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r	-	correlation coefficient
R	-	wt $BOD_{5,R}/t$
SA	-	solids age
SS	-	total suspended solids
SS_p	-	SS produced
STPP	-	sodium tripolyphosphate
SVI	-	sludge volume index
TSPP	-	tetrasodium pyrophosphate
t	-	time
t_o	-	lag time or lag period
VS	-	volatile suspended solids
VS_p	-	VS produced
y	-	BOD at time t

MATHEMATICAL SYMBOLS AND ABBREVIATIONS

$\sim$	-	approximately
$=$	-	equals
$\simeq$	-	equals approximately
$\neq$	-	unequal
log	-	common logarithm to base 10

RUN CODING

A-B-C-D - where

A = type of sewage
SS = synthetic sewage
DS = domestic sewage
B = process schematic
C = pH
D = Al:P ratio

DS-CR	-	domestic sewage biological control run
SS-CR	-	synthetic sewage biological control run

SUMMARY

It has been generally recognized and well documented that excessive fertilization or enrichment of surface waters leads to nuisance-level proliferation of aquatic vegetation. The deleterious effects of such unbalanced productivity on society are economic, recreative, and aesthetic in nature.

Minimization of an essential plant nutrient has been suggested as a method for controlling eutrophication. Phosphorus is the nutrient through which most authorities consider control most feasible. In many instances, the major source of surface water phosphorus and, therefore, the focus of removal attention, is domestic waste water. In view of the fact that conventional sewage treatment does not typically effect high removals of phosphorus, supplemental methods have been widely investigated. Chemical treatment has proven to be a highly successful and economical procedure.

It was the object of this research to develop and evaluate under continuous bench-scale operating conditions a combined chemical treatment-short term activated sludge process capable of producing from sewage an effluent low in phosphorus, BOD, and suspended solids. The short term biological process employed was European type high rate activated sludge which is characterized by high mixed liquor suspended solids concentrations. Aluminum sulfate was added directly to the mixed liquor for phosphorus removal.

INTRODUCTION

GENERAL STATEMENT OF THE PROBLEM

It has been generally recognized and well documented in extensive reviews (33,43,48,64) that excessive fertilization or enrichment of surface waters leads to nuisance-level proliferation of aquatic vegetation. The multitude of deleterious effects produced by unbalanced productivity is staggering. The major problems in lakes include hastening of the natural eutrophic process leading toward extinction, development of an anaerobic bottom environment resulting in an alteration of the ecological balance of existing fauna, prolific weed growths in littoral areas, algae accumulations on shore lines, and increases in water turbidity and discoloration. In streams, rooted aquatic plants and benthic algae frequently produce diurnal dissolved oxygen (DO) fluctuations with adverse effects on aquatic life. The DO problems may be further compounded by decomposition of dead plants. The rooted aquatics promote siltation and sludge bank deposition and increase channel roughness and water surface elevations. In general, excessive proliferation frequently causes changes in the equilibria of natural chemical reactions and may be unsightly and cause odors. Algae and/or algal excretions have been associated with animal, fish, algal, bacterial and human toxicity. Problems experienced with municipal and industrial water supplies include tastes, odors, interference with disinfection, increased requirements for treatment facilities and chemicals, corrosion, clogging

The research was conducted as two major investigative programs--Synthetic Sewage Investigations and Domestic Sewage Investigations. The former studies which included 356 days of continuous operation were designed to evaluate the influence of aluminum sulfate dosage and pH on process performance as measured by phosphorus and BOD residuals and removals. Consideration was given throughout to mixing and flocculation unit process requirements. The follow-up program during which the pilot plant was operated for 113 days was undertaken to ascertain the applicability of the synthetic sewage findings to actual clarified domestic sewage. Process and operational modifications to improve the observed performance with domestic sewage were investigated.

The investigations indicated that soluble phosphorus removals are dependent upon pH and the applied Al:P molar ratio. Relative to the latter, ratios between 1.5 to 2:1 were necessary to effect essentially complete removals.

