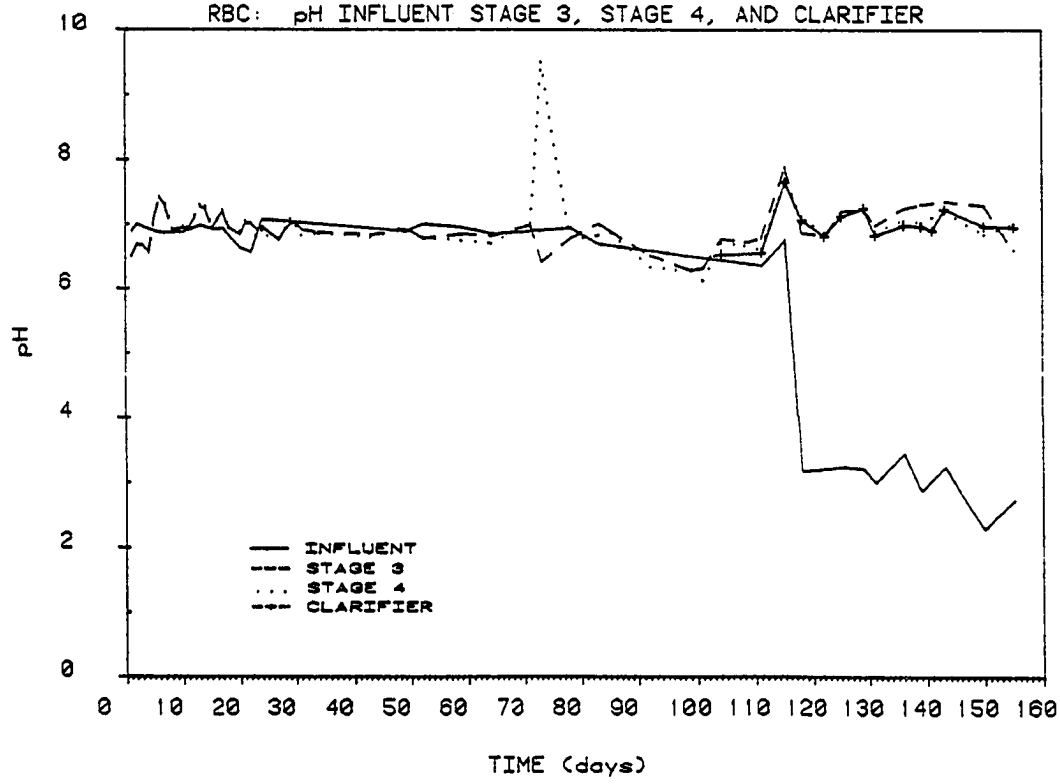

RBC: TEMPERATURE STAGE 1 AND STAGE 2
TEMPERATURE (celcius)
25
20
15
10
5
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
TIME (days)
STAGE 1
STAGE 2

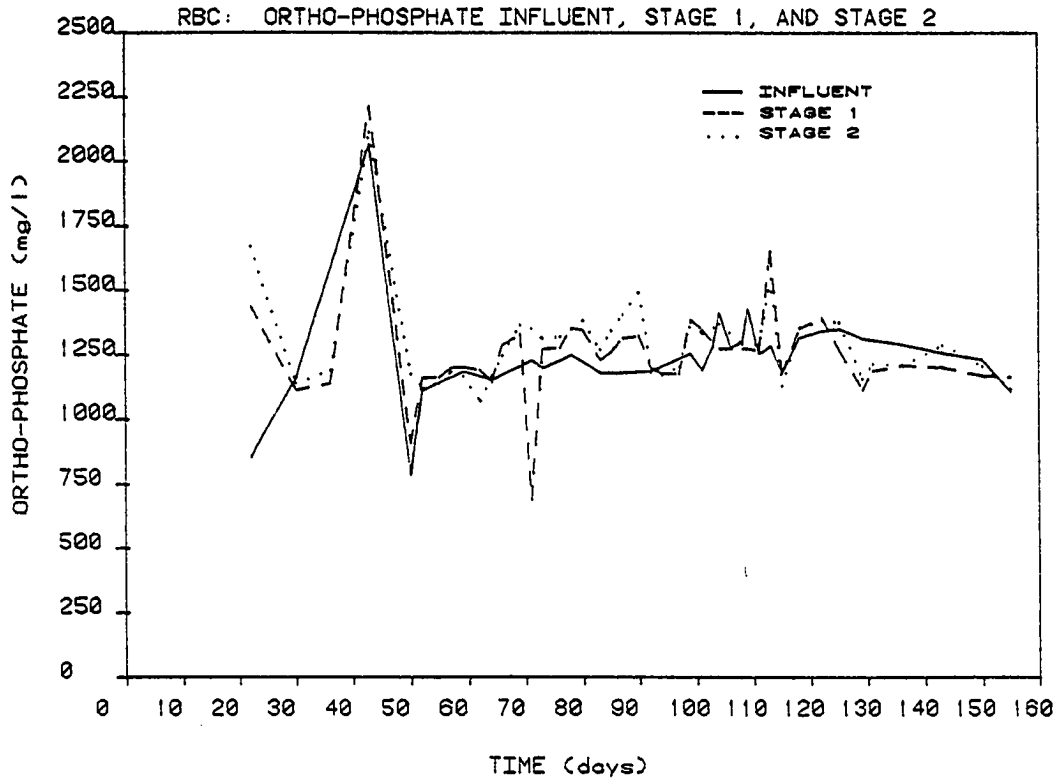

RBC: TEMPERATURE STAGE 3, STAGE 4, AND CLARIFIER
TEMPERATURE (celcius)
25
20
15
10
5
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
TIME (days)
INFLUENT
STAGE 3
STAGE 4
CLARIFIER

