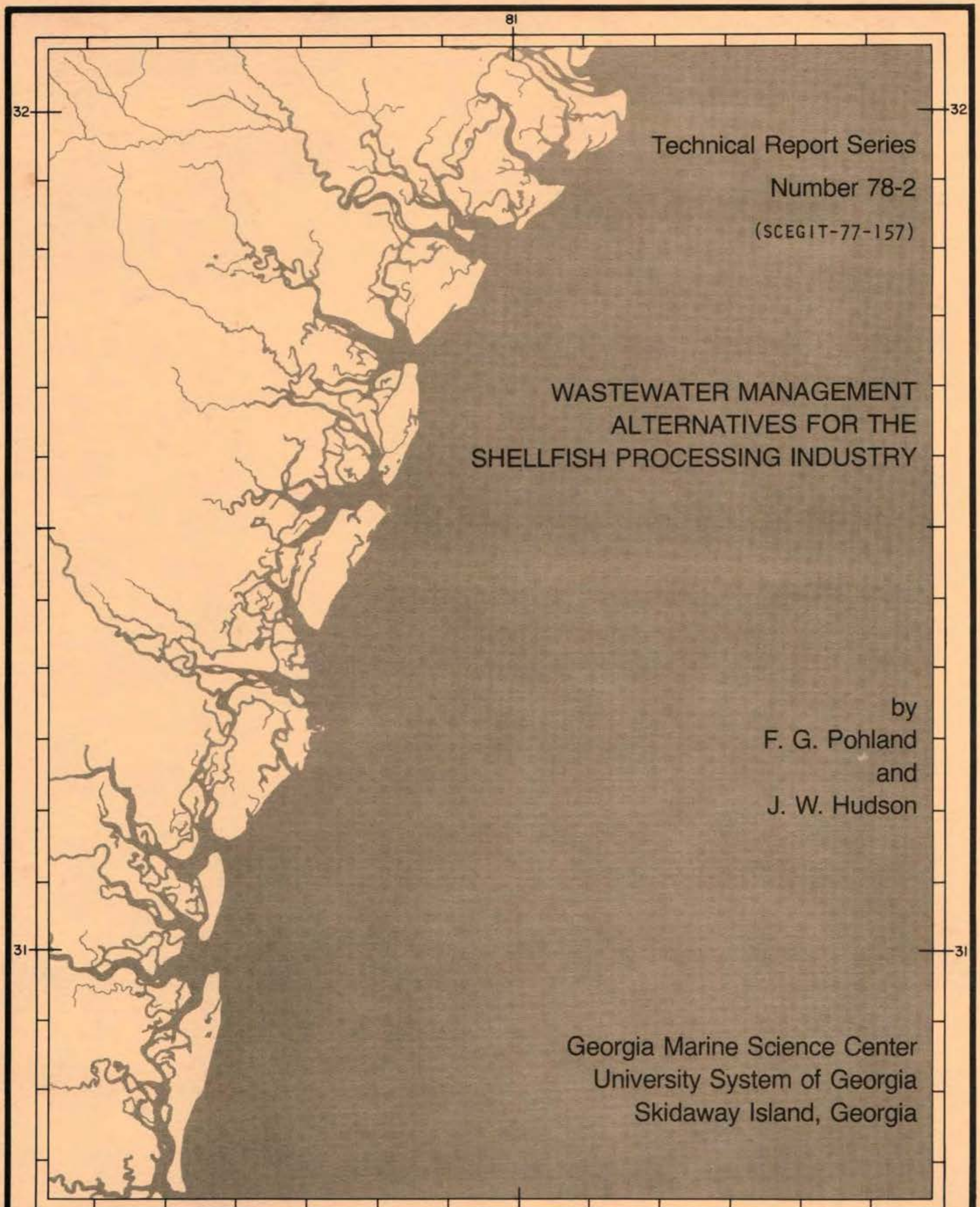

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WASTEWATER MANAGEMENT ALTERNATIVES FOR THE SHELLFISH PROCESSING INDUSTRY

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FINAL REPORT

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by

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INTRODUCTION AND RESEARCH RATIONALE

In recent years, the shellfish processing industry, like many in the industrial sector, has been faced with the responsibility of instituting wastewater management practices in compliance with pollution control regulations. Although many processors have demonstrated a willingness to initiate environmental protection measures, they have been reluctant to establish such measures without assurances that their economic viability would remain intact. To enable the industry better to review and assess possible wastewater management alternatives within an attractive economic perspective, comprehensive evaluations of treatment methods applicable and acceptable to both the industry and regulatory authorities were required. Investigations were initiated to evaluate methods for control of wastewater discharges emanating from a segment of the shellfish processing industry.

Industries typically have four general alternatives for control of wastewater discharges: 1) direct discharge to a municipal or cooperative sewerage system with cost allocation by surcharge; 2) wastewater pretreatment with subsequent discharge to municipal or cooperative treatment systems; 3) complete on-site wastewater treatment to levels acceptable for ultimate discharge or for industrial re-use; and 4) elimination of wastewater by in-plant process modifications or cessation of operation. Within these alternatives, other factors may further affect the ultimate choice. For example, some form of by-product recovery may be instituted to defray costs of providing an acceptable wastewater treatment system which would be economically unfavorable otherwise. (Although this aspect may show promise, it often entails considerable by-product testing, determination of marketability, distribution development, etc.) Selection of any alternative should not only be based on its potential for attaining a desired goal, but also on its maximum cost effectiveness.

Because little information was available relative to on-site pretreatment or complete treatment alternatives specific to the shellfish industry, laboratory studies were conducted at the Sanitary Engineering Laboratories of the Georgia Institute of Technology to establish the technical applicability of various wastewater treatment methods for shellfish processing waste discharges. The relative economies associated with the implementation of various selected wastewater management alternatives were also estimated and compared.

Preliminary Considerations

The direction and conduct of experimentation were oriented toward methodology applicable for on-site wastewater treatment methods which would satisfy requirements of Public Law 92-500, "The Federal Water Pollution Control Act Amendments of 1972" (1). The sections of P.L. 92-500 with the greatest potential impact for the shellfish processing industry are those stipulating requisite degrees of wastewater treatment and concomitant implementation schedules. Briefly, the law requires for point wastewater discharge sources, an "application of best practical control technology currently available by 1977" and "application of best available technology economically achievable by 1983," if and where determined feasible by the Environmental Protection Agency (EPA) Administrator, even to the point of "eliminating the discharge of all pollutants."

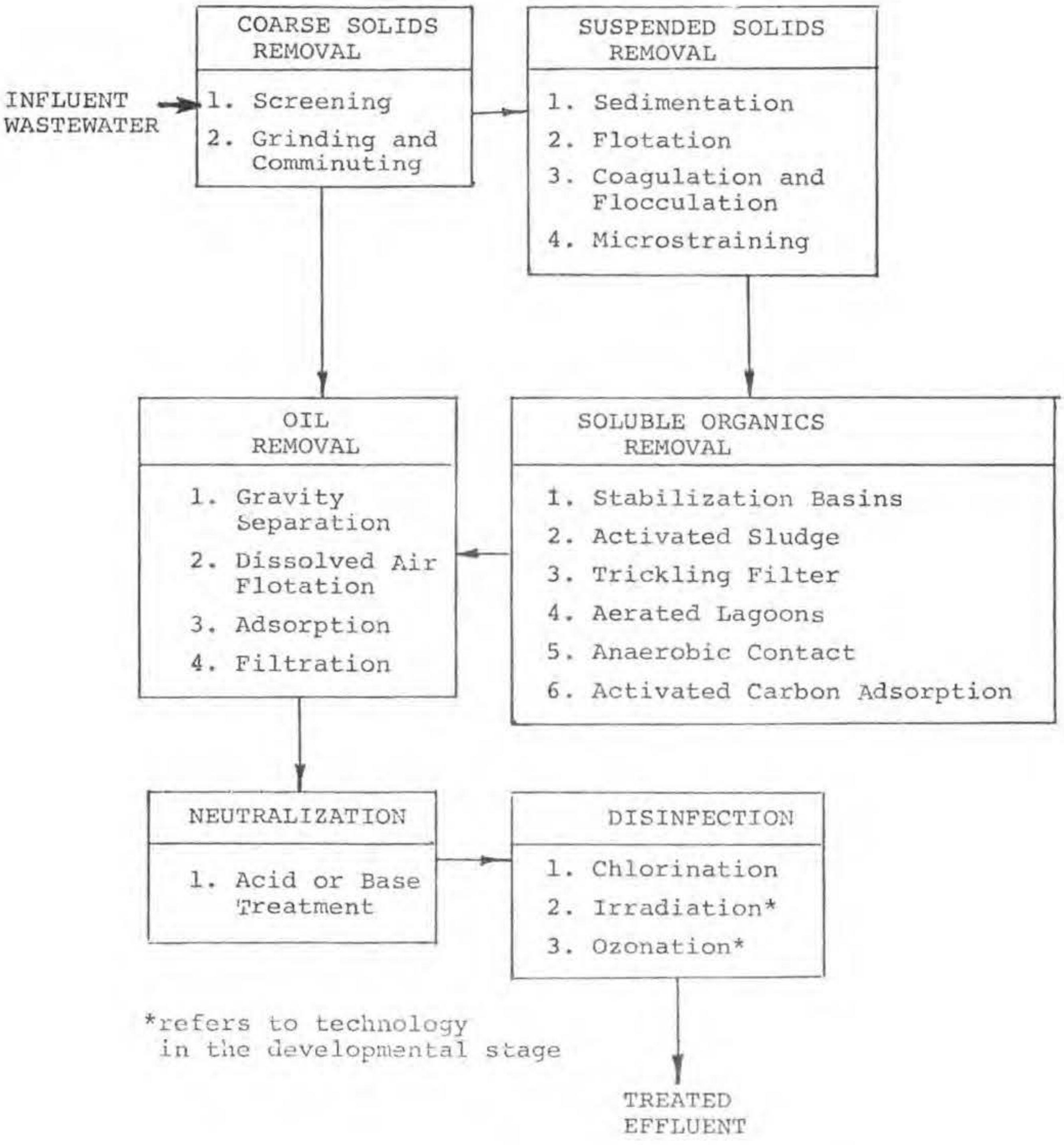
A problem confronting both processor and regulator is the definition of what comprises "best practical" or "best available" technology specific to shellfish processing effluents. Although effluent discharge limitations have been promulgated by the EPA for shellfish processing (2), they admittedly have been developed from relatively sparse information. Consequently, recommended control procedures have been based substantially on transfer technology derived from experience with similar industries. An additional goal of these investigations was to establish an enlarged and more reliable data base to provide extension and/or substantiation of wastewater control procedures specific to the shellfish processing industry.

Prior to the investigation of selected wastewater treatment methods, those "conventional" processes and operations which could best accommodate the particular wastewater under consideration were identified. A summary of currently accepted conventional-type treatment methods which have some level of established technological feasibility is presented in Figures 1, 2 and 3. Of these processes and operations, attention was focused upon those methods which appeared best suited to the wastewater on the basis of characterization analyses and engineering experience. Guided by the fact that shellfish processing wastewaters are reasonably typical of others within the food processing industry, i.e., relatively high solids and biodegradable organics content (3), several promising treatment options were selected.

As an initial treatment step, screening could be relied upon to remove significant amounts of coarse solids, exoskeletons, and larger tissue fragments resulting from normal processing activities. Since the efficiencies and technology associated with screening have been well established (4,5), further investigations on screening were not conducted during these investigations. Nevertheless, from considerations of the normal raw wastewater character for shellfish processing plants, it would appear that screening should be universally applied throughout the industry since waste strength and solids reductions may be quite significant and selective by-product recovery possibilities would be enhanced. Therefore, throughout these investigations, initial wastewater screening was considered a logical and prudent action, and studies on biological treatment methods were performed with prescreened wastewaters.

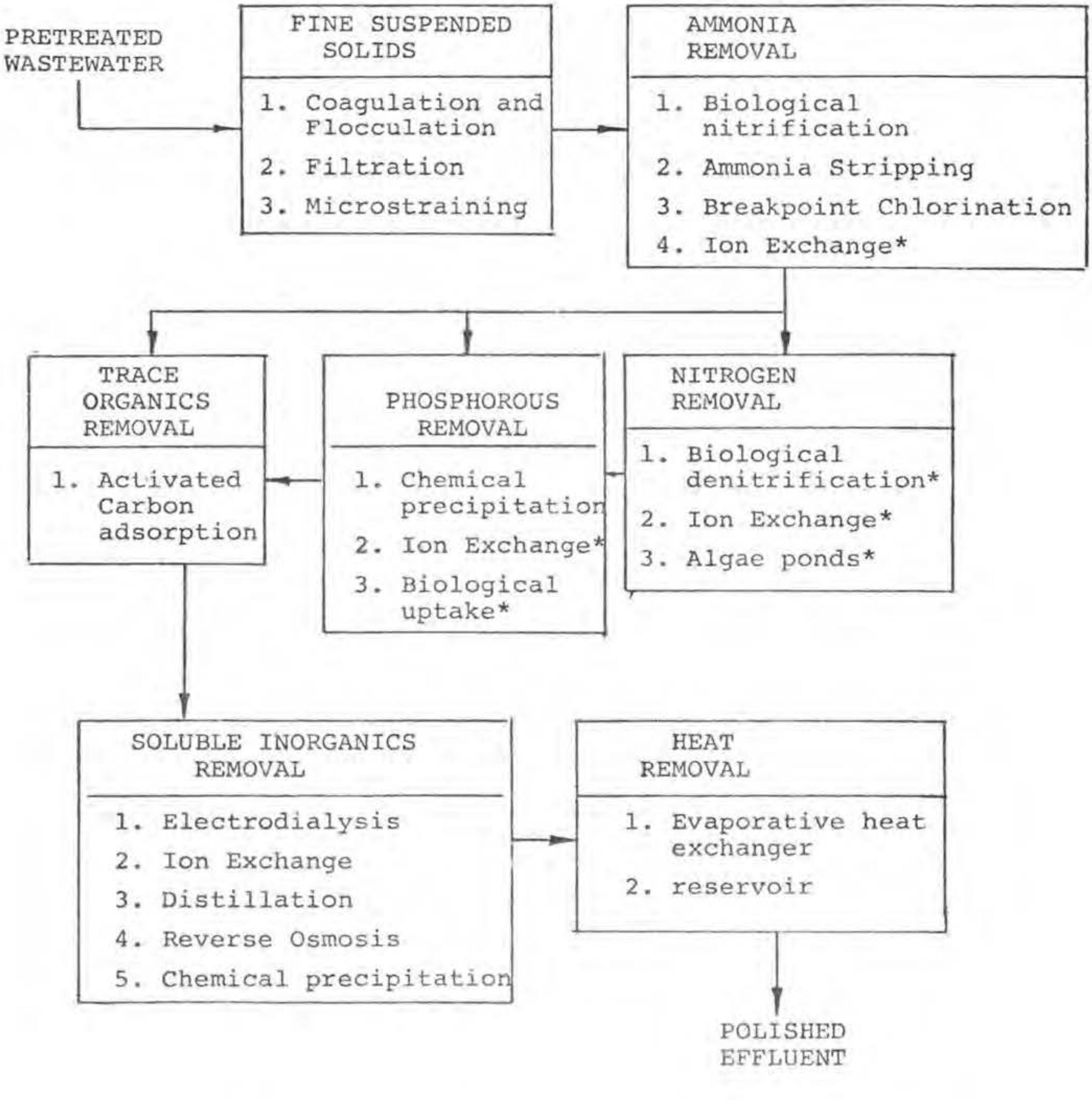
Removal of solids escaping screening may be accomplished by unit operations classed within the broad category of "primary treatment." Reasonably good suspended solids removals by air flotation methods have been reported (5,6). Micro-straining is not used extensively, except for very select wastewaters or as an advanced treatment, because of comparatively unfavorable economic and operational constraints. Only the prevalent method, simple and chemically aided sedimentation, was evaluated here, however, as a means for removal of suspended solids and some organics preparatory to further treatment or discharge.

After pretreatment for solids removal, major wastewater constituents from shellfish processing effluents which may seriously impair the quality of a receiving water are colloidal and soluble organic materials. These components are primarily carbonaceous in character but exceedingly diverse on the molecular level. They are usually determined collectively by evaluation of their overall effect upon the oxygen reserves of their aqueous environment. Since these materials are largely oxidized by means of



*refers to technology in the developmental stage

Figure 1. Conventional Industrial Wastewater Treatment Methods Having Established Technological Feasibility



* refers to technology in the developmental stage.

Figure 2. Advanced Wastewater Treatment Methods with Some Degree of Established Technological Feasibility.

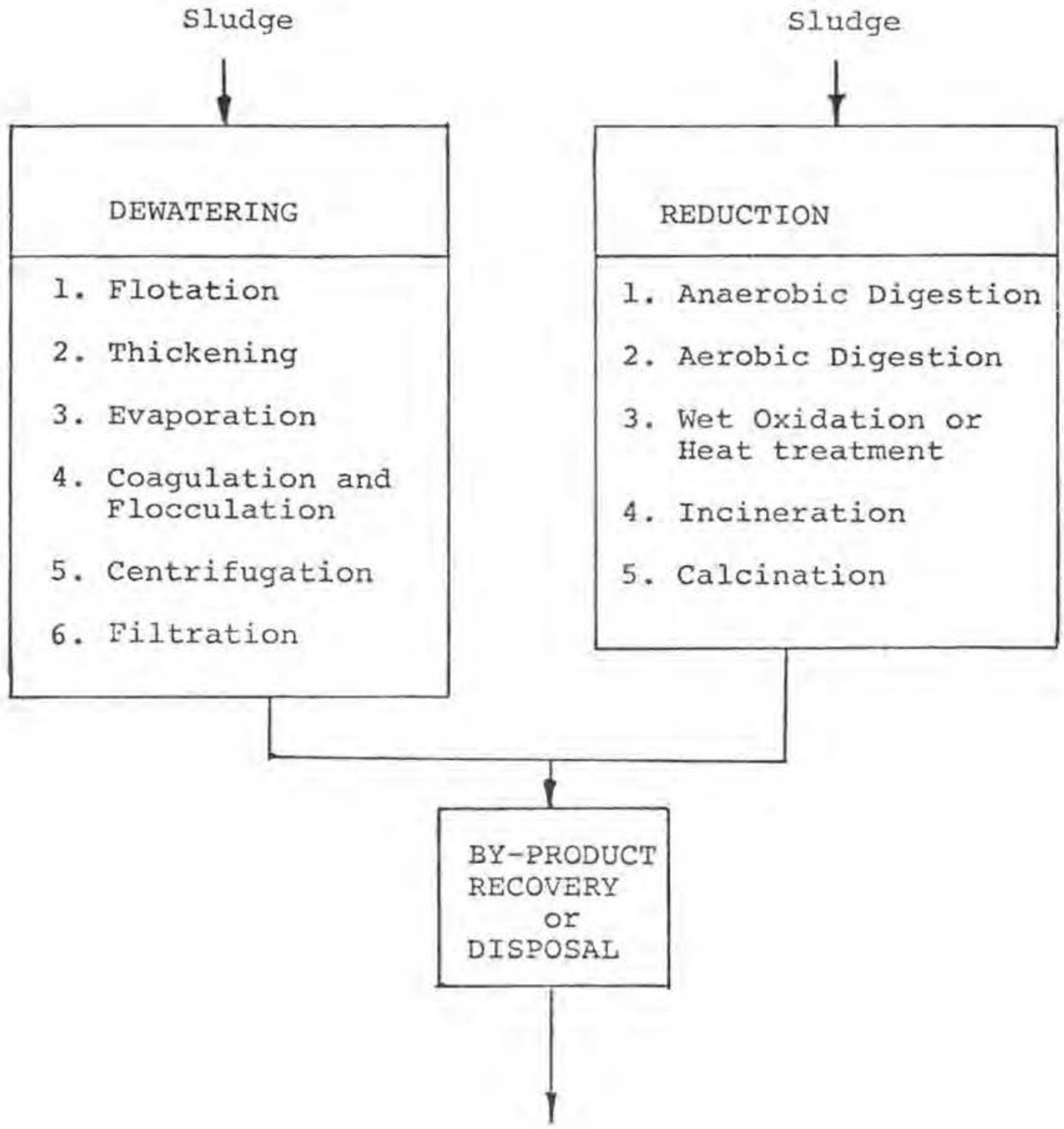


Figure 3. Conventional Sludge Treatment Methods with Established Technological Feasibility

biological activity in natural environments, their removal from a wastewater stream is primarily accomplished by controlled biological treatment, a method which has traditionally proven to be most effective and economical in comparison with other alternatives. The major thrust, therefore, focused upon both aerobic and anaerobic biological treatment of shellfish processing wastewaters. For comparative purposes, however, the relative applicability of activated carbon adsorption for removal of raw wastewater organics was also evaluated. The studies also were extended past so-called "secondary treatment methods" to evaluate the applicability and potential of advanced treatment for production of a final effluent of sufficient quality to meet very stringent regulatory demands or for industrial re-use. Following aerobic biological treatment, secondary effluents were treated by sand filtration for removal of residual solids escaping clarification, carbon adsorption for removal of residual or refractory organics, and ion exchange for reducing soluble inorganics. Investigations into residual nutrient (primarily nitrogen and phosphorus) removals were deemed unwarranted due to the low nutrient levels in comparison with concentrations normally found in estuarine receiving waters.

Ultimate treatment of sludges produced during the various biological treatment investigations was not examined because of their relatively low production and apparent nonuniformity. However, it was recognized that sludge handling will be an important consideration for any on-site alternative and estimates of economic impacts were included in subsequent economic evaluations. Moreover, by-product recovery potentials from sludges, which may lead to improved economic applications, were not investigated but have been reported elsewhere for shellfish processing wastes (7,8).

SOURCE, SAMPLING AND CHARACTERIZATION OF WASTEWATER

Sources and Sampling Procedures

Although several processing plant effluents were initially to be studied, it became apparent during the course of experimentation that comparisons between alternative treatment methods would be better founded if attention focused upon a single wastewater exhibiting minimal character variations. Moreover, limitations on equipment and the logistics of sampling precluded extensive investigations for more than one or two processing effluents. Consequently, a wastewater emanating from a processor which appeared to be reasonably typical of the industry was selected for rigorous treatability investigations. This approach enhanced the opportunity for: 1) continuity and comparability of treatment alternatives; 2) examination of seasonal wastewater variations; 3) sample collection procedures that could be tailored to existing outflow configurations; and 4) a seasonably reliable source of wastewater in sufficient quantity for all experimental needs. However, another processor's wastewater discharge was sampled and tested during a limited period for character comparisons and to confirm the general applicability of aerobic processes as a prime treatment alternative.

The source of wastewater selected for the research investigations was a shrimp processing operation located on the southern coast of Georgia. Major processing activities included the peeling and deveining of fresh or frozen deheaded shrimp followed by breading and packing for retail sale. The plant operated five days per week with a 9-hour processing shift followed by an 8-hour clean-up shift. Yearly operation was fairly uniform with slight production peaks in October and November which reflected the peak shrimping season and an effort to use as much fresh shrimp as possible. April and May were usually the months of lower production. An annual average of 40,000 pounds (19.8 Kg) per day of processed shrimp was the production rate at the beginning of the study. Plant expansion provided an additional 20-30% of this average just prior to project termination. Production line operations followed essentially the same flow pattern as described by Horn (3) in an earlier report.

The plant obtained water from a well which was supplemented by city water as required. Processing and cooling water were combined and discharged directly to an adjacent tidal river; sanitary wastes were discharged to the city sewerage system. Water was used in the processing department by the grading machines, thaw tanks, and both mechanical and manual peeler-deveining operations. Water was used in the breading area only for floor and equipment washdown. The processing operation involved an average flow of 326,000 gallons (1234 m^3) per day excluding an 8-hour flow from midnight to morning which consisted only of cooling water.

Since all treatability investigations and wastewater analyses were conducted within the Sanitary Engineering Laboratories at the Georgia Institute of Technology and the wastewater source was located some 300 miles away in the Brunswick, Georgia, area, arrangements for sampling and transport of processing effluents were necessary. Accordingly, sample collections during the initial phase of study totaled 140 gallons (530 liters) of composited wastewater per sampling trip. This wastewater was collected by screened, submersible pumps within the effluent stream at either in-line wet wells or manholes. A portable gasoline powered generator supplied the necessary power for equipment operation. Wastewater was pumped at prorated increments into each of three 55-gallon (208 ℓ) plastic-lined barrels at a rate commensurate with estimated plant discharges taking into account the normal hourly fluctuations correspondent to processing schedules. In addition, since the initial experimental procedures were conceptually based upon treatment of average daily wastewater flows with equalization as a required moderating unit operation, receipt of composited wastewater samples were necessary. (Rationale for approximating this anticipated pretreatment requirement will be discussed later in reviewing wastewater composition variabilities on a daily and seasonal basis.) Compositing of samples was effected over a 12-hour processing period which involved both normal processing and clean-up periods. By prorating incremental sample volumes in accordance with plant discharge records, a composite sample which reasonably approximated a mixed 24-hour average discharge could be collected.

To ensure minimal sample degradation throughout the duration of sampling and transport, a sealed, plastic-lined plywood structure within which the barrels were placed was filled with ice to surround the sample containers at the onset of sampling and immediately prior to site departure upon completion of sampling. On arrival at the research laboratory, the sample containers were transferred to a controlled temperature room maintained at 3°C (37°F). Wastewater samples obtained by this procedure were assumed to be reasonably representative of freshly collected plant effluents.

Subsequent investigations were concerned more with general applicabilities of specific treatment methodologies and as such were conducted using "grab" samples. Sampling methods were essentially identical to those for composite samples except that the wastewaters were collected within a period of 1.0 to 1.5 hours during normal processing. The samples collected were not iced as during composite sampling, which allowed elimination of the plywood "icing container" and a corresponding increased sample volume (an additional 55-gal drum) of 40 gallons (151 liters). This procedure facilitated longer experimental periods between sample collection trips. To maintain some degree of continuity from one sampling date to the next, sampling was performed at the same relative time of day (11:00 a.m. to 12:30 p.m.) during normal processing operations.

Characterization of Wastewaters

During the treatability investigations, the shellfish processing wastewaters were characterized for those constituents which required removal or could influence the treatment method under review. The choice of method and possible limitations on utilizing biological treatment for wastewater stabilization were determined following evaluation of the wastewater characteristics in terms of organic strength, nutrient content, metallic ion concentrations, and soluble and insoluble solids fractions. These parameters not only served as a guide in the selection of process configurations, but also provided a basis for eventual interpretation of experimental results.

The wastewater characteristics for a shellfish processing discharge designated as S1B are presented in Table 1. The organic strength parameters, BOD_5, COD, and TOC, for S1B wastewaters were seasonally variable but not unusually high. Moreover, the relatively high nitrogen and phosphorus content suggested that these wastewaters would be amenable to aerobic biological treatment without supplemental nutrients.

Table 1 also indicates a reduction in wastewater solids concentrations after May, 1975. Compared to the previous period of data collection, total solids (TS) and total suspended solids (TSS) showed an average reduction of 41% and 79%, respectively. This could be expected since tangential screening had been installed at the processing plant in April, 1975. It may also be noted that corresponding reductions in the organic strength parameters did not result. Moreover, comparisons of the ratios of effluent filtered solids COD to the TSS showed an increase as evidenced by a range of 0.12-0.34 for the prescreening period compared to 0.9-1.9 for the period following installation of screening. This not only correlated well with the noted solids reductions but also suggested that the material being screened had a low chemical oxidizability, a significant point when regarding ultimate disposal alternatives. Although the effect of screening had a pronounced positive influence on solids removals, removal of organic materials appeared to be negligible. This, coupled with a still significant screened effluent suspended solids content, suggested that further treatment would be an obvious requirement.

Table 1

Characterization Analyses of Shellfish Processing Wastewaters (Plant S1B)

Analysis	Sample Date												
	3-27-73	6-27-73	8-30-73	2-16-74	6-21-74	9-28-74	2-17-75	5-21-75	7-16-75	10-8-75	10-22-75	10-29-75	11-6-75
pH	7.80	7.90	7.90	7.20	7.80	7.50	7.70	7.50	7.40	6.25	5.15	6.80	7.10
Total Alkalinity, mg/l as $CaCO_3$	198	176	217	203	158	216	132	147	162	117	92	152	196
Total Chemical Oxygen Demand, mg/l	872	494	917	775	960	1183	1213	436	575	1206	1623	485	684
Filtered Chemical Oxygen Demand, mg/l	--	280	332	544	532	614	588	--	--	738	592	250	364
Total Organic Carbon, mg/l	410	118	225	280	--	203	171	--	--	184	142	133	148
Total 5-day Biochemical Oxygen Demand, mg/l	630	325	392	580	612	411	372	--	--	950	1075	280	480
Filtered 5-day Biochemical Oxygen Demand, mg/l	--	222	305	410	362	370	----	--	--	290	380	--	305
Total Kjeldahl Nitrogen, mg/l as N	38.0	26.0	23.5	45.0	39.0	27.0	52.0	68.0	65.0	39.0	45.0	36.0	36.0
Ammonia Nitrogen, mg/l as NH_4^+	6.5	4.3	5.2	7.9	11.3	16.2	7.7	31.0	28.0	8.0	15.0	13.0	13.0
Nitrate-Nitrite Nitrogen, mg/l as NO_3^-	0.11	--	0.17	0.23	0.15	0.09	0.02	0.03	0.05	0.07	0.06	0.07	0.07
Total Orthophosphate, mg/l as $PO_4^{\equiv}$	9.6	4.4	6.7	59.0	12.4	17.1	9.3	22.5	25.5	90.0	41.0	23.0	47.0
Sulfate, mg/l as $SO_4^{=}$	--	118	87	125	96	68	113	65	82	--	--	--	--
Total Solids, mg/l	2459	2358	2568	2175	2132	2692	2511	--	1240	1432	2000	776	1660
Total Volatile Solids, mg/l	1988	1980	2136	1838	1586	2123	1956	--	650	1016	1310	438	870
Total Suspended Solids, mg/l	1633	1782	2080	1862	1813	1932	1846	--	206	515	825	125	240
Total Volatile Suspended Solids, mg/l	1367	1533	1842	1712	1422	1721	1691	--	131	505	818	120	234
Chloride, mg/l as Cl^-	--	132	92	88	74	146	153	125	1120	--	--	--	--

NOTE: Analyses for collection dates 3-27-73 to 9-28-74 were for composited samples. Analyses for samples collected from 2-17-75 to 11-6-75 were for grab samples. All wastewaters collected on 5-21-75 and thereafter were subject to plant installed tangential screening.

The cationic and anionic wastewater constituents for the two samples indicated in Table 2 appear in concentrations that should not necessitate special removal methods nor be deleterious to biological treatment. The comparatively high sodium and chloride concentrations noted for one of the samples is probably a reflection of the specific processing activity occurring at the time of "grab" sampling. There was no evidence that these concentrations persisted within average flows, and flow equalization should provide much lower and more consistent values.

Characterization data obtained from "grab" samples at another processing plant, designated S2B, are given in Table 3. Comparatively, this wastewater had a much lower organic strength and solids content than that of Plant S1B; however, its average daily discharge (about 850,000 gpd) was almost three times greater, which would result in similar average mass discharge rates. Aerobic biological treatment appeared most favorable for this wastewater even though the relatively low nutrient content (particularly nitrogen) suggested the need for nutrient supplementation. The relatively low organic strength and volatile solids content can be considered too low to warrant successful application, a priori, of direct anaerobic treatment of the raw wastewater.

The noted character variability of shellfish processing wastewaters and fluctuating discharge rates on a daily as well as seasonal basis indicated that flow equalization would be necessary before conventional treatment methods could be expected to provide consistent removal efficiencies. Initial treatability investigations were conducted with wastewaters composited over a 12-hour period and as such would reflect treatment following a 12-hour equalization contact time. Considering the average plant flows (~300,000 gpd), this equalization period would result in a holding tank size of uneconomical proportions. Therefore, it would appear more feasible to provide equalization contact periods of 1.0 to 3.0 hours to dampen excessive fluctuations in wastewater constituency and flow, and to design treatment systems (especially biological systems) to accommodate the more moderate fluctuations. Another approach, which was subsequently addressed, would be to establish treatment systems which could accommodate flow-strength fluctuations without serious loss of process stability and effluent quality. Fixed film contact processes would be suggested in this instance.

INVESTIGATION OF SHELLFISH PROCESSING WASTEWATER TREATMENT ALTERNATIVES

Chemically Aided Coagulation and Settling of Raw Wastewaters

Initial efforts provided for the application of chemical coagulation-flocculation as a means for organics and TSS removal. Dissolved air flotation and micro-straining were not studied due to either equipment restrictions (micro-screening) or to the fact that studies elsewhere had reported upon their relative applicability (5,6).

Several coagulants and coagulant aids were applied in various combinations to samples of screened raw wastewater. Tests were performed in accordance to jar test procedures presented in the 13th edition of Standard Methods (9). The various coagulants and polyelectrolytes

Table 2

Ionic Constituents of Shellfish
Processing Wastewaters (Plant S1B)

Ion	Date Sample Collected 5/21/75	Date Sample Collected 7/16/75
Iron, mg/l Fe^{+++}	1.0	1.6
Manganese, mg/l Mn^{++}	trace	1.8
Nickel, mg/l Ni^{+}	trace	trace
Copper, mg/l Cn^{+}	trace	trace
Calcium, mg/l Ca^{++}	12.0	6.0
Magnesium, mg/l Mg^{++}	2.5	2.5
Potassium, mg/l K^{+}	13.0	12.0
Sodium, mg/l Na^{+}	115	1175
Chloride, mg/l Cl^{-}	125	1120
Iodide, mg/l I^{-}	-	38
Sulfate, mg/l $SO_4^{=}$	65.0	81.5

Table 3

Average Effluent Characteristics of Shellfish Processing Wastewaters (Plant S2B)*

	Sample Date	
Analysis	4/20/74	6/21/74
pH	7.1	7.0
Total Alkalinity, mg/l as $CaCO_3$	186	221
Total 5-day Biochemical Oxygen Demand, mg/l	152	173
Filtered 5-day Biochemical Oxygen Demand, mg/l	85**	110**
Total Chemical Oxygen Demand, mg/l	245	256
Filtered Chemical Oxygen Demand, mg/l	178**	162**
Total Organic Carbon, mg/l	97**	83**
Total Kjeldahl Nitrogen, mg/l N	7.0	8.2
Ammonia Nitrogen, mg/l NH_4^+	1.15**	1.7**
Nitrate Nitrogen, mg/l NO_3^-	0.04**	0.13**
Total Solids, mg/l	320	416
Total Suspended Solids, mg/l	31	52
Total Volatile Solids, mg/l	302	372
Total Volatile Suspended Solids, mg/l	26	46
Total Orthophosphate, mg/l $PO_4^{\equiv}$	2.1**	1.7**
Sulfate, mg/l $SO_4^=$	68	53

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* Results presented are averages of all tests performed on grab samples.

** Samples were filtered through 0.45 μ glass fiber filters prior to analysis.

investigated are presented in Table 4. Analyses on the treated wastewater were made for final pH, percent transmittance, TOC, and COD.

Results from the jar tests are presented in Table 5. These results indicated that, in certain applications, chemical coagulation was very effective for suspended solids removal. However, removal of organic fractions was not significantly enhanced over that found with simple sedimentation. This emphasized a limitation on using coagulation-flocculation procedures as a singular means of wastewater treatment, but provided evidence promoting its applicability for wastewater solids removal prior to either subsequent treatment and/or discharge to a municipal sewerage system. As indicated in Table 5, maximum solids and organics removals occurred following the application of 80 mg/l $FeCl_3$ with 0.5 mg/l of the polyelectrolyte, Nacolyte 110. A well settled, compacted sludge was obtained with COD and TOC reductions of 62 and 65%, respectively. This treatment probably represented the practical upper limit for organics removal since most of the organic matter removed was associated with the solids fraction, leaving a soluble organic fraction which would require additional treatment. As can be further noted in Table 5, maximum removals without the use of a polyelectrolyte occurred at a dose of 80 mg/l $FeCl_3$ and 70 mg/l $CaCO_3$ (i.e., 55% COD and 50% TOC removal and a well settling-compacting sludge).

Although chemical coagulation may be applicable to the goal of suspended solids removal, it must be realized that results reflected the testing procedure for wastewaters collected at specific times and, as such, would not necessarily be indicative of an actual continuous flow treatment system which must be capable of successfully handling both flow and character fluctuations. Therefore, the results, although promising, are not directly amenable to scale-up, *per se*. Pilot plant studies to better define operational constraints remain as a logical extension to these coagulation investigations.

Carbon Adsorption Treatment of Raw Settled Wastewater

Physical adsorption was explored with batch jar tests using serially increasing dosages of powdered activated carbon. After sufficient mixing time to insure equilibrium conditions (a minimum of one hour), the treated samples were filtered through Whatman No. 2 filter paper and the filtrate was analyzed for residual COD and/or TOC. Data were generated in this manner for four commercially available activated carbons and then used to determine the relative adsorptive capacity for each carbon by development of suitable adsorption isotherms. In addition to the batch tests, one of the carbons was selected for continuous flow column testing to confirm the applicability of using the adsorption isotherms in predicting carbon requirements for effective waste treatment.

