LIGHT - DEPTH RELATIONSHIP FOR ACTIVATED ALGAE

by

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LIGHT-DEPTH RELATIONSHIP FOR ACTIVATED ALGAE

Raymond W. Regan, Ph.D., Environmental Health Engineering

SIGNIFICANCE

Activated algae is a biological concept for providing total environmental protection. Several enhancing features of the approach include the following: (1) Nutrient removal and water quality is improved after wastewater treatment with the combined secondary-tertiary process; (2) The respired gases oxygen and carbon dioxide are internally recycled and reused; (3) Handling and disposal of the solid process wastes is simplified because of the nature of the material; (4) Overall cost for environmental protection can be reduced.

RESEARCH OBJECTIVE AND APPROACH

Activated algae has been a topic of research at Kansas University for the last eight years. The present research has considered a critical aspect of the future field application of activated algae, the economic use of light. Light availability was described in terms of the light-depth (L/D) relationship. Experiments were designed using fundamental principles to determine the microbial growth potenial for biological waste treatment. The investigation was conducted for 15 months using a battery of four laboratory reactors and a small pilot plant operated in the field.

FINDINGS

Experimental results were presented using basic parameters to show when the biological systems became limited by the L/D relationship, carbon and microbial growth rate. Fundamental knowledge of the process was broadened by considering the research information obtained from previous activated algae studies and other work dealing with algae in waste treatment.

CONCLUSION

Activated algae is a viable wastewater treatment approach which shows definite potential over a wide range of operating conditions. Future study is recommended to examine the activated algae process in the field on a pilot scale.

June 7, 1972

Adviser: Ross E. McKinney
Parker Professor of
Civil Engineering

ACKNOWLEDGEMENT

"The woods are lonely, dark and deep,
but I have promises to keep
and miles to go before I sleep
and miles to go before I sleep..."

Robert Frost.

To those who have helped me through the woods, I thank my adviser, Ross E. McKinney and the members of my committee

my associate, Martin Trnovsky

my wife, Mary Beth and family

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"Man finds no new processes in his exploration of natural phenomena; he only becomes aware of processes which extend back nearly to the beginning of time..." (16)

I. INTRODUCTION

Major research interest has been concerned with improved technology capable of providing greater removal of organic and nutrient components from wastewater beyond the levels normally obtained by conventional treatment. Most frequently the so-called "advanced" wastewater reclamation investigations have dealt with physio-chemical processes applied as tertiary stages to existing secondary sewage treatment facilities. Possible treatment schemes have made use of activated carbon, chemical additions, distillation, electrodialysis, ion exchange and reverse osmosis (1). Alternately, researchers have studied the possibilities of complete treatment of the raw sewage by physio-chemical procedures (2,3), and incorporating supplemental techniques into the design and operation of conventional biological facilities to improve overall process efficiency (4,5). Each of these approaches have several features in common. The proposed advanced wastewater treatment schemes have not been shown to be practical for large scale application. Frequently, the spent chemicals and waste sludges produced during plant operation are difficult to handle and can not be readily assimilated back into the environment. Physio-chemical processes are relatively expensive when compared to the cost of conventional sewage treatment (6).

An unfounded belief presently being espoused by the "p-chem" faction of the sanitary engineering profession is the idea that biological methods are unsuited for fulfilling contemporary wastewater treatment requirements. Because of the operational upsets experienced in the field, biologically oriented treatment systems are presented

as unreliable for maintaining high levels of quality control. Furthermore, conventional biological systems are slighted because of their limited capability for removing the undesired materials present in a typical domestic sewage. Classically, the maximum efficiency for secondary sewage treatment plants using activated sludge is a 90 per cent reduction in the carbonaceous biochemical oxygen demand (BOD) with a marginal decrease of about 20 per cent in the amount of nutrients, ammonia and phosphorus, present in the wastewater (8). Additional environmental problems are created when the remaining sewage components including residual BOD and nutrients are added to the receiving waterbody where the stabilization process is completed. Over the years the self-purification capacity of many streams, lakes and estuaries throughout the United States has been exceeded (9,10). Noticeable depreciation in water quality is frequently attributed to excessive enrichment by the nutrients present in treated sewage effluents (11). Since nutrient removal is limited, biological sewage treatment is therefore considered by some engineers to be at the worst outmoded and at the best incomplete.

The lack of confidence in biological systems to some extent is too often founded in erroneous engineering philosophies and a basic misunderstanding of the fundamental principles involved for the proper design of a wastewater treatment facility. As first conceived, spiral or plug flow activated sludge plants were designed on the basis of mechanical rather than biological concepts. Operation of these conventional systems was successful as long as the controlling process variables remained within rather defined limits. Since this design manual type of approach did not consider the effect of significant

operational fluctuations in terms of biological stability, process upsets were frequently reflected in poor quality effluent characteristics. A modification of the activated sludge concept, called complete mixing activated sludge (CMAS) has been developed as a means of providing improved biological stability and high quality effluent characteristics. McKinney (12) has demonstrated the potential of CMAS for improved wastewater treatment at Grand Island, Nebraska. Treatment efficiency as measured by BOD removal averaged 94 to 98 per cent on an annual basis over a three year study period. Residual BOD of the clarified effluent ranged from 7 to 24 mg/liter. Inherent faults associated with the reliability of biological waste treatment are therefore not rooted in fundamental theory, but rather, in unappropriate design practices.

Nutrient removal from domestic sewage by the heterotrophic microorganisms normally present in biological wastewater treatment plants is controlled by the availability of food and oxygen needed for synthesis. Assuming the oxygen requirement is met, modern sewage normally contains excess amounts of nutrients relative to the available organic carbon as estimated by BOD. If wastewater was nutritionally balanced, the concentration of nitrogen and phosphorus in the treated effluent from secondary sewage treatment facilities would be minimum. In some communities a balanced wastewater might be developed by combined treatment of the domestic sewage with an organically rich, but, nutrient deficient industrial waste. In addition, there are other biological approaches which can be used directly to enhance wastewater pollution control practices.

Although it is not a popularly recognized fact, advanced levels of wastewater reclamation can be obtained using biological methods. Activated algae, a process which has been shown to have definite potential, has been a topic of research at Kansas University since 1965 (13,14,15). Activated algae is a modification of the basic activated sludge concept in which the photosynthetic activity of algae is utilized to a significant advantage for application as a combined secondary-tertiary sewage treatment scheme.

The present activated algae research was designed to provide information which should be useful for directing future field studies toward the most favorable economic conditions. Specifically, the objectives of the research are:

(1) to investigate how the light-depth relationship controls the biological processes, so that the most efficient use of light energy can be established.

(2) to determine the full potential of activated algae in terms of maximizing the microbial growth rates as would be predicted by basic concepts.

(3) to study the ranges of process conditions required for enhanced nutrient removal.

(4) to test fundamental information developed in laboratory experiments under conditions more closely related to the field situation.

II. BASIC PRINCIPLES

Activated algae was developed as a wastewater treatment method for removing both organic and nutrient elements in a single stage, resulting in a combination secondary-tertiary process. Several physical, chemical and biological principles are applied as a means of obtaining improved levels of wastewater purification. Principles applied in the activated algae process include:

A. Biological Symbiosis

Fundamentally, activated algae is an example of biological symbiosis, algae and bacteria coexisting within an environment where each microbe requires the metabolic end products of the other. Bacteria utilize oxygen and organic food in wastewater and produce new cells, carbon dioxide and water. By photosynthesis, algae are able to combine carbon dioxide and bicarbonate alkalinity with light and water for energy needed for synthesis. Oxygen is created as an end product of the photosynthetic reaction.

A new biological reaction vessel specifically designed for activated algae most likely should be provided with an artificial illumination capability to insure optimum process effectiveness when natural light becomes limiting. Low energy mixers may provide the turbulence and hydraulic turnover rates required for light exposure to the maximum number of algae cells. Power costs to supply energy for artifical illumination can be significant for full scale application of activated algae. However, lighting expenses should be, at least, partially compensated for by a significant saving in capital

and operating costs associated with the aeration equipment used in present day activated sludge plants. Activated algae should not require high power consuming aeration equipment. The quantity of metabolic oxygen created by the algae should fulfill the requirements of the overall biological symbiosis. Table 1 of the Appendix includes oxygen production as part of the theoretical basis for activated algae for sewage treatment.

B. Bioflocculation and Settling

Naturally induced flocculation of microbial solids developed during operation of the activated algae process has been observed in previous investigations. Chemical additions were not required. After settling of the microbial solids, a well stabilized, high quality effluent was obtained. Flocculation of algae is predictable from basic theory (17) and is the result of several factors, namely:

(1) the algae are maintained in the low energy portion of the growth curve where carbon needed for synthesis is limiting.

(2) the number of intercellular collisions is increased by maintaining the mixed liquor suspended solids (MLSS) concentration at high levels.

In nature, algae remain in a dispersed condition because both of the above requirements for bioflocculation are not provided. Carbon in the inorganic form measured as alkalinity is frequently in excess, and algae concentrations are low.

C. Chemical Reactions

Limitations of available carbon in wastewater treated using

activated algae enables improved removals of nitrogen, phosphorus and other elements from the wastewater. Utilization of bicarbonate alkalinity by algae may cause a significant increase in the pH of the media, as indicated by the following equations:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \quad (1)$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^= \quad (2)$$

summing (1) and (2)

$$CO_2 + H_2O \rightleftharpoons CO_3^= + 2H^+ \quad (3)$$

As carbon dioxide is consumed by the algae, hydrogen ions are removed, adjusting the pH upward. This phenomena is known as the photosynthetic pH shift (18). At elevated pH values, significant amounts of ammonia, phosphorus, calcium and other ions can be removed from the liquid phase by chemical mechanisms (4,19). Since other ions including calcium, carbonate and hydroxide (20,21), can be expected to precipitate with the phosphorus in a typical domestic wastewater, the enhancement of water quality is a significant feature of the activated algae process.

D. Ultimate Disposal

Provisions for solids handling is required in all treatment schemes. Large quantities of materials must be added to the wastewater in many proposed physical-chemical treatment processes. Regeneration of chemicals is not always economically feasible (22). Waste chemicals solids after disposal may build up and deteriorate the environment (19). Biological solids are generally more readily

assimilated by nature than are chemical sludges. Solids harvested from the activated algae process may have potential value as a protein source by completing the food chain or simply dewatered and returned to the land to decompose (24).

E. Nature's Pathway

The application of the algae-bacteria symbiosis to wastewater treatment by activated algae is a streamlined, accelerated mimic of nature's own purification pathway. The beneficial use of algae and bacteria living in a common habitat has been applied by engineers for many years as a means of sewage treatment in stabilization ponds (25, 29). Elevated pH and supersaturated dissolved oxygen (DO) levels have been measured in these ponds on warm sunny days (24). The interrelationship of algal blooms, organic matter and high bacterial counts in lakes where taste and odor problems are of concern in domestic water supplies has been documented (27). Bacterial growth coincides closely with peak algal activity. Marl deposits in lakes containing highly mineralized water are the natural result of chemical precipitation enhanced by the photosynthetic pH shift (28).

III. LITERATURE REVIEW

A. Introduction

The literature review has been limited to a discussion of the use of algae in biological wastewater treatment. Emphasis has been directed towards reviewing research dealing with the light-depth relationship and with the investigations involving activated algae.

Engineers have long been aware that algae play an active role in the treatment of wastewater in stabilization ponds. In 1957, Oswald (29) reported results of the operation of pilot scale oxidation ponds at several pond depths and detention times. Light availability under various conditions effected the operation of these ponds.

The activated algae concept for biological waste treatment was originally formalized by Wahbeh (13) at Kansas University in 1965. Sherwood (14), also at Kansas University, investigated this process using a pilot scale treatment plant in 1966. In 1969 Hanna and Humenik (30) reported activated algae research performed at Ohio State University. Research by McGriff (15) at Kansas in 1970, has demonstrated most completely to date the potential of an activated algae process for removing advanced levels of BOD, nitrogen and phosphorus from domestic wastewater. For additional information reported in the literature dealing with the justification for tertiary treatment, alternative nutrient removal methods and a general discussion of the impact of nutrients on eutrophication, reference is made to the excellent review by McGriff (15). A comprehensive summary of trace element requirements, environmental factors and algae physiology in natural fresh water ecosystems has been published by Lund (31).

B. Oswald et al - 1957

Fundamental quantitative studies for the design and operation of waste stabilization ponds were initiated by the research team at the Sanitary Engineering Research Laboratory (SERL), University of California, Berkley, California. Experimental pilot ponds were operated using various depths, detention periods and loading rates under natural light conditions. The objective of this research was to obtain information concerning the attainable performance of stabilization ponds, their oxygenation factors and the depth and detention period ratio required for maximum efficiency.

The investigations were made with several pilot ponds, as shown in Figure 1 over the period December, 1953 to September, 1956. The dimensions of each of the ponds are as follows:

Pond I was 80 feet long, 3.5 feet wide at the top, tapering to 2.5 feet at the bottom.

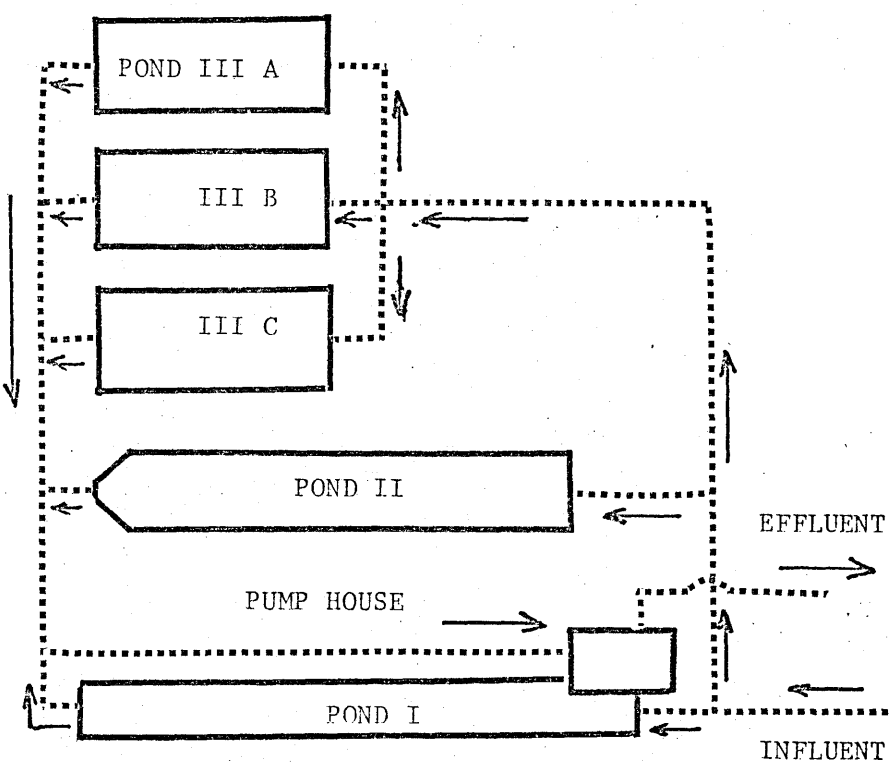
Pond II was 65 feet long, 14 feet wide at the top and 10 feet wide at the bottom.

Pond III was composed of three identical cells each operated independently. Each of the cells were 35 feet long, 11 feet wide at the top and decreasing to 5 feet at the bottom. Liquid depths were varied from 8 to 36 inches.

Domestic sewage was obtained from one of the main sewers of the city of Richmond, California. The incoming wastewater was settled for an average of 1.5 hours prior to its addition to the ponds. The ponds were operated continuously at the desired depths and detention periods for the shorter time interval of 30 days or three detention periods for acclimation to the new experimental conditions. Since the ponds

FIGURE 1

STABILIZATION PONDS USED BY OSWALD



were operated using the simple conventional flow through pattern, a significant concentration of dispersed microbial solids was removed from the systems with the treated effluent. Settleable solids formed a sludge blanket on the pond bottom. The results of experiments in which the depth and detention period were varied during the summer months are presented in Table 1. Results of similar studies conducted during winter conditions are summarized in Table 2.

Under summer conditions, day temperatures of 17° to 20°C, BOD removal ranged from 66 to 92 per cent for detention periods of 2 to 30 days, and did not appear to be directly related to the length of treatment. During the winter months, day temperatures of 8° to 17°C, BOD removal was 49 to 92 per cent for detention periods of 3 to 30 days. Ponds operating with detention periods of 1 to 1.5 days averaged 48 per cent BOD reduction.

Algae concentrations in the summer ponds ranged from approximately 100 to 300 mg/liter for loadings of 32 to 232 pounds BOD/acre-day. Algae content was less than 20 mg/liter when loading was increased to 440 pounds BOD/acre-day. Algae growth increased with loading rate until overloading conditions developed. Afternoon dissolved oxygen (DO) levels, reaching supersaturated concentration as high as 36 mg/liter, appear to be closely related to the algae growth.

In ponds operated during the winter, algae concentration ranged from approximately 20 to 270 mg/liter when loadings were 28 to 270 pounds BOD/acre-day. For a poorly operating system loaded at 610 pounds BOD/acre-day, the algae content was 12 mg/liter. Afternoon DO concentrations were most frequently found to be between 3 and 6 mg/liter but reached a maximum value of 19 mg/liter. As with summer

Data	Pond I	Pond I	Pond I	Pond II	Pond II	Pond II	Pond II	Pond III	Pond III	Pond III	Pond III	Pond III	Pond I	Pond I	Pond I	Pond I
1. Month	May	July	Aug.	July	Aug.	Aug.	Aug.	Aug.	Aug.	Aug.	Aug.	July	May	July	Aug.	Sept.
2. Year	1954	1954	1954	1954	1954	1954	1954	1955	1955	1955	1955	1955	1956	1956	1956	1956
3. Depth, d (in.)	8	8	8	12	12	12	12	14	14	24	24	24	36	36	36	36
4. Detention period, D (days)	3	3	3	4	3	2	1	4	4	7	4	1	30	20	10	5
5. Avg. water temp. (° C.)	21	19	20	18	19	20	18	19	17	17	19	18	20	21	22	21
6. Avg. vis. lt. energy, S (cal./cm.²/day)	168	145	138	251	225	238	195	258	287	287	258	259	189	212	216	148
7. Avg. vis. lt. energy, S' ($\times 10^{-2}$ cal./l./day)	83	72	68	83	74	78	64	73	81	47	42	42	31	23	24	16
8. Avg. sewage B.O.D., L_t, 5-day (mg./l.)	225	154	117	169*	169*	169*	169*	140	126	124	142	117	117	128	130	141
9. Algae wt., C_e (mg./l.)	124	152	164	287	249	103	12	188	220	170	163	20	246	185	125	65
10. Algae wt., Y_e (mg./l./day)	41	51	55	72	83	52	12	47	55	24	41	20	8.2	9.3	13	13
11. Algae heat, H (cal./l./day)	248	304	327	430	500	310	72	283	330	148	246	120	49	56	78	78
12. $F = H/S'$	3.0	4.2	4.8	5.2	6.8	4.0	1.1	3.9	4.1	3.2	5.8	2.9	2.4	2.4	3.2	4.8
13. d/D	2.7	2.7	2.7	3.0	4.0	6.0	12.0	3.5	3.5	3.4	6	24	1.2	1.8	3.6	7.2
14. L_t/S	0.7	0.9	0.9	0.7	0.8	0.7	0.9	0.5	0.4	0.43	0.55	0.45	0.6	0.6	0.5	0.9
15. $F_e = 0.94\ (L_t/S)(d/D)$	3.2	2.6	2.1	1.9	2.8	4.0	9.8	1.8	1.4	1.4	3.0	10	0.7	1.1	2.1	6.9
16. Oxygenation factor, $P = F/F_e$	0.9	1.6	2.3	2.8	2.4	1.0	0.1	2.2	2.8	2.3	1.9	0.3	3.2	2.2	1.5	0.7
17. AM dissolved oxygen (mg./l.)	3	0.9	1.5	3.4	9.6	1.7	0.0	5.9	4.6	5.3	7.2	0	13	10	0.7	0.0
18. PM dissolved oxygen (mg./l.)	22	19	23	17.3	15.6	9.6	0.0	20	22.0	18	17	0.1	36	31	22	4
19. B.O.D. load (lb./acre/day)	136	93	71	115	153	231	440	114	100	97	187	580	32	52	108	232
20. B.O.D. removed (lb./acre/day)	108	86	57	88	136	193	223	94	70	79	161	262	24	39	78	152
21. B.O.D. removal (%)	81	92	80	77	89	84	51	82	70	81	85	41	75	75	70	66
22. Effluent B.O.D. (mg./l.)	43	12	23	46	19	28	84	36	46	23	22	69	29	32	35	58

* Average for entire test period; measured values varied from 116 to 205 mg. per liter.

SUMMER RESULTS STABILIZATION PONDS

Data	Pond I	Pond I	Pond I	Pond I	Pond I	Pond I	Pond I	Pond I	Pond II	Pond II	Pond II	Pond II	Pond II	Pond II	Pond I	Pond I
1. Month	Dec.	Dec.	Nov.	Nov.	Dec.	Jan.	Jan.	Feb.	Nov.	Nov.	Dec.	Jan.	Feb.	Feb.	Nov.	Nov.
2. Year	1953	1953	1954	1954	1954	1955	1955	1955	1954	1954	1954	1955	1955	1955	1953	1953
3. Depth, d (in.)	18	18	24	30	36	36	36	36	12	12	12	12	12	12	18	18
4. Detention period, D (days)	3	1.5	10	10	10	10	10	30	3	3	3	3	3	3	7	5
5. Avg. water temp. (° C.)	17	17	15	13	11	8	8	11	14	13	11	8.1	8.3	11	19	17
6. Avg. vis. lt. energy, S (cal./cm.²/day)	52	54	110	68	48	54	56	72	110	68	60	54	56	72	73	50
7. Avg. vis. lt. energy, S' ($\times 10^{-2}$ cal./l./day)	11	12	18	9.0	4.4	4.9	5.1	7.8	36	22	16	18	18	24	16	11
8. Avg. sewage B.O.D., L_t, 5-day (mg./l.)	199	224	193	188	170	165	109	102	193	188	170	165	109	102	198	216
9. Algae wt., C_e (mg./l.)	20	12	60	58	27	49	49	128	101	117	143	81	62	170	96	76
10. Algae wt., Y_e (mg./l./day)	6	8	6	5.8	2.7	4.9	4.9	5.3	34	39	48	27	20	57	14	15
11. Algae heat, H (cal./l./day)	36	48	36	35	16	29	29	26	200	233	285	162	120	340	82	91
12. $F = H/S'$	3.6	4.0	2.2	4.0	3.6	5.8	5.7	3.3	5.5	10	18	9.1	6.6	14	5.1	8.2
13. d/D	6	12	2.4	3.0	3.6	3.6	3.6	1.2	4	4	4	4	4	4	2.6	3.6
14. L_t/S	3.8	4.1	1.8	2.8	3.5	3.1	2.0	1.4	1.8	2.8	3.5	3.1	2.0	1.4	2.7	4.3
15. $F_e = 0.94\ (L_t/S)(d/D)$	21	45	4.2	8.3	13	11	7.0	1.6	6.6	11	13	12	7.8	5.8	6.5	13
16. Oxygenation factor, $P = F/F_e$	0.17	0.09	0.5	0.5	0.3	0.5	0.8	2.1	0.8	1.0	1.4	0.8	0.9	2.4	0.79	0.57
17. AM dissolved oxygen (mg./l.)	0	0	0.3	1.2	2.2	0.5	—	4.3	3.8	4.1	9.1	7.6	—	—	1	2
18. PM dissolved oxygen (mg./l.)	3.0	0.0	3.1	2.4	2.8	2.3	0.3	14.2	13.1	15.3	12.1	19.1	6.3	—	6.2	9
19. B.O.D. load (lb./acre/day)	270	610	106	129	137	133	89	28	175	170	154	150	100	93	115	177
20. B.O.D. removed (lb./acre/day)	176	324	71	91	69	69	43	24	133	157	119	97	70	74	82	136
21. B.O.D. removal (%)	65	53	67	71	49	51	48	87	76	92	77	65	70	78	71	77
22. Effluent B.O.D. (mg./l.)	70	105	90	79	39	54	26	13	64	79	83	49	44	20	59	50

WINTER RESULTS STABILIZATION PONDS

operations, high DO levels corresponded closely to increased growth of algae.

Data concerning variations in pH and alkalinity of the incoming sewage and pond contents was indicated to have been measured but was not reported. Chemical analyses to determine changes in nitrogen and phosphorus concentrations of the wastewater was not considered at this time. Effluent BOD determinations were made after centrifuging to remove suspended algae.

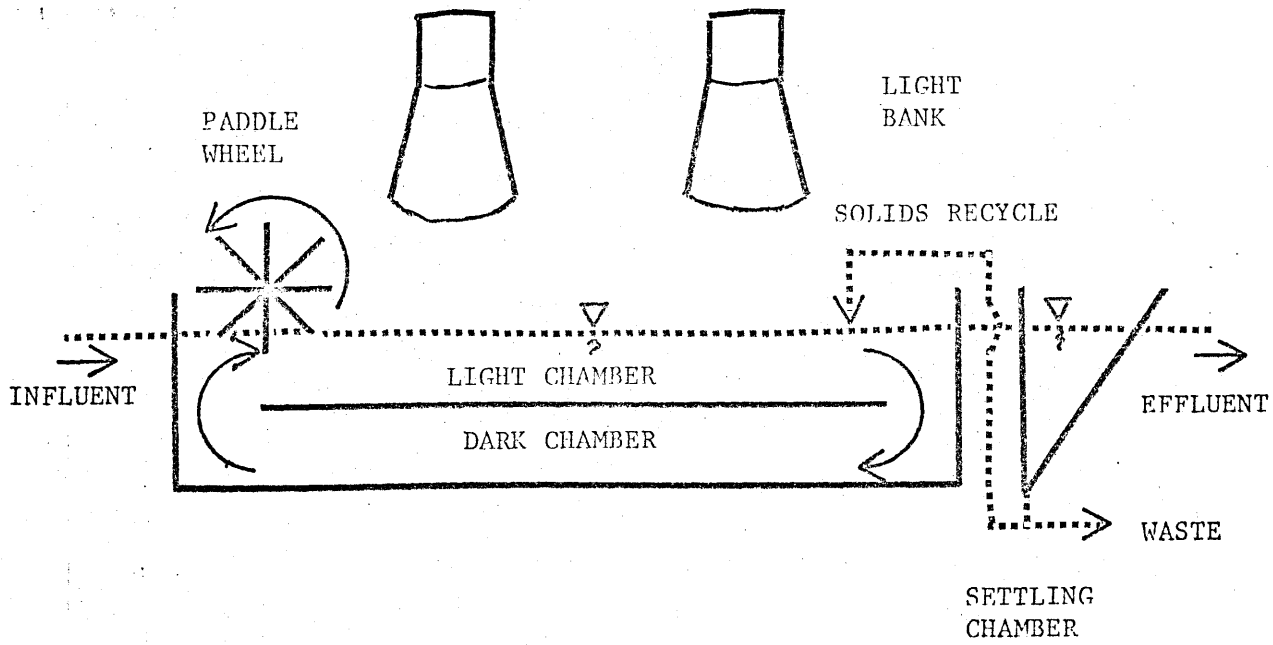
Through the analysis of the results of these experiments the authors proposed rational criteria that may be used as design parameters for stabilization ponds. Quantitative information has been provided by these studies for algae growth as related to BOD loading, detention period and pond depth. Similar factors can be expected to control the light availability and the biological responses of activated algae. In effect, the work of Oswald and his associates represented an investigation of the light-depth relationship for stabilization ponds.

C. Wahbeh - 1965

Wahbeh and his associates developed a series of three laboratory systems for the study of activated algae. The third and final experimental arrangement, shown in simplified form in Figure 2, proved the most acceptable for obtaining experimental results. A rectangular plastic tank, measuring 20x6x2 inches, was built and operated with approximately 2 liters of mixed liquor. A baffle placed horizontally one inch from the bottom, separated the light chamber and the dark chamber. A six inch wheel, with eight paddles, was rotated

FIGURE 2

EXPERIMENTAL APPARATUS USED BY WAHBEH



counterclockwise at 60 rpm and provided circulation of the mixed liquor in the reactor. Illumination of the upper chamber was provided by light bulbs suspended six inches above the surface. Domestic sewage from the Lawrence, Kansas treatment plant was fed continuously to the system. Biological solids were collected in a 1.5 liter settling chamber, before being returned in a concentrated form to the light chamber. Clarified effluent, flowing from the settling chamber was collected and analyzed to determine treatment efficienty. A line diagram showing the flow pattern during the research is presented in Figure 3.

Calculations were made to estimate hydraulic and illumination conditions in the reactor. For the final phase of the study the feed rate was 400 ml per hour, which produced a treatment and settling time 5.0 and 3.75 hours respectively. Circulation within the reactors encouraged by the paddle wheel action was estimated to be 3330 liter per hour; the ratio of the internal flow to the rate of feeding was 8300. Fluid velocity in the light and dark chambers averaged 0.79 ft. per second. Assuming all solids remained suspended, the algal population was exposed to equal intermittent light and dark periods of approximately 2.13 seconds each. Calculations for these hydraulic conditions are summarized in the appendix as Table 2.

Results of the analysis of the raw sewage substrate, mixed liquor and final effluent are summarized in Table 3, for studies when the detention time was five hours. Experimental variables included light intensity and the addition of sodium carbonate and iron to the influent sewage.

Mixed liquor concentrations were controlled at values between

FIGURE 3

BASIC FLOW PATTERN USED BY WAHBEH

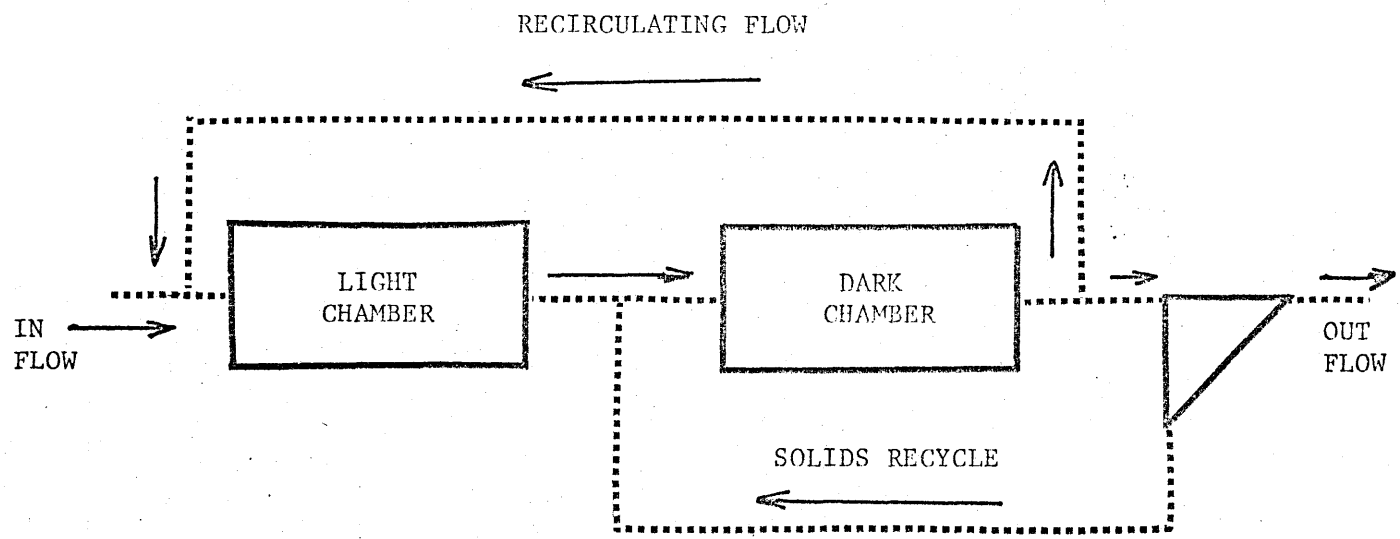


Table 3

EXPERIMENTAL RESULTS OBTAINED BY WAHBEH

		Parts 1	2	3	4
Time of operation (days)		30	30	30	30
Temperature (C)		-	-	30	35-37
Detention time (hrs.)		5	5	5	5
pH		7.7	8.0	8.1	8.0
Alkalinity (mg/lasCaCO$_3$)	in	210	290	320	240
	out	130	190	250	120
Na_2CO_3 added		NO	YES +3mg/l iron	YES	NO
Total MLSS(mg/l)		2000	3700	2800	2300
Total SS effluent (mg/l)		35	20	20	20
Dissolved 02 out (mg/l)		4.0	4.0	-	6.2
BOD (mg/l)	in	300	250	-	129
	out	13	11	-	19
	% removal	95	95	-	85
Ammonia (Nmg/l)	in	25	25	25	20
	out	5	0	0	0
Total Kjeldahl-N	in	60	50	70	50
	out	10	5	5	5
	% removal	83	90	93	90
Nitrate (NO_3-N) mg/l	out	8	5	7	5
Total N (Kjeldahland+NO_3)	in	60	50	70	50
	out	18	10	12	10
	% removal	70	80	83	80
Phosphorus (PO_4mg/l)	in	45	45	46	50
	out	25	35	33	30
	% removal	44	22	28	40
Light intensity (watts)		200	200	300	600
Mixed liquor wasted (l/day)		0	0	0	1.2
Solids produced	mg/l/day	118	96	96	1430
	%/day	8.3	1.3	1.7	62

2000 and 3700 mg/liter for 120 days of operation. Dissolved oxygen was 4 to 6 mg/liter. Under the experimental conditions imposed, BOD removals of 85 to 95 per cent were obtained. Significant reductions of ammonia and phosphorus were also measured. Effluent concentrations of nitrate nitrogen were 5 to 8 mg/liter. Total nitrogen removals of 70 to 87 per cent were calculated by adding the nitrate concentrations to the Kjeldahl nitrogen values. For systems operated with organic feed, the biological flora was comprised of bacteria, Chlorella, filamentous algae, protozoa and rotifers.

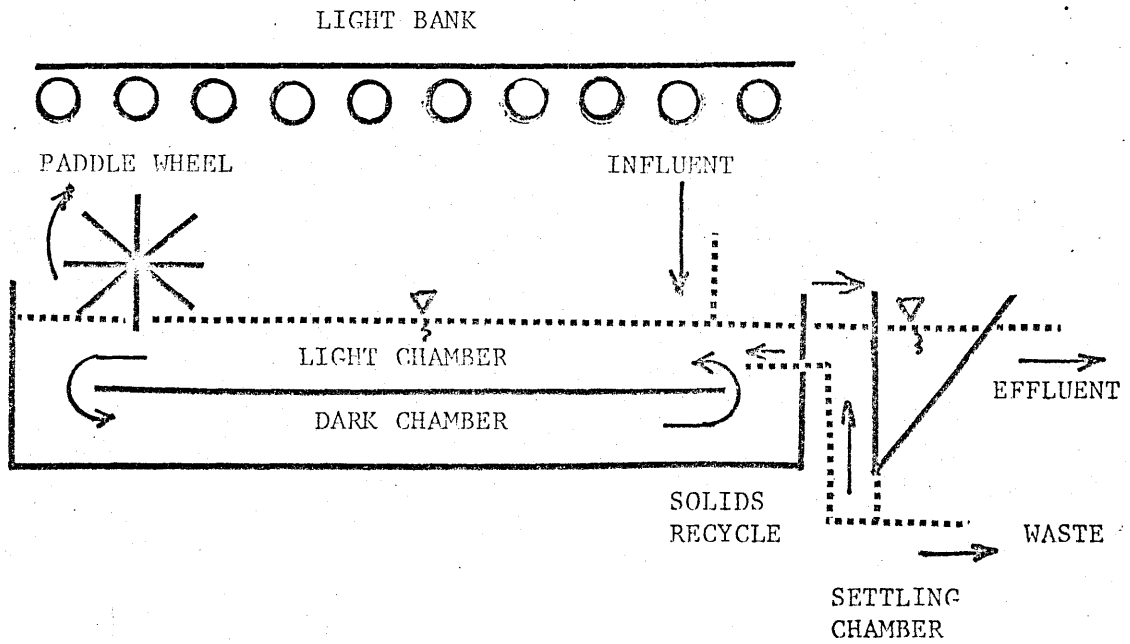
Improvement in the operation of the biological process by added carbonate is not apparent from the information reported. Iron was added to the substrate and was found to improve settling characteristics of the solids in Part 2. Separation of the biological floc from the final effluent was not a problem in Parts 3 and 4. The increase of mixed liquor temperature resulting from excess heat generated by tungsten lamps is demonstrated clearly in Parts 3 and 4. Light intensity, a desired parameter, was not reported for these investigations. Use of the symbiotic relationship of algae and bacteria as a biological system for treating wastewater was demonstrated.

D. Sherwood - 1966

On the basis of the research results obtained by Wahbeh, an activated algae field unit was constructed as shown in simplified form in Figure 4 and operated at the Lawrence treatment plant. The rectangular tank measured 20x6x2 feet, a direct scaleup of the previous laboratory reactor used by Wahbeh. A baffle, which separated the light and dark chambers was located one foot from the bottom. The

FIGURE 4

EXPERIMENTAL APPARATUS USED BY SHERWOOD

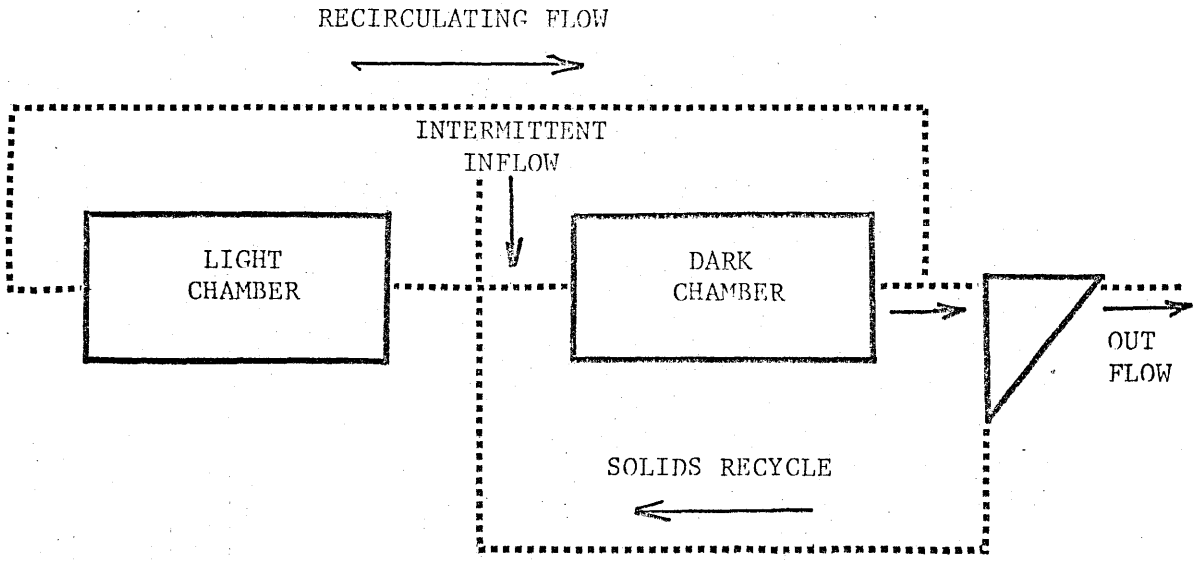


capacity of the field unit was 1800 gallons. Clockwise rotation of a wheel, with eight paddles, six feet in diameter was used to circulate the mixed liquor between the light and dark chambers. The rotation at the speed of the paddle wheel was not reported. For an assumed liquid velocity of two feet per second (32) the speed for the rotor was calculated to be 12.75 rpm. Illumination was provided by ten 200 watt fluorescent light bulbs, suspended ten inches above the liquid surface. Light intensity was rated at 1200 ft-candles. Direct sunlight also contributed additional radiant energy to the exposed chambers. Degritted domestic sewage was pumped into the reactor on a batch basis as needed. Carbon dioxide was bubbled through the mixed liquor at one to three cubic feet per hour. Separation of the biological solids and the clarified effluent was provided in a 370 gallon cone shaped settling chamber. Figure 5 presents the flow pattern during the field studies. Compared to flows in the laboratory reactor, the mixed liquor circulated in the opposite direction in the field unit due to differences of the paddle wheel rotation.

The pilot plant studies were hampered by mechanical and operational difficulties. Useful information was obtained from some experiments. Phase 3 of the field investigations provided the most consistent experimental results. Mixing patterns and feeding rates were varied during the experimental period. For Part A, 450 gallons of raw sewage were added every four days. The paddle wheel was activated only during feeding; quiescent conditions existed in the field unit between intervals. Feeding was increased to 450 gallons every two days then every day during Part B and C, respectively.

FIGURE 5

BASIC FLOW PATTERN USED BY SHERWOOD



Mixing was provided continuously for one minute out of every ten minute intervals for these studies. Detention times decreased from 16 to 8 to 4 days for Parts A, B and C, in that order. Assuming complete suspension of biological solids, the algae population was exposed to equal intermittent light and dark periods averaging 100 seconds, but, ranging from 10 to 550 seconds each. Calculations are summarized in Appendix Table 3.

Results of the field studies are presented as Table 4 and include 47 days of operation. A reduction of 64 per cent in chemical oxygen demand (COD) was determined in Part B. The pH of the mixed liquor was 7.4 to 7.8. Significant removals of ammonia and phosphorus were determined. The concentration of total and volatile effluent suspended solids obtained for Part B was 150 and 60 mg/liter, respectively. The high inert fraction may indicate phosphate or other inorganic compounds were formed and flushed out in the effluent. The influent sewage also contained a large amount of inert solids. Approximately 63 per cent of the total Kjeldahl nitrogen was removed in Part C. Solids production ranged from 7.5 to 11.6 per cent, corresponding to sludge ages of 13.4 to 8.6 days for the three parts of the study. Observation of the microbial population indicated the presence of Chlorella, Scenedesmus, Paramecium and Daphnia. High concentrations of suspended solids in the final effluent indicated poor settling characteristics of the biological floc for Parts B and C.

The contribution of these field activated algae studies is limited. The attempt to move directly from the laboratory to the field was premature. On the basis of this attempt the critical nature of a light-depth relationship for successful operation was recognized

Table 4

EXPERIMENTAL RESULTS OBTAINED BY SHERWOOD

		Parts		
		A	B	C
Time of operation (days)		18	14	15
Temperature (^{o}C)		12-26	-	-
Detention time (days)		16	8	4
pH		7.8	7.5	7.4
Alkalinity ($mgCaCO_3$)		325	275	-
Total MLSS (mg/l)		300	600	850
Total SS(mg/l)	in		600	400
	out		150	200
	% removal		75	50
Volatile	in		300	
	out		60	
	% removal		80	
COD	in		700	
	out		250	
	% removal		64	
Ammonia (mgN-/l)	in	25	20	20
	out	-	7	10
	% removal	-	71	50
Total N(Kjeldahl-N $\frac{mg}{l}$)	in			80
	out			30
	% removal			63
Total phosphorus (mgP/l)	in			15
	out			9
	% removal			40
Soluble phosphorus (mgP/l)	in	6	6	7
	out	-	2	3
	% removal	-	66	57
Solids produced ($\frac{mg/l}{day}$)		35	45	82
%/day		11.6	7.5	9.7

as a future need (32). Measurement of the dissolved oxygen in the light and dark chambers during the investigations would have indicated if the symbiotic relationship of algae and bacteria was operating effectively. Light intensities at the reactor surface were not monitored closely and probably varied significantly during the study. Intensity of light energy is related to the depths of its penetration and corresponding algae growth. An advance in the knowledge concerning activated algae determined from this research was the procedure in which a large scale algae seed population was developed using an inorganic substrate as a start-up operation prior to the addition of raw sewage.