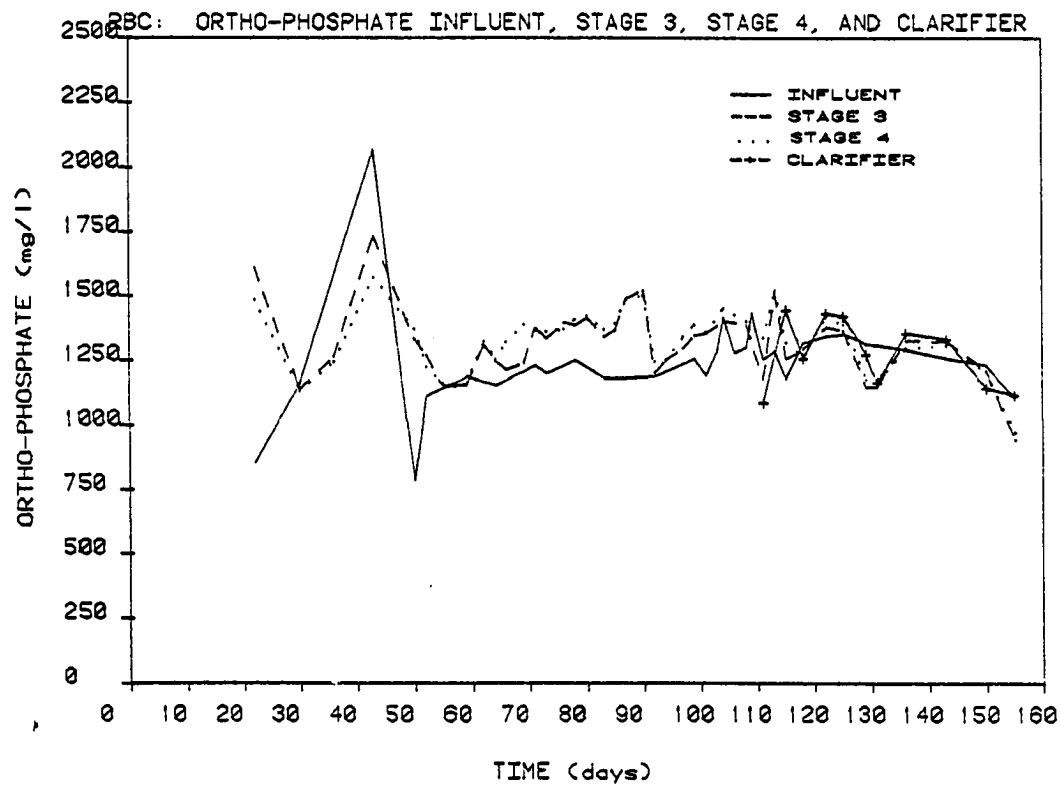

RBC: SEDIMENTATION STAGE 1 AND STAGE 2
STAGE 1
STAGE 2
SEDIMENTATION (ml/l)
50
40
30
20
10
0
100
110
120
130
140
150
160
TIME (days)