The effectiveness of four commercially available activated carbons (Nuchar VW-L, Nuchar C-190-N, Witco Grades 235 and 517) for reducing the wastewater organic strength, as measured by COD, TOC, or BOD_5 removals following slurry contact to equilibrium, was delineated by Freundlich adsorption isotherm analysis. Isotherms are presented in Figures 4, 5, 6, and 7 for the respective carbons investigated. Results for the organic parameters used, though somewhat variant in slope and intercept, basically obeyed the empirical Freundlich model. Accordingly, the isotherms could

Table 4

Coagulants/Coagulant Aids Used for Raw Shellfish Processing Wastewater (Plant S1B) Treatability Studies

Test Number	Coagulant	Coagulant Aid
1	Aluminum Sulfate	--
2	Ferrous Sulfate	--
3	Ferric Chloride	--
4	Aluminum Sulfate	Calcium Carbonate
5	Ferrous Sulfate	Calcium Carbonate
6	Ferric Chloride	Calcium Carbonate
7	--	Polyfloc
8	--	Purifloc N-17
9	--	Purifloc A-21
10	--	Nalcolyte 110
11	--	Separan NP20
12	Aluminum Sulfate	Purifloc N-17
13	Aluminum Sulfate	Nalcolyte 110
14	Ferric Chloride	Purifloc N-17
15	Ferric Chloride	Nalcolyte 110

Table 5

Coagulation Treatability Results (Jar Test Procedure) for Screened Shellfish Processing Wastewaters (Plant S1B)

Initial screened wastewater characteristics: COD = 960 mg/1
TOC = 435 mg/1
Total Alkalinity as $CaCO_3$ = 198 mg/1
Percent Transmittance = 65

		Applied		Supernatant		
Test Number	Coagulant/Coagulant Aid	Dosage, mg/1	Final pH	% Transmittance	TOC, mg/1	COD, mg/1
1	$Al_2(SO_4)_3$/--	0/0	6.50	78	406	810
		40/0	6.10	79	318	620
		80/0	5.80	77	319	700
		100/0	5.60	89	247	522
		140/0	5.30	94	246	520
		180/0	5.10	94	271	530
2	$FeSO_4$/--	0/0	6.70	77	388	845
		40/0	6.70	78	264	570
		80/0	6.65	75	294	560
		100/0	6.60	83	-	-
		120/0	6.60	82	270	580
		140/0	6.60	83	279	582
3	$FeCl_3$/--	0/0	6.5	83	341	630
		60/0	6.0	83	320	621
		100/0	5.6	93	260	502
		180/0	5.1	74	290	575
		260/0	4.6	67	294	600
		340/0	4.1	65	300	618
4	$Al_2(SO_4)_3/CaCO_3$	50/10	6.50	87	234	494
		50/20	6.60	88	-	-
		50/30	6.60	88	264	530
		50/50	6.60	92	228	495
		50/80	6.62	87	252	505
		50/100	6.60	87	238	490
5	$FeSO_4/CaCO_3$	80/10	6.75	80	287	514
		280/20	6.60	74	291	632
		80/30	6.70	80	252	532
		380/50	6.55	75	265	542
		80/80	6.70	78	286	615
		680/100	6.5	75	270	562

Table 5 (Continued)

Coagulation Treatability Results (Jar Test Procedure) for Screened Shellfish Processing Wastewaters (Plant S1B)

Initial screened wastewater characteristics: COD = 960 mg/l
TOC = 435 mg/l
Total Alkalinity as $CaCO_3$ = 198 mg/l
Percent Transmittance = 65

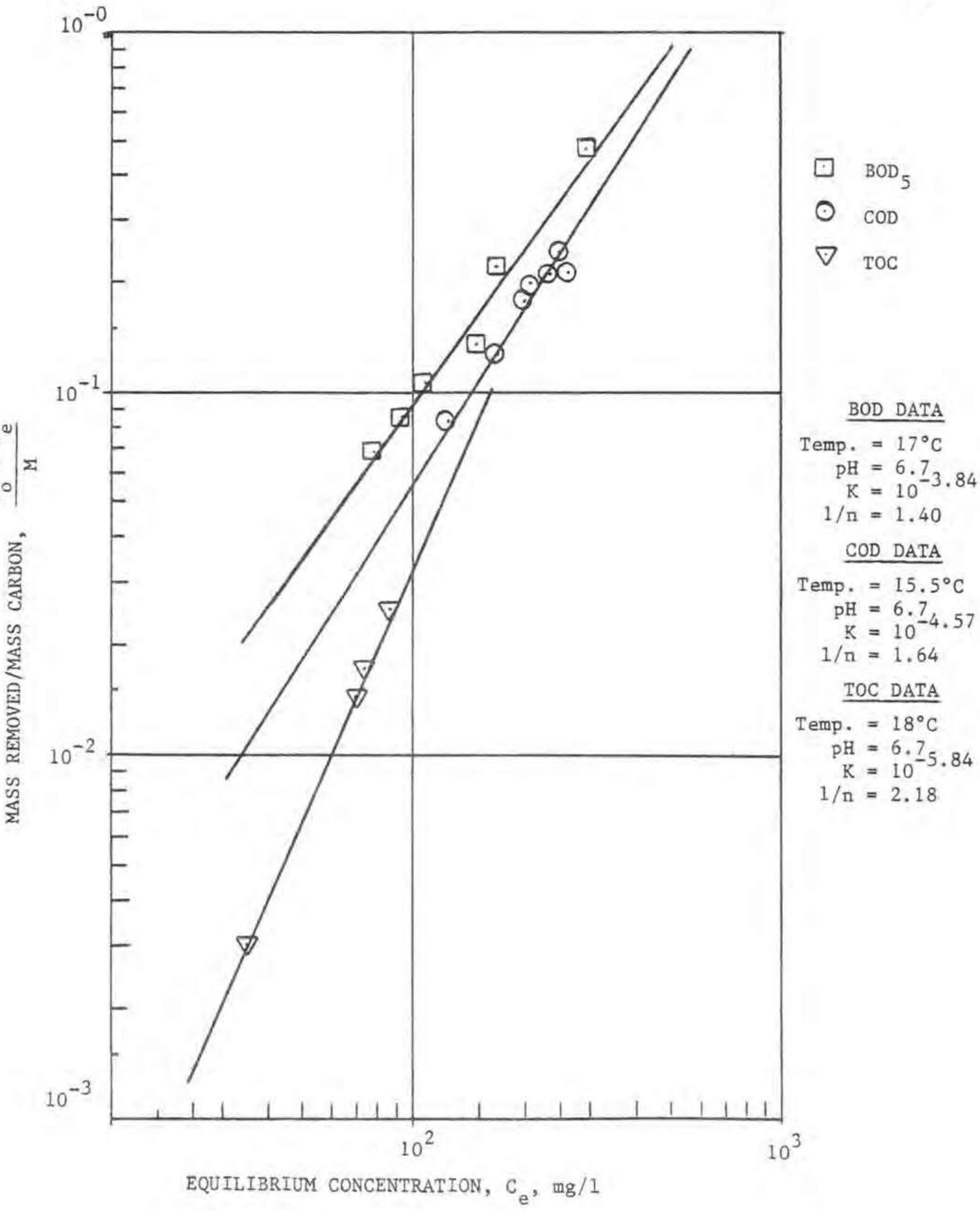
Test Number	Coagulant/Coagulant Aid	Applied Dosage, mg/l	Final pH	Supernatant		
				% Transmittance	TOC, mg/l	COD, mg/l
6	$FeCl_3/CaCO_3$	80/10	6.10	89	222	434
		80/20	6.20	90	240	480
		80/30	6.20	94	240	465
		80/50	6.20	95	216	472
		80/70	6.20	97	216	434
		80/90	6.20	99	230	440
7	--/Polyfloc	5/0	6.70	86	294	600
		15/0	6.70	87	286	582
		25/0	6.70	86	294	572
		35/0	6.70	86	291	585
		45/0	6.70	87	288	591
		55/0	6.70	87	290	580
8	--/Purifloc N-17	1/0	6.70	88	288	-
		2/0	6.70	89	300	-
		5/0	6.70	88	296	-
		10/0	6.70	87	290	-
		20/0	6.70	87	288	-
		30/0	6.70	88	290	-
9	--/Purifloc A21	1/0	6.60	86	294	-
		2/0	6.70	86	292	-
		5/0	6.70	88	286	-
		10/0	6.80	88	280	-
		20/0	6.80	86	290	-
		30/0	6.80	84	302	-
10	--/Nalcolyte 110	0.1/0	6.6	90	275	-
		0.5/0	6.6	92	280	-
		0.75/0	6.7	88	285	-
		1.0/0	6.7	92	261	-
		2.0/0	6.8	90	272	-
		5.0/0	6.8	90	270	-

Table 5 (Continued)

Coagulation Treatability Results (Jar Test Procedure) for Screened Shellfish Processign Wastewaters (Plant S1B)

Initial Screened Wastewater Characteristics: COD = 960 mg/1
TOC = 435 mg/1
Total Alkalinity as $CaCO_3$ = 198 mg/1
Percent Transmittance = 65

Test Number	Coagulant/Coagulant Aid	Applied Dosage, mg/1	Final pH	Supernatant % Transmittance	TOC, mg/1	COD, mg/1
11	--/Separan NP20	0.2/0	6.7	86	350	682
		0.5/0	6.7	86	342	671
		1.0/0	6.7	88	310	640
		2.0/0	6.7	88	310	638
		5.0/0	6.7	87	317	640
		10.0/0	6.7	89	302	621
12	$Al_2(SO_4)_3$/Purifloc N-17	50/0.1	6.60	89	185	420
		50/0.5	6.50	90	190	415
		50/1.0	6.50	94	180	425
13	$Al_2(SO_4)_3$/Nalcolyte 110	50/0.1	6.60	90	190	410
		50/0.5	6.60	92	182	408
		50/1.0	6.60	92	185	398
14	$FeCl_3$/Purifloc N-17	80/0.1	6.50	97	160	383
		80/0.5	6.45	98	158	400
		80/1.0	6.45	98	152	396
15	$FeCl_3$/Nalcolyte 110	80/0.1	6.5	98	152	390
		80/0.5	6.5	99	152	365
		80/1.0	6.5	97	158	412



BOD DATA

Temp. = 17°C
pH = 6.7
$K = 10^{-3.84}$
$1/n = 1.40$

COD DATA

Temp. = 15.5°C
pH = 6.7
$K = 10^{-4.57}$
$1/n = 1.64$

TOC DATA

Temp. = 18°C
pH = 6.7
$K = 10^{-5.84}$
$1/n = 2.18$

Figure 4. Freundlich Adsorption Isotherms for Treatment of Raw Shellfish Processing Wastewater (SlB) with Powdered Activated Carbon (Nuchar WV-L)

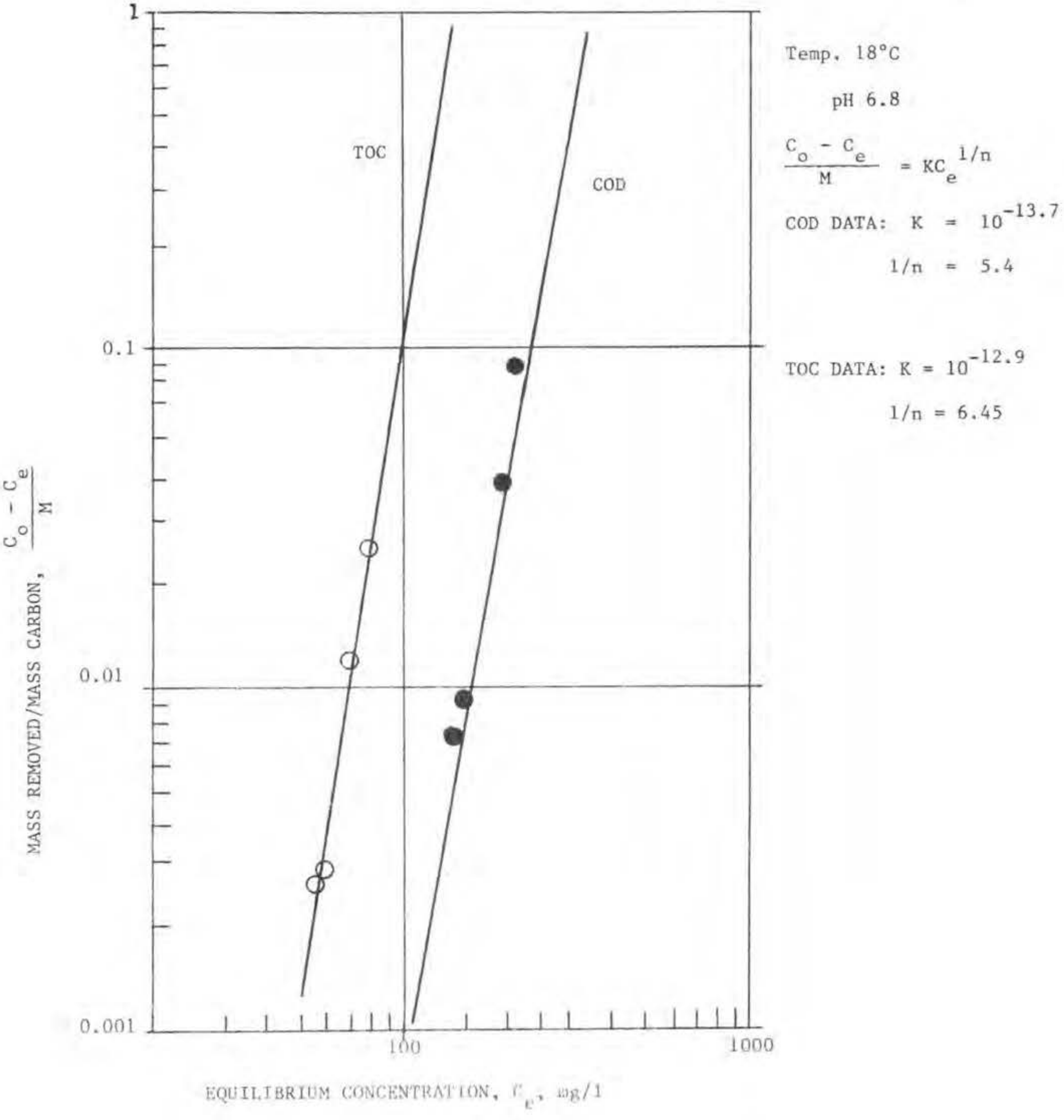


Figure 5. Freundlich Adsorption Isotherm for Nuchar C-190-N Powdered Carbon with Raw Shrimp Processing Wastewater (S1B)

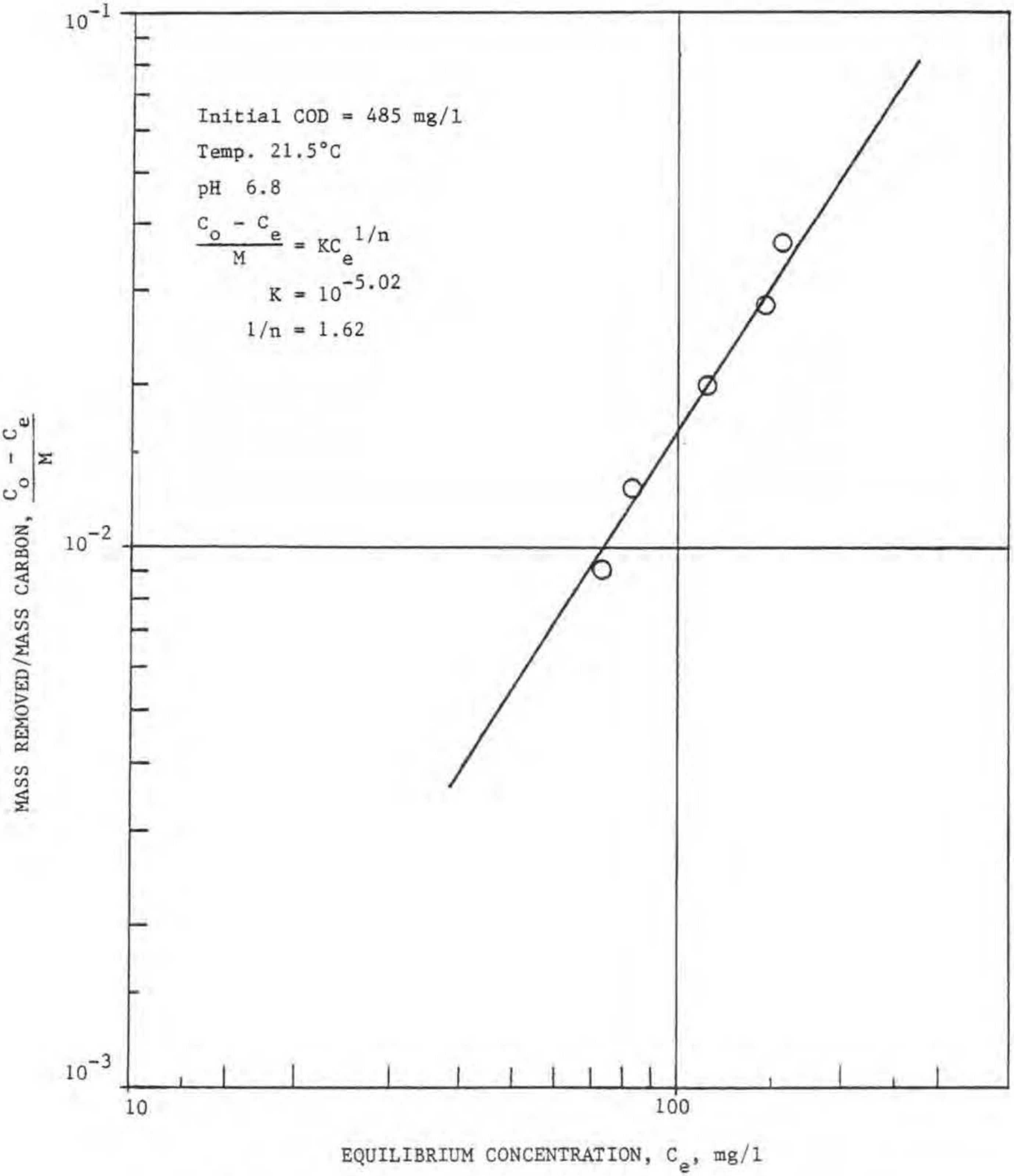


Figure 6. Freundlich Adsorption Isotherm for Witco Grade 235 Powdered Carbon with Raw Shrimp Processing Waste (S1B)

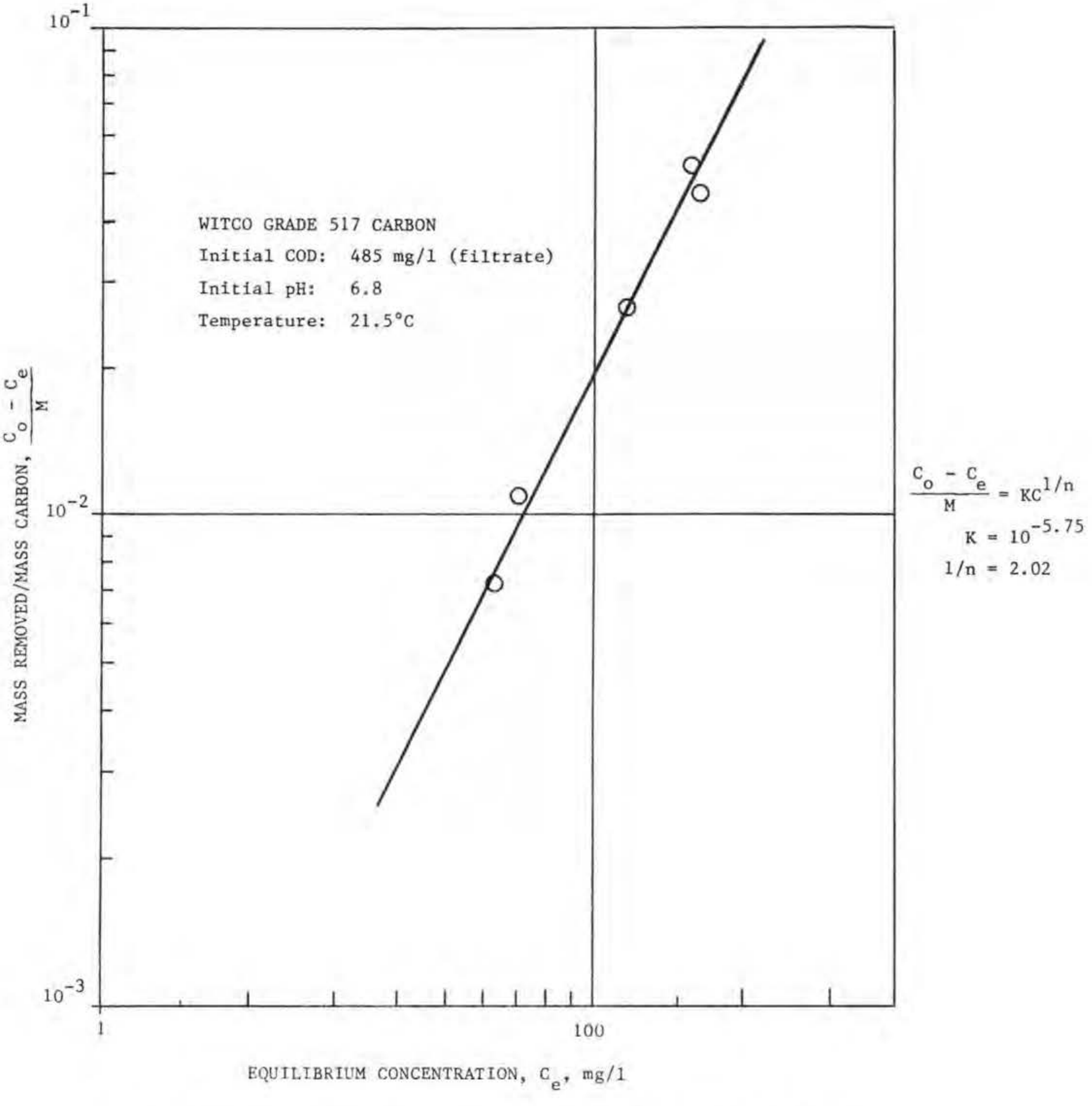


Figure 7. Freundlich COD Adsorption Isotherm for Screened Shrimp Processing Wastewater (S1B)

be used to extend predictions for carbon requirements in treating the wastewaters. However, the economic considerations associated with carbon application, including regeneration or make-up requirements which were not specifically investigated but can be estimated, may pose restrictive limitations upon the acceptance of this treatment method.

The initial carbon studies employed slurry contact modes of operation with powdered carbons that simulated treatment in batch-type contact systems which would attain a relatively rapid equilibrium. The intent of these studies was to determine capacities of the carbons for organics removal and no attempt was made to evaluate adsorption rates. As carbon particle size increases, longer contact times would be required in batch operations to attain similar treatment. The need for favorable carbon mass to organic solute ratios, coupled with a reasonable means for carbon recovery, usually precludes direct application of batch treatment methods in comparison with column-type continuous flow contact operations. Since the rate of adsorption depends on the concentration of the organic solute in the wastewater, and since this solute within a column contacts progressive layers of carbon in a relatively continuous manner until bed exhaustion occurs, continuous flow columns are preferred for carbon contact operations. Moreover, the normally more efficient methods for exhausted carbon removal and addition of make-up carbon make column operation even more attractive.

Because slurry contact adsorption studies provide information pertinent to continuous flow column operation, a laboratory-scale carbon column study was initiated to check the validity of using the developed isotherms for predicting carbon requirements in column operation. The results of the column study are presented in Figure 8. Comparison of mass balance calculations using the column data against results predicted from the appropriate Freundlich isotherm indicated good agreement with TOC adsorption as the indicating parameter. Less than 5% difference between predicted and actual TOC mass adsorption was noted. Calculated breakthrough time compared with the actual column breakthrough did, however, show a difference of 20% with the actual breakthrough time as the larger value, a result not uncommon in this type of study.

The information substantiates the relative applicability of carbon adsorption for treatment of organics in the wastewater as well as the validity of using the developed isotherms for extending predictions of carbon requirements in field systems. However, the ultimate use of carbon treatment would necessitate some pretreatment for suspended solids removal and, depending upon any processor's particular waste volume, waste strength, and financial position, may not in itself provide complete or optimal treatment.

Biological Treatability of Shellfish Processing Wastewaters

Methods and Procedures. Experimental studies were conducted on both aerobic and anaerobic, completely mixed, biological processes in order to determine their relative efficiencies, limitations, and operational requirements. These systems were evaluated both with and without solids recycle. Each experimental run was directed toward the acquisition of process performance data which could be used in the determination of certain microbial

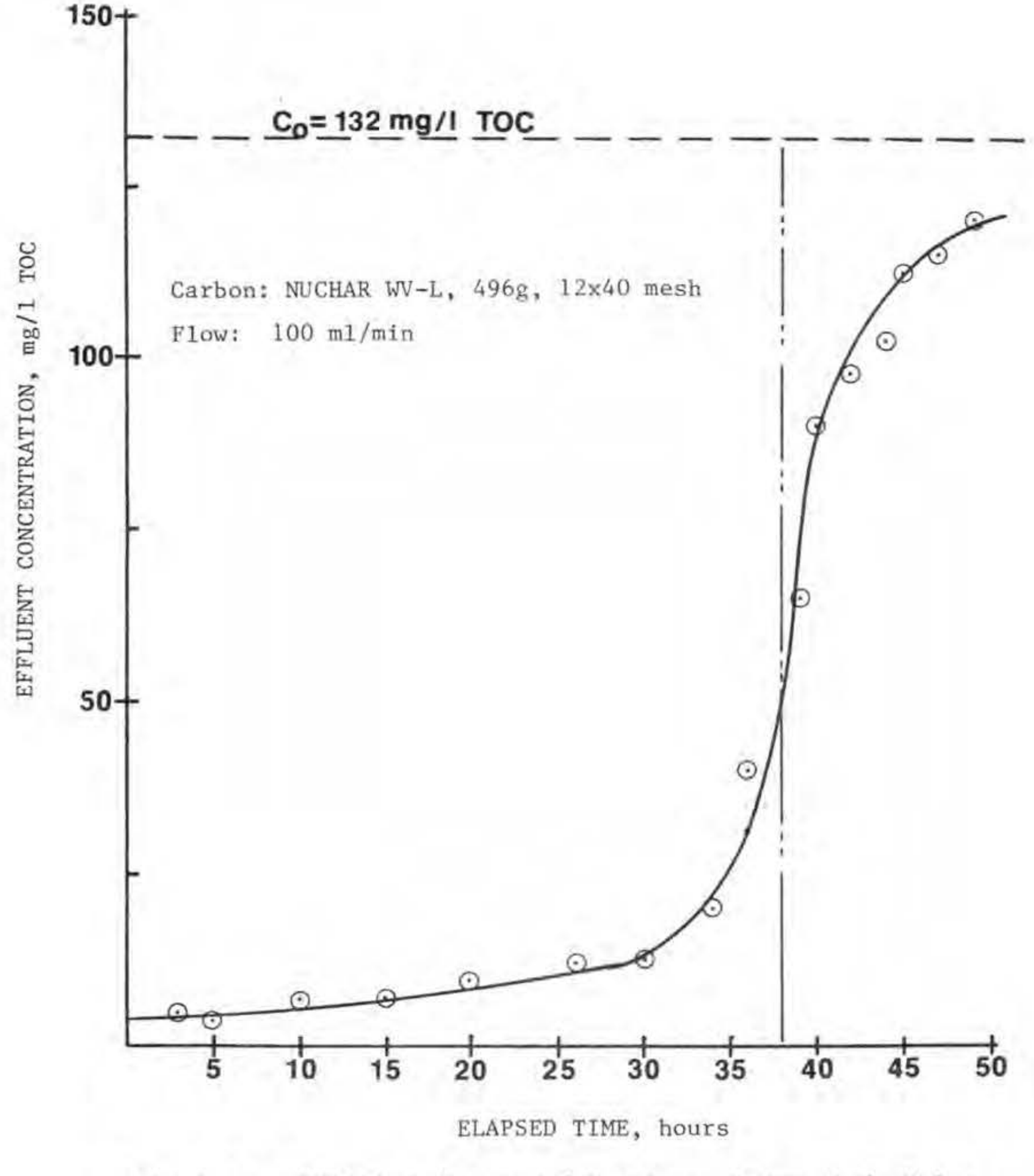


Figure 8. Breakthrough Curve for Carbon Column Study Using Shellfish (Shrimp) Processing Wastewater (S1B).

growth and substrate utilization parameters useful for establishing system response to wastewater loadings.

The initial selection of biological methods for treatment of shellfish processing wastewaters was based upon their proven applicability for satisfactory and economical treatment of various food processing wastewaters and the requirement of "secondary treatment" by state regulatory authorities for industrial wastewater control with biological treatment as the defining component. Moreover, the nature and character of shellfish processing wastewaters indicated that biotreatment would be a likely candidate for more economical wastewater strength reduction when compared with other available treatment methods.

Experimental laboratory-scale reactors were designed, controlled, and operated to provide data which could be applied to subsequent kinetic evaluations within the scope of continuous culture theory. Schematically shown in Figures 9 and 10, the reactors were constructed from plexiglass cylinders with a permanently sealed base and removable top which could be sealed gas-tight during operation. The aerobic reactor had an 8-inch (20.32 cm) inside diameter and was operated with a 10-liter liquid capacity during all experiments. The larger but similarly constructed anaerobic reactor had a 10.7-inch (27.18 cm) inside diameter and was operated with a liquid capacity of 20 liters. Two inches (5.08 cm) of free space separated the surface of the liquid and the reactor cover to allow for gas transfer and pressure equilibrium.

Wastewater was continuously fed to the reactor by peristaltic laboratory pumps equipped with variable speed controls. Provisions were also made for culture mixing, temperature monitoring and control, liquid level control, and air injection in the case of the aerobic system. The anaerobic reactor, while not requiring air, had additional provisions for heating and metered gas collection. Both reactor systems were connected to clarification units which were employed in the studies involving solids separation and recycle. The clarifiers were constructed from the same cylindrical material as used for the aerobic reactor. Bottoms were sloped at 35 degrees and a sludge scraper operated at one rpm aided in solids transfer to a bottom center port for pumped removal.

The experimental studies were initiated by first acclimating the organism populations within the reactors by batch operation with the shellfish processing wastewaters for several days. Initial seeding was not practiced for development of the aerobic populations, however, for the anaerobic reactor, approximately 40% of the initial batch volume was made up of active anaerobic digester sludge obtained from a local municipal treatment system.

After establishing a suitable organism population, continuous flow operation was commenced. The initial applied dilution rate (reciprocal of hydraulic retention time) was set to provide for the longest retention time used in any given experimental run and was progressively increased at approximately equal increments following data collection at each "steady-state" condition. Steady-state conditions were presumed when duplicative effluent organic substrate and solids concentrations were obtained at two consecutive sampling periods separated by at least one hydraulic retention

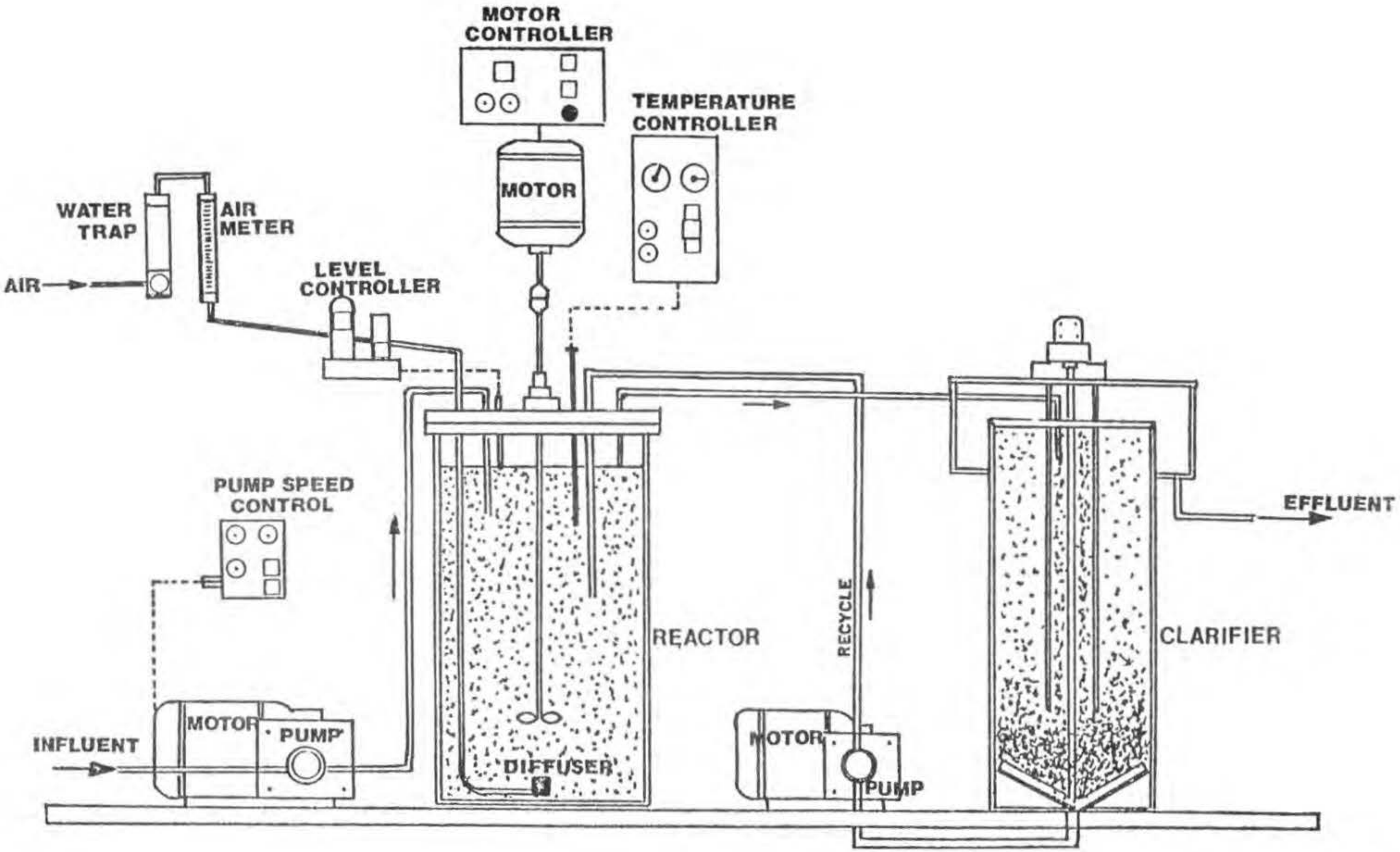


Figure 9. Completely Mixed, Continuous Flow Reactor System Used for Aerobic Treatability Studies.

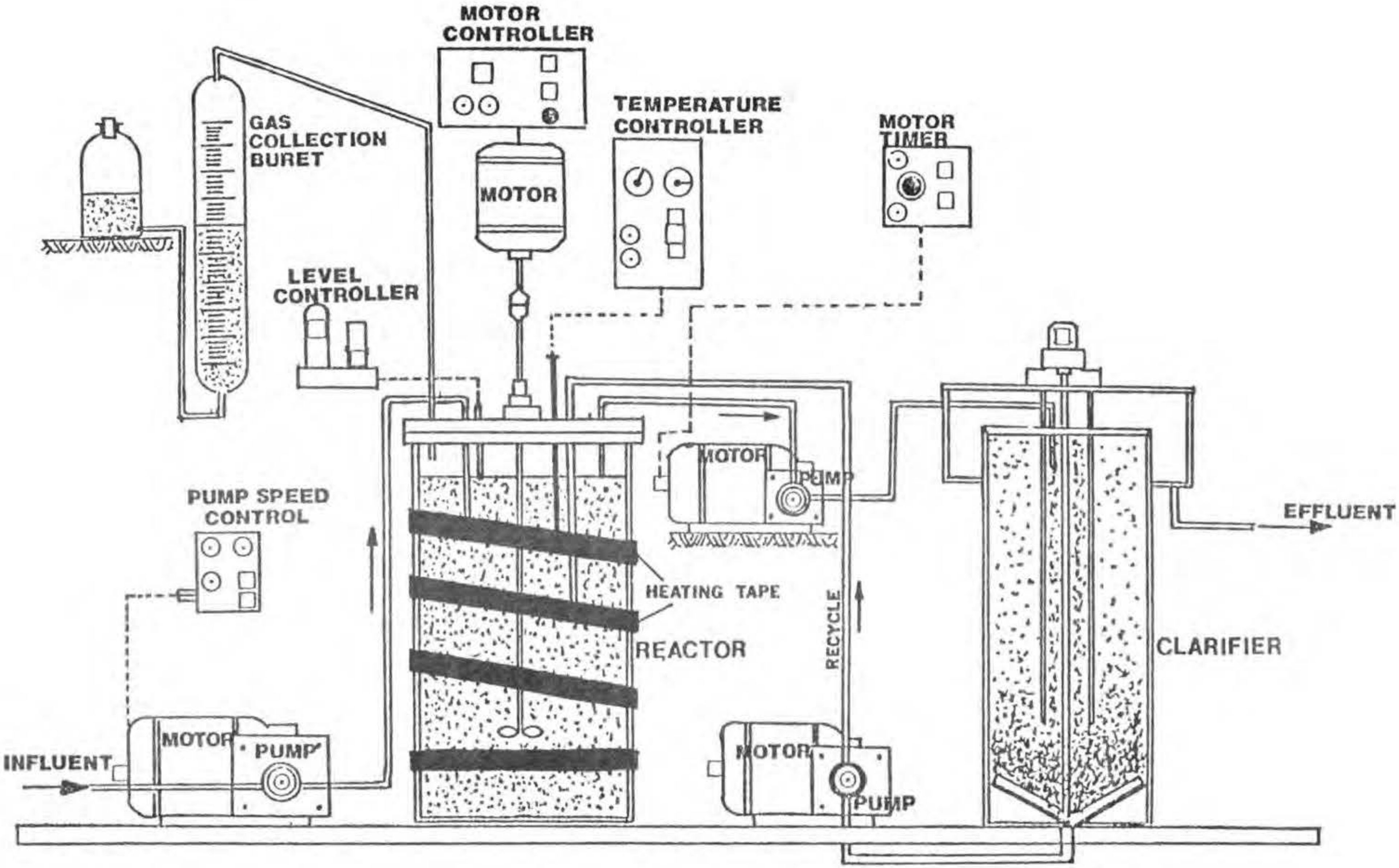


Figure 10. Completely Mixed, Continuous Flow Reactor System Used for Anaerobic Treatability Studies.

time. Normally three or four retention times of operation allowed such nominal steady-state conditions to prevail.

Once steady-state performance was established for the aerobic studies, influent and effluent analyses for BOD_5, COD, TOC, TSS and TVSS were obtained. Since the basic growth relationships used in data interpretation were expressed in terms of readily available substrate, analyses on filtered samples were used to evaluate kinetic response. These analyses also permitted an estimation of the gross pollution potential of the treated effluent. In addition to these parameters, gas production and composition were also measured and used to verify steady-state conditions as well as to estimate steady-state growth during the anaerobic treatment investigations. All chemical analyses were conducted in accordance with Standard Methods (9).

Organism concentrations were estimated by TSS and/or TVSS measurements. Although it was recognized that neither of these measurements were sufficient to accurately determine viable biomass, other more sophisticated methods were not available at the time of the study. Moreover, in keeping with those parameters best understood by wastewater treatment practitioners, solids measurements were considered of greater value for data presentation.

Two different shellfish processing wastewaters were used during the treatability studies. Both, designated S1B and S2B respectively, were studied under aerobic single-pass reactor operation with the former (S1B) also being used in aerobic studies employing reactor solids separation/ recycle and in all anaerobic system investigations.

As hydraulic retention time was intended to be the only growth related system variable, other environmental influences were controlled within reasonably definitive limits. Mixing speeds in all reactors were set and maintained at 250 rpm. Mixed aerobic reactor temperatures were at $20° \pm 2°C$ and anaerobic temperatures at $37° \pm 0.5°C$ throughout all studies. The S1B wastewaters showed adequate nutrient content (nitrogen and phosphorus) thus precluding their addition. However, S2B wastewaters were nutrient deficient and sufficient nitrogen (as NH_4SO_4) and phosphorus (as $K_2HPO_4 - KH_2PO_4$) were added to provide a BOD_5 to nitrogen to phosphorus ratio greater than those reported necessary for normal stoichiometric biological growth, i.e., 100:5:1 (10). With such a technique, the wastewater organic fraction could be assumed to constitute the growth-limiting nutrient of concern.

Process Model Development. In recent years, continuous pure culture growth and substrate utilization kinetics have gained in popularity for describing biological wastewater treatment system potential and/or limitations. This has occurred in part by the assumption that the overall process rate is governed by the rate of the slowest step, thereby allowing the kinetic model commonly used to describe continuous pure culture growth to be applied to the description of complex waste treatment processes. Several researchers (11-14) have documented results supporting the validity of the basic kinetic model for pure cultures as well as its extension to the more complex heterogeneous systems.

Although a detailed review of the theory of continuous culture kinetics was considered unwarranted here, the basic kinetic model used for this research data analysis has been developed and is presented in Appendix A.

Moreover, rather than using the mean cell residence time concept attendant with the food-to-microorganism ratio and solids wastage rate as a basic variable relatable to organic conversions, biomass production rates, and treatment efficiency, the kinetic constants were evaluated using a continuous culture theory approach with the major system variable being hydraulic retention time (reciprocal of dilution rate). The kinetic model thus appears well suited to accommodate the evaluation of the data acquired for both single-pass and recycle systems. Measurement of influent and effluent solids and organics fractions for each steady-state reactor run at each applied hydraulic retention time provided data which were subsequently reduced to linearized functions allowing estimation of the kinetic parameters descriptive of system performance. The kinetic parameters thereby determined were: maximum specific growth rate, μ_{max}; specific death rate, k_d; saturation constant, K_s; and apparent yield coefficient, Y.

Experimental Results and Discussion - Completely Mixed Aerobic Biotreatment. The results from the completely mixed, continuous flow, aerobic biological treatability studies of shellfish processing wastewaters were applicable to evaluation by the kinetic approach presented in Appendix A. The nominal steady-state effluent concentrations of organics and suspended solids fractions associated with single-pass aerobic treatment of plant S1B wastewaters at retention times of 12.10, 9.95, 8.00, 6.00, 4.04, and 2.05 hours, respectively, are included in Table 6. These data have been plotted in Figure 11 to provide smooth functions which enable better data reduction and analyses in determination of system descriptive kinetic coefficients. The resultant curves were then used to construct the linearized plots given in Figures 12 and 13. Since the measureable waste characteristic which was limiting to microorganism growth and most reflective of substrate assimilation and subsequent biomass generation was BOD_5, BOD_5 data were used as the basis in calculations leading to development of the linear functions shown in the figures.

Once evaluated, the kinetic constants may be used to establish limitations or criteria for successful aerobic treatment in mixed contact processes. For example, the critical retention time, i.e., that retention time at which the system is most unstable and subject to "washout" of the microorganism population, was determined to be about two hours (1.90 hours calculated). In the design and operation of an actual system, this information would be important as periodic hydraulic surges could reduce the retention time below two hours resulting in elimination or significant reduction of the microbial populations and consequent loss of final effluent quality. Additionally, the parameters K_s and Y can give an indication of the relative affinity of the growing biomass for the wastewater as well as provide an estimate of the quantities of biological sludge requiring treatment in a secondary clarification unit. The values for K_s, Y, and μ_{max} for wastewaters (Plant S1B) undergoing single-pass treatment were considered reasonably typical of values encountered for other food processing wastes of moderate strength and there appeared to be no pronounced limitation to the use of conventional aerobic treatment methods as far as organic substrate removals were concerned.

Table 6

Steady-State Effluent Concentrations of Organics and Suspended Solids at Various Hydraulic Retention Times for Plant S1B Wastewaters Under Single-Pass Aerobic Biotreatment in Mixed Culture

Applied Reactor Hydraulic Retention Time, hours	Reactor Effluent Concentration*, mg/l			
	COD	BOD_5	TOC	TSS
12.10	147	32	-	166
9.95	156	21	54	-
8.00	141	-	62	191
6.00	162	48	-	211
4.04	139	87	71	235
2.05	248	192	131	202

* Results given are averages of at least two replicate samples taken one hydraulic residence time apart after attainment of nominal steady-state conditions.