E. Hanna and Humenik - 1969

Research, developed around the activated algae concept, was investigated by Hanna and Humenik. An experimental system was developed for laboratory use which is shown in Figure 6. Light and dark reactions were isolated by the use of a distinct two chamber system. Each chamber had a volume of two liters. A mixture of raw and synthetic sewage was pumped continuously at a rate of 330 milliliters per hour into the completely mixed dark chamber. Mixed liquor was circulated between the dark and annular type light chamber at a rate of 2000 milliliters per minute. For this flow rate equal light and dark periods of one minute each were provided. The circulation to feed ratio was calculated as 358. Algae mass was removed from the walls of the annulus by a scrapper revolving at a rate of 1 rpm.

Illumination was provided by a 20 watt, cool white, fluorescent lamp placed through the center of the light chamber, and a 100 watt

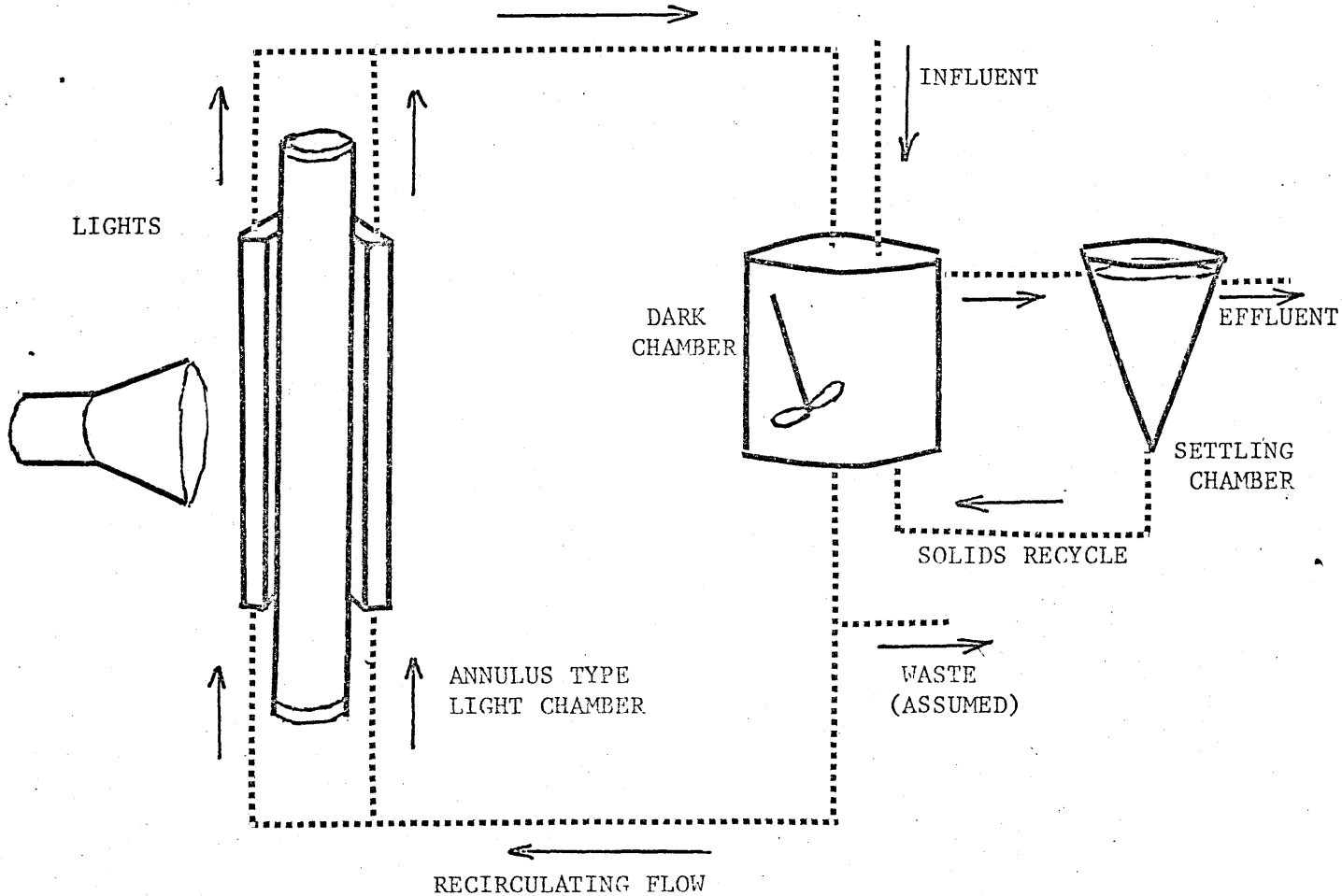


FIGURE 6

EXPERIMENTAL APPARATUS USED BY HANNA AND HUMENIK

tungsten bulb in a reflector on the outer side of the chamber. Light intensity was 1600 ft-candles at the surface of the fluorescent lamp and 600 ft-candles were provided by the bulb.

Sludge was concentrated in a 2.7 liter settling chamber and returned intermittently to the dark reactor at an average rate of 4 milliliters per minute. The sludge recycle ratio was calculated to be 0.72 on the basis of incoming flow. The treatment and settling periods were 12 and 8.2 hours respectively, for all of the studies. The flow pattern of the experimental system is summarized in Figure 7. Hydraulic analysis to estimate the internal flow velocities was limited as dimensions of the light and dark chambers were reported in terms of volume rather than physical size.

Results of the 144 days of operation are presented in Table 5. Experiments included phases during which the oxygen produced by the algae was maintained at a sufficiently high level and other phases in which supplemental aeration was required. During the studies, total mixed liquor suspended solids were varied to investigate the removals obtained at different solids levels. Unfortunately, the data reported was not as complete as would have been desired. Information obtained during Parts C and F is considered most useful as the algae population produced all the oxygen required by the system and solids were controlled at desired levels.

During Part C, the total suspended solids were maintained at approximately 2700 mg/liter COD removals after settling and centrifuging the effluent were 77 and 90 per cent, respectively. An average of 87 per cent reduction in organic nitrogen was obtained. Phosphorus removal was not significant. The solids wasting schedule was

FIGURE 7

BASIC FLOW PATTERN USED BY HANNA AND HUMENIK

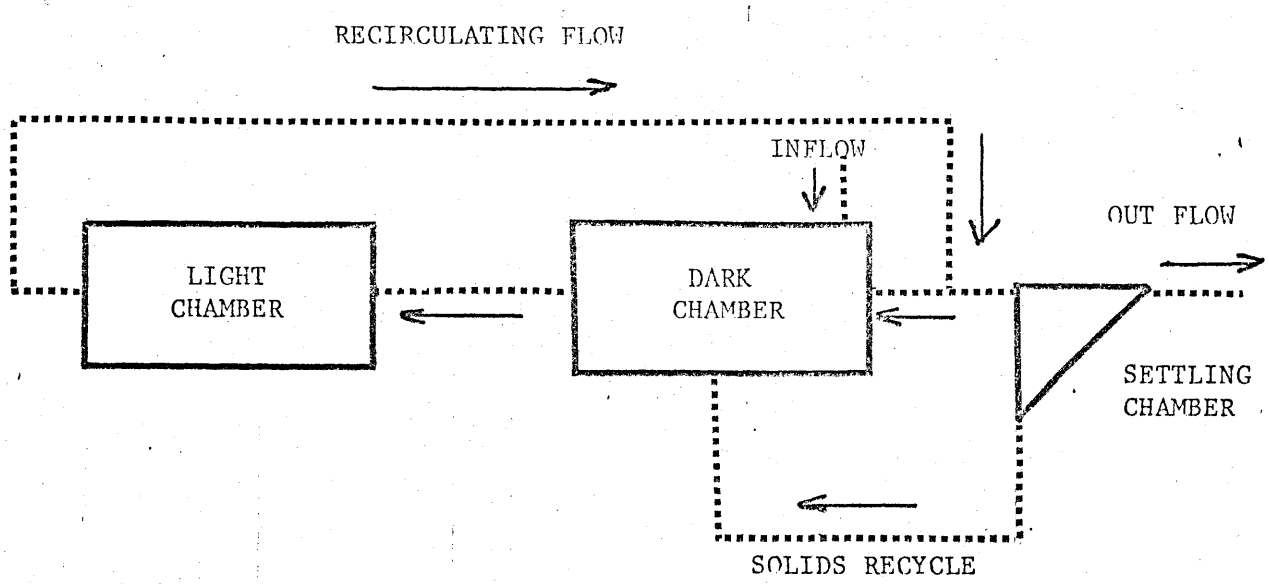


Table 5

EXPERIMENTAL RESULTS OBTAINED BY HANNA AND HUMENIK

	Parts						
	A	B	C	D	E	F	G
Time of operation (days)	58	10	13	20	4	17	22
Description							
supplemental air	YES	YES	NO	YES	YES	NO	YES
solids wasted	NO	NO	YES	NO	NO	YES	NO
Temperature (°C)	20°C room, 31°C reactors, 20°C settling unit						
Max. light intensity (ft-candles)	1200	1200	1200	1200	1200	1200	1200
Detention time (hrs)	12	12	12	12	12	12	12
pH							7.3
Total MLSS (mg/1)	5000	3500	2700	3000	1500	1400	1100
Dissolved oxygen (mg/1)		5-6	5-6	3-5	2	2	4.5
Ammonia (Nmg/1)							
in							
out	0						
% removed	100						
Organic nitrogen (Nmg/1)							
in	12.8	7.7	9.6	14.7	13.9	16.7	
out	1.6	1.0	1.3	2.5	2.5	2.5	
% removed	88	87	87	83	85	85	
Phosphorus (PO_4mg/1)							
in/out	20-40	30	35	30-40			
% removed	0	0	0	0			
COD (mg/1)							
centrifuged in	300	300	300	430	380	380	
centrifuged out	30	30	30	30	30	30	
Centrifuged % removed (mg/1)	90	90	90	93	92	92	
settling out			70	70	90	70	
settled % removed			77	84	76	82	
Solids produced							
mg/1/day	88	50-170	?	-	230	266	
%/day	5	1.4-4.9	-	-	15.4	19	

not reported for Part C.

Mixed liquor suspended solids were controlled at an average of 1400 mg/liter for Part F. Reduction in COD after settling and centrifuging the effluent were 82 and 92 per cent, in that order. Organic nitrogen reduction was 85 per cent. Daily solids production was calculated to be 19 per cent. The authors reported that during Part F, the residual illumination of the fluorescent tube after passing through the light chamber was 20 ft-candles. Illumination was calculated to be 690 ft-candles at the incoming light surface, using the equation proposed by Oswald (33) for depth of light penetration. Use of this equation in a sample calculation is demonstrated in Table 4 of the Appendix.

Hanna and Humenik apparently were not concerned with improving nutrient removals by chemical mechanisms. The authors reported only one ammonia analysis for 144 days of operation in which 100 per cent removal was obtained at pH 7. Reduction in the phosphorus level of the wastewater was minimum.

Treatment efficiency in terms of BOD were not provided. Although not indicated as such, the effluent quality was poor, as judged by the organic nitrogen concentration present. The results of chemical removals represent maximum values as the analyses were made after centrifuging the effluent at 6000 RPM for 20 minutes, except for settled COD results as indicated. Suspended solids of the effluent were not reported. Settling was probably hindered by the 11°C temperature gradient between the reactor and the sedimentation unit. Excess heat would have been generated by the tungsten bulb used to supplement the fluorescent tube. The effect of solids levels

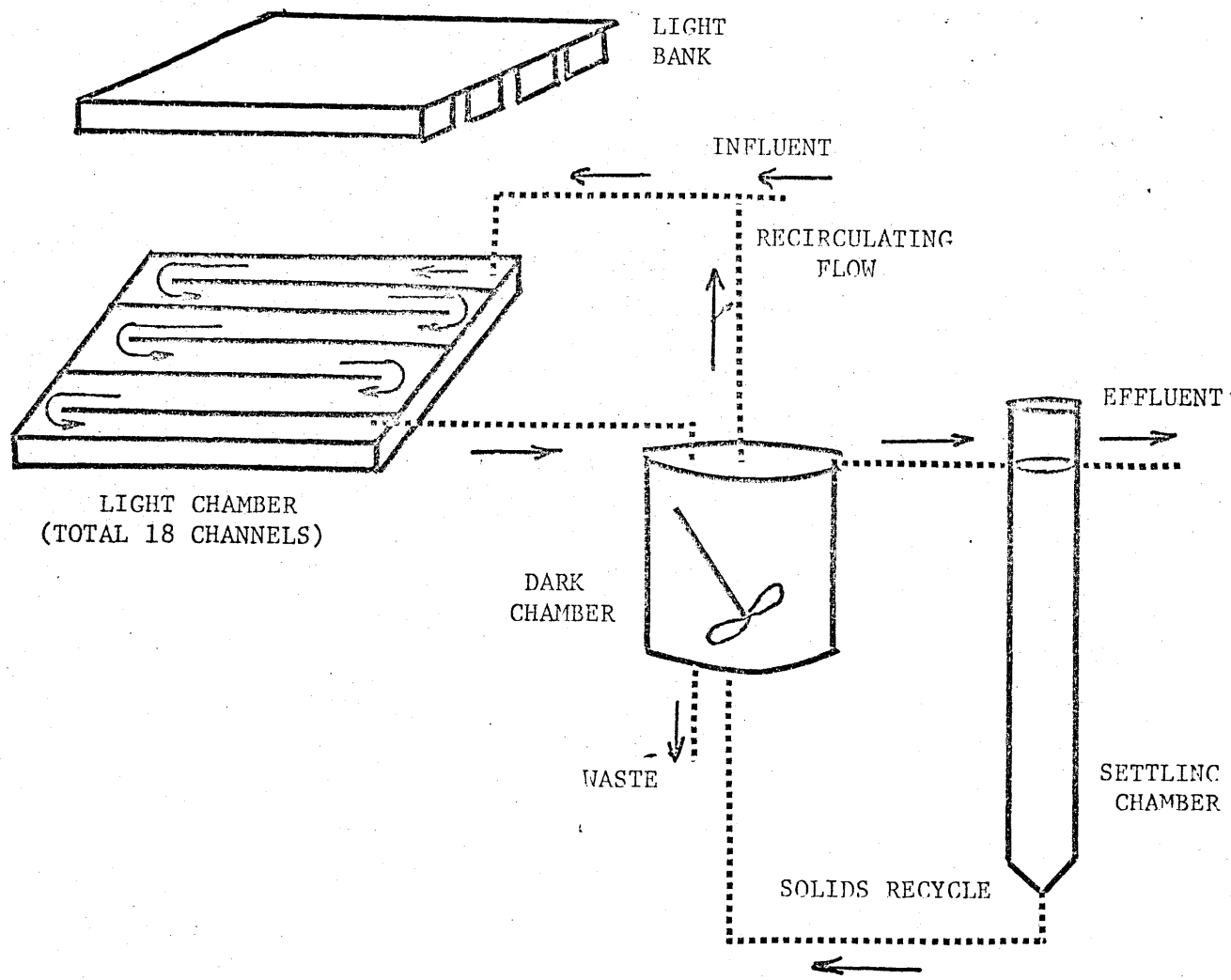
of 2700 and 1400 mg/liter on treatment efficiency is not clear from the information presented. The ability of the algae-bacteria symbiosis to operate effectively, under the experimental conditions imposed, was demonstrated.

F. McGriff - 1970

Research was continued by McGriff at Kansas University using a newly designed laboratory reactor to determine the nutrient removal capability of activated algae. Several experimental set-ups were tested, until the final design presented in Figure 8 was established for Phases 2 and 3 of the research. The apparatus shown provided separate light and dark chambers between which the mixed liquor was pumped at a high rate to simulate intermittent illumination periods. The light chamber consisted in a series of 18 connected channels each approximately 122 cm long and 3.4 cm wide. Substrate was added at one channel to a depth of about 1.5 cm. Flow continued through all 18 passes before entering a completely mixed dark chamber. Volumes within the light and dark chambers, as well as the recirculation flow between these units, were varied during the research to create different illumination periods. Total volume within the chambers ranged from 15 to 21.5 liters. Recirculation rates between the chambers was 3000 and 4600 milliliters per minute. Sewage was fed continuously to the light chamber at the rate of 25 milliliters per minute. Settling of the solids was provided in an 8 liter sedimentation vessel. Concentrated solids were returned to the dark chamber at rates of 500 or 750 milliliters per minute. Final effluent was collected and analyzed to determine treatment efficiency. Solids levels were controlled only during Phase 3 by daily wasting the suspended

FIGURE 8

EXPERIMENTAL APPARATUS USED BY McGRIFF



materials present in four liters of mixed liquor from the dark chamber. The flow pattern during the research is presented in Figure 9.

Calculations were made to estimate hydraulic conditions in the reactor as summarized in Table 6. The ratio of internal recirculation and flow rates was 120 except for Phase II, Part 1, where the ratio was 184. Average culture depths of 1.35 and 1.55 centimeters were determined by considering the total volume and gross surface area of the light chamber. For these depths, velocity of mixed liquor within the channels ranged from 0.36 to 0.48 feet per second. Solids accumulated within dead spaces and algae growth occurred on the channel walls under these flow conditions (32). The light and dark periods were 3.3 and 2.4 minutes, respectively, for the final research period. Settling was accomplished with 5.3 hours detention, with solids returned continually to the dark chamber using a recycle ratio of 20 or 30, based on incoming flow.

Preliminary research reported as Phase 1 dealt with developing a viable experimental apparatus. Algae were batch fed an inorganic substrate during this period. Results for 109 days of operation encompassing Phases 2 and 3 for continuous feeding of inorganic fed and settled domestic sewage are presented in Table 7. During Phases 2 and 3 of the research experimental variables included feed characteristics, light intensity, duration of light and dark periods detention time and concentration of mixed liquor suspended solids. Information presented by the author as Phase 3, Part 3 has been subdivided into two periods, since the results were obtained when mixed liquor concentration, pH and dissolved oxygen in the reactor were significantly different.

FIGURE 9

BASIC FLOW PATTERN USED BY McGRIFF

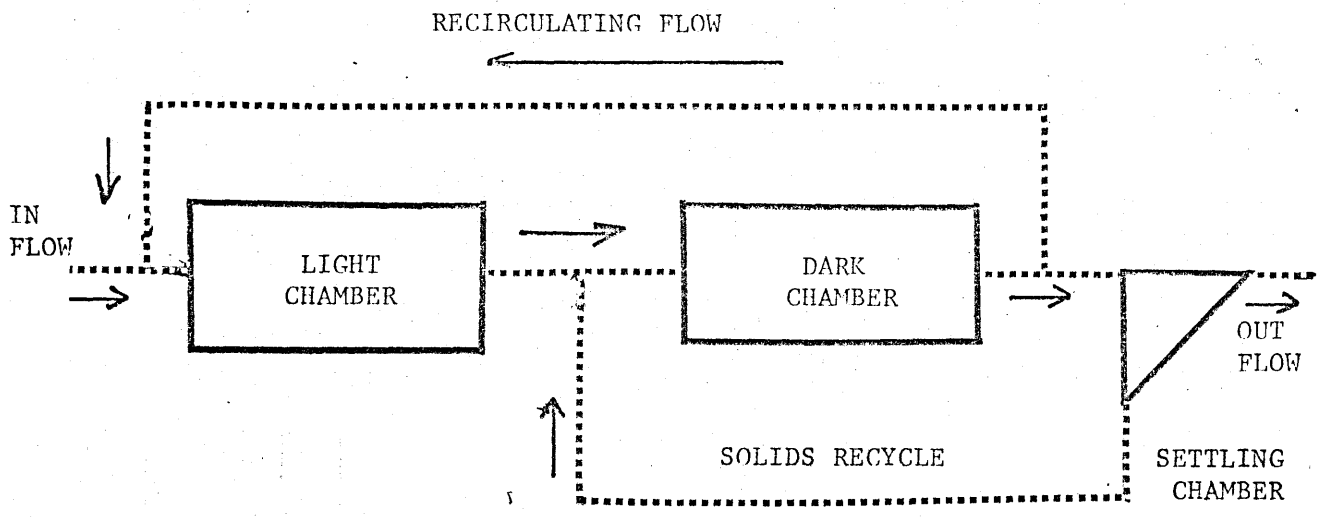


Table 6

HYDRAULIC CONDITIONS USED BY MCGRIFF

Feed rate (ml/min)	25	25	25	25	25
Recirculation rate (ml/min)	4600	3000	3000	3000	3000
Recirculation/feed ratio	184	120	120	120	120
Volume light chamber (l)	11.5	10.0	10.0	10.0	10.0
Volume dark chamber (l)	10.0	10.0	10.0	7.0	5.0
Total reactor volume (l)	21.5	20.0	20.0	17.0	15.0
Average depth (cm) light chamber	1.55	1.35	1.35	1.35	1.35
Detention time (hrs)	14.3	13.3	13.3	11.3	10.0
Velocity in light chamber (fps)	0.48	0.36	0.36	0.36	0.36
Volume settling chamber (l)	8.0	8.0	8.0	8.0	8.0
Settling time (hrs)	5.3	5.3	5.3	5.3	5.3
Sludge recycle (ml/min)	500	500	500	500	500
Sludge recycle ratio	20	20	20	20	20

Table 7

EXPERIMENTAL RESULTS OBTAINED BY MCGRIFF

	Phase 2, Inorganic Feed		Phase 3, Domestic Sewage			
	1	2	1	2	3	3A
Time of operation (days)	17	19	16	17	25	15
Temperature (°C)	25	27	26	26	25	25
Light intensity (ft-c)	300	300	300	300	400	400
Detention time (hrs)	14.3	13.3	13.3	11.3	10.0	10.0
pH light chamber	9.0	8.3	9.0	7.7	8.4	9.2
dark chamber	- - -	- - -	- - -	- - -	8.4	9.2
settling chamber	8.8	8.2	7.4	7.7	8.2	9.1
recycle flow	- - -	- - -	- - -	- - -	7.3	9.1
Total alkalinity ($mg/las CaCO_3$) in	1100	490	230	255	240	230
out	1100	230	140	160	120	130
Calcium (mg/l) in	- - -	- - -	88	95	115	150
Total MLSS (mg/l)	1200	2100	2800	1900	1800	1200
Volatil MLSS (mg/l)	900	1700	2400	1600	1500	1000
Effluent suspended solids (mg/l) total	35	30	30	26	4	3
volatile	25	20	27	20	3	3

Table 7 (continued)

	Phase 2, Inorganic Feed		Phase 3, Domestic Sewage			
	1	2	1	2	3	3A
Dissolved oxygen (mg/l)						
light chamber in	6.3	5.2	4.0	6.0	7.0	7.2
light chamber out	7.5	6.4	5.0	6.5	7.7	8.4
dark chamber	6.4	6.0	4.5	6.5	7.5	8.2
settling unit	3.0	1.0	1.0	1.8	5.2	6.2
Ammonia (NH_3-Nmg/l)						
in	55	60	28	22	26	23
out	4	3	2.5	4.5	1.0	0.5
% removed	92.5	95	91	80	96	98
Organic nitrogen (Org-Nmg/l)						
in	- - -	- - -	23	13	28	31
out	- - -	- - -	2.0	0	0.2	0.4
% removed	- - -	- - -	91	100	99	99
Total nitrogen*(Nmg/l)						
in	- - -	- - -	51	35	54	54
out	42	13	7.7	8.5	4.0	2.8
% removed	- - -	- - -	85	76	92.5	94.2
Phosphorus (filtered)(Pmg/l)						
in	11.5	10.0	9.5	6.0	8.4	6.0
out	5.0	6.0	6.3	4.5	2.7	1.2
% removed	57	40	34	25	68	80
BOD (mg/l)						
in	- - -	- - -	120	105	110	80
out (filtered)	- - -	- - -	3	7	4	3
% removed	- - -	- - -	97.5	93.5	96.5	96.5

* total nitrogen includes Kjedahl nitrogen, ammonia, nitrite and nitrate.

Table 7 (continued)

	Phase 2, Inorganic Feed		Phase 3, Domestic Sewage			
	1	2	1	2	3	3A
COD mg/l						
in	- - -	- - -	250	170	250	190
out	- - -	- - -	45	22	25	30
% removed	- - -	- - -	82	87	90	84
Solids wasted (l/day)	0	0	0	4	4	4
Solids produced (mg/l/day)	59	54	54	500	490	330
(%/day)	4.9**	2.6**	1.9**	26.3	27.2	27.6
Light and dark period (min)	2.5,3.0	3.3,4.1	3.3,4.1	3.3,3.1	3.3,2.4	3.3,2.4

** calculated based on effluent solids concentration.

The results of the final phase show that pH and dissolved oxygen levels rose to maximum levels after increasing the light intensity from 300 to 400 ft-candles and decreasing the dark period from 4.1 to 2.4 minutes for a constant light period of 3.3 minutes. Removals of an average 96 per cent BOD and 86 per cent COD appear not to have been affected by decreasing the detention time in the reactor from 14.3 to 10.0 hours. Improved reductions in ammonia and phosphorus appear to be functions of increased pH levels. Ammonia and phosphorus removals of 98 and 80 per cent, respectively, were obtained when the pH was 9.2 in the reactor. During the research, volatile mixed liquor suspended solids were controlled at desired concentrations between 2800 and 1000 mg/liter. Maximum solids produced were calculated to be approximately 27 per cent per day. During the research the predominant form of algae was identified as Chlorella and a secondary predominance of the diatom Nitschia.

Conditions suitable for operation of activated algae as a secondary-tertiary treatment system had been presented. Excellent separation of the biological floc by settling to produce a clarified effluent was shown by the low suspended solids level, 3 to 4 mg/liter. Nutrient concentrations in the treated effluent averaged 3.5 and 2.0 mg/liter for total nitrogen and phosphorus, respectively. Residual BOD concentrations of only 3.0 mg/liter were present in the effluent. Further research is needed to optimize the biological processes before the most economical activated algae nutrient removal can be developed on a larger scale.

G. Summary

Oswald et al (29) used a fundamental approach for analyzing and interpreting results obtained for the light-depth effects on stabilization pond performance. A significant amount of research information has been provided by the limited number of investigations dealing with activated algae. Laboratory experiments have shown the capability of activated algae for improved wastewater treatment. Valuable information concerning the critical nature of light availability resulted from a pilot plant investigation although the experiments were hindered by operational difficulties. Previous research however, did not attempt to establish the full potential of the process in terms of maximizing microbial growth rates. Microbial growth rates in an activated algae process would be expected to be functions of several control parameters, including the liquid detention time, the sludge retention time (SRT) and the light-depth relationship. The present laboratory research is directed towards better defining the limits of each of these conditions. Experimental information provided by the earlier researchers will be useful to confirm, extend and unify overall knowledge of photosynthetic microorganisms for activated algae and other treatment systems where algae are used.

IV. EXPERIMENTAL APPROACH

A. Introduction

The availability of sufficient quantities of light energy was recognized as a factor controlling photosynthetic performance of the activated algae process. Fundamental concepts applicable to the microbial responses operative in the more common biological waste treatment systems were also expected to control activated algae.

Design of the laboratory reactors was simplified and operating procedures were standardized to minimize experimental error. For example, algae growth on exposed solid surfaces was minimized by designing the laboratory reactors with low surface area to volume ratios. This precaution effectively provided the operation of the experimental systems with almost complete suspension of microbial solids when continuously mixed, with a minimum of maintainence. If the solids were not suspended, investigation of a light-depth relationship would be adversely effected because of the undesired changes in light penetration.

The research was accomplished in three data collection and analysis phases. Data collection phases were differentiated from each other by the substrate used during a given series of experimental runs. Parts of the experiments designated as Phase 1 overlapped chronologically with studies performed for Phase 2. Data analysis was kept as current as possible to allow for efficient carry over of the research information to operating experiments.

Experimental knowledge acquired was desired to be of a basic nature and to be expressed in practical terms for direct translation from the laboratory to future pilot and field studies.

B. Experimental Systems

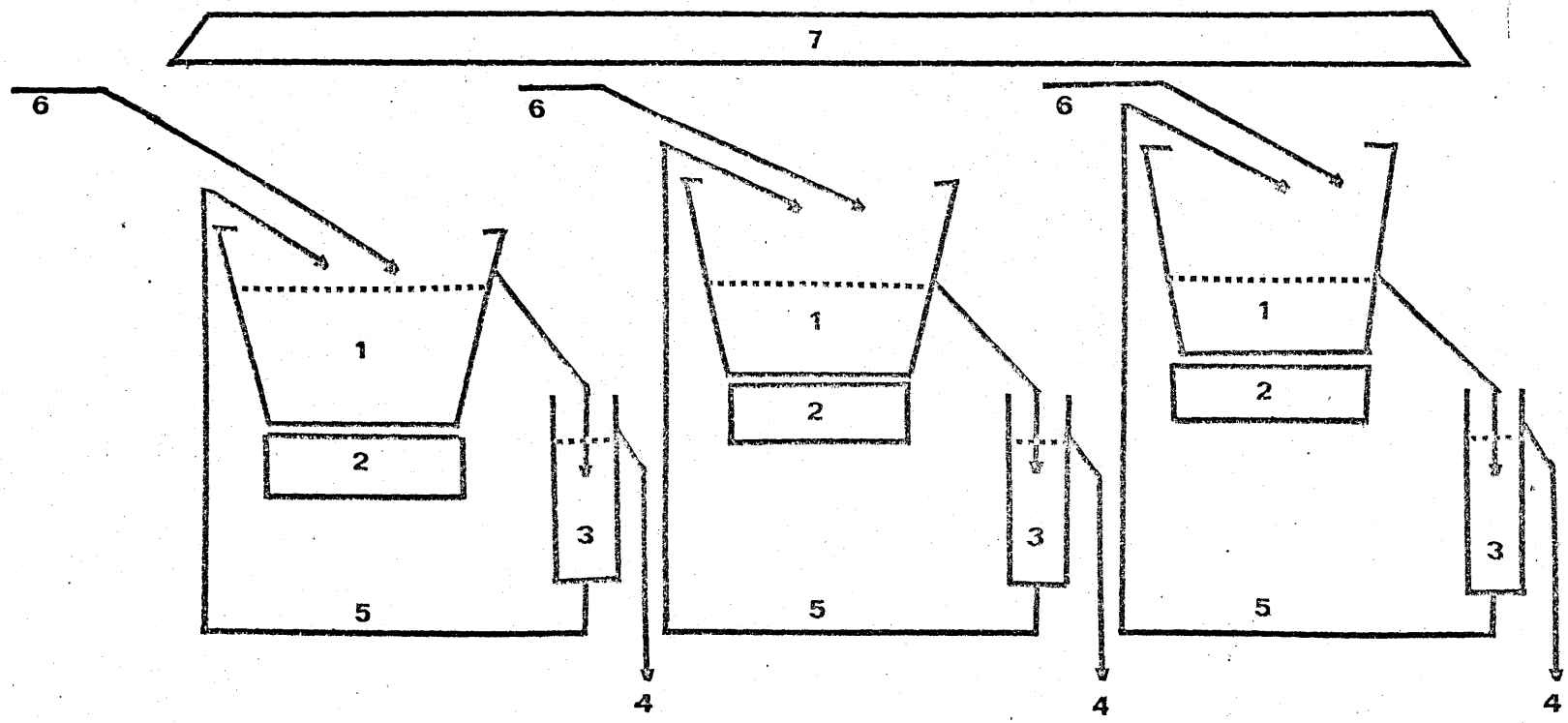
Phase 1 and Phase 2

The experimental systems used for Phases 1 and 2 are presented in Figures 10, 11 and 12. A series of four reactors, each controlled at desired depths were operated in parallel on a continuous basis. Liquid depths were varied at 1.7, 3.3 and 5.0 inches. Corresponding volumes within the reactors were 1.5, 2.5 and 3.5 liters. The lighted surface area for all the reactors was 314 cm^2. The feed pump rates were adjusted to provide the desired waste detention time in each reactor. Biological solids were kept in suspension by mixing action provided by a magnetic stirrer under each reactor. Mixed liquor from each reactor flowed by gravity to 0.8 liter settling columns which provided a suitable period for separation of biological solids from the clarified effluent. Concentrated solids were continuously returned to the reactors at a rate of approximately 100 ml/minute. A high solids recycle rate was required to minimize solids settling in the return line. Effluent was collected from each reactor in containers having a capacity suitable for a daily composite sample. After samples were obtained for chemical analysis the effluent containers were emptied and returned in place for the next daily sample.

For part of Phase 1 and all of Phase 2 an intensity of 200

FIGURE 10

EXPERIMENTAL SETUP WITH CONSTANT LIGHT INTENSITY



Legend

1 mixed liquor
2 magnetic mixer
3 settling column
4 effluent
5 solids recycle
6 feed
7 light

FIGURE 11

EXPERIMENTAL SETUP FOR VARIABLE LIGHT INTENSITY

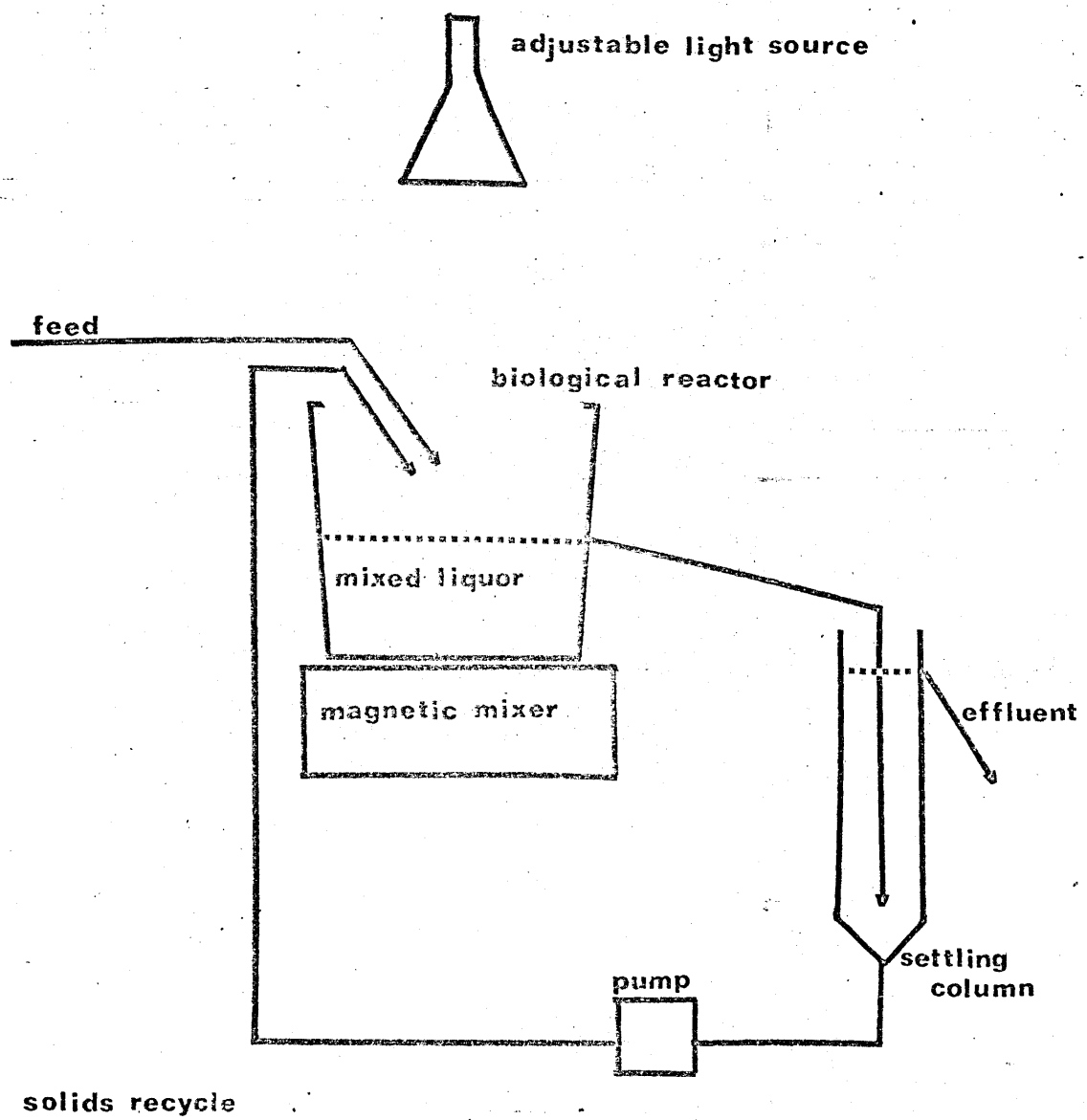
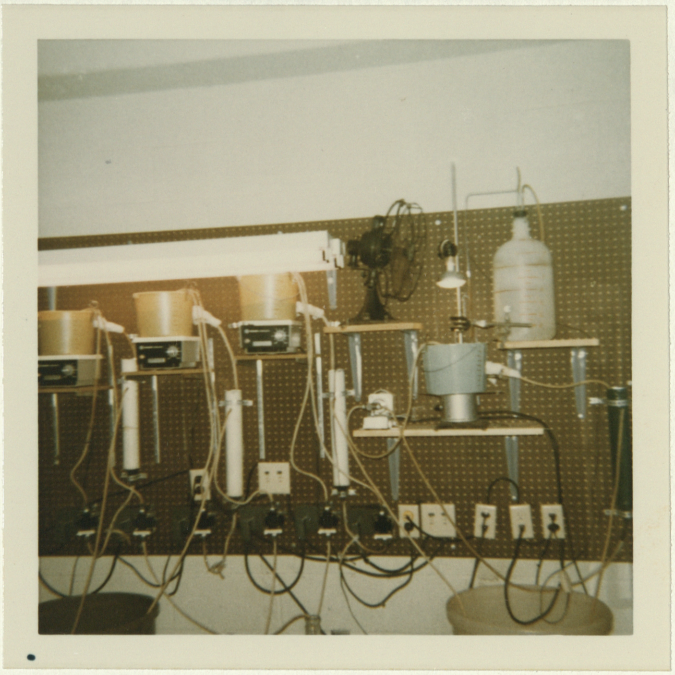


FIGURE 12

PHOTOGRAPH OF LABORATORY SYSTEM IN OPERATION



ft-candle was provided by four 48 inch fluorescent tubes suspended over three of the reactors. The fourth reactor used during Phase 1 was illuminated by means of a floor lamp. Light intensities were varied from 200 to 600 ft-candles.

The experimental setup including the biological reactors, pumps, mixing and lighting equipment and associated apparatus was built as a semipermanent fixture on the East wall of Room 200 of the C. L. Burt Environmental Health Research Laboratory at the University of Kansas, in Lawrence, Kansas.

Phase 3

The experimental system used for Phase 3 is presented in Figures 13 and 14. The lighted mixing tank was operated at a depth of 1.7 inches. A small plastic cylinder, placed in one corner, was used as the exit spout and depth controller. The volume of mixed liquor in the reactor was 29 liters. The lighted surface area was 6960 cm^2. Primary treated domestic sewage was added to the mixing tank on a continuous gravity controlled basis. The waste flow rate was controlled at the incoming sewage tap by means of a plug type valve to provide the desired detention period. Microbial solids were kept in suspension by the fluid velocity maintained by a small submersible pump placed near the center of the mixing tank.

Mixed liquor overflowed the depth control weir into a 12 liter settling column. Concentrated solids were continuously pumped from the bottom of the column and returned to the mixing tank at approximately 100 or 700 ml/minute. The final effluent volume was collected in 200 liter containers. The incoming and outgoing waste streams

FIGURE 13

EXPERIMENTAL SETUP FOR PILOT PLANT

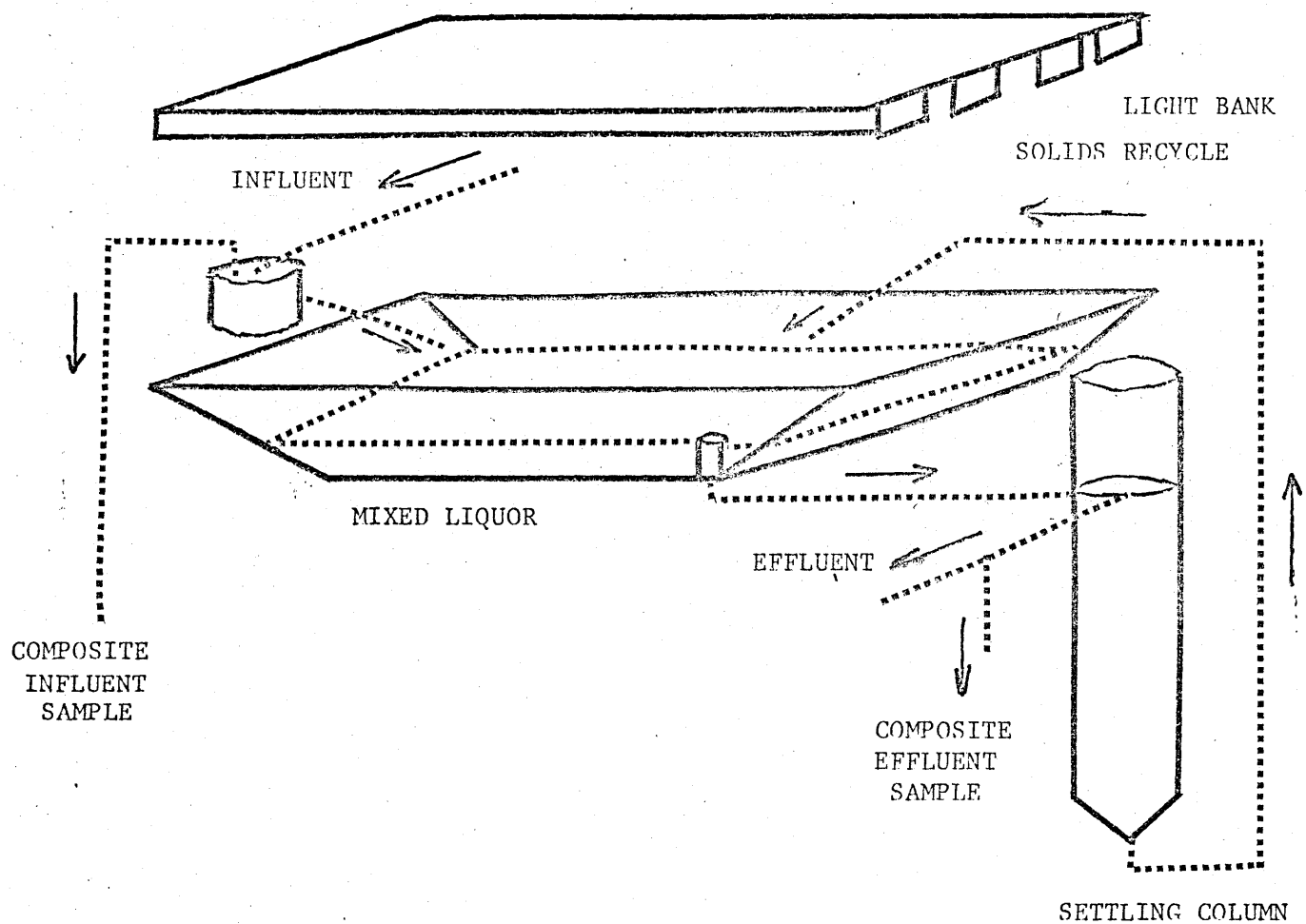
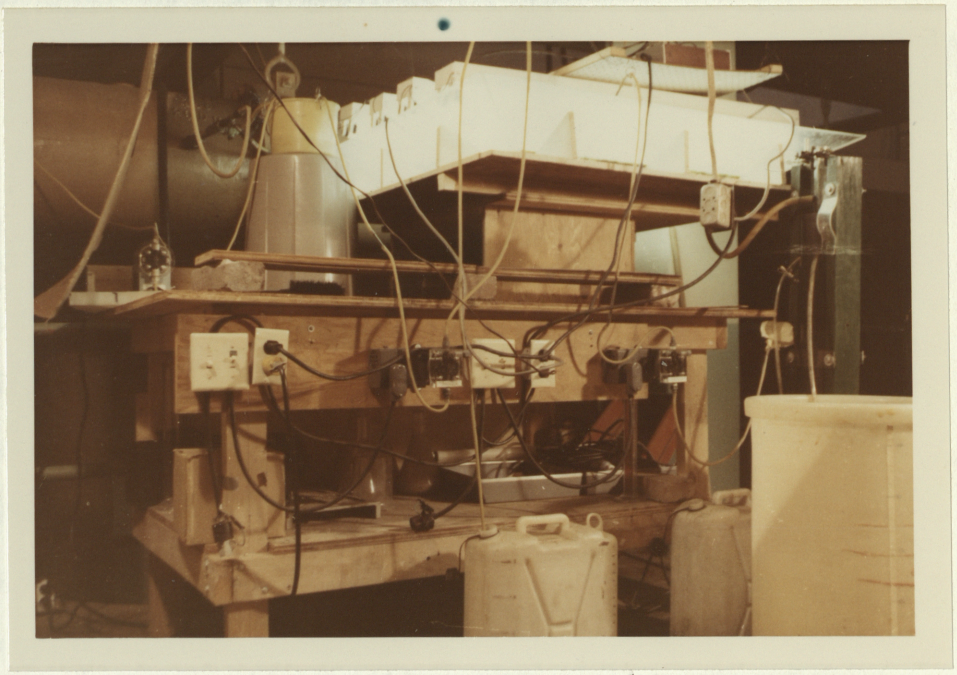


FIGURE 14

PHOTOGRAPH OF PILOT PLANT IN OPERATION



were monitored continuously, each using diaphragm action sampling pumps. Accumulation of the samples in 20 liter containers provided daily composited volumes for determining the efficiency of biological treatment.