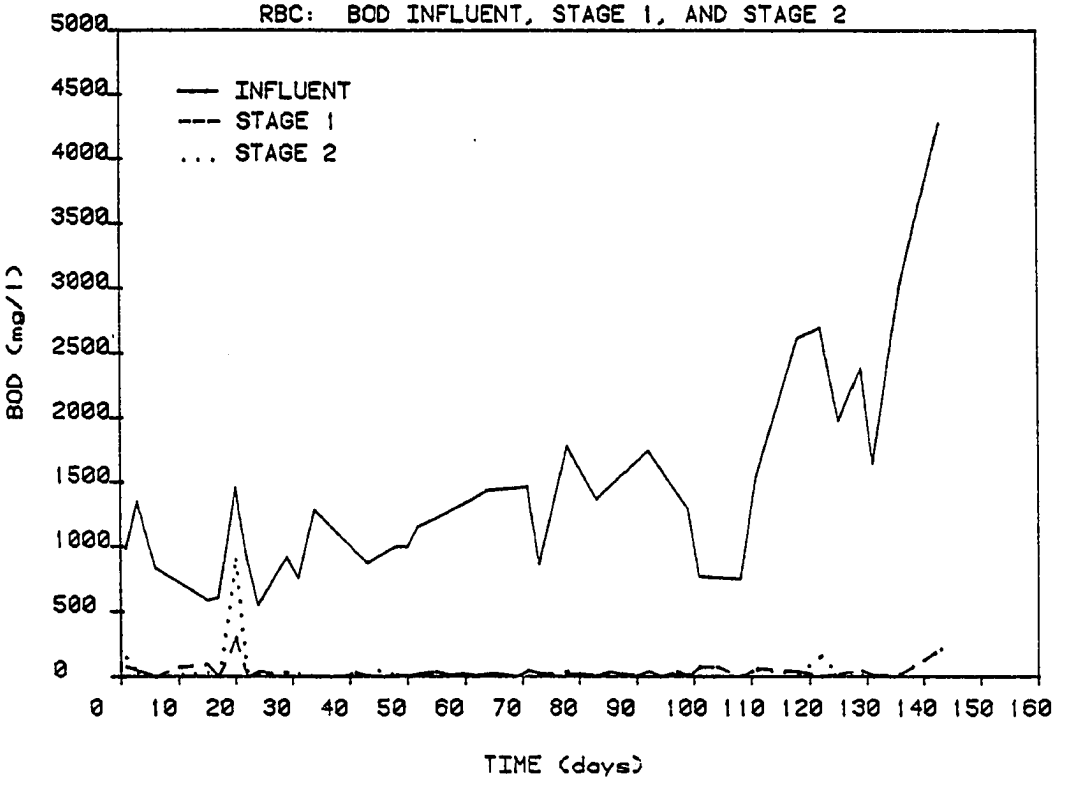

RBC: SEDIMENTATION STAGE 3 AND STAGE 4
STAGE 3
STAGE 4
SEDIMENTATION (ml/l)
50
40
30
20
10
0
100
110
120
130
140
150
160
TIME (days)