NOTE:

Average Influent COD = 438 mg/l
Average Influent BOD_5 = 288 mg/l
Average Influent TOC = 158 mg/l
Average Influent TSS = 28 mg/l

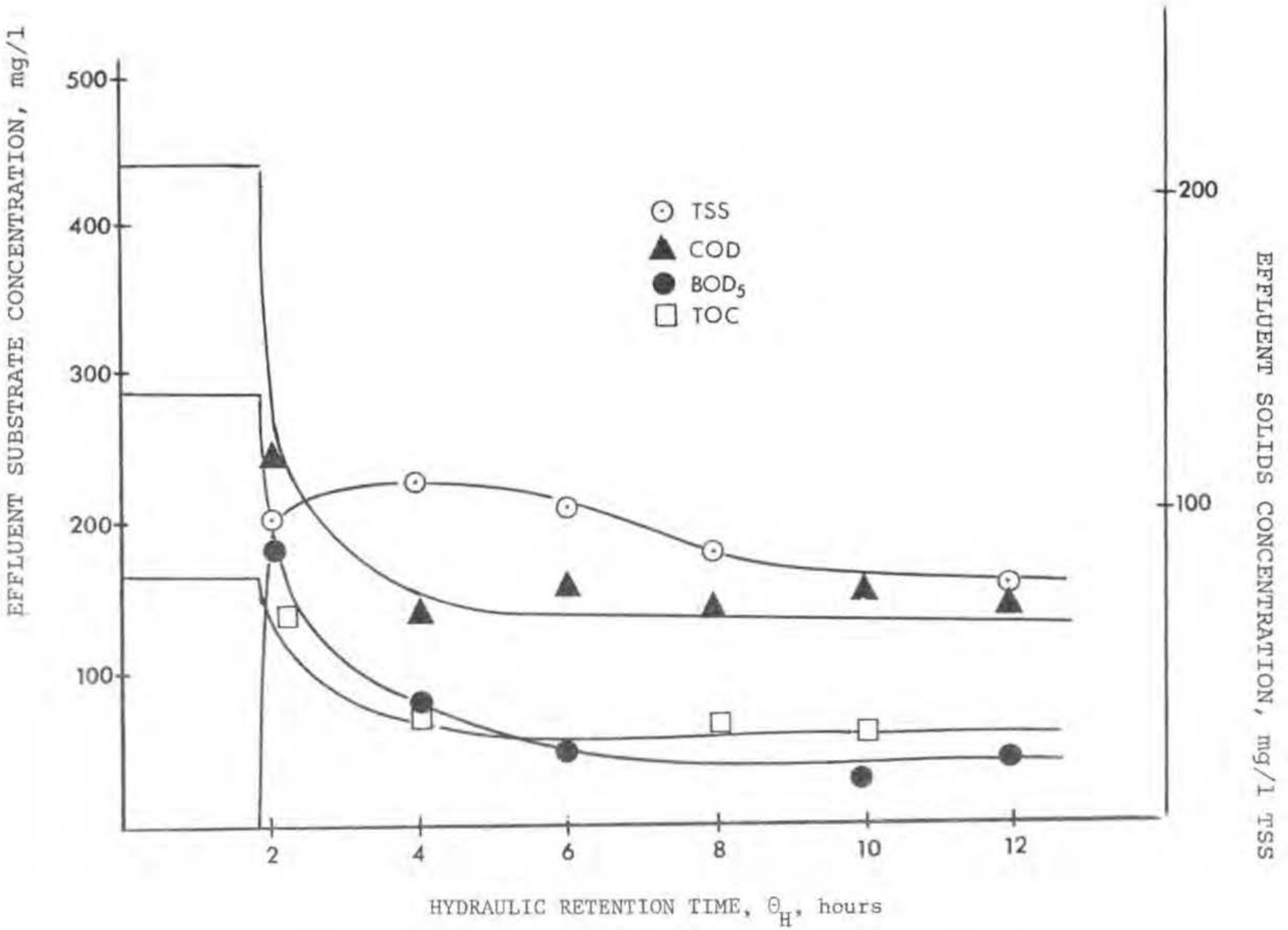


Figure 11. Steady-State Effluent Substrate and Biological Solids Concentrations for One-pass Completely Mixed Reactor Study on Shrimp Processing Wastewater (S1B)

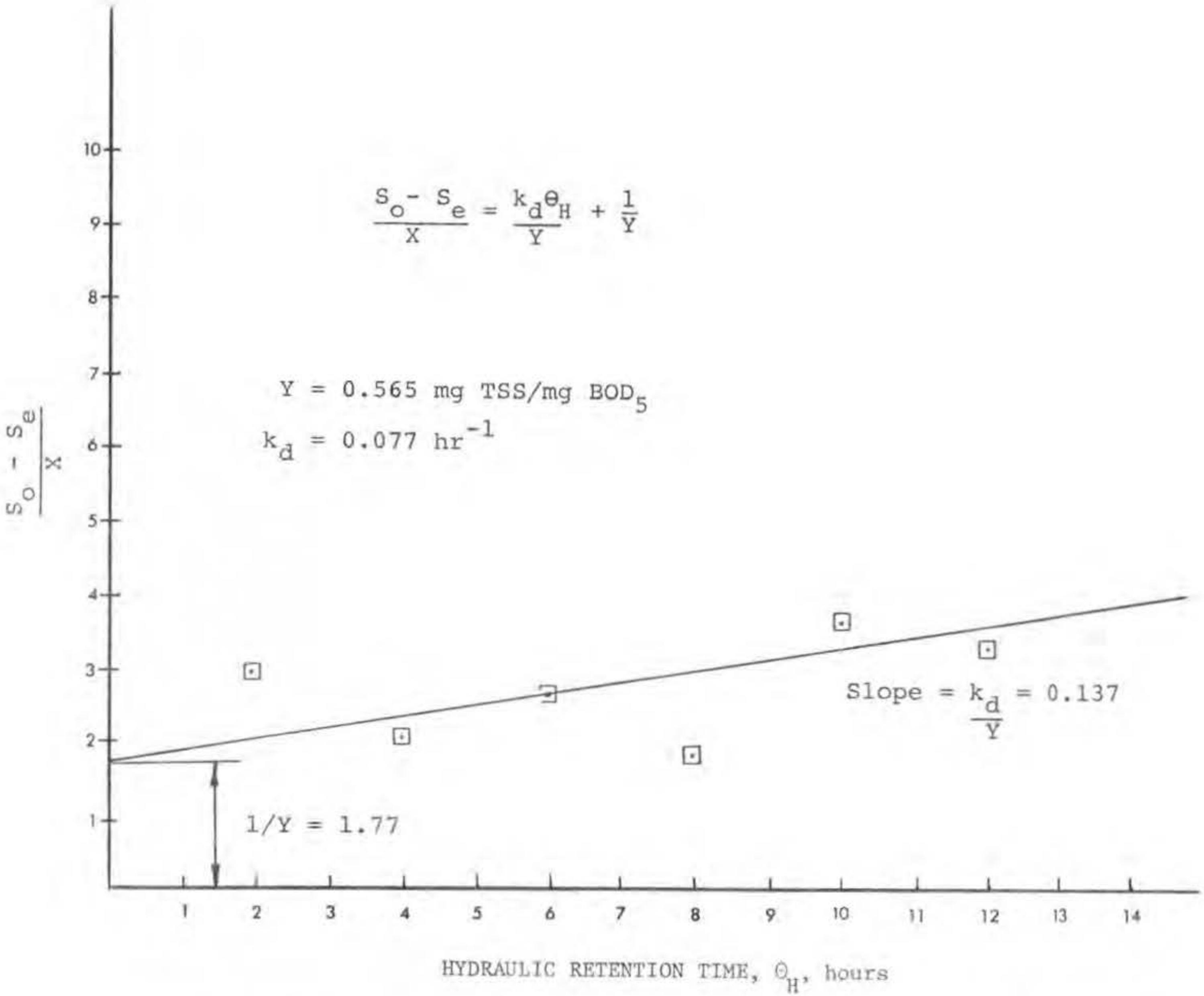


Figure 12. Determination of the Yield Coefficient, Y, and the Specific Decay Rate, k_d, for Aerobic Treatment of Shrimp Processing Wastewaters (S1B)

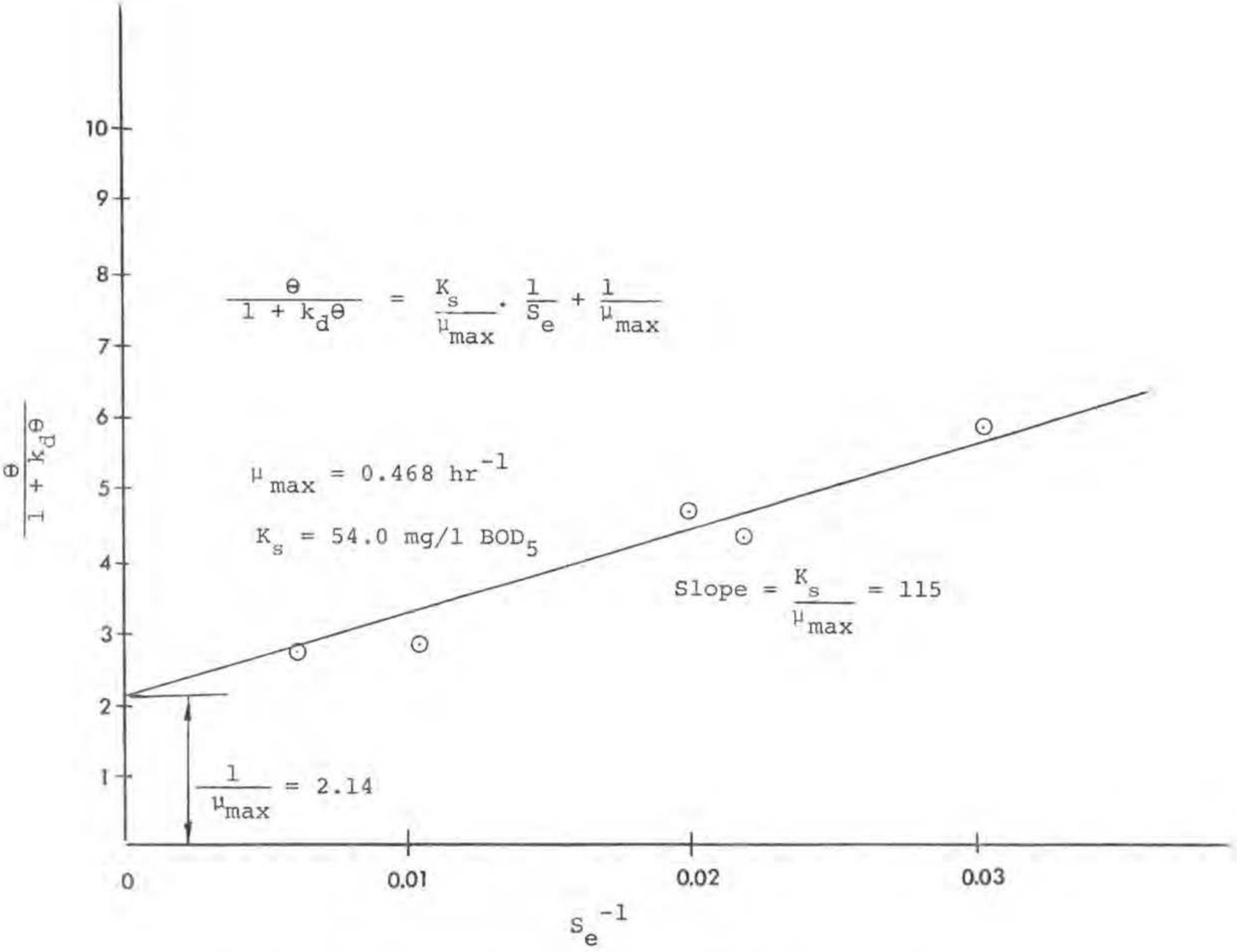


Figure 13. Determination of the Maximum Specific Growth Rate, μ_{max}, and the Saturation Constant, K_s, for Aerobic Treatment of Shrimp Processing Wastewaters (SIB).

Although single-pass systems are adequate for evaluating the pertinent kinetic parameters descriptive of biotreatability of wastewaters, they do not entirely simulate nor fully describe other facets of conventional systems which normally include some type of solids separation-concentration unit for controlled solids recycle and sludge wasting. Therefore, using the same experimental apparatus and techniques as for the single-pass studies but including a solids separation unit and recycle, effects on reactor and clarifier performance at varying hydraulic loading rates were again examined.

Steady-state influent and effluent substrate and solids concentrations as functions of reactor hydraulic retention time are presented in Table 7 for a recycle study using Plant S1B wastewaters. As with the single-pass study, these data were plotted to attain smooth functions as indicated in Figure 14. The resultant curves were then used for calculation of system kinetic parameters as shown in Figures 15 and 16. As before, the BOD_5 data provided the most interpretable results and were used in the subsequent data reductions. Two points in Figure 15 deviated from the linearized function plotted and were not considered for purposes of data evaluation since they most probably resulted from reduced clarifier performance at both high and low retention times, or to the effects of wall growths, population dynamics, or an inability to control vacillations about steady-state conditions within the reactor (15).

As may be anticipated, the kinetic constants obtained were similar to those secured from the single-pass study with the same wastewater. A calculated critical retention time of less than one hour demonstrated the positive influence of solids recycle on system performance; biomass retention under periods of hydraulic stress would be significantly enhanced. However, the secondary clarifier performance tempers the overall system efficiency as increased hydraulic loadings led to reduced solids separation capability.

The relative settleabilities of the biological solids produced at varying reactor dilution rates were assessed by calculation of the commonly applied parameter, Sludge Volume Index (SVI). Although SVI values alone should not be used for ultimate clarifier design, they do represent the gross changes in solids separation capacities resulting from changes in overflow rates or general system biomass morphology. The changes in SVI obtained as a function of reactor retention time are presented in Figure 17. Applied dilution rates had a pronounced effect on clarification capacity with optimal results (as indicated by SVI values of 100 ml/gm or less) noted when the reactor was operated at hydraulic retention times of from 4 to 7 hours. On either side of this range, the clarifier performance rapidly became less efficient. Whether this was due to clarifier design limitations (overflow rate) or to basic changes in biological population morphology (or to something not conceived) was not determined. However, considering the relatively inefficient clarifier operation at high retention times, the effect of overflow rate was probably less a reason than dynamic population shifts.

The efficiency of solids separation/concentration capacity suggests a constraining limitation to the final design and operation of an aerobic biological treatment system. Aeration tank design should provide for a detention time of from 4 to 7 hours to achieve adequate organics conversions

Table 7

Average Steady-State Concentrations for Aerobic Biological Treatment of Raw Shellfish Processing Wastewaters (Plant S1B) Employing Biological Solids Recycle

Hydraulic Retention Time, θ_h, hours	Reactor Sample Location**	TSS, mg/l	TVSS, mg/l	t-COD, mg/l	f-COD,* mg/l	f-BOD$_5$,* mg/l	TOC,* mg/l
10.90	A	76	75	300	282	230	118
	B	207	207	180	36	22	44
	C	38	37	70	46	18	25
	D	2650	2610	-	63	35	35
5.80	A	85	-	342	302	224	115
	B	190	189	122	45	28	25
	C	40	40	-	48	25	32
	D	502	-	-	257	42	150
2.87	A	95	90	319	296	240	109
	B	396	388	525	103	25	77
	C	80	80	282	73	15	112
	D	285	280	352	285	36	-
1.36	A	-	-	335	310	210	112
	B	140	140	298	96	62	66
	C	19	19	109	98	65	41
	D	205	197	-	-	75	-
0.98	A	86	84	319	285	205	120
	B	184	-	207	205	170	-
	C	58	57	191	178	150	66
	D	63	-	226	116	184	71

* Samples filtered through 0.45μ glass fiber filters prior to analyses

** Sample location designations:
A = Reactor Influent
B = Reactor Effluent
C = Clarifier Overflow
D = Clarifier Underflow

NOTE: Average raw wastewater unfiltered BOD$_5$ = 380 mg/l.

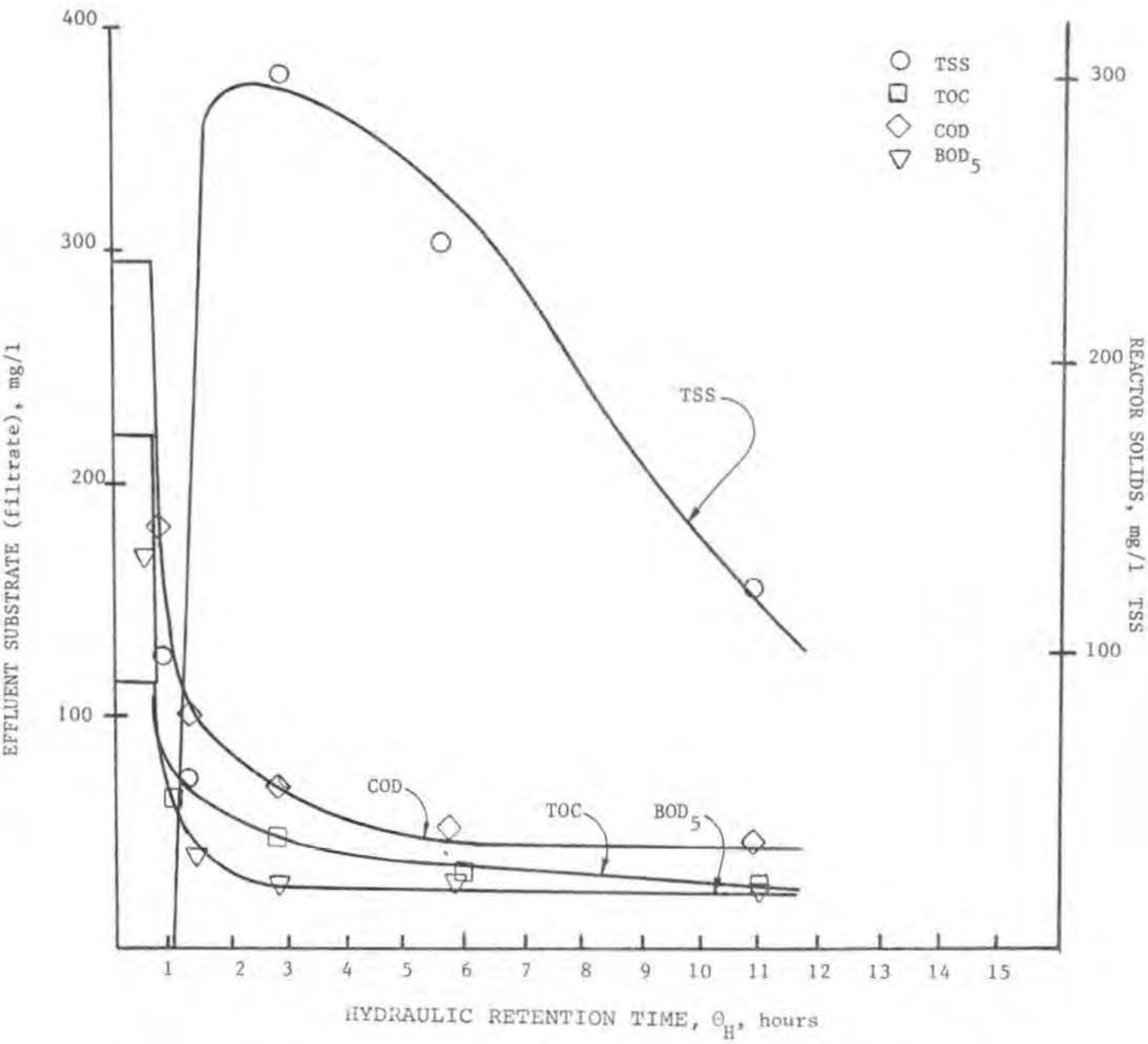


Figure 14. Steady-State Effluent Substrate and Solids Concentrations from Aerobic Treatment of Shrimp Processing Wastewater Employing Solids Recycle (S1B).

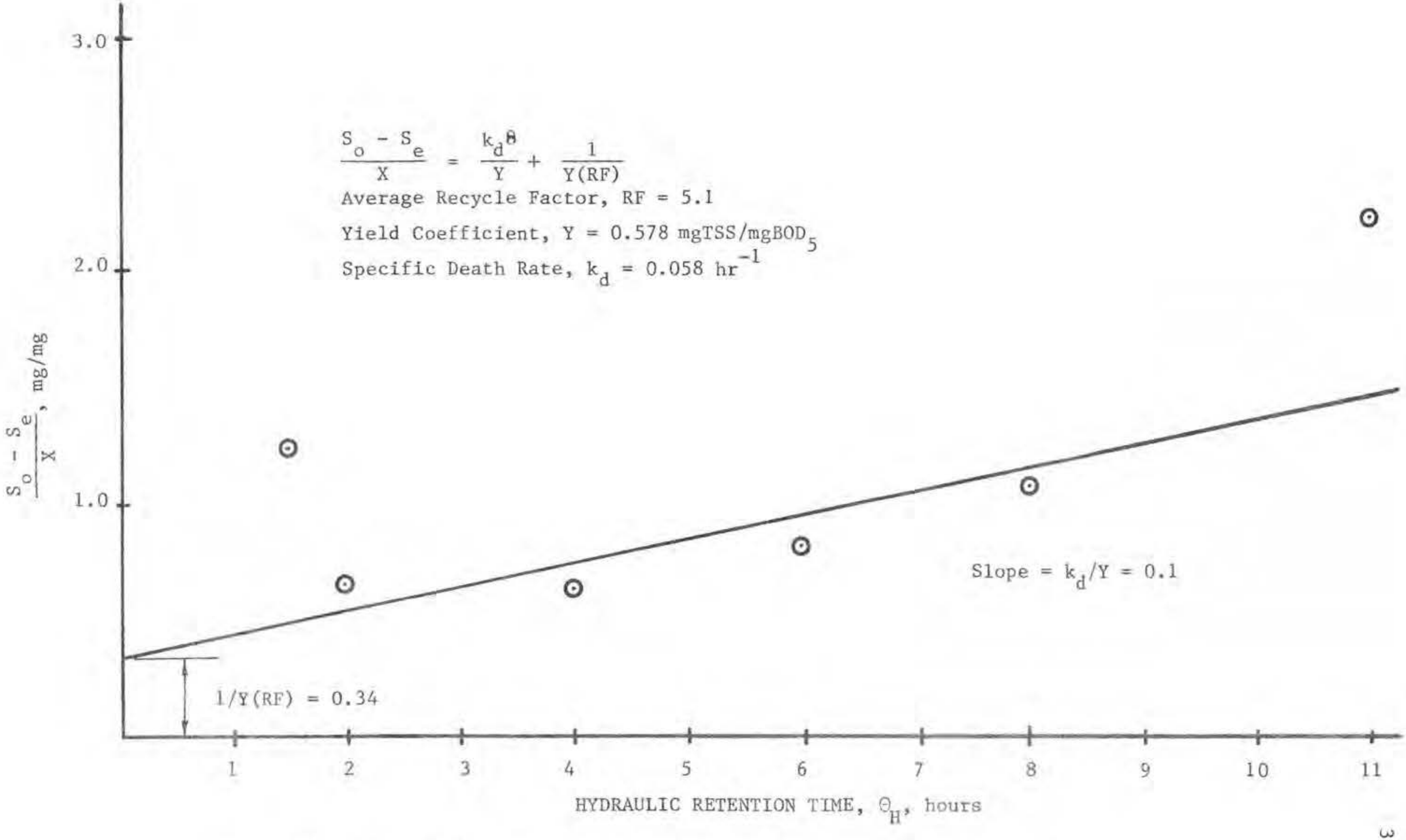


Figure 15. BOD$_5$ Based Determination of Y and k_d for Shrimp Processing Wastewater Treatment Employing Solids Recycle (S1B)

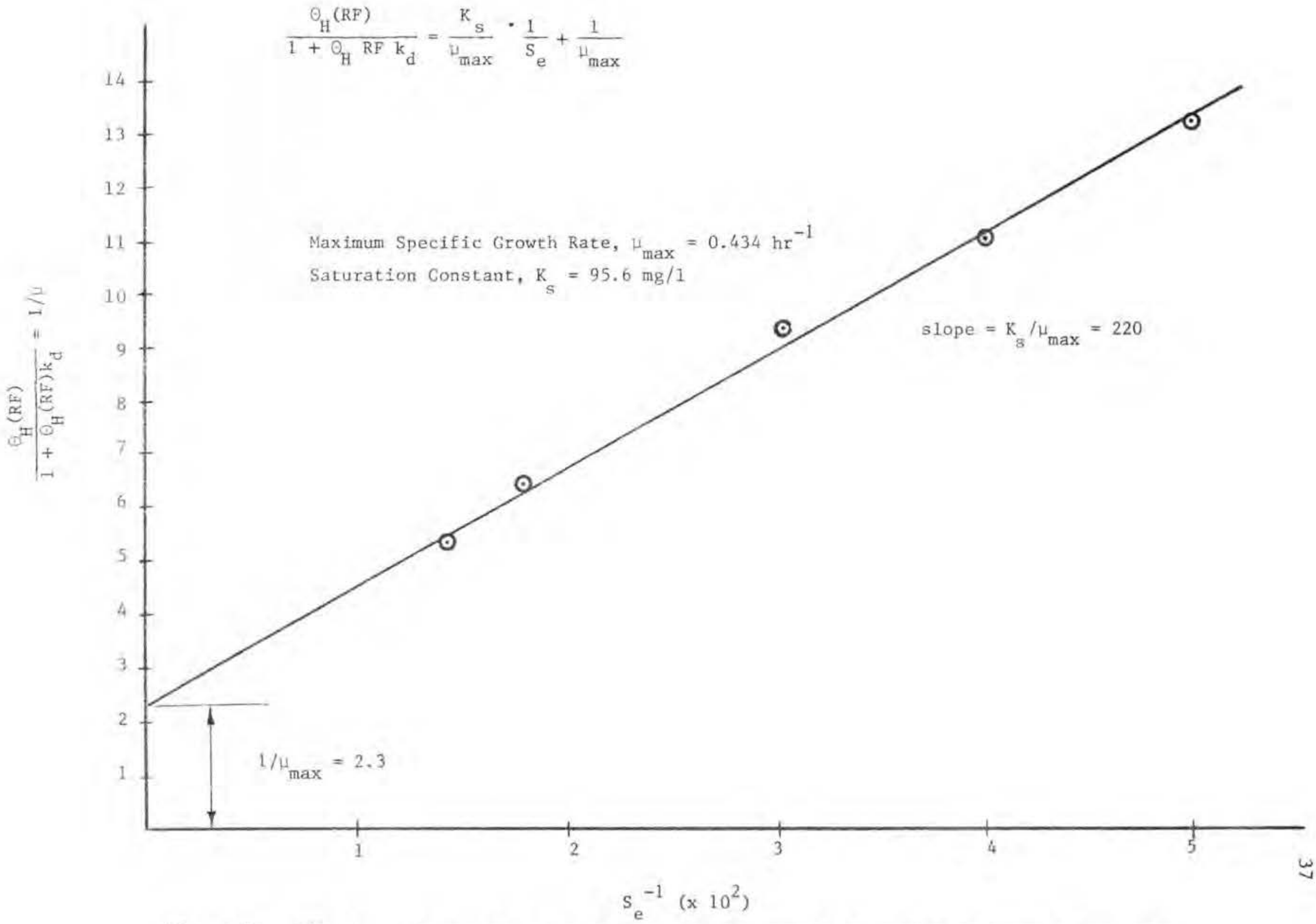


Figure 16. BOD_5 Based Determination of μ_{max} and K_s for Shrimp Processing Wastewater Treatment Employing Solids Recycle (S1B)

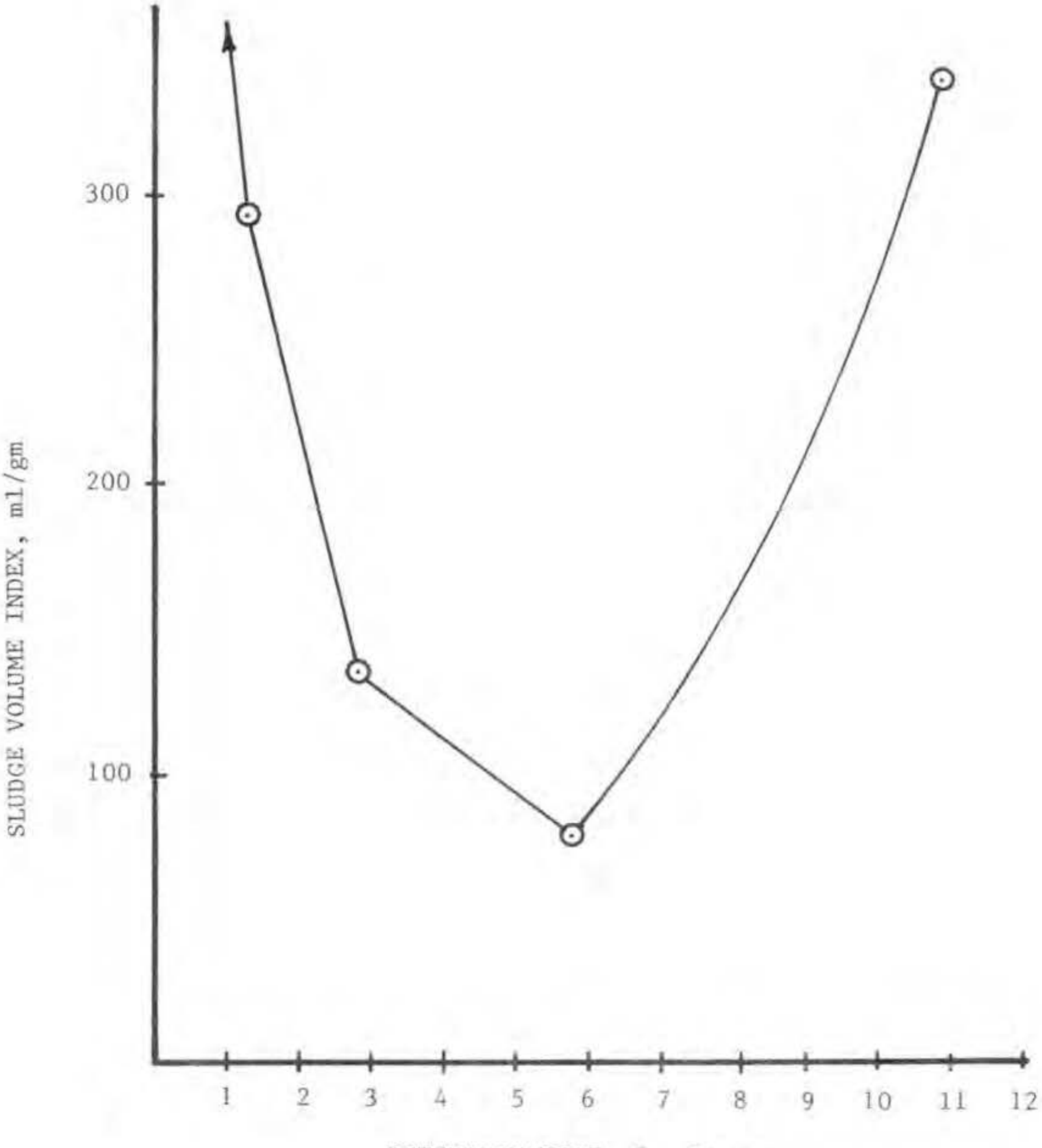


Figure 17. Sludge Volume Index as a Function of Reactor Retention Time during Aerobic Treatment of Shrimp Processing Wastewaters (Plant S1B).

and yet maintain reasonable clarifier performance. Shorter detention times may be used but consideration of increasing clarifier surface area would probably be necessary. A detention time approaching 9 hours would likely lead to problems in clarification since the biological population tends toward an increasingly dispersed character with poorer settling characteristics. This study serves to exemplify the sometimes overlooked dependency of system clarification capacity upon the biological phase of treatment. The settling data presented provided a reasonable indication of overall system application and limitation. However, clarifier scale-up to field systems presents problems that would require more extensive study.

Aerobic mixed culture treatability studies conducted on another shellfish processing wastewater, Plant S2B, resulted in the steady-state values presented in Table 8 for respective applied hydraulic retention times of 12.80, 8.36, 5.3, 1.98, and 0.88 hours. These data, as with Plant S1B wastewater treatment data, were plotted as shown in Figure 18. These data curves were then used in kinetic constant determinations as indicated by the reciprocal plots presented in Figures 19 and 20. Once obtained, the kinetic values were used to calculate predicted steady-state effluent substrate (BOD_5) and solids (TVSS) concentrations at various selected system hydraulic retention times.

The agreement between actual and predicted effluent concentrations indicated in Figure 18 is apparent and demonstrates model applicability for system description. The only assumption made in kinetic constant evaluation which was not specifically accounted for in model development was that influent solids concentrations were stable within the system and as such were not appreciably contributory as solid phase substrate or viable biological solids. This allowed linear subtraction of influent solids from reactor solids and, therefore, the solids concentrations reported are net steady-state values at each applied retention time.

Comparison of Aerobic Treatability Results. Data collected through the analogous studies for shellfish processing wastewaters were reduced to provide kinetic parameters for comparison as indicated in Table 9. All experimental and analytical procedures were duplicative (except that nutrient supplements, nitrogen and phosphorus, were required for the wastewater from Plant S2B). The appropriate kinetic constants were determined as before.

The results indicated that two of the wastewaters provided similar kinetic response under aerobic treatment while the third differed significantly. This variability inferred that care must be exercised in the projection of certain treatability results to wastewaters not well characterized or examined with respect to treatability. Differences in processing rates, operational modes, and main-line product types lead to basic differences in wastewater characteristics and these differences lead in turn to the need for determining treatment system requirements on a plant-by-plant basis. Although the kinetic values lead to similar aerobic contact times for design purposes for all three plants, the last plant listed (Plant S2B) had a reduced tendency for hydraulic "washout" of biomass, had a greater affinity for the wastewater substrate organics, and produced more biological solids per increment of BOD_5 removal.

Table 8

Average Steady-State Organics and Solids Concentrations for Single-Pass, Completely Mixed, Aerobic Treatment of Raw Shellfish Processing Wastewaters (Plant S2B)

Hydraulic Retention Time, hours	Influent					Effluent				
	COD,* mg/l	BOD_5,* mg/l	TOC,* mg/l	TSS, mg/l	TVSS, mg/l	COD,* mg/l	BOD_5,* mg/l	TOC,* mg/l	TSS, mg/l	TVSS, mg/l
12.80	176	146	74	20	19	0	5	34	67	67
8.35	182	147	76	20	19	8	7	33	73	73
5.30	198	132	75	20	19	37	12	36	86	86
1.98	171	141	--	20	19	74	48	49	46	39
0.88	164	128	70	44	44	82	104	69	112	112

* All values derived from analyses on samples after filtration through 0.45μ glass fiber filters

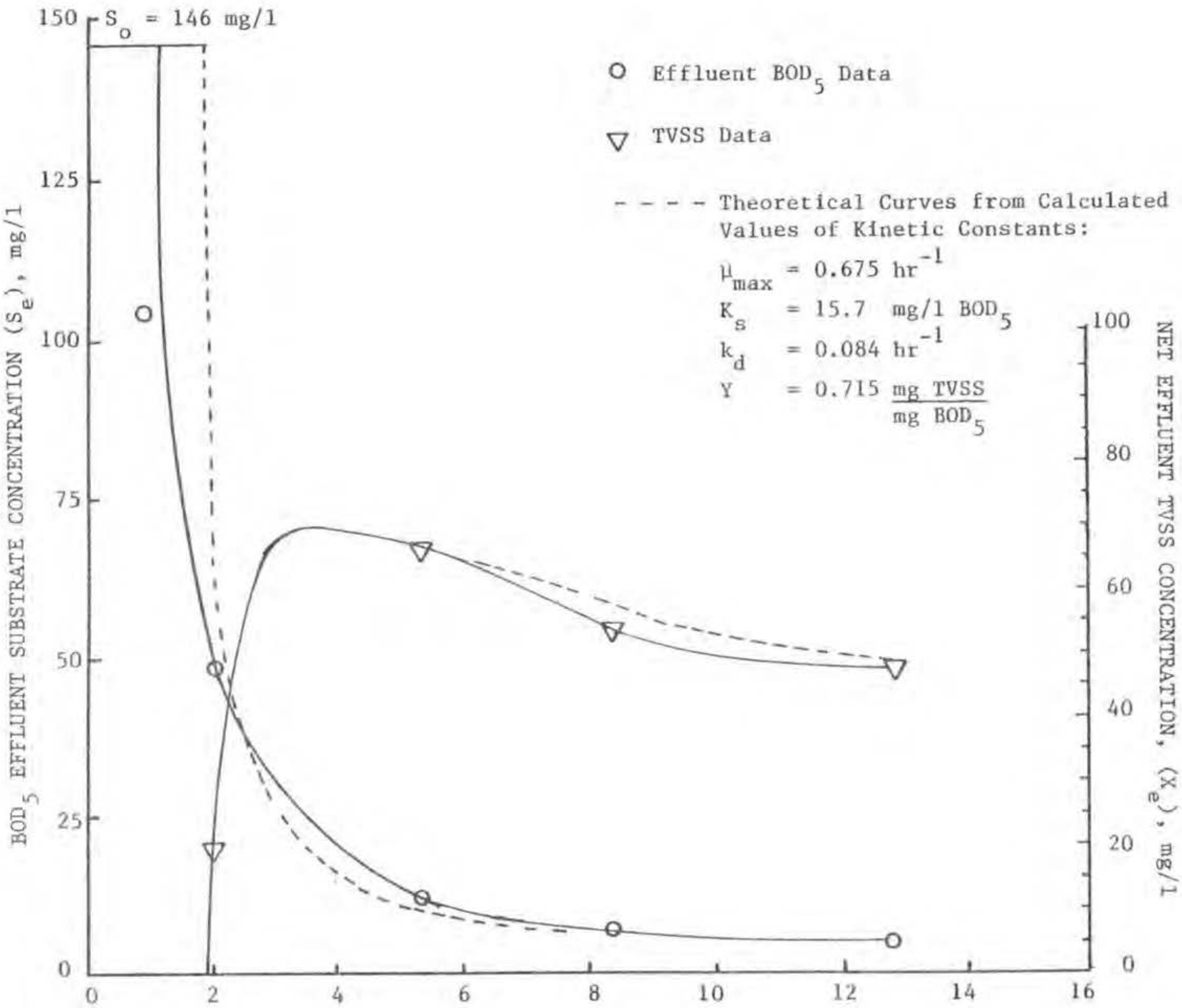


Figure 18. Steady-State Effluent Substrate and Biological Solids Concentrations for Single-Pass Aerobic Treatment of S2B Shellfish Processing Wastewaters

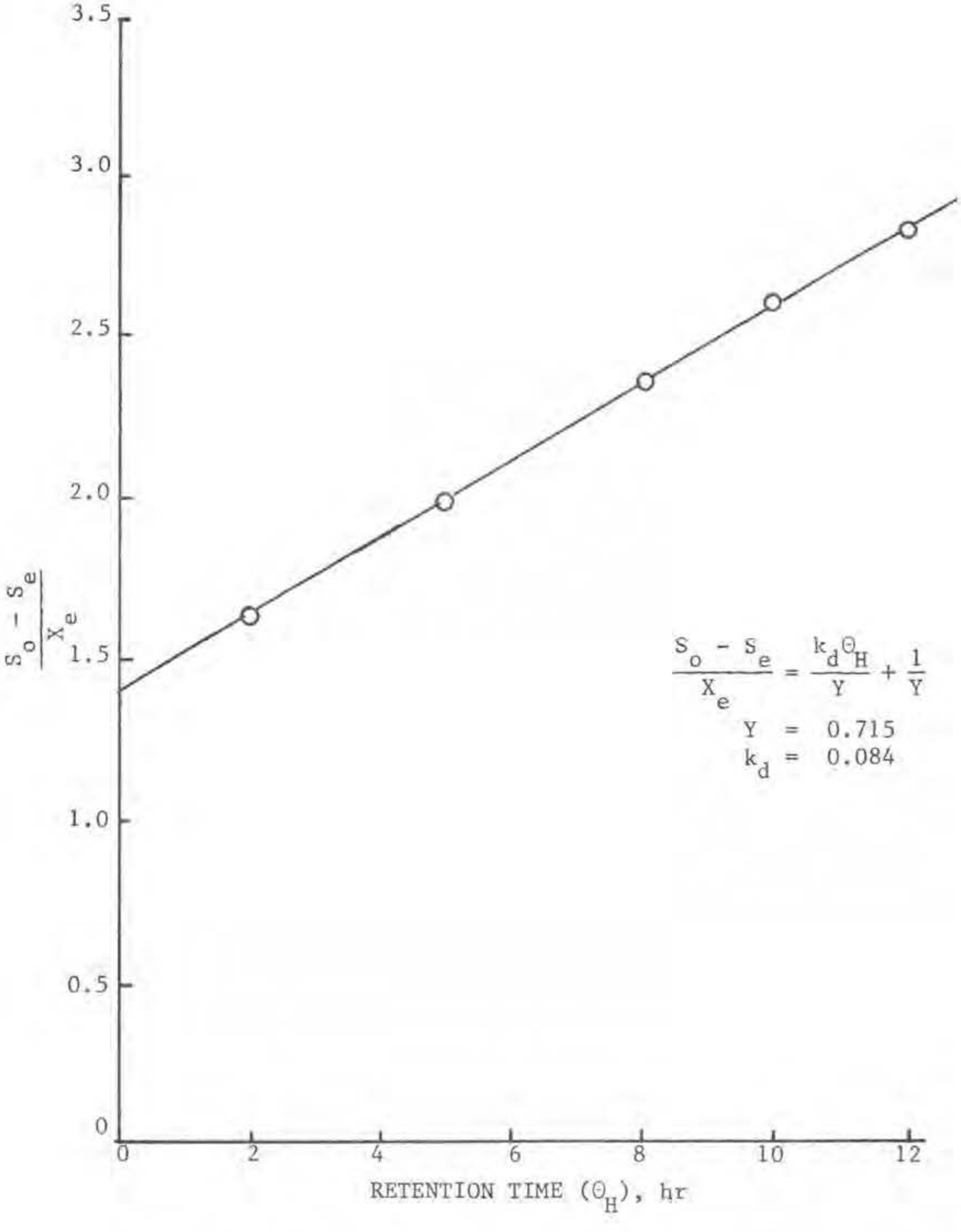


Figure 19. BOD_5 Based Reciprocal Plot Determination of the Yield Coefficient, Y, and the Specific Decay Constant, k_d, for Aerobic Treatment of S2B Shellfish Processing Wastewaters.