For Phase 3, radiant energy at intensities of 200 and 600 ft-candles were provided by eight 48 inch fluorescent tubes suspended over the mixing tank. The experimental system was set up and operated on the second level of the control building at the Lawrence Sewage Treatment Plant, Lawrence, Kansas.

C. Description of Experiments

The laboratory studies made use of the series of four continuously fed biological reactors. Information obtained from the experiments was used to evaluate the biological and chemical responses and wastewater treatment efficiency for several variable conditions. Experimental variables included: (1) wastewater characteristics, (2) liquid detention time, (3) sludge retention time, (4) light intensity and (5) liquid depth within the reactor. A media prepared in the laboratory and containing inorganic components similar to domestic sewage was prepared daily during Phase 1. The formulation of this substrate is presented in the Appendix Table 5. For Phase 2, the substrate was changed to a synthetic wastewater with characteristics similar to a typical settled domestic sewage as shown in Table 6 of the Appendix.

The third experimental phase was designed to gain information concerning the characteristics of an activated algae system operating under conditions more typical of the actual field situation. Primary

treated sewage was used as feed for the experiments performed as Phase 3. The small pilot size biological reactor was placed directly on line at the treatment plant with primary effluent continuously flowing into the system.

A detailed outline of the experiments and a schedule for completion of each of the research phases is presented as follows:

Phase 1 Synthetic Inorganic Fraction of Domestic Sewage

Part 1 - Startup

Seeding a single 4 inch deep reactor with pond water was followed by batch feeding of synthetic substrate on an every other day basis. Detention time within the reactor was approximately six days. The feed rate was then increased to allow a detention period of three days. Light intensity was 75 to 100 ft-candles at the liquid surface as provided by Westinghouse "Gro-Well" fluorescent tubes. The lighted surface area was 1135 cm^2.

Research period - 1/14/71 to 4/10/71

Part 2 - Continuous Feeding - Constant Light Intensity

The series of three reactors with constant light intensity was used for continuous feeding studies at desired detention times and sludge wasting rates. A range SRT was provided by daily wasting of desired quantities of mixed liquor suspended solids (MLSS). Experimental studies were performed using various combinations of feed detention time and solids wasting to determine the potential maximum growth rates of the microbial solids. Experimental conditions studied in the three reactors included:

Run No.	Approximate Detention Time (hrs)	Wasting Per Cent Per Day	Light Intensity (ft-c)	Time Required (weeks)
1	12	no wasting	200	4
2	12	20	200	2
3	12	10	200	2
4	12	13.3	200	2
5	6	13.3	200	2
6	3	20	200	2

Research period - 4/15/71 to 7/30/71

Part 3 - Variation of Light Intensity

Experiments were performed to determine the effect of light intensity on algae response. A 2.5 liter reactor shown in Figure 11 was operated on a continuous feed basis at a liquid depth of 3.3 inches. The operating variables included: liquid detention time, light intensity and wasting rate. Illumination was provided by a flood lamp. Excess heat generated by the lamp was expelled by an electric fan. Experimental conditions in this study included:

Run No.	Approximate Detention Time (hrs)	Wasting Per Cent Per Day	Light Intensity (ft-c)	Time Required (weeks)
1	12	20	200	2
2	12	20	300	2
3	12	20	400	2
4	16	20	500	2
5	12	20	500	2
6	9	20	500	2
7	6	20	500	2
8	6	20	600	2
9	6	40	600	2

Research period - 6/8/71 to 12/8/71

Phase 2 Synthetic Domestic Sewage

Further investigations were concerned with evaluating activated algae systems when fed a synthetic domestic sewage. The light intensity was maintained at 200 ft-candles by the use of "Gro-Well" fluorescent tubes. Experiments using the series of three reactors included the following:

Run No.	Approximate Detention Time (hrs)	Wasting Per Cent Per Day	Light Intensity (ft-c)	Time Required (weeks)
1	6	20	200	3
2	6	25	200	2
3	6	30	200	2
4	6	40	200	2
5	3	40	200	2
6	3	80	200	2

Research period - 9/10/71 to 12/15/71

Phase 3 Field Operation Using Domestic Sewage

The culmination of the experimental research involved the examination of the light-depth relationship for activated algae under conditions resembling an actual field situation. Design of the biological system for this phase of the research was made upon consideration of several sources of information, namely:

(1) results obtained in Phases 1 and 2 of the present research,

(2) results and operating experiences reported for previous activated algae studies,

(3) fundamental relationships for biological waste treatment in association with the expected variation of flow and chemical quality of the incoming wastewater,

(4) discussions with the plant supervisor concerning peculiar operating conditions to be expected at the Lawrence Sewage Treatment Plant.

Experimental conditions studied using the small pilot plan included:

Run No.	Approximate Detention Time (hrs)	Wasting Per cent Per Day	Light Intensity (ft-c)	Time Required (weeks)
1	3.5	38	200	1.8
2	3.5	38	200	1.8
3	3.5	38	600	1.4
4	3.5	52	600	1.7
5	9	52	600	1.0
6	9	21	600	1.7
7	20	0	600	1.7

Research period - 1/17/72 to 4/1/72

The overall period of the research extended for 15 months, January 14, 1971 to April 1, 1972.

D. Operation and Data Collection

Procedures used for the operation of the experimental systems and for the collection of data necessary for characterizing activated algae under various conditions included the following:

(1) Operation and Maintainence

Operation of the experimental systems used during each of the three phases and data collection practices were maintained with the awareness that small research oversights may lead to significant error in the results of data analysis. Experimental error in small scale systems can be magnified when the information is translated to

large scale investigations. The following procedures were used to insure the data collected was representative of the operation of the experimental systems.

(a) Data collection schedules and practices were physically maintained as uniformly as possible over the entire research period. Sample collection and routine maintainence was generally provided each day at the same hour.

(b) Temperature and DO readings were taken and recorded with a minimum of operational upset. All pumps were then temporarily stopped. Volume of the composite effluent for each reactor was recorded.

(c) Mixed liquor solids were allowed to settle within the reactors by turning off the magnetic stirrer or submersible pump.

(d) Microbial solids were removed from the walls of the settling column, recycle pump and associated lines and collected for return as part of the mixed liquor.

(e) Mixed liquor supernatant replaced the fluid volume loss to the settling column.

(f) The combined mixed liquor solids were thoroughly stirred as a volume was removed for the desired wasting rate. A portion of composite effluent was exchanged to replace the fluid volume removed from the reactor by wasting.

(g) Aliquots of incoming feed, mixed liquor and composite effluent were collected each day for further chemical analysis.

(h) For the laboratory studies, fresh feed was generally made up daily. All effluent containers were drained, rinsed clean and returned to operating position. Pumps and mixers were cleansed and

maintained when required.

(i) The experimental system would normally be returned to operation within 60 minutes.

(2) Data Collection and Chemical Analysis

Phase 1 and Phase 2

Data analysis for the operation of the reactors in the laboratory included measurement of the conditions shown in Table 8.

Table 8

DATA ANALYSIS - LABORATORY STUDIES

	Number of Replicates			
Analysis	Feed	Mixed Liquor	Settling Column	Effluent
pH	1	1		
DO	1	1	1	
Temperature	1	1		
TSS		1		1
VSS		1		
Volume	1			1

The pH was measured using a Fisher pH meter operated with a glass electrode. A Precision DO probe was used to estimate the oxygen concentration in the system. The probe was calibrated in air to allow correction of the meter reading to units of mg/liter dissolved oxygen. Temperature was determined using a thermometer to the nearest Centigrade degree. TSS and VSS were measured by the membrane filter technique suggested by Englebrecht and McKinney (23). Difference in feed used and effluent volume produced represents evaporation and other experimental losses.

Operation of the biological reactors at the desired conditions were continued until equilibrium conditions were obtained. Equilibrium was judged primarily on the basis of maintaining levels of mixed liquor TSS and VSS within close ranges. In addition, during Phase 2, the experiments were continued for approximately three solids turnover times. Using this procedure it was assumed that the microbial flora present had developed under the enviromental conditions imposed for a given run. When the systems meet these criterion for equilibrium, samples of feed and composite effluent were collected for at least three consecutive days. In addition, to the routine procedures, analysis performed on the equilibrium samples included: alkalinity, ammonia, oxidized nitrogen, total phosphorus and calcium. The microbial flora present was also observed under the microscope. For Phase 2, soluble and total COD were measured to estimate the removal of organic materials from synthetic sewage substrate.

Procedures described in Standard Methods (26) were utilized in the research to estimate alkalinity, ammonia, total phosphorus and calcium. Alkalinity was determined potentiometrically by titration to an end point of pH 4.5. A direct Nesslerization technique was used to measure ammonia. Total phosphate was determined by the stannous chloride procedure after autoclaving the samples at a pressure of 15 psi for 30 minutes. The calcium content of the samples were determined by titration with EDTA using hydroxy naphtol blue as the indicator.

Combined nitrate and nitrite were measured by the Hach cadmium reduction method (34). A rapid COD procedure (35) was used extensively

in the research in preference to the standard COD technique. Table 7 of the Appendix provides details of the laboratory procedures used.

Phase 3

Daily analysis of the operation of the small pilot scale reactor was more extensive as shown in Table 9.

Table 9

DATA ANALYSIS - PILOT PLANT STUDIES

Analysis	Number of Replicates Influent	Mixed Liquor	Settling Column	Effluent
pH	2	2		2
DO	1	3	1	2
Temperature	1	3	1	2
TSS	2	2		2
VSS		2		
Sludge Volume Index (SVI)		1		
Flow Rate or Volume	1			1
Alkalinity	2	1*		2
Calcium	2	1*		2
COD Total	1			1
Soluble	1			1

* When detention time was 9 hours and greater.

Many of the measurements were made using duplicate and triplicate samples. Settling characteristics of the mixed liquor was monitored by the daily sludge volume index (SVI) tests. Influent and effluent samples were taken daily for analysis of alkalinity,

calcium, soluble and total COD. Alkalinity and calcium of the mixed liquor was determined in systems operating with longer detention periods because of the damping effect of the mixing tank when incoming sewage characteristics changed significantly.

More extensive sampling during the pilot plant study appeared to be desirable for several reasons. A limited degree of control was possible over the characteristics of the domestic sewage used as feed. Increasing the samples used for a chemical analysis provided greater confidence in obtaining a representative estimate of the sewage characteristic measured. Daily analysis of soluble and total COD provided a rapid monitor of organic carbon loading and removal during the investigation. Significant reduction in the amount of alkalinity and changes in the calcium content of the wastewater would be expected to provide some indication of enhanced nutrient removal by the chemical mechanisms that may be operative in activated algae.

At least once each week during the pilot plant study chemical analyses were made to estimate soluble and total BOD and nutrient characteristics of the influent and effluent waste streams. Nutrient analyses were performed on the waste mixed liquor solids in order that total nitrogen and total phosphorus balances would be established for the experimental system. Double and triplicate aliquots were used on the samples for each of the analyses. Five day BOD was performed in accordance with Standard Methods (26). Ammonia and total nitrogen were measured using a semi-micro-Kjeldahl apparatus, and boric acid-mixed indicator solution. Oxidized nitrogen and total phosphorus were measured using procedures mentioned previously. Microbial observations were made once or twice each week. Table 7

of the Appendix includes the additional procedures used for analyzing the wastewater during Phase 3.

E. Precision and Experimental Error

The reported precision for the chemical tests used for this research are summarized in Table 10. Included in this table is the estimated precision expected after the reported values were adjusted to the sampling conditions used during the experimental runs.

Table 10

REPORTED PRECISION OF CHEMICAL TESTS

Test	Reported Precision	Conversion to Sampling Conditions	Estimated Precision (mg/l)	Ref.	Remarks
TSS & VSS	0.4mg	40-67* 10**	16-31 4	26	settled sewage using gooch crucibles
Alkalinity	0.06ml	40	2.4	26	filtered sewage using indicators
Calcium	6.2mg/l	2	12.4	26	for 108mg/l Ca^{++} using undiluted 50ml sample
Ammonia Nesslerization mg/l	1mg/l	1	1	26	1ml sample used
Kjeldahl	0.18ml	112	0.5 2.5	26	for 100 ml sample for 20 ml sample
Total Kjeldahl Nitrogen	0.18ml	112	0.13 1.3	26	assumed 50ml sample for 5ml sample

(continued)

Table 10
(continued)

Test	Reported Precision	Conversion to Sampling Conditions	Estimated Precision	Ref.	Remarks
Oxidized Nitrogen	None reported				
Total Phosphate	0.001mg	1000	1.0	26	
COD	14.2mg/1		14.2	35	settled sewage
BOD	0.07ml	6-30	0.4-2	26	settled sewage
SVI	1.69		1.69 units	26	average SVI 72
pH	0.13		.13 units	26	standard pH 7.3

* mixed liquor samples
** effluent samples

For the research, expectation of obtaining the degree of data reproducibility indicated by Table 10 would appear to be unrealistic. Errors associated with sample collection and preparation would be expected to control the level of precision obtained for all of the chemical tests involved. Difficulty in obtaining reproducible aliquots of the feed substrate and effluent samples cannot be overlooked or minimized especially when normal domestic sewage is involved.

Improved control of the composition of the laboratory prepared feed substrates reduced but did not eliminate sampling errors. Materials added to the tapwater were not instantaneously solubilized. Biological activity and chemical precipitation were encountered during the

24 hour period a given batch of feed was used. For Phases 1 and 2, chemical analyses were made on samples of fresh and leftover substrate. Changes in the feed characteristics were determined.

For Phase 3, chemical analyses were performed on 24 hour composite wastewater samples. Soluble and total incoming and effluent wastewater samples were acidified and refrigerated daily. Determination of COD was performed once each week on all collected samples using the rapid procedure (35). Efficiency of laboratory time utilized was improved. Deterioration of the samples during storage was a possible experimental error. Chemical procedures for measuring nutrient levels were generally less time consuming and were performed on the day the samples were collected.

Over the 15 month research period, equipment faults and human factors were recognized as possibilities for contributing to data inaccuracies.

A typical sampling of the data obtained during the pilot study is presented in Table 11. Two 200 milliliter plastic containers were used to procure duplicates of each of the desired samples. Chemical analyses performed using each of the duplicate samples are listed in column form. Replicate tests on a single sample are listed in the rows. Alkalinity and calcium were determined sequentially using the filtrate collected from the suspended solids analysis. Soluble COD and BOD were estimated using filtered samples. All of the remaining chemical tests were made on "as is" samples. At times significant variability in the phosphorus results was observed reflecting the uneven distribution of particulate matter in the wastewater. For the phosphorus analysis small aliquots were diluted to allow for the

Table 11

SAMPLING OF PILOT PLANT DATA

Tests Performed	Concentrations		
Jan. 26, 1972	Influent	Effluent	Mixed Liquor
pH	7.4	7.7	7.4
	7.4	7.7	7.4
Alkalinity ($CaCO_3$ mg/l)	270	261	
	279	262	
Calcium ($CaCO_3$ mg/l)	179	173	
	191	171	
TSS(mg/l)	54	52	885
	46	48	930
COD (mg/l)			
Soluble	101		63
	94		59
Total	143		101
Ammonia (Nmg/l) by Nessler	43,41	32,32	
	43,40	34,34	
Total Phosphorus (Pmg/l)	7.0,14.0	4.5,4.5	
	6.5, 6.2	4.0,3.5	
BOD_5 (mg/l)			
Soluble	54,91,82	20,20,25	
Total	131,135	60,56	

spectrophotometric measurement of the concentration. Generally, a sufficient number of values for a test were in agreement to allow for rejection of nonrepresentative data. Ammonia, being completely soluble, provided less variable results.

During the course of research, numerous calibration curves were prepared using standard solutions for measuring ammonia by direct Nesslerization and total phosphorus. Typical curves are included in Table 7 of the Appendix. Statistical estimates of the precision for these calibration curves were determined by subjecting the data to a computerized regression analysis (36). Standard deviation, as a measure of precision, was 1.3 and 2.1 mg/liter for ammonia and phosphorus, respectively.

Experimental error may still be significant even when samples are reproduced with high precision. Uncertainity in the accuracy of the sample data as truly representing the system studied is a fact of life applicable to all environmental research work. The method of sample collection may influence the results obtained. Maximum confidence in the experimental results is best established by repetitive sample collection and data analysis averaged over a period of time.

F. Correlation of COD Data

A study was made to determine the amount of COD recovered by the rapid procedure using samples of the synthetic sewage used as feed for Phase 2. Results of five replicate samples were determined for the COD analysis to be 208, 208, 212, 214, and 218 mg/liter. The average COD obtained was 212 mg/liter. Overall range of the samples was 208 to 218 mg/liter. Based on the estimated theoretical COD value of 203 mg/liter as was shown in Table 6 of the Appendix, the COD recovery was approximately 104 per cent.

A computerized regression analysis (36) was employed to determine the relationship of COD values obtained for domestic sewage by the standard and rapid procedures.

Samples of primary treated domestic sewage, used as feed for Phase 3 experiments, were analyzed over the 77 day period for total and soluble COD by both procedures (44). The relationships determined from the analyses at the 5 per cent significance level were as follows:

1. Total COD Standard (X) vs Rapid Procedures (Y)

Sample size 51

Regression equation $Y = 85.5 + 0.314\ X$

Mean X = 223

Mean Y = 156

Variance X = 2650

Variance Y = 907

95% confidence for slope are 0.173 and 0.456

The regression equation can be used to adjust rapid procedure COD loading rates determined for Phase 3 to the standard test.

2. Rapid Procedure Total COD (X) vs Soluble COD (Y)

Sample size 53

Regression equation Y = 21.7 + 0.507 X

Mean X = 154

Mean Y = 99.9

Variance X = 619

Variance Y = 535

95% confidence for slope are 0.288 and 0.726

3. Standard Procedure Total COD (X) vs Soluble COD (Y)

Sample size 58

Regression equation Y = 8.48 + 0.576 X

Mean X = 219

Mean Y = 134

Variance X = 2410

Variance Y = 1830

95% confidence for slope are 0.402 and 0.750

V RESULTS

The experimental results were easily divided into three phases, one each for studies with inorganic feed, synthetic sewage and typical domestic sewage. Primary emphasis was placed on reporting the experimental results when the biological systems had reached equilibrium conditions. At equilibrium, time was not treated as a dependent variable. Levels of the chemical parameters were approximately constant and the biological responses were represented in terms of reaction rates. Overall, this approach for handling the research information was found useful for comparing and correlating the results of many experiments controlled at widely varied conditions.

Phase 1 - Inorganic Feed

Part 1 - Start-up and Preliminary Experiments

Approximately 30 days were required to establish an active flocculating algae population from the pond water seed. The biological culture was developed as a batch operated system with fresh feed added approximately every 5 to 7 days. Distilled water was added between feeding for evaporation losses. Light was provided at an intensity of 75 ft-candles. Small point flocs of microbial cells began to appear as the MLSS concentration approached 250 mg/liter. The corresponding MLVSS concentration was close to 200 mg/liter. Settling of the microbial solids was incomplete when quiescient conditions were provided. Since only inorganic carbon sources were added with the feed, the growth of autotrophic microorganisms was stimulated.

The growth of the algae began to accelerate at the increased solids level. After 10 days the MLSS level approached 600 mg/liter. Solids settling improved, so that only supernatant was wasted. Microbial solids accumulated more rapidly. The pH of the media increased from 9.1 to as high as 10.4 over the same ten-day period indicating the greater uptake of inorganic carbon added as alkalinity in the feed. Mixed liquor temperature averaged 22°C for the period. After an additional 9 days of operation the system reached an equilibrium condition. At equilibrium, batch feeding was provided daily resulting in a six day treatment period.

Results obtained for 14 days at equilibrium are presented in Table 12. The MLSS and MLVSS concentrations were 1100 and 900 mg/liter, respectively. Suspended solids of the supernatant after settling for one hour averaged 120 mg/liter with a volatile fraction of 88 to 90 per cent. Based on VSS wasted, the microbial growth rate was mg/liter/day and the SRT was 50 days. The mixed liquor pH ranged between an average of 10.3 before feeding to 9.5 after feeding. Alkalinity was approximately 1600 mg/liter as equivalent $CaCO_3$. Temperature averaged 23°C. Evaporation losses ranged from 164 to 246 milliliters/ft^2/day. Microscopic observation indicated a predominance of Scenedesmus with a significant number of Chlorella present. A limited bacterial and protozoan population was also noted.

The feed volume was increased to two liters daily so that a detention period of three days developed. A significant amount of dispersed growth was wasted with the supernatant each day. The alkalinity of the feed was reduced from 1600 to 600 mg/liter. Results

Table 12

SUMMARY OF RESULTS, PHASE 1, PART 1

Start-up Experiments

Run	1	2
Date started	3-15-71	3-30-71
Length (days)	14	8
Volume (liter)	6.0	6.0
Depth (inches)	4	4
Surface area (cm^2)	1135	1135
Light intensity (ft-candle)	75	75
Feed rate (liter/day)	1.0	2.0
Detention time (days)	6.0	3.0
MLSS (mg/liter)	1100	1100-900
MLVSS (mg/liter)	900	900-700
Waste (TSS mg/day)	120	280
(VSS mg/day)	108	280
Growth (VSS mg/l/day)	18	- -
SRT (days)	50	- -
pH	9.5-10.3	8.7-9.1
Alkalinity ($CaCO_3$ mg/l)	1600	500
Temperature (^oC)	23	22
Evaporation (l/day)	.200-.300	.100-.500
(l/ft^2/day)	.164-.246	.082-.410

obtained for 8 days of operation are included in Table 12. A new equilibrium solids level was not established in the eight day period. MLSS and MLVSS levels decreased to 900 and 700 mg/liter, respectively. Suspended solids of the wasted supernatant averaged 140 mg/liter with a volatile fraction of 95 to 100 per cent. Mixed liquor pH decreased from 9.1 to 8.7 when fresh feed was added. The fresh feed measured pH 7.8. Alkalinity concentrations of 500 mg/liter were obtained when the feed was diluted with mixed liquor. Only one sample was analyzed for nutrient concentrations. Negligable ammonia was measured in the supernatant. Oxidized nitrogen levels were significant, measuring approximately 13 mg/liter. Phosphorus was 3.2 mg/liter while the calcium content was 70 $CaCO_3$ mg/liter. Temperature averaged 22°C in the mixed liquor during the run. Evaporation losses ranged from 82 to 410 milliliters/ft^2/day. The mixed algae population present was more diverse than was indicated for the previous study. Significant numbers of Scenedesmus, Chlorella and filamentous algae were observed.

A series of two experiments were performed to determine the endogenous respiration and oxygen production rates of the algae during the preliminary study. Light was restricted from the reactor as the endogenous rate was estimated by monitoring the decrease in the mixed liquor DO concentration. The rate of increase of the DO level when light was provided to the reactor was used to measure the oxygen production rate.

The results of the endogenous respiration-oxygen production studies are presented in Figures 15 and 16. When light was restricted, the DO decreased from approximately 9 to 6 mg/liter in 150 minutes.

FIGURE 15

OXYGEN PRODUCTION - RESPIRATION STUDY NO. 1

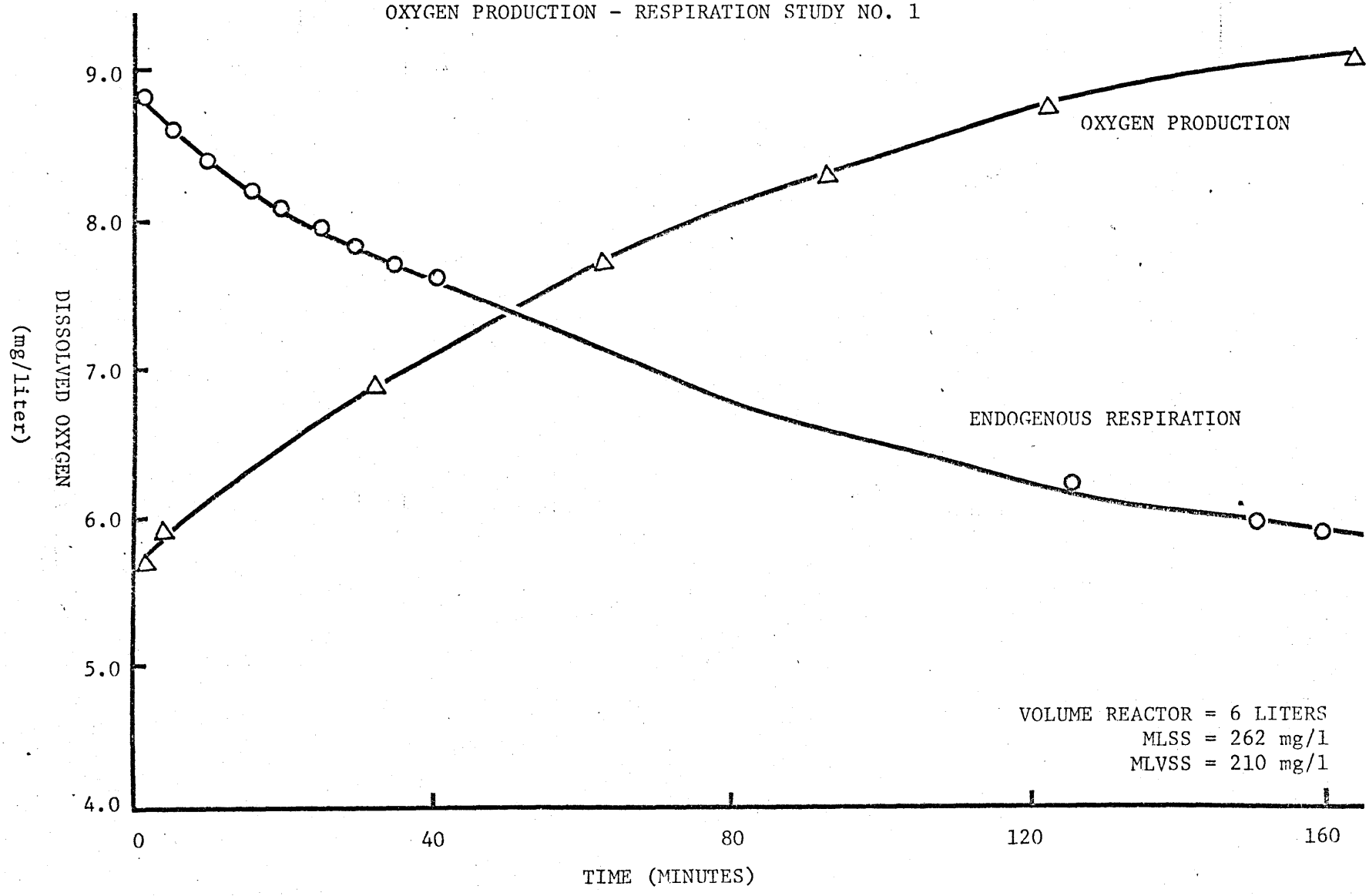
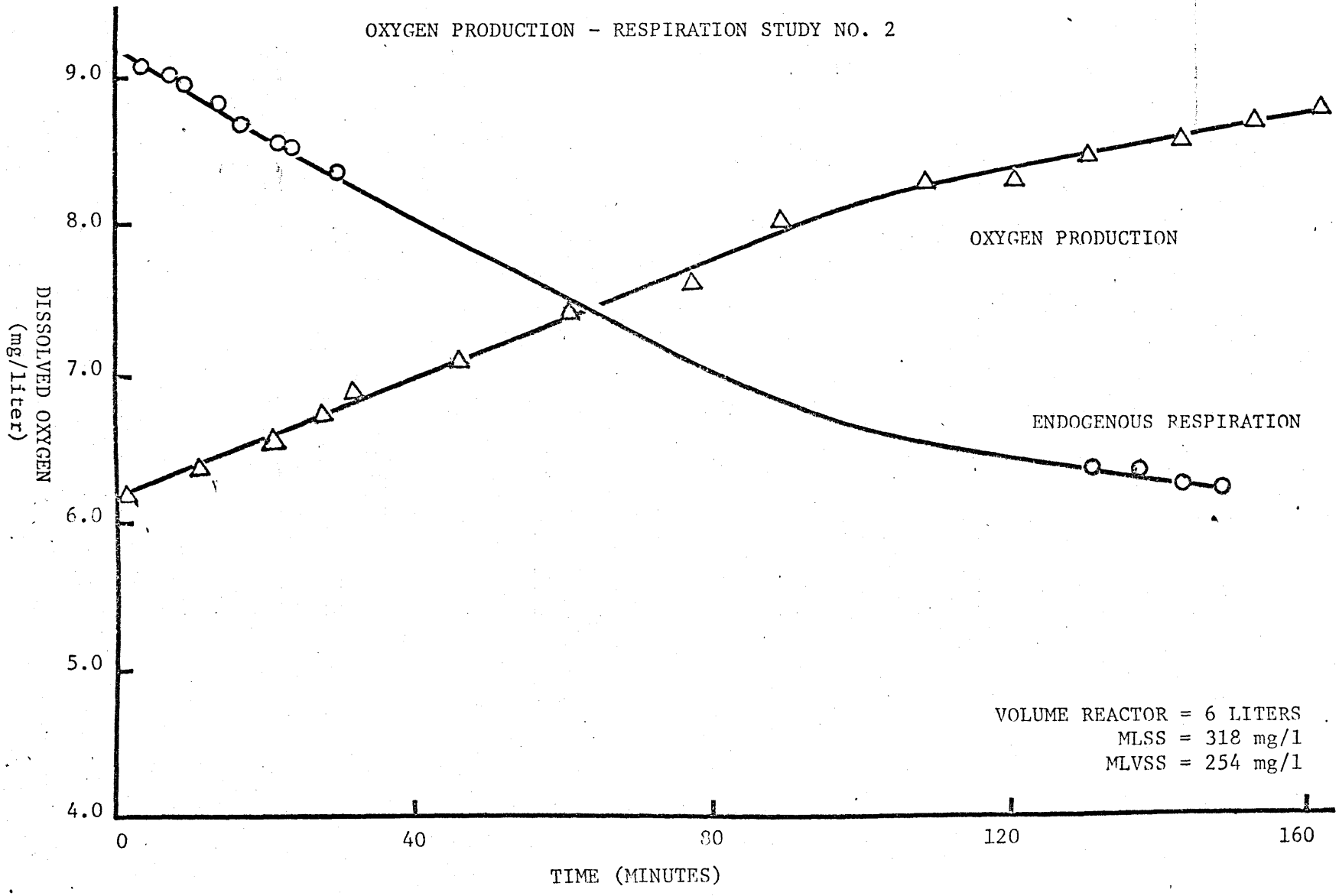


FIGURE 16

OXYGEN PRODUCTION - RESPIRATION STUDY NO. 2



Initial oxygen uptake rates were 0.030 and 0.040 mg/liter/minute. The average DO depletion for the runs were 0.016 and 0.019 mg/liter/minute. When the mixed liquor was illuminated, DO concentrations increased from approximately 6 to 9 mg/liter in 160 to 180 minutes, at average rates of 0.017 to 0.019 mg/liter/hr. The maximum oxygen production rates were 0.020 and 0.035 mg/liter/minute. On the basis of VSS the average endogenous rate was 0.046 per cent/hour. The average oxygen production rates were 0.040 to 0.054 per cent/hr.

Part 2 - Constant Light Intensity

The continuous feeding studies were initiated by adding portions of the mixed liquor developed in the batch fed unit to the battery of three reactors. Inorganic feed was pumped at the flow rate required to provide a uniform detention period of approximately 12 hours. Light intensity was increased to 200 ft-candles. Operation for 10 days was sufficient to shake down the experimental apparatus and to develop a well flocculating algae mass in each of the reactors.

The reactors were operated with a constant mixing rate and varied liquid depth. Because of the different hydraulic turnover times in each of the mixing tanks, a range of illumination frequencies was provided to the algae. This approach was used to simulate different light-depth relationships within the experimental system. The speed of each of the magnetic mixers was adjusted to maintain suspension of the microbial solids while minimizing surface reaeration. Sources of oxygen were desired to be limited to algae photosynthesis.

Experiments were continued for 90 days during which time a series of six runs were carried out. Experimental runs were continued

for periods of 10 to 29 days. Information presented in Tables 13, 14 and 15 summarizes the research results. Average data values of the final five days of a run were used to estimate equilibrium conditions. Variables controlled at desired levels included detention period, solids wasting rate and liquid depth in the mixing tank. Measured detention periods ranges from 2.5 to 14.3 hours. Wasting rates when adjusted to include effluent suspended solids removed were calculated to be 5.1 to 31.5 per cent per day. Designations of Unit 1, 2 and 3 refer to the biological reactors operating at 5.0, 3.3 and 1.7 inches respectively.

Daily temperature readings for all experiments averaged 24 to 28°C. Average pH levels ranged from 6.4 to 8.0 and tended towards more basic values in the shallow reactor. Mixed liquor DO concentrations were greater than 3.3 mg/liter in all experiments, with one exception. During Run 5, Unit 1 had a DO concentration of 0.8 mg/liter. Oxygen levels were significantly increased as the depth of mixed liquor decreased, approaching saturation in Unit 3. DO in the settling column was generally slightly less than the mixed liquor concentration.

The concentration of microbial solids, as estimated as MLSS and MLVSS, were found to be significantly effected by each of the experimental conditions imposed. The small arrows indicate changing trends of the MLSS and MLVSS levels during the runs. Equilibrium conditions may not have been obtained. For Unit 1, MLSS ranged from 380 to 820 mg/liter for six runs. Corresponding MLVSS values were 320 to 720 mg/liter. For Unit 2, the mixed liquor concentrations were increased over the levels obtained for Unit 1. MLSS ranged from 460 to 1170

Table 13

SUMMARY OF RESULTS, PHASE 1, PART 2

UNIT 1

Run No.	1	2	3	4	5	6
1971 Start Date	4-19	5-17	6-2	6-17	7-6	7-17
Length (days)	29	10	14	14	11	12
Light Intensity (ft-c)	200	200	200	200	200	200
Temperature (^{o}C)	27	25	27	28	27	24
Dissolved Oxygen (mg/l)						
ML	5.7	5.0	3.8	3.9	.8	3.3
SC	- -	4.2	3.4	3.6	1.6	3.1
pH	7.7	7.1	6.6	6.5	7.3	7.6
Volume Effluent (l)	6.3	6.9	6.5	6.8	14.0	24.0
Detention Time (hrs)	13.3	12.2	12.9	12.3	6.0	3.5
Settling Time (hrs)	3.0	2.8	3.0	2.8	1.4	0.8
MLSS (mg/l)	715	380	645	715	820	400↓
MLVSS (mg/l)	580	320	555	615	720	320↓
Per Cent VSS	80	84	86	86	88	80
Effluent TSS	20	14	4	5	4	5
Alkalinity ($CaCO_3$ mg/l) in	720	360	360	360	360	360
out	400	120	38	24	120	235
Evaporation (l/day)	.27	.22	.26	.31	.24	.15
(l/ft^2/day)	.79	.65	.76	.91	.71	.15
(%/day)	4.3	3.2	4.0	4.6	1.7	0.6

Table 14

SUMMARY OF RESULTS, PHASE 1, PART 2

UNIT 2

Run No.	1	2	3	4	5	6
1971 Start Date	4-19	5-17	6-2	6-17	7-6	7-17
Length (days)	29	10.	14	14	11	12
Light Intensity	200	200	200	200	200	200
Temperature (^{o}C)	27	25	27	28	27	25
Dissolved Oxygen (mg/l)						
ML	7.3	7.3	4.9	5.2	4.2	5.9
SC	- -	5.5	4.0	4.1	3.1	3.8
pH	7.8	7.3	6.9	6.4	7.5	7.7
Volume Effluent	4.5	4.2	5.6	4.4	9.9	14.5
Detention Time (hrs)	13.4	14.3	10.7	13.6	6.1	4.2
Settling Time (hrs)	4.3	4.6	3.4	4.4	1.9	1.3
MLSS (mg/l)	1170	460	790	910	975↓	565
MLVSS (mg/l)	1020	420	680	820	890↓	480
Per Cent VSS	90	91	86	90	91	85
Effluent TSS	50	30	5	8	2	5
Alkalinity in	720	360	360	360	360	360
($CaCO_3$ mg/l) out	436	90	38	20	140	215
Evaporation (l/day)	.27	.22	.26	.31	.24	.15
(l/ft^2 day)	.79	.65	.76	.91	.71	.44
(%/day)	6.0	5.2	4.6	7.1	2.4	1.0

Table 15

SUMMARY OF RESULTS, PHASE 1, PART 2

UNIT 3

Run No.	1	2	3	4	5	6
1971 Start Date	4-19	5-17	6-2	6-17	7-6	7-17
Length (days)	29	10	14	14	11	12
Light Intensity	200	200	200	200	200	200
Temperature (^{o}C)	27	25	27	28	27	25
Dissolved Oxygen (mg/l)						
ML	7.8	7.7	7.7	7.0	6.1	7.1
SC	- -	6.4	4.9	4.0	2.3	4.1
pH	7.7	7.5	7.6	7.5	7.8	8.0
Volume Effluent	3.5	3.0	2.9	2.9	6.1	12.5
Detention Time (hrs)	8.9	10.4	10.8	10.8	5.1	2.5
Settling Time (hrs)	5.5	6.4	6.6	6.6	3.2	1.5
MLSS (mg/l)	1375↑	615	775	820	965	720
MLVSS (mg/l)	1160	520	665	675	795	530
Per Cent VSS	85	85	86	82	83	74
Effluent TSS	35	11	10	10	3	6
Alkalinity in	720	360	360	360	360	360
($CaCO_3$ mg/l) out	385	93	70	43	162	265
Evaporation (l/day)	.27	.22	.26	.31	.24	.15
($l/ft^2 day$)	.79	.65	.76	.91	.71	.44
(%/day)	7.7	7.3	9.0	10.6	3.9	1.2

mg/liter. Corresponding MLVSS values were 420 to 1020 mg/liter. Increased MLSS and MLVSS concentration were obtained for Unit 3. MLSS was 615 to 1375 mg/liter while the MLVSS was 520 to 1160 mg/liter.

Separation of the microbial solids from the treated wastewater was generally satisfactory as judged by the effluent TSS concentrations. An average effluent TSS concentration of 5 mg/liter resulted after a 0.8 hour settling time for Run 6, Unit 1. Less efficient results were obtained when solids were only wasted with the effluent. For Run 1, effluent TSS ranged from 20 to 50 mg/liter.

Reduction of alkalinity in the wastewater after treatment was used as a measure of inorganic carbon utilization by the activated algae. Alkalinity in the feed was 720 or 360 mg/liter. Residual alkalinity concentrations as low as 20 to 40 mg/liter were determined in several experiments. Loss of water by evaporation was considered because of the increase of mixed liquor temperature associated with continuous illumination. Evaporation loss was estimated by measuring the feed used and combined effluent collected, then dividing the difference equally among the three reactors. Water loss during the experiments ranged from 0.6 to 10.6 per cent of the effluent volume.

Calculations were made to improve the value of the activated algae research by converting the data into fundamental biological waste treatment parameters. Results of the calculations are presented in Tables 16, 17 and 18. The average residence time of the solids within the reactors, SRT, ranged from 3.19 to 19.8 days. Determination of the average MLVSS concentration was made to correct for the fluctuation of the

Table 16

ANALYSIS OF RESULTS, PHASE 1, PART 2

UNIT 1

Run No.	1	2	3	4	5	6
Waste (per cent/day)	5.1	26.5	11.2	15.0	15.3	21
SRT (days)	19.8	3.80	8.95	6.65	6.55	4.80
Average MLVSS (mg/l)	580	280	520	540	295	285
Growth						
(VSS mg/l-day)	30	85	62	92	110	67
(VSSg/day/gMLVSS)	.055	.304	.119	.170	.374	.235
F/M Correlation	35.7	7.5	16.7	12.9	26.2	33.0
Alkalinity Loading						
(mg/l/day)	1300	710	670	700	1440	2470
(g/day/gMLVSS)	2.36	2.54	1.29	1.30	4.90	8.67
Alkalinity Removal						
(mg/l)	320	240	322	336	240	125
(mg/l/day)	575	475	600	665	960	855
(g/day/gMLVSS)	1.04	1.70	1.15	1.21	3.26	3.00

Table 17

ANALYSIS OF RESULTS, PHASE 1, PART 2

UNIT 2

Run No.	1	2	3	4	5	6
Waste (per cent/day)	7.7	31.0	11.5	15.0	13.5	25.
SRT (days)	13.1	3.24	8.76	6.70	7.45	4.0
Average MLVSS (mg/l)	1020	355	640	760	830	420
Growth						
(Vss mg/l-day)	79	130	78	123	120	120
(Vssg/day/gMLVSS)	.079	.377	.122	.162	.144	.286
F/M Correlation	23.4	5.5	19.7	11.8	29.3	22.9
Alkalinity Loading						
(mg/l/day)	1290	605	805	630	1430	2090
(g/day/gMLVSS)	1.29	1.70	1.26	0.83	1.72	5.0
Alkalinity Removed						
(mg/l)	284	270	322	340	220	145
(mg/l/day)	510	475	720	600	870	840
(g/day/gMLVSS)	0.51	1.34	1.13	0.79	1.05	2.00

Table 18

ANALYSIS OF RESULTS, PHASE 1, PART 2

UNIT 3

Run No.	1	2	3	4	5	6
Waste (per cent/day)	6.8	27.2	15.0	17.7	16.9	31.5
SRT (days)	14.65	3.69	6.65	5.66	5.95	3.19
Average MLVSS (mg/l)	1165	450	615	615	725	445
Growth						
(VSS mg/l-day)	58	141	100	120	134	167
(VSSg/day/gMLVSS)	.052	.314	.163	.195	.185	.374
F/M Correlation	39.5	8.5	14.8	12.6	28.0	30.6
Alkalinity Loading						
(mg/l/day)	1920	830	800	800	1670	3440
(g/day/gMLVSS)	1.72	1.85	1.30	1.30	2.30	7.71
Alkalinity Removal						
(mg/l)	335	267	290	317	198	95
(mg/l/day)	900	615	646	706	930	910
(g/day/gMLVSS)	0.80	1.37	1.05	1.15	1.28	2.04

active microbe level due to the daily solids wasting procedure. Average MLVSS was used to calculate loading and removal rates. Algae growth rate, on a concentration basis, ranged from 30 to 167 mg VSS/liter/day. Algae growth, in terms of the amount of solids present, were 0.052 to 0.377 g VSS/day/g MLVSS. The food to microbial mass correlation for the experiments was determined to range from 5.5 to 39.5.