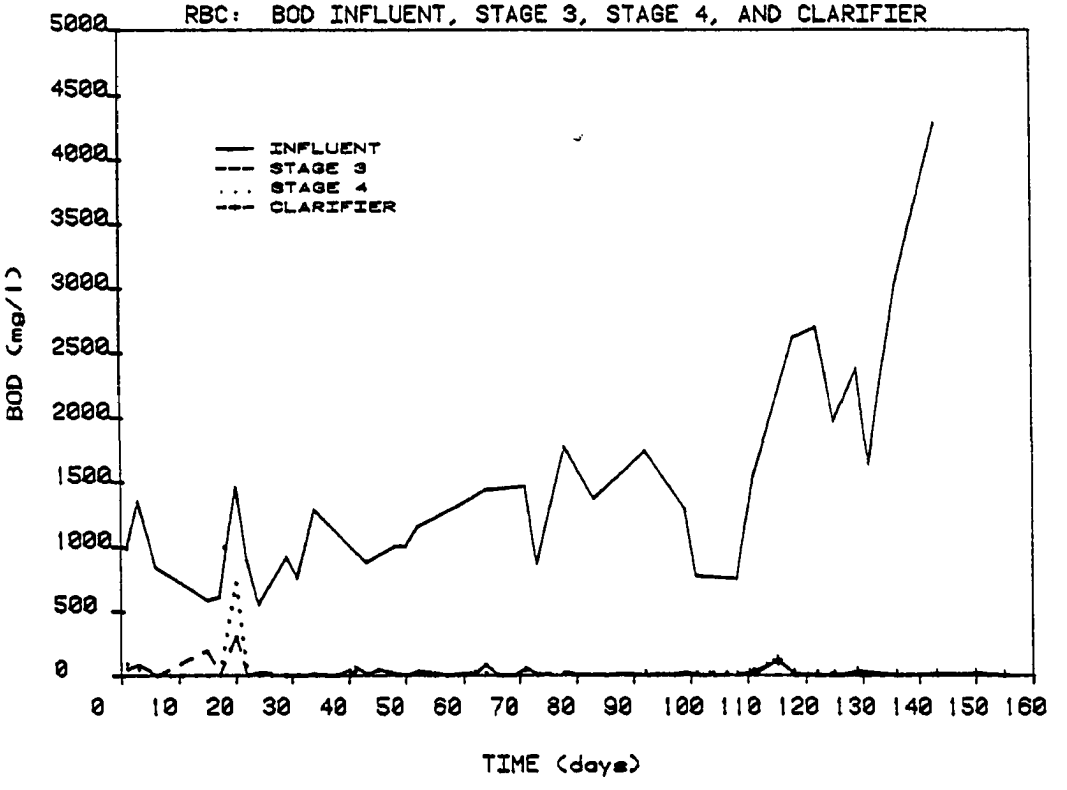

RBC: pH INFLUENT, STAGE 1, AND STAGE 2
pH
TIME (days)
INFLUENT
STAGE 1
STAGE 2

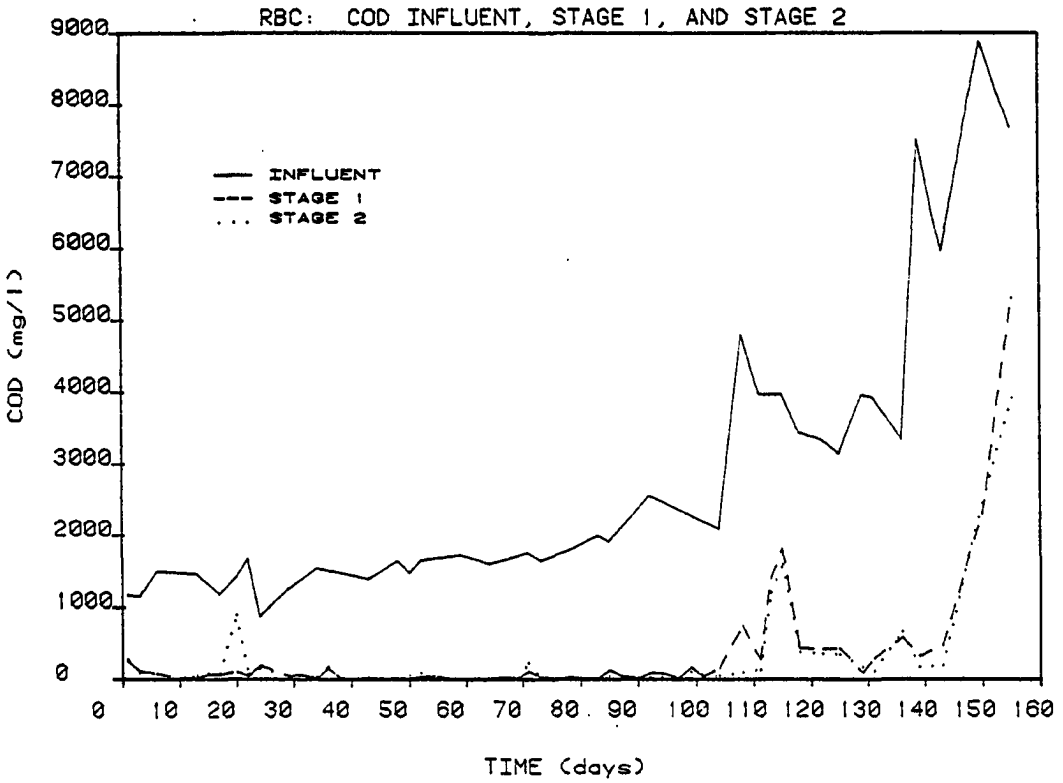

RBC: pH INFLUENT STAGE 3, STAGE 4, AND CLARIFIER
pH
TIME (days)
INFLUENT
STAGE 3
STAGE 4
CLARIFIER

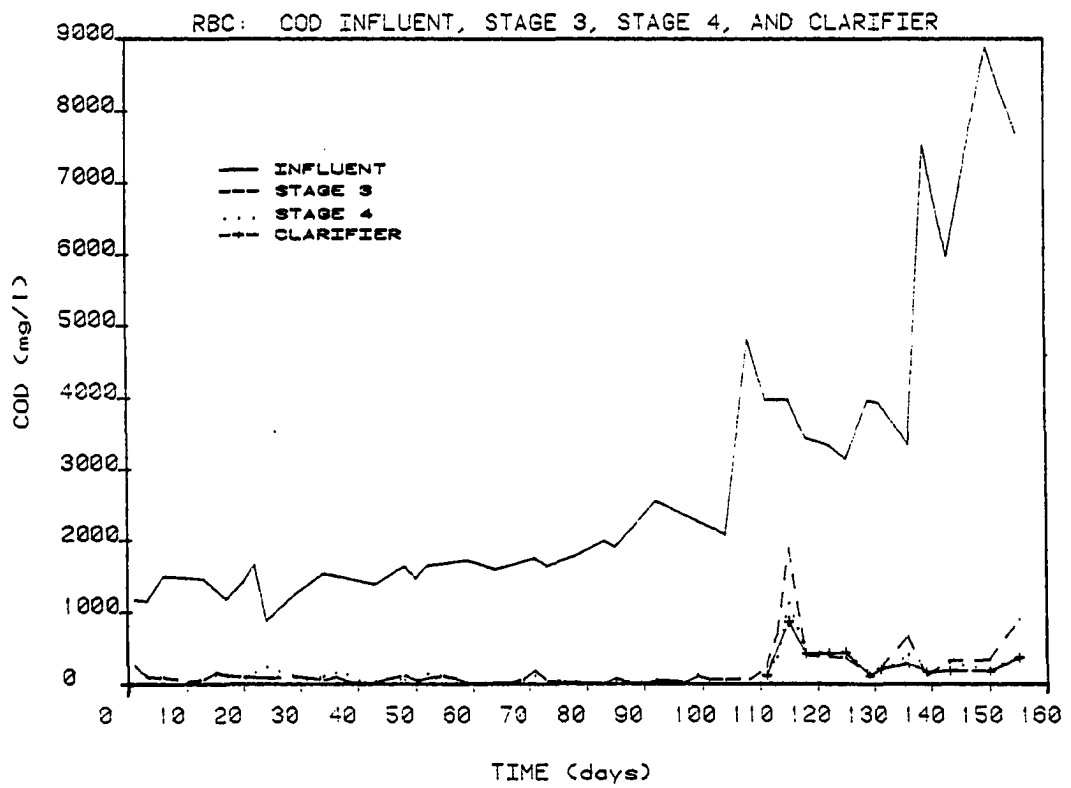

RBC: ORTHO-PHOSPHATE INFLUENT, STAGE 1, AND STAGE 2
INFLUENT
STAGE 1
STAGE 2
ORTHO-PHOSPHATE (mg/l)
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
TIME (days)