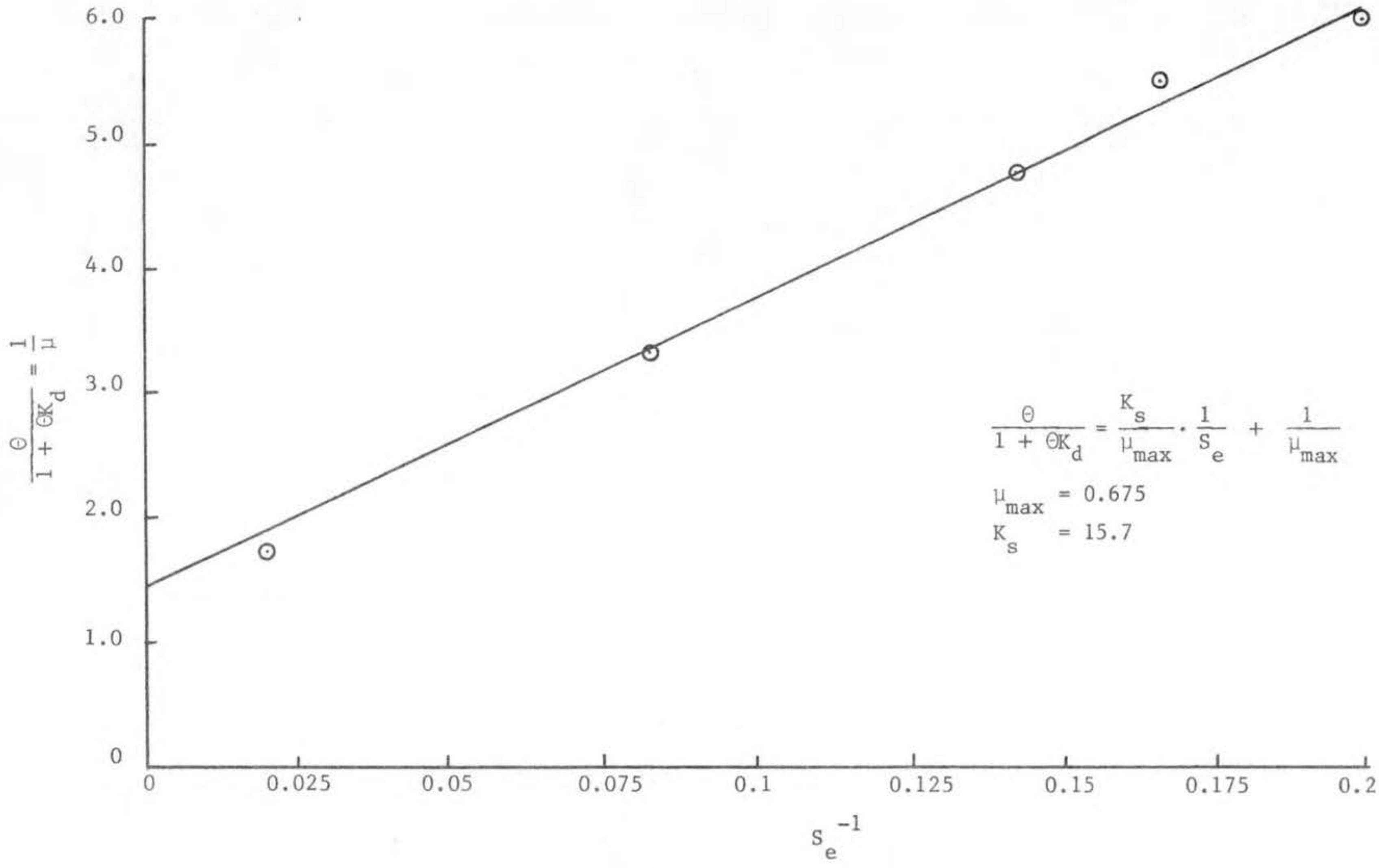


Figure 20. BOD_5 Based Reciprocal Plot Determination of the Maximum Specific Growth Rate, μ_{max}, and the Saturation Constant, K_s, for Aerobic Treatment of S2B Shellfish Processing Wastewaters

Table 9

Comparison of Kinetic Parameters Applicable to Aerobic Treatment of Three Shellfish (Shrimp) Processing Wastewaters

Wastewater Code (Reactor Mode)	Maximum Specific Growth Rate, μ_{max}, (hr^{-1})	Specific Decay Rate, k_d, (hr^{-1})	Saturation Constant, K_s, (mg/l BOD_5)	Yield Coefficient, Y, ($\frac{mg\ TSS}{mg\ BOD_5}$)
SOB (single-pass)*	0.417	0.067	85.5	0.500
S1B (single-pass)	0.468	0.077	54.0	0.565
S1B (recycle)	0.434	0.058	95.6	0.578
S2B (single-pass)	0.675	0.084	15.7	0.715

*Values computed from data collected from a previous study(3).

Based upon the experimental results and irrespective of the noted variability in the kinetic parameters which can be used to provide certain eventual design criteria, the establishment of aerobic biological treatment as a means of handling shellfish processing wastewaters generally appears to be operationally feasible and applicable.

Application of Kinetic Data to Aerobic Treatment Systems

Once evaluated, the system-descriptive kinetic parameters may be applied to the determination of certain criteria important for treatment system design and operation. Among these criteria are estimations of 1) the reactor retention time at which organism "washout" may occur, 2) minimum effluent substrate concentration possible, and 3) amount of solids anticipated for recycle and/or final disposal.

Equations 23 and 24 (Appendix A) can be used to calculate the critical retention time and minimum substrate concentration, respectively. Estimates of solids (sludge) production directly follows from the yield coefficient, Y, assuming complete capture and separation of all produced solids. For the wastewaters investigated, little difference in critical retention times were noted with about two hours being calculated and verified experimentally. Design criteria would necessarily involve a safety factor to allow for the possibility of hydraulic surges which could vary the retention time to or below critical levels.

Minimum final effluent substrate concentrations attainable from aerobic biological systems, as determined from the kinetic parameters, ranged from 3 to 15 mg/l BOD_5 for the S2B and S1B wastewaters, respectively. In actual practice these absolute levels might not be obtained. However, as the experimental results indicate, the final treated effluent concentration of near 20 mg/l BOD_5 approximates these values with about 90-95% removal efficiencies obtained.

Knowledge of the wastewater flow, organic strength as BOD_5, and the yield can be used to estimate solids mass anticipated from the secondary clarifier and determination of the specific gravity of the settled solids allows estimation of the daily sludge volumes. This would enable the rational selection of sludge handling facilities and attendant pump sizes as well as provide information pertinent to final sludge disposal requirements.

One important consideration which was not specifically evaluated in the course of these studies was the rate of oxygen (air) demand exerted by the developed biological population. This information would be essential to the economical sizing of aeration equipment for a field installation, but was not of major concern to the laboratory studies since oxygen (air) was supplied in excess at all times to prevent it from becoming "limiting" and lending difficulty to subsequent data evaluations. For all investigations, only organic matter as COD, TOC, or BOD_5 was maintained as the growth-limiting nutrient. However, oxygen requirements could be estimated for a treatment system by using conventionally applied values reported in the literature, e.g. 0.6 lb O_2/lb BOD_5 (1.32 Kg/Kg) removed and 0.003 lb O_2/lb TVSS/hour (1.36 g/g/h) (10).

Completely Mixed Anaerobic Biotreatment

Following the aerobic biological investigations, a similarly conducted anaerobic treatability study was performed to determine system applicability and operational limitations for raw wastewater treatment. The moderate organic strength and volatile solids content suggested that anaerobic treatment methods might possibly be applicable as a means for successful preliminary wastewater control.

The results of the continuous flow anaerobic biological treatment investigations are summarized in Table 10. These data could not be readily evaluated with the kinetic equations presented in Appendix A and all attempts to utilize the data within the restrictions of the predictive model were unsuccessful. However, after considering certain phenomena observed as a result of final data analysis, several reasons for the inordinate biokinetic response could be advanced.

One of the basic requirements of continuous culture theory, using the Monod relationship, is that the substrate parameter selected for data analysis must be the only nutrient which limits organism growth. The selection of soluble COD as a gross determinant for the limiting nutrient appeared to be ill-suited for the results from the anaerobic treatability investigation. In order to adequately employ soluble COD values as substrate, all wastewater constituents that could ultimately be metabolized must be reflected by the COD test itself. That the COD test may be deficient in this regard is exemplified by the relationships shown in Figure 21. It is noted that although the ratio of effluent to influent soluble COD decreased with an increase in steady-state retention time as would be expected, the ratio of effluent to influent total COD increased to a point where the effluent total COD was greater than the applied influent total COD. In addition, this ratio increased at a greater rate than the soluble COD ratio decreased. This phenomenon, which seemingly defies the concept of mass conservancy, can be rationally explained provided there were certain wastewater organic constituents which, although not initially represented by the COD test, were amenable to chemical oxidation following modification by biological action. The determination of each wastewater constituent which might have contributed to the total COD was considered beyond the scope of the investigation; however, it is known that certain straight chain aliphatic compounds and aromatic hydrocarbons are not appreciably oxidized with standard COD test procedures. However, the catabolic activity of microorganisms, probably through extracellular enzymatic hydrolysis, could alter these or other compounds to forms capable of being oxidized in the COD test. The overall effect of these occurrences would be inaccurate determination of the organic substrate actually available for biological consumption.

Additional data reductions and evaluations not only support the hypothesis of measurable COD conversions, but also infer that the additional COD appears at the expense of the wastewater suspended solids content. This, in turn, limits the use of TVSS as an estimate of biomass concentrations. However, if the filtered COD is subtracted from the total COD, the COD due only to the suspended solids may be determined. Assuming that the wastewater suspended solids were stable and, as such, not considered either as substrate or organisms, the equivalent solids COD value would necessarily be a system constant throughout the biological

Table 10

Summary of Steady-State Process Performance Results for Continuous Flow Anaerobic Treatment of Plant S1B Shellfish Processing Wastewater

Hydraulic Retention Time, days	5	15	20	7.7*	10**
Effluent Total Chemical Oxygen Demand, mg/l	179	336	360	290	718
Effluent Total to Influent Total Chemical Oxygen Demand Ratio, %	66	93	106	52	105
Effluent Soluble Chemical Oxygen Demand, mg/l	126	189	144	164	482
Effluent Soluble to Influent Soluble Chemical Oxygen Demand Ratio, %	82	94	65	40	67
Effluent Total Suspended Solids, mg/l	198	285	160	291	630
Effluent to Influent Total Suspended Solids Ratio, %	102	93	152	60	61
Effluent Total Volatile Suspended Solids, mg/l	85	197	124	141	236
Effluent to Influent Total Volatile Suspended Solids Ratio, %	76	109	264	81	72
Total Gas Production Rate, ml/liter of reactor volume/ day	5.0	13.1	11.5	12.1	10.4
Percent Methane in Gas	78	80.2	76	71.6	70
Methane Production Rate, ml/liter reactor volume/day	3.9	10.5	8.7	8.7	7.5
Effluent Total Volatile Acids, mg/l as Acetic Acid	141	141	103	65	441
pH	7.15	7.25	7.10	7.25	7.20
Total Alkalinity, mg/l as Calcium Carbonate	1825	2304	1550	2200	5415

* Steady-State values for reactor system operated with a 50% by volume recycle ratio of settled biological solids.

** Reactor operated with ammonia-nitrogen nutrient supplement; 50 mg/l $(NH_4)_2HPO_4$.

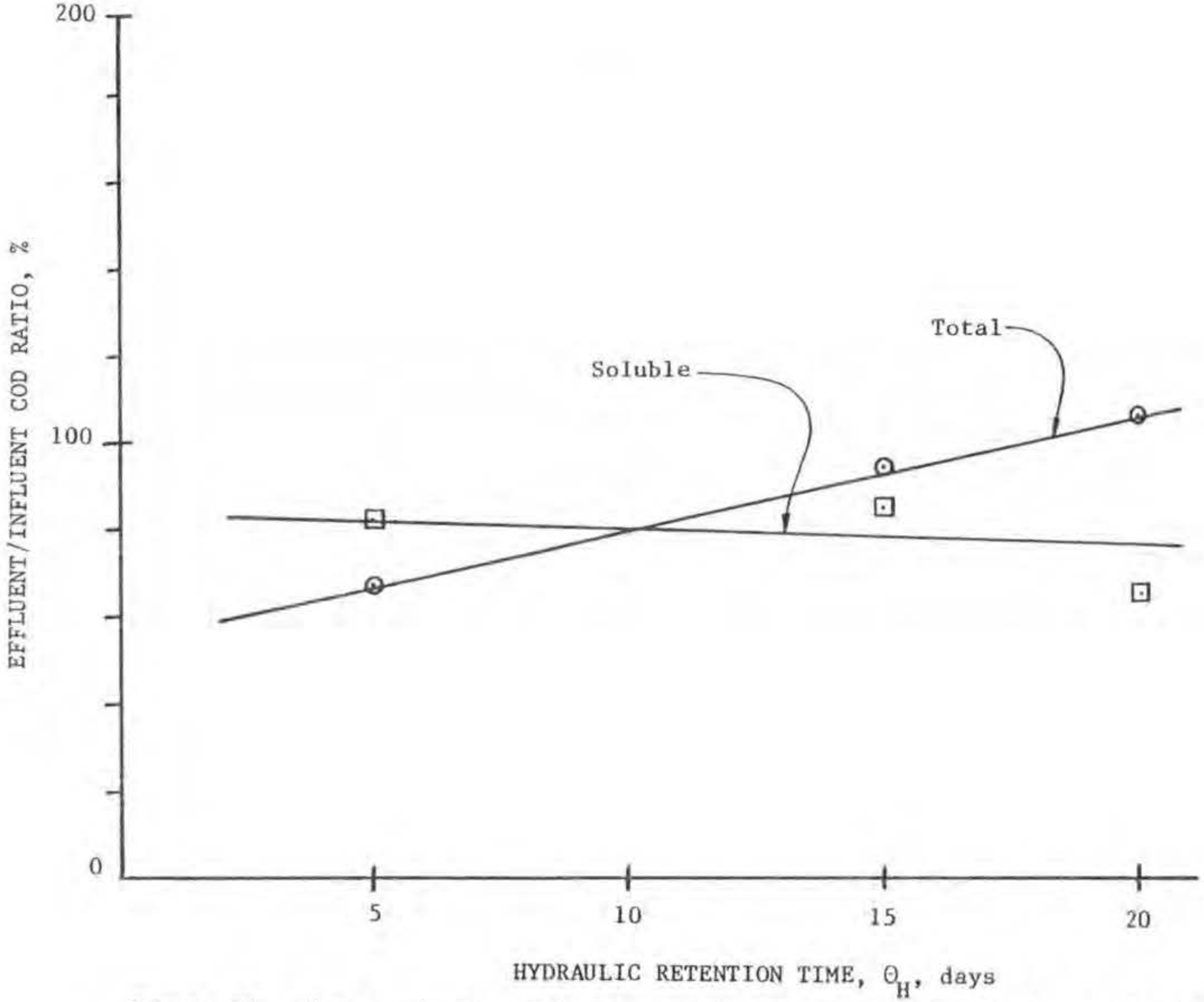


Figure 21. Changes in the Effluent to Influent Total and Soluble COD Ratio with Reactor Hydraulic Retention Time During Single-Pass Anaerobic Treatment of SIB Shellfish Processing Wastewaters

phase. Subtraction of the COD equivalent for influent solids from that of the effluent solids should reflect a net solids COD increase as biomass is generated from the soluble substrate. In addition, this increase should be positive as long as system washout does not occur, at which time it would be zero.

The data from the three retention times employed in single-pass anaerobic operation were used to determine the solid COD fractions in the influent and effluent streams. The difference in solid COD from effluent to influent was plotted against reactor retention time and indicated in Figure 22 that a net increase in solids COD across the reactor was not obtained until a retention time of about 11 days was reached. At shorter retention times, the influent solids COD was greater than solids COD within the reactor. This strongly indicated that COD due to solids was being transformed to soluble COD, a result commensurate with the noted increase in total COD. This phenomenon obviously would cause difficulty in applying kinetic evaluations with the model as given. With the data available, the actual biomass concentration within the reactor could not be explicitly specified nor could it be assumed that soluble COD (as volatile acids) conversions to carbon dioxide and methane governed the rate of the phasic metabolic activity as has been previously reported (16). However, it was apparent that the system was not sufficiently stressed hydraulically to cause "washout" as indicated by the lower but significant steady-state methane production rate. In fact, it was possible that solid COD conversions to soluble COD may have been the growth-rate-limiting consideration for this system.

To further compound the problems encountered with kinetic evaluations, there was evidence of some inhibition of the methanogenic organisms. Using the Eadie-Hofstee modification of the Lineweaver-Burke type reciprocal plot (17) (i.e., plotting the specific growth rate, μ, against the product of the specific growth rate and the reciprocal of the effluent substrate concentration, μ/S_e), a linear relationship with a negative slope equal to the saturation constant, K_S, and an ordinate intercept at the maximum specific growth rate, μ_{max}, should be produced. Using methane production as an estimate of methanogenic organism growth rate and steady-state effluent soluble COD or total volatile acids (as acetic acid) as an indication of the available substrate, an Eadie-Hofstee type plot was constructed as indicated in Figure 23. Although only a few data points were available, a general trend, applicable to the retention times applied, emerged which indicated some form of substrate associated inhibition. Instead of a linear function with a negative slope, a definite trend toward a positive slope was indicated. As effluent substrate concentrations increased, a decrease in specific growth rate ensued. This is not unusual for inhibition attributable to the volatile acids except that such inhibition with high volatile acids concentrations is thought to occur primarily through attendant environmental alterations of pH and loss of buffering capacity (18). However, as indicated in Table 10, the volatile acids were not sufficiently concentrated to impose such a stress upon the system throughout the study. Therefore, the available information was not conclusive and insufficient to actually delineate the specific cause of the suspected inhibitory influence, although it appeared to be associated with the soluble COD concentrations possibly originating from the COD transformations previously discussed. Whether this inhibitory influence would manifest itself at longer retention times than examined was not ascertained.

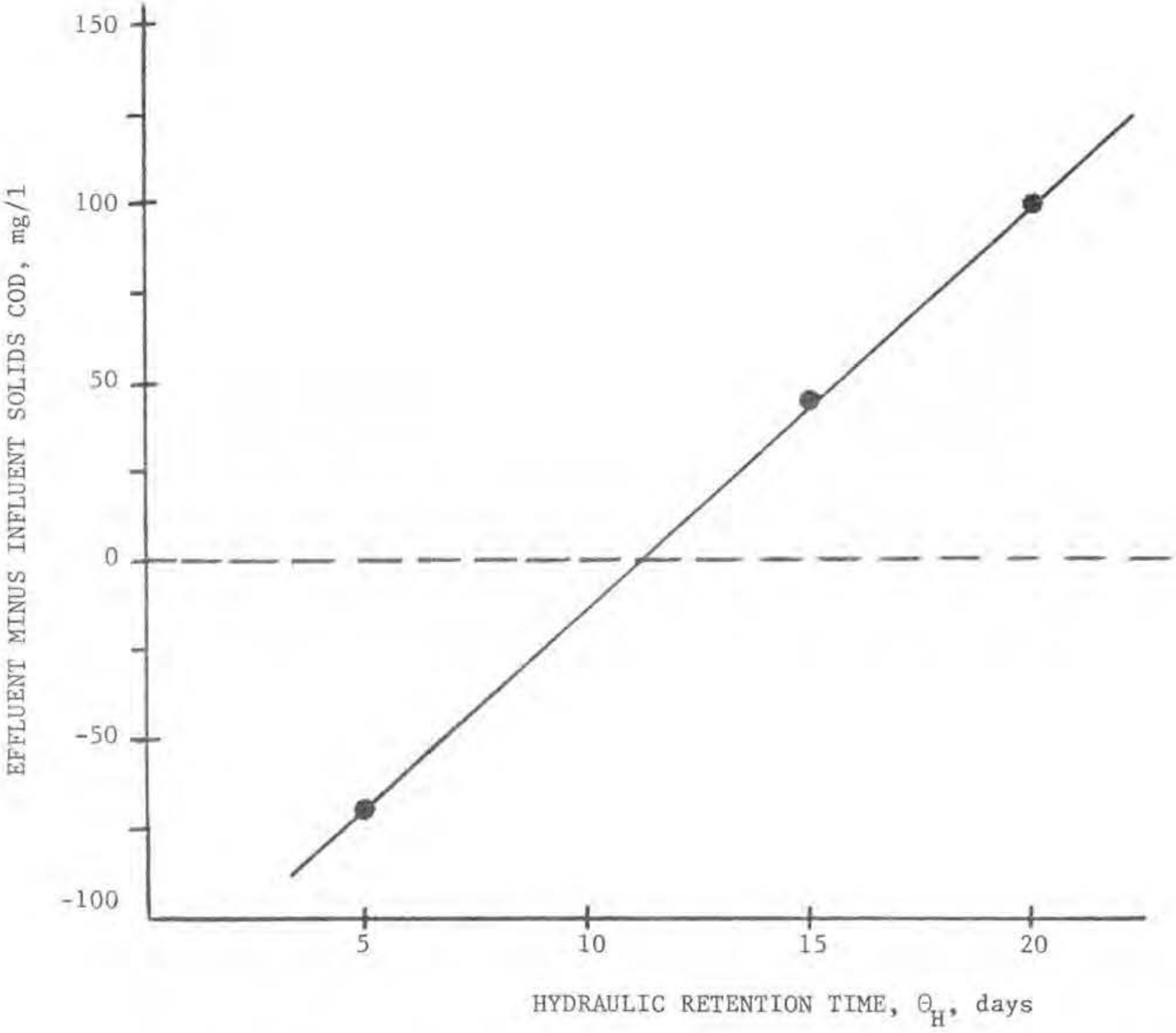


Figure 22. Difference in Reactor Effluent to Influent Solids COD at Various Hydraulic Retention Times during Single-Pass Anaerobic Treatment of SlB Shellfish Processing Wastewaters.

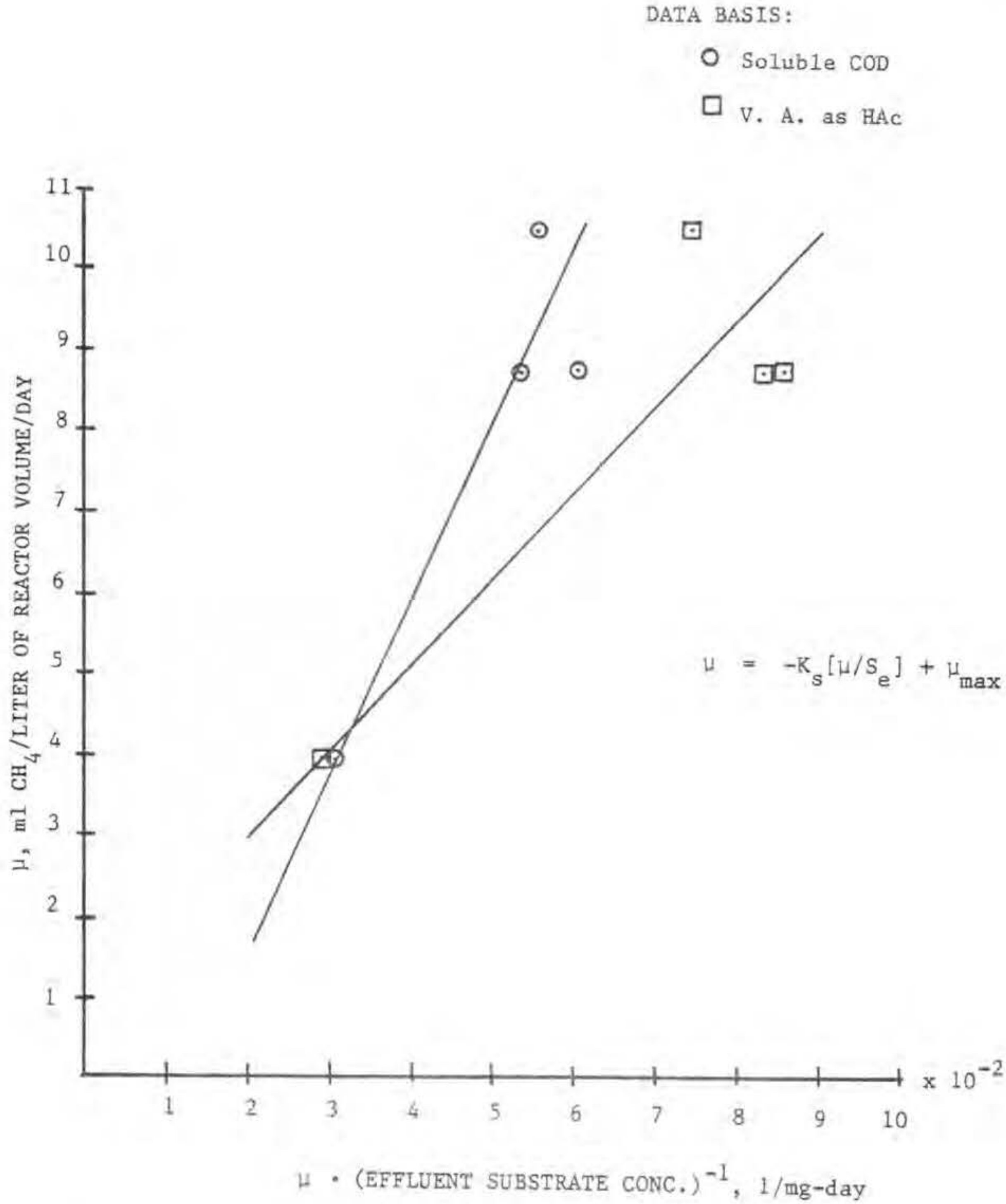


Figure 23. Eadie-Hofstee Reciprocal Plot Using Methane Production Rate and Effluent Substrate Concentrations, Soluble COD or Total Volatile Acids as Acetic Acid, for Single-Pass Anaerobic Treatment of SlB Shellfish Processing Wastewaters.

In addition to the preceding discussion, some comment may be made concerning acidogenesis within the reactor system. Although the wastewater characterization indicated the adequacy of nutrients for biosynthesis, the form and availability of a specific nutrient may have restricted growth under certain conditions. This appeared to be valid with nitrogen. When supplemental nitrogen [as $(NH_4)_2HPO_4$] was added to the reactor operated at a 10-day retention time, an almost four-fold increase in volatile acids resulted. Even though there appeared to be enough nitrogen in the wastewater to be stoichiometrically non-restrictive to growth, it was mostly in the form of organic nitrogen. The availability of a more readily usable nitrogen form reduced the energy-consuming burden for transformation of the organic nitrogen source to a metabolically more usable form. This emphasizes a certain advantage for nutrient supplementation even when seemingly unwarranted by results of wastewater characterization. Whether supplemental nitrogen would have improved the analysis of results and allowed better kinetic evaluation for the anaerobic treatability investigations could not be determined; however, the lack of increase in methane production rate with the increased volatile acids substrate availability would suggest that such interpretative difficulties would persist.

The wastewater under consideration was studied for only one attempt at solids recycle (Table 10) and, although little could be provided concerning specific system-descriptive kinetics, one notable improvement was observed in that the methane production rate increased by about 35 percent over what was estimated by graphical extrapolation of single-pass operation data at the retention time used (7.7 days). Complementing this increased gas production was a corresponding reduction in steady-state volatile acids concentration, which indicated that possible inhibitory influences had less effect upon the system when recycle was practiced.

On the basis of the treatability investigations performed on the wastewaters collected, it appears that conventional anaerobic treatment of raw shellfish processing effluents, even with solids recycle, would be unjustified. Studies were conducted with comparative economics in mind and consequently were not extended to encompass treatment evaluations for extended holding periods (hydraulic retention times). Therefore, anaerobic treatment may exhibit better functional organic removal efficiencies with longer stabilization periods, say 30 days or more. However, the cost effectiveness of establishing and maintaining a facility (containment vessel or lagoon) of such size to accommodate a holding time for raw wastewater flows normally encountered with the shellfish processing industry would most likely be unfavorable compared to the aerobic treatment alternative. This would not preclude conventional anaerobic applications for sludges arising from other treatment operations since flow quantities would be considerably reduced and organic strengths much greater, thus favoring anaerobic stabilization process application. Unfortuantely, anaerobic treatment of biologically or chemically derived sludges was not evaluated in the course of experimentation since quantities produced were insufficient to allow their continual and reliable use. Moreover, determination of feasible sludge handling and disposal methodology would be better effected on the pilot-scale level.

FIXED FILM BIOLOGICAL CONTACT PROCESSES FOR TREATMENT OF SHELLFISH Processing Wastewaters

As investigative efforts on shellfish processing wastewater treatment by conventional methods progressed, sufficient information was accumulated to suggest other avenues of investigation which were more specifically oriented toward optimal solutions for wastewater treatment problems considering the overall economy involved and currently available alternatives. Shellfish processing wastes, because of their particular characteristics, flow variability, and substantial biodegradability, appear to be very well suited to treatment by certain methods not presently considered as "conventional." Two distinct processes which seem to be uniquely applicable are biological contact processes: the rotating disc and the anaerobic filter. Both methods employ attached and/or physically contained microorganism populations which, since they are not subject to the degree of hydraulic removal notable with conventional mixed systems, provide for high treatment efficiencies without the need for significant and costly biomass recycle. Moreover, the low space, power, and maintenance requirements, coupled with an ability to handle fluctuating and short-term shock loadings, place these processes in a very favorable position. In addition, the overall capital and operational costs associated with these systems can be markedly lower than those for conventional systems.

Description of Fixed Film Biological Contact Processes - Rotating Biological Contactor. The rotating biological disc contactor, hereafter abbreviated as RBC, employs a fixed-film, aerobic biological process within which microorganisms utilizing waste pollutants adhere to the surface of thin discs mounted on a rotating shaft in a flow-through containment tank. As the shaft turns, the attached organisms are alternately immersed in the wastewater and exposed to air. This operational feature offers solutions to a few of the major problems associated with conventional biological treatment, i.e., ensuring adequate oxygen supply without auxilliary facilities, providing and maintaining a sufficient organism population to readily accommodate fluctuating or shock loadings, and economy of operation.

The RBC system is similar in some respects to the conventional trickling filter process in that large biomass populations can be obtained, short-term shock loadings can be reasonably accommodated, and oxygen supply is not mechanically derived. However, the conventional-type trickling filter requires much more areal space, has relatively high head losses (hence, greater operating costs), and may be subject to flooding if hydraulically overloaded or clogged by excessive organism growth. To date, the RBC system has gained only limited "conventional" status in the United States because of its relatively recent application as a means of waste treatment and correspondently sparse operational and performance record. Yet, as a potential process, the RBC system is not new even though its use has been restricted in favor of more conventional waste treatment systems.

The RBC system has exhibited effectiveness for the treatment of several food processing wastes (19-22) including those from chicken, tuna, and fish processing plants. The organic characteristics of some of these wastes were similar to those of shellfish processing wastes and relatively high treatment efficiencies were obtained. Moreover, treatability studies (23), which compared conventional systems (aerated lagoons and activated sludge) to the RBC system, indicated comparable waste strength reductions with a distinct economic edge for the RBC.

Shellfish processing wastes, because of their high biodegradability, variable flow, and organic characteristics, should also be amenable to RBC treatment. In fact, due to unique features of the RBC - high biological solids retention capability and small flow resistance - it is well suited to handle the moderately high organic content and flow variations normally encountered with shellfish processing wastes. Another RBC system advantage of great importance to the shellfish processor is its relatively low cost. Initial capital outlay is less than for conventional systems, particularly for small to medium size plants (24). This would be of particular pertinence to most shellfish processors in Georgia. The RBC system is also inexpensive to control, operate, and maintain. Its operation requires no sophisticated control and thus no highly trained personnel, an obvious advantage to many shellfish processors.

Treatment of Shellfish Wastewaters by Rotating Biological Contactors - Laboratory Apparatus and Experimental Methods. Schematic representation of the experimental RBC apparatus is presented in Figure 24. The apparatus was composed of two distinct stages with 17 plexiglass discs in each stage. The two sets of discs were set in a single unit assembly on an "A"-frame which allowed simultaneous placement into the reactor basins. Both sets of discs were then rotated by a single variable speed motor with "O"-ring linkages. Overall dimensions of the total unit were 30.5 x 66.8 x 30.5 centimeters with each stage having a 5.1-liter weir controlled liquid capacity. To minimize dead zones, each stage was bottom contoured to provide a 2.54 cm clearance between disc edge and basin bottom. Each stage from influent to effluent had plexiglass serrated weirs installed along distribution and collection channels to reduce short-circuiting potentials. The discs were 0.32 cm thick by 20.3 cm in diameter set at 1.3 cm spacings on a stainless steel shaft.

Wastewaters were transferred as needed in 20-liter carboys from the cold storage room to a refrigerator, maintained at 4°C, proximal to the experimental unit and distributed to the unit's first stage with a variable speed peristatic pump. Prior to the initial experimental run, a disc biomass population was established by batch operation of the system after inoculation with municipal sewage seed. The attached biomass was gradually acclimated to the shellfish processing wastewaters by first applying a 1:1 mixture of 100 mg/l glucose-wastewater, then adding 500 ml of wastewater daily. Approximately 10 days of batch operation by this method was sufficent to produce a well-developed growth upon all disc surfaces.

System operation basically employed hydraulic retention time (or dilution rate) as an independent variable with nominal steady-state performance evaluations determined by organic removal efficiencies. Total system hydraulic retention times of 8, 5.5, 4, 2, and 1 hours were employed in this study. All experimental runs presented were at a constant disc rotational speed of 28 rpm. (Although the RBC system was operated at other rotational speeds of 15 and 44 rpm, the results were not significantly different from those at 28 rpm and are therefore not presented.) Upon attainment of nominal steady-state conditions the reactor was sampled at

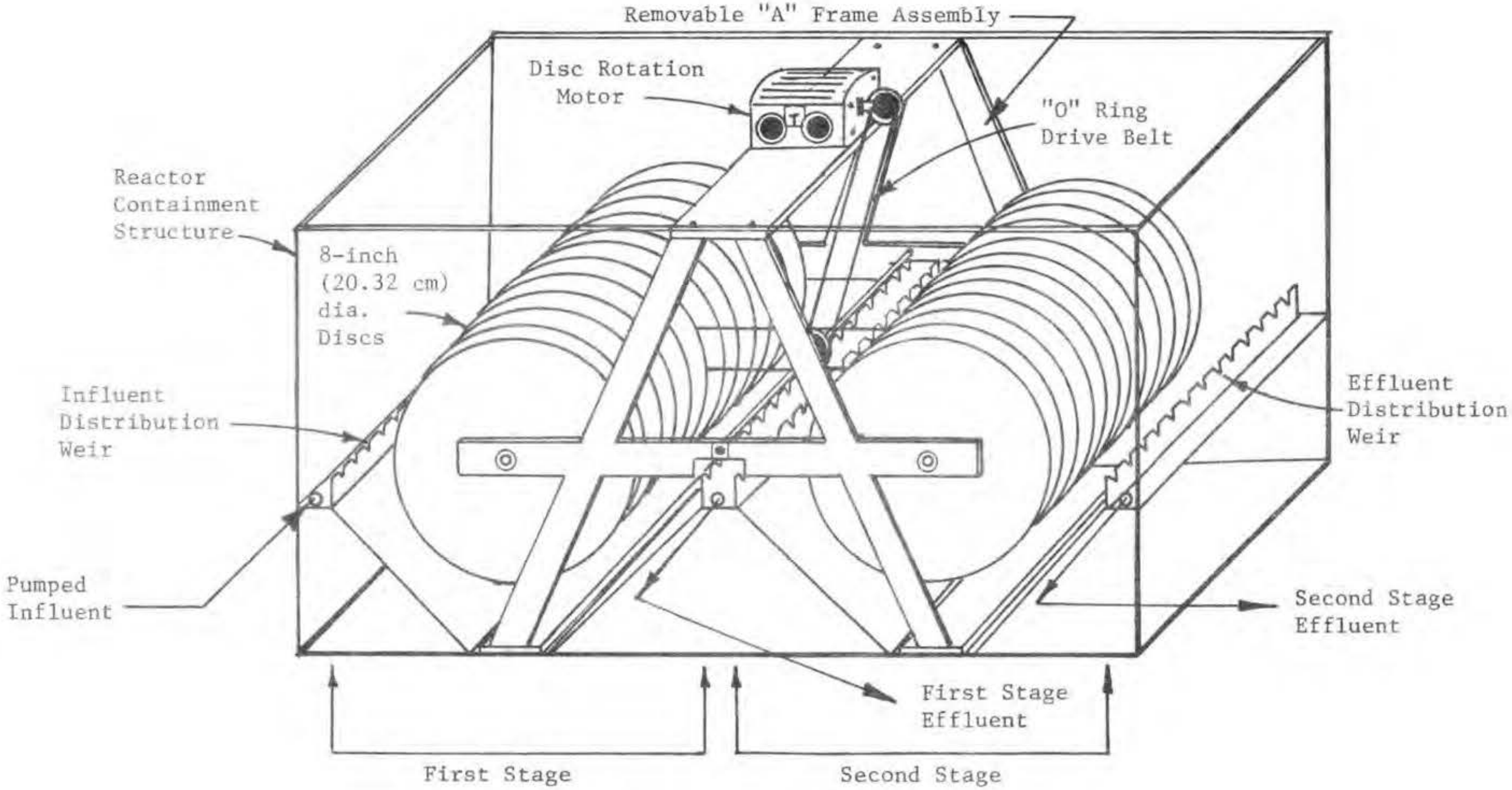


Figure 24. Continuous Flow, Two-Stage Rotating Biological Contactor System Used for Treatability Studies on Shellfish Processing Wastewaters (Plant S1B).

the system influent, first-stage effluent, and second-stage effluent ports. Steady-state conditions were assumed to prevail when two consecutive monitoring samples for organic removal (as COD reduction) and effluent suspended solids were essentially the same (less than 5% difference) when taken at least one theoretical hydraulic retention time apart. Steady-state analyses were performed for BOD_5, COD, pH, TSS, and TVSS. Additionally, for each retention time at nominal steady-state, one disc from each reactor stage was removed, scraped clean, and the scrapings analyzed for TS and TVS. On all except one of the experimental retention time runs, the total solution suspended solids contained in each reactor stage and their associated SVI's were also determined.

At the conclusion of system sampling, the disc assembly was removed and the reactor basin rinsed of biological solids. The disc assembly with its biological film intact from the previous run was then returned to the RBC basins and the wastewater pumping rate adjusted to a new value. Operation of the apparatus proceeded in this manner for collection of all performance data.

All analytical procedures conformed with methods outlined in the 13th edition of Standard Methods (9).

Wastewater Characterization. To determine the nature of the collected wastewater, characterization analyses were performed. Five collections were necessary during the study; four were taken within a month in middle fall and one in middle winter. The characterization results for the four fall sample collections have been previously presented in Table 1 under the collection dates of October 8, 22, 29, 1975, and November 6, 1975. The midwinter sample (collected February 13, 1976) was used to enlarge upon and confirm the results of one of the earlier experimental runs (8-hour total retention time) and was not characterized to the extent of the previous samples. Analyses performed on this sample for soluble BOD_5 and COD, pH, TSS, and TVSS are given in Table 11 under sample date 2-13-76, influent column.

As can be typical of many industrial discharges, the wastewater character was not consistent from sample to sample. This is particularly apparent with those analyses related to organic strength (BOD_5, COD) and solids (TSS, TVSS). In fact, the noted variability lends support to the application of RBC treatment since the fixed-film biomass availability should more efficiently accommodate fluctuating wastewater loadings.

Organic Removal Efficiencies. The primary concern of this study was determination of organic removal efficiencies obtainable with RBC treatment of the shellfish processing wastewaters. Additional regard was given to effluent suspended solids settleabilities as well as estimations of both suspended and fixed-film biomass production. The nominal steady-state RBC performance data for the series of applied hydraulic retention times employed in this study are given in Table 11. The designations for reactor influent, first-stage effluent, and second-stage effluent are given as Inf, Eff-1 and Eff-2, respectively. It should be noted that the hydraulic retention times given are for the total system and that each of the two equal volume stages would individually experience one-half of the stated residence period.