The loading of alkalinity was determined to be 605 to 3440 mg/liter/day and 0.83 to 8.67 g/day/g MLVSS. Estimates of the alkalinity removal rates were 475 to 960 mg/liter/day and 0.51 to 3.26 g/day/g MLVSS.

The efficiency of nutrient removal was of special importance during this phase of the research. Utilization of inorganic carbon by the algae was expected to affect the chemical equilibrium of the wastewater and provide conditions for enhanced removals of ammonia and phosphorus. A summary of the chemical changes occurring during the experiments for Units 1, 2 and 3 are shown in Table 19. Significant reduction in the alkalinity concentrations were determined. Calcium content, expressed as $CaCO_3$, decreased a maximum of 45 mg/liter. Nitrification was significant in all of the experiments. Materials balances for total nitrogen averaged 99 per cent recovery, with an overall range of 72 to 115 per cent. Ammonia nitrogen in the feed was 54 and 62 mg/liter. A pattern for phosphorus removal was not easily recognized from the data obtained. For Unit 1, total phosphorus in the effluent increased 22 per cent and decreased 68 per cent. Phosphorus reduction in Units 2 and 3 ranged from 3 to 70 per

Table 19

SUMMARY OF CHEMICAL ANALYSES, PHASE 1, PART 2

UNIT 1

Run No.	1	2	3	4	5	6
pH	7.7	7.1	6.6	6.5	7.3	7.6
Alkalinity Removed ($CaCO_3$ mg/l)	- -	245	322	336	240	120
Per cent	- -	68	72	93	67	33
Calcium Removed ($CaCO_3$ mg/l)	30	12	38	0	30	5
Per cent	25	11	25	0	25	4
Ammonia (Nmg/l)	11	15	9	5	23	26
Nitrite and Nitrate (Nmg/l)	28	31	50	43	28	37
Waste Nitrogen (Nmg/l)	0	3	3	4	3	1
SUM (Nmg/l)	39	49	62	52	54	64
Per cent N Recovered	72	92	115	97	100	106
Phosphorus Removed (Pmg/l)	6.8	6.3	+2.5	4.3	+2.3	4.6
Per cent P Removed	68	63	+14	25	+22	46

Table 19

(continued)

SUMMARY OF CHEMICAL ANALYSES, PHASE 1, PART 2

UNIT 2

Run No.	1	2	3	4	5	6
pH	7.8	7.3	6.9	6.4	7.5	7.6
Alkalinity Removed ($CaCO_3$ mg/l)	- -	270	320	340	220	145
Per cent	- -	75	88	95	61	40
Calcium Removed ($CaCO_3$ mg/l)	28	17	40	+8	23	3
Per cent	23	14	27	+7	12	2
Ammonia (Nmg/l)	12	12	6	5	19	25
Nitrite and Nitrate (Nmg/l)	27	40	48	48	26	33
Waste Nitrogen (Nmg/l)	0	5	3	7	3	2
SUM (Nmg/l)	39	57	57	60	48	60
Per cent N Recovered	72	104	104	111	89	100
Phosphorus Removed (Pmg/l)	7.0	4.5	0.5	4.5	0.7	5.3
Per cent P Removed	70	45	3	26	7	53

Table 19

(continued)

SUMMARY OF CHEMICAL ANALYSES, PHASE 1, PART 2

UNIT 3

Run No.	1	2	3	4	5	6
pH	7.7	7.5	7.6	7.5	7.7	8.0
Alkalinity Removed ($CaCO_3$mg/l)	- -	255	290	315	200	100
Per Cent	- -	71	81	88	56	28
Calcium Removed ($CaCO_3$mg/l)	29	30	45	0	0	0
Per cent	24	25	30	0	0	0
Ammonia (Nmg/l)	4	11	4	7	25	30
Nitrite and Nitrate (Nmg/l)	44	44	46	41	27	32
Waste Nitrogen (Nmg/l)	0	5	3	5	3	1
SUM (Nmg/l)	48	60	53	53	55	63
Per cent Recovered	89	111	98	98	101	105
Phosphorus Removed (Pmg/l)	5.7	3.7	5.5	6.5	+1.0	5.5
Per cent P Removed	57	63	32	37	+10	55

cent for feed concentrations of 10.0 and 17.5 mg/liter.

Microbial species making up the flora during the experiments varied among the three reactors and shifted with time as shown in Table 20. Initially, the mixed liquor used as contained predominately Scenedesmus, with some Chlorella and small ciliated protozoa. With time the Chlorella increased to predominate the mixed algae population in many experiments. The flora observed in Unit 3, for Run 4, 5 and 6, contained significant numbers of the diatom Nitzschia. A yellow-brown pigmentation of the mixed liquor appeared to be associated with significant diatom populations. Filamentous green algae, believed to be Cladophora, were frequently present. Free swimming ciliated protozoa were common while stalked forms were not observed. Rotifers, nematodes and other small animals sometimes made appearances.

During the months of May, June and July significant numbers of small flying insects were attracted by the fluorescent lighting and ended up in the mixed liquor. The solids recycle pumps sometimes became clogged with dead insects, thus disrupting normal operations. As many as 30 to 40 insect bodies were removed daily from each of the reactors. Passing the mixed liquor through a piece of window screening was found to be an effective means of minimizing the operational difficulty caused by the insects.

Part 3 - Variable Light Intensity

A single continuously fed reactor operated at a depth of 3.3 inches was used to study the responses of an activated algae system to varying light intensities. Inorganic feed was provided at desired detention times, while microbial solids were wasted daily. Light

Table 20

MICROBIOLOGY FOR PHASE 1, PART 2

(LEGEND SEE APPENDIX, TABLE 9)

1971 Date	Unit	Mixed Liquor Color	Algae				Protozoa				
			Scenedesmus	Chlorella	Filamentous	Diatoms	Small	Large	Stalked	Rotifer	Others
4-9	Seed	G	P	X	X	0	X	0	0	0	
4-16	1	G	P	X	X	0	P	X	0	0	
	2	G	X	P	0	0	X	0	0	0	Nematode
	3	G	X	P	0	0	P	X	0	0	Suctoria
4-24	1-3	G									
5-3	1-2	G									
	3	YB									
5-18	3	YB	X	P	0	X	X	X	0	0	Insects
6-30	1	G	X	P	X	0	X	0	0	0	Insects
	2	G	X	P	X	X	X	0	0	0	Anaebana
	3	YB	0	X	X	P	X	X	0	0	Many Bacteria
7-17	1-2	G	X	P	X	0	X	0	0	0	
	3	G,YB	X	X	X	P	P	X	0	X	
7-21	1-2	G	X	X	X	0	X	X	0	X	
	3	G,YB	0	X	0	P	X	X	0	X	
7-29	1	G	0	P	X	0	X	0	0	0	
	2	G	0	P	X	0	P	0	0	0	
	3	G,YB	X	X	X	X	P	0	0	0	Nematode

intensity was adjusted from 200 to 600 ft-candles for the nine experimental runs, covering 127 days of operation. Experiments were conducted for 11 to 17 days each. Results of the studies are summarized in Table 21. Equilibrium conditions were estimated from the operating data by taking the average value of the final five days of the run.

Detention times ranged from 5.5 to 17.2 hours. Adjusted daily solids wasting rates were approximately 22 per cent for seven runs and 40 per cent for the remaining two studies. Temperature ranged from averages of 21 to 27°C. Average pH was 6.5 to 7.8. The concentration of DO in the mixed liquor reactors and settling columns varied from 2.5 to 8.1 and 1.7 to 6.8 mg/liter, respectively.

Significantly different MLSS and MLVSS concentrations were obtained for the experiments. At 200 ft-candles, MLSS and MLVSS were 215 and 180 mg/liter, respectively. When 600 ft-candles illuminated the surface, MLSS and MLVSS increased to 1170 and 1040 mg/liter, respectively. Mixed liquor concentrations tended to decrease as wasting rates and detention times were increased.

Effluent TSS concentrations of 3 to 20 mg/liter were obtained using settling times of 1.8 to 5.5 hours. For a settling time of 1.8 to 2.2 hours, effluent TSS averaged 6 to 8 mg/liter. For a limited number of samples, significant reductions in alkalinity occurred during the treatment period studied. A minimum alkalinity of 34 mg/liter was determined for Run 2. Overall, the results indicate limitations of available carbon and light intensity controlled the biological reactions under the conditions imposed. Evaporation was estimated to be 6.2 to 18.5 per cent of the effluent volume.

The data, presented in fundamental engineering parameters, is

Table 21

SUMMARY OF RESULTS, PHASE 1, PART 3

Run No.	1	2	3	4	5	6	7	8	9
1971 Start Date	6-9	6-29	7-16	10-8	9-10	9-22	10-23	11-8	11-22
Length (days)	12	14	13	15	11	15	16	14	17
Light Intensity (ft-c)	200	300	400	500	500	500	500	600	600
Temperature (°C)	27	27	24	24	21	22	21	23	22
Dissolved Oxygen (mg/l)									
ML	5.7	5.8	7.8	4.8	8.1	6.9	2.9	2.5	7.3
SC	4.3	5.4	6.5	2.6	6.8	5.3	2.2	1.7	5.6
pH	7.3	6.8	7.7	6.5	7.8	7.6	7.3	7.3	7.7
Volume Effluent (l)	5.0	3.8	3.7	6.3	3.5	5.4	11.0	10.6	8.6
Detention Time (hrs)	12.0	15.8	16.2	9.8	17.2	11.1	5.5	6.0	7.0
Settling Time (hrs)	3.8	5.1	5.2	3.0	5.5	3.6	1.8	1.8	2.2
MLSS (mg/l)	215	430	525	1000	570	800	1060	1170	535
MLVSS (mg/l)	180	350	445	890	510	720	920	1040	460
Per Cent VSS	84	82	85	89	89	90	87	89	86
Effluent TSS (mg/l)	20	3	10	7	8	15	8	6	8
Alkalinity ($CaCO_3$ mg/l) in	360	360	360	360	360	360	360	360	360
out	- -	34	58	- -	- -	- -	170	- -	125
Evaporation (l/day)	- -	.31	.50	.95	.50	1.0	.90	1.0	1.0
(l/ft^2 day)	- -	.91	1.5	2.8	1.5	3.0	2.7	3.0	3.0
(%/day)	- -	6.2	13.0	14.8	14.2	18.5	8.2	8.5	11.6

summarized in Table 22. Average SRT values were 4.15 to 4.75 days in Runs 2 through 8, and 2.22 to 2.64 in Runs 1 and 9. The growth rate of algae solids was 68 to 228 mg/liter/day and tended to increase with light intensity. Microbial growth was approximately 0.26 g VSS/day/g MLVSS when the SRT was maintained near 4.5 days. For SRT values of about 2.5 days, the growth rate increased to 0.425 and 0.500 g VSS/day/g MLVSS. The food to microbial growth correlation was estimated to vary from 5.3 to 18.8.

Alkalinity loading was calculated to be 505 to 1580 mg/liter/day and 1.12 to 4.50 g/day/g MLVSS. For a limited number of the runs, alkalinity removal rates were 440 to 835 mg/liter/day and 1.01 to 1.95 g/day/g MLVSS.

Chemical analyses were made at the termination of Run 3. Calcium, as $CaCO_3$, averaged 150 mg/liter in both the feed and effluent samples. Nitrogen, added to the feed in the form of ammonium chloride, was 60 mg/liter. Effluent ammonia averaged 17 mg/liter. Combined nitrite and nitrate nitrogen was 39 mg/liter. Wasting accounted for an estimated nitrogen reduction of 6 mg/liter. Comparison of incoming and effluent nigrogen indicates a recovery of 62 mg/liter or 103 per cent. Phosphorus was reduced 57 per cent from 10.8 to 4.6 mg/liter. Algae synthesis may have accounted for an estimated 11 per cent of the total phosphorus reduction.

The microbial flora for Run 3 was comprised of predominately filamentous green and blue-green algae. Many rotifers were observed grazing among the floc paricles. Very few individual microbial cells remained dispersed. Relatively few small motile forms were observed. During Run 3, the mixed liquor turned deep forest green and started

Table 22

ANALYSIS OF RESULTS, PHASE 1, PART 3

Run No.	1	2	3	4	5	6	7	8	9
Waste (per cent/day)	38.0	21.1	23.0	22.0	22.0	24.1	23.5	22.0	45
SRT (days)	2.6	4.75	4.36	4.55	4.55	4.15	4.29	4.55	2.22
Average MLVSS (mg/l)	160	315	395	790	450	650	830	935	415
Growth									
(VSS mg/l/day)	68	74	102	198	112	173	216	228	207
(VSSg/day/gMLVSS	.425	.235	.258	.250	.249	.266	.260	.244	.500
FM Correlation	5.3	7.3	11.3	6.5	6.4	9.0	18.8	18.2	7.6
Alkalinity Loading									
(mg/l/day)	720	550	535	910	505	780	1580	1520	1240
(g/day/gMLVSS	4.50	1.75	1.35	1.15	1.12	1.20	1.91	1.63	3.00
Alkalinity Removed									
(mg/l)	- -	326	302	- -	- -	- -	190	- -	235
(mg/l/day)	- -	495	440	- -	- -	- -	835	- -	810
(g/day/gMLVSS)	- -	1.57	1.11	- -	- -	- -	1.01	- -	1.95

to form stringy floating patches of solids. The microbial solids were discarded and the system was reseeded for the start of Run 4.

Phase 2 - Synthetic Sewage

Continuous feeding experiments were conducted using a substrate designed to simulate the chemical characteristics of a typical domestic wastewater. The battery of three reactors was used for this phase of the research. Operation of the experimental system was essentially the same as was described previously in Phase 1, Part 2. Seed developed using inorganic media was gradually acclimated to synthetic sewage by increasing the organic loading 25 per cent every third day until the desired level was obtained. Approximately 14 days were found suitable for the start-up procedure.

A series of six experiments were carried out over a period of 85 days. Each of the runs lasted for eight to 22 days. Average data values for the final five operating days of a run were used to provide the research results summarized in Tables 23, 24 and 25. Experimental variables included detention time, solids wasting rate and liquid depth. Measured treatment times ranged from 2.6 to 7.3 hours. Solids were wasted daily at rates of 20 to 80 per cent. Both detention time and wasting rates were increased over ranges used for Phase 1. Units 1, 2 and 3 were operated at mixed liquor depths of 5.0, 3.3 and 1.7 inches, respectively. Addition of synthetic sewage was expected to stimulate the growth rate of heterotrophic microorganisms including bacteria. Production of large quantities of carbon dioxide by the respiration of aerobic microorganisms was also expected to accelerate the growth of algae when the availability of carbon was

Table 23

SUMMARY OF RESULTS, PHASE 2

UNIT 1

Run No.	1	2	3	4	5	6
1971 Start Date	9-10	10-2	10-18	11-1	11-15	11-30
Length (days)	22	15	14	14	12	8
Light Intensity (ft-c)	200	200	200	200	200	200
Temperature (°C)	28	25	25	26	23	23
Dissolved Oxygen (mg/l)						
ML	2.0	0.5	0.9	0.7	0.3	0
SC	0.2	0.4	0.7	0.4	0.3	0
pH	7.9	7.8	7.8	7.8	7.8	7.6
Volume Effluent (l)	14.5	13.9	14.0	12.4	24.0	22.0
Detention Time (hrs)	5.8	6.0	6.0	6.8	3.5	3.8
Settling Time (hrs)	1.3	1.4	1.4	1.6	0.8	0.9
MLSS (mg/l)	765	750	840	670	640	270
MLVSS (mg/l)	660	660	730	590	545	235
Per Cent VSS	86	88	87	88	85	87
Effluent TSS (mg/l)	26	40	33	20	36	30
Alkalinity in	360	360	360	360	360	390
($CaCO_3$ mg/l) out	300	315	330	335	350	385
Evaporation (l/day)	.40	.40	.15	.30	.35	.70
(l/ft^2 day)	1.2	1.2	.44	.88	1.0	2.0
(%/day)	2.8	2.9	1.1	2.4	1.5	3.2

Table 24

SUMMARY OF RESULTS, PHASE 2

UNIT 2

Run No.	1	2	3	4	5	6
1971 Start Date	9-10	10-2	10-18	11-1	11-15	11-30
Length (days)	22	15	14	14	12	8
Light Intensity (ft-c)	200	200	200	200	200	200
Temperature (^{o}C)	27	25	25	26	23	23
Dissolved Oxygen (mg/l)						
ML	1.2	.9	1.3	3.3	.3	.2
SC	1.1	.9	1.0	.6	.3	.2
pH	7.6	7.4	7.7	7.8	7.9	7.8
Volume Effluent (l)	12.0	10.2	10.0	8.2	17.6	16.0
Detention Time (hrs)	5.0	5.9	6.0	7.3	4.4	3.8
Settling Time (hrs)	1.6	1.9	1.9	2.3	1.1	1.2
MLSS (mg/l)	1635	1440	1350	660	870	455
MLVSS (mg/l)	1440	1300	1190	585	750	400
Per Cent VSS	88	90	88	89	86	87
Effluent TSS (mg/l)	12	12	14	32	29	34
Alkalinity in	360	360	360	360	360	390
($CaCO_3$ mg/l) out	200	170	225	220	340	380
Evaporation (l/day)	.40	.40	.15	.30	.35	.70
(l/ft^2 day)	1.2	1.2	.44	.88	1.0	2.0
(%/day)	3.3	3.9	1.5	3.7	2.0	4.4

Table 25

SUMMARY OF RESULTS, PHASE 2

UNIT 3

Run No.	1	2	3	4	5	6
1971 Start Date	9-10	10-2	10-18	11-1	11-15	11-30
Length (days)	22	15	14	14	12	8
Light Intensity (ft-c)	200	200	200	200	200	200
Temperature (^{o}C)	27	24	24	25	22	23
Dissolved Oxygen (mg/1)						
ML	1.5	2.5	4.3	4.8	1.9	.5
SC	.7	1.6	2.6	1.9	.5	.4
pH	7.9	7.9	8.0	7.9	8.0	7.9
Volume Effluent (1)	8.2	6.5	6.5	5.7	11.8	10.6
Detention Time (hrs)	3.8	4.8	4.8	5.5	2.6	3.0
Settling Time (hrs)	2.3	3.0	3.0	3.4	1.3	1.8
MLSS (mg/1)	2000	1860	1420	1100	1325	925
MLVSS (mg/1)	1780	1650	1240	970	1150	795
Per Cent VSS	89	89	88	88	81	86
Effluent TSS (mg/1)	25	13	12	16	30	27
Alkalinity ($CaCO_3$ mg/1) in	360	360	360	360	360	390
out	260	240	275	230	330	375
Evaporation (1/day)	.40	.40	.15	.30	.35	.70
($1/ft^2$ day)	1.2	1.2	.44	.88	1.0	2.0
(%/day)	4.9	6.2	2.3	5.3	3.0	6.6

limiting. Carbon limitations were believed to have occurred in several of Phase 1 studies.

Temperature readings ranged from 22 to 28°C. Average pH levels were fairly uniform, ranging from 7.4 to 8.0. Limitation of oxygen in many experiments was indicated when the mixed liquor DO decreased to 0 and 0.3 mg/liter. An egg odor was sometimes apparent in Unit 1. Operation of the biological system in Unit 1 did not appear to be seriously affected by continued low DO levels. The DO levels in Unit 3 tended to be increased. Settling column DO concentrations were 0 to 0.7 mg/liter in Unit 1; 0.2 to 1.1 mg/liter in Unit 2 and 0.4 to 2.6 mg/liter in Unit 3.

The concentration of MLSS for the experiments ranged from 270 to 2000 mg/liter. Corresponding MLVSS levels were 235 to 1780 mg/liter. For any one run, MLSS and MLVSS were maximum in Unit 3.

Satisfactory flocculation and settling was obtained in all six studies. Effluent TSS were 12 to 40 mg/liter. Settling times of 0.8 to 3.4 hours were generally less than those for Phase 1, Part 2 because of the increase of feed flow rates during Phase 2.

Significant reductions in the organic fraction of the synthetic feed as estimated by COD, were determined in all experiments. COD removals of 71 to 96 per cent were determined. Feed COD concentration was approximately 200 mg/liter. Alkalinity in the feed was measured to be 360 and 390 mg/liter. Reductions in the alkalinity after treatment were 5 to 190 mg/liter. Evaporation ranged from 1.1 to 6.6 per cent of the effluent volumes.

Presentation of the data in terms of fundamental parameters is shown in Tables 26, 27 and 28. Ranges of SRT investigated were 0.67

Table 26

ANALYSIS OF RESULTS, PHASE 2

UNIT 1

Run No.	1	2	3	4	5	6
Waste (per cent/day)	34.2	46.0	45.5	51.0	79	150
SRT (days)	2.93	2.17	2.20	1.97	1.27	0.67
Average MLVSS (mg/1)	595	580	620	470	435	140
Growth						
(VSS mg/1-day)	225	305	332	300	430	352
(VSSg/day/gMLVSS)	.380	.528	.536	.640	.990	1.37
F/M Correlation	12.1	8.7	8.8	7.0	8.7	4.3
Alkalinity Loading						
(mg/1/day)	1490	1430	1440	1280	2470	2260
(g/day/gMLVSS)	2.50	2.47	2.32	2.73	5.70	8.78
Alkalinity Removed						
(mg/1)	60	45	30	24	10	5
(mg/1/day)	248	178	120	88	69	31
(g/day/gMLVSS)	0.415	0.308	.193	.187	.159	.221
COD Total (mg/1) in	200	200	200	200	200	200
COD Soluble (mg/1) out	32	27	12	30	45	58
Total (mg/1) out	56	62	40	48	67	84
COD Removed (%)	84.0	86.5	94.0	85.0	77.5	71.0
COD Loading (mg/1/day)	830	790	800	705	1370	1255
(g/day/gMLVSS)	1.40	1.36	1.29	1.50	3.15	8.97
COD Removed (mg/1)	168	173	188	170	155	142
(mg/1/day)	690	682	750	605	1060	895
(g/day/gMLVSS)	1.15	1.18	1.20	1.27	2.44	6.45

Table 27

ANALYSIS OF RESULTS, PHASE 2

UNIT 2

Run No.	1	2	3	4	5	6
Waste (per cent/day)	23.5	28.5	34.2	56	64	130
SRT (days)	4.25	3.54	7.93	1.79	1.57	.77
Average MLVSS (mg/1)	1300	1140	1000	470	600	240
Growth						
(VSS mg/1/day)	340	370	405	330	480	520
(VSSg/day/gMLVSS)	.262	.375	.405	.700	.800	2.17
F/MCorrelation	20.4	8.3	7.0	5.9	8.6	4.9
Alkalinity Loading						
(mg/1/day)	1730	1470	1440	1180	2530	2300
(g/day/gMLVSS)	1.32	1.29	1.44	2.51	4.21	9.55
Alkalinity Removed						
(mg/1)	160	190	135	140	20	10
(mg/1/day)	770	750	540	460	140	64
(g/day/gMLVSS)	.590	.681	.540	.980	.234	.665
COD Total (mg/1) in	200	200	200	200	200	200
COD Soluble (mg/1) out	33	44	20	37	34	36
Total (mg/1) out	100	47	35	78	56	70
COD Removed (%)	83.5	78.0	90.0	81.5	83.0	82.0
COD Loading (mg/1/day)	960	815	800	660	1410	1280
(g/day/gMLVSS)	.740	.715	.800	1.40	2.35	5.35
COD Removed (mg/1)	167	156	180	163	166	164
(mg/1/day)	800	635	720	540	1170	1050
(g/day/gMLVSS)	.616	.559	.720	1.14	1.95	4.40

Table 28

ANALYSIS OF RESULTS, PHASE 2

UNIT 3

Run No.	1	2	3	4	5	6
Waste (per cent/day)	31.0	32.5	38.7	53.0	67.0	101
SRT (days)	3.22	3.08	2.58	1.90	1.50	0.99
Average MLVSS (mg/1)	1580	1400	1020	750	890	485
Growth (VSS mg/1/day)	550	535	480	515	770	805
(VSSg/day/gMLVSS)	.350	.382	.470	.688	.865	1.66
F/M Correlation	20.4	15.4	12.9	8.3	13.6	8.1
Alkalinity Loading (mg/1/day)	2270	1800	1800	1580	3270	2940
(g/day/gMLVSS)	1.44	1.28	1.78	2.10	3.68	6.06
Alkalinity Removed (mg/1)	100	120	85	130	30	15
(mg/1/day)	630	600	425	550	270	120
(g/day/gMLVSS)	.400	.430	.420	.735	.304	.328
COD Total (mg/1) in	200	200	200	200	200	200
COD Soluble (mg/1) out	46	24	8	41	29	28
Total (mg/1) out	65	33	13	52	40	63
COD Removed (%)	77	88	96	80	86	86
COD Loading (mg/1/day)	1260	1000	1000	880	1820	1630
(g/day/gMLVSS)	.800	.715	.960	1.18	2.04	3.36
COD Removed (mg/1)	154	176	192	159	171	172
(mg/1/day)	970	875	960	700	1560	1400
(g/day/gMLVSS)	.615	.625	.920	.945	1.76	2.89

to 4.25 days. Microbial growth was estimated as 225 to 805 mg VSS/liter/day and 0.262 to 2.17 g VSS/day/g MLVSS. The food to microbial growth correlation ranged from 4.3 to 20.4.

COD loading rates were 660 to 1820 mg/liter/day and 0.715 to 8.97 g/day/g MLVSS. Removal rate of COD was 540 to 1560 mg/liter/day and 0.559 to 6.44 g/day/g MLVSS. Alkalinity loading and removal rates were calculated because of the significant removals of inorganic carbon in many of the experiments. Alkalinity was provided at a rate of 1180 to 3270 mg/liter/day and removed at a rate of 31 to 780 mg/liter/day. On a MLVSS basis, alkalinity loading was 1.28 to 9.55 g/day/g MLVSS while removal was 0.159 to 0.98 g/day/g MLVSS.

Chemical changes and nutrient removals determined during Phase 2 are summarized in Table 29. Chemical analysis, made to determine nutrient levels on two consecutive days after feeding was terminated for Run 6, are included in the summary. For the continuously fed experiments, alkalinity reductions were 1.3 to 53 per cent. For Run 6, when the SRT was 0.67 to 0.99 days, the alkalinity decreased 1.3 to 3.8 per cent. Changes in the calcium content of the wastewater were erratic and generally insignificant. Nitrification was significant in Runs 1 to 4, and decreased in Runs 5 and 6. Within two days after terminating Run 6, combined nitrite and nitrate nitrogen increased from 1 and 2 to 27 to 56 mg/liter in unfed systems. Experimental error was indicated in the nitrogen analyses for many of the experiments. Nitrogen recovery ranged from 78 to 138 per cent. Phosphorus removel was approximately 10 per cent in most continuously fed experiments. In the unfed study, phosphorus reductions increased significantly to as high as 71 per cent when the pH was 8.5.

Table 29

SUMMARY OF EFFLUENT CHEMICAL ANALYSES, PHASE 2

			Alkalinity (as $CaCO_3$)		Calcium	
Unit	Run	pH	mg/l	% Decrease	mg/l	% Decrease
1	1	7.9	300	17	110	9
	2	7.8	315	13	160	0
	3	7.8	330	8.0	200	+5
	4	7.8	335	7.0	165	9
	5	7.8	350	2.8	160	16
	6	7.6	385	1.3	175	5
	-	8.5	350	10.	200	+8
	-	8.0	265	32	200	+8
2	1	7.6	200	44	110	9
	2	7.4	170	53	145	10
	3	7.7	225	37	200	+5
	4	7.8	220	39	180	0
	5	7.9	340	5.5	160	16
	6	7.8	380	3.6	180	3
	-	8.5	305	22	180	3
	-	8.0	135	66	185	0
3	1	7.9	260	28	110	9
	2	7.9	240	33	135	19
	3	8.0	275	24	200	+5
	4	7.9	230	36	180	0
	5	8.0	330	8.0	170	11
	6	7.9	375	3.8	180	3
	-	8.1	250	36	195	5
	-	8.5	100	74	180	3

Table 29

(continued)

SUMMARY OF EFFLUENT CHEMICAL ANALYSES, PHASE 2

		Nitrogen (Nmg/l)				Phosphorus (Pmg/l)	
Unit	Run	NH_3	NO_2+NO_3	N-Waste	% Recovery	Total	% Reduction
1	1	39	5	3	87	10.5	0
	2	38	4	5	87	11.0	+4.5
	3	41	5	6	97	9.4	11
	4	49	5	6	111	9.1	13
	5	57	0	3	111	11.6	+11
	6	54	1	3	108	11.4	+8.6
	-	24	-	0	- -	9.5	9.5
	-	22	27	0	91	7.0	33
2	1	28	36	6	130	10.1	3.0
	2	22	35	8	120	11.0	+4.5
	3	33	32	9	137	10.4	0
	4	33	35	7	138	10.1	2.8
	5	56	0	4	111	10.8	+2.8
	6	36	1	5	78	9.0	14
	-	21	-	0	- -	9.5	9.5
	-	1	48	0	90	7.5	29
3	1	35	9	7	95	9.3	11
	2	27	19	9	101	9.8	6.7
	3	36	29	9	120	9.7	7.6
	4	29	35	9	135	9.3	11
	5	50	2	6	105	11.0	+4.4
	6	37	2	7	85	9.8	6.7
	-	14	48	0	115	8.8	16
	-	1	56	0	105	3.0	71

The diversity of the microbial floc increased for experiments conducted as Phase 2, as shown in Table 30. With the conversion to an organic feed, bacteria and actinomycetes became familiar members of the biological populations. Chlorella and filamentous forms including Spirogyra and Cladophora, represented the algae species. Generally, as the COD loading rates were increased the population observed for Unit 1 became less diverse. For Unit 3 during Run 6, filamentous growth and large free swimming ciliates increased significantly. Appearences of nematodes were frequent during the studies. Scenedesmus and diatoms were rarely observed. Recurrences of the flying insect problem did not occur during the experiments conducted in the Fall.

Oxygen transfer rates due to mixing and surface reaeration were estimated at the terminaiton of Phase 2. Distilled water was added to each of the three reactors and stirred at the normal speed used during the experiments. Dissolved oxygen was stripped from solution by the use of sodium sulfite with cobalt chloride as the catalyst. Oxygen uptake was estimated by monitoring the increase of DO probe readings with time in each of the systems. The rate of oxygen transfer was estimated by calculation of $K_L a$.

Results of the oxygen transfer study are summarized in Figure 17. Reaeration of the distilled water by mixing required approximately 80 to 220 minutes. The most rapid reaeration rate was obtained in Unit 3, where the liquid depth was minimum. Oxygen transfer rate, as estimated by $K_L a$, was 0.0195, 0.0245 and 0.050 per minute, in Units 1, 2 and 3, respectively. Temperature of the distilled water was 19°C for the studies. An estimated 0.2 to 0.4 mg/liter/minute was the

Table 30

MICROBIOLOGY FOR PHASE 2

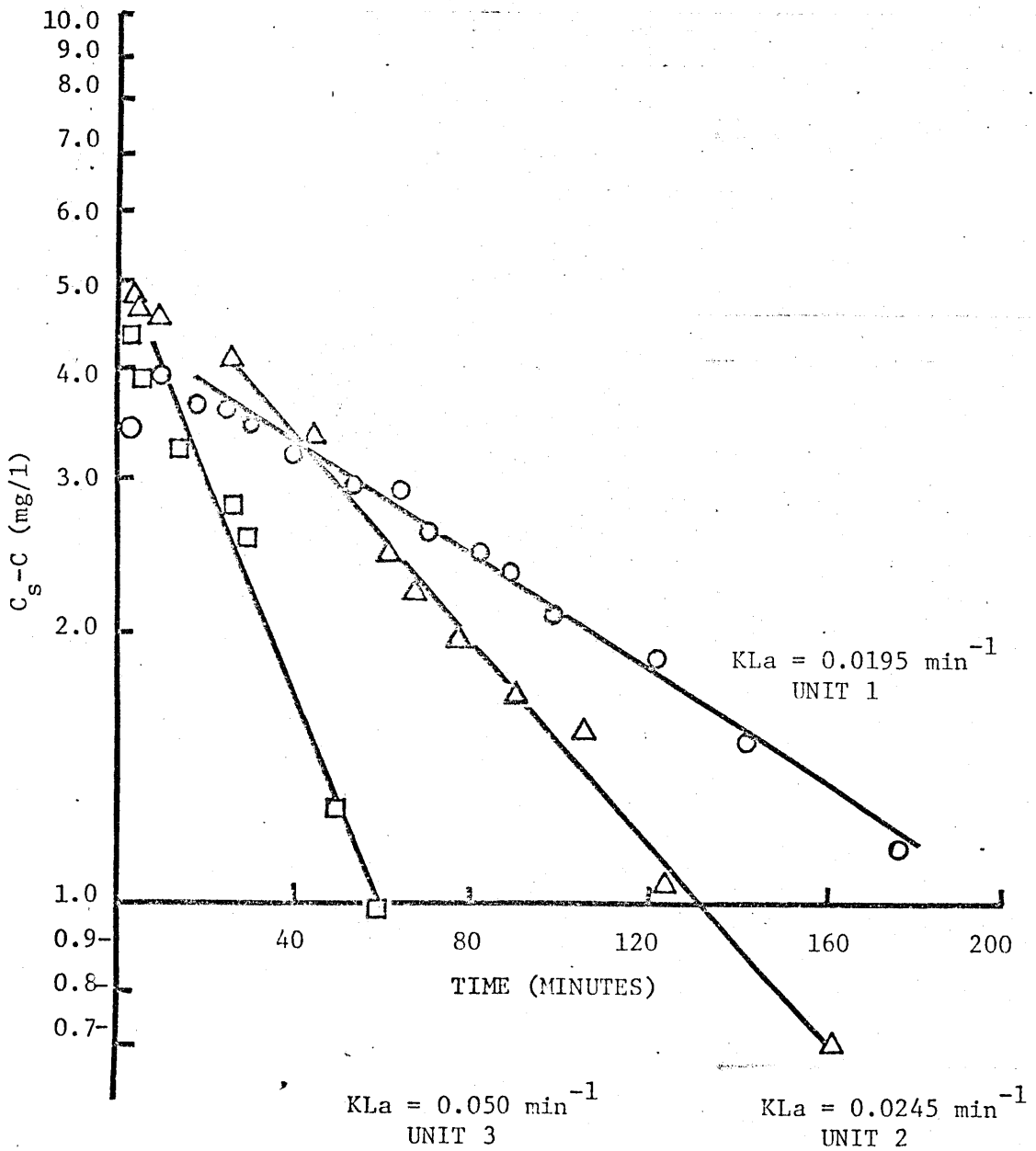
(LEGEND SEE APPENDIX, TABLE 9)

1971 Date	Unit	Mixed Liquor Color	Algae				Bacteria	Actino Mycetes	Protozoa			Rotifer	Other
			Scenedesmus	Chlorella	Filamentous	Diatoms			Sm	Lr	Stalked		
10- 1	1	G	O	P	X	O	X	O	X	X	X	O	Euglena
	2	G	O	P	X	O	X	O	P	X	X	X	Nematode
	3	G	O	P	X	O	X	X	P	X	X	X	Nematode
11-12	1	G	O	X	P	O	X	X	P	X	O	O	
	2	G	O	X	P	O	X	X	P	X	O	O	
	3	G	O	X	P	O	X	X	P	X	O	X	Nematode
11-23	1	G	O	X	X	O	X	O	O	O	O	O	
	2	G	O	X	X	O	X	O	X	O	O	O	
	3	G	O	X	P		X	X	X	X	O	O	Nematode
12- 6	1	G	O	P	X	O	O	O	O	O	O	O	
	2	G	O	P	X	O		X	X	X	O	O	Nematode
	3	G,YB	O	X	P	X		P	X	P	O	O	

FIGURE 17

OXYGEN TRANSFER STUDY FOR LABORATORY SYSTEMS

TEMPERATURE = 19°C



maximum rate of oxygen which could be transferred by surface reaeration at zero DO during the laboratory experiments. Oxygen required for the stabilization of the synthetic wastewater would be expected to be significantly greater. Photosynthesis of the algae provided the primary source of oxygen production in Phase 2 of this investigation.

Phase 3 - Domestic Sewage

Research information provided by Phase 2, indicated light was the controlling factor in many of the experiments. Maximum microbial growth was obtained in Unit 3, operated at a liquid depth of 1.7 inches. Results also indicated ranges for the COD loading rate, SRT and light intensity suitable for optimum synthesis rates.

Studies made for Phase 3 were designed to scrutinize the research results obtained in the laboratory. On the basis of laboratory parameters, pilot plant operation suitable for the desired results was established. A significant research problem involved whether operation most suited for enhanced nutrient removal would be obtainable when high rate growth conditions prevailed. The maximum potential of activated algae would be shown if advanced levels of wastewater purification were obtained under optimum growth conditions. Examination of activated algae under more realistic operating conditions was expected to help delineate some of the problems and their solutions associated with translation of the research results to future field studies. Experiments were conducted with a small pilot scale activated algae system using a continuous flow of primary treated domestic wastewater as feed. The reactor consisted of a

mixing tank having a 29 liter capacity and a settling column with a volume of 12 liters. Liquid depth in the mixing tank was controlled at 1.7 inches. Activated algae solids saved from Phase 2 were used to start-up the experimental system. Acclimation of the system to domestic sewage was provided by gradually increasing the feeding rate for 11 days until the desired detention period was obtained.

The pilot plant studies were divided into a series of seven experiments covering 77 days of operation. Each run was continued for seven to 13 days. Experimental variables included treatment time, solids wasting rate and light intensity. Operational difficulties encountered included: bulking solids, organic overloading and dispersed growth.

Detention time in the pilot mixing tank was controlled at levels of approximately 3, 9 and 20 hours. Solids wasting rates of approximately 20, 35 and 55 per cent/day were used during Runs 1 through 6. Additional wasting of solids was provided by TSS removed with the effluent. For Run 7, the only solids removed were those suspended in the effluent. Light intensity was 200 ft-candles for Run 1 and 2, followed by 600 ft-candles for the remaining studies. Ferric chloride was added at a concentration of approximately 5 mg/liter Fe^{+3} to the incoming sewage for Runs 2 through 6.

An overall summary of the Phase 3 results are presented in Table 31. Day to day summaries of the data collected and experimental results provided are presented in Table 8 of the Appendix. A computer program (37) was written to aid in the analysis and tabulation of the information for Phase 3.

Values reported for temperature and DO represent the average of

Table 31

SUMMARY OF PHASE 3 RESULTS

Run		1	2	3	4	5	6	7
Tempature (°C)	in	15	14	15	14	16	17	17
	ML	20	19	20	19	21	24	24
	SC	19	18	19	19	20	23	24
DO (mg/l)	in	1.5	1.0	1.1	1.0	1.1	1.0	1.0
	ML	4.7	3.0	3.0	2.1	7.4	6.9	7.1
	SC	2.0	1.5	1.0	1.7	3.4	3.5	4.2
pH	in	7.4	7.5	7.4	7.3	7.3	7.3	7.5
	ML	7.4	7.5	7.2	7.1	7.9	7.6	8.0
	out	7.7	7.6	7.5	7.5	7.7	7.9	8.5
Alkalinity	in	273	270	282	292	277	278	264
(mg/l AS $CaCO_3$)	out	259	241	230	225	239	249	202
Calcium	in	165	173	178	190	152	153	149
(mg/l AS $CaCO_3$)	out	171	168	175	190	158	162	146
MLSS(mg/l)		920	975	1510	1420	770	1180	1030-3400
MLVSS(mg/l)		780	830	1220	1160	590	830	730-2500
% VSS		85	85	81	82	77	71	70-73
TSS(mg/l)	in	47	49	45	44	56	67	72
	out	50	57	52	28	47	51	13
COD Total	in	144	142	157	164	173	165	139
Soluble	out	57	56	59	49	56	56	40
% COD Removed		60	60	62	70	68	66	72

(continued)

Table 31

(continued)

SUMMARY OF PHASE 3 RESULTS

Run	1	2	3	4	5	6	7
Detention Time (hrs)	3.8	3.6	3.6	3.5	8.7	9.0	19.3
Settling Time (hrs)	1.6	1.5	1.5	1.5	3.6	3 7	8.0
SRT (days)	1.34	1.37	2.02	1.50	1.40	2.82	135
Average MLVSS(mg/l)	645	785	990	905	460	740	2200
Growth (VSS mg/l/day)	620	660	780	740	450	320	180
(VSSg day/g MLVSS)	0.96	0.96	0.79	0.82	0.98	0.43	0.08
COD Loading(mg/l/day)	910	945	1040	1120	475	430	170
(g/day/g MLVSS)	1.507	1.438	1.076	1.299	1.186	0.578	0.065
COD Removed (mg/l/day)	545	570	645	785	320	285	120
(g/day/g MLVSS)	0.904	0.865	0.666	0.896	0.815	0.422	0.057

all measurements made at approximately the same time each day during a run. Daily variation of temperature and DO was determined only on a limited basis. Incoming wastewater temperature averaged for the runs approximately 14 to 17°C and ranged daily from 13 to 23°C. Temperature of the mixed liquor was elevated 5 to 7°C in the mixing tank and approximately 4 to 7°C in the settling column. DO levels of the feed were generally near 1 mg/liter and increased significantly in the mixed liquor in many experiments. Mixed liquor DO concentrations sometimes varied widely within short periods as shown in Table 32. Significant increase in the incoming sewage BOD would be expected to create temporary increases in the oxygen demand of the system, thereby reducing the DO level. As the BOD loading decreases, the DO level might increase.

The pH of the wastewater feed was usually near 7.3 to 7.5. Effluent pH increased to as high as 8.5. Composite alkalinity samples indicated a decreased concentration in the effluent within the range of 14 to 62 mg/liter. Calcium content of the wastewater was generally unchanged after biological treatment.