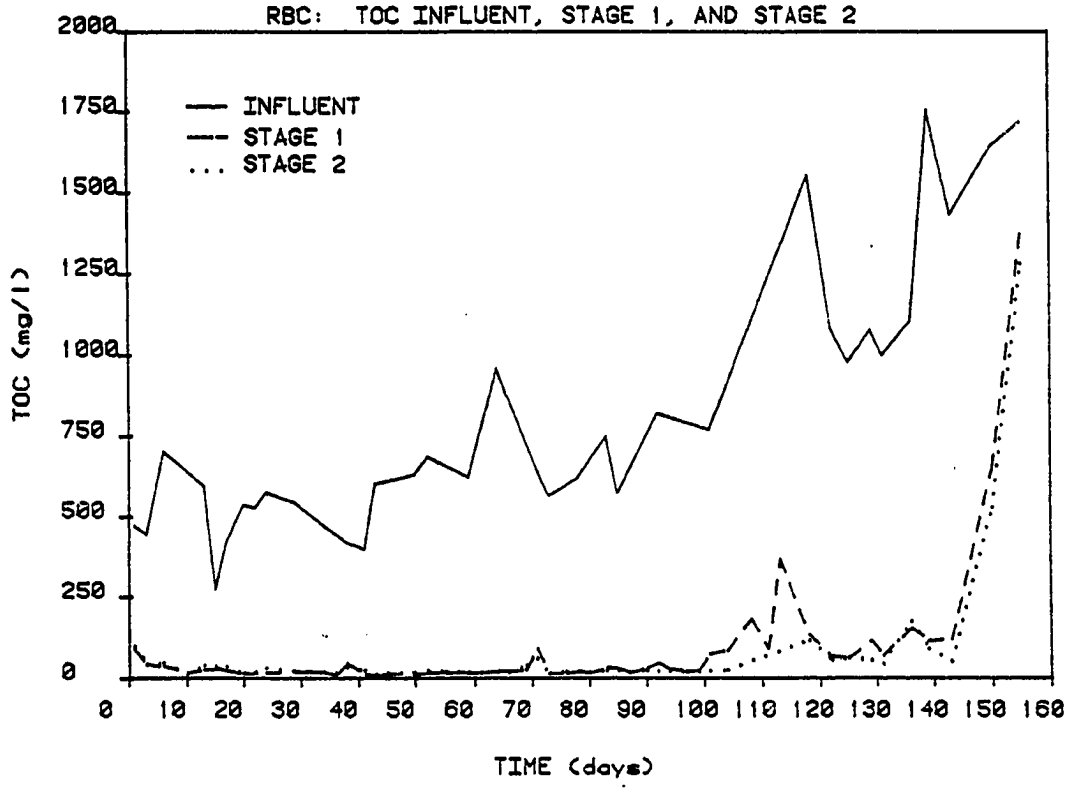

RBC: ORTHO-PHOSPHATE INFLUENT, STAGE 3, STAGE 4, AND CLARIFIER
INFLUENT
STAGE 3
STAGE 4
CLARIFIER
ORTHO-PHOSPHATE (mg/l)
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
TIME (days)

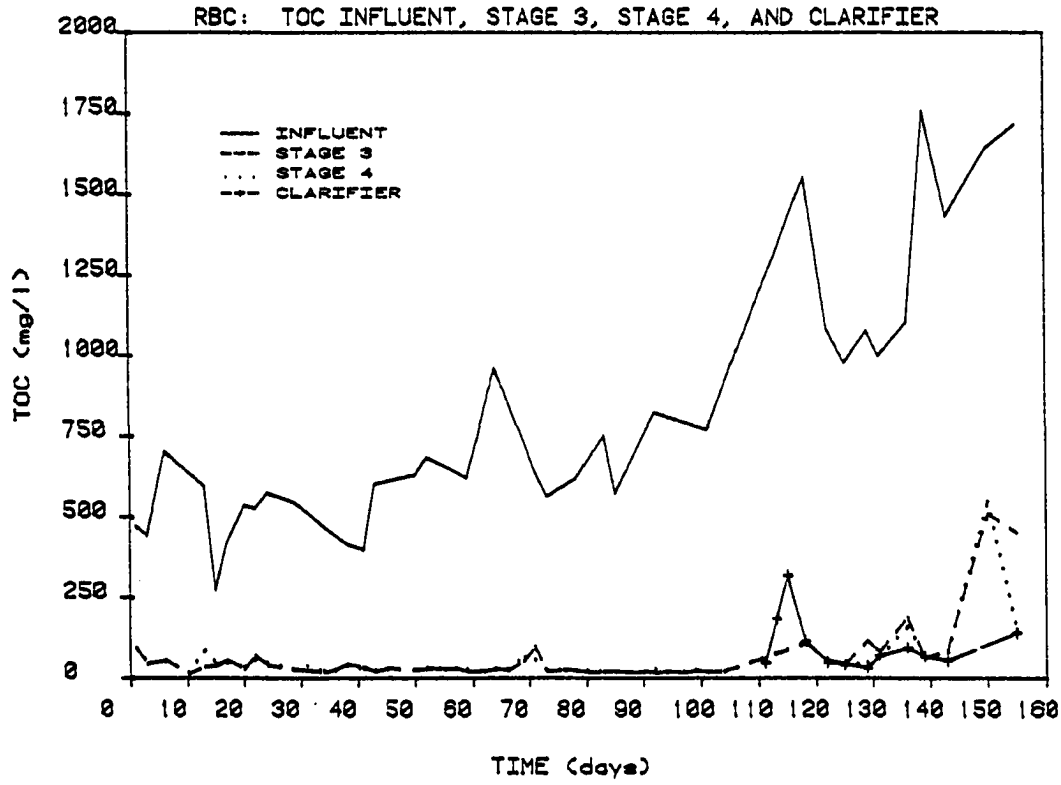

RBC: BOD INFLUENT, STAGE 1, AND STAGE 2
INFLUENT
STAGE 1
STAGE 2
BOD (mg/l)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
TIME (days)