Table 11

Summary of Nominal Steady-State RBC Performance Data During Treatment of Shellfish Processing Wastewater*

Total System Hydraulic Retention Period, hours		1.0			2.0			4.0			5.5			8.0	
Date Wastewater Collected		10-29-75			10-29-75			10-22-75			10-8-75			2-13-76	
Reactor Sample Point	Inf	Eff-1	Eff-2	Inf	Eff-1	Eff-2	Inf	Eff-1	Eff-2	Inf	Eff-1	Eff-2	Inf	Eff-1	Eff-2
Test Parameter**															
Flow, liters/day		256.32			122.40			61.92			44.64			31.68	
Soluble BOD_5, mg/1	119	66	47	151	51	24	400	32	6	505	51	15	295	25	9
Soluble COD, mg/1	193	106	79	253	61	39	603	84	49	867	162	86	520	140	64
pH	7.3	7.7	7.83	7.25	7.72	7.87	6.05	7.63	7.73	5.18	7.43	7.73	6.91	7.87	7.89
Dissolved Oxygen, mg/1	–	3.3	5.3	–	3.5	6.8	–	1.8	6.2	–	3.8	6.5	–	2.7	7.1
Total Suspended Solids, mg/1	84	79	104	33	53	57	87	121	61	187	168	97	65	143	234
Volatile Suspended Solids, mg/1	79	73	98	30	52	54	85	118	61	185	151	95	65	137	229

* Disc rotational speed was at 28 rpm.

** All analytical values shown are averages of tests performed for three samplings taken one hydraulic retention time apart after attaining nominal steady-state conditions.

Removal efficiencies calculated from soluble BOD_5 and COD data from influent to effluent across the two-stage system are shown in Figure 25 as a function of nominal reactor hydraulic retention time. (It should be noted that the use of hydraulic retention time as a system variable is more for convenience than as a regulatory parameter since overall organic removals will be more a function of available contact surface area than displacement time for fixed volume RBC systems. For any fixed system, however, retention time can be readily converted to an area loading term more descriptive and useful for design and evaluation purposes.) It may be readily observed that total removal efficiencies approaching 97% and 92% for BOD_5 and COD, respectively, can be obtained with two-stage RBC treatment of the wastewater.

The relative contributions to overall soluble COD removal efficiency by each of the two stages is shown in Figure 26. The majority (as much as 73% of the total) of removal can be seen to occur within the first stage. However, with decreasing dilution rates (increasing residence time) the first stage appears to exhibit a limited COD removal efficiency, maximizing around 85% then slightly declining, whereas the removal efficiency for the second stage shows a continual, though slight increase.

The decline in system efficiency noted for hydraulic retention periods below two hours is attributable to the increase in organic loading intensities associated with increased dilution rates. In this range the substrate utilization capacity of the system's biomass is exceeded by the hydraulic application rate of organic substrate with a resultant diminishment of overall removal. This points out a limitation on system operation similar to findings documented elsewhere (25,26). The decline in total COD removal efficiency for the first stage at the higher retention times was not attributable to intrinsic system response. An examination of the influent wastewater's BOD_5 to COD ratio for applied retention times above four hours indicated values approximately 67% less than those for the lower retention times. The larger fraction of organic material which was not readily biodegradable most likely resulted in larger amounts of residual or refractory organics (as COD) leading to corresponding lower calculated efficiencies. This premise gains additional support since corresponding filtered BOD_5 removal efficiencies, as indicated in Figure 27, showed no comparable decreases with increasing retention period within the first stage. The drop in second stage soluble BOD_5 efficiency also observed in Figure 27 should not be construed as a basic system phenomena since the BOD_5 concentrations for second stage influent (i.e., first stage effluent) and effluent at the longer applied retention times were not sufficiently high to preclude the inherent low level accuracy limitations of the BOD_5 test.

Several investigators have advocated use of BOD_5 or COD removal efficiency as functions of a hydraulic loading-area parameter (i.e. gallon per day applied per square foot of wetted surface) to provide design criteria for the RBC process (19,23,26,27). In the absence of suitable kinetic expressions allowing rational predictions of system performance, this appears to be sufficiently justified. If given the process performance curve related to applied loadings (gpd/ft^2 or $\ell pd/m^2$) and a design wastewater flow, once an acceptable degree of treatment is selected, disc area requirements can be determined. The performance curve generated for the shellfish processing wastewater is shown in Figure 28 together with several curves developed for other industrial as well as domestic wastewaters

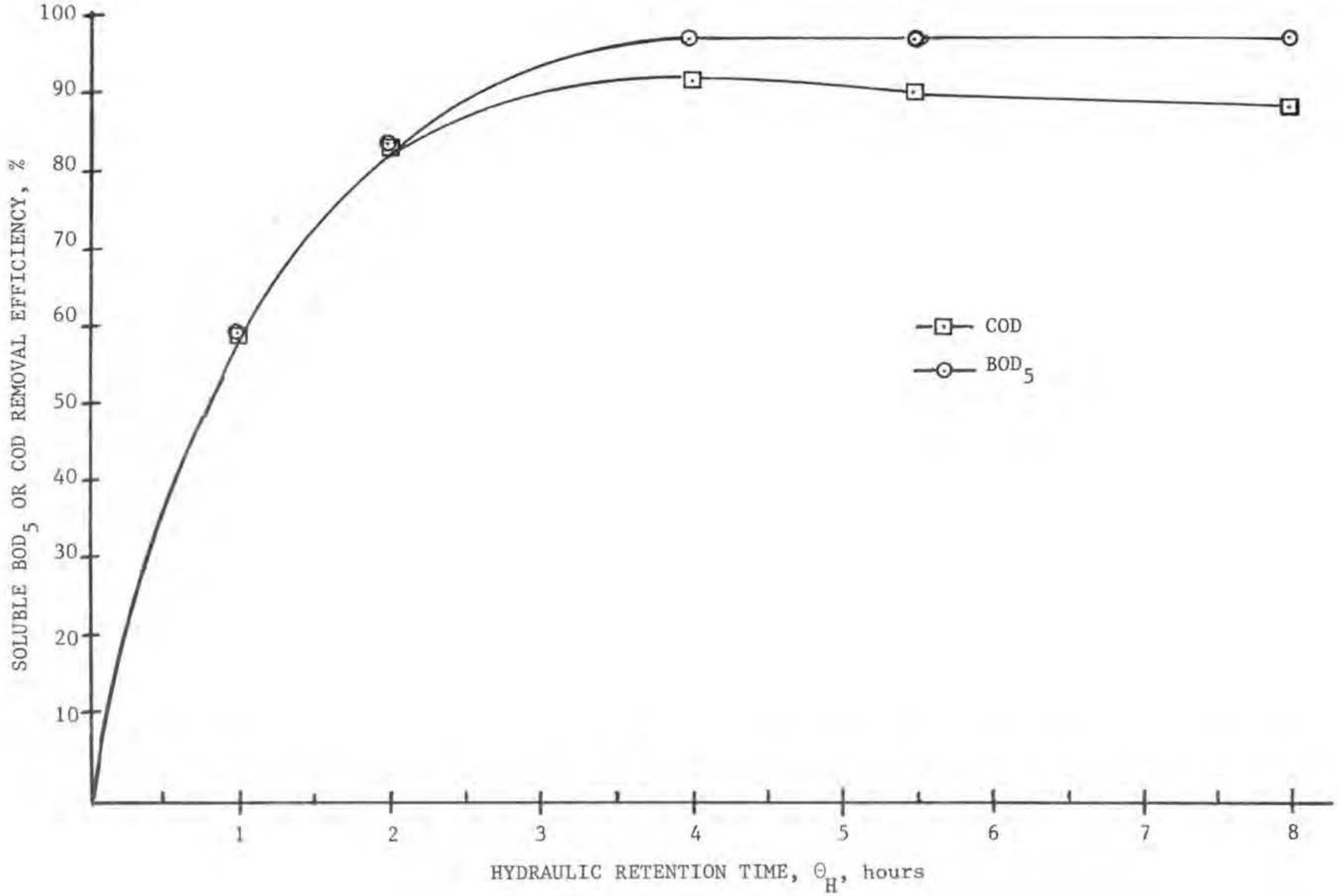


Figure 25. Shellfish Processing Wastewater BOD_5 and COD Removal Efficiency as a Function of Total Hydraulic Retention Time in the Rotating Biological Contactor at 28 RPM.

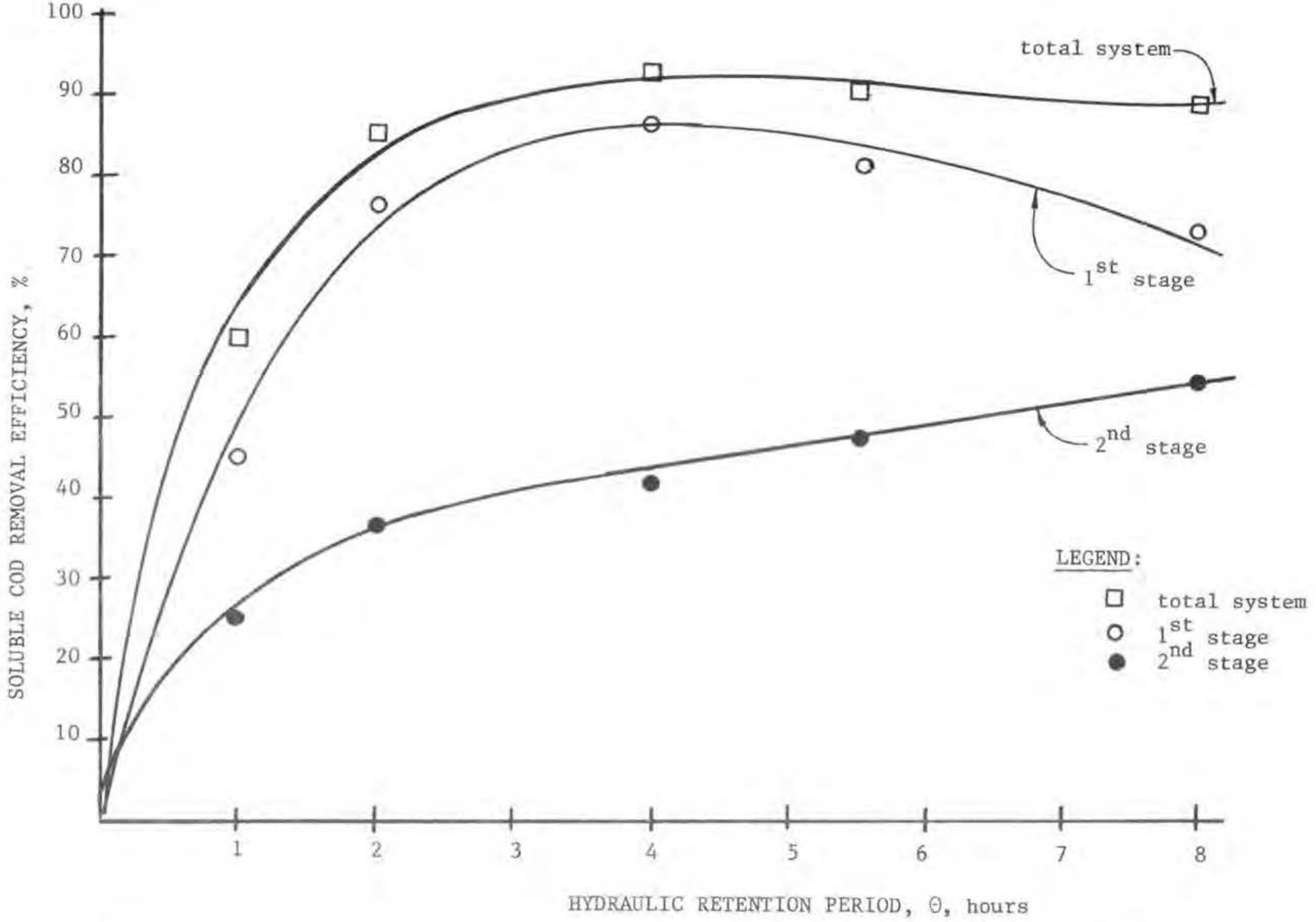


Figure 26. Shellfish Processing Wastewater COD Removal Efficiency for the First Stage, Second Stage, and Total System as a Function of Hydraulic Retention Time in the Rotating Biological Contactor at 28 RPM Disc Rotational Speed.

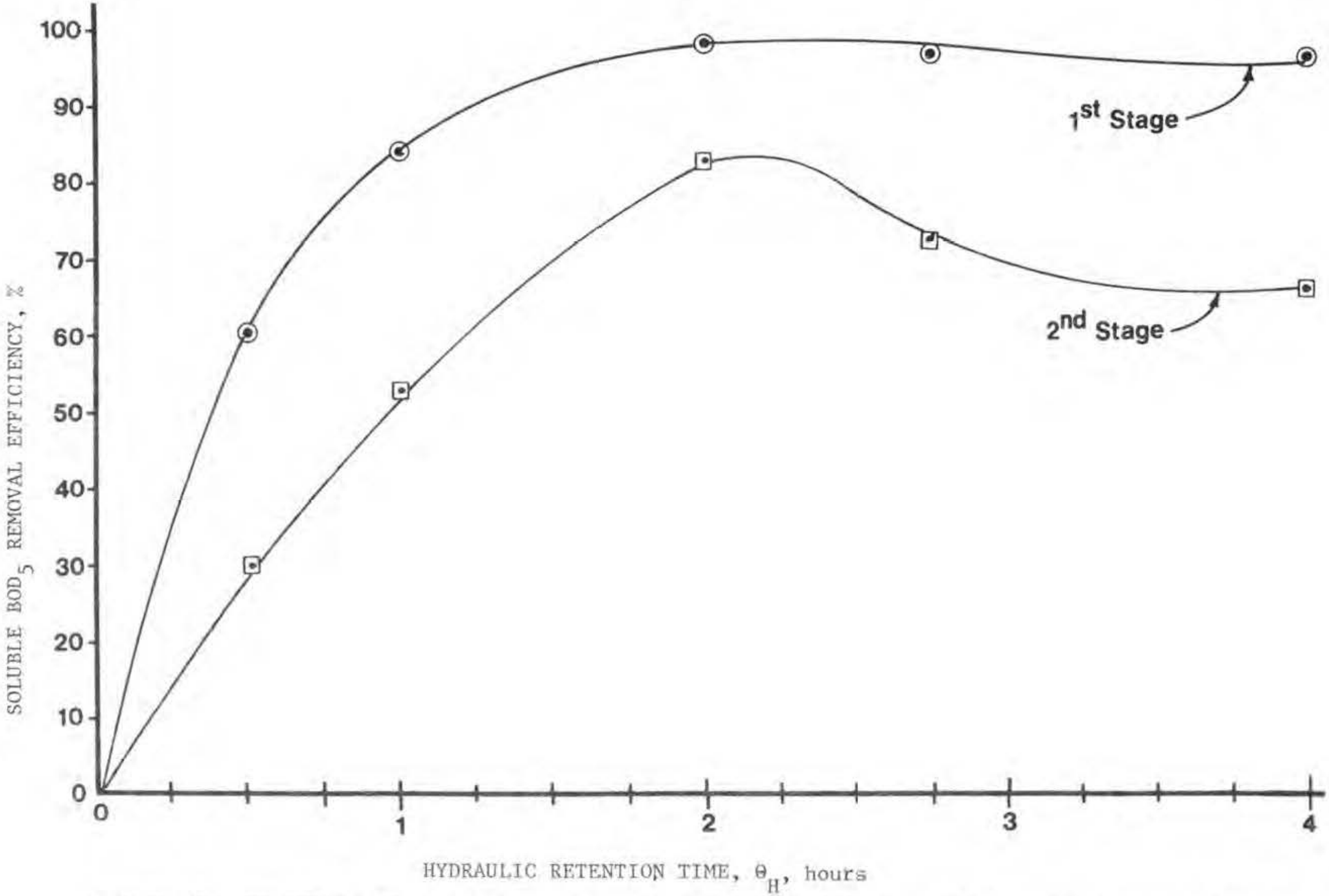


Figure 27. Shellfish Processing Wastewater Steady-State BOD_5 Removal Efficiencies as a Function of System Single Stage Hydraulic Retention Time for the Rotating Biological Contactor at 28 RPM.

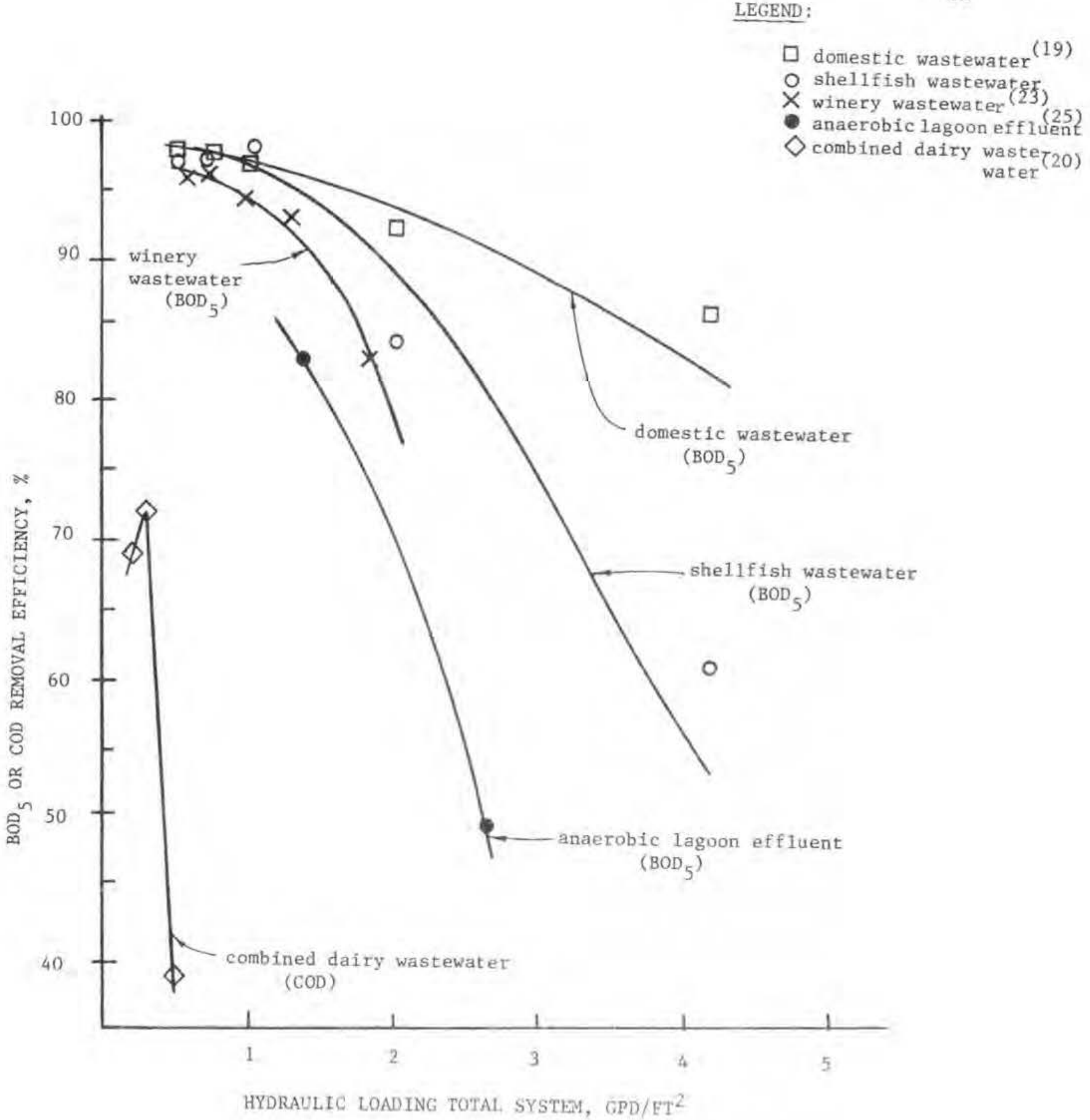


Figure 28. Rotating Biological Contactor Hydraulic Loading versus Removal Efficiency Performance Curves for Selected Wastewaters

reported in the literature (19,20,23,25). The various curves are presented for relative comparison realizing that variables inherent in their formation, such as pH, temperature, number of stages used, etc., could not be normalized. Nevertheless, shellfish processing wastewaters are notably more amenable to treatment at comparable loadings than the other industrial wastewaters indicated, and the application of the RBC process to this wastewater was capable of producing organic (BOD_5) removal efficiencies greater than 90% at loadings near and below 2 gpd/ft^2 (81.5 $\ell pd/m^2$), a result which compares well with that experienced for domestic wastewaters.

Biological Solids Production. Throughout all experimental runs, both reactor stages exhibited flourishing disc growths and relatively significant amounts of sloughed suspended solids. Figures 29 and 30, respectively, indicate the steady-state volatile solids content of the first and second stages. Note that the fixed volatile solids are given as mg/l, a value derived by dividing the total measured disc volatile mass by the stage liquid volume. Total suspended solids were obtained by normal analytical procedures (Standard Methods) using 0.45 μ glass fiber filters following manual homogenization of sloughed solids.

The higher volatile solids (biomass) concentrations occurred at the higher flow rates as would be expected since the biomass would respond to the higher organic loading intensities (increased substrate availability) associated with increased hydraulic loading. This is also apparent when comparing TVS production between the two stages. At any given flow rate the TVS in the first stage are about a factor of three times those of the second stage due to the much larger first stage organic loading.

As might be expected, Figures 29 and 30 indicate a limited fixed-film organism mass evidenced by a relatively constant equivalent suspended solids concentration as organic loading rates increase. This occurs most likely as the final result of oxygen and/or substrate mass transfer limitations through the attached film with a resultant weakening of the cohesive forces between the inactive (or anaerobic) and active biomass allowing for consequent sloughing induced by shearing forces developed by rotational and gravitational effects.

Sloughed Solids Settleability. As with conventional biological treatment, solids produced and escaping from the process must be removed in a manner satisfactory to the maintenance of an acceptable final effluent quality. In order to estimate the relative potential for applying typical solids separation techniques (clarification), the gross parameter often applied to solids settleabilities (Sludge Volume Index (SVI) was determined for the sloughed solids within each stage at each applied hydraulic retention time. The results of the SVI determinations are presented in Table 12. With the exception of the second stage at a flow rate of 29 liters per day, all SVI values were under 100 which would indicate little problem for clarification of the treated shellfish wastewater. Other investigators have found similar settling properties for RBC produced solids when treating other wastewater types (23,28).

Nutrient Variations. The nitrogen species (total Kjeldahl, ammonia, and nitrite-nitrate) and phosphorous (as orthophosphate) concentrations were determined at each nominal steady-state sampling for the system influent, first-stage effluent, and second-stage effluent. These values

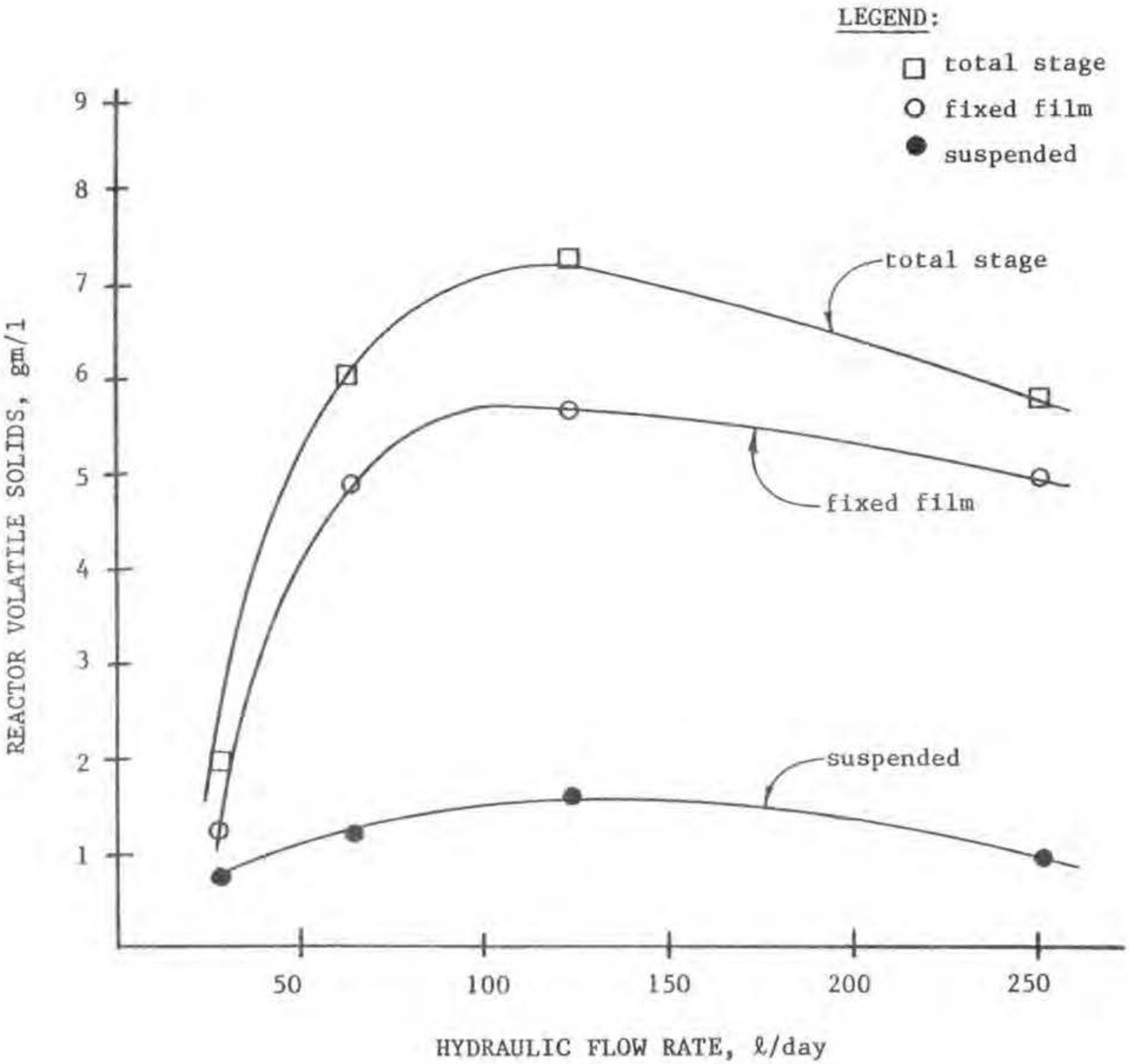


Figure 29. First Stage Biological Solids Production as a Function of Hydraulic Flow Rate in the Rotating Biological Contactor at 28 RPM Disc Rotational Speed.

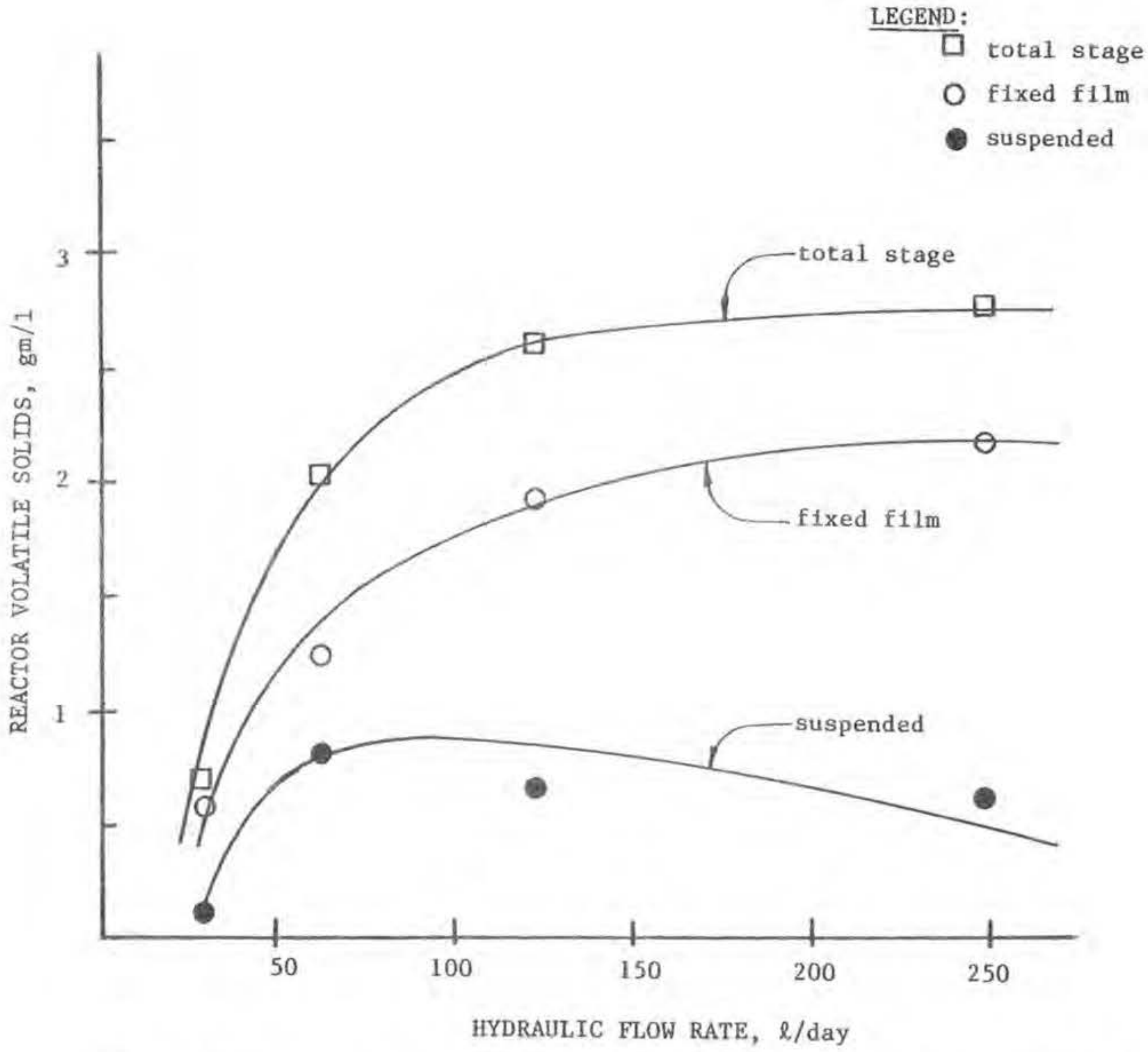


Figure 30. Second Stage Biological Solids Production as a Function of Hydraulic Flow Rate in the Rotating Biological Contactor at 28 RPM Disc Rotational Speed.

Table 12

Sludge Volume Index of First and Second Stage Mixed Liquor Versus Hydraulic Retention Period and Hydraulic Flow in the RBC.

Hydraulic Retention Period, hours	Hydraulic Flow Rate, liters/day	First Stage Settleable Solids, ml/l	First Stage Suspended Solids, mg/l	First Stage Sludge Volume Index, ml/gm	Second Stage Settleable Solids, ml/l	Second Stage Suspended Solids, mg/l	Second Stage Sludge Volume Index, ml/gm
1	256.32	92	1030	89	43	750	57
2	122.40	116	1670	69	51	727	70
4	61.92	112	1273	88	33	870	38
8	31.68	80	885	90	36	150	240

provided confirmation for RBC treatment of the experimental shellfish processing wastewaters without the necessity for nutrient supplementation. The only collected wastewater sample that showed some potential nutrient deficiency was that used for the experimental 8-hour retention time; for that run, no significant loss of organic removal efficiency was noted. Figures 31 and 32 indicate the variations in the nitrogen species and orthophosphate, respectively, in terms of mass rates from the applied influent to each stage's effluent. In most instances a general decrease in nitrogen and phosphorous was observed through the system with the higher fractional removals occurring within the first stage. The noted decreases occur most probably as a result of microorganism synthesis requirements. In only one instance, at the 1-hour applied retention time, was nitrification observed to occur. This was not anticipated for a two-stage system as findings by others (22,28,29,30) indicated nitrification generally occurred only after three to four stages of RBC treatment. In this case, however, nitrification may have been favored since the organics (BOD_5 or COD) to nitrogen (TKN) ratio of the influent wastewater was considerably lower then that of the other applied retention times and may have allowed a more favorable environment for nitrifying organism competition with the heterotrophic population. Under usual operating conditions, however, nitrification would probably not be prevalent for two-stage RBC treatment.

ANAEROBIC FIXED FILM CONTACT PROCESS - ANAEROBIC FILTER

System Description

Results of previous investigations on the anaerobic treatability of shellfish processing wastes by conventional means have been demonstrated as only partially successful. The reasons for observed treatment difficulties have not been thoroughly documented; however, the low loading intensities and associated inability of the biomass to be sufficiently sustained under the periodic application of relatively low strength wastes were suspect. Conventional anaerobic treatment has not normally been successful nor economical for wastes with less than one percent biodegradable material (31). Raw shellfish processing waste effluents characteristically contain only about 0.1 percent biodegradable matter and, therefore, are not well suited for conventional anaerobic digestion.

Considering the character of shellfish processing wastewaters, the fixed-film anaerobic contact treatment process appears to be particularly applicable. Its ability to efficiently accommodate wastes of comparatively low to moderate organic strength by means of, and along with, its high solids conservation capacity may provide a treatment method for the shellfish processing industry which can be both effective and economical.

The fixed-film anaerobic contact process, sometimes referred to as an anaerobic filter, is a relatively new method of wastewater treatment which has been demonstrated to be particularly effective for comparatively moderate strength soluble organic wastes (31,32,33,34). Its configuration is similar to that of conventional aerobic trickling filters using stone contact media; however, the operation and mode of waste stabilization within the anaerobic contact process, by providing upward flow of wastewater through

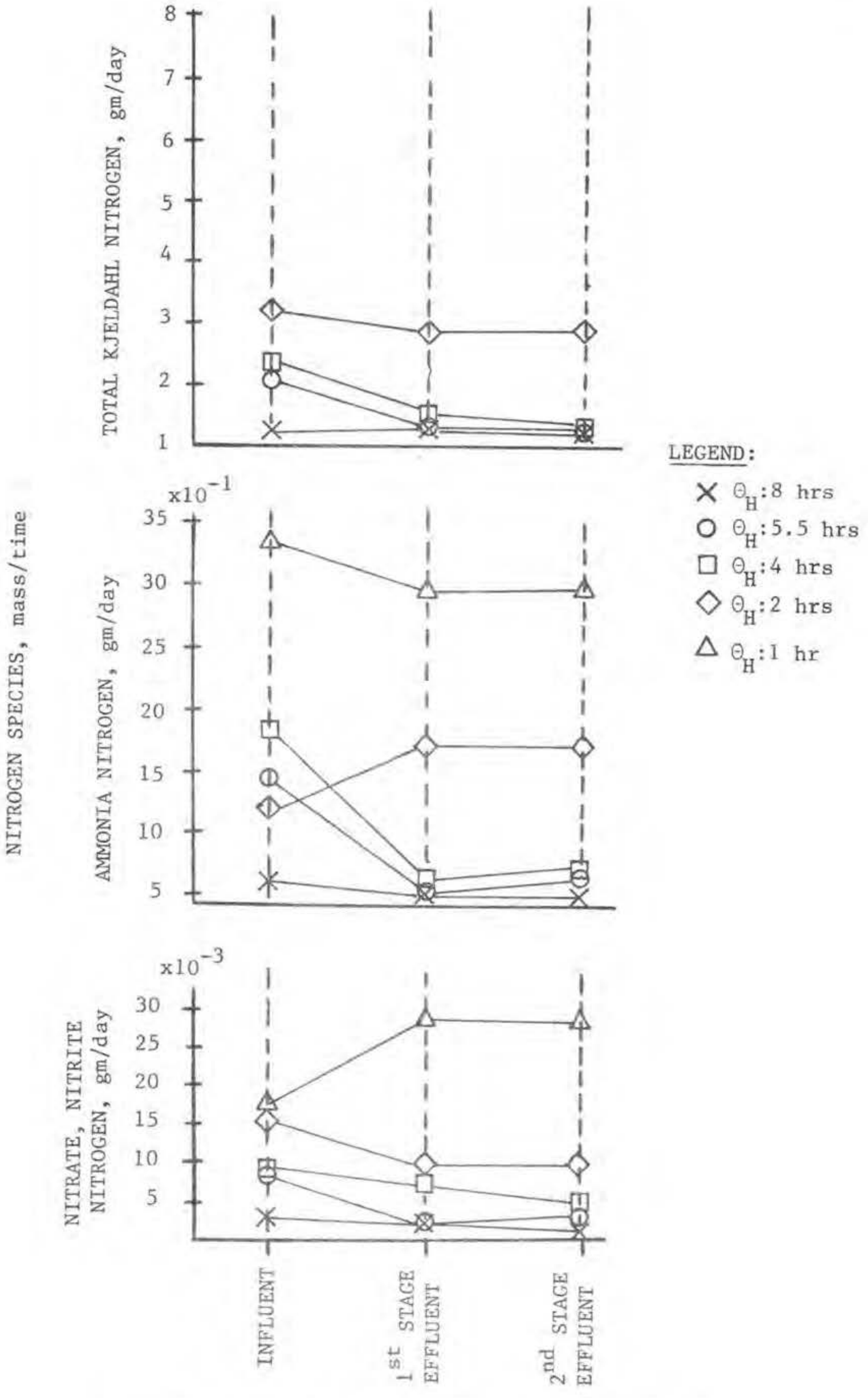


Figure 31. Nitrogen Mass Variation at Each Stage of Rotating Biological Contactor Treatment at 28 RPM Disc Rotational Speed.

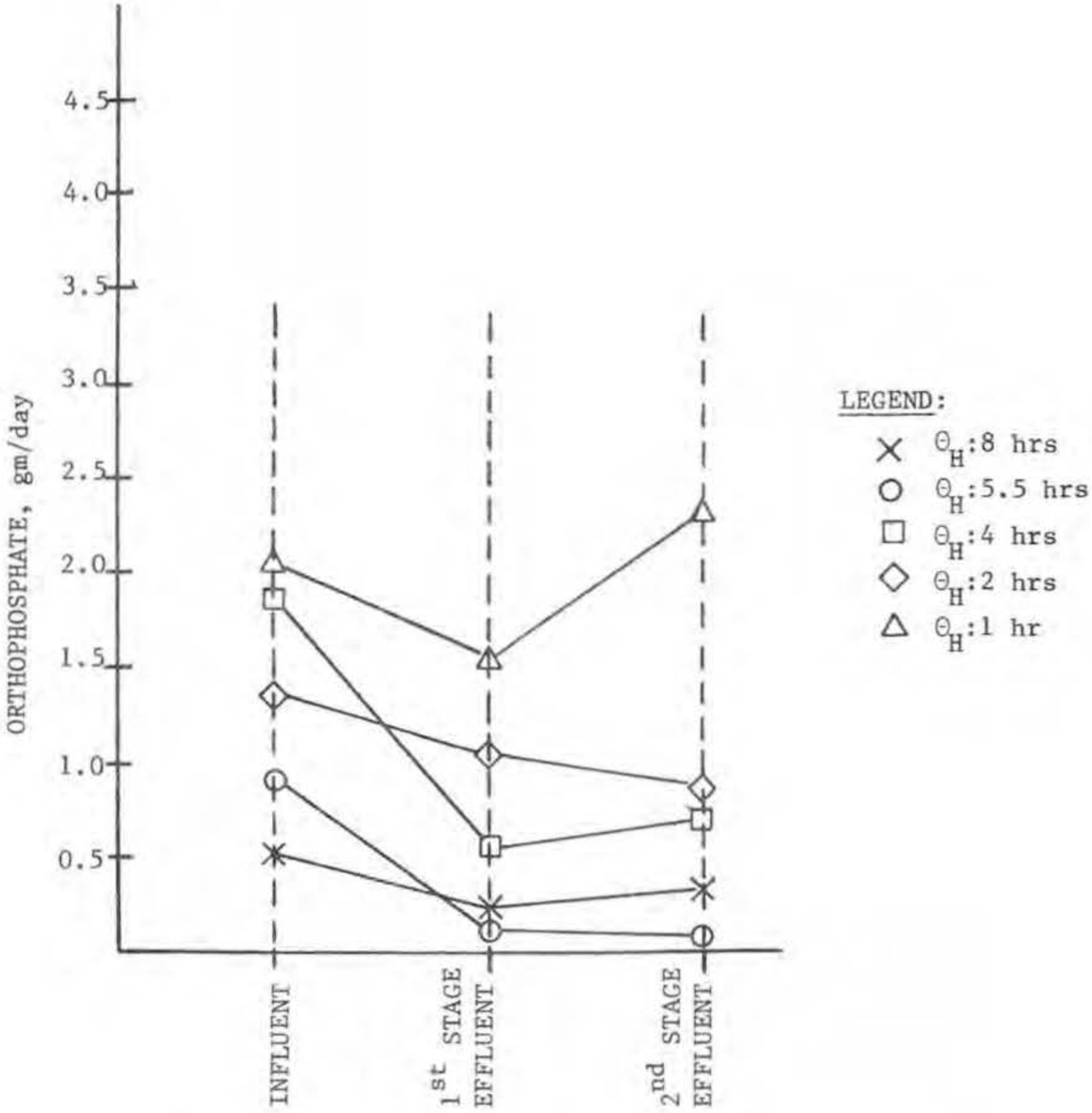


Figure 32. Orthophosphate Mass Variation at Each Stage of Rotating Biological Contactor Treatment at 28 RPM Disc Rotational Speed.

the contact media, completely submerges the filter and thereby allows maintenance of anaerobic conditions. Accordingly, facultative and obligate anaerobic organisms utilize organic substrates as an energy source and tend to accumulate in significant quantities within the void spaces and upon the media. This feature of the anaerobic contact process provides for high solids retention capability as the solids are essentially "trapped" and therefore not normally subject to sloughing and subsequent washout. This phenomenon, coupled with the advantages of the anaerobic waste stabilization process (i.e., low solids production with comparatively high energy utilization and potential for energy recovery as methane), leads to very low effluent solids concentrations and high substrate conversion efficiencies. Consequently, the need for extensive and costly solids separation and recycle facilities may be minimized. The advantages of the anaerobic contact process may be itemized to include (31,35):

1. Suitability of application for treatment of soluble organic wastes
2. Successful operation without effluent or solids recycle
3. Provisions for accumulation of high concentrations of active solids (biomass) in the filter which permits treatment of relatively dilute and fluctuating waste concentrations at ambient temperatures; heating is not required as for conventional anaerobic systems to maintain high system efficiencies
4. Production of very low volumes of sludge with an effluent relatively free of suspended solids; sludge wasting may be minimal and infrequent
5. Simplicity of design, construction, and operation
6. Resistance to short-term shock loadings without significant reduction in efficiency
7. Suitability for treatment of intermittent waste discharges
8. Production of a valuable by-product, methane, as a recoverable energy source

The combined advantages of the anaerobic filter suggest a treatment plant with low maintenance requirements and minimal sludge handling and disposal problems while providing high and economically attainable substrate removal efficiencies.