For Runs 1 thorugh 6 the contents of the reactor were thoroughly mixed as the desired volume was removed for solids wasting. Suspended solids measured in the waste sample represented the peak daily MLSS and MLVSS concentration. Biological waste treatment plants frequently waste solids only once daily and thereby normally operate within a range of mixed liquor levels (32). Wasting solids on a once a day basis created an immediate reduction in the experimental system of mixed liquor concentration, which gradually increased due to the growth of microbial solids. When solids wasting rates were significantly

Table 32

REPRESENTATIVE FLUCTUATIONS IN MIXED LIQUOR TEMPERATURE AND DISSOLVED OXYGEN LEVELS

PHASE 3, RUN 3

Week of February 14, 1972

Day	Time	Temperature (°C)	DO(mg/liter)
Monday	1:30 p.m.	22	5.0
	4:00 p.m.	21	2.8
Tuesday	11:30 a.m.	20	7.0
	3:00 p.m.	21	2.2
Wednesday	11:30 a.m.	19	4.2
	2:00 p.m.	19	2.1
	4:00 p.m.	20	1.5
Thursday	8:00 a.m.	21	3.9
	1:00 p.m.	21	6.5
	3:30 p.m.	21	3.9
Friday	11:30 a.m.	19	0.6
	3:30 p.m.	21	0.1
Saturday	8:00 a.m.	20	0.3
	10:00 a.m.	19	1.6
	3:00 p.m.	18	6.4
Sunday	9:00 a.m.	18	7.3

increased the effect of the once a day procedure on the biological equilibrium established was most pronounced. Marked deviations of the daily mixed liquor concentration from a true equilibrium condition was recognized as an experimental error.

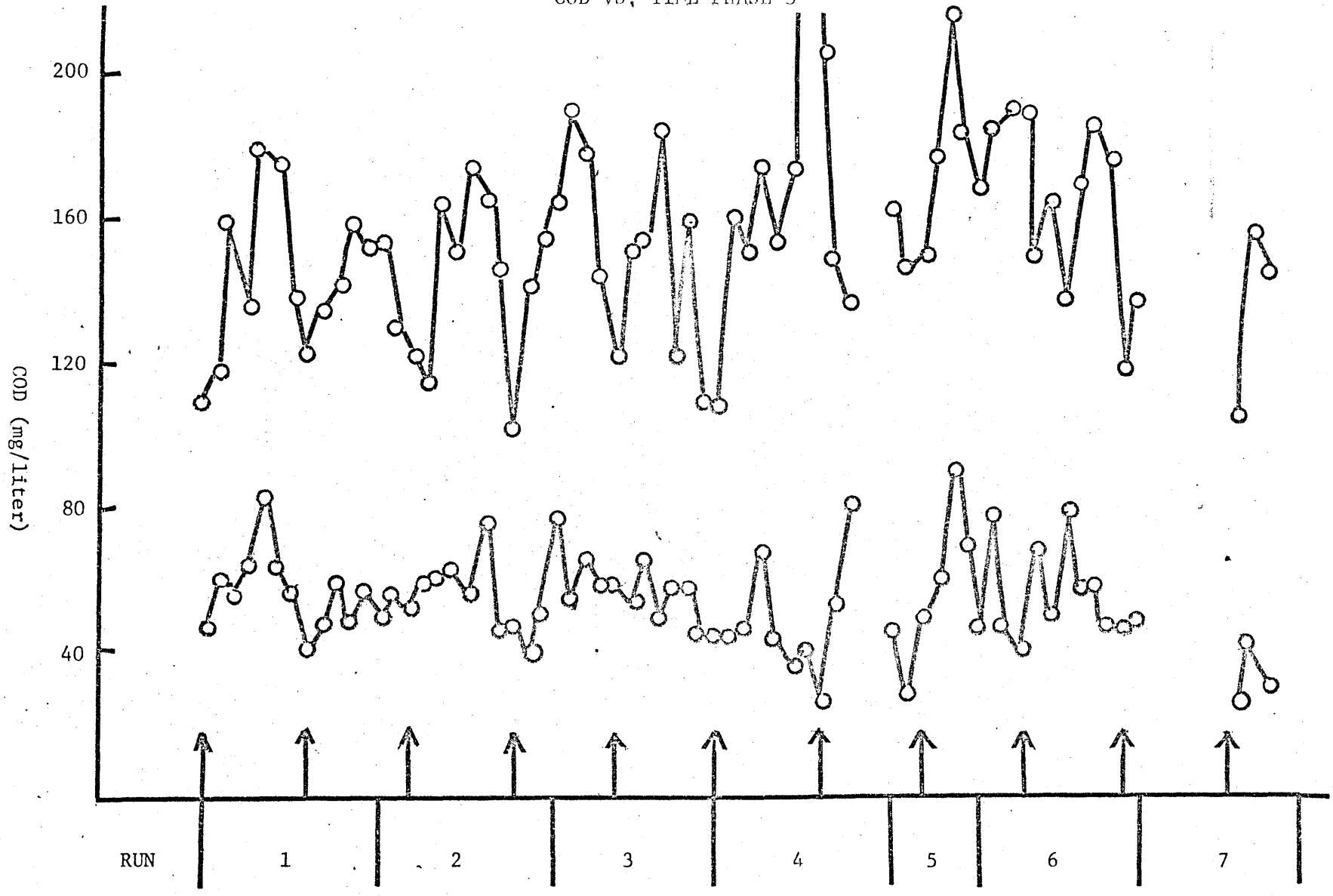
Under the experimental parameters imposed, peak daily MLSS and MLVSS concentrations for Run 1 through 6 ranged from 770 to 1510 mg/liter and 590 to 1220 mg/liter, respectively. For Run 7, MLSS increased from 1030 to 3400 mg/liter over 10 days with no wasting. Corresponding MLVSS increased from 730 to 2500 mg/liter. Incoming TSS averaged 44 to 72 mg/liter. Effluent TSS ranged from 13 to 57 mg/liter. Total COD of the incoming wastewater averaged 139 to 173 mg/liter for 24 hours composite samples. Soluble COD averaged 40 to 59 mg/liter in effluent samples.

The detention period for Run 1 through 4 was controlled at 3.5 to 3.8 hours. Wastewater detention was increased to approximately 9 and 19 hours for the remaining experiments. Settling times ranged from 1.5 to 8.0 hours. SRT were calculated to be 1.34 to 135 days. Average MLVSS levels were used to correct for the effect of solids wasting on the effective biological concentration during the experiments. Average MLVSS ranged from 460 to 2200 mg/liter. Estimated growth rates were 180 to 780 mg VSS/liter/day and 0.08 to 0.98 g VSS/day/g MLVSS. Loading in terms of the rapid COD were 170 to 1120 mg/liter/day and 0.065 to 1.507 g/day/g MLVSS. COD removal rates were 120 to 785 mg/liter/day and 0.047 to 0.904 g/day/g MLVSS.

Data for total incoming COD and soluble effluent for Phase 3 are tabulated in Figure 18. The arrows shown in the Figure refer to samples composited over Sunday to Monday morning. Incoming COD

FIGURE 18

COD VS. TIME PHASE 3

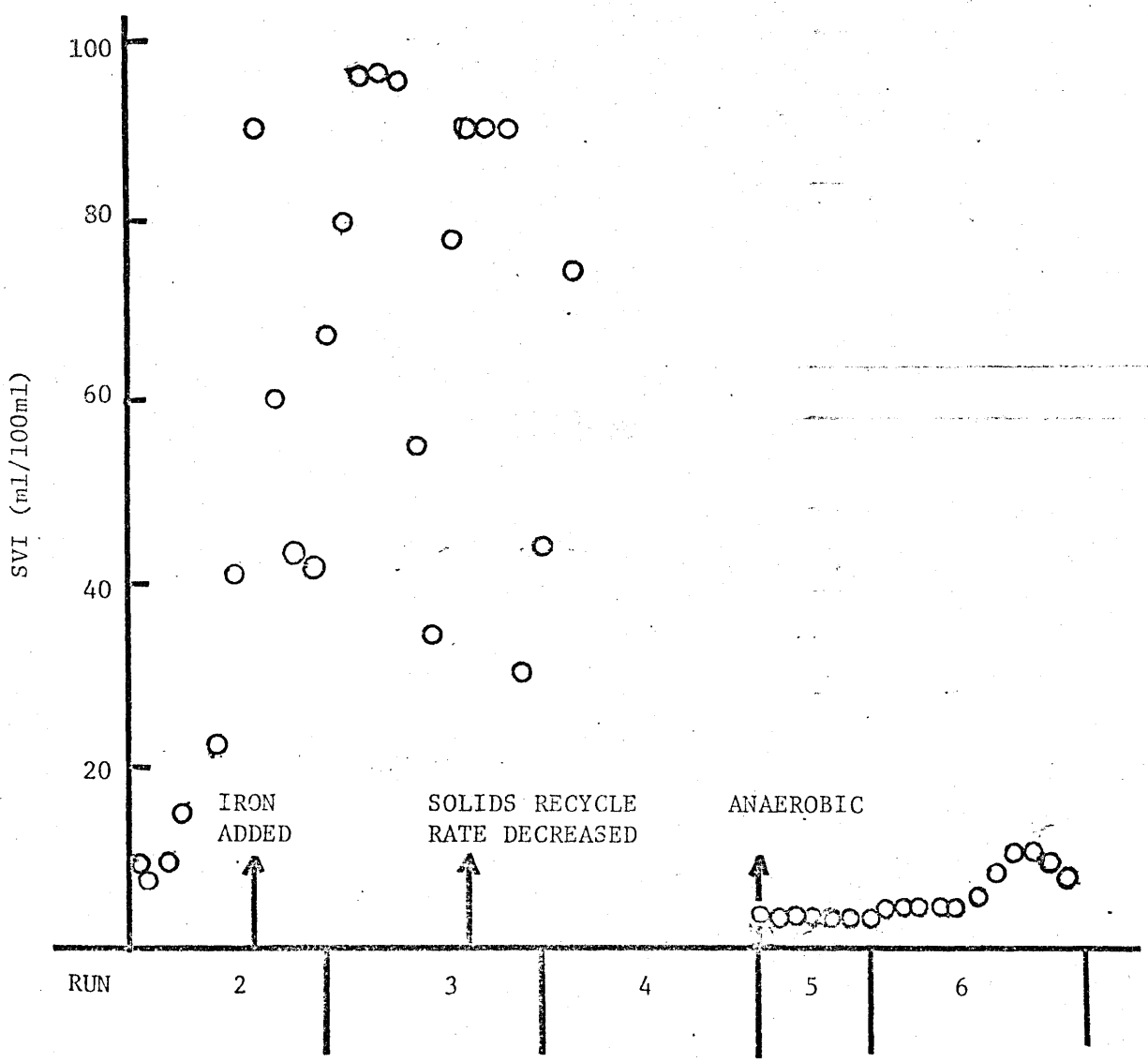


concentration followed a distinct pattern over a weekly period based on 24 hours composite samples. Minimum COD was generally obtained on Monday mornings. Friday and Saturday samples indicated the strongest sewage concentration. Soluble COD in the effluent remained fairly constant at approximately 50 to 60 mg/liter, indicating for Runs 1 through 6 that COD removal efficiency was not significantly improved by increasing the detention time from 3.5 to 9 hours. Limited COD measurements for Run 7 indicated effluent COD concentrations of 26 to 42 mg/liter when a treatment period of 19 hours was provided.

Abnormally high COD concentrations of 208 and 272 mg/liter were measured over the weekend of February 26 and 27. This organic overload contributed to septic conditions which disrupted the normal operation of the pilot reactor at the end of Run 4.

The settling characteristics of the mixed liquor were monitored during the pilot studies using a modified procedure for sludge volume index (SVI). A sample of mixed liquor was placed in a 100 milliliter graduated cylinder and the volume of compacted cells after 30 minutes settling was used as the measure of SVI. Measurements of SVI are shown in Figure 19. Starting during Run 2, the gradual deterioration of the solids settling rate was indicated by the increasing SVI values. Bulking sludge appeared to be related to the growth of filamentous microbial forms, including actinomycetes. Daily additions of iron salt improved the settling characteristics as indicated by the decrease in SVI after February 5. A significant amount of filamentous growth persisted in the mixed liquor flora. Towards the end of Run 3, the solids return rate was reduced from 700 to 100 milliliter/minute, or from 350 to 50 per cent of the incoming flow rate. It appeared that

FIGURE 19
SLUDGE VOLUME INDEX (SUI)
VERSUS TIME, PHASE 3



at a recycle of 350 per cent the Master-flex solids return pump was shearing the microbial floc excessively. Within a period of three days after reducing the recycle rate, the SVI decreased from 90 to 30 indicating improved settling.

For the overloaded condition which developed at the end of Run 4, the DO level decreased to minimum values for several days. Mixed liquor solids turned completely black indicating anaerobic activity. Recovery of the microbial solids to normal operation resulted in a dramatic change in the SVI. For Runs 5 and 6, SVI ranged from 3 to 10. Microbial solids settled to the minimum volume in as few as two to five minutes. For the recovering biological flora, filamentous growth was significantly reduced. Septic conditions apparently proved unsatisfactory for the survival of poorly settling microorganisms.

Results of chemical analyses for nitrogen, phosphorus and BOD are summarized for Phase 3 in Table 33. Ammonia concentration generally decreased 4 to 20 mg/liter. Total Kjeldahl nitrogen in the influent was 32 to 58 mg/liter. The most significant reductions in total nitrogen and ammonia, averaging 68 and 65 per cent, respectively, were obtained for Run 7. Total Kjeldahl nitrogen in the waste mixed liquor was 85 to 267 mg/liter. Based on results presented organic nitrogen was calculated to average 13.3 per cent of the volatile fraction for 11 sludge samples. Nitrification was insignificant for the Runs 1 through 6. Combined nitrite and nitrate nitrogen was measured as 2 to 4 mg/liter for Run 7. Calculated total nitrogen balances indicated recoveries of 64 to 116 per cent. Experimental error in measuring Kjeldahl nitrogen or ammonia stripping were indicated. When incoming

Table 33

SUMMARY OF CHEMICAL ANALYSES, PHASE 3

Run	1972 Date	Nitrogen (Nmg/l) NH3 in	NH3 out	% Decrease	NO_2NO_3 in	NO_2NO_3 out	Total Kjeldahl & Oxidized in	Total Kjeldahl & Oxidized out	% Decrease	Total Kjeldahl Mixed Liquor	% Total Recovery
1	1-18	63	55	13	-	-	-	-	-	-	-
	1-25	42	33	21	1	1	-	-	-	175	-
2	2-1	59	50	18	<1	1	-	-	-	131	-
	2-8	29	19	35	<1	<1	58	29	50	177	64
3	2-15	28	18	36	<1	1	50	22	58	267	81
4	2-23	22	17	23	<1	<1	32	25	22	153	107
	2-28	40	28	30	-	-	-	-	-	152	-
5	3-9	30	17	43	<1	<1	39	22	44	85	92
6	3-18	21	17	19	<1	<1	33	28	15	157	116
7	3-28	24	4	83	<1	4	38	11	71	70*	76
	3-29	28	13	54	<1	2	39	15	62	84*	85
	3-30	22	9	59	<1	2	38	11	71	610*	76

* Samples of Sludge Rather Than Mixed Liquor Measured

Table 33
(continued)

SUMMARY OF CHEMICAL ANALYSES, PHASE 3

Total Phosphorus (Pmg/l)	Run	1972 Date	in	out	Mixed Liquor	Total Insoluble	% Decrease	% Recovery
	1	1-18	11.2	8.6	-	-	23	-
		1-25	6.6	4.1	-	-	38	-
	2	2- 1	11.5	8.2	-	-	29	-
		2- 8	9.5	7.1	-	-	25	-
	3	2-15	8.8	6.1	41.3	35.2	31	101
	4	2-23	10.8	5.8	33.0	27.2	47	71
		2-28	12.2	9.8	25.3	15.5	20	91
	5	3- 9	11.7	5.9	17.3	11.4	50	73
	6	3-18	10.9	6.6	24.3	17.7	39	73
	7	3-28	20.9	5.3	30.6*	25.3	75	53
		3-29	11.4	6.6	26.7*	20.1	42	109
		3-30	12.3	4.6	73.0*	68.4	63	85

* Samples of Sludge Rather Than Mixed Liquor Measured

Table 33
(continued)

SUMMARY OF CHEMICAL ANALYSES, PHASE 3

Biochemical Oxygen Demand (mg/l)	Run	1972 Date	In Total	In Soluble	Out Total	Out Soluble	% Decrease
	1	1-20	113	-	78	-	-
		1-28	133	87	58	22	84
	2	2- 4	148	101	79	20	87
	3	2-11	170	101	78	15	92
		2-18	98	42	48	16	84
	4	2-25	163	103	41	22	87
	5	3- 9	133	88	50	15	89
	6	3-17	101	45	27	11	90
	7	3-29	92	50	13	9	90

total phosphorus was 6.6 to 20.9 mg/liter reductions of 20 to 75 per cent were obtained. Total phosphorus in the waste mixed liquor was 17.3 to 41.3 mg/liter. Enhanced phosphorus removal appeared to be related to pH levels of 8 or greater. Total phosphorus recovery was determined to be 53 to 109 per cent. Based on the results presented insoluble phosphate in the sludge averaged 2.4 per cent for eight samples. BOD removal averaged 84 to 92 per cent using a detention period of approximately 3.5 hours. Filtered effluent BOD was 15 to 22 mg/liter. Average reduction of BOD was 87 to 90 per cent in detention periods of approximately 9 to 19 hours. Residual effluent BOD concentrations were 11 to 22 mg/liter.

A diverse microbial flora was observed during the pilot experiments as shown in Table 34. Initially the mixed liquor used as seed contained a significant number of filamentous algae. At the start of Run 1, the bacterial population included Zoogloea ramigera, an indicator of the presence of organic ring compounds such as those found in detergents (32). Observation of actinomycetes might indicate iron or nutrient deficiency in the sewage. Iron deficiency has been found to be a waste treatment problem during the colder winter months in hard water areas (32). The green algae flora contained Chlorella, Euglena and Cladophora. Blue green algae Oscillatora and the diatom Navicula were present. Small flagellated and ciliated protozoa were observed. Toward the end of Run 1 the presence of large protozoa, such as Paramecium, and stalked ciliates, including Epistylis and Vorticella, indicated that biological equilibrium was becoming established. Vorticella was indicative of a high nitrogen content in the system (32). Actinomycetes and Chlorella populations increased significantly. At

Table 34

MICROBIOLOGY FOR PHASE 3

(LEGEND SEE APPENDIX, TABLE 9)

1972 Date	Mixed Liquor Color	Algae				Bacteria	Actino Mycetes	Protozoa			Rotifer	Other
		Scenedesmus	Chlorella	Filamentous	Diatoms			Sm	Lr	Stalked		
1- 6	G	O	X	P	X	O	O	X	X	O	X	
1-19	G	O	X	X	X	X	X	X	O	O	O	Euglena
1-25	G	O	X	X	X	X	X	X	P	X	O	
1-28	G	O	X	X	X	P	X	P	X	O	X	Nematode
1-31	G	O	X	X	X	X	X	P	X	O	X	Nematode
2- 4	G	O	P	O	X	X	P	P	X	O	O	
2- 8	G	O	P	O	O	P	X	X	X	X	O	
2-11	G	O	P	O	O	X	X	X	O	X	O	
2-14	G	O	P	O	O	X	X	P	X	X	O	
2-17	G	O	P	X	X	X	X	P	X	X	O	
2-21	G	O	P	X	X	X	X	P	X	P	O	
2-24	G	O	P	O	O	X	P	X	X	P	O	
3- 1	B	O	X	X	O	X	P	X	O	O	O	Nematode
3- 4	B-G	O	P	O	X	P	X	X	X	X		
3- 8	G	O	P	O	X	X	O	P	X	O	O	Nematode
3-12	G-YB	O	X	O	X	X	O	X	X	X	O	
3-16	YB	O	P	O	X	X	O	O	X	X	O	Nematode
3-19	YB	O	X	O	P	X	O	O	P	X	O	

the end of Run 1 a limited presence of rotifers and nematodes indicated stable biological conditions. The excessive growth of filamentous bacteria caused a sludge bulking problem.

The addition of supplemental iron during Run 2 stimulated the growth of Chlorella and motile short rod shaped bacteria. Filamentous algae and diatoms were decreasing before the iron was added. Increased bacterial food was a favorable stimulant to small protozoa. Improved algae growth increased the DO levels and stalked ciliates returned. Actinomycetes numbers remained significant, but, created less of an operational problem.

During Run 3, the predominant algae was Chlorella. Filamentous algae might be expected to grow less favorably because the effectively small surface area to volume ratio of this type of microorganism would inhibit food competition ability compared to Chlorella. Colonial forms of Epistylis and Vorticella were recorded. An adult stage of suctoria developed in response to the large population of small ciliated protozoa used as food (32). Stylonichia were observed in significant numbers.

Actinomycetes tended to increase during Run 4. The number of small ciliated protozoa decreased markedly. A limited number of large flagellated and ciliated protozoa was present. Flocculated solids contained equal predominance of Chlorella and actinomycetes. Nematodes were observed grazing in the partially septic floc.

During Run 5 the activated algae flora was reviving from disruption by septic conditions. Actinomycetes and filamentous algae were not observed. The bacterial population contained large numbers of motile short rod shaped and spirillum forms. Chlorella predominated

the floc particles. A diatom, Nitzschia, was present in small numbers. Free swimming and stalked ciliates were abundant. The mixed liquor turned from an olive drab to bright green color. Algae solids tended to tenaciously adhere to the solid surface of the experimental reactor and mixing pump.

By the end of Run 6 Nitzschia predominated the biological flora. A limited number of Chlorella and filamentous algae were observed. The diatoms readily formed flocculated masses. Large numbers of Stylonichia were found grazing in the floc. Spirillium bacteria were common. Mixed liquor became a yellow-brown color.

Mixing of microbial solids was limited during Run 7, so that a blanket of sludge covered the bottom of the pilot reactor. A shift in the microbial population was indicated by the color of the solids blanket. Sludge surface exposed to the light turned bright green. Chlorella increased to significant numbers, while Nitzschia decreased. Filamentous algae growth increased. Stylonchia, stalked ciliates, Paramecium, rotifers and nematodes balanced out the population observed. Bottom layers of the blanket had darkened indicating oxygen limiting conditions were present within the sludge.

Statistical Evaluation of Operating Data

An examination of the data collected indicated MLVSS and feeding rate were suitable for statistical evaluations. During the investigation MLVSS and feed rates were controlled over a series of desired conditions. Daily measurement of these parameters varied within ranges for a given experiment. As indicators of the biological system, MLVSS was related to the availability of food. Measurable differences in MLVSS concentrations among the three reactors was expected when light or other factors limited activated algae growth. Since the volume of the reactors was varied, different feed rates were needed to provide a constant detention time for a given run.

Statistical parameters calculated to define the precision of MLVSS and the feeding rate for the continuously operated laboratory studies were the mean and the standard deviation as shown in Tables 35 and 36. Measurements made on each of the final five days of a run were used for the calculations. Means were calculated to three significant figures. Standard deviations were determined to two or three significant figures. For MLVSS the range of standard deviation was 6.71 to 238 mg/liter. Difficulty of obtaining a reproducible MLVSS level appeared to increase in reactors operated with the more concentrated mixed liquor. Based on the MLVSS level, per cent variation from the mean appear to be more constant. Standard deviation of the feed rate had a range of 0.01 to 2.64 liter/day. Increased variability in the feed rate was related to random operating difficulties. During Phase 1, chemical precipitates sometimes accumulated in the feed lines and the pumps, hindering desired flow rates.

Table 35

MEAN AND STANDARD DEVIATION, PHASE 1

Part 2

Run	Unit	Mixed Liquor Mean (mg/l)	Mixed Liquor Standard Deviation	Volume Mean (liters)	Volume Standard Deviation
1	1	580	95.5	6.00	0.27
	2	1020	106	4.52	0.51
	3	1160	83.2	3.64	0.15
2	1	320	36.7	6.90	0.30
	2	424	71.8	4.22	1.68
	3	520	62.8	2.98	0.45
3	1	556	43.6	6.44	0.63
	2	682	30.5	5.60	0.69
	3	668	67.8	2.84	0.24
4	1	613	6.71	6.62	0.49
	2	818	64.8	4.42	0.37
	3	675	29.5	2.92	0.17
5	1	722	30.5	13.7	2.64
	2	889	80.2	9.22	2.21
	3	797	32.9	6.06	0.01
6	1	318	49.5	24.2	1.21
	2	479	48.4	14.6	1.94
	3	530	32.2	12.5	0.47

Table 35

(continued)

MEAN AND STANDARD DEVIATION, PHASE 1

Part 3

Run	Mean (mg/l)	Standard Deviation	Mean (liters)	Standard Deviation
1	180	67.9	4.44	0.57
2	352	31.3	3.76	0.70
3	446	20.1	3.68	0.80
4	512	76.8	3.36	0.89
5	694	85.8	4.44	1.13
6	898	29.2	6.48	0.71
7	923	84.5	10.9	0.54
8	1040	83.9	10.1	2.15
9	468	74.0	8.64	0.48

Table 36

MEAN AND STANDARD DEVIATION, PHASE 2

Run	Unit	Mixed Liquor Mean (mg/l)	Mixed Liquor Standard Deviation	Volume Mean (liters)	Volume Standard Deviation
1	1	674	47.2	14.7	0.60
	2	1440	109	12.4	2.40
	3	1750	238	8.14	0.68
2	1	795	79.8	13.7	0.45
	2	1290	52.5	10.4	0.66
	3	1650	48.0	6.44	0.19
3	1	732	36.5	13.4	1.30
	2	1130	177	9.98	0.16
	3	1260	164	6.48	0.21
4	1	588	59.8	12.5	2.55
	2	582	29.3	8.32	1.07
	3	958	107	5.68	0.27
5	1	547	28.4	24.4	3.40
	2	744	55.7	17.6	1.20
	3	1150	158	11.7	1.20
6	1	236	43.7	22.2	2.25
	2	395	48.2	16.4	1.12
	3	813	102	11.4	1.24

Biological growth in the feeding system was significant during Phase 2. Feed lines were flushed daily to remove a large amount of the accumulated debris. A significant reduction in the feeding rate over a single day resulted when a relatively small amount of material effectively clogged the pump. Variability from the mean feeding rate was reflected in the magnitude of the standard deviation.

VI DISCUSSION OF RESULTS

The data obtained in this research was designed to furnish a better understanding of the light-depth considerations in the activated algae process. Previous investigations have shown the ability of activated algae to perform in the laboratory. Failure in the field using a larger scale unit was believed to be related to the limitation of light penetration into the mixed liquor. If activated algae is to be a viable treatment process, it is important to develop sound design concepts on a fundamental basis. Research was approached from the view of investigating operating conditions for activated algae in terms of maximum growth. Operation at the full biological potential will provide the most promising economics.

A Fundamental Relationships

A basic difference recognized in examining the data of previous investigations was the effect of a completely inorganic and a combined organic - inorganic substrate. Fundamental concepts indicated that algae and autotrophic bacteria would be the primary microorganisms growing in an inorganic substrate. The addition of organic matter would permit a diverse population of heterotrophic bacteria to grow in the treatment system along with the algae and other autotrophic microorganisms. The influence of each group of microbes on the overall activated algae process would be controlled by the nature of the substrate and the range of operating conditions chosen.

For an inorganic substrate, it is possible to examine quantitatively the potential growth of algae from the synthesis equation

reported by Fogg, as presented by McKinney (25);

$$NH_3 + 5.7CO_2 + 12.5\ H_2O \xrightarrow{\text{light}} C_{5.7}H_{9.8}O_{2.3}N + 6.25O_2 + 9.1H_2O$$

This equation indicates that the algae cells contain 53 per cent carbon based on volatile suspended solids. Each pound of carbon metabolized by the algae should produce 1.9 pounds of VSS from synthesis. The nitrogen requirements would be 0.11 pounds for each pound of VSS produced, or 0.21 pounds for each pound of carbon metabolized. The phosphorus requirement on a weight basis is approximately one-fifth the nitrogen requirement. One of the important aspects in algae metabolism is the production of oxygen. The equation of Fogg indicates that 2.9 pounds of oxygen will be released for each pound of carbon metabolized or 1.6 pounds of oxygen released for each pound of VSS formed.

With an excess of ammonia nitrogen and inorganic carbon, nitrifying bacteria would also be stimulated. Very little quantitative data is available for synthesis of nitrifying bacteria. The nitrification synthesis equation (32) is estimated as:

$$100(NH_4)HCO_3 + 193O_2 \longrightarrow C_5H_7O_2N + 99HNO_3 + 197H_2O + 95CO_2$$

The oxygen uptake indicated in this equation is 4.4 pounds per pound of ammonia nitrogen metabolized. For each pound of nitrate nigrogen formed, 3.6 pounds of bicarbonate alkalinity, as $CaCO_3$ is consumed as about 3.0 pounds of carbon dioxide is released. The carbon dioxide is available for autotrophic growth or removed as a gas from the system.

The production of nitric acid has the additional effect of neutralizing alkalinity as indicated in the following equation:

$$HNO_3 + NaHCO_3 \longrightarrow NaNO_3 + H_2O + CO_2$$

For each pound of nitrogen, present as nitric acid, 3.6 pounds of bicarbonate alkalinity, as $CaCO_3$, are neutralized, as 3.2 pounds of carbon dioxide are released. Nitrification provides a significant mechanism for inorganic carbon reduction from wastewater.

The complexity of the biological reactions is increased when the system is fed an inorganic-organic substrate, such as domestic sewage. Establishment of a symbiotic relationship between algae and aerobic bacteria is the foundation of activated algae as a combined secondary-tertiary treatment process. A quantitative approximation of the synthesis for the heterotrophic and photosynthetic phases of activated algae is detailed in Table 1 of the Appendix. The stabilization of the organic fraction of the sewage with oxygen results in bacterial protoplasm, carbon dioxide and water.

Carbon dioxide can be converted in the presence of light to form algae cells and sufficient oxygen for the aerobic demand. Concepts applicable to high rate activated sludge predict that about 0.7 pounds VSS would be produced for each pound of BOD_5 added. In terms of carbon, addition of approximately 0.85 pounds would result in the creation of 0.37 pounds of cells. In activated algae if all carbon dioxide were reclaimed from the BOD stabilization, 0.48 pounds of carbon would result in an estimated maximum of 0.91 pounds of algae cells. The combined cell yield for activated algae would be 1.61 pounds VSS/pound BOD_5 added. Based on the cell yield, combined

sludge in the high rate activated algae system would be 230 per cent of the production of a normal biological treatment plant.

Oxygen production must meet the demand of a symbiotic balance. Oxygen supply based on BOD added is projected to exceed the metabolic and respiration demand in a high rate system. Ratio of oxygen production to consumption is estimated to be 2.82.

Breakdown of photoplasm by endogenous respiration occurs simultaneously with all synthesis reactions in both inorganic and organic media. Endogenous respiration is represented by the equation:

$$C_5H_7O_2N + 5O_2 \longrightarrow 5CO_2 + 2H_2O + NH_3$$

For each pound of VSS reduced, 1.4 pounds of oxygen are required. It has been found that the VSS are reduced a maximum of 80 per cent. Remaining VSS are nonbiodegradable polysaccarides. Due to endogenous respiration the maximum cell yield indicated previously would be reduced as SRT is increased corresponding to the buildup of inert materials in the sludge. The reduction in VSS by endogenous respiration in activated algae system would create a range of cell yield of 0.32 to 1.61 pounds VSS/pound BOD_5 added. On a total inorganic and organic carbon added basis, the cell yield would range from 0.20 to 1.0.

Nutrient removal by assimilation is expected to improve for activated algae because of the duel biological growth potential for a given supply of BOD added. Nitrogen assimilation based on BOD is calculated to 0.037 to 0.187 pounds N/pound VSS, depending upon endogenous respiration. Phosphorus required range from 0.007 to 0.037 pounds/pound VSS. The total amount of nitrogen and phosphorus

assimilated can be increased if inorganic carbon stored as alkalinity is also utilized as a source of food.

Application of basic principles to the research data will indicate the composite effect of the fundamental reactions outlined on the activated algae process.

B Application of Principles

Information provided by previous researchers was incorporated into the experimental analysis. Experimental findings by the earlier and present studies were combined and analyzed in similar engineering parameters. The analytical approach was to provide a more meaningful description of algae in biological waste treatment with specific emphasis on the activated algae concept.

The summary of computations for previous activated algae research is presented in Table 37. For each of the investigations, BOD loading and removal rates were determined on a weight basis as g/day/g MLSS and on a concentration basis as mg/liter/day. Microbial growth rates representing solids production/day were also presented in weight and concentration basis.

Additional parameters included average MLSS and MLVSS, sludge retention time (SRT), food-mass (F-M) correlation, MLVSS-detention time (Sat) value and light-depth (L/D) relationship.

1 - Organic Loading, Removal and Growth

Loading and removal rates in terms of COD were determined for Phases 2 and 3 of the research and supplemental information reported by earlier studies (13, 14, 15, 30). COD loading and removal rates

Table 37

SUMMARY OF PREVIOUS ACTIVATED ALGAE ANALYSIS

	RUN	SURFACE AREA (cm^2)	DETENTION TIME (hrs)	LOADING/REMOVAL BOD g/day-gMLSS		BOD mg/l/day	
Wahbeh	1	775	5	0.75	0.72	1500	1440
	2	775	5	0.34	0.32	1260	1180
	3	775	5	- -	- -	- -	- -
	4	775	5	0.47	0.40	650	640
Sherwood	A	111,000	384	- -	- -	- -	- -
	B	111,000	192	.14*	.09*	85*	54*
	C	111,000	96	- -	- -	- -	- -
Humenik and Hanna	C	- - -	12	0.22*	0.20*	600*	540*
	F	- - -	12	0.60*	0.56*	760*	700*
McGriff	2-1	7200	14.3	- - -	- - -	- - -	- - -
	2-2	6450	13.3	- - -	- - -	- - -	- - -
	3-1	6450	13.3	0.093	0.089	218	210
	3-2	6450	11.3	0.16	0.15	222	208
	3-3	6450	10.0	0.20	0.19	265	248
	3-3A	6450	10.0	0.23	0.22	195	187

* Based on COD

Table 37
(continued)

	RUN	SOLIDS PRODUCED VSSg/day-gMLSS	SOLIDS PRODUCED VSS mg/l-day	AVERAGE MLSS (mg/l)	Satx10^{-3} $\frac{mg\text{-}hr}{l}$	SRT (days)	F-M CORRE-LATION	L/D FT-CANDLES/CM
Wahbeh	1	0.059	118	2000	10.0	12.1	58	39**
	2	0.026	96	3700	18.5	77	370	39**
	3	0.034	96	2800	14.0	59	280	58**
	4	0.89	1430	1600	8.0	1.61	7.8	116**
Sherwood	A	.12	35	300	115	8.6	.54	20.4
	B	.075	45	600	115	13.4	1.7	20.4
	C	.096	82	850	81.5	10.3	2.6	20.4
Humenik and Hanna	C	- - -	- - -	2700	32.4	- - -	- - -	- - -
	F	.21	266	1260 (MLVSS)	15.1	5.3	10.6	- - -
McGriff	2-1	0.050	59	900	12.9	20.5	34.5	102
	2-2	0.026	54	1700	22.6	38.5	68.5	96.5
	3-1	0.019	54	2400	32.0	53.0	94.0	96.5
	3-2	0.263	500	1400	15.8	3.80	8.1	152
	3-3	0.272	490	1290	12.9	3.68	8.9	172
	3-3A	0.276	330	860	8.6	3.62	8.7	172

** Units of watts/cm

were related as shown in Figure 20. Information provided by previous researchers based on BOD was converted to biodegradable COD by multiplying the data by a factor of 1.5. Removal efficienty with synthetic sewage increased to an estimated 96 per cent when the loading was decreased to 0.3 g COD/day/g MLVSS.

Results for Phase 3 indicate the significant impact of nonbiodegradable soluble COD in treated domestic sewage as compared to the synthetic wastewater and adjusted data based on BOD. Removal rates were decreased corresponding to the quantity on inert COD added in the sewage.

Growth rate, as estimated by the MLVSS production, and loading of carbon to the experimental systems is shown in Figure 21 for all three experimental phases. Carbon loading was determined to provided a uniform comparison for experiments operated with inorganic and organic feed. The loading rate was estimated by assuming alkalinity and COD were 12 and 44 per cent carbon, respectively. Supporting calculations are provided in Table 10 of the Appendix. For laboratory studies at a light intensity of 200 ft-candles a maximum growth rate of approximately 800 mg/liter/day resulted at a carbon loading of 1485 to 1660 mg/liter/day. Carbon dioxide produced by microbial respiration during Phase 2 may have increased algae growth rates if carbon was limiting in the systems. Intensifying the light source to 600 ft-candles and using normal domestic sewage during Phase 3 appears to have resulted in improved synthesis. The limiting carbon loading rate was not obtained. Limiting conditions would have been indicated if growth reached a plateau level as loading increased.

Figure 20
COD LOADING VS. COD REMOVAL

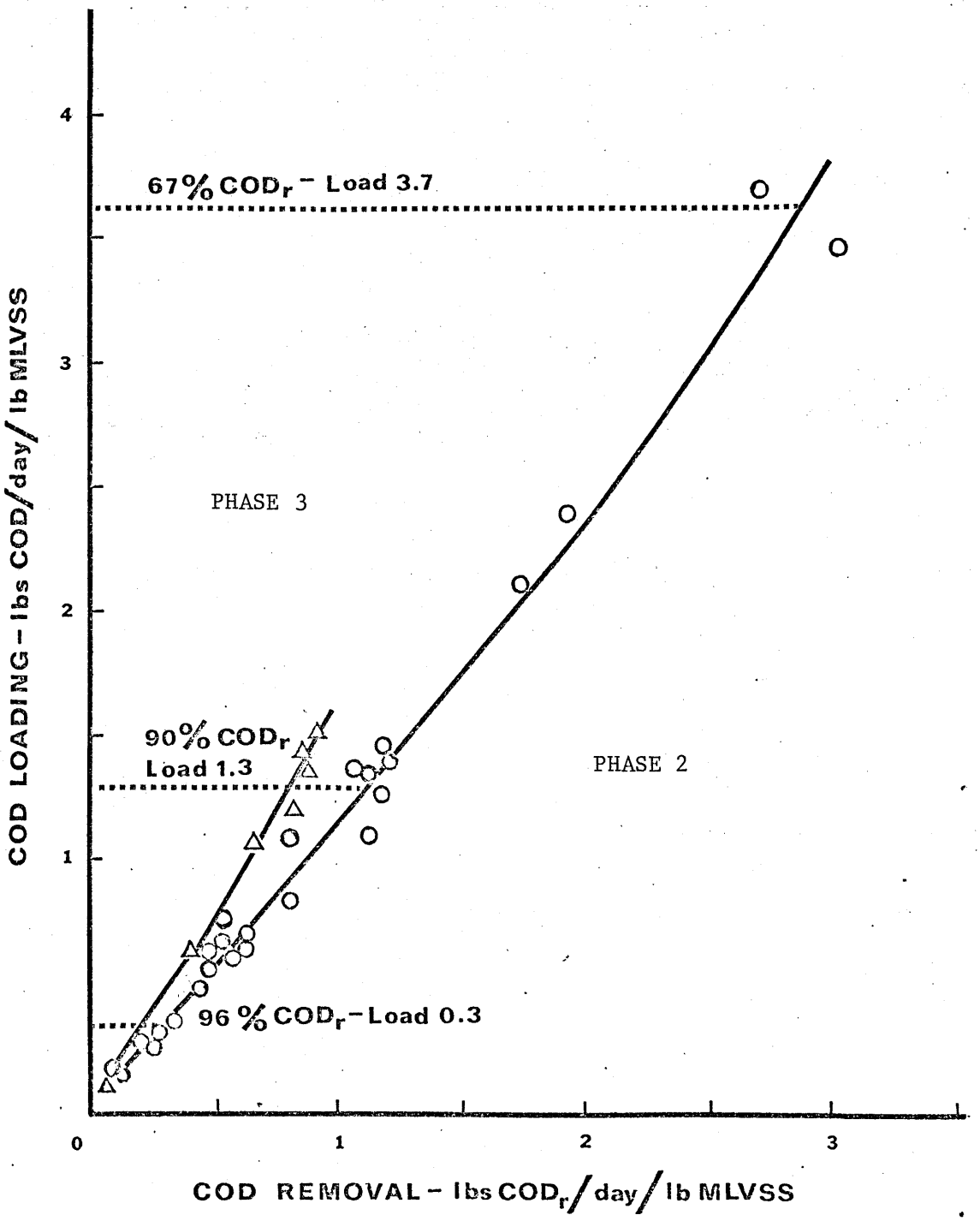
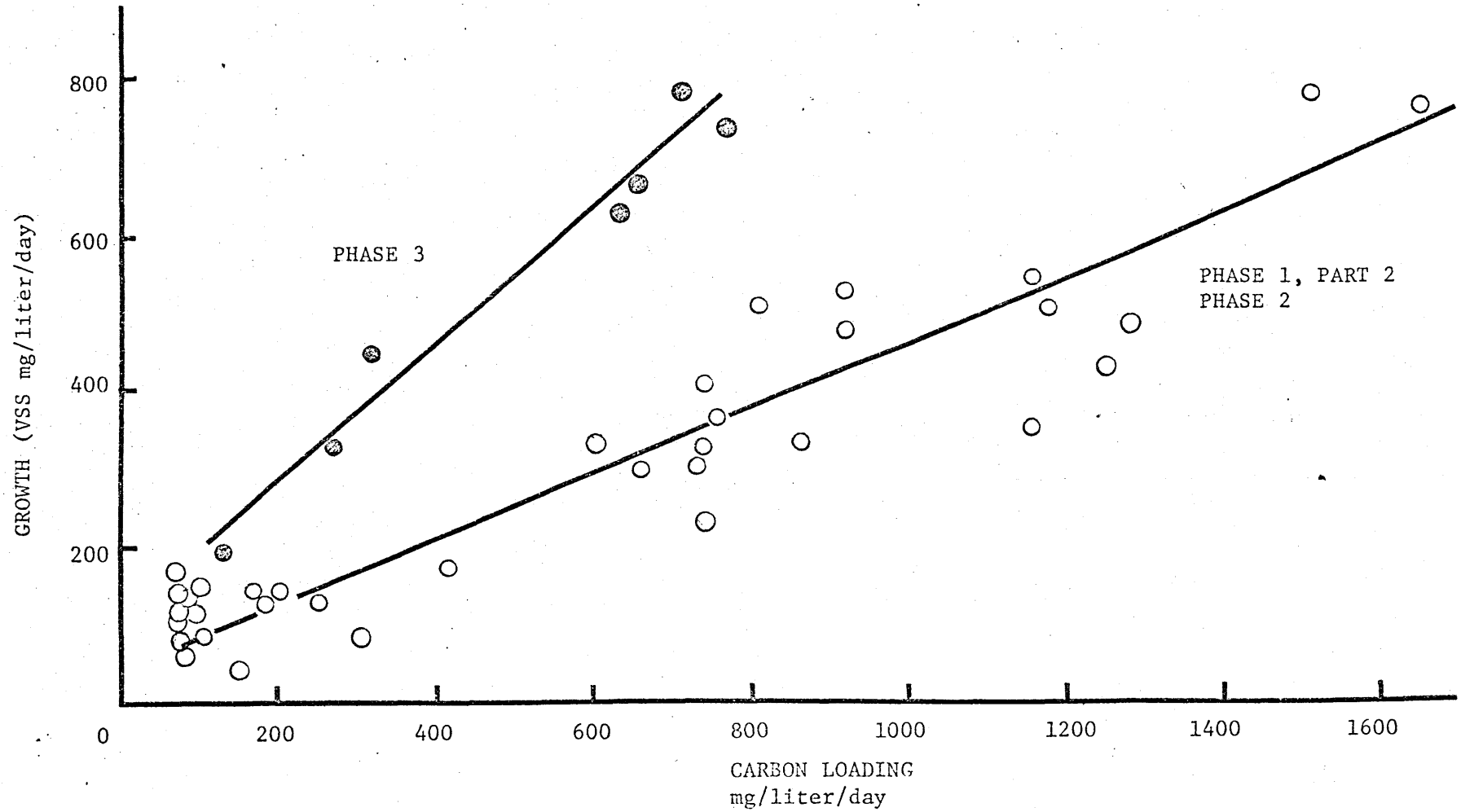


FIGURE 21

GROWTH RATE VERSUS CARBON LOADING



2 - Sludge Retention Time (SRT) and Growth

For Figure 22 growth rate was related to SRT for studies performed for Phase 1 and Phase 2 at 200 ft-candles. Results provided by Phase 3 and other researchers (14, 15) were included. Growth improved in response to SRT as the endogenous respiration effect became less pronounced. For 4 to 20 day SRT, growth increased from 30 to 180 mg VSS/liter/day. For SRT less than 4 days growth rate began to accelerate. At one day SRT maximum growth of 800 mg/VSS/liter/day was obtained. Below one day SRT, the decrease in growth was indicative of limiting conditions. Microbial cells were removed from the system at a rate exceeding the generation time. Growth did not cease completely at the limiting SRT. Because the SRT represents the average time cells remain in the system, some microbes were present less time than the indicated SRT while others were present for a longer period. The result is a finite growth reduction rate after the limiting SRT.