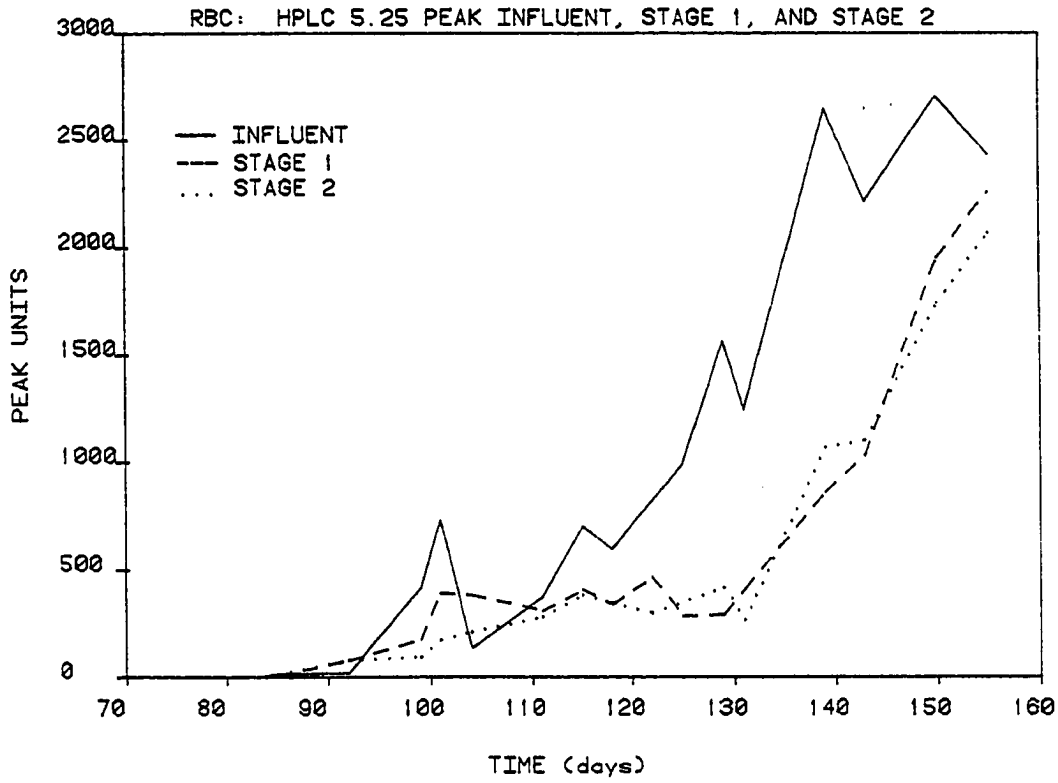

RBC: BOD INFLUENT, STAGE 3, STAGE 4, AND CLARIFIER
INFLUENT
STAGE 3
STAGE 4
CLARIFIER
BOD (mg/l)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
TIME (days)

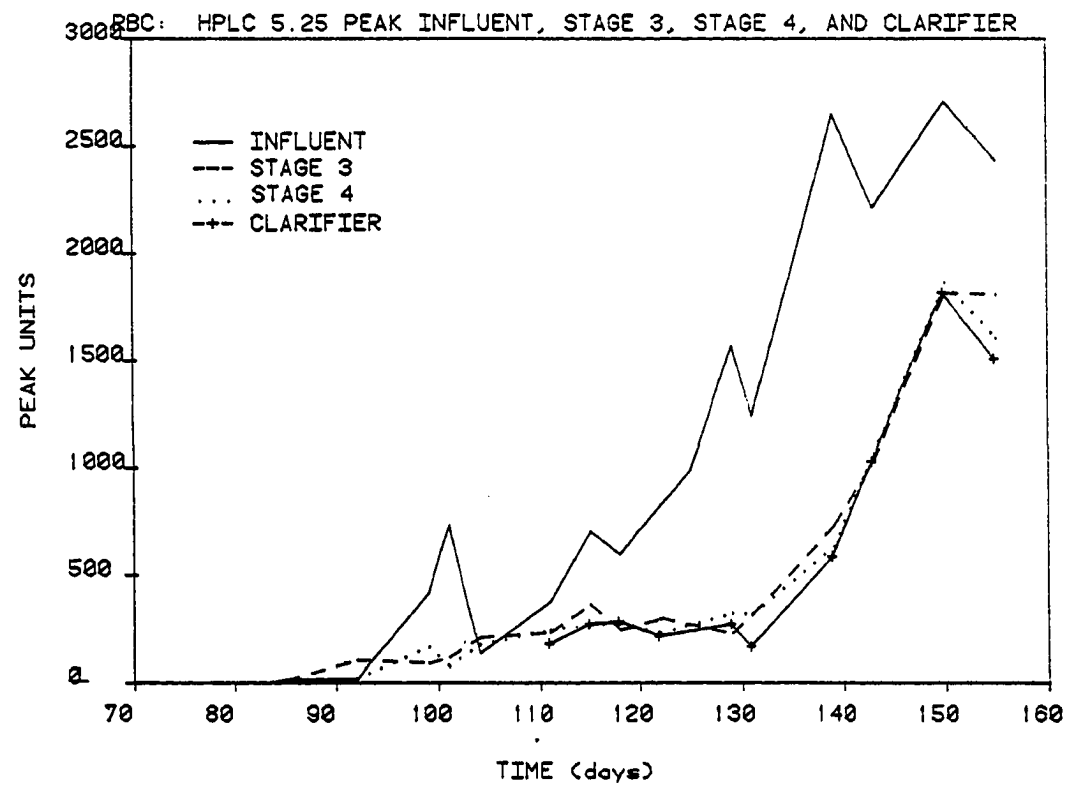

RBC: COD INFLUENT, STAGE 1, AND STAGE 2
INFLUENT
STAGE 1
STAGE 2
COD (mg/l)
TIME (days)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160


RBC: COD INFLUENT, STAGE 3, STAGE 4, AND CLARIFIER
INFLUENT
STAGE 3
STAGE 4
CLARIFIER
COD (mg/l)
TIME (days)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160