Experimental System

The bench-scale experimental anaerobic filters consisted of 15.24 cm I.D. by 152.5 cm high plexiglass columns with packed media depths of 128.1 centimeters. Two columns were concurrently operated during each experimental run with a singular wastewater source supplying both columns. A schematic diagram of the two column arrangement is shown in Figure 33. Wastewaters stored in 55-gallon (208-liter) barrels within a refrigerated room maintained at 4°C were delivered to the experimental units by a variable speed bellows pump. A three-way solenoid value was used to split the influent between each of the columns. Actuation of solenoid value was effected by a rotating cam timer assembly which could be incrementally

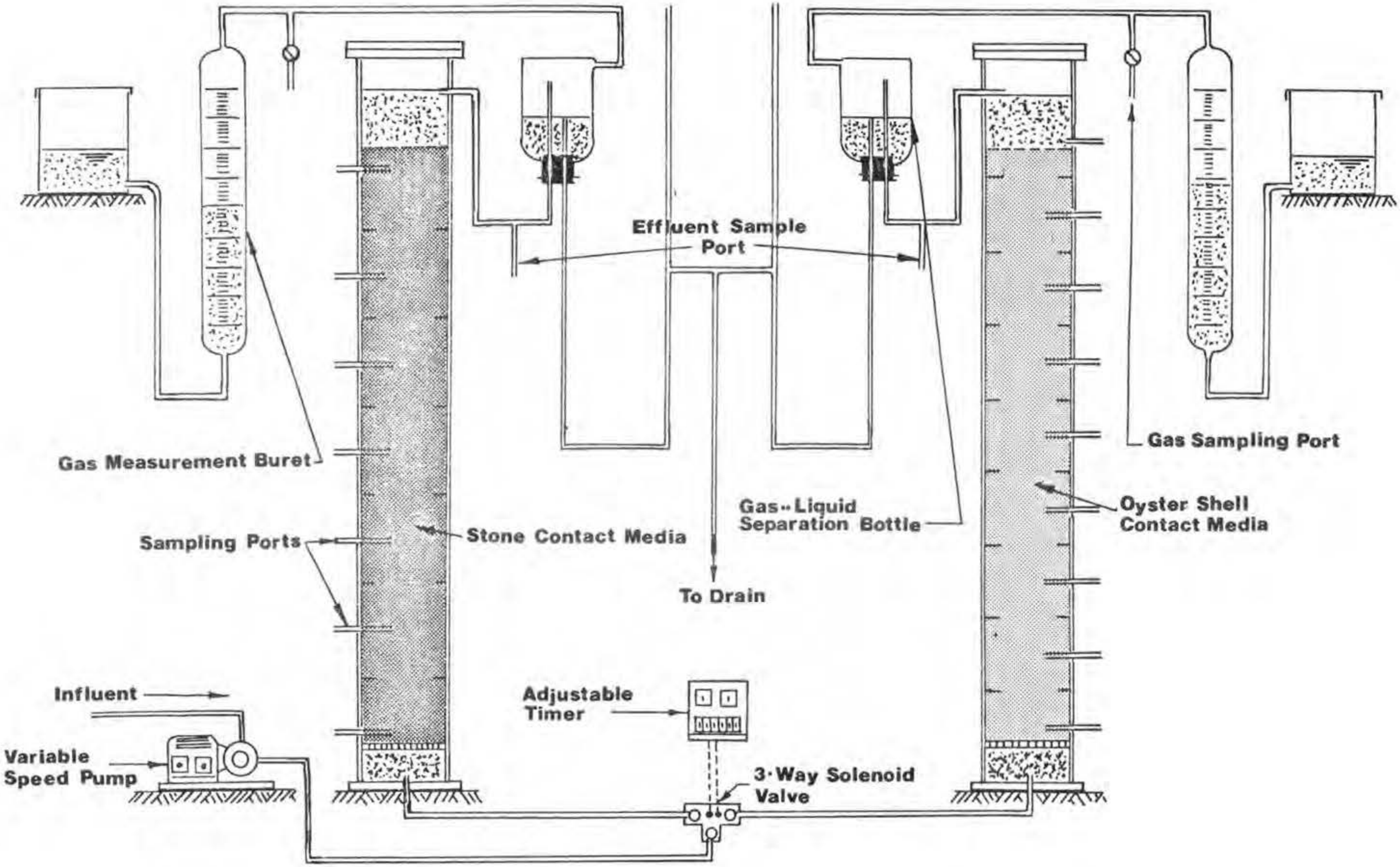


Figure 33. Schematic Diagram of Concurrently Operated Anaerobic Packed Columns with Oyster Shell and Rock Contact Media Used for Shellfish Processing Wastewater Treatability Investigations.

regulated throughout any percentage of its cycle rotation of 2.5 rpm. Thus by setting a pump speed and solenoid actuation time, both columns could be operated concurrently at differing flow rates.

Each column contained a plastic flow distribution plate located at 10 centimeters from the bottom. This plate served to evenly distribute the influent wastewater prior to its contact with the column media. sample ports were located at 15.5-centimeter intervals along the column height.

Gas collection and measurement was facilitated by adaptation of an inverted, stoppered aspirator bottle for liquid-gas phase separation followed by a 2500 ml gas measuring buret.

The column bottom was sealed by a permanently bonded 0.95 cm plexiglass plate while the top was sealed by a fabricated bolted-flange arrangement containing a butyl rubber gasket. Both columns were tested to be air tight under applied pressures as great as 1.76 Kg/cm^2 (25 psi). All sample ports and tubing interconnections, where needed, were sealed with either screw-type hosecocks or glass stopcocks.

Two types of filter contact media were employed for these investigations. One column, designated as column R, contained a rock packing consisting of 2.5-3.8 cm (1½-inch) nominal size granitic stone while the other, designated as column S, contained an oyster shell packing which came from waste shells secured from the southern Georgia coastal region. Both media types were thoroughly washed and rinsed prior to placement within the columns.

The use of the oyster shell packing for the anaerobic filter represents a unique feature which may hold some specific system advantages compared to other packing types available. The anaerobic contact process relies upon the metabolic action of certain microorganisms which require relatively restrictive environmental conditions. One environmental condition of great importance is the maintenance of an optimum pH within a rather narrow range. In most anaerobic systems, pH levels are maintained within acceptable limits through the action of the natural carbonate-bicarbonate buffering system. However, certain conditions related primarily to substrate constituents or loading intensity may stress the natural buffering capacity to exhaustion and lead to subsequent pH levels deleterious to continued pollutant removal efficiencies. When this occurs, either modifications in substrate loading intensities are made or chemicals are administered in an attempt to reestablish requisite pH levels.

Any material in the anaerobic environment which could enhance the buffering capacity would be advantageous to satisfactory system performance during periods of stress. The use of oyster shells, considering their high carbonate content, may well serve as an important addition to an anaerobic system's bicarbonate buffering capability. Moreover, the anaerobic filter provides a unique opportunity for the use of waste oyster shells as contact media thereby decreasing installation costs for coastal processors.

Experimental Procedures

Following random packing, the filter media of each column were flushed and rinsed to remove any residual fines. During this period the porosities of the packing materials and total reactor liquid displacement volumes were determined. From measurements of time-distance relationships for a given flow rate within each column as well as determination of drainage volumes, the average porosities were determined to be 0.82 and 0.53 for the oyster shell column (Column S) and the rock column (Column R), respectively. The corresponding actual reactor liquid volumes for Column S and Column R were 18.46 liters and 12.51 liters, respectively, calculated on the basis of a total empty column volume of 22.51 liters. The actual void volumes calculated were then used in determining reactor liquid residence times for the flow rates applied to each column. As with previous investigations, various applied hydraulic retention times, which could be directly related to loading intensities, were employed as the major system variable allowing process performance comparisons and evaluations.

The initial phase of the anaerobic column investigatory effort involved start-up. Development of an anaerobic biological population within each column was accelerated by the addition of five liters of fresh anaerobic digester sludge collected from the R. M. Clayton plant in Atlanta, Georgia. After seeding with the digester sludge, settled shellfish processing wastewaters were administered at the incremental rate of two liters per day in each column. At this preliminary loading, the gas production rates were initially erratic and 22 days of operation were required before some stability in gas productivity and corresponding methane formation were noted.

Once methane formation was accruing on a regular basis, the influent wastewater flow rate for each column was increased to provide the upper hydraulic retention time used in these studies and, as such at that point, signified the beginning of the first test run. Influent flows were then maintained constant to provide for the selected reactor residence time (based on column void volume) until some nominal steady-state condition, as evidenced by reasonably unvarying system gas production rates and COD removal efficiencies, was obtained for both column reactors. Samples of reactor influent and effluent, sequentially taken at times separated by one theoretical hydraulic residence time, were used to determine the approach and attainment of the approximate steady-state conditions. Once a nominal steady-state gas production and COD removal percentage was apparent, the columns were incrementally sampled along their heights to evaluate the possible stratification of organics, volatile fatty acids, total alkalinity, pH, temperature and nitrogen. After sampling, the influent flow rate was set and maintained to provide a lower hydraulic retention time (increased organic loading intensity) until nominal steady-state once again ensued. Three hydraulic residence times were applied to each column in the course of experimentation. For the oyster shell column (Column S), hydraulic residence periods of 3.10, 1.60, and 0.33 days were employed. The rock filled column (Column R) was operated at correspondent residence times of 2.51, 1.68, and 0.35 days. Selection of these operating residence periods was based upon the range of values for which successful wastewater treatment had been reported in the literature (31-34).

At the beginning of each test run (change in hydraulic retention time), the gas collection system and head space for each column was flushed with nitrogen gas to insure that no air contamination would prevail, or if it did, that it could be adequately monitored until corrected. Once a reasonably steady gas production rate was noted, the gas collection system was again flushed with nitrogen. This procedure allowed for estimations of actual methane production within the columns by relating the time change in measured gas (methane) compositions in the collection systems to theoretical dilution patterns expected from the daily gas wastage. This was accomplished by bringing the liquid in the collection burets to equal levels each day by releasing a measurable quantity of gas, assuming that the percentage of methane in the total gas produced each day was constant, a reasonable assumption for conditions of steady gas production rates.

For each test run performed, data were collected to provide for the evaluation of: 1) total treatment efficiency; 2) wastewater quality changes with column height; 3) gas quantities and composition; 4) internal environmental conditions of pH, temperature, alkalinity, etc. with column height; and 5) suspended solids concentrations escapting the system as well as their profile along the column. Analytical procedures followed methods outlined in Standard Methods (9), except for volatile acids which were determined using a Hewlett-Packard Model 5771A Gas Chromatograph and gas analyses which were determined with a Fisher Model 25V gas partitioner.

Experimental Results and Discussion

The packed columns were operated at each hydraulic retention time until some degree of equilibrium or nominal steady-state performance was evident. Normally, such conditions did not prevail until after 10 hydraulic retention periods of time had elapsed. Influent and effluent COD values were monitored during the transitory period with samples taken at least once every hydraulic retention time apart. Gas production was monitored on a daily basis. Since the intent of these studies was to establish the overall feasibility of the anaerobic packed bed for treatment of shellfish processing wastewaters, transitory data for COD removals are not presented. However, daily gas production can present information indicating the establishment of equilibrium within the operating system and may also demonstrate system stability and response under variable influences that can alter approaches to steady conditions.

The daily gas production data for Columns S and R during operation at the respective retention times of 3.10 and 2.51 days are presented in Figure 34. It should be mentioned that these data do not coincide on the time axis with initiation of wastewater application. Nine days of system operation had occurred before the initial gas measurement shown in Figure 34 was taken. Gas measurement and sampling were started after the appearance of at least 3% methane in the gas phase at which time the gas collection system was purged with nitrogen gas and regular measurements were recorded thereafter. Figure 34 emphasizes two observations of interest which are reflective of system response to variable wastewater input and short-term periods of inoperation. It is readily apparent that, with the introduction of wastewater from a freshly collected sample on day 14, gas productivity rapidly increases, taking but two days to reestablish levels observed previously. In addition, following a 3-day period (days 20 to 23) of system inoperation due to a pump malfunction, the gas production rapidly reached normal levels upon restart. This points out an obvious advantage in the operation of this type of wastewater treatment method as it appears quite capable of accommodating fluctuating wastewater character and temporary periods of shutdown. This feature is even more apparent in

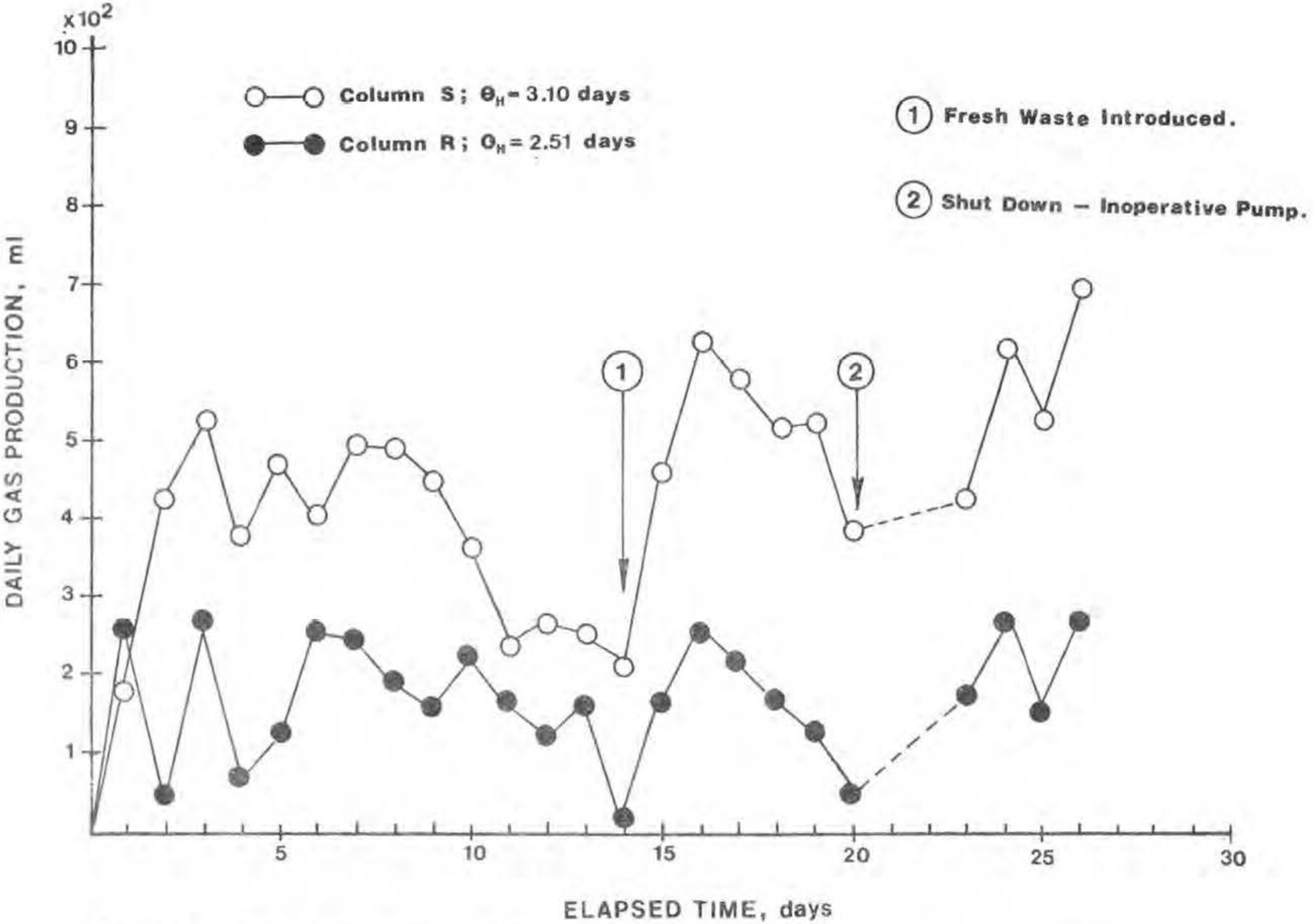


Figure 34. Daily Gas Production for the Oyster Shell (Column S) Operated at 3.10 days and the Rock Column (Column R) at 2.51 days Hydraulic Retention Times.

Figure 35 which gives daily gas production for Columns S and R operated at respective retention times of 1.60 and 1.68 days. These data were generated commencing three days after adjusting the flow rates to produce the new residence times. Reasonably steady gas production was noted up to day 19, at which time the wastewater supply on hand was exhausted. A fresh batch of wastewater was then collected and flow reestablished after five days of reactor shutdown. System response to the fresh loading was dramatic, with gas production immediately reaching levels higher than those for the preceding period and, after three days, rapidly increasing to the highest levels noted throughout these investigations.

To provide better for estimations of nominal steady-state gas production, the data shown in Figures 34 and 35 were plotted on a cumulative basis. This technique allows for weighted averaging of the noted daily fluctuations apparent from the figures. Linear portions of the cumulative gas production versus time plots shown in Figure 36 would be indicative of steady-state conditions. It may be noted that each of the curves shown exhibit periods of steady gas production with inflections corresponding to the times when either inoperation or wastewater character shifts accrued. Nominal steady-state conditions were assumed when such linearity prevailed correspondent to constancy of COD removal efficiencies over at least one hydraulic retention period. Since 3.10 days was the longest retention time employed in these investigations, four days of data collection to confirm steady operation was considered sufficient before complete profile sampling was done. The last four days of each of the curves in Figure 36 were used as indications for equilibrium conditions since they demonstrated linearity for the applied loadings. The relative rates of gas production were then estimated from the slopes of these linear portions for the respective applied column retention periods. Therefore, the nominal steady-state gas production rates observed prior to column profile sampling were approximately: 1) 620 ml per day for Column S at a 3.10-day retention time; 2) 240 ml per day for Column R at a 2.51-day retention time; 3) 1915 ml per day for Column S at a 1.60-day retention time; and 4) 1230 ml per day for Column R at a 1.68-day retention time.

The gas production data are not presented for either Column S or R operated at respective retention periods of 0.33 and 0.35 days. It was anticipated that process performance at these loadings would be poor and thus demonstrate a system operational limitation. Moreover, logistic and economic restraints precluded acquisition of sufficient wastewater to accommodate an extensive run time at these loadings; therefore, the remainder of the wastewater used for the previous experimental run was used until exhaustion. Enough wastewater was available to provide for nine hydraulic turnovers which allowed for only three days of gas data collection. This limited amount of data was erratic and considered insufficient to enable assurance of steady conditions. That process performance suffered at these high hydraulic loadings was suggested, however, by a significant decrease in gas productivity and methane content over the three days of operation.

Gas quantity measurements are useful for determining system response to and biological conversion of applied waste loadings, but of equal importance is the gas quality, particularly its methane content, which relates to its usefulness as a potentially recoverable by-product. Using an incremental analysis of daily methane production related to what would

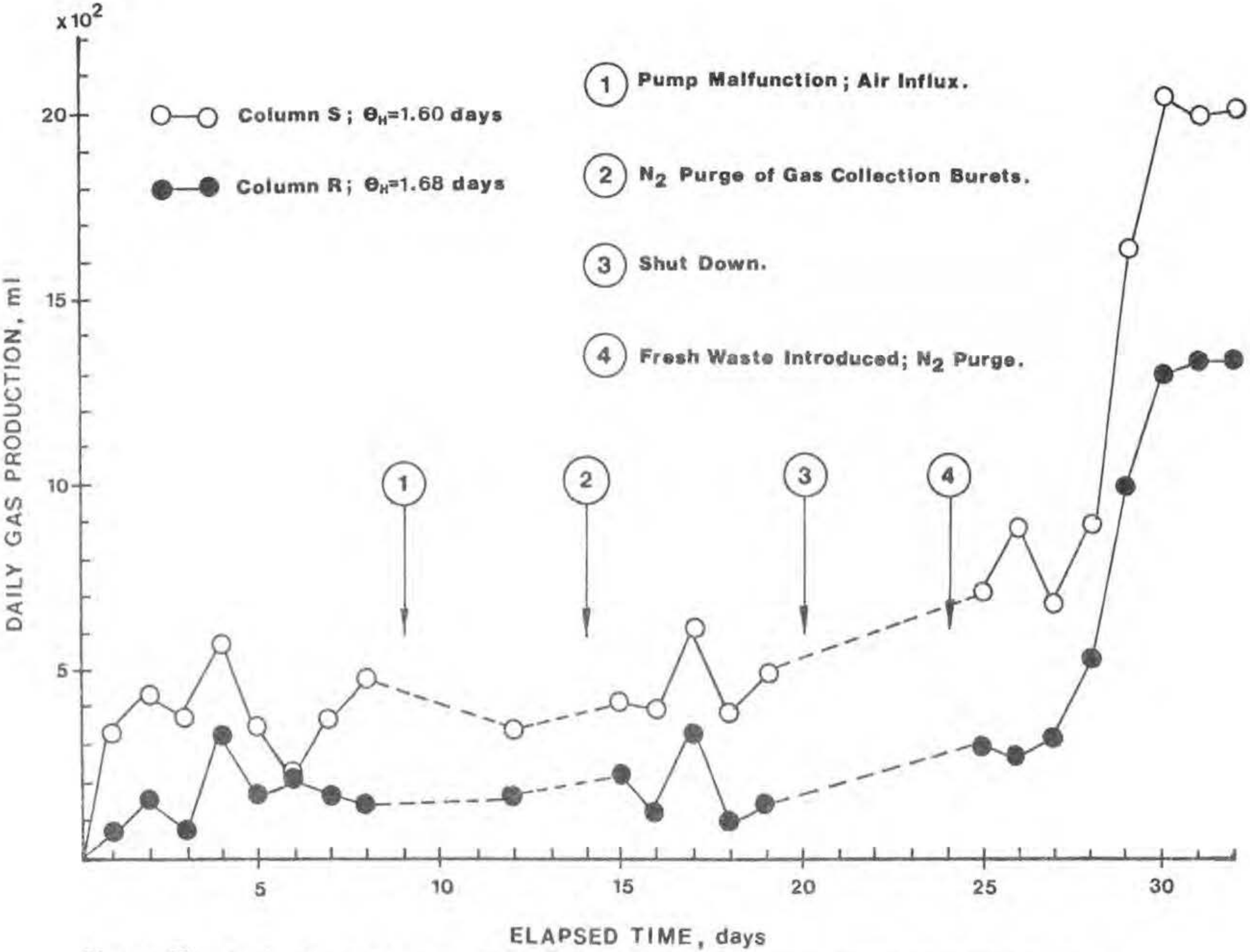


Figure 35. Daily Gas Production for the Oyster Shell Column (Column S) Operated at 1.60 days and the Rock Column (Column R) at 1.68 days Hydraulic Retention Time.

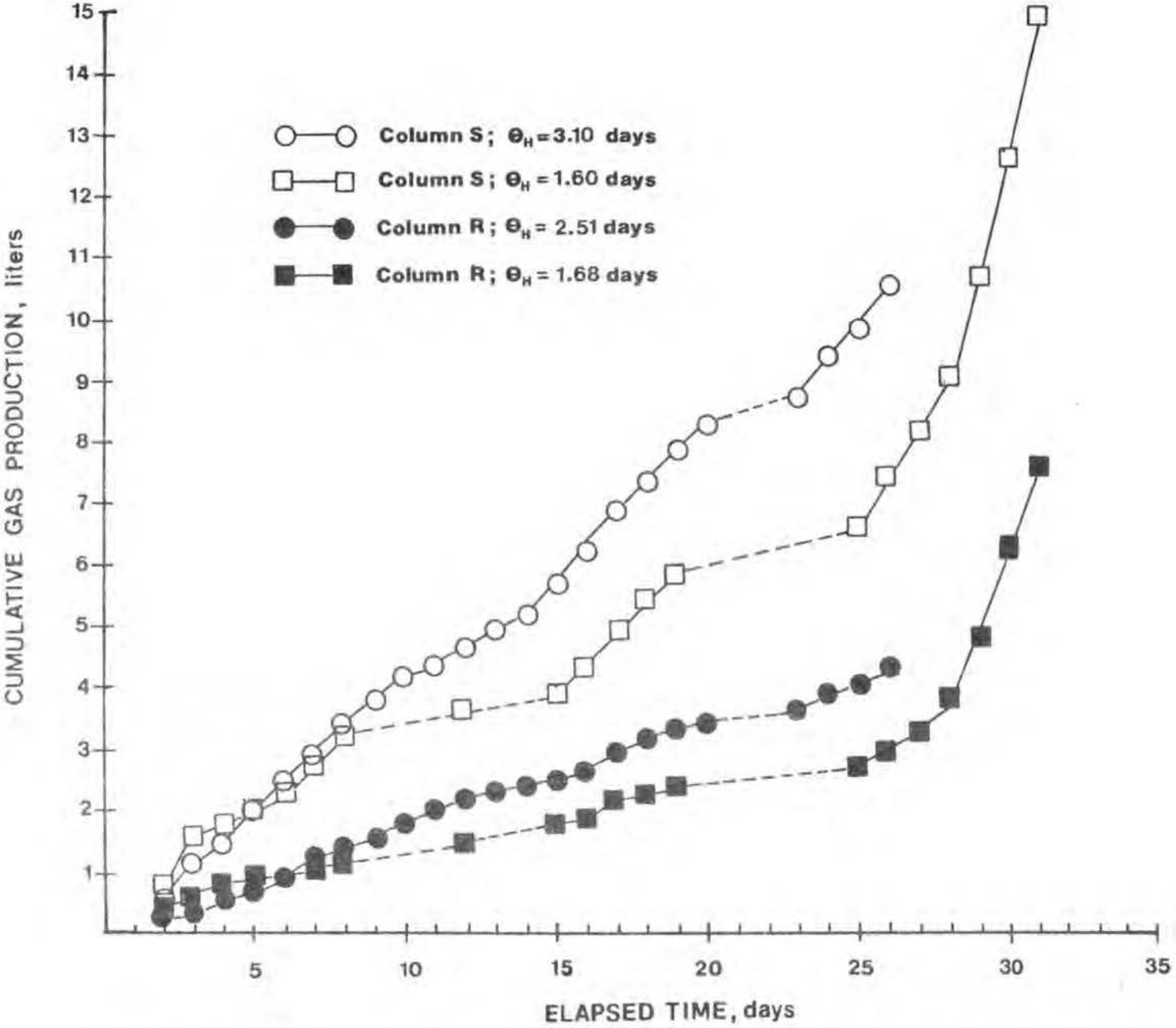


Figure 36. Cumulative Gas Production for the Oyster Shell Column Operated at 3.10 and 1.60, and the Rock Column at 2.51 and 1.68 days Hydraulic Retention Times.

be expected for a normal dilution pattern in the gas collection system with an initial gas composition of 100% nitrogen, the percentage of methane evolved in the reactor gas could be determined. The nominal steady-state methane fractions in the gas phases for Column S operated at retention times of 3.10 and 1.60 days were 85% and 88%, respectively. Similar determinations for Column R yielded 62% and 73% methane for the respective retention times of 2.51 and 1.68 days. These values are indicative of a high quality gas, in terms of methane production, which could be beneficial as a recoverable energy by-product.

Once nominal steady-state conditions had been established, the columns were sampled along their height to provide some indication of possible profiles of organic conversions, suspended solids content, pH and temperature changes, etc. This allowed an estimation of bioconversion locations and provided insight as to possible operational needs which could influence any final engineering design and/or application. The data collected for the three hydraulic retention times employed with Column S are presented in Tables 13, 14, and 15. The data contained in these tables emphasize several important aspects which merit additional comment. At all retention times, the pH of the column environment remained close to 7.0 which is normally considered near optimum for methanogenesis. This is important in an operational sense since the requirement for chemical buffering additives would appear to be unwarranted for treatment of these wastewaters. In addition, the effluent suspended solids concentrations are quite low, suggesting that minimal solids handling appurtences would be required. As expected, the suspended solids concentrations are higher in the lower portions of the column where the majority of biological activity occurs. Flow rate effects on effluent solids values are apparent by comparing the results of Table 15 to both Tables 13 and 14. Although not significant in terms of nominal differences, the concentration of effluent solids for the 0.33-day retention time is almost twice the value noted for the other experimental runs. For field-scale operations, this occurrence may scale up to significant proportions and thereby lead to an operational limitation regarding hydraulic loading rates.

Table 13 values for total nitrogen and orthophosphate along the column show that ample amounts of these nutrients prevailed within the system. The low uptake of nitrogen, which mostly occurred in the bottom of the column, corresponds to the low biomass production characteristic of anaerobic systems. The data indicate that supplemental nutrient additions probably would not be required for successful wastewater stabilization by this treatment method.

It is interesting to follow the calcium profile within the oyster shell column. In all instances a notable increase in soluble calcium occurred along the column. This would be expected under the environmental conditions imposed by an anaerobic system containing a contact media with a high calcium content such as oyster shells. More importantly, it may be assumed, although not particularly well verified by the alkalinity results, that associated with calcium dissolution is a correspondent release of carbonate which could materially enhance system stability and performance.

For the Column S profile of volatile acids, it was expected that they would exhibit a peak concentration somewhere above, but near, the column bottom as a result of initial and relatively rapid wastewater organics

Table 13

Profile of Nominal Steady-State Analytical Results for the Oyster Shell Column Operated at a 3.10-day Hydraulic Retention Time

	Column Height, centimeters										
Analyses	0 (Influent)	5.5	21.0	38.0	51.5	63.5	82.0	94.5	112.5	124.5	145.0 (Effluent)
pH	7.24	7.02	7.10	7.10	7.05	7.05	7.09	7.05	7.07	7.10	7.29
Total Chemical Oxygen Demand, mg/l	466	325	261	176	188	157	196	116	118	122	90
Filtered Chemical Oxygen Demand, mg/l	404	251	180	149	147	123	107	107	83	107	79
Total Suspended Solids, mg/l	18	36	28	26	66	24	48	24	24	18	8
Total Volatile Suspended Solids, mg/l	-	36	28	26	58	20	48	20	-	12	7
Temperature, °C	20.6	23.0	23.0	23.6	24.0	24.2	24.5	25.1	25.5	26.0	-
Total Alkalinity, mg/l $CaCO_3$	454	454	486	491	486	416	459	437	454	437	459
Total Nitrogen, mg/l N	79.3	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	72.9	69.4
Orthophosphate, mg/l $PO_4^{\equiv}$	8.2	8.2	8.2	8.4	8.4	8.4	8.4	9.5	8.8	8.8	9.5
Calcium, mg/l Ca^{++}	32	33	35	35	35	35	35	38	39	40	40
Magnesium, mg/l Mg^{++}	19	20	20	21	21	23	23	22	22	22	22
Sodium, mg/l Na^{+}	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2
Acetic Acid, mg/l	105	95	75	72	85	72	84	72	74	83	83
Propionic Acid, mg/l	10	20	15	15	15	15	15	15	15	15	10
Butyric Acid, mg/l	0	0	0	0	0	0	0	0	0	0	0

Table 14

Profile of Nominal Steady-State Analytical Results for the Oyster Shell Column Operated at a 1.60-day Hydraulic Retention Time

	Column Height, centimeters										
Analyses	0 (Influent)	5.5	21.0	38.0	51.5	63.5	82.0	94.5	112.5	124.5	145.0 (Effluent)
pH	7.02	6.92	7.00	7.02	7.01	7.09	7.04	7.04	7.08	7.05	7.21
Total Chemical Oxygen Demand, mg/l	407	372	361	301	312	143	116	116	120	116	102
Filtered Chemical Oxygen Demand, mg/l	357	384	282	222	213	120	111	93	79	79	70
Total 5-day Biochemical Oxygen Demand, mg/l	310	265	218	205	102	81	-	70	-	64	58
Filtered 5-day Biochemical Oxygen Demand, mg/l	282	210	150	142	68	48	-	38	-	38	35
Total Suspended Solids, mg/l	12	33	43	24	28	10	10	11	12	9	9
Total Volatile Suspended Solids, mg/l	11	30	30	19	24	10	10	11	10	9	9
Temperature, $^{\circ}$C	18.5	19.5	19.8	20.5	21.0	21.8	22.0	22.5	23.0	23.5	23.5
Total Alkalinity, mg/l $CaCO_3$	270	292	329	351	378	373	400	389	410	416	427
Calcium, mg/l Ca^{++}	19.2	18.2	20.0	20.0	20.0	22.4	22.8	22.8	22.8	22.8	22.8
Magnesium, mg/l Mg^{++}	23.0	22.8	22.6	22.7	22.3	22.3	21.2	20.7	20.0	20.0	20.0
Acetic Acid, mg/l	51	63	105	89	66	41	35	35	35	30	21
Propionic Acid, mg/l	20	21	0	0	0	0	0	0	0	0	0
Butyric Acid, mg/l	11	12	0	6	8	5	0	0	0	0	0

Table 15

Profile of Analytical Results for the Oyster Shell Column Operated at a 0.33-day Hydraulic Retention Time

Analyses	Column Height, centimeters										
	0 (Influent)	5.5	21.0	38.0	51.5	63.5	82.0	94.5	112.5	124.5	145.0 (Effluent)
pH	7.13	7.19	7.15	7.20	7.11	7.11	7.09	7.11	7.12	7.11	7.18
Total Chemical Oxygen Demand, mg/l	121	132	126	91	89	89	87	87	87	80	66
Filtered Chemical Oxygen Demand, mg/l	89	91	88	81	72	63	59	68	78	73	43
Total Suspended Solids, mg/l	39	36	27	20	18	19	18	16	16	18	16
Total Volatile Suspended Solids, mg/l	32	31	25	19	18	16	15	13	14	18	16
Temperature, °C	9.8	12.0	13.8	15.0	16.0	17.0	18.0	19.0	20.3	21.0	22.3
Total Alkalinity, mg/l $CaCO_3$	194	194	205	216	238	249	254	254	265	265	265
Calcium, mg/l Ca^{++}	36	36	36	37	37	37	37	40	40	41	43
Magnesium, mg/l Mg^{++}	24	24	23	24	23	23	22	22	22	22	22
Acetic Acid, mg/l	56	42	72	57	45	45	51	48	46	43	41
Propionic Acid, mg/l	18	0	0	8	11	0	0	0	0	0	0
Butyric Acid, mg/l	0	0	0	0	0	0	0	0	0	0	0

conversions to fatty acids. Figure 37 presents the plotted data for specific volatile acids profiles in Column S for each of the three applied retention times. It is apparent that at the lowest laoding (3.10-day retention time) the volatile acids in the influent wastewater were being metabolized through methane fermentation immediately upon introduction to the column. At the intermediate loading (1.60-day retention time), a net production of volatile acids can be seen for the first 25 cm of the column with subsequent reductions through the remaining height. Why the volatile acids, acetic and propionic, did not drop to the lower levels anticipated for the 3.10-day retention time could not be explained readily. Possibly the column biomass, although thought to have been given sufficient time for acclimation prior to initiation of this first run, could not satisfactorily accommodate the wastewater initially administered. That a combination of wastewater character and biomass incompatibility may have been causative is suggested by both the fluctuating acetic acid concentrations with column height and the relatively constant levels of propionic acid from influent to effluent.

Column R profile data for the applied retention times of 2.51, 1.68 and 0.35 days are given in Tables 16, 17, and 18, respectively. Patterns similar to Column S profile analyses are noted; however, the magnitudes of values are significantly different in several instances, particularly regarding organic removal efficiencies. These differences are addressed in the following section.

Comparison of Process Performances for the Oyster Shell and Rock Columns

It can be noted from Tables 13 to 18 that the process performance of the oyster shell column is almost categorically better than that of the rock column. Both columns were operated with similar hydraulic flows for each concurrent experimental run. Moreover, the organic loading for each column was essentially the same. The total applied COD in terms of pounds per thousand cubic feet of empty bed void space per day was calculated to be 9.3, 15.8, and 22.8 lb/1000 ft^3/day for the retention times of 3.10, 1.60 and 0.33 days used with the oyster shell column. (Metric equivalents may be determined by applying a conversion factor of 0.016 Kg/m^3/day = lb/1000 ft^3/day.) Corresponding values of 11.5, 15.1, and 21.5 lb/1000 ft^3/day were calculated for the retention times of 2.51, 1.68 and 0.35 days used with the rock column. Therefore, differences in column performance are probably related to some internal phenomenon or feature and not to differences in wastewater loadings. This is also suggested by Figures 34 and 35 which show correlative gas production rates even though significant differences in magniture are apparent.