Mixed liquor concentration was closely related to SRT as shown in Figure 23. Results were provided by experiments conducted with organic feed at liquid depths of 1.7 inches. This type of relationship should be useful in future studies to indicate wasting rates required to provide a desired mixed liquor concentration. For example, for the sewage used an average MLVSS of 1000 mg/liter was obtained when the SRT was 2.5 days. MLVSS level in other wastewaters will be a function of the amount of nonbiodegradable VSS present as well as SRT.

Control of the MLVSS level takes on added dimension in the activated algae process. For the effective use of light, increased

Figure 22
GROWTH RATE VS. SRT-CONSTANT
LIGHT INTENSITY

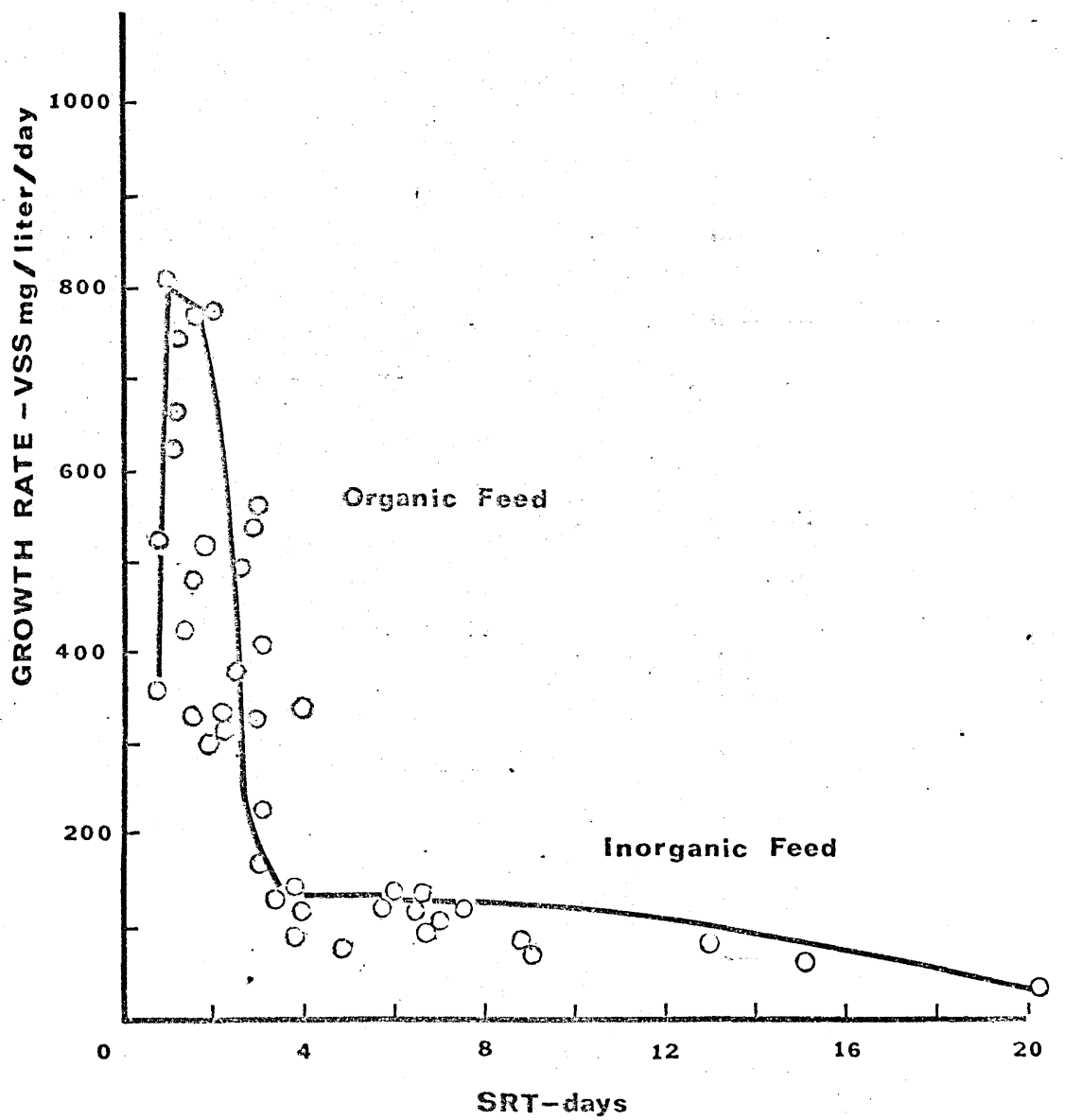
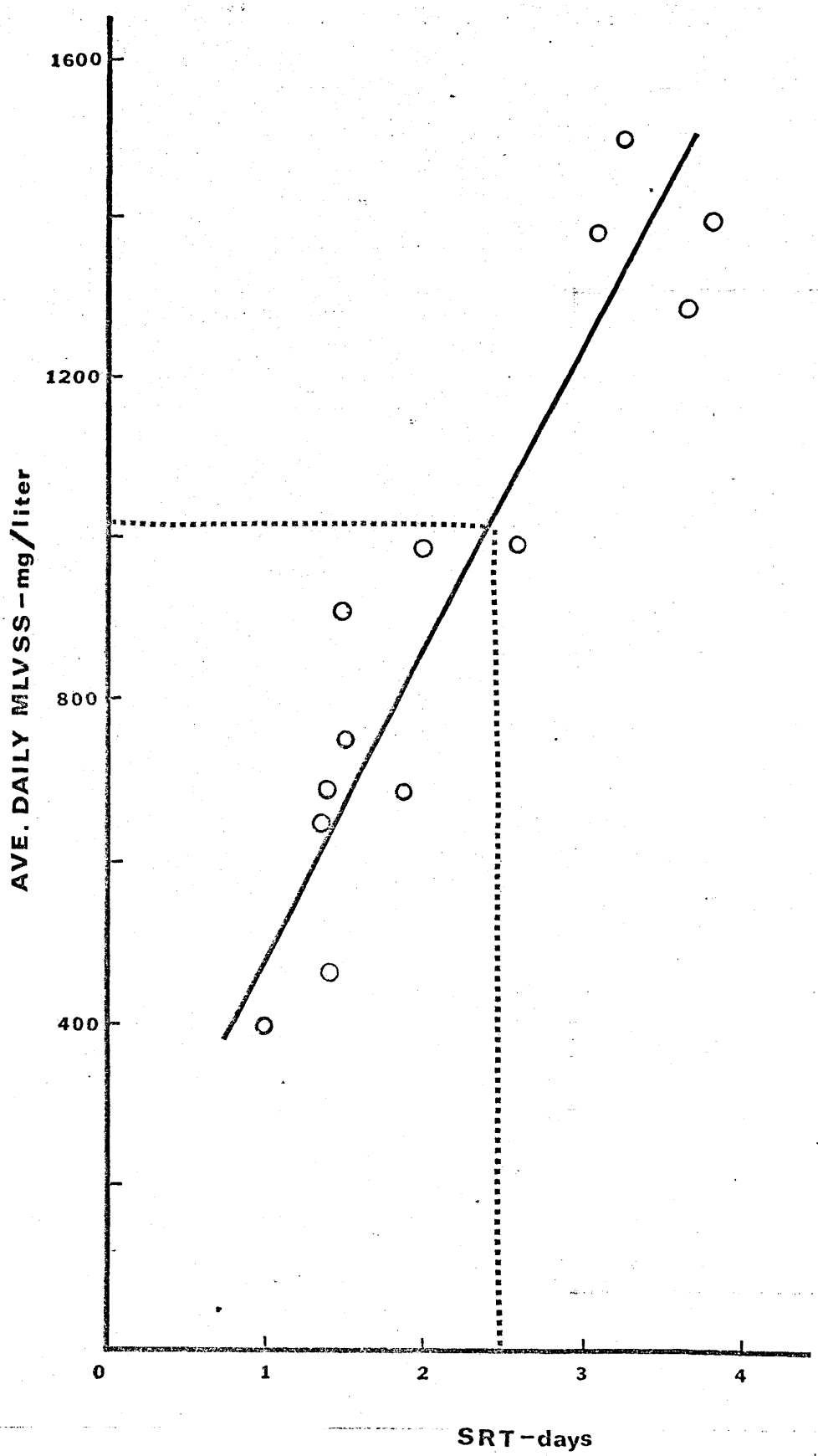


Figure 23
AVERAGE DAILY MLVSS VS. SRT



solids wasting rates will be required for the activated algae process to maintain lower MLVSS levels as compared to the present biological waste treatment systems. Light effects will be discussed in detail.

3 - Light Intensity Effect

The effect of light intensity on the VSS production using inorganic feed was investigated during Phase 1, Part 3, as shown in Figure 24. Appropriate results obtained during other experiments and by previous research (15) was incorporated into the presentation. Light intensity was increased from 75 to 600 ft-candles as measured at the liquid surface. For systems operated at SRT of 4.2 to 4.8 days, solids production reached a maximum level near 300 ft-candles of 0.26 g VSS/day g MLVSS. The average MLVSS concentrations representing about 85 per cent of MLSS increased from 200 to 935 mg/liter.

A limited number of data at different SRT levels not included in Figure 24 indicated the potential for a family of light intensity curves, as effected by endogenous respiration. When SRT was decreased to 2.22 days growth was significantly accelerated at 600 ft-candles. Lower mixed liquor concentrations and reduced endogenous respiration effected the results. Solids production decreased at 300 ft-candles to less than 0.05 g VSS/day/g MLVSS when SRT was extended beyond 20 days. The buildup of nonbiodegradable solids for extended SRT values was indicated by the reduced growth rates and appear to control the light effect.

A relationship between microbial growth, SRT and light intensity is shown in Figure 25. Growth rates obtained for Phase 1, Part 2 at 200 ft-candles over a range of SRT appear to be poorly related. A

FIGURE 24

GROWTH RATE
VERSUS
LIGHT INTENSITY CONSTANT SRT

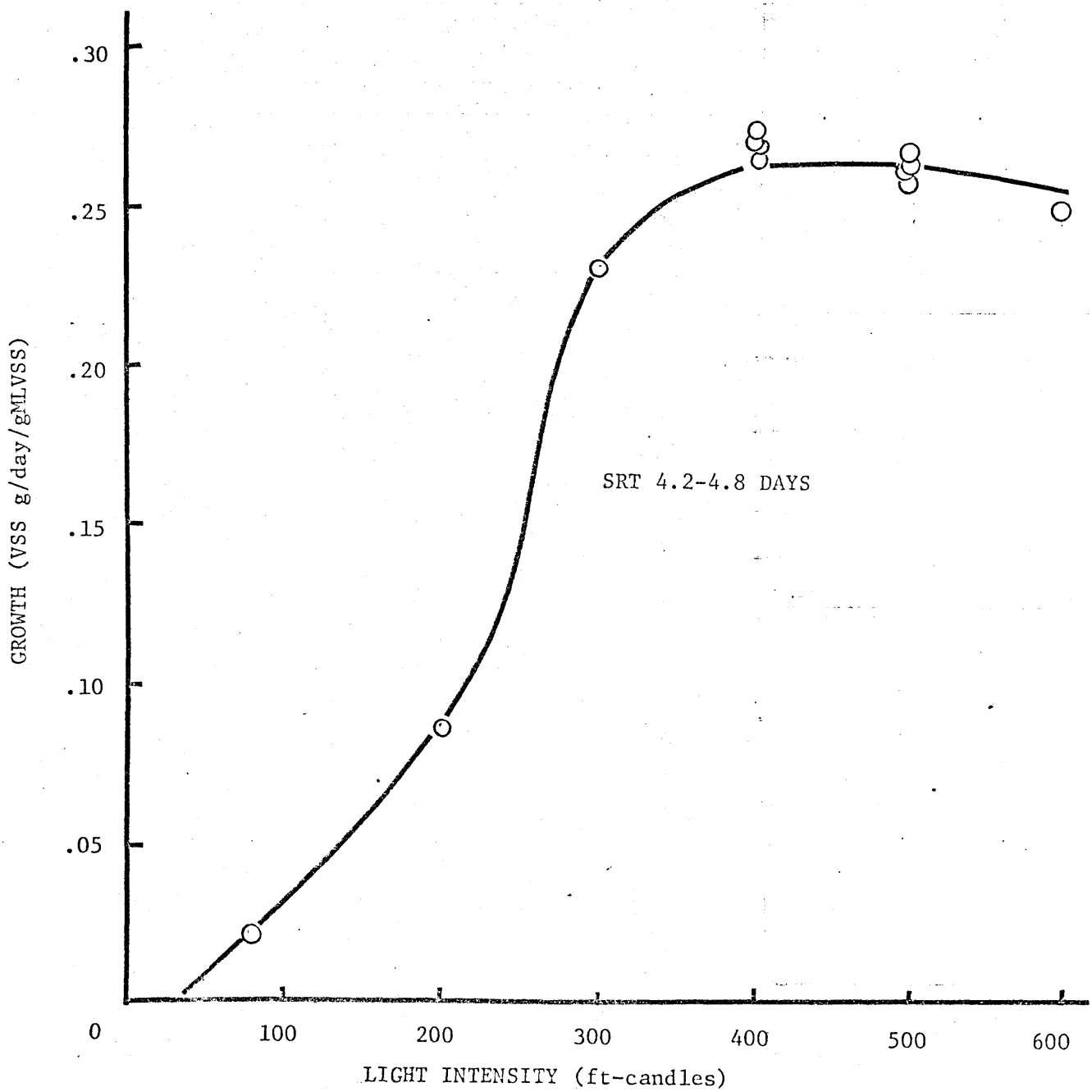
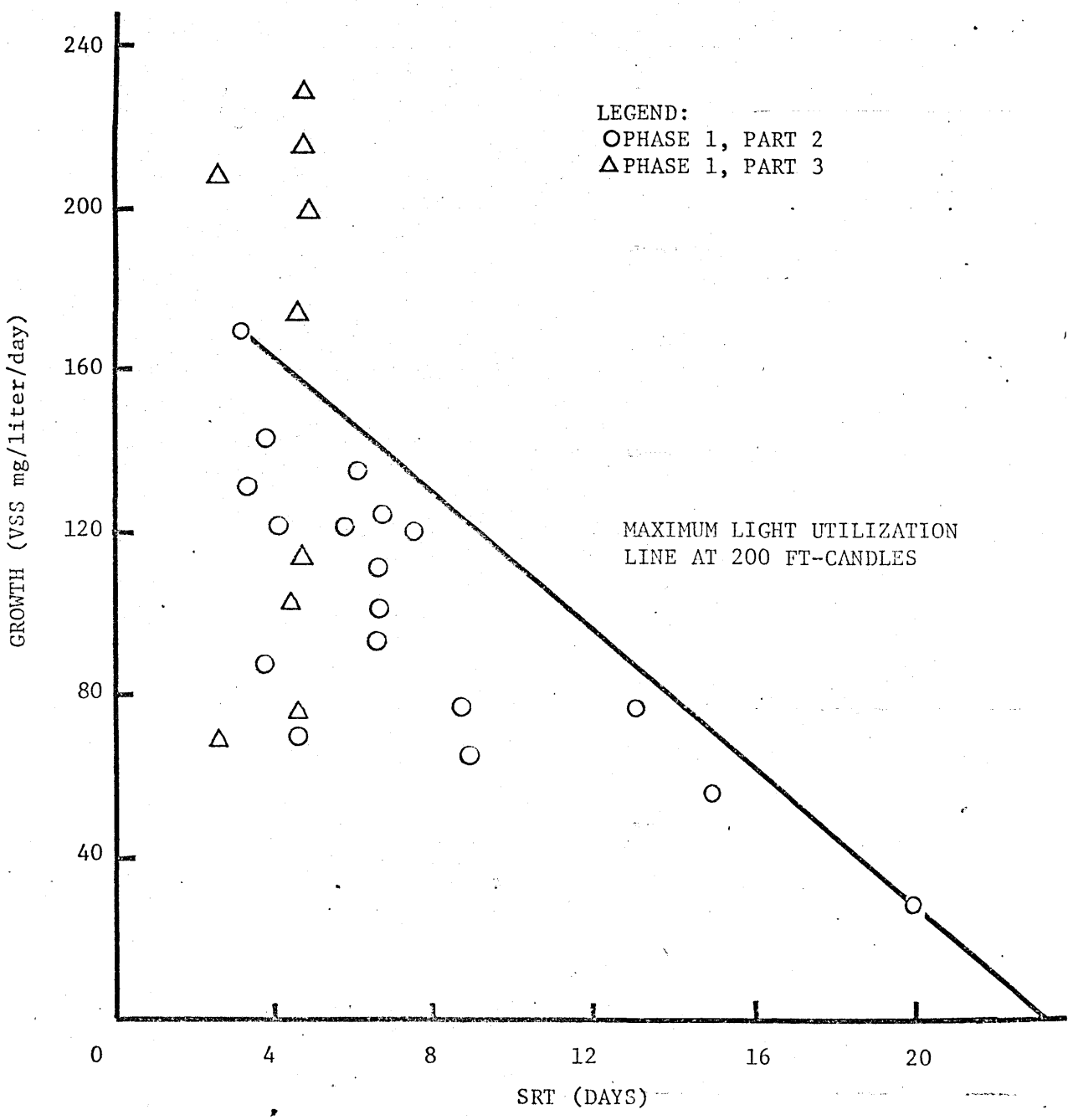


FIGURE 25

GROWTH RATE
VERSUS
SRT-VARIABLE LIGHT INTENSITY



line was drawn between growth rates at 3.2 and 20 day SRT to indicate a possible maximum light utilization level for 200 ft-candles. For both limiting experiments the effluent contained sufficient residual alkalinity minimizing the possibility of insufficient carbon. Superimposing the results obtained for Phase 1, Part 3, growth improved as light intensity increased to 600 ft-candles provided carbon nutrients or some other factor was not limiting as indicated when growth rate remained above the level. Therefore, light intensity effected algae synthesis when SRT remained fairly constant. The possibility of a family of light intensity SRT curves for activated algae is indicated. Extrapolation of the light utilization line at 200 ft-candles to the X-axis shows that minimum growth is expected for operation of an activated algae process at greater than 23 days SRT, independent of the light intensity. The buildup of inert solids overrides the lighting effect.

In activated algae, because of the elevated MLSS levels, light availability controls algae synthesis, rather than direct light exposure when endogenous effects are minimized.

4 - Light-Depth Relationship

In activated algae, because of the elevated mixed liquor levels, algae synthesis is controlled by the energy availability near the lighted surface. Direct light penetration into suspensions is limited as demonstrated in Table 4 of the Appendix. Algae are exposed to light intermittently by turbulence and the hydraulic turnover in the treatment unit. Any given algae cell moves in and out of shaded and lighted areas. As a practical measure of the amount of light energy

provided for photosynthesis, the light-depth (L/D) relationship was developed for use in the activated algae process. L/D relationship, ft-candles/cm, was created as a measure of the surface area (cm^2) exposed to a given light intensity (ft-candles) as a function of the volume of mixed liquor (cm^3).

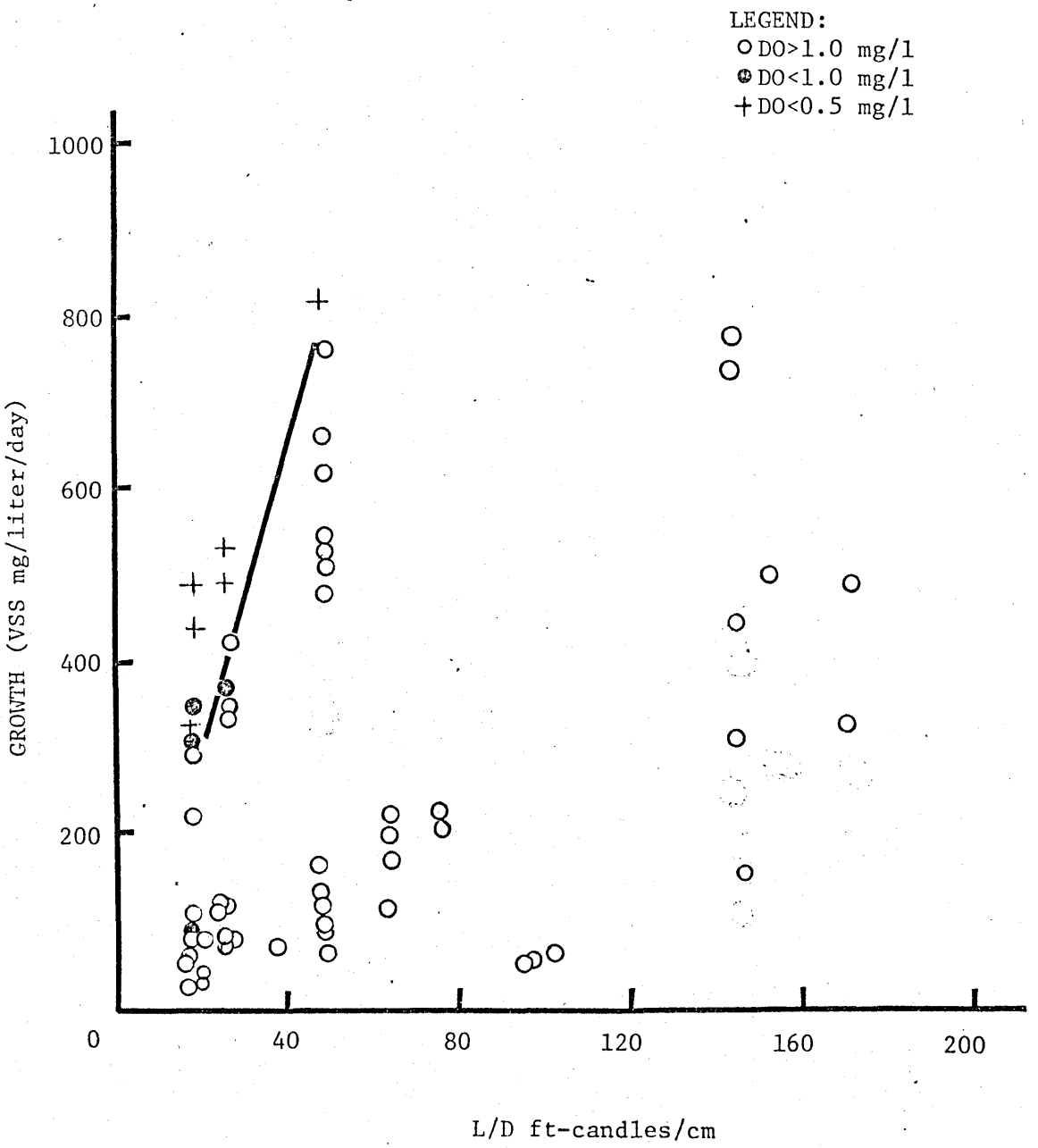
L/D = Light intensity X surface area/volume.

The L/D ratio was useful for comparing the results obtained for the several different types of experimental systems used in activated algae research. For the laboratory systems used for Phases 1 and 2 when the light intensity was 200 ft-candles L/D was 18.0, 25.2 and 48.1 ft-candles/cm for Units 1, 2 and 3 respectively. During Phase 3 the L/D ratio was 48.1 and 145 ft-candles/cm. In previous research studies estimated L/D values ranged from 20.4 to 172.

The L/D ratio was applied for the description of the effect of light limitations on microbial growth. Microbial growth rates were related to the L/D ratio as shown in Figure 26. Results were provided by each of the three experimental phases and previous studies (14, 15). At first glance the significance of the relationship of L/D to growth was not apparent. Satisfactory light for photosynthetic activity was then judged by the oxygen level. A close examination of the individual experiments indicated when the DO within the reactors dropped below specified limits. Satisfactory, marginal and poor operation were judged by DO concentrations of greater than 1.0 mg/liter, less than 1.0 mg/liter and less than 0.5 mg/liter, respectively. Using this criterion, light limitations appeared to control growth at 300 to 770 mg VSS/liter/day as L/D was increased from 18 to 48 ft-candles/cm. For many experiments, light was not the controlling factor as indicated

FIGURE 26

GROWTH RATE VERSUS L/D



by the large number of results falling below the limiting line. Maximum growth at L/D greater than 48 ft-candles/cm would be predicted to be at least 770 mg VSS/liter/day.

The relationship between carbon loading and L/D ratio was investigated using results provided by each of the research phases and previous studies (14, 15) as shown in Figure 27. Interpretation of the desired results was aided by rating the condition of the biological systems by DO level. Satisfactory, marginal and poor operation were indicated by DO levels of greater than 1.0 mg/liter, less than 1.0 mg/liter and less than 0.5 mg/liter, respectively. At a maximum carbon loading rate of 1150 mg/liter/day satisfactory operation was provided when the L/D ratio was 48 ft-candles/cm. Poor operation resulted when the carbon loading was increased to 1660 mg/liter/day. When the L/D ratio was reduced to near 20 ft-candles/cm light appeared to become limiting at a carbon loading of 750 mg/liter/day.

For activated algae experiments, DO levels were related to L/D and COD loading rate as shown in Figure 28. DO concentrations at carbon loading rates less than 100 mg/liter/day were least influenced by the increase in L/D ratio. As a low rate system activated algae can be effectively operated at lower L/D ratios since carbon appears to limit the microbial systhesis. A greater L/D ratio was needed as loading was increased indicating the need for more light when the experiments simulated a high rate process.

Research information presented in Figure 28 was used to illustrate the relationship of loading rate and reactor depth for the laboratory studies. In practice an average DO level of 1 mg/liter is recommended during normal operation to reduce the possibility of

FIGURE 27

CARBON LOADING
VERSUS
L/D

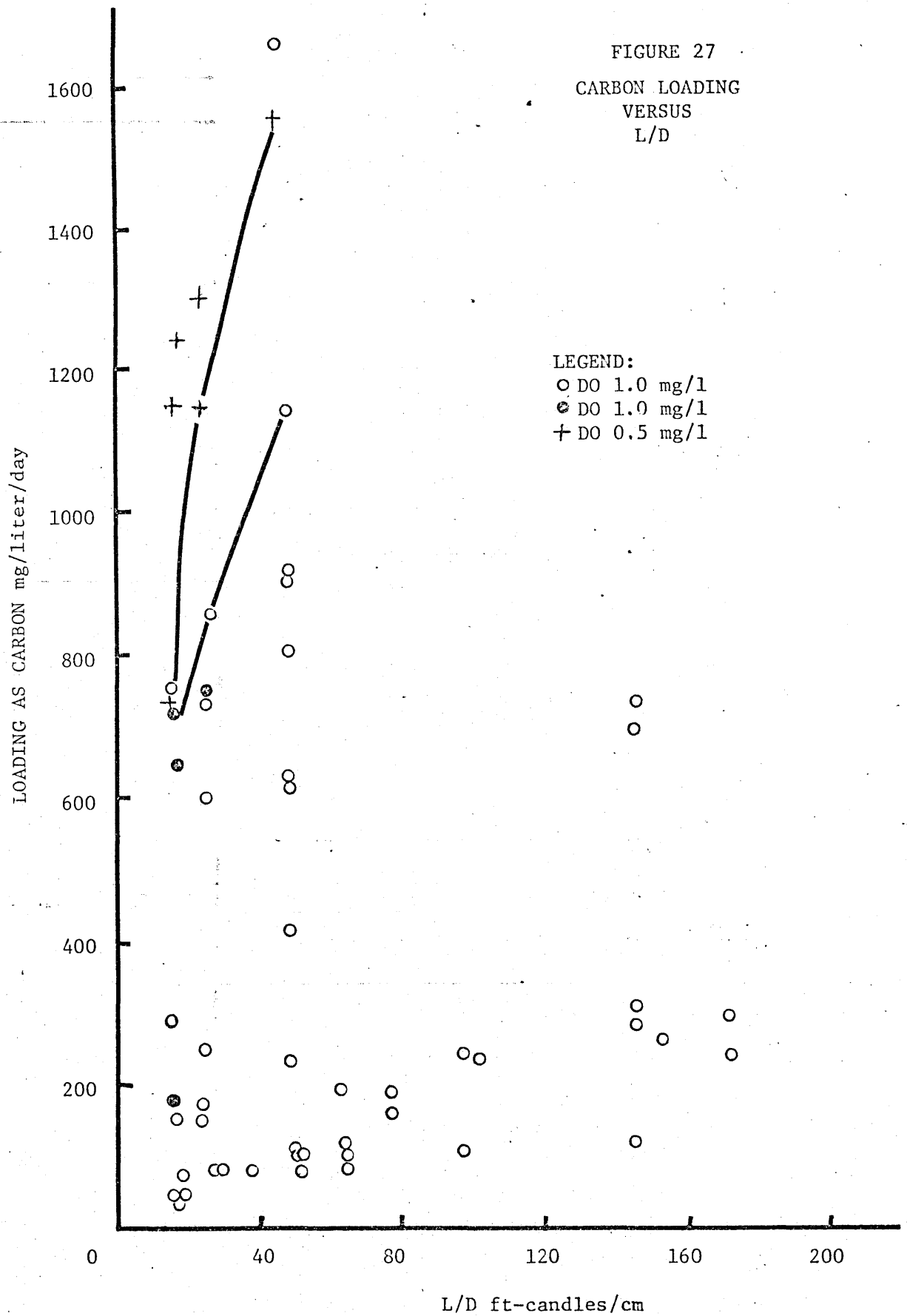
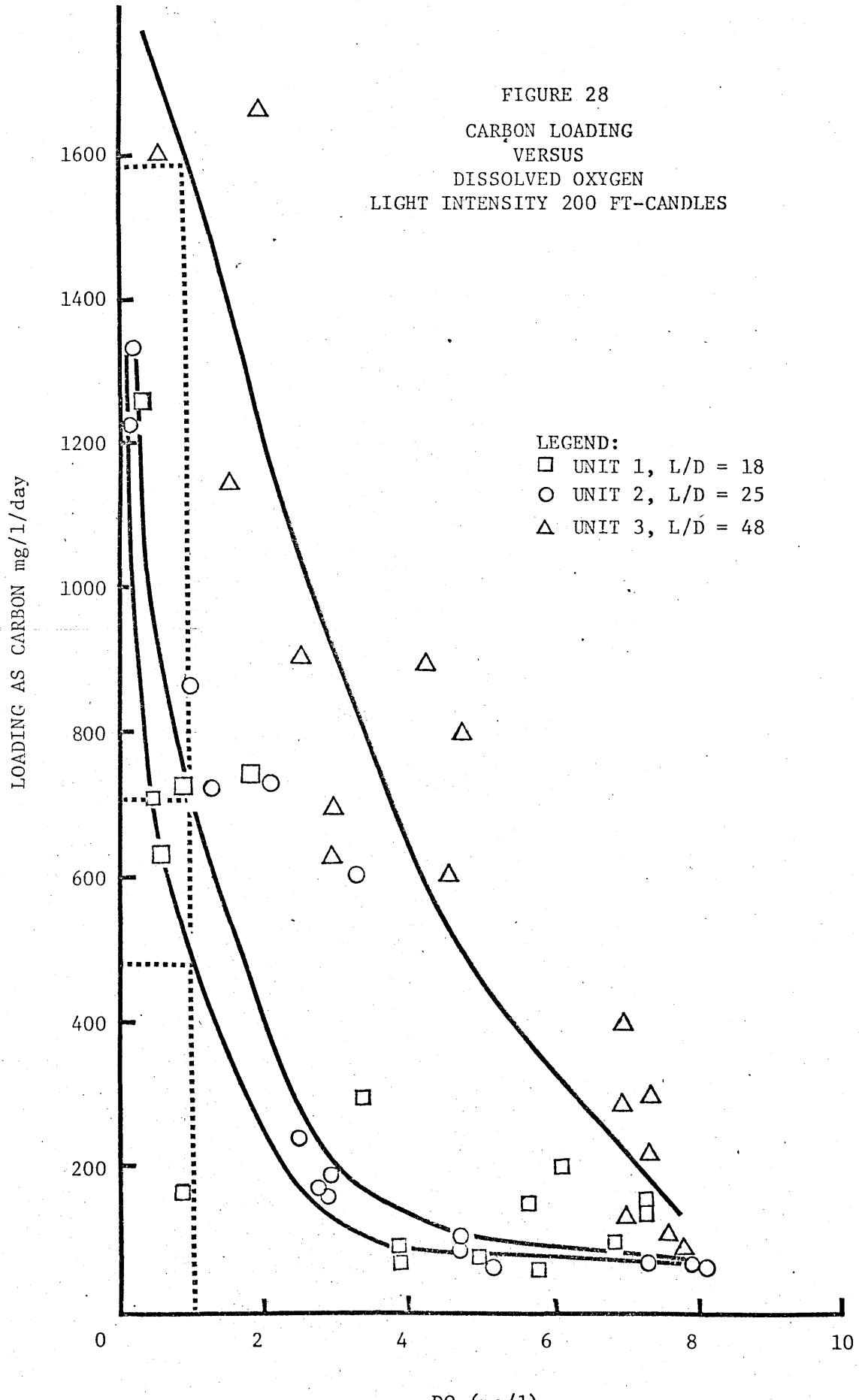


FIGURE 28

CARBON LOADING
VERSUS
DISSOLVED OXYGEN
LIGHT INTENSITY 200 FT-CANDLES



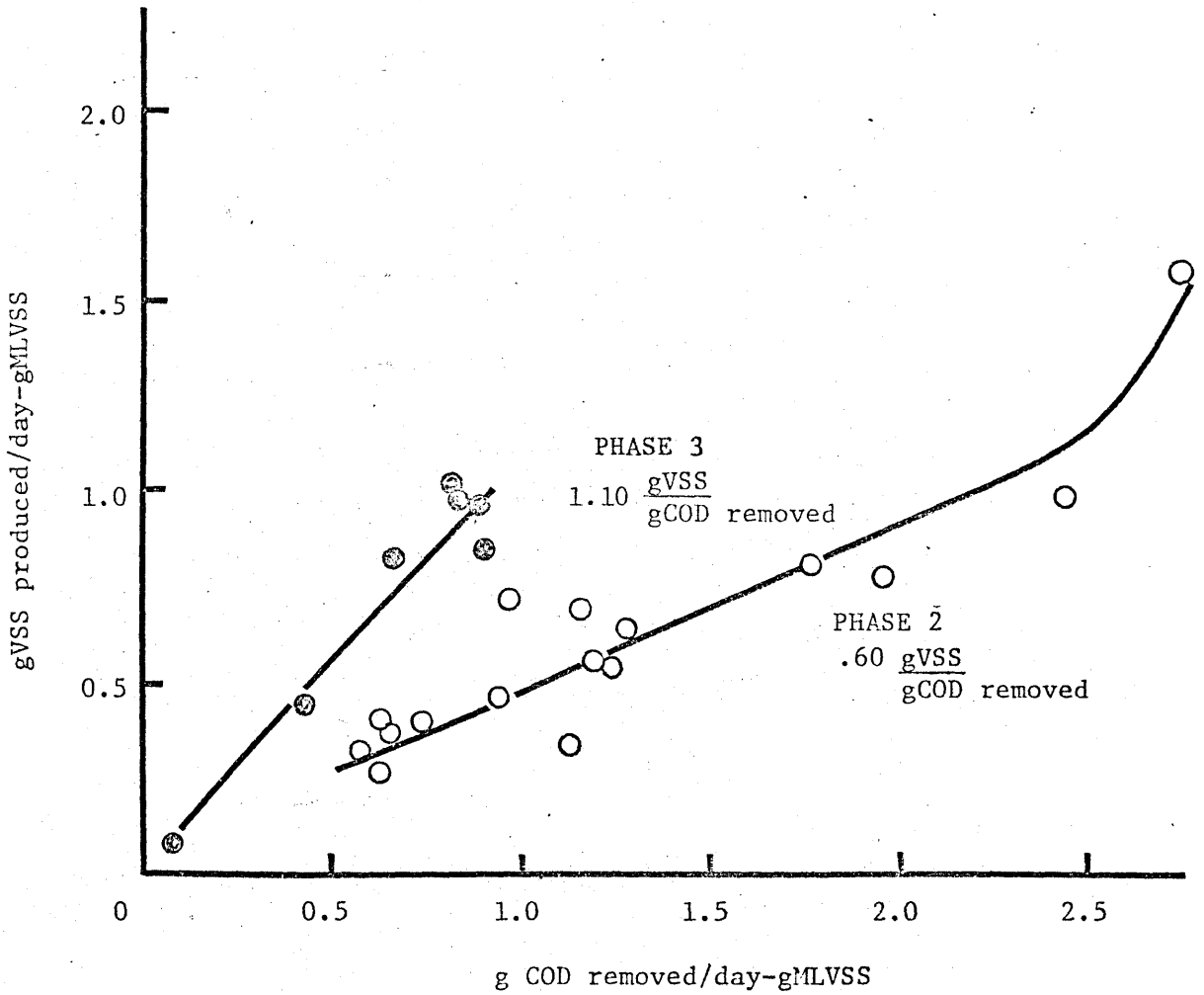
light limitation when carbon loading fluctuates during the daily cycle. The critical loading to Units 1, 2 and 3 would be 500, 700 and 1600 mg/liter/day, respectively. By calculating the sum of the loading rate, multiplied by the liquid depth within each reactor, a relatively constant value of 2300 to 2700 mg carbon-inch/liter/day was produced. Within experimental error, the surface area exposed to light appears to control the photosynthetic rate. The results indicate for a constant surface area and light intensity, the L/D ratio would decrease as the depth of the reactor increases. A corresponding reduction in the carbon loading would be affected by the greater volume. Detention time required for treatment would increase to a corresponding degree. Experimental results indicate activated algae was most efficient at a shallow depth of 1.7 inches. No improvement would be indicated for operating the deeper reactors. The impact of the release of nutrients by algae lysing during endogenous respiration would be more pronounced during the longer dark periods at deeper operating depths.

5 - Cell Yield

The effect of endogenous respiration can be recognized by determining the cell yield. The yield of microbial cells based on COD removal for activated algae studies is presented in Figure 29. For studies using synthetic wastewater the average yield was 0.60 g VSS/g COD removed. Cell yield was 1.10 g VSS/g COD removed for experiments using domestic sewage. The use of the rapid COD procedure effected the results by providing a different recovery ratio for each substrate (47). Adjusting the results to a BOD_5 basis indicated cell yield of 0.90 and 1.10 g VSS/g BOD removed for synthetic and domestic wastewater,

FIGURE 29

GROWTH RATE
VERSUS
COD REMOVAL RATE
SRT 1.0 TO 4.3 DAYS



respectively. For high rate biological treatment it was expected that bacterial synthesis would account for approximately 0.70 g VSS/g BOD removed. The remaining 0.20 to 0.40 g VSS should indicate algae synthesis resulting from the symbiotic relationship with aerobic microbes as predicted by the calculations presented in Table 1 of the Appendix. The actual yield is related to the SRT and inert VSS in the sludge. As predicted by the cell yield measured, the activated algae flora was estimated to contain 22 to 36 per cent algae on a weight basis.

Cell yield was determined on a carbon basis for experiments of each of the three research phases and other research (15), as shown in Figures 30 and Table 38. Supporting calculations are provided as Tables 11 and 12 of the Appendix. In terms of total inorganic and organic carbon added, cell yield would range from about 0.20 to 1.00 depending on the effect of the endogenous respiration. As summarized in Table 38 in each of the series of experiments, cell yield increased as SRT decreased until the limiting generation time of one day SRT was exceeded. The minimum cell yield of 0.23 obtained at 19.8 days SRT during Phase 1 approached the predicted limiting value. Cell yield greater than 1.0 indicate possible experimental error. As shown in Figure 30, cell yields were frequently lower than predicted based on carbon removed. Significant quantities of carbon dioxide were not absorbed by the algae and escaped from the reactors in the gas phase. The conversion of alkalinity to carbon dioxide during nitrification appears to be a possible mechanism causing reduced cell yield.