RBC: TOC INFLUENT, STAGE 1, AND STAGE 2
INFLUENT
STAGE 1
STAGE 2
TOC (mg/l)
2000
1750
1500
1250
1000
750
500
250
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
TIME (days)


RBC: TOC INFLUENT, STAGE 3, STAGE 4, AND CLARIFIER
INFLUENT
STAGE 3
STAGE 4
CLARIFIER
TOC (mg/l)
2000
1750
1500
1250
1000
750
500
250
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
TIME (days)


RBC: HPLC 5.25 PEAK INFLUENT, STAGE 1, AND STAGE 2
INFLUENT
STAGE 1
STAGE 2
PEAK UNITS
TIME (days)
0
500
1000
1500
2000
2500
3000
70
80
90
100
110
120
130
140
150
160


RBC: HPLC 5.25 PEAK INFLUENT, STAGE 3, STAGE 4, AND CLARIFIER
INFLUENT
STAGE 3
STAGE 4
CLARIFIER
PEAK UNITS
TIME (days)
0
500
1000
1500
2000
2500
3000
70
80
90
100
110
120
130
140
150
160

APPENDIX F

AUTOTROL RBC PILOT PLANT STUDY

The Navy has acquired an Autotrol RBC pilot plant from the U.S. Army Medical Bioengineering Research and Development Laboratory (Figure 34). The dimensions of the unit are:

Overall dimensions, ft, unmounted	2 x 2 x 6
Disk area, ft^2	250
Disk diameter, m	0.5
Speed, rpm	13
Maximum flow, gpd	1,000
Minimum flow, gpd	0.5
Number of stages	4

Research is now in progress to verify and expand the design findings from the bench-top RBC. The findings will be used for scale-up to an on-line RBC process at the Naval Air Station, North Island. The Autotrol will also be tested on actual firefighting school wastewater.

Inoculum and media are the same as that used on the bench-top RBC in Chapter 3. To date the concentration of AFFF is 4,000 mg $liter^{-1}$ COD. The analytical parameters taken are COD, BOD, and TOC, as described in Chapters 2 and 3. Results are given in Table F-1.

As can be seen from Table F-1, the pilot plant has achieved greater than 90% removal from a 4,000-mg $liter^{-1}$ COD influent of AFFF synthetic wastewater. Decreases in TOC and BOD are similar. Foaming,

however, poses a problem as mentioned in Chapter 3. The Navy is pursuing research into cost effective mechanical and/or chemical means of suppressing foam.

Table F-1. Results of Autotrol Pilot Plant Treating AFFF Synthetic Wastewater

Item	Organic Loading ($kg\ m^{-3}\ d^{-1}$)	COD		BOD		TOC		% AFFF
		$mg\ liter^{-1}$	% Removal	$mg\ liter^{-1}$	% Removal	$mg\ liter^{-1}$	% Removal	
Influent	0.29	1,018		--		592		0.5
Stage 1		161	84	719	--	71	88	
Stage 2		178	83	82	--	77	87	
Stage 3		175	83	80	--	77	87	
Stage 4		160	84	83	--	75	87	
Stage 5		177	83	92	--			
Influent	0.59	3,672	--	1,750		1,179		1.0
Stage 1		199	95	90	95			
Stage 2		214	94	63	93			
Stage 3		190	95	111	94	d	d	
Stage 4		195	95	79	96			