The total phosphorus content of the combined biological-chemical process unfiltered effluent was dependent both upon soluble levels and suspended solids concentrations. For the domestic sewage investigative conditions, aluminum sulfate dosages in excess of those necessary to produce low soluble residuals were required to effect satisfactory flocculation and clarification.

Biological performance as measured by soluble substrate removal was not adversely affected by additions of aluminum sulfate as high as 335 mg/l. Moreover, the aluminum sulfate itself did not effect significant removals of soluble BOD_5 or LAS.

At optimum dosage, the aluminum sulfate produced better clarification than observed under high rate activated sludge operation without chemical addition. As a result, BOD_5 (unfiltered) and suspended solids removals were improved. The removals attained, however, were about comparable to those likely with conventional activated sludge.

The combined biological-chemical process produced significantly more sludge by weight than that observed under similar high rate activated sludge operation without chemical addition or that expected from conventional activated sludge. The aluminum sulfate, however, did cause marked reductions in mixed liquor SVI's. Accordingly, the volume of sludge produced would be less than that produced by the comparative high rate process and about equal to that from the conventional process.

The theoretical aeration period required by the biological-chemical process was from one-third to one-half that employed typically with conventional activated sludge. Moreover, although the time of combined chemical mixing and flocculation was critical for the domestic sewage work, successful operation without a separate flocculation basin was demonstrated. Accordingly, the cost of chemical treatment for the combined biological-chemical process will be partially offset by savings realized from reduced basin volume requirements.

INTRODUCTION

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Sawyer (54) related the phenomena of surface water enrichment and subsequent eutrophication to Liebig's Law of the Minimum--"the variation in productivity of land areas is most often determined by limitations imposed by lack of some nutritional element." He recommended application of this principle as a scientific approach to the control of undesirable aquatic growths. Of the essential plant nutrients considered for minimization, phosphorus has been selected by most authorities as the one having the greatest promise relative to both practical application and successful ecological control (33,54,55 66).

The major sources of surface water phosphorus are groundwater, urban and agricultural runoff, and domestic and industrial wastewaters (55). Evidence in the literature indicates that in most instances contributions from domestic wastewaters represent by far the largest fraction (43). Levin and Shapiro (33) in 1963 reviewed reported total phosphorus concentrations in sewage. Starting chronologically with Helmers _et al_. (19) who in 1951 cited concentrations ranging from 12.2 to 17.1 $mgPO_4/L$ for three sewages to the report of 32.8 $mgPO_4/L$ in 1961 by Oswald (44), a trend of increasing concentration is evident. As early as 1952 Sawyer (54) reported a doubling in concentration since the advent of modern synthetic detergents. Recently, 1967, Jenkins and Menar (23) reported five-day, hourly composite mean total phosphorus levels of 31.2 and 42.2 $mgPO_4/L$ for two plants. In addition, they reported _clarified_ sewage total phosphorus concentrations for another plant ranging from 41.0 to 55.7 $mgPO_4/L$. It is apparent that the removal of phosphorus during sewage treatment would significantly reduce its concentration in most troubled waters.

In view of the foregoing, the potential of conventional secondary treatment processes to remove phosphorus is of great importance. Since raw sewage levels vary significantly and the objective is a minimization of stream and lake phosphorus concentrations, plant effluent residuals rather than per cent removals are of interest. Nesbitt (43) concluded from a review of reported data that the orthophosphate concentration in completely treated sewage effluents averages approximately 24.5 $mgPO_4/L$ with a high degree of variation among individual values. In many instances, the associated total phosphate values would be considerably higher. The indicated inability of conventional treatment processes to effect high removals of phosphorus from sewage has been attributed to a nutritional imbalance.

Work reported in 1963 by Lea and Nichols (31) on the influence of inorganic nutrients on BOD progression carried the implication that the phosphorus content of sewage exceeds that required for the biological stabilization of the available carbon. Later Sawyer (53) and Wuhrman (76) demonstrated that carbonaceous supplements are required to effect almost complete phosphorus removals from typical sewages using activated sludge. Others (5,23,62) have expressed this conviction on the basis of the relative C:P ratios of activated sludge and sewage -- that of the former generally being significantly larger.