Organic strength reduction profiles are presented for both columns in Figures 38, 39 and 40 for each of the three operational retention times. Each of the figures show, on a comparative basis, the reductions in total and soluble COD and, in one instance, soluble BOD_5 for the oyster shell and rock columns operated under comparable loadings. It can be noted in Figure 38 that, for the oyster shell column operated at a 3.10-day hydraulic retention (9.3 lb total applied COD/1000 ft^3/day), the relative overall COD removal efficiency is much greater than that of the rock column operated at a 2.51-day hydraulic retention time (11.5 lb total applied COD/1000 ft^3/day). The overall Column S total and soluble COD removals are 81% and 80%, respectively; for Column R, comparable efficiencies of only 33% and

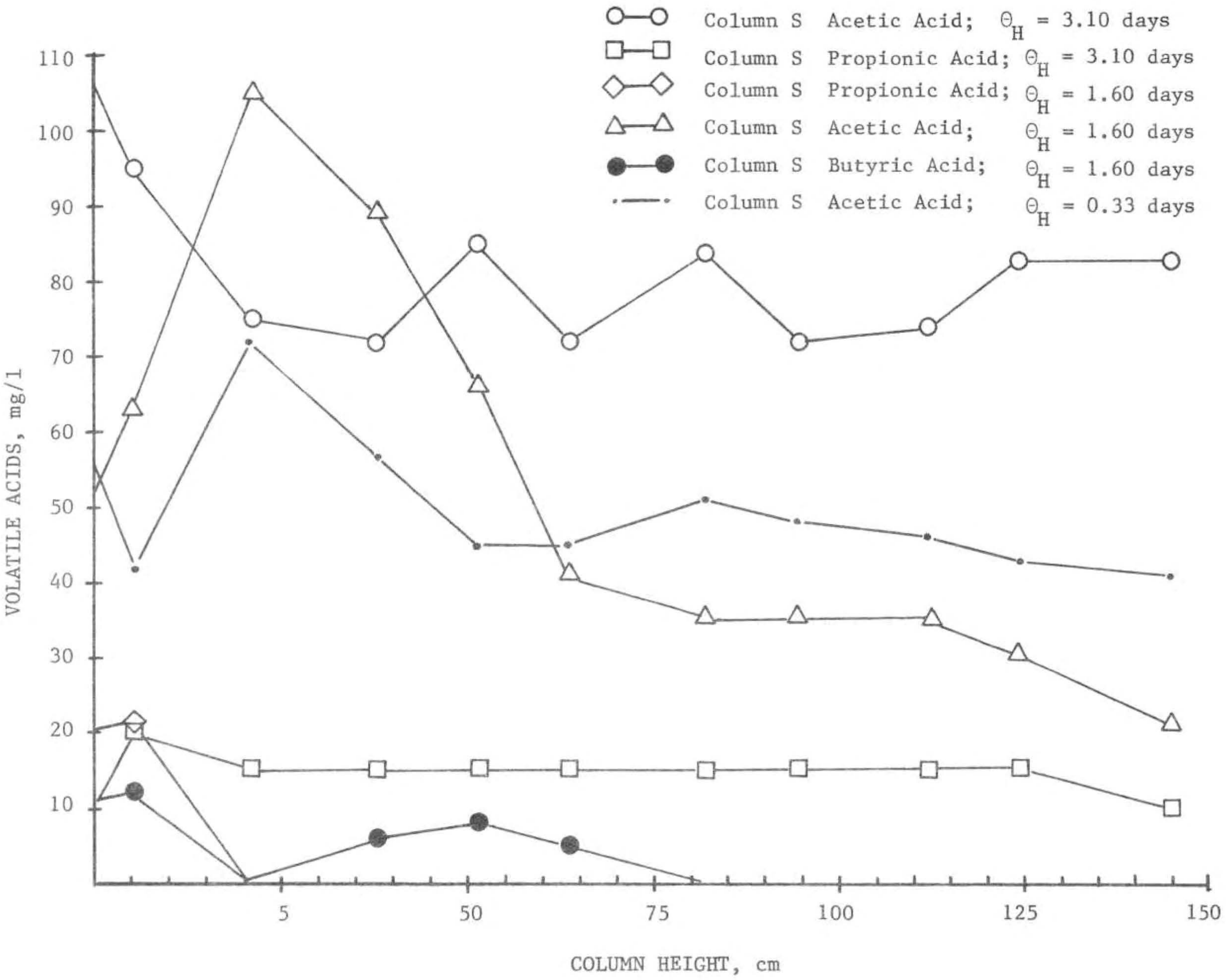


Figure 37. Volatile Acids Concentrations versus Column Height for the Oyster Shell Column Operated at Hydraulic Retention Times of 3.10, 1.60, and 0.33 days

Table 16

Profile of Nominal Steady-State Analytical Results for the Rock Column Operated at a 2.51-day Hydraulic Retention Time

	Column Height, centimeters						
Analyses	0 (Influent)	6.5	22.0	52.5	83.0	113.5	145.0 (Effluent)
pH	7.24	7.02	7.05	7.05	7.05	7.20	7.20
Total Chemical Oxygen Demand, mg/l	466	439	368	348	344	313	312
Filtered Chemical Oxygen Demand, mg/l	404	361	329	314	290	285	284
Total Suspended Solids, mg/l	18	26	20	10	20	18	8
Total Volatile Suspended Solids, mg/l	-	24	20	10	20	18	8
Temperature, ° C	20.6	23.2	23.5	24.0	24.5	25.5	-
Total Alkalinity, mg/l $CaCO_3$	454	475	454	459	437	410	459
Total Nitrogen, mg/l N	79.3	76.5	74.0	74.0	74.0	74.1	72.5
Orthophosphate, mg/l $PO_4^{\equiv}$	8.2	7.1	8.0	7.8	7.8	7.8	-
Calcium, mg/l Ca^{++}	32	28	28	28	29	29	29
Magnesium, mg/l Mg^{++}	19	21	21	22	23	24	28
Sodium, mg/l Na^{+}	8.2	8.2	8.2	8.2	8.2	8.2	8.2
Acetic Acid, mg/l	105	115	102	95	95	102	115
Propionic Acid, mg/l	10	26	26	20	20	26	-
Butyric Acid, mg/l	0	0	0	0	0	0	0

Table 17

Profile of Nominal Steady-State Analytical Results for the Rock Column Operated at a 1.68-day Hydraulic Retention Time

	Column Height, centimeters						
Analyses	0 (Influent)	6.5	22.0	52.5	83.0	113.5	145.0 (Effluent)
pH	7.02	6.95	7.01	6.95	6.98	6.95	7.08
Total Chemical Oxygen Demand, mg/l	407	389	379	273	204	194	185
Filtered Chemical Oxygen Demand, mg/l	357	329	328	227	190	176	158
Total 5-day Biochemical Oxygen Demand, mg/l	310	285	-	185	115	-	88
Filtered 5-day Biochemical Oxygen Demand, mg/l	282	250	-	160	96	-	62
Total Suspended Solids, mg/l	12	20	11	11	12	8	9
Total Volatile Suspended Solids, mg/l	11	13	10	10	11	8	9
Temperature, ° C	18.5	19.5	20.0	21.0	22.0	23.0	23.5
Total Alkalinity, mg/l $CaCO_3$	270	351	356	356	367	378	373
Calcium, mg/l Ca^{++}	19.2	17.9	17.9	17.9	17.9	17.9	17.9
Magnesium, mg/l Mg^{++}	23.0	22.3	22.0	21.5	21.3	21.3	21.2
Acetic Acid, mg/l	51	77	81	72	40	35	29
Propionic Acid, mg/l	20	14	14	12	9	8	7
Butyric Acid, mg/l	11	7	4	4	0	0	0

Table 18

Profile of Analytical Results for the Rock Column
Operated at a 0.35-day Hydraulic Retention Time

	Column Height, centimeters						
Analyses	0 (Influent)	6.5	22.0	52.5	83.0	113.5	145.0 (Effluent)
pH	7.13	7.12	7.11	7.10	7.05	7.02	7.13
Total Chemical Oxygen Demand, mg/l	121	129	123	95	86	81	75
Filtered Chemical Oxygen Demand, mg/l	89	93	86	61	53	51	43
Total Suspended Solids, mg/l	39	38	26	19	16	18	15
Total Volatile Suspended Solids, mg/l	32	33	26	17	16	17	15
Temperature, °C	9.8	12.8	14.2	16.8	19.0	21.0	23.8
Total Alkalinity, mg/l $CaCO_3$	194	211	130	238	249	238	243
Calcium, mg/l Ca^{++}	36	35	35	33	32	32	31
Magnesium, mg/l Mg^{++}	24	24	25	25	27	27	29
Acetic Acid, mg/l	56	35	32	43	39	37	37
Propionic Acid, mg/l	18	0	0	0	0	0	0
Butyric Acid, mg/l	0	0	0	0	0	0	0

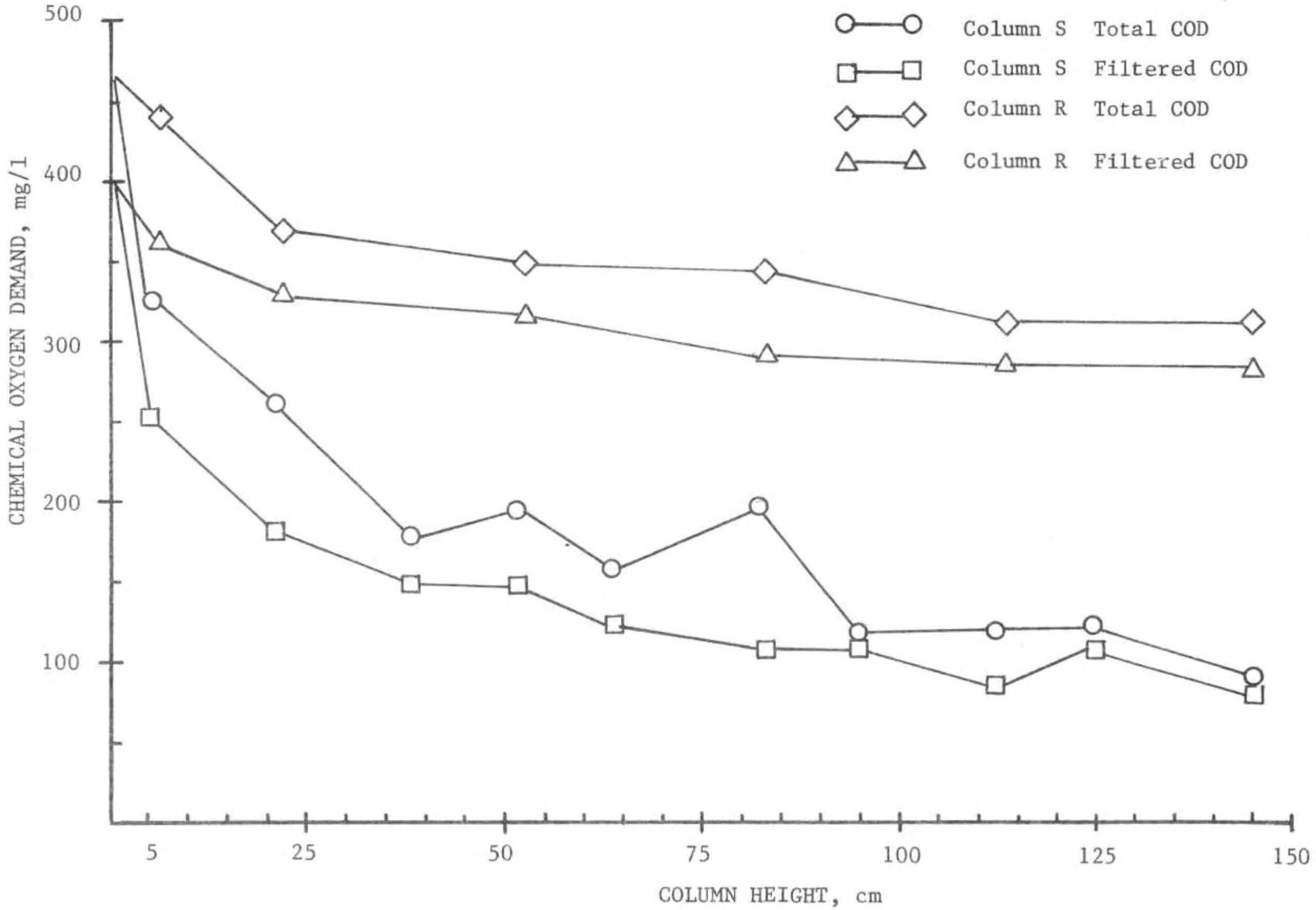


Figure 38. Total and Soluble COD Concentrations at Various Column Heights for the Oyster Shell Column Operated at 3.10 days and the Rock Column at 2.51 days Hydraulic Retention Time.

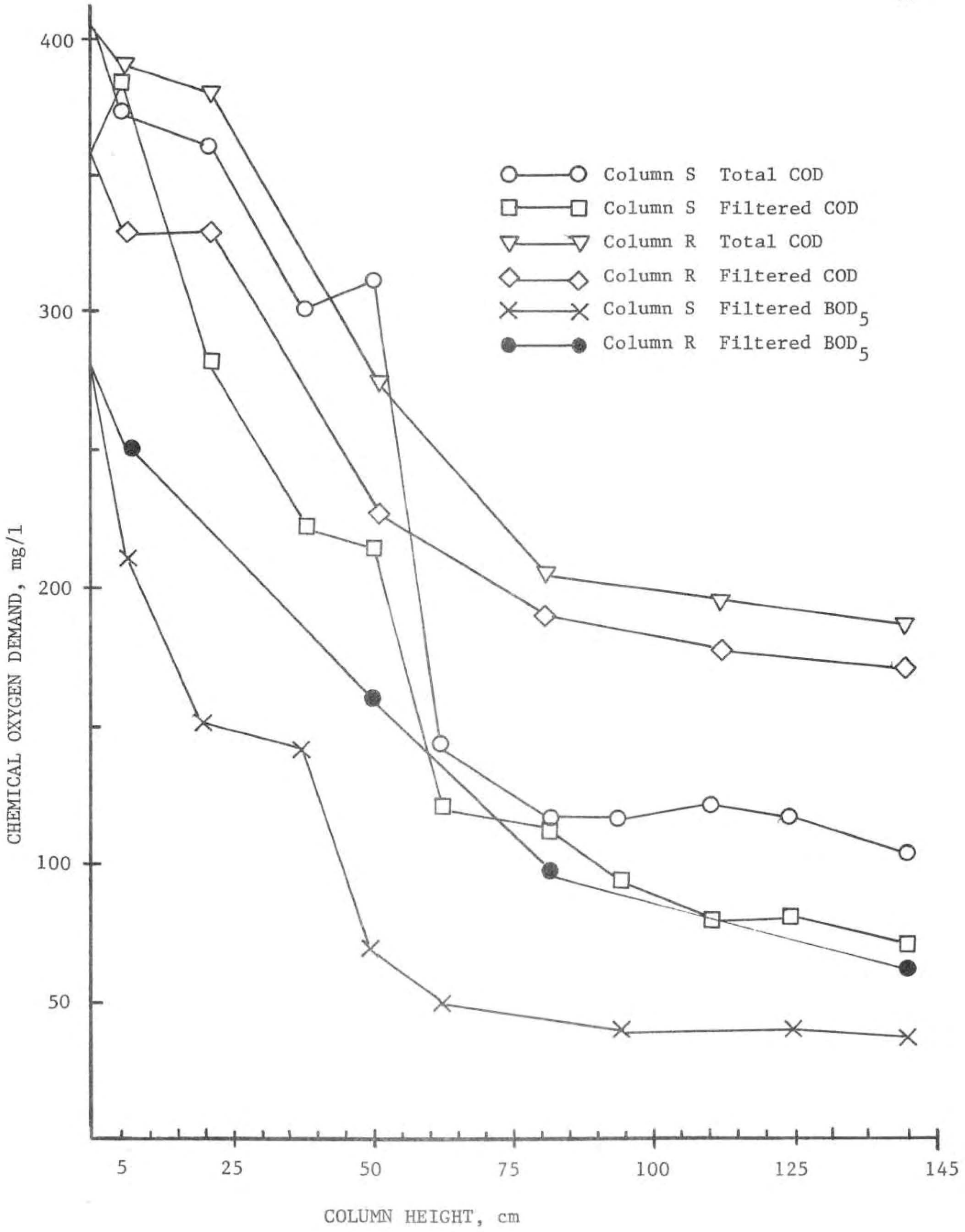


Figure 39. Total COD, Soluble COD, and Soluble BOD_5 Concentrations as Functions of Column Height for the Oyster Shell Column Operated at 1.60 days and the Rock Column at 1.68 days Hydraulic Retention Time.

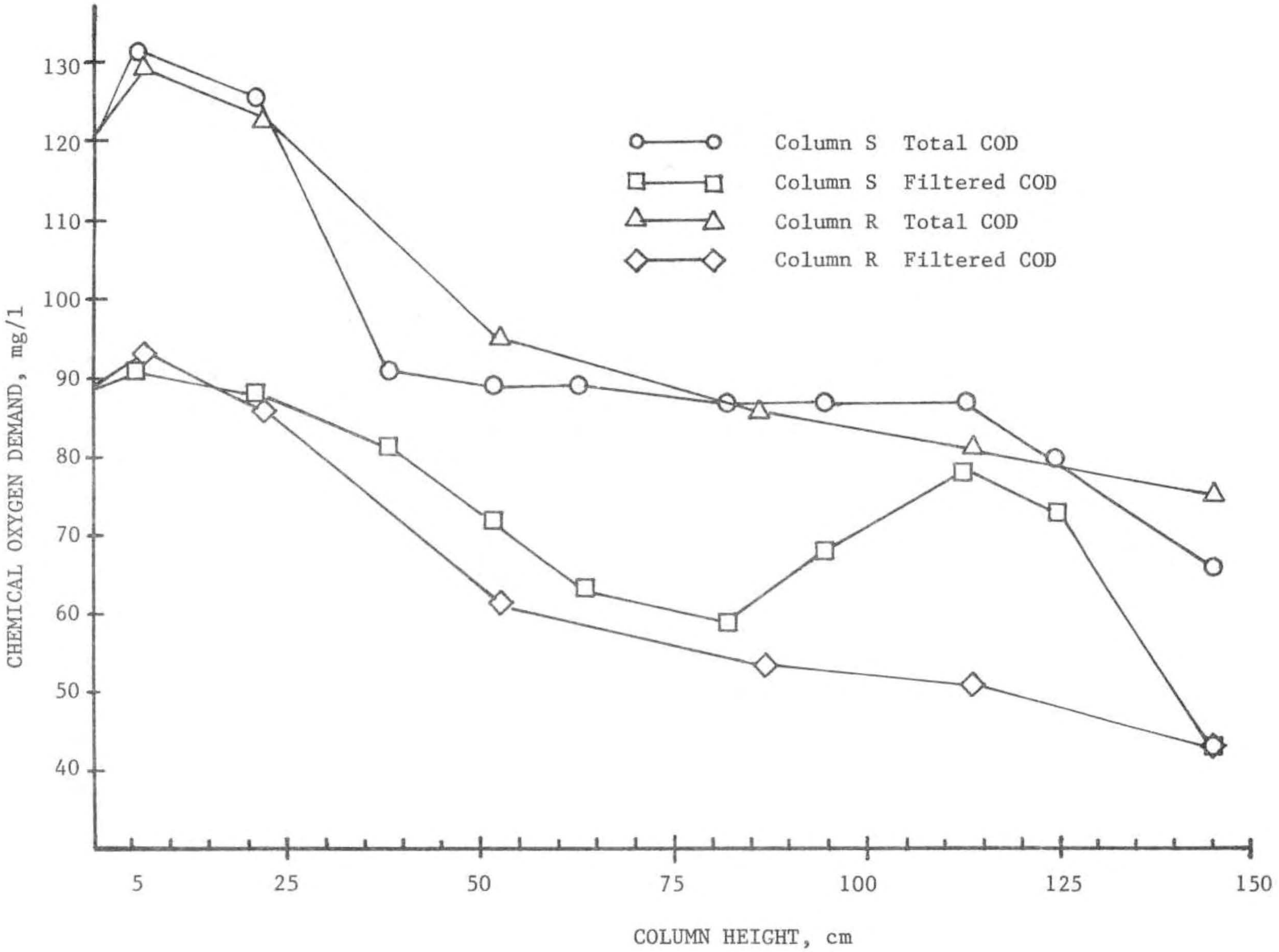


Figure 40. Total and Soluble COD Concentrations as Functions of Column Height for the Oyster Shell Column Operated at 0.33 days and the Rock Column at 0.35 days Hydraulic Retention Time.

30% were obtained. Similar results occur for the columns operated at the next higher loading with Figure 39 indicating overall removal efficiencies for Column S of 74% for total COD, 80% for soluble COD, and 88% for soluble BOD_5. Column R performance at a comparable loading rate resulted in removal efficiencies of 55% for total COD, 56% for soluble COD, and 78% for soluble BOD_5.

In Figure 40, the comparative results for column operation at the highest loading imposed (0.33 and 0.35-day hydraulic retention times) were not as markedly disparent relative to the preceding loadings. Comparable overall removal efficiencies of 45% to 38% for total COD and the same value of 52% for soluble COD, when comparing Column S to Column R, would suggest that little difference accrues between overall process performances. This would further suggest that hydraulic influences are affecting the system response and in effect are masking any potential differences that may be attributable to internal biological activity. It is interesting to note, however, that at this loading and with a relatively low wastewater organic concentration removal efficiency in the range of 40-50% is still obtained. Whether this efficiency would improve or diminish with longer periods of system operation could not be ascertained. However, it would probably decrease to lower levels under the influence of the high hydraulic flows and low wastewater organic strengths. Shellfish processing wastewater treatment by anaerobic packed columns would not be advisable under these conditions on a continual basis.

Just what caused better performance in the oyster shell column at comparable loadings cannot be immediately surmised. However, three major differences pertaining to the internal packing media of each column may have provided for the observed variance of results. First, there is an obvious, albeit not well defined, difference in the chemical composition between oyster shells and granite stone. It was evident throughout these investigations (Tables 13, 14 and 15) that calcium, and by assumption carbonate, was being added to the oyster shell column environment as flows progressed through the reactor. This did not occur with the rock column (Tables 16, 17 and 18). In fact, the calcium levels were noted to decrease, although only slightly, through the column. Initially, it was thought that this phenomena would aid oyster shell column performance by maintaining a more well buffered anaerobic environment. This may be true; however, neither pH nor alkalinity measurements for the two columns are particularly supportive of this contention as little comparative differences are exhibited, and at no place within either column were any adverse environmental conditions noted.

Another difference which may have had some influence on process performance was packed bed porosity. The oyster shell column porosity was 0.82 while that of the rock column was 0.53. It is not known what relative effect this difference in porosities may have had on the observed results. One problem with ascribing enhanced performance to increased porosity is that a column with no packing media would logically be optimal if this line of reasoning were maintained. This may well be the case, but additional study would be required to fully evaluate porosity effects on process performance. If proven correct, this hypothesis would contradict the premise that a contact surface for biomass attachment or containment is required to allow high solids retention capacity under economical wastewater delivery rates. Yet, such a configuration would certainly decrease volumetric requirements and, hence, the overall installation costs.

Finally, an interesting difference between the two types of packed media, which appeared to have great significance, was their surface area to volume ratios. The ratio for the rock packing, consisting of 2.54 to 3.81-cm (1-1.5 inch) stone, has been determined to be approximately 40 ft^2/ft^3 (1.3 cm^2/cm^3)(36). Using a crude technique for estimating this ratio for the oyster shells, a value of somewhere between 200 and 300 ft^2/ft^3 (6.59-9.84 cm^2/cm^3) was determined. The technique employed consisted of: 1) measuring and weighing a large piece of heavy paper; 2) placing several (47 were used) oyster shells of varying size on the paper and tracing their outline; 3) cutting the shell outlines out and weighing the cuttings; 4) establishing a ratio of cuttings weight to total paper weight; 5) multiplying this weight ratio by the total initial paper area times two (for both sides); 6) determining the volume of the shells used in area estimations by simple liquid displacement measurements and then dividing the estimated shell area by the measured shell volume. This procedure, since the oyster shells are concave with convolutions on the outer surface, would lead to areal estimates lower than actual. Therefore, the surface area to volume ratio calculated, although comparatively quite large, probably underestimates the true value.

Using area to volume ratios of 200 ft^2/ft^3 (6.56 cm^2/cm^3) for the oyster shells and 40 ft^2/ft^3 (1.3 cm^2/cm^3) for the rock contact media, the respective porosities of 0.82 and 0.53, and the volume occupied by the packing, calculations of available contact surface areas for each column (neglecting sidewalls) yielded values of 28.6 ft^2 (2.66 m^2) for the oyster shell and 14.9 ft^2 (1.38 m^2) for the rock packings. It is apparent that the available surface area in the shell column is about twice that of the rock column. Since total surface attachment availability for biological growth would relate to the total potential biomass within a system which correlates with the system's capacity to accommodate a given wastewater flow and strength, there is little doubt that an oyster shell media would provide for enhanced process performance compared to that of a rock media under similar loadings.

There is a strong suggestion that oyster shell packing media for anaerobic columns would be beneficial for treatment of many types of industrial effluents other than shellfish processing wastewaters. Compared to other available packing materials, oyster shells have advantageous features that cannot be inherently reproduced such as : 1) a potential for aiding buffering potential within the liquid phase of the anaerobic environment; 2) a high porosity upon packing which can lead to lower interstitial velocities within a column and, therefore, reduced solids transport potential; and 3) a high surface area to volume ratio which provides a significantly increased biomass contact surface for a given volume.

ADVANCED TREATMENT OF AEROBIC BIOLOGICALLY TREATED SHELLFISH PROCESSING WASTEWATERS

To establish the feasibility and potential for providing a final effluent discharge of sufficient quality to comply with very stringent regulatory standards or for eventual industrial reuse, selected conventional advanced treatment methodologies were applied to overflow effluents from an aerobic biological treatment system receiving shellfish processing wastewaters. Aerobic biotreatment was selected as the focal wastewater control process because of its previously demonstrated applicability and general acceptance as the most economical means for effective reduction of organic waste strengths.

Treated wastewaters were collected from an aerobic recycle reactor operated at a reactor hydraulic retention time of 7.6 hours. The overflow effluent contained relatively low refractory organics, measured as COD, and a low to moderate amount of residual suspended solids, measured as TSS. The steady-state treated effluent was composited and kept under refrigeration at 4°C until employed in the subsequent treatability investigations. This allowed for greater comparability of the advanced methods under consideration as all studies were then conducted with treated wastewater of essentially the same constituency.

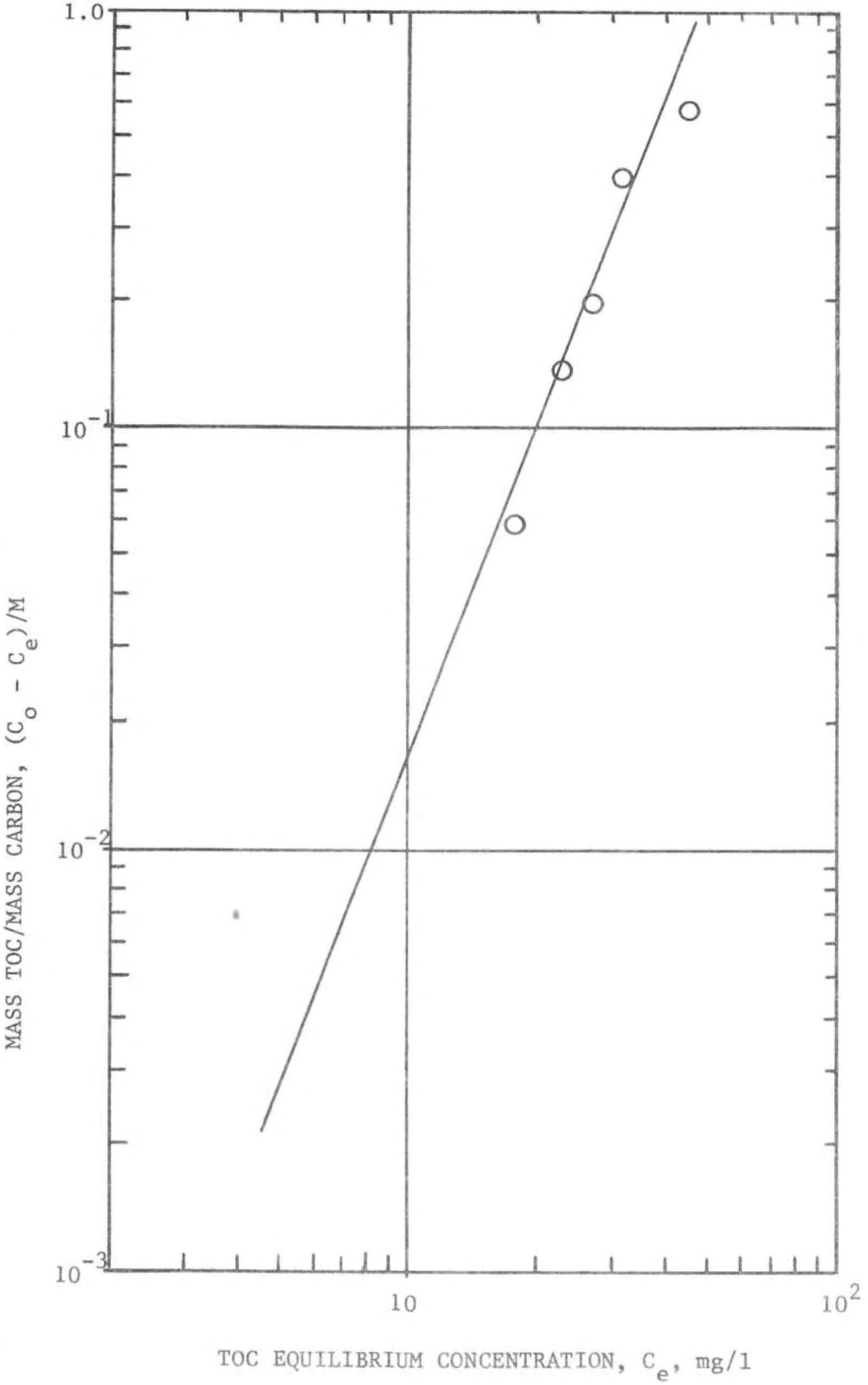
The separate advanced treatment systems examined were: 1) batch activated carbon treatment; 2) short-term sand filtration; and 3) sand filtration followed by batch activated carbon, then ion exchange treatment. Sand filtration was by continuous gravity flow through a 3.81 cm (1.5-inch) I.D. column with a 48.26 cm (19-inch) packed bed depth of Ottawa sand. The applied flow rate was maintained at 35 ml/min throughout the filtration study. The total liquid volume administered to the sand column was 10 liters prior to collection of effluent samples for subsequent analyses. Both activated carbon and ion exchange studies employed batch slurry contact methods (Standard Jar Test Procedures). Appropriate adsorption isotherms were developed for the carbon applications while ion exchange resin requirements were estimated by evaluation of simple dosage versus effluent quality relationships.

Selection of these advanced treatment methods was founded largely upon their simplicity and established technological feasibility, both aspects being considered as essential attributes for any potential advanced treatment scheme that may be devised for the shellfish processing industry with its recognized marginal economic posture. More sophisticated methodologies were not considered since the basic investigatory intent was to demonstrate that very high effluent quality levels were attainable with simple treatment methods. Specific operational criteria could be elucidated on the pilot scale if and when such advanced methods were deemed necessary.

Advanced Treatment Results

Data generated from batch process activated carbon treatment of refractory organics escaping in aerobically treated, clarified effluents were reduced and accordingly found to conform to simple Freundlich adsorption isotherm relationships. The isotherms for the two carbons (Witco Grade 517 and Nuchar WV-L) which had shown the greatest potential in previous studies on raw wastewaters are presented in Figures 41 and 42. As previously mentioned, these isotherms may be applied to estimations of carbon requirements for residual organic matter removals. However, eventual field-scale activated carbon applications would still be highly dependent upon a processor's economic position, other applicable and available treatment alternatives, and regulatory demands.

The results of sand filtration of aerobically treated, clarified effluents followed by subsequent treatment with batch activated carbon

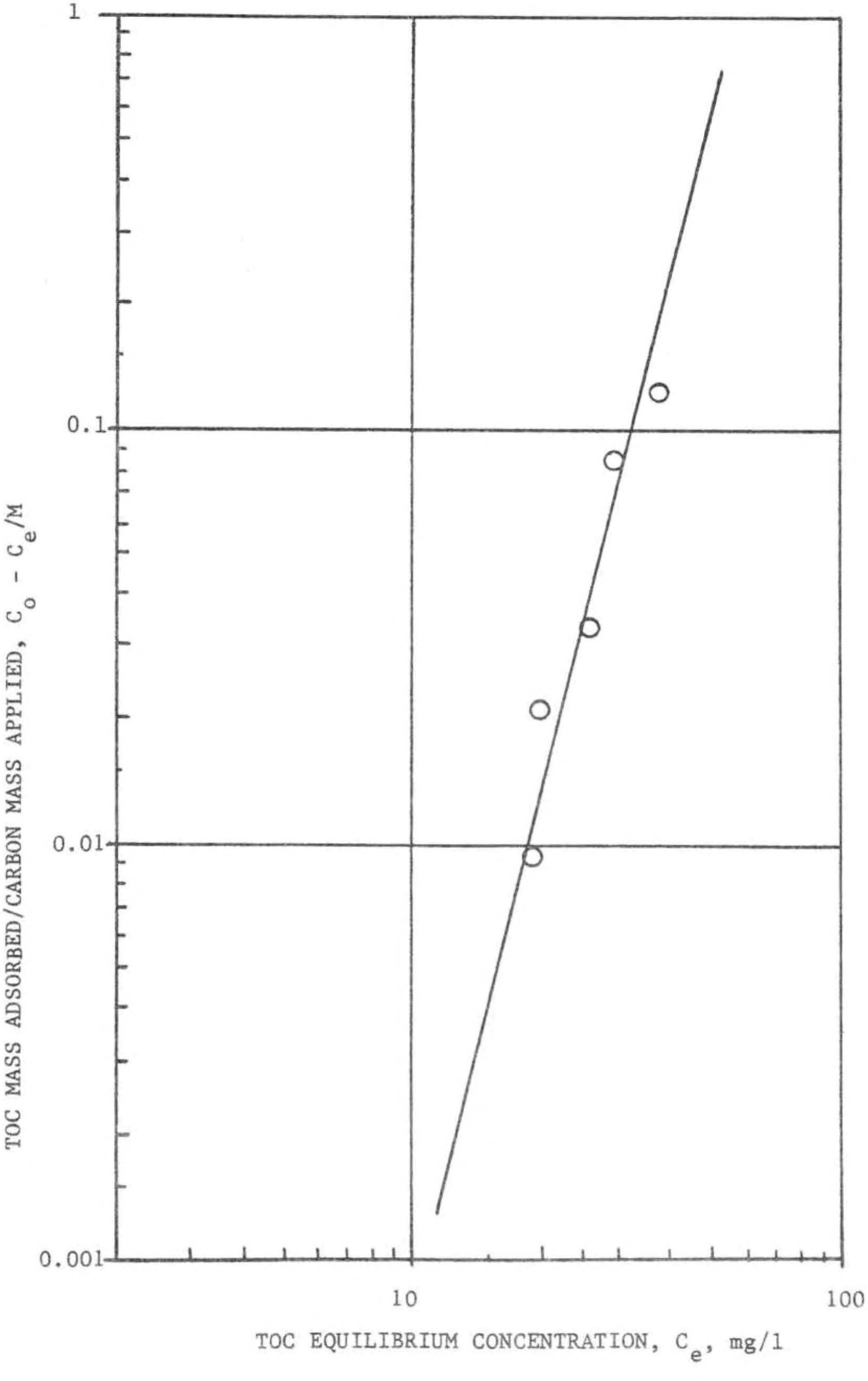


Temperature = 20°C

pH = 6.7

$$\frac{C_o - C_e}{M} = 10^{-4.57}(C_e)^{2.74}$$

Figure 41. Freundlich Adsorption Isotherm for Witco Grade 517 Powdered Carbon with Aerobically Treated Shrimp Processing Wastewater



Temperature = 20°C
pH = 4.5

$$\frac{C_o - C_e}{M} = KC_e^{1/n}$$

$K = 10^{-7.07}$
$1/n = 3.96$

Figure 42. Freundlich Adsorption Isotherm for Nuchar WV-L Powdered Carbon with Aerobically Treated Waste.

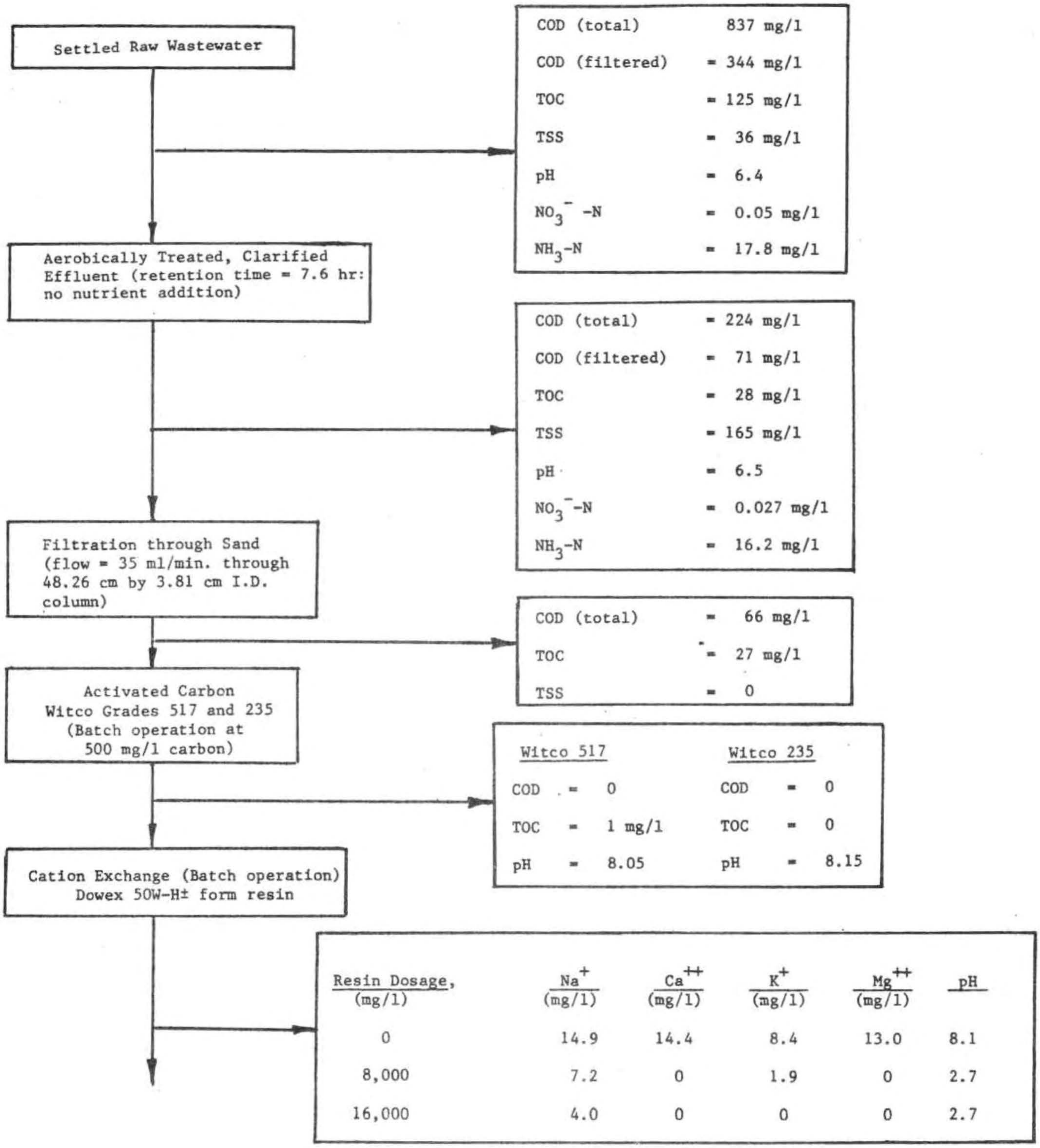
then cation exchange resins are summarized in Figure 43. Since these investigations were oriented only to the demonstration of treatment capability for generation of high effluent quality, the processes and operations were not so extensively evaluated that operational criteria (backwashing requirements, time of operation, etc.) could be advanced. It is apparent from Figure 43 that sand filtration for residual solids removal could be effective; however, only minimal removal of residual organics was noted.

Batch slurry treatment of the sand filtered effluent with 500 mg/l of powdered activated carbon using a one hour contact time proved sufficient for removing the residual organic fraction. It would appear that the residual organics are essentially completely absorable and should pose little problem for carbon applications which could render a final effluent practically devoid of organic contaminants. In addition, removal of heavy metals could be successfully accomplished by ion exchange methods as indicated in Figure 44. It may be noted from this figure that, as expected, exchange selectivity is more pronounced for divalent over monovalent cations. This would lead to the expectation that other divalent cation species of particular importance to human health, such as mercury or cadmium, would be removed readily through ion exchange applications. Although the concentrations of those ions found in the wastewaters used during the investigations (calcium, magnesium, sodium and potassium) were too dilute to rationally warrant their removal for either normal effluent discharge requirements or industrial reuse, it appears that ion exchange technology could suffice as a treatment means for heavy metal removals under conditions where they may pose a problem if uncontrolled.

ECONOMIC ANALYSES OF SHELLFISH PROCESSING WASTEWATER MANAGEMENT ALTERNATIVES

On-site treatment technology applied to the control of pollutional discharge from shellfish processing operations appears to be substantially capable of providing for most any terminal effluent quality desired. However, as with most industrial concerns, it is the financial cost effectiveness of any given system implementation that ultimately dictates what wastewater management alternative should be provided. An economically optimum wastewater management alternative with pronounced applicability for the whole of the shellfish processing industry cannot be selectively defined since the cost effectiveness of a specific technology depends upon those pollutants to be removed, the required degree of removal, scale of industrial operation, the individual processor's financial perspective, and, quite importantly, on certain local factors such as treatment site availability, topography, climate, and proximity to municipal or cooperative jurisdictions. These factors can obviously vary greatly among the compendium of shellfish processors comprising the industry.

The results of the laboratory treatability investigations reported upon herein, as well as documented findings for other treatment schemes reported in the literature, may be used as a basis for cursory economic evaluations of various wastewater management alternatives specifically applicable to the shellfish processing industry. In order that all evaluations may be founded within a common framework, certain qualifying assumptions must be provided which are reasonably reflective of typical



Resin Dosage, (mg/l)	Na^+ (mg/l)	Ca^{++} (mg/l)	K^+ (mg/l)	Mg^{++} (mg/l)	pH
0	14.9	14.4	8.4	13.0	8.1
8,000	7.2	0	1.9	0	2.7
16,000	4.0	0	0	0	2.7

Figure 43. Experimental Combined Treatment Scheme for Shellfish Processing Wastewaters (Plant S1B) Capable of Providing High Levels of Effluent Quality.