d = data not available

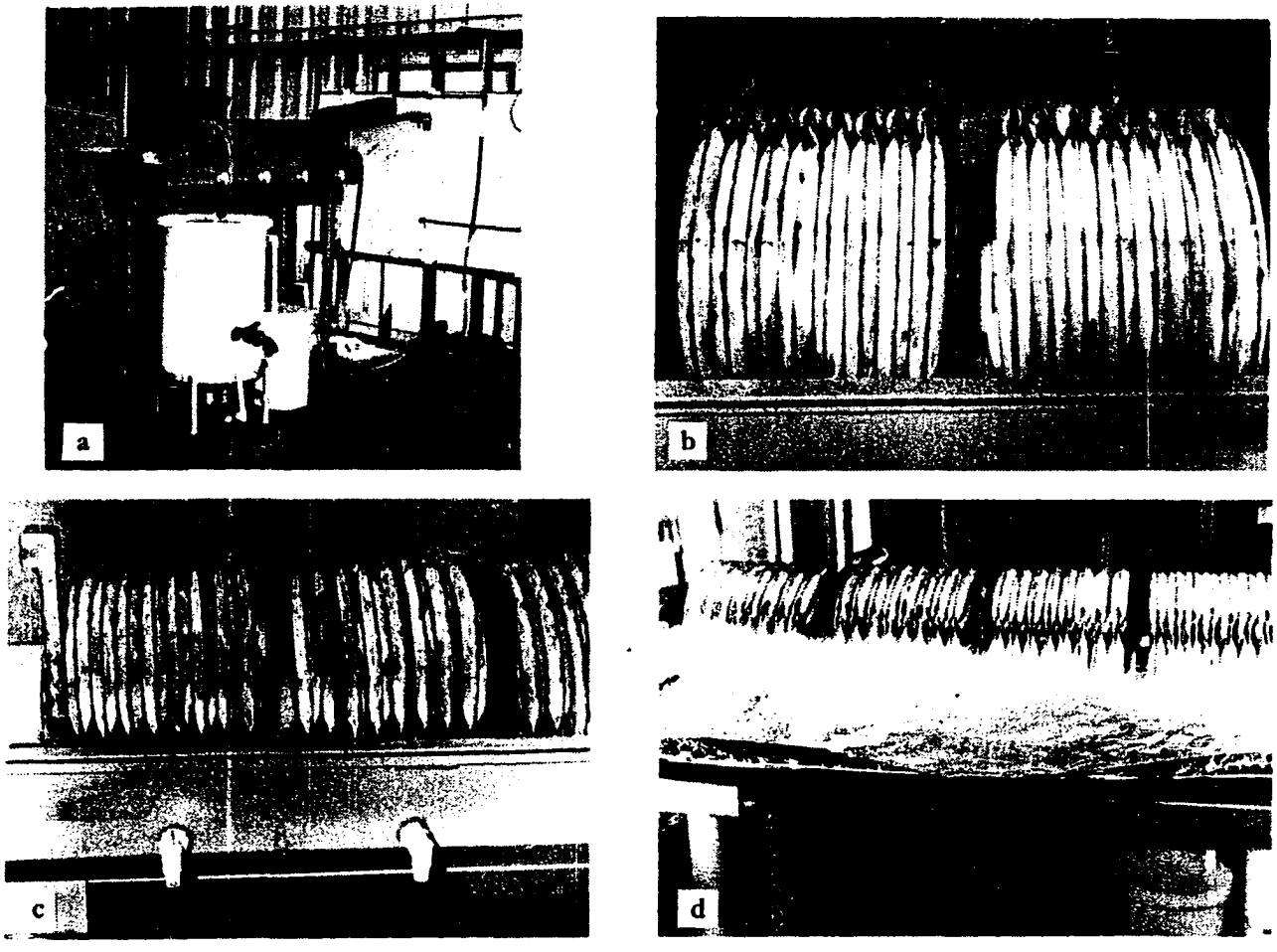


Figure 35. Pilot plant RBC. Carbon source was 4000 mg. liter^{-1} AFFF added via the influent. (a) View of RBC setup. (b) Close-up of disks in stages 1 and 2. (c) Close-up of disks in stages 3 and 4. (d) View of foam produced by the RBC at this concentration.

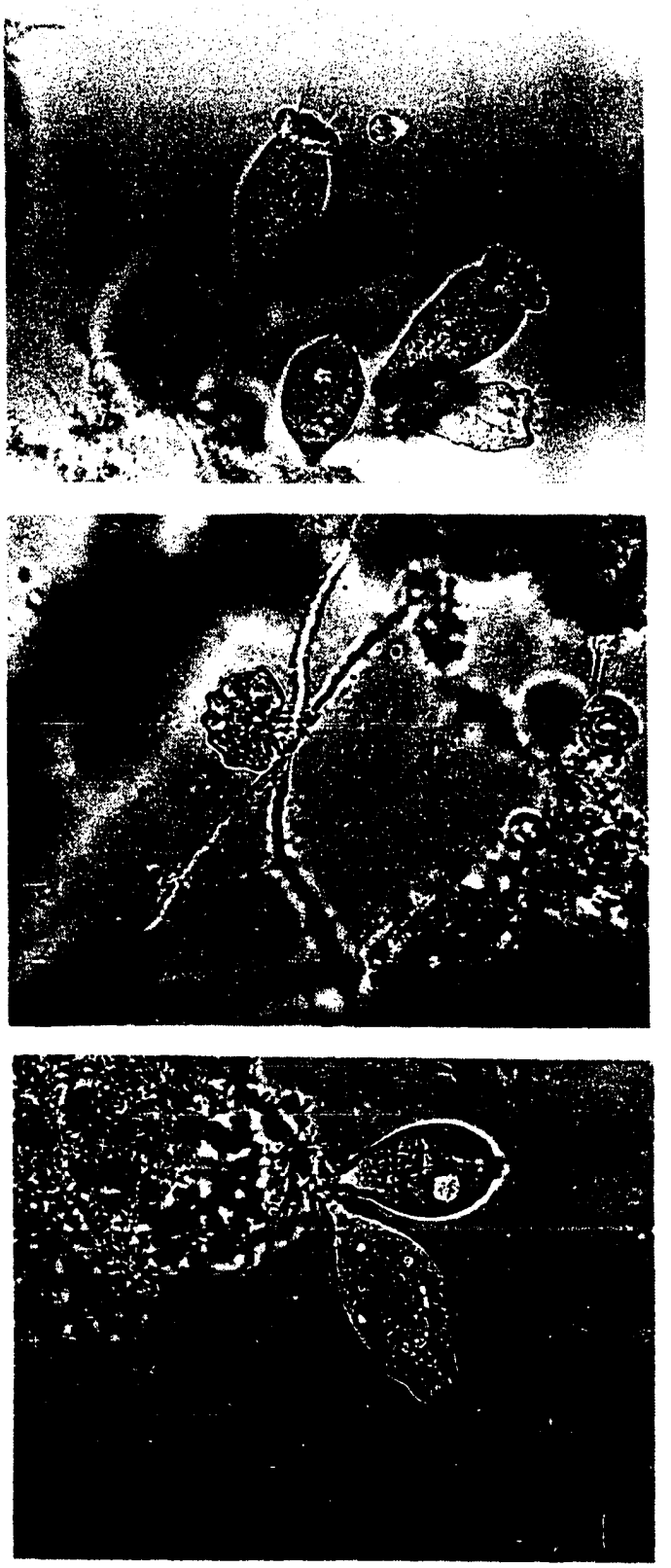


Figure 36. Representative microorganisms observed in disk scrapings from the pilot plant RBC. (800x)