Table 38

SUMMARY OF CELL YIELD-CARBON BASES

UNIT	RUN	CELL YIELD (AS CARBON)	SRT (days)	
Phase 1, Part 2				
1	1	.23	19.8	Min
	2	.80	3.8	Max
	3	.46	8.9	
	4	.62	6.7	
	5	.50	6.6	
	6	.35	4.8	
2	1	.69	13.1	Min
	2	1.21	3.2	Max
	3	.48	8.8	
	4	.91	6.7	
	5	.63	7.5	
	6	.64	4.0	
3	1	.29	14.7	Min
	2	1.37	3.7	Max
	3	.92	6.7	
	4	1.00	5.7	
	5	.85	6.0	
	6	1.07	3.2	
Phase 2				
1	1	.36	2.9	Min
	2	.51	2.2	
	3	.51	2.2	Max
	4	.57	2.0	
	5	.48	1.3	
	6	.47	.70	Exceed
2	1	.41	4.3	Min
	2	.53	3.5	
	3	.57	2.9	
	4	.60	1.8	
	5	.48	1.6	
	6	.59	.80	Exceed

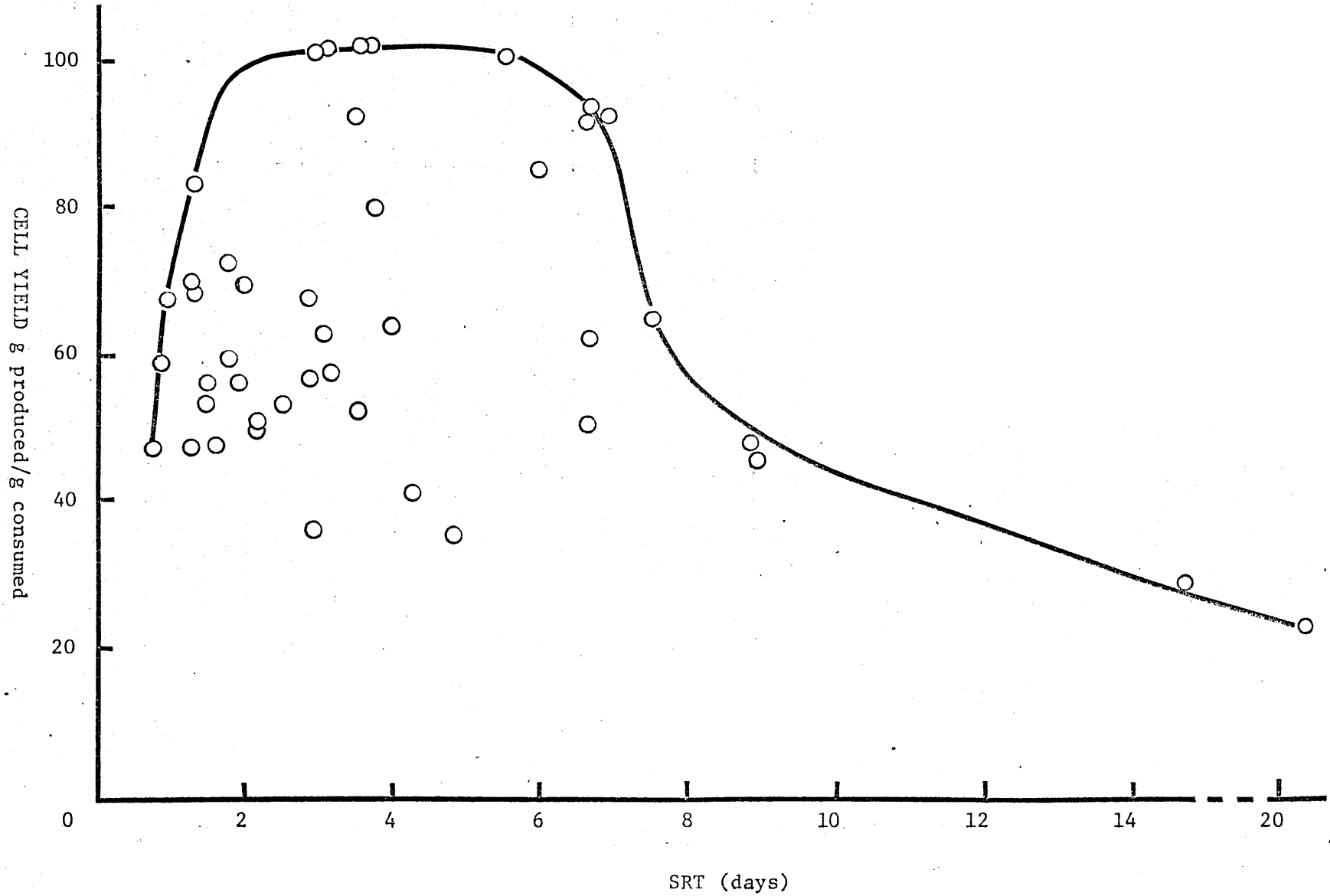
Table 38
(continued)

SUMMARY OF CELL YIELD-CARBON BASES

UNIT	RUN	CELL YIELD (AS CARBON)	SRT (days)	
Phase 2				
3	1	.58	3.2	Min
	2	.62	3.1	
	3	.54	2.6	
	4	.73	1.9	Max
	5	.57	1.5	
	6	.68	1.0	Exceed
Phase 3				
	1	.71	1.34	
	2	.69	1.37	
	3	.70	2.02	
	4	.54	1.50	
	5	.84	1.40	
	6	.68	2.85	
	7	.87	135	Not at equilibrium
McGriff (15)				
	2-1	- -	- -	
	2-2	.52	38.5	
	3-1	.15	53	
	3-2	1.32	3.8	
	3-3	1.06	3.7	
	3-dA	.93	3.6	

FIGURE 30

CELL YIELD AS CARBON
VERSUS SRT



6 - Nitrification Effect

Based on previous activated algae experiments (15) the pH was expected to be elevated during Phase 1 experiments by the photosynthetic pH effect. Against expectations, pH was depressed below 7 for many studies. In the Phase 2 the pH remained between 7 and 8. The measured pH effect was explained by the influence of nitrification.

As summarized by Eckenfelder (42), data reported by Downing indicated conditions suitable for nitrification include: DO greater than 2.0 mg/liter, ammonia above 0.5 mg/liter and a pH near 7.8. Warmer temperatures generally stimulate nitrifying organisms. Data for annual operation cited by Eckenfelder (42) indicates that almost complete nitrification was obtained for SRT near 2 days and greater in conventional sewage treatment plants. Therefore, environmental conditions suitable for nitrifying bacteria were provided during many of the activated algae experiments.

Significant activity by autotrophic nitrifying microorganisms was expected to influence both the pH and alkalinity as predicted by fundamental concepts. Calculations have shown 3.6 pounds of bicarbonate, as $CaCO_3$, were reduced for each pound of nitrate produced. Further, one pound of nitric acid as nitrogen requires 3.6 pounds of alkalinity for neutralization.

The relationship between rate of oxidized nitrogen production and alkalinity consumption for Phase 1, Part 2 and Phase 2 are summarized in Tables 39 and 40. Potential alkalinity associated with nitrification frequently exceeded the total consumed. Limitation of alkalinity during Phase 1 prevented complete neutralization of the

Table 39

EFFECT OF NITRIFICATION ON ALKALINITY REDUCTION
PHASE 1, PART 2

UNIT	RUN	NO_2+NO_3asN (mg/l)	NO_2+NO_3asN (mg/l/day)	TOTAL MEASURED ALKALINITY CONSUMED (mg/l/day)	PROJECTED ALKALINITY FOR NITRIFICATION
1	1	28	50	573	360
	2	31	61	475	440
	3	50	93	600	665*
	4	43	84	665	604
	5	28	112	960	808
	6	37	244	855	1616*
2	1	27	49	510	355
	2	40	67	475	485*
	3	48	108	720	780*
	4	48	85	600	613*
	5	26	103	870	740
	6	33	191	840	1380*
3	1	44	119	900	850
	2	44	101	615	720*
	3	46	103	646	733*
	4	41	92	706	665
	5	27	126	930	900
	6	32	308	910	2200*

* Alkalinity Deficit

Table 40

EFFECT OF NITRIFICATION ON ALKALINITY REDUCTION
PHASE 2

UNIT	RUN	(mg/1)	(mg/1/day)	TOTAL MEASURED ALKALINITY CONSUMED (mg/1/day)	PROJECTED ALKALINITY FOR NITRIFICATION
1	1	5	15	248	108
	2	4	11	178	80
	3	5	14	120	100
	4	5	12	88	86
	5	0	0	69	0
	6	1	4	31	28
2	1	36	173	770	1240*
	2	35	143	780	1030*
	3	32	128	540	920*
	4	35	115	460	830*
	5	0	0	140	0
	6	1	6	64	44
3	1	9	57	630	412
	2	19	95	600	680*
	3	20	100	425	720*
	4	35	153	550	2100*
	5	2	18	270	130
	6	2	16	120	116

* Alkalinity Deficit

nitric acid formed and the pH dropped below 7.0. Increased alkalinity loading during Phase 2 permitted the pH to remain above 7 by neutralizing more of the acid formed. However, nitrification counterbalanced the photosynthetic pH shift. The reduced total rate of alkalinity consumption during Phase 2 indicates that algae carbon requirements were being met by bacterial respiration to a greater degree.

During Phase 2, oxidized nitrogen production was reduced in Unit 1 where the DO levels were marginal. Minimum nitrification occurred in Runs 5 and 6 in all three reactors when DO was increased but solids were wasted at maximum rates. In Figure 31, combined nitrate and nitrite production is related to SRT for the experiments. The rapid decrease in nitrification when SRT were reduced below 3 days indicates growth limiting conditions by the bacteria. The growth of nitrifying bacteria will be controlled in activated algae by operation at SRT of less than 3 days.

7 - Empirical Correlations

Empirical relationships applicable to other biological processes were tested using activated algae data. The purpose of including these correlations in the discussion was to demonstrate the conformity of activated algae to other waste treatment processes.

Sat Correlation

Sat, determined by multiplying the average MLVSS (Sa) and the detention time (t), has been used to indicate operating ranges suited for efficient BOD removal and increased microbial sysnthesis (39). Presentation is made in Figure 32 for solids production as related

FIGURE 31

OXIDIZED NITROGEN PRODUCTION
VERSUS
SRT

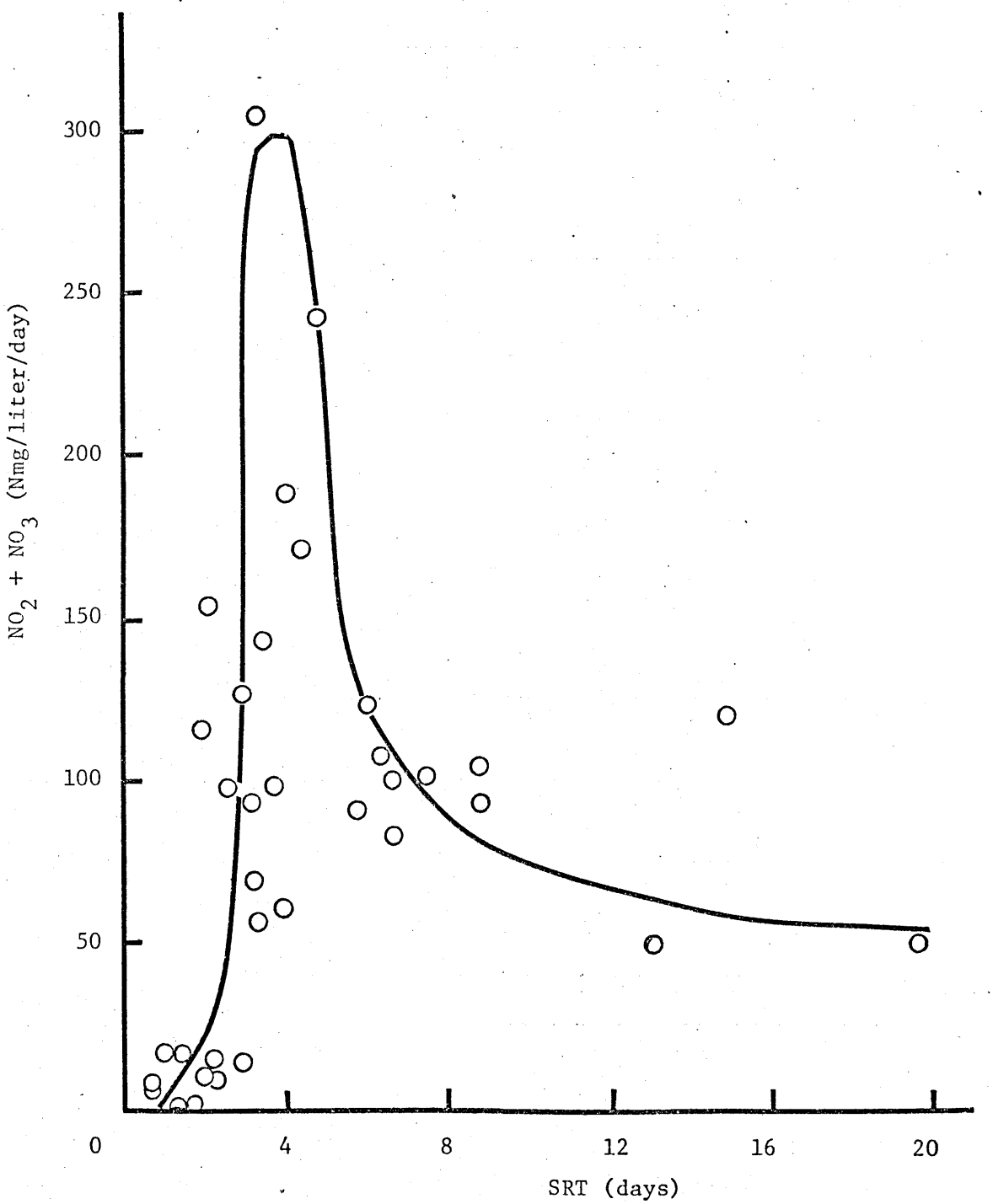
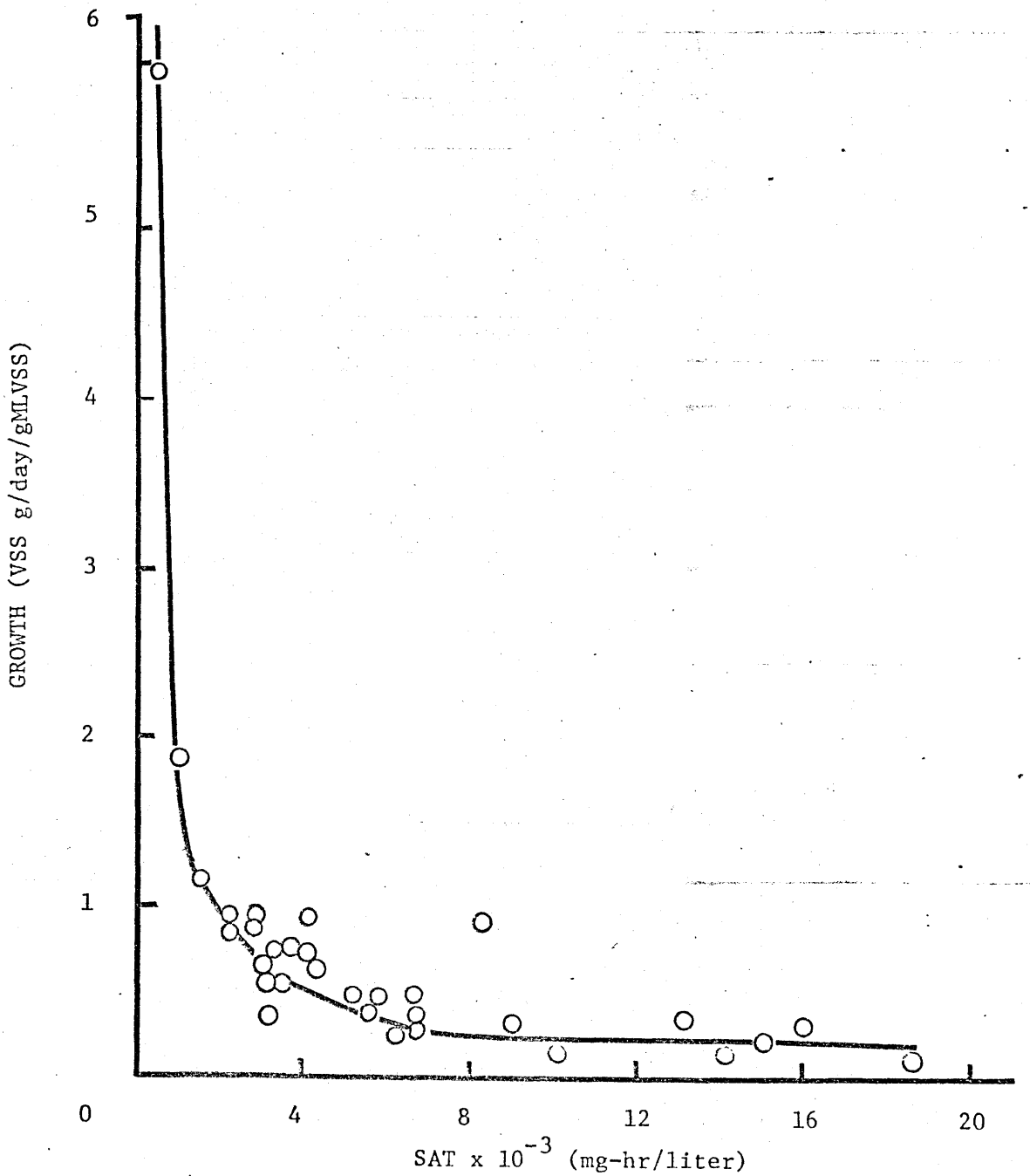


FIGURE 32

GROWTH VERSUS SAT CORRELATION



to Sat for the research. The results show that solids production was most significantly effected for Sat values less than 5,000 mg-hr/liter. In terms of maximizing the microbial growth rate the Sat correlation indicates an activated algae system controlled at an average MLVSS level of 1,000 mg/liter should be operated with a treatment time of five hours or less.

Translation of the Sat information to other studies requires an understanding of the limitations of this correlation. The magnitude of Sa is related to the accumulation of inert volatile materials present in the substrate used. The concentration of nonbiodegradable materials in several wastewaters may be significantly different, causing deviations in the results determined from this research.

F-M Correlation

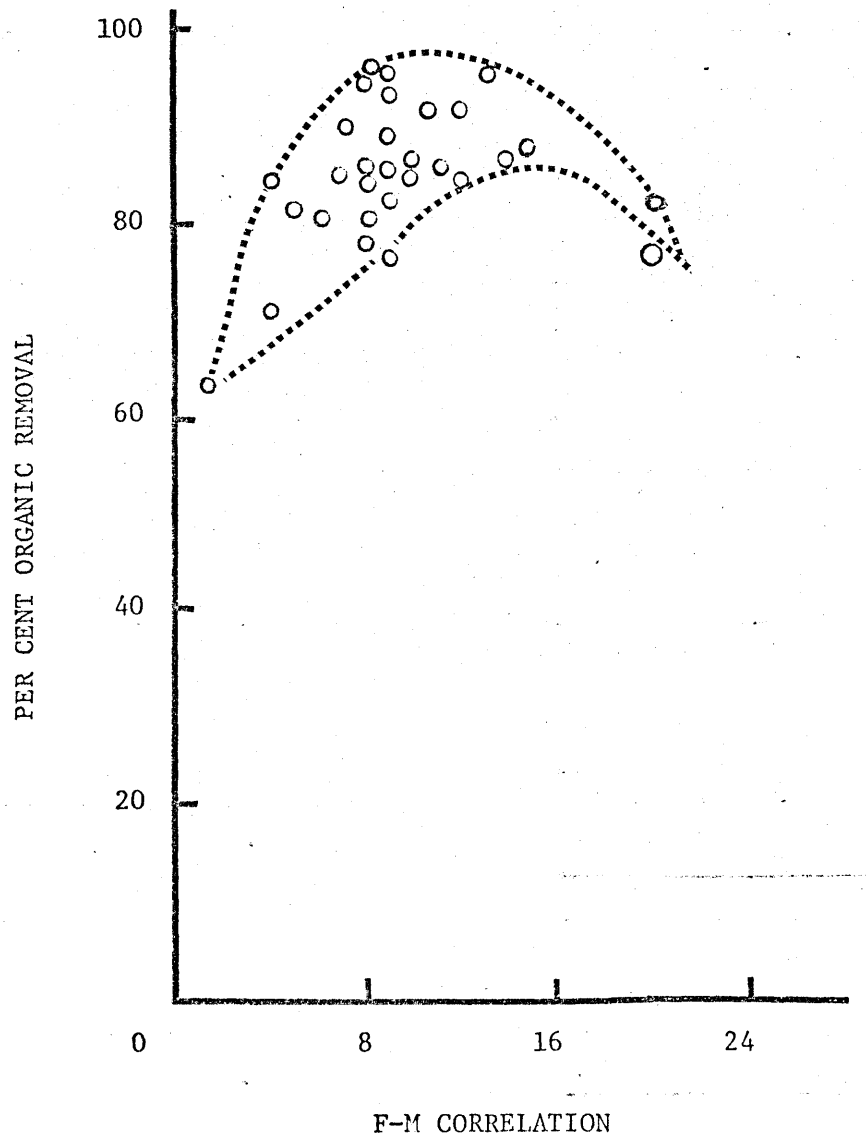
The F-M correlation indicates the combination of detention times per day and SRT should be near 10 (32) for satisfactory activated sludge operation. The following examples are presented to illustrate the use of the F-M correlation:

DETENTION TIME (hrs)	DETENTION TIMES PER DAY	SRT (days)	F-M
12	2	5	10
6	4	2.5	10
3	8	1.25	10

For the correlation an assumption was made that the feed concentration as estimated by BOD was typical of normal domestic sewage. The F-M correlation determined for activated algae investigations are shown in Figure 33. Data was scattered fairly widely over the F-M

FIGURE 33

ORGANIC REMOVAL
VERSUS
F-M CORRELATION



range of 1.7 to 20.5. As would be expected from the operation of activated sludge facilities treating normal domestic sewage optimum organic removal was obtained near F-M values of 8 to 12.

8 - Nutrient Removal

Results of chemical analyses indicating levels of nutrient removal during Phase 3 are summarized in Table 41. BOD removal averaged 84 to 92 per cent. Reductions in ammonia and total nigrogen ranged from 19 to 83 per cent and 15 to 71 per cent, respectively. Efficiency of total phosphorus removal was 25 to 75 per cent.

The nutrient removal rate from the wastewater is summarized in Table 42. Ammonia and total phosphorus reductions were used to indicate microbial assimilation. Incoming organic nitrogen was considered to be removed primarily by wasting with the mixed liquor in high rate activated algae systems. Ammonia nitrogen was removed at 11 to 83 mg/liter/day. Total phosphorus was removed at 3.9 to 34 mg/liter/day. The removal rate decreased as detention time was extended. As predicted by the theory presented in Table 1 of the Appendix, nutrient assimilation was generally within the expected ranges. Enhanced phosphorus removal appeared to be a possibility for Runs 3 and 7 where metabolic requirements were exceeded.

Significantly, improved nutrient reductions were determined in many previous activated algae experiments (13, 14, 15). Enhanced nutrient removal was believed to result as the combined effect of microbial metabolism and chemical reactions by ammonia stripping and phosphorus precipitation. In these studies, overall metabolic requirements of algae and bacteria could not account for the levels of nutrient removed from domestic sewage (40). Chemical reactions

Table 41

SUMMARY OF NUTRIENT REMOVAL, PHASE 3

RUN	pH	EFFLUENT CONCENTRATIONS							
		BOD		AMMONIA		TOTAL NITROGEN		TOTAL PHOSPHATE	
		mg/1	% REMOVED	mg/1	% REMOVED	mg/1	% REMOVED	mg/1	% REMOVED
1	7.7	22	84	33	21	--	--	4.1	38
2	7.6	20	87	19	35	29	50	7.1	25
3	7.5	15	92	18	36	22	58	6.1	31
	7.5	16	84	17	23	25	22	5.8	47
4	7.5	22	87	28	30	--	--	9.8	20
5	7.7	15	89	17	43	22	44	5.9	50
6	7.9	11	90	17	19	28	15	6.6	39
7	8.5	--	--	4	83	11	71	5.3	75
	8.5	9	90	13	54	15	62	6.6	42
	8.5	--	--	9	59	11	71	4.6	63

Table 42

NUTRIENT REMOVAL RATES, PHASE 3

RUN	AMMONIA REMOVED mg/1	AMMONIA REMOVED mg/1/day	GROWTH mg/1/day	N VSS
1	9	57	620	.092
2	10	67	660	.102
3	10	67	780	.086
	8	53	780	.068
4	12	83	740	.112
5	13	36	450	.080
6	4	11	320	.034
7	20	25	180	.139
	15	19	180	.167
	13	16	180	.089
1	2.5	15.7	620	.025
2	2.3	15.2	660	.023
3	2.7	18.0	780	.023
	5.1	34.0	780	.044*
4	2.5	17.2	740	.023
5	5.9	16.2	450	.036
6	4.2	11.2	320	.035
7	16.0	12.9	180	.072*
	4.8	3.9	180	.022
	7.8	6.3	180	.035

* Possible Enhanced Results

providing increased nutrient removal may become operative in activated algae when photosynthetic activity causes an elevation of the pH level during treatment.

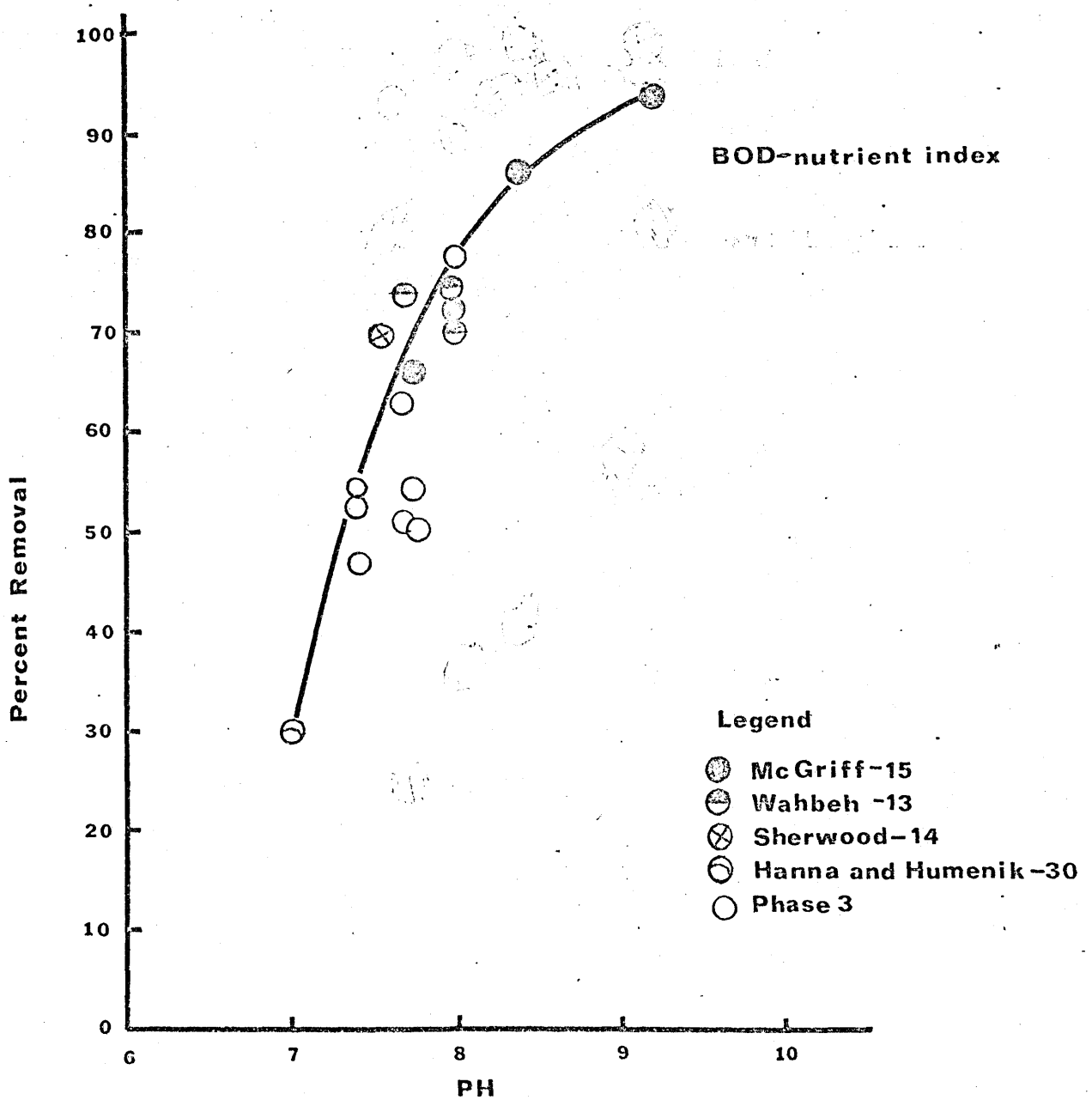
A "BOD-nutrient" index was created to compare reductions of organic matter, ammonia and phosphorus, at the pH levels studied, as presented in Figure 34. This index was determined by summing the per cent removals measured for each of the nutrient factors, then dividing the total by three. "BOD-nutrient" index was determined for previous studies and Phase 3. Phase 2 results were not included because nitrite and nitrate production were primarily responsible for the ammonia reduction.

For previous research at pH 9.2 the "BOD-nutrient" index reached the maximum value of 91 per cent. Removals of BOD, ammonia and phosphorus were 96.5, 98 and 80 per cent in that order. For the present research where experiments were directed towards maximizing microbial growth, the pH level rarely exceeded 8.0. The maximum "BOD-nutrient" index of 78 was significantly reduced compared to earlier research. Experimental differences probably contributed to the results obtained.

BOD removal efficiency was reported for earlier activated algae studied to be as high as 95 and 98.5 per cent for 5 and 10 hour detention times, respectively (13, 15). Results of analyses measured during Phase 3 provided 84 to 92 per cent removals for 3.5 hour treatment periods. Soluble BOD residuals were 15 to 22 mg/liter. Fundamental concepts developed for activated sludge would predict effluent BOD levels for 3.5 hours aeration to be near 4 mg/liter (41). In activated algae experiments using 9 and 19 hour treatment times residual soluble BOD decreased slightly to an average of 12 mg/liter. The

FIGURE 34

EFFECT OF PH ON ORGANIC AND NUTRIENT REMOVAL USING ACTIVATED ALGAE



magnitude of the measured soluble BOD residual obtained in Phase 3 studies indicates experimental errors may have been created by short circuiting within the pilot reactor or nitrification during the BOD incubation time. The pilot plant mixing tank was operated with a minimum of turbulence. The normal mixing established by the pump created a circular flow pattern which passed near the effluent control weir. No baffles were used to divert the flow. For the BOD analyses filtered samples were seeded with primary treated sewage. Nitrification inhibitor was not included with the dilution water. However samples provided for seed corrections indicated DO depletions of less than 0.3 milliliters of thiosulfate titrant.

Levels of nitrogen removal reported by previous researchers were not obtained in the present investigation. Stripping of ammonia at alkaline pH levels was reported by McGriff (15) to be significant, while nitrification was minimum. In the most recent investigation, for Phases 1 and 2, much of the incoming ammonia was converted to nitrite and nitrate during treatment under high rate conditions. For Phase 3, although nitrification was not generally significant, ammonia concentration in the effluent remained high. Materials balances for nitrogen indicated that loss of ammonia by stripping was not a major mechanism for nutrient removal under the experimental conditions imposed where pH was generally below 8.0.

In the present investigation, nitrification was significant during Phases 1 and 2 when the SRT was approximately 2.5 to 20 days. For Phases 2 and 3 when the SRT was less than 2.5 days only limited nitrification was measured. During the last run of Phase 3, nitrite and nitrate increased to 4 mg/liter when minimum solids were wasted.

A nitrate nitrogen concentration of 5 mg/liter was reported by Wahbeh (13), when the SRT was 1.6 days. McGriff (15) reported 2 to 4 mg/liter oxidized nitrogen when the SRT was 3.5 to 53 days.

Experimental factors proposed to explain the differences observed in ammonia reduction were as follows:

a) Increased Turbulence

Increased turbulence in the earlier studies may have aided in the process of stripping ammonia gas. Chemical equilibrium consideration predict the effect of pH on ammonia ionization (48). Formation of NH_3 from NH_4 ions increased from 5.23 to 84.7 per cent as pH was elevated from 8 to 10.

b) Experimental Limitations

Over the 15 month research period a high level of control over the operating conditions were maintained for the present research. The duration of the previous laboratory studies under a given set of conditions may have been insufficient to allow complete development of nitrifying microorganisms.

Quality control was poor in previous studies where individual grab samples of sewage were collected and used as feed. As was shown in Figure 18, chemical characteristics of 24 hour composite samples of sewage used in Phase 3 varied widely. Grab samples would be expected to show greater variability. To compound the degree of unpredictability, chemical analysis for all sample batches were not reported by previous researchers. Complete chemical analyses for nitrogen compounds in effluent samples on a daily basis were also limited.

c) Error in Ammonia Procedure

The method used to measure nitrogen by the direct Nesslerization technique indicated by McGriff (15) may have contributed to significant error in the results reported. Trnovsky (43) never was able to obtain reproducible nitrogen results when the reported chemical procedure was examined under closely controlled conditions. Recovery of nitrogen from the standard solutions used was generally erratic and poor. Small deviations in the digestion procedure and volatile ammonia loss when the sample was diluted and mixed at pH 10 appeared to be a source of experimental error. Stripping of ammonia gas may have resulted in the chemical analysis rather than during the treatment.

To improve the reliability of the present nitrogen analyses, determinations for Phase 3 were made by distillation of the samples into boric acid and back titrating with sulfuric acid for ammonia and total Kjeldahl nitrogen. Nitrogen analyses of the waste sludge enabled materials balances to be made.

Removal of phosphorus for activated algae was considered to be obtained by the dual mechanisms of microbial metabolism and chemical precipitation as calcium apatite (15). Phosphorus removal in previous activated algae investigations appeared to be strongly related to pH. McGriff (15) determined phosphorus reductions of 25 and 80 per cent at an average pH levels of 7.8 and 9.2, respectively. In the present research total phosphorus in the treated wastewater decreased as much as 50 per cent, while th pH remained between 7.5 to 8.0. Removal of phosphorus for microbial synthesis appeared to be the primary mechanism for nutrient removal in high rate activated algae experiments.

In low rate studies the pH increased to 8.5 and phosphorus removal increased to 75 per cent, indicative of chemical precipitation.

9 - Overview

In order to determine the full potential of activated algae, the laboratory experiments were designed for approaching limiting conditions for light, carbon and microbial generation time. For Phase 1, feeding an inorganic substrate was found to stimulate autotrophic microorganisms, including algae and nitrifying bacteria for the experimental conditions imposed. The results of the experiments were indicative of the potential of activated algae for use as a tertiary treatment device. During Phases 2 and 3 a symbiotic relationship developed between aerobic and autotrophic microorganisms as the organic substrate was utilized. Research information dealt with the application of activated algae as a combined secondary-tertiary approach. A shift in pH level associated with algae growth at low organic carbon loading rates and limited nitrification was believed to be associated with the limitation of organic carbon and carbon dioxide provided by bacterial respiration. As the supply of organic sources became limiting the algae were forced to dip into the inorganic carbon alkalinity reservoir. Reestablished chemical equilibrium in the wastewater resulted in an elevation of the pH level which in turn was suitable for precipitation of phosphorus as calcium apatite.

The research approach for Phase 3 was to investigate the possibility of accelerating the algae growth rate until organic carbon sources became limiting. An initial experiment for Phase 3 was based

on the results of Phase 2. In progressive steps, light was then intensified from 200 to 600 ft-candles. Wasting was increased from 38 to 52 per cent/day. As indicated by the limited pH elevation to about 7.8, the organic carbon supply was not exceeded. Growth of bacteria, subject to the same control parameters, apparently exceeded the synthesis rate of the algae. Advanced levels of nutrient removal were not obtained under high rate conditions.

A less desirable approach was followed for the remaining experiments. The loading and wasting rates were reduced. As indicated by the rise in the pH to above 8, a low organic loading rate provided improved phosphorus removal. Ammonia removal for the present research was more closely related to microbial metabolism, than by physical-chemical removal mechanisms under the ocnditions imposed. Experimental results obtained during Phase 3 indicate minimum nitrification when the SRT was less than 2.5 days verifying Phase 2 studies.

C - Cost Comparison

An estimation of treatment costs for high rate activated algae was developed using information reported for the 7.5 MGD advanced wastewater treatment plant at South Lake Tahoe, California (19). Cost estimates for each of the conventional unit operations were obtained using the percentage of total cost procedure used by Schmid and McKinney (4). The breakdown and comparison of treatment costs is presented in Table 43.

Reported total costs at Lake Tahoe was $396 per MG for complete treatment where $172.5 per MG was associated with secondary treatment. Treatment to advanced levels resulted in a cost increase of approxi-

Table 43

COMPARISON OF TREATMENT COSTS

OPERATION	$/MG CONVENTIONAL APPROACH	HIGH RATE ACTIVATED ALGAE
Preliminary Treatment	7.0	7.0
Primary Settling	21.5	21.5
Aeration Tanks and Equipment		
Operating	55.5	40.5*
Capital	38.0	143 **
Secondary Settling	21.5	49.5
Sludge Disposal (Vacuum Filtration)	29	67
Subtotal Conventional Treatment	172.5	- - -
Advanced Treatment		
Operating	137.5	
Capital	74.5	
Miscellaneous Costs	11.5	11.5
	396.0	340.0

* Includes $14.5/MGD for Electricity

** Includes $107.0/MGD for Lighting Equipment

mately 130 per cent. By comparison projected cost for high rate activated algae was $340 per MG, an increase of 98 per cent above secondary treatment.

Lighting costs for high rate activated algae were projected for equipment and operating expense associated with the small pilot plant used for Phase 3. The breakdown of the cost was determined on the following basis:

ITEM	UNIT CHARGE	ESTIMATED COST $1 MGD
Electric power (halftime lighting)	$0.02/KWH	14.5
Light Fixtures (five year life)	$12./Double 48" Unit	72
Fluorescent tubes (1500 (hour) service life)	$2./tube	35

Sludge handling and disposal charges for activated algae were increased 230 per cent over secondary plants in direct proportion to the quantity of sludge produced.

D. Practical Aspects

How practical is the activated algae approach for wastewater reclamation? There are several factors to consider. Because of the duel use of organic carbon by bacteria and algae sources more sludge is produced. Greater sludge wasting rates are required to allow operation at short SRT levels. Increasing wasting is needed to improve light penetration by providing lower MLSS concentrations. Operation at shallow depths are required to maximize algae synthesis.

There are distinct operational differences for activated algae

as compared to conventional wastewater treatment schemes. Differences shouldn't necessarily mean disadvantages when recognized in the framework of the environmental problems engineers are being asked to solve. Solids handling and disposal is less of a problem with organic sludge. Algae protein may be recycled and used to complete the food chain more directly as an animal food or plant fertilizer. Algae are capable of stripping nutrients from water almost to undetectable levels. The possibility exists for reducing overall wastewater treatment costs.

Fundamental research has combined the knowledge of activated algae and other photosynthetic treatment processes into a unified scheme. To date the use of algae in biological waste treatment has not been fully exploited. Tired of being the villians in so many polluted waterways, the algae wait for mankind to put nature to the task.

E - Future Research

Basic information obtained in the laboratory shows the strong potential for application of the activated algae concept over a full range of operating conditions. Future research is recommended to be directed towards pilot scale field application of the process. Research areas suggested for development include the following:

1 - As indicated in Figure 28, lighted surface area controlled the rate of algae activity in shallow high rate systems. Research should be concerned with the relationship between loading rate, microbial growth and significantly increased tank depths as predicted by the light-depth relationship (L/D).

2 - Under high rate conditions the cost of electricity was estimated as $29./MG treated. For 100 watts of electricity in flourescent tubes the conversion to usable light was estimated to be 22 watts (45). Significantly reduced operating costs for artificially illuminated activated algae systems would be possible if the efficiency of light production in commercially available fixtures were improved.

3 - Under natural illumination conditions, algae are active in stabilization ponds. Since the algae remain dispersed, benefits related to photosynthesis are not obtained. Research would provide information needed for applying activated algae concepts in this type of treatment system. The relationship of periodicity of sunlight and bacteriostasis due to the photosynthetic pH shift might be of concern (46).

4 - Further laboratory research could be concerned more closely with the mechanisms of enhanced nitrogen and phosphorus removal by activated algae.

VII CONCLUSIONS

Based on the research information presented and within experimental limits, the following conclusions have been drawn:

1 - Relationships developed on fundamental concepts indicated activated algae was controlled by light, organic loading and SRT similar to other biological waste treatment systems. Light availability was described in terms of light-depth (L/D) relationship as ft-candles/cm.

2 - For a high rate activated algae process, growth rates increased to the maximum of 800 VSS mg/liter/day when the L/D ratio increased to 48 ft-candles/cm.

3 - At an L/D ratio of 48 ft-candles/cm satisfactory operation resulted when systems were loaded at a carbon rate of 1150 mg/liter/day. Light rather than carbon became limiting at a loading of 1560 to 1660 mg/liter/day. Carbon limitations were not reached in the research.

4 - Limiting generation time for activated algae was near 1 day SRT.

5 - Surface area exposed to light controlled the photosynthetic rate in laboratory systems. To maintain a 1.0 mg/liter DO level, carbon loading was 2300 to 2700 mg/liter/day for each inch of reactor depth.

6 - Minimum cell yield was 0.23 near 20 day SRT. Maximum cell yield was 1.0 when the SRT was 2 to 6 days.

7 - Nitrification was a primary mechanism for alkalinity removal.

For each pound of nitrogen as nitrate, 7.2 pounds of alkalinity were needed.

8 - Limiting generation time for nitrifying bacteria was near 3 days SRT.

9 - Nutrient removal for activated algae operated at 1.0 to 1.5 BOD/day/lb MLVSS was accounted for by microbial synthesis. Enhanced phosphorus removal was provided when the pH rose to 8.5 due to the photosynthetic pH shift. At this time the experiments were operated at 0.07 lbs BOD/day/lb MLVSS.

10 - The maximum "BOD-nutrient" index obtained during Phase 3 was 78. During previous research the optimum "BOD-nutrient" index obtained was 91.

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APPENDIX

Table 1

FUNDAMENTAL BASIS FOR SEWAGE FED ACTIVATED ALGAE

Cell Yield Based on BOD_5

For High Rate Activated Sludge System

1# BOD_5 Added → .7#VSS

→ .5#O_2 Required

Assuming BOD_5 ∿ 85% Carbon

VSS ∿ 53% Carbon

.85# Carbon → .37# Carbon in Cells

Carbon Remainder Released as CO_2

∴ .85 - .37 = .48 # Carbon Released

If Algae VSS 53% Carbon .48 # Carbon = .91 # Algae

Total VSS Produced = .70 + .91 = $\frac{1.61\#VSS}{\#BOD_5}$ = Yield/min

If 80% VSS Are Biodegradable

For Extended Aeration Yield $_{Min}$ = .20(1.61) = 0.31 $\frac{\#VSS}{\#BOD_5}$

On Carbon Basis Yield max = 1.0

Yield min = .20

Sludge = 1.61/.70 = 230% of Aerobic System Alone

Based on FOGG Eq. (25)

$$NH_3 + 5.7CO_2 + 12.5H_2O \xrightarrow{SUN} C_{5.7}H_{9.8}O_{2.3}N + 6.25\ O_2 + 9.1H_2O$$

$$\frac{6.25 \text{ moles } O_2 \text{ released}}{5.7 \text{ moles } CO_2 \text{ consumed}} = 1.1$$

For High Rate System

.48 # C = 1.76 # CO_2

= .04 moles CO_2 → .044 moles O_2

→ 1.41 # O_2

$$\frac{\#O_2 \text{ produced}}{\#O_2 \text{required}} = \frac{1.41}{.5} = 2.82$$

Excess Oxygen is Produced.

Table 1

(continued)

FUNDAMENTAL BASIS FOR SEWAGE FED ACTIVATED ALGAE

Nitrogen Assimilated

Aerobic System $\frac{14}{113}$ as N $= \frac{.125\#N}{\#VSS}$

assuming VSS = $C_5H_7O_2N$

Algae

$\frac{14}{129}$ as N $= .109 \frac{\#N}{\#VSS}$

assuming VSS = $C_{5.7}H_{9.8}O_{2.3}N$

For Activated Algae

(1) Maximum N Assimilated = Yield x (NasVSS)

$= .70 \times .125 + .91 \times .109$

$= .087 + .100$

max N Assimilated = .187 # N/#VSS

min N Assimilated = (1-.80) x .187 = $.037 \frac{\#N}{\#VSS}$

(2) Assume N/P = 5 / 1

max P assimilated = $.70 \times \frac{.125}{5} + .91 \times \frac{.109}{5}$

$= .017 + .02 = .037$ # P/#VSS

Range P assimilated .007 to .037 # P/#VSS

Table 2

HYDRAULIC CALCULATIONS FOR EXPERIMENTAL

REACTOR USED BY WAHBEH(13)

1 - Calculation of Recirculation Flow Based on Speed of Paddle Wheel

60 RPM

2 - Diameter of Wheel = 6"

3 - Length of Channel = 30"; Width = 6"

A. Velocity = 60 RPM = 1 RPS

Distance Traveled = Circumference
by Paddle = π Diameter = 1.57 ft.