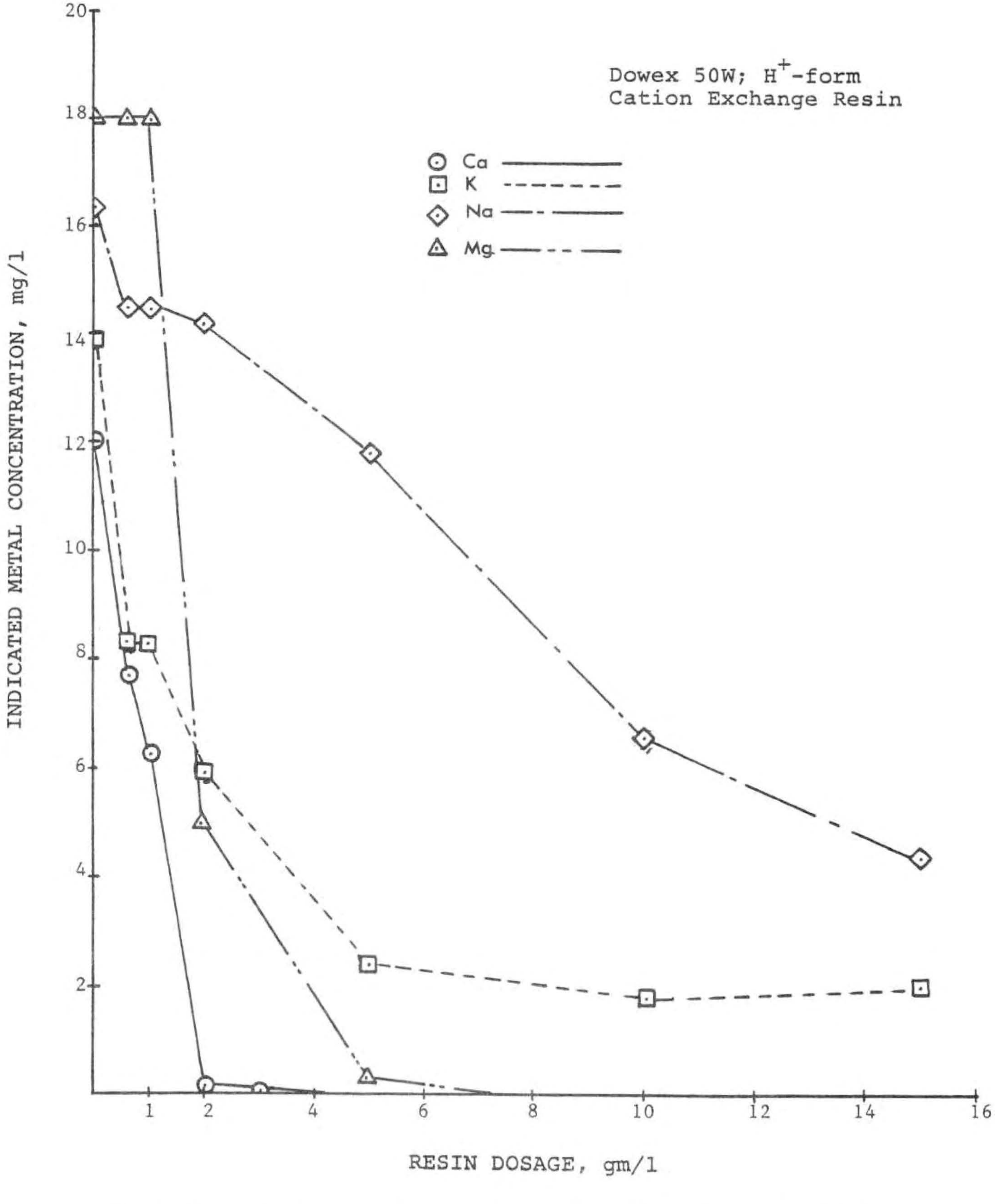


Figure 44. Cation Exchange on Aerobically Treated, Sand Filtered Shellfish (Shrimp) Processing Waste (SlB)

processing operations and financial expectations. The economic appraisals formed within this report have been based upon an average daily processing flow of 0.5 million gallons (1893 cubic meters), a finance interest rate of 12%, and an expected facility installation life of 20 years. All applicable construction, operation and maintenance cost estimates have been adjusted to the Environmental Protection Agency January, 1974, treatment plant cost index of 170.4 for Atlanta, Georgia (37).

A model wastewater constituency generated from the results of characterization analyses performed both preceding and following the installation of tangential screening at one of the processing plants surveyed is presented in Table 19. These data, together with laboratory treatability results, were used to estimate unit operations and process capacities capable of treatment efficiencies equalling or exceeding 90% for BOD_5 and TSS. Associated capital, maintenance, and operating costs could subsequently be allocated. Moreover, since effluent surcharges as levied in Georgia are based in part upon waste constituency, allowance is made for estimations of municipal sewerage charges attendant with pollutional levels of BOD_5 and TSS, both with and without some form of pretreatment. Unit cost estimates were derived from various manufacturer and public works manuals as well as other values documented in the pertinent literature (37-44). The comparative basis for all economic evaluations was the expected capital recovery (annual costs) for all alternatives considered.

Ten wastewater management alternatives considered feasible and applicable to shellfish processing effluents were compared with respect to their estimated annual costs. A delineation of these alternatives is presented in Table 20. Several assumptions and conditions have been advanced for these alternatives to facilitate a greater ease of analyses without detracting significantly from basic treatment schemes which could be expected for actual field installations. Although the direct discharge to municipal sewerage without pretreatment alternative has been allocated an estimated annual cost (based entirely upon flow and character of the wastewater), it most probably would not find acceptance by either regulatory authorities or the controlling municipal works since gross solids removal (i.e., larger bone fragments, exoskeletons, etc.) will undoubtedly be required before introduction of the wastewater stream to the conveyance system. Therefore, the simplest acceptable scheme appears to be simple screening followed by direct municipal sewerage interception. Moreover, initial removal of gross solids has additional logic as a means for recovery of a potentially salable by-product (particularly shellfish exoskeletons), which may be used as sources for chitin and its deacetylated derivative chitosan.

At this point it is well to note that one aspect involving a potentially significant capital outlay for those alternatives requiring interconnection with local or cooperative sewerage is the direct cost associated with development and installation of connecting laterals. This cost would in all likelihood be the most widely variant from processor to processor and as such has not been specifically included in the economic evaluations. Individual processing firms can, however, estimate these particular capital costs associated with their particular situation by contacting proximal consulting firms for nominal estimates accounting for local cost differences commensurate with the existing geographical, geological, and political situation. Once the initial investment has been estimated, its capital

Table 19

Average Shellfish Processing Wastewater Characteristics Used in Economic Evaluations of Alternative Methods of Treatment

Wastewater Quality Parameter	24-hour Composite Raw Wastewater Character	24-hour Composite Screened Wastewater Character
pH	6.8	6.8
Total 5-day Biochemical Oxygen Demand, mg/l	650	500
Soluble 5-day Biochemical Oxygen Demand, mg/l	420	350
Total Chemical Oxygen Demand, mg/l	1000	700
Soluble Chemical Oxygen Demand, mg/l	550	500
Total Solids, mg/l	2500	1500
Total Suspended Solids, mg/l	1800	400

Table 20

Selected Management Alternatives for Shellfish Processing Wastewaters

Alternative A - DIRECT DISCHARGE TO MUNICIPAL SYSTEM WITH NO PRIOR TREATMENT. CONNECTING SEWERAGE NOT ACCOUNTED.

Alternative B - SIMPLE SCREENING AND DISCHARGE TO MUNICIPAL SYSTEM. CONNECTING SEWERAGE NOT ACCOUNTED.

Alternative C - PRIMARY CLARIFICATION WITH OVERFLOW DISCHARGE TO MUNICIPAL SYSTEM. CONNECTING SEWERAGE AND SOLIDS HANDLING NOT ACCOUNTED.

Alternative D - DISSOLVED AIR FLOTATION AND DISCHARGE TO MUNICIPAL SYSTEM. CONNECTING SEWERAGE AND SOLIDS HANDLING NOT ACCOUNTED.

Alternative E - ON-SITE TREATMENT: SCREENING, CONVENTIONAL ACTIVATED SLUDGE (4-hour retention time), SECONDARY CLARIFICATION, SOLIDS HANDLING.

Alternative F - ON-SITE TREATMENT: SCREENING, ROTATING BIOLOGICAL CONTACTOR (4-stage), SOLIDS CLARIFICATION, SOLIDS HANDLING.

Alternative G - ON-SITE TREATMENT: SCREENING, EXTENDED AERATION, SOLIDS HANDLING.

Alternative H - ON-SITE TREATMENT: SCREENING, PRIMARY CLARIFICATION, GRANULAR ACTIVATED CARBON COLUMN, SOLIDS HANDLING.

Alternative I - ON-SITE TREATMENT: SCREENING, ANAEROBIC FILTRATION, RESIDUAL ORGANICS TREATMENT, SOLIDS HANDLING.

Alternative J - ON-SITE TREATMENT TO FEDERAL 1983 REQUIREMENTS: SCREENING, ROTATING BIOLOGICAL CONTACTOR, MULTIMEDIA FILTRATION, ACTIVATED CARBON, SOLIDS HANDLING.

Note: Ultimate Solids Disposal and Final Effluent Disinfection are not Considered for Any of the Alternatives.

recovery cost may be added to any alternative involving interception with local sewerage and subsequently compared with the on-site treatment alternatives. Also excluded from these analyses are the cash flow benefits that may be derived from tax subsidies, depreciation allowances and investment credits available to qualified firms for installation of pollution control equipment. As these factors are somewhat variant, depending upon legislative review and alteration as well as processing plant eligibility and certification, they can be subsequently incorporated into any final economic analysis on an individual plant basis.

The comparison of the ten alternatives indicated in Table 20 are shown by histogram in Figure 45. Certain assumptions and cost allocations for estimated capital investments, operation and maintenance, chemical costs, etc. derived from the previously referenced sources are presented in Appendix B. The economic comparisons shown in Figure 43, although not founded upon an extensive analytical framework inclusive of all financial influences, should serve to provide a reasonable basis for alternative review. It would appear that Alternative B, direct discharge to an existing sewerage system after screening, offers the best economics of the alternatives analyzed. However, it must be remembered that in most cases a processing firm will be required to share or encumber the costs for establishing the necessary collection and conveyance lines adjunct to sewerage interception. As these costs have not been included, they could alter the favorability of any alternative involving municipal sewerage interception. Of the on-site treatment alternatives, it is apparent that employment of rotating biological contactor systems (Alternative F) would constitute the most economically favorable method followed by extended aeration (Alternative G) which would probably be employed as a package plant system.

As expected, the costs associated with an extensive treatment scheme capable of meeting the most stringent effluent quality requirements (Alternative J) are substantially greater than costs incurrable for production of a lesser effluent quality. The primary financial influence for this alternative, as well as for Alternative H, was the annual cost of make-up carbon required. For a plant of this designated size, it is usually less economical to provide carbon regeneration facilities (44). Therefore, any alternative involving activated carbon treatment for this wastewater type will be economically unattractive primarily due to high carbon requirements.

SUMMARY AND CONCLUSIONS

Southeastern Georgia coastal shellfish processing wastewaters were subjected to laboratory-scale treatability investigations using a variety of conventional and modern treatment mechanisms alone and in combination. Physical-chemical treatability applications included chemically aided coagulation-flocculation, activated carbon adsorption, ion exchange and sand filtration. Biological modes for wastewater stabilization consisted of aerobic slurry (activated sludge-type) treatment, single-stage and recycle contact anaerobic treatment, rotating biological contactors, and anaerobic packed bed columns.

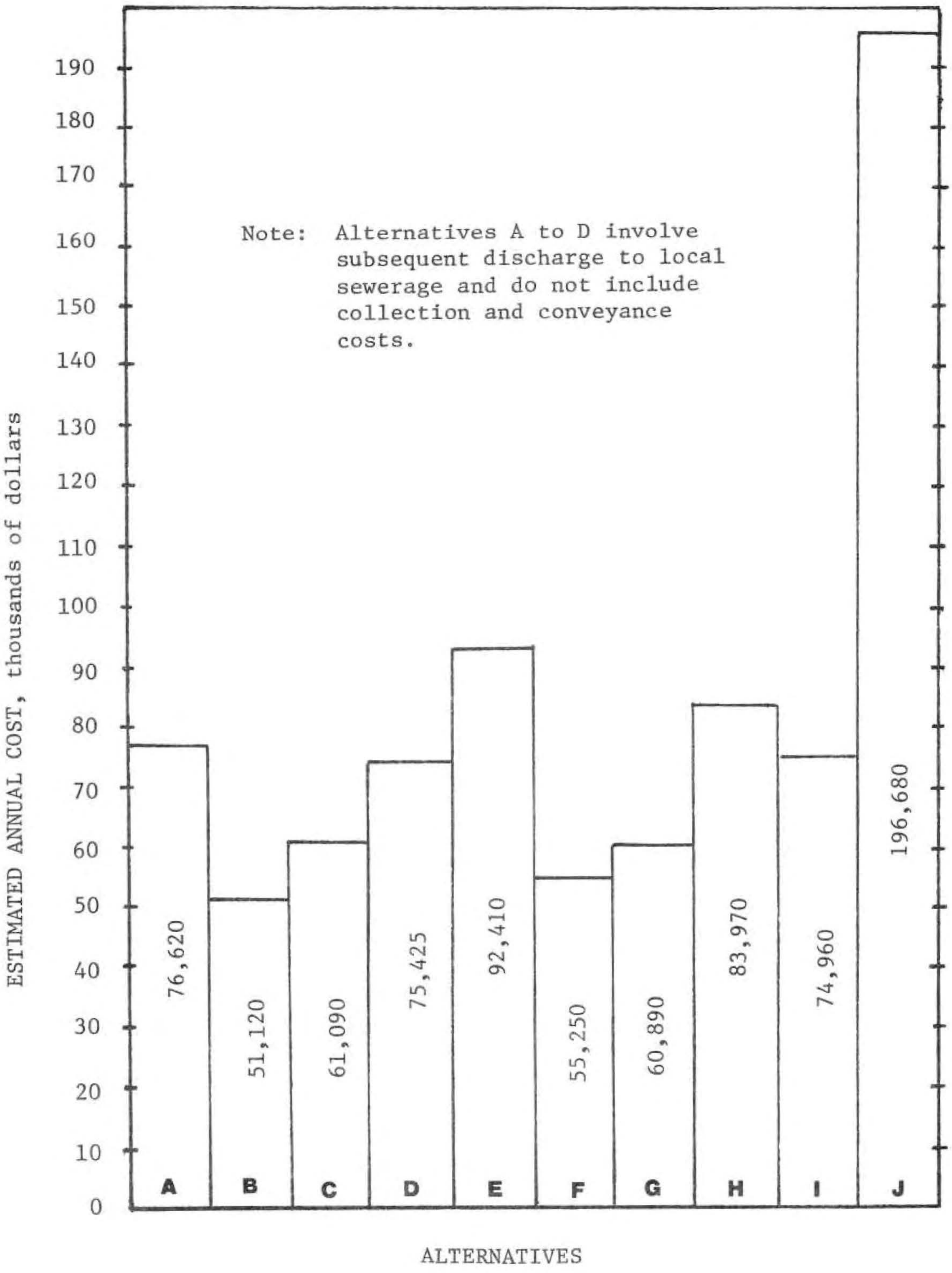


Figure 45. Annual Cost Comparison of Wastewater Management Alternatives for the Shellfish Processing Industry (0.5 MGD average flow, finance interest at 12%, expected facility life at 20 years).

Chemical Treatment

Chemical coagulation of raw shellfish processing wastewaters was effective for suspended solids removal but, compared to unaided sedimentation, proved limited in its ability to materially enhance removal of organic constituents. Almost complete removal of suspended solids may be obtained with ferric chloride as the coagulating agent when aided by small amounts of polyelectrolyte. Removals of organics in excess of 60% were obtainable with combined ferric chloride and polyelectrolyte (Nalcolyte 110) dosages of 80 mg/l and 0.5 mg/l, respectively. On a routine basis, ferric chloride coagulation of shellfish processing wastewaters aided by polyelectrolytes or lime should provide removal efficiencies of 85-95% for suspended solids and 50-60% for organic constituents.

Adsorption

Activated carbon treatment of screened, settled shellfish processing wastewaters was effective in removing organic material. However, results of Freudlich adsorption isotherm analyses and carbon column studies indicate that high equilibrium levels of treatment were obtained at low organics removed to carbon mass ratios which suggests excessive carbon requirements. Economic rather than technical feasibility appears to be the greatest deterrent to favorable applicability of activated carbon for wastewater organics removals.

Ion Exchange

Ion exchange methods for soluble metals reductions can be successfully applied to clarified wastewaters. No significant or adverse concentrations of metal ions were noted in the wastewaters used throughout the investigations. For this reason, metalic ion removal, either prior to another treatment process (i.e., biological system) or for effluent polishing, appears unwarranted. Nonetheless, if through characterization analyses a processing wastewater exhibits ionic constituents requiring removal, ion exchange should be an acceptable treatment method.

Aerobic Biological Treatment

Aerobic biological oxidation of screened and settled shellfish processing wastewaters was determined to be a satisfactory means for reducing soluble organic constituents to levels acceptable for discharge in accordance with current regulatory requirements. Moreover, the results of bench-scale studies were amenable to continuous culture analysis which enabled certain design and operational criteria to be formulated. For the wastewaters under investigation, a critical hydraulic retention period of about two hours for single-pass and one hour for solids recycle modes of operation was determined. Therefore, system design and operation should be such to satisfy these limiting constraints and hydraulic retention times ranging from four to eight hours appeared best for overall treatment efficiency and economy.

The efficiency of biological solids separation by secondary clarification was markedly affected by operation of the aerated unit. Differences in applied dilution rates were of major importance for solids settleabilities and concomitant overall system performance. Adequate solids separations occurred only when the aerobic reactor was operated in the range of four to nine hours retention time. Although both hydraulic characteristics and biomass morphology dynamics were believed to influence solids removal efficiencies, the latter appeared to exert the greatest influence when decreases in efficiencies were noted.

The mixed system aerobic biological treatment analyses were facilitated using a kinetic model without any major limiting assumptions. However, it was necessary to consider certain inherent influences that may have caused deviations from steady-state reactor operation. These were particularly apparent at the lower and higher hydraulic retention times employed and mainly consisted of attached growth effects, population dynamics, and minor hydraulic fluctuation effects.

For the primary wastewater investigated, no nutrient (phosphorous or nitrogen) limitations to biotreatment were apparent. However, one of the wastewater samples used in aerobic investigations was very limited in nutrient content and was not successfully treated until nutrient supplementation was provided. Therefore, characterization analyses of shellfish processing wastewaters are important on an individual basis to ascertain the specific nutrient availability and amount possibly required to allow satisfactory biological treatment.

RBC Treatment

The rotating biological contactor investigations indicated that treatment of shellfish processing wastewaters by this process was quite feasible. It is suggested that this process should receive serious consideration when alternatives related to the resolution of waste discharge problems are reviewed by shellfish processors. Results indicated that relatively high degrees of organic removals could be obtained without additional pretreatment or nutrient supplementation of screened wastewater. Organic removal efficiencies, as reflected by the change in BOD_5 or COD across the system, approached 95% and 92%, respectively, at system loadings of approximately two gallons per square foot of disc area per day ($81.4\ l/m^2$) and below. These results compare favorably with those found for other industrial wastewaters as well as for municipal sewage.

The removal of the biological solids developed in the RBC process does not appear to be a significant problem. Gross solids separation evaluations by development of Sludge Volume Indices for the sloughed solids provided no reason to anticipate significant problems when using conventional clarification techniques. In addition, although little evidence supporting the occurrence of nitrification within a two-stage RBC system was noted, it appears probable that this phenomena would result if additional stages were employed.

Anaerobic Biological Treatment

On the basis of these investigations, conventional anaerobic or anaerobic contact treatment of screened shellfish processing wastewaters does not appear to be feasible. The relatively dilute organic strength of the wastewater coupled with the need for economic hydraulic applications (i.e., sufficiently low residence times to preclude construction of excessively large holding reactors) limits the establishment and maintenance of adequate methanogenic populations necessary for successful waste stabilization. However, conventional anaerobic treatment of wastewaters that are more concentrated in organics, or of sludges derived from other treatment applications, cannot be entirely discounted on the basis of these investigations.

Anaerobic Filter

Shellfish processing wastewater treatment by fixed-film, anaerobic packed beds proved to be significantly better than with conventional anaerobic methods. Organic removal efficiencies of about 80% for COD and 88% for soluble BOD_5 were demonstrated. Since a low influent organic strength allowed only low to moderate organic loadings while maintaining an acceptable hydraulic stress, it is conceivable that higher efficiencies would occur with higher wastewater organic strengths as has been noted for other anaerobic packed bed studies involving similar hydraulic applications (31,32,34).

Stated as a generally favorable feature of anaerobic packed bed systems, the effluent suspended solids concentration arising from treatment of shellfish processing wastewaters were very low, never exceeding 20 mg/1 throughout the study, and this system characteristic should lead to minimal solids handling requirements. Moreover, after short periods of inoperation or system malfunction due to air contamination or pumping problems, the anaerobic packed bed exhibited a marked ability to rapidly reestablish efficient levels of treatment upon return to normal operating conditions. The system also demonstrated a relatively rapid response to fluctuating wastewater loadings which should enable it to accomodate processing flows with a reduced need for flow equalization.

Gas productivity was substantial, although not as high as reported for similar systems treating other wastewater types (32-34) because of the low organic character of the shellfish processing wastewater examined. Moreover, the gas quality in terms of methane content was very high (>80%) and could possibly be exploited as a valuable by-product.

Oyster shells used as contact-containment packing in the anaerobic column proved more effective than normal rock packing material. It would appear that oyster shells, due to their ability to aid system buffer requirements, higher porosity upon packing, and higher surface area to volume ratio, could serve as excellent contact media for wastewaters from other industries for which anaerobic packed bed treatment may be under consideration.

Treatment Alternatives

Extensive treatment of shellfish processing wastewaters to meet the most stringent regulatory requirements anticipated was technologically feasible by the sequential application of screening, primary sedimentation, aerobic biological treatment, sand filtration, and carbon adsorption. The final effluent from this treatment scheme can have very minimal organic and suspended solids content. Ionic constituents may be at levels sufficiently low to preclude further treatment but, if deemed necessary, could be removed with ion exchange techniques. Although technology does not limit treatment of shellfish processing effluents to very exacting levels, the economic feasibility of such complete treatment appears unfavorable for normal processing firms. Final selection of a wastewater management alternative will probably be governed more by a processor's financial capacity and general economic posture than by availability of technological means.

For a moderately sized processing firm, it was apparent that simple screening followed by effluent discharge to municipal or cooperative sewerage systems offered the most advantageous economic alternative. However, the costs associated with development of collection and conveyance works for sewerage interception, as well as the potential for escalation of cost sharing surcharges, may place on-site treatment in a more favorable perspective. The on-site alternative may become even more attractive if effects of tax considerations, depreciation allowances, investment credits, and changing legislative viewpoints are taken into account. Of the potential on-site treatment methods available, rotating biological contactor treatment is suggested, since it provides the greatest comparative economy for those alternatives reviewed which are capable of meeting current regulatory requirements. Moreover, it offers advantages of requiring minimal space, having low power demands, and only moderate operation and maintenance expenditures while effecting relatively high levels of waste strength removal efficiencies on a continual basis - all important aspects to the shellfish processor encumbered with the responsibility of adequate wastewater management.

It must be remembered, however, that wastewaters from any particular shellfish processing operation may be highly variable and should be analyzed and subjected to specific treatability investigations before initiating design and installation of an on-site treatment facility.

ACKNOWLEDGEMENTS

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APPENDIX A

Development of a Kinetic Model for Completely Mixed Biological Systems Based upon Limiting Substrate Continuous Culture Theory

For both single-pass and recycle completely mixed treatment systems as depicted schematically in Figure A-1, simple substrate and organism mass balances can be made across the respective units from influent to final effluent.

Organism Balance

The wastewater enters the reactor volume, V, at a flow rate, Q, a biological solids concentration, X_o, and substrate concentration, S_o. The final effluent leaves with a flow rate, Q, biological solids concentration, X_e, and residual substrate concentration, S_e. An organism mass balance across either reactor system follows the basic principle of conservation:

Net Change = Inflow - Outflow + Growth - Decay

Expressing each term by functions descriptive of component phenomena results in:

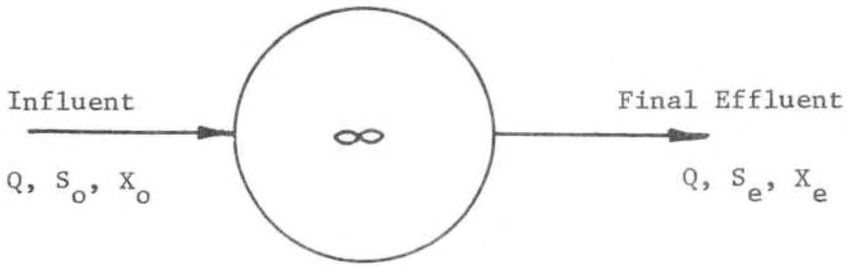
$$V \frac{dx}{dt}_{net} = QX_o - QX_e + V\mu X_e - Vk_d X_e \qquad (1)$$

where; μ = specific organism growth rate, and k_d = specific organism death rate.

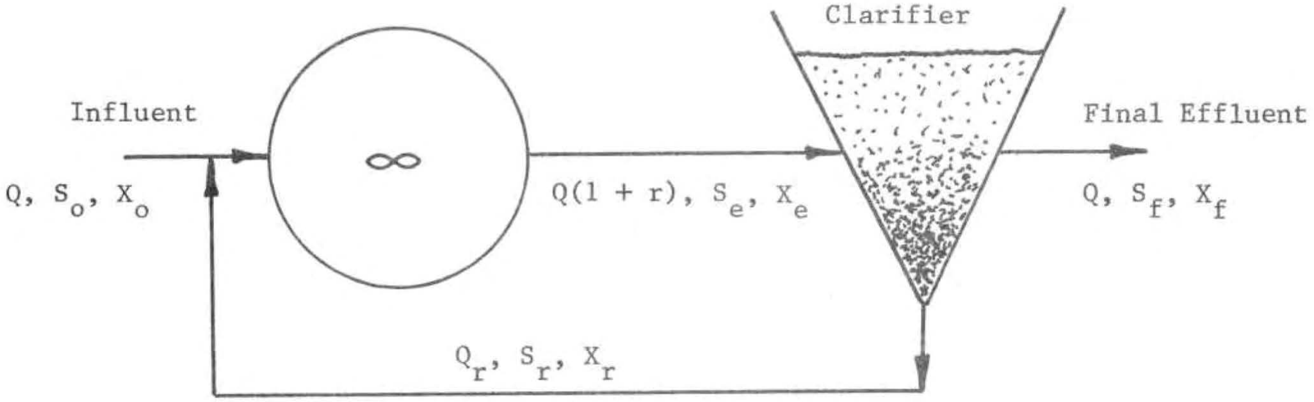
Applying the definition of steady-state conditions, i.e., no net change in organism concentration with time, yields

$$0 = QX_o - QX_e + V\mu X_e - Vk_d X_e \qquad (2)$$

for the single-pass reactor system.



SINGLE PASS COMPLETELY MIXED BIOLOGICAL TREATMENT SYSTEM



RECYCLE COMPLETELY MIXED BIOLOGICAL TREATMENT SYSTEM

Figure A-1. Schematic Diagrams of Single-Pass and Recycle Biological Treatment Systems

For the recycle system without reaction occurring in the clarifier, the expression analogous to Eq. 2 would be:

$$0 = QX_o - QX_f + V\mu X_e - Vk_dX_e \qquad (3)$$

For the recycle reactor system, the clarifier efficiency may be represented by a recycle factor which, over the normal operating ranges of conventional treatment systems, should be essentially a system constant. Therefore, the recycle factor may be defined as the ratio of the biological solids concentration leaving the reactor over the solids concentration appearing in the clarifier effluent, or

$$RF \equiv X_e/X_f \qquad (4)$$

This expression indicates that the recycle factor will always have a value of one or greater and is a direct function of overall clarifier efficiency.

If the concentration of organisms in the influent, X_o, can be assumed to be negligible when compared with reactor organism concentration, X_e, (as is usually the case) then Eq. 2 reduces to

$$QX_e = V\mu X_e - Vk_dX_e \qquad (5)$$

for single-pass systems. Similarly, if the recycle factor is introduced, Eq. 3 becomes

$$Q\left(\frac{X_e}{RF}\right) = V\mu X_e - Vk_dX_e \ . \qquad (6)$$

Using the definition of hydraulic retention time, $\Theta_H = V/Q$, Eqs. 5 and 6 may be rearranged and reduced respectively to

$$\mu = \frac{1}{\Theta_H} + k_d \qquad (7)$$

for single-pass reactors, and

$$\mu = \frac{1}{(RF)\Theta_H} + k_d \tag{8}$$

for recycle reactors.

Substrate Balance

Employing the same mass balance approach for substrate gives:

Net Change = Inflow - Outflow - Utilization

or in mathematical terms;

$$\left(\frac{dS}{dt}\right)_{net} = QS_o - QS_e - V\left(\frac{dS}{dt}\right)_g \tag{9}$$

The relationship between substrate utilization and biological growth can be expressed as:

$$-\left(\frac{dS}{dt}\right)_g = \frac{1}{Y}\left(\frac{dx}{dt}\right) \tag{10}$$

where; Y = yield coefficient in terms of unit mass biomass produced per unit mass of substrate consumed.

Since $dx/dt = \mu X_e$, Eq. 10 may be expressed as

$$-\left(\frac{dS}{dt}\right)_g = \frac{\mu X_e}{Y} \tag{11}$$

Substituting Eq. 11 into Eq. 9, applying the definition of hydraulic retention time, $\Theta_H = V/Q$, rearranging, and assuming steady-state conditions results in the relationship,

$$\frac{S_o}{\Theta_H} - \frac{S_e}{\Theta_H} = \frac{\mu X_e}{Y} \tag{12}$$

for the single-pass reactor. This same relationship may be obtained for recycle reactor systems when it is assumed that the reactor soluble effluent substrate concentration, S_e, does not differ from the clarifier soluble effluent substrate concentrations, S_f, i.e., all reactions occur in the reactor only.

General Equation for Completely Mixed Reactor Systems

Within the completely mixed reactor, the substrate and organism concentrations are the same as those exiting the reactor and may be determined by equating certain of the foregoing relationships and applying a similar expression to that formulated by Monod (11) for describing the limiting substrate-organism growth rate function, or

$$\mu = \frac{\mu_{max} S}{K_s + S} \qquad (13)$$

where: μ_{max} = maximum specific growth rate of organisms

S = concentration of growth limiting substrate

K_s = saturation constant, i.e., the substrate concentration at which the specific growth rate is one-half of the maximum attainable

Combining Eqs. 7 and 12 and rearranging provides a relationship descriptive of the interdependence between organism concentration, substrate removal, and hydraulic retention time for simple single-pass systems, or

$$X_e = \frac{Y(S_o - S_e)}{1 + k_d \Theta_H} \quad . \qquad (14)$$

The same procedure applied to Eqs. 8 and 12 gives

$$X_e = \frac{Y(S_o - S_e)(RF)}{1 + (RF)\, k_d \Theta_H} \qquad (15)$$

for recycle reactor systems.

The soluble effluent substrate concentration may be determined by equating Eqs. 7 and 8, respectively, for single-pass and recycle reactors with the Monod relationship, Eq. 13, to yield for single-pass systems,

$$S_e = \frac{K_s(1 + k_d \Theta_H)}{\Theta_H \mu_{max} - (1 + k_d \Theta_H)} \tag{16}$$

and for recycle systems,

$$S_e = \frac{K_s [1 + (RF) k_d \Theta_H]}{(RF) \mu_{max} \Theta_H - [1 + (RF) k_d \Theta_H]} \tag{17}$$

Eqs. 14-17 can, after further rearrangement, be employed in the determination of the system-descriptive kinetic constants, μ_{max}, k_d, Y, and K_s. Similar to the method used in formulating the Lineweaver-Burke equation used for evaluating enzyme kinetic data (17), inversion of Eqs. 14 and 16 for single-pass systems and Eqs. 15 and 17 for recycle systems, respectively, yields

$$\frac{S_o - S_e}{X_e} = \frac{k_d \Theta_H}{Y} + \frac{1}{Y} \tag{18}$$

and

$$\frac{\Theta_H}{1 + k_d \Theta_H} = \frac{K_s}{\mu_{max}} \frac{1}{S_e} + \frac{1}{\mu_{max}} \tag{19}$$

for single-pass reactor, and

$$\frac{S_o - S_e}{X_e} = \frac{k_d \Theta_H}{Y} + \frac{1}{Y(RF)} \tag{20}$$

and

$$\frac{(RF) \Theta_H}{1 + (RF) k_d \Theta_H} = \frac{K_s}{\mu_{max}} \frac{1}{S_e} + \frac{1}{\mu_{max}} \tag{21}$$

for the recycle reactor.

All of these equations conform to an arithmetic linear function; plotting $(S_o - S_e)/X_e$ against Θ_H should produce a straight line with slope equal to k_d/Y (for either reactor mode) and an intercept of 1/Y for the single-pass reactor or $1/Y(RF)$ for the recycle reactor. Once k_d has been evaluated, $\frac{\Theta_H}{1 + k_d\Theta_H}$ for single-pass or $\frac{\Theta_H(RF)}{1 + (RF)\ k_d\ \Theta_H}$ for recycle systems can be plotted against $1/S_e$ which should result in a straight line with a slope, K_s/μ_{max}, and an intercept, $1/\mu_{max}$.

Once the system parameters are evaluated, they can be applied in the design and operation of field-scale systems for wastewater treatment. Determination of the critical hydraulic retention time, Θ_{HC} (that retention time which is less than the generation time of fastest growing organisms), follows from complete organism "washout" or when effluent substrate concentration equals influent substrate concentration. The relationships generated from the process model which facilitate determination of Θ_{HC} are

$$\frac{1}{\Theta_{HC}} = \mu_{max}\left(\frac{S_o}{K_s + S_o}\right) - k_d \qquad (22)$$

for single-pass systems, and

$$\frac{1}{\Theta_{HC}} = (RF)\ \mu_{max}\left(\frac{S_o}{K_s + S_o}\right) - k_d \qquad (23)$$

for recycle systems. The effect of recycle on the critical retention time is readily apparent; the critical retention time, though not eliminated, is significantly reduced by practicing recycle.

Similarly, the minimum effluent substrate concentration, S_{min}, may be predicted from the kinetic constants, or

$$S_{min} = \frac{K_s\ k_d}{\mu_{max} - k_d} \qquad (24)$$

Eq. 24 theoretically results when Θ_H approaches infinity or $\mu = k_d$ (i.e., no net growth occurs).

In a more practical sense, the kinetic model presented heretofore has found only limited use as a means for evaluating biological treatment of wastewaters. Historically, the model verification has involved use of synthetic substrates and reasonably well defined biological cultures. Its application to actual wastewater treatment evaluation has been limited by the complexity of both the substrates and heterogeneous microorganism populations involved. Difficulty arises when attempting to use such gross parameters as BOD_5 or COD to measure substrate concentrations. Complete assurance that these parameters represent the singular growth-limiting nutrient cannot always be assumed. A similar difficulty arises in accurate measurement of organism concentrations by gross solids analyses (TSS or TVSS). Nevertheless, in certain instances, particularly with food processing type wastewaters, these gross parameters can well serve to estimate the mass changes which may occur and will allow kinetic model application without many model-deviant assumptions.

APPENDIX B

COST ALLOCATIONS PERTINENT TO WASTEWATER MANAGEMENT ALTERNATIVES FOR A MODERATELY SIZED SHELLFISH PROCESSING PLANT

GENERAL BASES FOR ECONOMIC COMPARISONS

1. Average plant discharge at 0.5 MGD.
2. Annual days of processing operation at 264 days.
3. Expected treatment facility life at 20 years.
4. Capital recoveries (CR) calculated on the basis of an annual finance interest rate of 12%.
5. All estimates prorated to 1974 EPA sewage treatment plant cost index of 170.4 for Atlanta, Georgia (37).
6. Discharge quality parameters before and after screening are as presented in Table 19.
7. Final effluent disinfection costs for on-site alternatives not included due to assumed common value of this aspect for all on-site methods.
8. Ultimate disposition of solids (sludge) not allocated specific costs due to high variability depending upon method employed as well as potential for by-product recovery which can not now be quantified.

Alternative A: Direct discharge to municipal sewerage with no prior treatment.

Annual Flow surcharge*	$34,800
Annual Excess Waste loading surcharge*	$41,820
Total annual cost	$76,620

*Surcharges based upon values reported for the State of Georgia:

1) $0.55 for first 300 cu. ft. flow per month
2) $0.20 per 100 cu. ft. for flows over 300 cu. ft. per month

3) \$0.02 per pound of excess (>250 mg/l each) TSS and BOD_5 per day based upon 24-hour composite sample concentrations and average daily flow.

Alternative B: Screening followed by discharge to municipal sewerage.

Screen Capital Cost	\$30,000 (CR = \$4020)
Annual O & M	\$ 3,500
Annual Surcharges:	
Flow	\$34,800
Excess TSS and BOD_5 (>250 mg/l each)	\$ 8,800
Total annual cost	\$51,120

Alternative C: Primary clarification (600 gpd/ft^2) with overflow discharge to municipal sewerage. 35% BOD_5 and 90% TSS reduction.

Sedimentation Unit Capital Cost	\$100,000 (CR = \$13,390)
Annual O & M.	\$ 8,500
Annual Surcharges:	
Flow	\$ 34,800
Excess BOD_5	\$ 4,400
Total annual cost	\$ 61,090

Alternative D: Chemically aided Dissolved Air Flotation with discharge to municipal sewerage. (80 mg/l $FeCl_3$ + 0.5 mg/l polymer) 40% BOD_5 and 75% TSS removal.

Flotation Unit Capital Cost	\$35,000 (CR = \$4690)
Auxillary Equipment (pressure tank, valves, etc.).	\$45,000 (CR = \$6025)
Annual O & M	\$18,700
Annual $FeCl_3$ chemical cost**	\$ 2,640
Annual Polymer cost**	\$ 950

Annual Surcharges:

Excess BOD_5 and TSS	\$ 6,820
Flow	\$35,600
Total annual cost	\$75,425

**Chemical costs calculated at \$60 per ton for $FeCl_3$ and \$1.50 per pound for polymer.

Alternative E: Field scale treatment with screening, diffused air conventional activated sludge (4-hour retention time), secondary clarification (800 gpd/ft^2) and sludge handling.

Annual Screening cost	\$ 7,520	
Primary clarifier-equalization capital cost	\$ 80,000	(CR = \$10,700)
Aeration tank capital cost	\$ 90,000	(CR = \$12,050)
Secondary clarifier capital cost	\$ 70,000	(CR = \$9370)
Total annual O & M	\$ 36,700	
Annual sludge handling cost (estimated from 50% of capital costs)	\$120,000	(CR = \$16,070)
Total annual cost	\$ 92,410	

Alternative F: Field scale treatment with screening, four-stage rotating biological contactor (1.67 gpd/ft^2), secondary clarification (800 gpd/ft^2), and solids handling.

Annual screening	\$ 7,520	
RBC capital cost (including clarifier, pumps, covers, etc.)	\$140,000	(CR = \$18,750)
Annual O & M	\$ 5,300	
Annual sludge handling cost (estimated at 75% of other annual costs)	\$ 23,090	
Total annual cost	\$ 55,250	

Alternative G: Field scale treatment with screening, extended aeration (18-24 hour) and solids handling.

Annual Screening	$ 7,520	
Unit capital cost	$110,000	(CR = $14,730)
Air blowers and appurentances	$ 90,000	(CR = $12,050)
Annual O & M	$ 13,200	
Solids handling (estimated from 50% of capital costs)	$100,000	(CR = $13,390)
Total annual cost	$ 60,890	

Alternative H: Field scale treatment with screening, primary clarification, granular activated carbon column (counter-current), and solids handling.

Annual screening	$ 7,520	
Annual primary clarification	$13,390	
Carbon column capital cost	$60,000	(CR = $8030)
Annual O & M	$ 9,000	
Annual make-up carbon ($0.12/lb)	$40,000	
Annual solids handling (estimated from 75% of column capital cost)	$ 6,030	
Total annual cost	$83,970	

Alternative I: Field scale treatment with screening, anaerobic packed column ($\Theta_H = 1.5$ days), residual organics and solids treatment, and solids handling. Oyster shell packing media used ($\varepsilon = 0.82$)

Annual screening	$ 7,520	
Anaerobic unit capital cost (100,160 ft^3)	$320,000	(CR = $42,850)
Distribution network, gas collection, etc.	$ 90,000	(CR = $12,050)

Annual residual treatment cost	$ 5,000	
Solids handling (estimated 10% of unit capital cost)	$19,000	(CR = $2540)
Annual O & M	$ 5,000	
Total annual cost	$74,960	

Alternative J: Field scale treatment to Federal 1983 requirements with screening, four-stage rotating biological contactor, multimedia filtration (5 gpm/ft^2), activated carbon slurry, and solids handling.

Annual screening	$ 7,520	
RBC Unit (1.67 gpd/ft^2)	$140,000	(CR = $18,750)
Filtration Unit	$160,000	(CR = $21,420)
Carbon slurry tank and appurtenances	$ 50,000	(CR = $6700)
Total annual O & M	$ 52,500	
Annual make-up carbon ($0.12/#)	$ 42,930	
Annual sludge handling (estimated from 50% of capital costs)	$ 46,860	
Total annual cost	$196,680	