As suggested by the preceding workers, phosphorus removals during biological treatment can be calculated stoichiometrically under the assumption that the primary removal mechanism is the incorporation of phosphorus into cellular material. First, however, the phosphorus content and the quantity of wasted sludge must be known. Reported values of the former for activated sludge are summarized in Table I and range

TABLE I

PHOSPHORUS CONTENT OF ACTIVATED SLUDGE

Reference	Substrate	Per Cent Phosphorus (as P) Range	Average
(53)	Sewage	---	2.20
(19)	Sewage	1.35-2.00	1.78
(20)[b]	3.5% Rope Waste 5.0% Sewage	1.12-1.62	1.39
	95% Brewery Waste 5% Sewage	2.22-2.76	2.45
(75)	Sewage	1.75-2.54	2.09
(16)[c]	Synthetic Sewage	---	2.37
(33)	Sewage	2.69-3.27	--
(70)	Sewage	5.0-8.5	--
(23)	Sewage	2.45-3.03	2.62
(1)	Sewage	---	3.0

[a]Values reported on a SS basis were converted using per cent VS.

[b]Only data where both P and N were in excess is included.

[c]Phosphorus non-limiting condition.

from 1.12 to 8.5 per cent P (volatile solids [VS] basis). The majority, however, are three per cent or less. Levin and Shapiro (33) and Vacker, et al. (70) whose data, respectively, fall within the ranges of 2.69-3.27 and 5.0-8.5 per cent prescribed the operating conditions they considered essential toward promoting luxury uptakes by activated sludge.

Subsequently, Jenkins and Menar (23) concluded from investigations during which the aforementioned conditions were maintained that over a substrate removal rate range of 0.3-42.5 lb COD removed/lb. VS/day, the phosphorus content of the activated sludge did not vary significantly and averaged 2.62 per cent of the VS.

Using then a sludge (VS) content of 2.62 per cent and the sludge production versus solids age relationship shown in Figure 24 (p.114-115) and described by Eq. 12, the following approximations of phosphorus removal by activated sludge under two distinct process operating conditions can be made:

Condition	A	B
Solids age, days	1.5	5.0
BOD_5 removed, mg/L	200.0	200.0
Sludge produced and wasted at equilibrium, mg VS/L[a]	129.0	82.0
Phosphorus, $mgPO_4/L$		
Removed[b]	7.1	5.0
Influent	30.0	30.0
Per cent removal	23.7	16.7
Effluent[a]	22.9	25.0

[a]Includes effluent solids which were assumed as 40 and 20 mg/L, respectively, for the 1.5 and 5 day solids ages.

[b]Excludes phosphorus in effluent solids.

It is seen that these predictions are in general agreement with typical reported field observations.

In view of the evidence that conventional sewage treatment processes are unable to produce effluents essentially free of phosphorus, considerable research has been and presently is being directed toward the development of practical means to achieve this end. The investigations reported herein have been designed accordingly.

SUPPLEMENTAL PHOSPHORUS REMOVAL FOR CONVENTIONAL SEWAGE TREATMENT

Proposed and investigated phosphorus removal methods designed to augment conventional treatment capabilities include algal culturing, chemical treatment, deionization, distillation, electrochemical treatment, and spray irrigation. Reported works in these areas have been summarized in several reviews (33,43,48,50,64). Economic and performance evaluations (43) indicate that the greatest promise for general application resides with chemical removal techniques.

Chemical Treatment

Experimental success in removing phosphates from chemical solutions, sewage, and sewage treatment plant effluents has been reported for a number of individual and combinations of chemicals--aluminum sulfate (9,14,15,21,32,39,54,60,65,74), ferric chloride (14,15,53,54,74), ferric sulfate (14,21), ferrous sulfate (14,15,74), lime (15,22,24,35,36, 39,45,48,54,60,74), sodium aluminate (32,50,54), "alum" plus activated silica (42), aluminum sulfate plus lime (1,15), and ferric chloride plus ferric sulfate (66). Table II, after Nesbitt (43), presents phosphorus and organic matter removal data for most of these chemicals.