Max Tip Speed = 1.57 fps

Ave Tip Speed = 0.785 fps Velocity in Channel

B. Light and Dark Intervals

Total Length Flow Path = 20" x 2 = 40"
= 3.34 ft

Time of One Cycle of Flow = 3.34 ft ÷ 0.785 ft/sec
= 4.25 sec.

If Equal Light and Dark Time
Periods $t_l = t_d = \frac{4.25}{2} = 2.13$ sec

C. Recirculating Flow

Depth of Liquor in Light Chamber is 1".

Cross Sectional Area
in Light Chamber = wxd = 6"x1" = 6 in^2
= 38.6 cm^2

Velocity of Liquid = 0.785 fps = 23.9 $\frac{cm}{sec}$

Velocity x Area = $\frac{volume}{sec}$ = 925 $\frac{ml}{sec}$

Recirculating Flow = 55.5 l/min

= 3,330 l/hr

(continued)

Table 2
(continued)

HYDRAULIC CALCULATIONS FOR EXPERIMENTAL

REACTOR USED BY WAHBEH (13)

D. Ratio $\frac{\text{Recirculating Flow}}{\text{Feed Flow}}$

Feed Flow = 400 ml/hr

$= 6.67 \times 10^{-3}$ 1/min

Ratio $= \frac{55.5 \text{ 1/min}}{6.67 \times 10^{-3} \text{ 1/min}} = 8300$

Table 3

LIGHT AND DARK PERIOD CALCULATIONS

FOR EXPERIMENTAL REACTOR USED BY SHERWOOD (14)

Velocity of Mixed Liquor Due to Paddle Wheel = 2 fps

Length of Reactor = 20 ft

Total Length of Flow Path = 40 ft

Time Required for One Flow Cycle = 40 ft ÷ 2 fps

= 20 sec

Mixer Activated 1 Minute Every 10 Minutes

Average Cycle Time = 200 sec

Since Length of Light and Dark Chambers are Equal Time = 100 sec in Light Followed by Similar Dark Period

If Liquor is Caught in Dark Chamber, Longest Inactive Period Could be 9 Minutes = 540 seconds

Added to 10 Second Time of Passage

Range of Light and Dark Periods 10 to 550 seconds

Table 4

EQUATION FOR LIGHT PENETRATION AND SAMPLE CALCULATION

PRESENTED BY OSWALD (33)

$$d = \frac{\ln Sv_o - \ln Sv_d}{C_c \alpha}$$

α = extinction coefficient

Sv_o = light intensity at surface

Sv_d = light intensity at d, depth

C_c = algae concentration

Sv_o = 700 mgcal/cm^2-min in full sunlight

Sv_d = natural log constant, e, = 2.71

C_c = 400 mg/1

α = 1.0×10^{-3} $(mg\text{-}1\text{-}cm)^{-1}$

then:

$\ln Sv_o = 6.55$

$\ln Sv_d = 1.0$

$$d = \frac{6.55-1.0}{400 \times 1.0 \times 10^{-3}} = 13.9 \text{ cm}$$

depth of light penetration = 13.9 cm

Table 5

INORGANIC FEED USED FOR PHASE 1

Weight of Salts Added to 80 Liters of Tapwater

Component	Weight (g)
$FeCl_3$	0.11
KH_2PO_4	3.55
NH_4Cl	16.0
$NaHCO_3$	40.0

On the Basis of Elements Added

Element	Conc. (mg/l)
Fe	0.47
K	12.7
P	10.1
N	51.6
Na	136
Cl	134
HCO_3	364
C	71.4

Table 6

SYNTHETIC SEWAGE USED FOR PHASE 2

Synthetic Sewage Was Created by Adding Organic Materials to the Inorganic Feed Outlined in Table 5.

Component	Conc. (mg/l)
dry milk solids	200
Castile soap	7.0

Approximate Composition of the Substrate Was

	Component	Per Cent	Conc. (mg/l)
Milk	Lactose	51.6	103
	Protein	36.6	73
	Fat	0.8	1.6
	Mineral	8	16
	Moisture	3	
Soap	Fat	100	7.0

Converted to COD Basis

Component	COD Equivalent	Conc. (mg/l)	Per Cent
Carbohydrate	1.07	110	54
Protein	1	73	36
Fat	2.3	20	10
Total		203	

Table 7

CHEMICAL PROCEDURES

Chemical analyses made during the research were based on the procedures outlined in the following listing.

	Component	Procedure	Reference
1	total suspended solids (SS)	membrane filter	23
2	volatile suspended solids (VSS)	modified	26
3	dissolved oxygen (DO)	probe	
4	alkalinity	potent iometric	26
5	calcium	EDTA titeimetric	26
6	total phosphate	Stanneous chloride	26
7	ammonia	direct Nesslerization distillation	26 26
8	total Kjeldahl	digestion and distillation	26
9	nitrite and nitrate	cadmium reduction	34
10	biochemical oxygen demand (BOD)	5-day	26
11	chemical oxygen demand (COD)	rapid	35
12	sludge volume index (SVI)	modified	26

Details of the actual laboratory practices were as follows:

1. Total Suspended Solids

Fiberglass filter pads were tared directly. Weight of the aluminum pans were not included in the tare. For mixed liquor determinations 10 to 25 milliliter (ml) samples were used, so that the SS on the pad was at least 10 mg. Samples for influent and effluent

SS measurements were 50 and 100 ml. Filter pads containing SS were dried at 102°C for one hour.

2. Volatile Suspended Solids

After determining the SS, the filter pads were placed in the muffle furnace for 10 minutes for determining VSS. As recommended in the 13th edition of Standard Methods (1971), the temperature was maintained at 550°C.

3. Dissolved Oxygen

A Precision DO probe was used during the research. Calibration of the probe was accomplished by determining the DO reading and temperature in air. The probe reading was adjusted to the saturated DO concentration on the basis of reported data presented in Table 25 on p. 409 of Standard Methods (26). DO within the reactors was estimated by DO mg/l = saturated DO mg/l x $\frac{\text{DO Reading}}{\text{Air Reading}}$

4. Alkalinity

Alkalinity measurements were determined by titrating with sulfuric acid to an end point of pH 4.5. Samples of 50 ml were diluted to 100 ml and titrated with 0.020N H_2SO_4. The titrant was standardized frequently during the studies.

5. Calcium

Calcium was measured using the previous alkalinity sample directly. A normality of 0.01N EDTA was used. Hydrox-naphtol blue indicator was used because of the improved endpoint change, from red to blue.

6. Total Phosphate

The stannous chloride procedure was followed as prescribed (26).

Samples were diluted 1 to 50 ml for the analysis. After an average color development time of 11 minutes at room temperature, the intensity was measured using 1 cm. matched Pyrex cuvettes at 690 mμ. Standard curves were prepared on each day analyses were made. Reagent blanks were used to zero the spectrophotometer. A typical calabration was describe as follows (36):

Sample	Concentration (Pmg/1)	Transmittance	Log Trans.
1	0	90.0	1.954
2	8.15	71.0	1.851
3	16.3	55.5	1.744
4	24.5	39.5	1.597
5	37.6	32.0	1.505

The Regression Equation was

$$Y = 1.945 - 0.01242\ x$$

95 per cent confidence limits for slope were - 0.0158 and -0.0091.

7. Ammonia

Two methods were used to determine ammonia, direct Nesslerization and distillation.

The direct Nesslerization procedure was followed as prescribed (26). Samples were diluted 1 to 50 ml for the analysis. After an average color development time of 10 minutes at room temperature, the intensity was measured using 1 cm. matched Pyrex cuvettes at 520 mμ. Standard curves were prepared for each day analyses were made. Reagent blanks were used to zero the spectraphotometer. A typical calibration was described as follows (36):

Sample	X Concentration (Nmg/1)	Transmittance	Y Log Trans.
1	0	91.5	1.961
2	10.0	84.0	1.942
3	20.0	78.0	1.892
4	30.0	72.5	1.860
5	40.0	64.5	1.810
6	50.0	62.0	1.792
7	60.0	53.5	1.784

The regression equation was

$$Y = 1.965 - 0.00373\ x$$

The distillation method for ammonia was modified for use with semi-microKjeldahl apparatus, having 30 ml flasks. Sample volumes were 25 ml. to which 5 ml of phosphate buffer were added. Ammonia was distilled over into beakers containing 20 ml of boric acid mixed indicator solution. Ammonia nitrogen was determined after titrating with 0.020N H^2SO_4.

8. Total Kjeldahl Nitrogen

The semi-micro Kjeldahl apparatus was used to estimate total reduced nitrogen. Reagents requirements were scaled down from quantities listed for the full size apparatus (26). Sample volumes were 5 and 25 ml for mixed liquor and sewage, respectively. Digestion with 5 ml of acid reagent proceeded satisfactorily. After adding 5 ml basic reagent, total nitrogen was recovered by distillation into 20 ml of boric acid.

9. Nitrite and Nitrate

Nitrite and nitrate were estimated as prescribed by the cadmium reduction method (34). An attempt was made to improve the precision of the results. The sample size was increased from the suggested 0.25 ml to 0.50 or 1.0 ml. Reagent blanks were used to further

refine the results indicated.

10. Biochemical Oxygen Demand

Seed corrections and dilution water controls were included in all determinations. During the incubation period, all BOD bottles were submerged in a cooler bath maintained at 20°C. Sample sizes were adjusted to provide the required DO depletions. Sodium thiosulphate titrant was standardized before each use.

11. Chemical Oxygen Demand

The rapid COD test was used extensively for the research. Advantages and limitations of the procedure were reported by Jeris (35).

The following procedure was found to give satisfactory results:

a. Pipet 5.0 ml aliquot to a 500 ml Erlenmeyer flask (or a known volume diluted to 5 ml to provide 2-8 mg COD in sample). Note step (h).

b. To the flask add approximately 0.3 g of $HgSO_4$. Mix well.

c. Add 25.0 ml of dichromate-acid-silver solution to flask and swirl contents.

d. Place flask on preheated hot plate and heat to 165± 1°C. (Takes approximately 5 minutes.) Frequently swirl the solution, taking care not to damage thermometer immersed in the solution.

e. Add approximately 300 ml distilled water.

f. Cool mixture in water bath to approximately room temperature.

g. Add 3 drops of ferroin indicator and titrate with ferrous ammonium sulfate to orange end point.

h. Run two blanks using 5 ml distilled water as aliquot sample.

i. To determine normality of Fe $(NH_4)_2(SO_4)_2 .6H_2O$ 2 standards are

run by adding 25 ml of .050N dichromate, acidifying with 20 ml concentrated H_2SO_4, and continuing with steps 5, 6, and 7. The average is used for calculations.

j. COD is calculated.

$$\text{Normality of } Fe(NH_4)2(SO_4)_2 = \frac{(25)\ (.05)}{\text{ml titration from step 9}} = N$$

$$\text{Mg/l COD} = N \times 8000 \times \frac{\text{ml(step h)} - \text{ml (titration) step g}}{\text{ml undiluted sample}}$$

The following list ennumerates the chemical reagents necessary for the rapid procedure of determining COD:

a. Dichromate-acid solution

Five grams of potassium dichromate and twenty grams of silver sulfate are dissolved in a solution consisting of one liter each of concentrated sulfuric and phosphoric acid.

b. Ferrous ammonium sulfate, .05 normal

Dissolve twenty grams of $Fe(NH_4)_2(SO_4)_2$ in distilled water, add twenty milliliters of concentrated sulfuric acid and dilute to one liter. This solution must be standardized against the 0.050 normal potassium dichromate when used.

c. Ferroin indicator solution.

d. Mercuric sulfate.

e. Dichromate acid standard 0.050N

Dissolve 2.452 grams potassium dichromate, dried, primary standard grade in 1.00 liters of distilled water.

The SVI was estimated in a simplified fashion during the research. A 100 ml sample of mixed liquor was settled for 30 minutes in a graduated cylinder. The volume of compacted solids was recorded as the SVI value.

TABLE 8

DAILY SUMMARIES OF DATA

PHASE 3

RUN 1

OPERATION OF ACTIVATED ALGAE PILOT PLANT

TIME PERIOD STUDIED FROM 1 17 72 TO 1 29 72

INITIAL DATA

DAY	TEMP(C) IN	ML	SC	DO(MG/L) IN	ML	SC	PH IN	ML	OUT	ALK-AS CACO3-CA IN	OUT	IN	OUT	FEED L/DAY
1	15.	20.	19.2	4.5	2.7		7.5	7.7	7.3	255.	259.	171.	174.	182.
2	16.	21.	21.4	6.6	2.0		7.4	7.4	7.7	259.	249.	165.	162.	175.
3	15.	21.	20.1	2.6	0.3		7.1	7.0	7.4	273.	261.	176.	170.	203.
4	15.	19.	19.2	1.1	0.3		7.1	7.2	7.3	245.	240.	171.	169.	244.
5	14.	19.	19.0	0.8	0.3		7.2	7.3	7.5	282.	260.	184.	168.	249.
6	17.	21.	20.0	8.0	3.4		7.2	7.5	7.7	286.	259.	169.	170.	133.
7	16.	21.	20.1	7.0	2.6		7.5	7.4	7.3	275.	261.	175.	169.	164.
8	16.	21.	21.1	6.7	5.2		7.5	7.3	7.3	270.	259.	172.	175.	161.
9	15.	20.	19.2	10.4	3.1		7.4	7.5	7.5	293.	265.	190.	183.	157.
10	16.	18.	18.1	1.4	1.0		7.4	7.4	7.7	275.	261.	185.	172.	236.
11	15.	19.	18.1	3.0	0.6		7.5	7.4	7.7	275.	260.	165.	173.	193.
12	14.	19.	18.1	4.0	1.2		7.4	7.5	7.7	283.	268.	158.	161.	177.

WHEN 11. LITERS OF MIXED LIQUOR WASTED DAILY

INITIAL DATA CONTINUED

DAY	MLTSS	MLVSS	PERVSS	INSS	OUTSS	TOTA_COD IN	TOTA_COD OUT	SOLUBLE IN	SOLUBLE OUT	PERREM
1	1050.	890.	84.8	46.	46.	110.	90.	70.	48.	56.4
2	955.	805.	84.3	48.	50.	113.	90.	74.	60.	49.2
3	1010.	840.	83.2	55.	68.	153.	99.	92.	55.	65.2
4	940.	795.	84.6	44.	62.	135.	125.	89.	65.	52.2
5	710.	580.	81.7	50.	80.	173.	149.	103.	83.	53.4
6	705.	585.	83.0	52.	51.	175.	112.	128.	62.	64.6
7	895.	735.	82.1	49.	38.	133.	77.	95.	55.	60.1
8	810.	665.	82.1	45.	24.	123.	72.	63.	39.	68.3
9	950.	830.	87.4	36.	41.	135.	103.	94.	48.	64.7
10	905.	795.	87.8	50.	50.	143.	101.	97.	60.	58.0
11	1040.	925.	88.9	44.	50.	153.	112.	102.	49.	69.0
12	1025.	900.	87.8	48.	50.	152.	102.	137.	55.	63.2

CALCULATED RESULTS FOR ACTIVATED ALGAE

DAY	D,T, HRS	SRT DAYS	WASTESRTX PER DT/DA	GROWTH MG/L-DAY	AVEM,VSS MG/L	CODLOAD LBS/DAY/LB MLVSS	REMCOD
1	3,8	1.49	67,1	9.3	0.	890.	0,774	0,436
2	4,0	1.40	71,6	8,4	552.	679.	1,047	0,515
3	3,4	1.12	89,1	7,9	752.	670.	1,555	1,079
4	2,9	1.03	97,0	8,7	770.	658.	1,739	0,908
5	2,8	0.69	144,4	5,9	933.	537.	2,344	1,518
6	5,2	1.35	73,9	6.2	434.	473.	1,598	1,096
7	4,3	1.56	64,2	8,8	525.	549.	1,418	0,853
8	4,3	1.79	55,9	9,9	341.	551.	1,216	0,830
9	4,4	1.61	61,9	8,7	577.	621.	1,181	0,754
10	3,0	1.19	84,0	9,7	662.	655.	1,775	1,030
11	3,6	1.42	70,3	9,5	689.	709.	1,483	1,023
12	3,9	1.46	68,4	8,9	608.	737.	1,256	0,794

RUN 2

OPERATION OF ACTIVATED ALGAE PILOT PLANT

TIME PERIOD STUDIED FROM 1 29 72 TO 2 10 72

INITIAL DATA

DAY	TEMP(C)			DO(MG/L)			PH			ALK-AS CACO3-CA				FEED
	IN	ML	SC	IN	ML	SC	IN	ML	OUT	IN	OUT	IN	OUT	L/DAY
1	14.	16.	17.	2.3	3.7	2.3	7.7	7.4	7.7	263.	250.	159.	162.	175.
2	15.	19.	18.	0.4	3.4	0.2	7.5	7.6	7.5	238.	244.	158.	156.	231.
3	13.	18.	18.	1.1	4.1	1.9	7.7	7.6	7.3	240.	233.	174.	169.	214.
4	15.	19.	19.	1.5	1.9	0.8	7.7	7.7	7.3	254.	253.	181.	174.	214.
5	16.	20.	20.	1.7	0.3	0.2	7.3	7.5	7.5	285.	256.	196.	182.	207.
6	15.	19.	18.	0.7	2.9	0.5	7.0	7.0	7.0	261.	243.	151.	168.	168.
7	14.	18.	18.	1.6	2.1	0.4	7.2	7.1	7.4	285.	246.	176.	165.	188.
8	15.	20.	19.	0.7	0.4	0.2	7.1	7.1	7.4	295.	259.	0.	0.	186.
9	15.	19.	19.	0.9	6.5	2.5	7.5	7.5	7.3	264.	228.	183.	163.	155.
10	14.	18.	18.	0.2	6.2	3.2	7.4	7.2	7.7	252.	222.	163.	165.	201.
11	14.	19.	18.	1.6	3.6	1.8	7.4	7.2	7.5	267.	215.	168.	168.	214.
12	13.	18.	18.	1.9	0.7	0.6	7.5	7.3	7.5	290.	236.	177.	174.	220.
13	15.	19.	19.	0.9	0.4	0.2	7.5	7.2	7.5	293.	243.	171.	174.	206.

WHEN 11. LITERS OF MIXED LIQUOR WASTED DAILY

INITIAL DATA CONTINUED

DAY	MLTSS	MLVSS	PERVSS	INSS	OUTSS	TOTAL COD IN	TOTAL COD OUT	SOLUBLE IN	SOLUBLE OUT	PERREM
1	955,	930,	97.4	56,	45,	152,	90,	96,	50,	57.1
2	845,	735,	87.0	61,	39,	129,	54,	73,	54,	58.1
3	760,	665,	87.5	55,	26,	122,	76,	64,	52,	57.4
4	780,	690,	88.5	56,	53,	114,	105,	106,	60,	47.4
5	820,	710,	86.6	48,	68,	154,	124,	102,	50,	63.4
6	860,	760,	88.4	59,	36,	152,	104,	98,	62,	59.2
7	925,	810,	87.6	43,	95,	173,	124,	130,	56,	67.6
8	950,	845,	88.9	36,	101,	155,	151,	132,	76,	53.9
9	1050,	855,	81.4	39,	47,	145,	112,	86,	45,	69.2
10	1020,	830,	81.4	43,	51,	103,	84,	76,	45,	56.3
11	1170,	940,	80.3	46,	46,	142,	89,	72,	39,	72.5
12	1245,	1005,	80.7	45,	44,	120,	101,	107,	51,	57.5
13	1285,	1040,	80.9	48,	92,	155,	142,	99,	76,	53.9

CALCULATED RESULTS FOR ACTIVATED ALGAE

DAY	D.T. HRS	SRT DAYS	WASTESRTX PER DT/DA	GROWTH MG/L-DAY	AVEM_VSS MG/_L	CODLOAD LBS/DAY/LB	REMCOD MLVSS
1	4.0	1.56	64.2	9.4	0.	930.	0.985	0.661
2	3.0	1.32	76.0	10.5	512.	656.	1.566	0.911
3	3.2	1.56	63.9	11.6	400.	551.	1.508	0.923
4	3.3	1.12	88.9	8.3	616.	551.	1.525	0.722
5	3.4	1.01	99.3	7.2	705.	559.	2.053	1.302
6	4.1	1.60	62.6	9.3	495.	600.	1.467	0.858
7	3.7	0.94	106.3	6.1	858.	641.	1.748	1.182
8	3.7	0.93	107.0	6.0	902.	674.	1.573	0.848
9	4.5	1.55	64.3	8.3	553.	690.	1.129	0.731
10	3.5	1.31	76.3	9.1	627.	630.	1.050	0.591
11	3.3	1.42	70.4	10.5	694.	728.	1.440	1.044
12	3.2	1.47	67.8	11.2	703.	794.	1.147	0.650
13	3.4	1.06	94.4	7.5	983.	832.	1.406	0.758

RUN 3

OPERATION OF ACTIVATED ALGAE PILOT PLANT

TIME PERIOD STUDIED FROM 2 10 72 TO 2 19 72

INITIAL DATA

DAY	TEMP(C)			DO(MG/L)			PH			ALK-AS CACO3-CA				FEED
	IN	ML	SC	IN	ML	SC	IN	ML	OUT	IN	OUT	IN	OUT	L/DAY
1	15.	19.	19.0	0.9	0.4	0.2	7.5	7.2	7.5	298.	243.	171.	174.	206.
2	15.	19.	20.1	3	0.2	0.2	7.4	7.1	7.5	297.	241.	176.	179.	209.
3	14.	19.	19.0	7	0.5	0.2	7.6	7.4	7.7	298.	248.	181.	178.	193.
4	14.	20.	19.0	7	7.2	3.0	7.4	7.3	7.5	263.	226.	137.	167.	196.
5	15.	20.	20.1	0	7.0	3.6	7.4	7.4	7.7	242.	214.	153.	164.	213.
6	15.	21.	20.1	9	8.0	4.4	7.6	7.6	7.8	292.	230.	170.	172.	164.
7	15.	21.	20.1	6	5.5	3.0	7.5	7.2	7.7	275.	229.	200.	178.	185.
8	15.	21.	20.1	0	4.4	2.6	7.1	7.0	7.4	298.	220.	166.	165.	177.
9	14.	19.	18.1	0	1.8	1.6	7.1	6.9	7.2	270.	220.	154.	169.	230.
10	14.	19.	18.1	7	1.8	1.7	7.4	7.1	7.4	277.	233.	197.	200.	191.

WHEN 11. LITERS OF MIXED LIQUOR WASTED DAILY

INITIAL DATA CONTINUED

DAY	MLTSS	MLVSS	PERVSS	INSS	OUTSS	TOTAL COD IN	TOTAL COD OUT	SOLUBLE IN	SOLUBLE OUT	PERREM
1	1285.	1040.	80.9	48.	92.	155.	142.	99.	75.	53.9
2	1500.	1240.	82.7	50.	120.	191.	185.	111.	55.	71.2
3	1515.	1255.	82.8	50.	86.	173.	122.	164.	65.	63.5
4	1350.	1085.	80.4	39.	43.	144.	101.	96.	59.	59.0
5	1320.	1040.	78.8	39.	53.	123.	78.	84.	59.	52.0
6	1370.	1070.	78.1	43.	28.	152.	74.	98.	53.	65.1
7	1485.	1190.	80.1	50.	25.	154.	82.	117.	65.	57.8
8	1680.	1350.	80.4	42.	23.	184.	60.	145.	50.	72.8
9	1690.	1370.	81.1	47.	24.	122.	90.	88.	56.	54.1
10	1880.	1515.	80.6	41.	26.	150.	68.	104.	56.	65.0

CALCULATED RESULTS FOR ACTIVATED ALGAE

DAY	D.T. HRS	SRT DAYS	WASTESRTX PER DT/DA	GROWTH MG/L-DAY	AVEM_VSS MG/L	CODLOAD LBS/DAY/LB MLVSS	REMCOD
1	3,4	1.06	94,4 7,5	0.	1040.	1,125	0,607
2	3,3	0.99	100,8 7,2	1248.	943.	1,463	1,041
3	3,6	1.27	79,0 8,4	994.	1012.	1,170	0,743
4	3,5	1.61	62,1 10.9	609.	932.	1,046	0,618
5	3,3	1.40	71,6 10.2	732.	857.	1,053	0,548
6	4,2	1.95	51,3 11.0	563.	858.	1,004	0,654
7	3,8	2.00	50,0 12.8	655.	927.	1,059	0,612
8	3,9	2.11	47,3 12.9	723.	1044.	1,075	0,783
9	3,0	1.98	50,4 15.7	701.	1104.	0,876	0,474
10	3,6	2.08	48,1 13.7	804.	1133.	0,891	0,579

RUN 4

OPERATION OF ACTIVATED ALGAE PILOT PLANT

TIME PERIOD STUDIED FROM 2 19 72 TO 3 01 72

INITIAL DATA

DAY	TEMP(C)			DO(MG/L)			PH			ALK-AS CACO3-CA				FEED
	IN	ML	SC	IN	ML	SC	IN	ML	OUT	IN	OUT	IN	OUT	L/DAY
1	14.	19.	18.	1.7	1.8	1.7	7.4	7.1	7.4	277.	233.	197.	200.	191.
2	14.	18.	17.	1.2	7.5	3.9	7.4	7.3	7.8	285.	211.	187.	187.	165.
3	15.	22.	21.	0.3	5.7	4.5	7.3	7.4	7.7	250.	220.	191.	198.	219.
4	14.	17.	16.	1.1	1.1	1.1	7.4	7.1	7.5	298.	231.	191.	192.	219.
5	14.	19.	20.	1.2	0.4	0.3	7.4	7.1	7.5	311.	229.	192.	189.	212.
6	13.	19.	18.	0.4	0.3	0.4	7.2	7.2	7.5	318.	227.	192.	185.	201.
7	14.	21.	20.	1.1	0.3	0.3	6.8	6.9	7.2	302.	221.	178.	178.	196.
8	15.	19.	19.	0.	0.	0.	0.	0.	7.3	0.	0.	0.	0.	177.
9	14.	19.	19.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	230.
10	14.	20.	19.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	191.
11	15.	21.	21.	0.	0.	0.	0.	0.	7.3	0.	0.	0.	0.	214.
12	15.	21.	21.	0.	0.	0.	0.	0.	7.4	0.	0.	0.	0.	220.

WHEN 15. LITERS OF MIXED LIQUOR WASTED DAILY

INITIAL DATA CONTINUED

DAY	MLTSS	MLVSS	PERVSS	INSS	OUTSS	TOTALCOD IN	TOTALCOD OUT	SOLUBLE IN	SOLUBLE OUT	PERREM
1	1880.	1515.	80.6	41.	26.	150.	68.	104.	56.	65.0
2	1435.	1135.	79.1	47.	32.	110.	54.	80.	46.	58.2
3	1345.	1065.	79.2	43.	25.	110.	50.	56.	44.	60.0
4	1450.	1150.	79.3	42.	23.	150.	74.	94.	46.	71.2
5	1525.	1230.	80.7	46.	25.	152.	78.	114.	48.	68.4
6	1575.	1290.	81.9	45.	35.	175.	82.	124.	68.	61.1
7	1600.	1330.	83.1	47.	36.	154.	60.	116.	42.	72.7
8	1860.	1560.	83.9	48.	22.	174.	68.	0.	38.	78.2
9	1050.	890.	84.8	50.	16.	274.	70.	0.	40.	85.4
10	1390.	1170.	84.2	34.	34.	209.	50.	0.	25.	87.6
11	780.	670.	85.9	50.	26.	150.	78.	0.	54.	64.0
12	1160.	930.	80.2	34.	36.	135.	120.	0.	80.	41.2

CALCULATED RESULTS FOR ACTIVATED ALGAE

DAY	D.T. HRS	SRT DAYS	WASTESRTX PER DT/DA	GROWTH MG/L-DAY	AVEM_VSS MG/L	ODLOAD LBS/DAY/LB	REMCOD MLVSS
1	3.6	1.62	61.9	10.6	0. 1515.	0.596	0.452
2	4.2	1.51	66.2	8.6	623. 933.	0.573	0.391
3	3.2	1.48	67.7	11.1	698. 805.	1.028	0.617
4	3.2	1.53	65.3	11.6	781. 832.	1.453	1.035
5	3.3	1.54	65.1	11.2	829. 893.	1.247	0.853
6	3.5	1.46	68.7	10.1	905. 942.	1.290	0.789
7	3.5	1.47	68.2	9.9	920. 975.	1.067	0.776
8	3.9	1.68	59.5	10.3	1021. 1101.	0.965	0.754
9	3.0	1.55	64.5	12.3	337. 822.	2.543	2.257
10	3.6	1.45	68.9	9.6	894. 800.	1.721	1.507
11	3.3	1.29	77.5	9.5	407. 617.	1.792	1.147
12	3.2	1.28	78.2	9.7	784. 627.	1.548	0.678

RUN 5

OPERATION OF ACTIVATED ALGAE PILOT PLANT

TIME PERIOD STUDIED FROM 3 04 72 TO 3 10 72

INITIAL DATA

DAY	TEMP(C) IN	ML	SC	DO(MG/L) IN	ML	SC	PH IN	ML	OUT	ALK-AS CACO3-CA IN	OUT	IN	OUT	FEED L/DAY
1	15.	20.	19.	1.3	9.8	3.8	7.5	8.0	8.0	288.	192.	152.	160.	69.
2	14.	20.	19.	0.6	4.7	2.5	7.4	7.5	7.8	263.	225.	152.	156.	170.
3	16.	22.	21.	0.9	10.8	5.5	7.5	8.4	8.4	277.	240.	140.	142.	62.
4	17.	23.	23.	1.6	11.5	5.1	7.0	7.7	7.4	267.	228.	154.	157.	71.
5	16.	21.	21.	0.7	1.9	0.9	7.1	7.2	7.3	231.	273.	165.	157.	125.
6	16.	21.	19.	1.0	3.9	3.2	7.2	7.4	7.4	279.	267.	149.	170.	70.
7	17.	22.	21.	1.5	8.8	2.9	7.1	7.6	7.4	285.	245.	140.	167.	68.

WHEN 15. LITERS OF MIXED LIQUOR WASTED DAILY

INITIAL DATA CONTINUED

DAY	MLTSS	MLVSS	PERVSS	INSS	OUTSS	TOTA_COD IN	TOTA_COD OUT	SOLUBLE IN	SOLUBLE OUT	PERREM
1	690.	540.	78.3	56.	24.	164.	0.	78.	46.	72.0
2	830.	645.	77.7	64.	31.	148.	42.	66.	28.	81.1
3	720.	540.	75.0	38.	24.	150.	90.	98.	50.	66.7
4	720.	540.	75.0	52.	32.	173.	85.	125.	60.	56.3
5	845.	670.	79.3	52.	68.	215.	163.	127.	89.	58.8
6	850.	645.	75.9	68.	66.	185.	167.	109.	69.	62.7
7	750.	560.	74.7	64.	84.	169.	149.	125.	47.	72.2

CALCULATED RESULTS FOR ACTIVATED ALGAE

DAY	D,T, HRS	SRT DAYS	WASTESRTX PER DT/DA	GROWTH MG/L-DAY	AVEM_VSS M3/_I	CODLOAD LBS/DAY/LB	REMCOD MLVSS
1	10,0	1.63	61,3	3,9	0.	540.	0,727	0,523
2	4,1	1.30	77,1	7.6	521.	453.	1,916	1,553
3	11,3	1.66	60,2	3,5	283.	425.	0,748	0,499
4	9,8	1.54	64,8	3.8	350.	400.	1,087	0,721
5	5,6	1.10	91,1	4.7	622.	455.	2,001	1,176
6	10,0	1.35	73,9	3.3	470.	434.	0,921	0,573
7	10,3	1.20	83,2	2.8	452.	436.	0,905	0,653

RUN 6

OPERATION OF ACTIVATED ALGAE PILOT PLANT

TIME PERIOD STUDIED FROM 3 10 72 TO 3 21 72

INITIAL DATA

DAY	TEMP(C)			DO(MG/L)			PH			ALK-AS CACO3-CA				FEED
	IN	ML	SC	IN	ML	SC	IN	ML	OUT	IN	OUT	IN	OUT	L/DAY
1	17.	22.	21.1	1.5	8.8	2.9	7.1	7.6	7.4	285.	245.	140.	167.	68.
2	23.	24.	22.1	1.3	7.4	3.2	7.3	7.7	7.5	293.	243.	147.	155.	65.
3	18.	24.	23.1	1.1	8.0	3.5	7.3	7.4	7.5	268.	226.	157.	159.	103.
4	17.	24.	23.1	1.0	8.1	4.3	7.3	7.5	7.7	264.	220.	148.	145.	79.
5	17.	22.	22.0	1.6	8.6	3.9	7.3	7.7	7.7	264.	280.	148.	190.	78.
6	18.	24.	23.1	1.7	3.1	1.7	7.4	7.5	7.7	293.	263.	156.	166.	75.
7	18.	25.	24.0	1.6	5.7	2.1	7.3	7.6	7.8	285.	264.	145.	157.	84.
8	17.	25.	24.1	1.5	5.8	2.7	7.4	7.6	7.8	283.	254.	150.	154.	84.
9	18.	25.	24.0	1.7	6.8	2.9	7.3	7.5	7.9	292.	255.	150.	170.	79.
10	17.	25.	24.0	1.6	8.8	4.6	7.3	7.8	8.0	271.	246.	145.	166.	74.
11	18.	24.	23.0	1.6	9.1	4.0	7.3	7.6	8.0	258.	233.	156.	147.	73.
12	17.	26.	25.0	1.8	7.2	3.6	7.4	7.6	7.8	282.	248.	170.	166.	81.

WHEN 6. LITERS OF MIXED LIQUOR WASTED DAILY

INITIAL DATA CONTINUED

DAY	MLTSS	MLVSS	PERVSS	INSS	OUTSS	TOTAL COD IN	TOTAL COD OUT	SOLUBLE COD IN	SOLUBLE COD OUT	PERREM
1	750.	560.	74.7	64.	84.	159.	149.	125.	47.	72.2
2	910.	650.	71.4	76.	110.	185.	185.	105.	73.	57.8
3	990.	700.	70.7	60.	102.	190.	180.	102.	47.	75.3
4	1040.	730.	70.2	76.	46.	189.	120.	85.	40.	78.8
5	1100.	745.	67.7	60.	40.	151.	102.	80.	71.	53.0
6	1100.	760.	69.1	60.	38.	173.	111.	89.	51.	70.5
7	1130.	780.	69.0	54.	42.	133.	114.	116.	80.	42.0
8	1350.	950.	70.4	70.	38.	169.	74.	122.	58.	65.7
9	1500.	1090.	72.7	88.	30.	137.	67.	93.	58.	69.0
10	1450.	1030.	71.0	74.	27.	173.	71.	80.	47.	73.6
11	1490.	1060.	71.1	96.	26.	113.	69.	82.	47.	60.2
12	1300.	920.	70.8	62.	28.	133.	63.	99.	51.	63.0

CALCULATED RESULTS FOR ACTIVATED ALGAE

DAY	D.T. HRS	SRT DAYS	WASTESRTX PER DT/DA	GROWTH MG/L-DAY	AVEM_VSS MG/_I	CODLOAD LBS/DAY/LB	REMCOD MLVSS
1	10,3	1.92	52,2	4.5	0.	550.	0,704	0,508
2	10,8	1.83	54,6	4,1	396.	547.	0,753	0,436
3	6,7	1.48	67,5	5.3	489.	608.	1,115	0,839
4	8,8	2.77	36,1	7,5	283.	643.	0,301	0,631
5	8,9	2.96	33,7	8,0	261.	652.	0,516	0,326
6	9,3	3.10	32,3	8,0	256.	675.	0,561	0,456
7	8,3	2.88	34,7	8,3	284.	691.	0,578	0,243
8	8,3	3.22	31,1	9.3	412.	734.	0,522	0,409
9	8,8	3.64	27,4	9,9	401.	922.	0,553	0,382
10	9,3	3.74	26,7	9,6	232.	947.	0,482	0,355
11	9,6	3.81	26,2	9,6	300.	938.	0,315	0,189
12	8,6	3.53	28,3	9,8	160.	880.	0,436	0,275

RUN 7

TIME PERIOD STUDIED FROM 3 21 72 TO 4 1 72

Day		1	2	3	4	5	7	8	9	10
Temperature	in	18	17	19	18	19	17	17	17	
	ML	25	24	23	24	24	24	24	24	
	ST	24	-	-	-	-	24	23	24	
DO	in	1.7	1.4	0.8	0.5	0.8	0.8	1.4	1.1	
	ML	6.1	6.1	6.5	6.6	10.0	8.0	7.0	7.4	
	ST	3.4	-	-	-	-	3.8	4.1	4.6	
pH	in	-	7.7	7.5	7.7	7.8	7.4	7.5	7.4	7.6
	ML	-	-	-	-	-	8.4	8.1	7.9	7.5
	out	-	8.2	8.4	8.9	9.3	8.6	8.1	8.6	7.6
Alkalinity	in						259	289	242	
	out						188	216	202	
Calcium	in						155	145	147	
	out						146	150	143	
TSS	in						66	66	84	
	out						14	13	10	
COD Total	in						107	158	144	
Soluble	out						26	42	51	
% COD Removed							75	75	65	
Detention Time		10.8	20.0	26.2	26.8	24.0	-	12.0	23.0	11.6

Table 9

LEGEND FOR MICROBIOLOGY

Mixed Liquor Color

G	Green
YB	Yellow Brown
B	Black

Enumeration of Flora

0	None or Limited Number Observed
X	Significant Number Observed
P	Predominent Species Listed for Each Group, Algae, Bacteria and Protozoa.

Table 10

SUMMARY OF LOADING ON BASIS OF CARBON

Run	Unit	DOmg/1	Carbon Loading mg/1/day 1		L/D ft-candles/cm.	Carbon Loading mg/1/day 2		L/D ft-candles/cm.	Carbon Loading mg/1/day 3	
Phase 1, Part 2										
1		5.7	156	18.0	7.3	155	25.2	7.8	230	48.1
2		5.0	85		7.3	73		7.7	99	
3		3.8	80		4.9	96		7.7	96	
4		3.9	84		5.2	76		7.0	96	
5		.8	173		4.2	171		6.1	200	
6		3.3	295		5.9	250		7.1	413	
Phase 1, Part 3										
1					5.7	86	25.2			
2					5.8	66	37.8			
3					7.8	64	50.4			
4					4.8	109	63			
5					8.1	61	63			
6					6.9	94	63			
7					2.9	190	63			
8					2.5	182	89			
9					7.3	149	89			
Phase 2										
1		2.0	755	18.0	1.2	855	25.2	1.5	1151	48.1
2		0.5	725		0.9	738		2.5	910	
3		0.9	731		1.3	731		4.5	910	
4		0.7	650		3.3	599		4.8	801	
5		0.3	1245		0.3	1284		1.9	1658	
6		0	1146		0.2	1164		0.5	1485	

Table 10

(continued)

Phase 3

Run	DO	Loading	L/D
1	4.7	607	48.1
2	3.0	632	48.1
3	3.0	687	145
4	2.1	735	145
5	7.4	298	145
6	6.9	274	145
7	7.1	115	145
McGriff (15)			
1	7.5	226	102
2	6.4	106	96.5
3	5.0	235	96.5
4	6.5	254	152
5	7.7	297	172
6	8.4	232	172

Table 11

GROWTH RATE CONVERTED FROM
VSS TO CARBON

RUN	UNIT	Growth VSS mg/l/day - Carbon mg/l/day* 1		2		3	
PHASE 1, PART 2							
1		30	16	79	42	58	31
2		85	45	130	69	141	75
3		62	33	78	41	100	53
4		92	49	123	65	120	64
5		110	58	120	64	134	71
6		67	36	120	64	167	88
PHASE 1, PART 3							
1				68	36		
2				74	39		
3				102	54		
4				198	105		
5				112	60		
6				173	92		
7				216	115		
8				228	131		
9				207	-10		
PHASE 2							
1		225	120	340	180	550	292
2		305	162	370	196	535	284
3		332	176	405	215	480	254
4		300	159	330	175	515	273
5		430	228	480	254	770	409
6		352	187	520	276	805	426

* .53 x VSS = carbon

Table 11
(continued)

SUMMARY OF GROWTH RATE DATA

PHASE 3	VSS mb/1/day	Carbon mg/1/day
1	620	330
2	660	350
3	780	414
4	740	392
5	450	239
6	320	170
7	180	96
McGriff (15)		
2-1	59	31
2-2	54	29
3-1	54	29
3-2	500	265
3-3	490	260
3-3A	330	175
Sherwood (14)		
A	35	19
B	45	24
C	82	44
Wahbeh (13)		
1	118	63
2	96	51
3	96	51
4	1430	760

Table 12

CELL YIELD ON CARBON BASIS AND SRT

UNIT	RUN	TOTAL CARBON USED mg/l/day	CARBON GROWTH mg/l/day	CELL YIELD (CARBON)	SRT (days)
1	1	69	16	.23	19.8
	2	57	45	.80	3.8
	3	72	33	.46	8.9
	4	80	49	.62	6.7
	5	115	58	.50	6.6
	6	103	36	.35	4.8
2	1	61	42	.69	13.1
	2	57	69	1.21	3.2
	3	86	41	.48	8.8
	4	72	65	.91	6.7
	5	104	64	.63	7.5
	6	101	64	.64	4.0
3	1	108	31	.29	14.7
	2	55	75	1.37	3.7
	3	58	53	.92	6.7
	4	64	64	1.00	5.7
	5	84	71	.85	6.0
	6	82	88	1.07	3.2

Table 12
(continued)

CONVERSION OF CARBON

UNIT	RUN	AIR CARBON USED	COD CARBON USED	SUM CARBON USED	GROWTH CARBON	CELL YIELD	SRT (days)
		mg/l/day					
PHASE 2							
1	1	30	305	335	120	.36	2.9
	2	21	300	321	162	.51	2.2
	3	14	330	344	176	.51	2.2
	4	11	266	277	159	.57	2.0
	5	8	470	478	228	.48	1.3
	6	4	395	399	187	.47	0.70
2	1	93	350	443	180	.41	4.3
	2	94	280	374	196	.53	3.5
	3	65	316	381	215	.57	2.9
	4	55	238	293	175	.60	1.8
	5	17	515	532	254	.48	1.6
	6	8	461	469	276	.59	0.80
3	1	75	425	500	292	.58	3.2
	2	72	385	457	284	.62	3.1
	3	51	421	472	254	.54	2.6
	4	66	308	374	273	.73	1.9
	5	32	385	717	409	.57	1.5
	6	14	615	629	426	.68	1.0
PHASE 3							
	1	11	465	476	330	.71	1.34
	2	25	485	510	350	.69	1.37
	3	41	550	591	414	.70	2.02
	4	55	670	725	392	.54	1.50
	5	13	272	285	239	.84	1. 0
	6	9	243	252	170	.68	2.85
	7	9	102	111	96	.87	135
McGriff's Data (15)			BOD				
		0	- -	0	31	- -	- -
		56	- -	56	29	52	38.5
		19	179	198	29	15	53
		23	177	200	265	132	3.8
		34	211	245	260	106	3.7
		29	159	188	175	93	3.6