TABLE II

SUMMARY OF CHEMICAL PRECIPITATION DATA FOR PHOSPHORUS REMOVAL

Coagulant	Reference	Optimum Dose, mg/L	Orthophosphate: Initial Conc. mgP/L	Orthophosphate: Final Conc. mgP/L	Orthophosphate: Removal, percent	Complex Inorganic Phosphate: Initial Conc. mgP/L	Complex Inorganic Phosphate: Final Conc. mgP/L	Complex Inorganic Phosphate: Removal percent	Sludge Produced per MGD Flow: Volume, gal/day	Sludge Produced per MGD Flow: Solids, percent	Removal of Organic Matter	Remarks
$Ca(OH)_2$	45	720	4.3	0.13	97	3.1	1.56	50	10,000	6.6	--	One hr. sett. Filt. eff.= 0.04 mgP/L.
	54	280	7.0	0.5	93	--	--	Good	--	--	--	
	39	330	9.0	0.8	91	1.7	0.2	88	11,000	--	63%	Two hr. sett.
	74	660	--	--	--	--	--	--	--	--	60mgCOD/L	COD removal was from prefilt. secondary eff.
	60	540	6.25	--	88	--	--	--	--	--	--	
	35	200+	--	--	--	--	--	--	--	--	--	This is a flotation process.
$Al_2(SO_4)_3 \cdot 14\ H_4O$	32	200	--	--	90	--	--	--	--	--	87% BOD	Flocc. time 10 min., sett., 2 hr. Filt. eff.= 97% removal. Alum recovery system reduces chemical cost 80%.
$\cdot 18H_2O$	54	130	6.0	0.5	92	4.0	--	Good	--	--	--	80 mg alum/L needed for PO_4^{-3} alone.
"	39	240	(5.2)	(0.4)	(92)	--	--	Good	--	--	60% BOD	Removals reported are total P. Gelatinous sludge, filt. difficult.

TABLE II (continued)

Coagulant	Reference	Optimum Dose, mg/L	Orthophosphate: Initial Conc. mgP/L	Orthophosphate: Final Conc. mgP/L	Orthophosphate: Removal, percent	Complex Inorganic Phosphate: Initial Conc. mgP/L	Complex Inorganic Phosphate: Final Conc. mgP/L	Complex Inorganic Phosphate: Removal percent	Sludge Produced per MGD Flow: Volume, gal/day	Sludge Produced per MGD Flow: Solids, percent	Removal of Organic Matter	Remarks
$\cdot 18H_2O$	74	100	--	--	--	--	--	--	--	--	--	
"	60	400	6.25	--	94	--	--	--	--	--	--	
"	14	300	7.0	0.18	98	--	--	--	--	--	--	Alum and $Fe_2(SO_4)_3$ best of 7 coag. tried.
	9	200	4.0	--	97	--	--	--	--	--	--	
$FeCl_3$	54	100	6.0	0.5	92	4.0	--	Good	--	--	--	
	74	100	--	--	--	--	--	--	--	--	--	
	53	70	3.2	0.05	99	1.0	0.15	85	--	--	--	
$Fe_2(SO_4)_3$	74	100	--	--	--	--	--	--	--	--	--	
	14	230	7.0	0.18	98	--	--	--	--	--	--	
$NaAlO_2$	54	130	--	--	Good	--	--	--	--	--	--	Needed additional 150 mg alum/L or H_2SO_4 to reduce pH to remove complex inorganic phosphate.

Note: Except where indicated, values are for flocculation and settling only.

Relative to the employment of these phosphorus removal agents in conjunction with conventional sewage treatment processes, two distinct operational approaches exist. They may be added in a separate stage requiring new facilities for reaction and clarification or they may be introduced in combination with existing stages, thus minimizing requirements for additional equipment. In either event, overall process performance (i.e., the cumulative effects of the conventional and chemical treatment) is the most useful criterion for evaluating the benefits of the chemical application. Available overall performance data are summarized in Table III.

Neil (42) and Rand and Nemerow (48) investigated processes without biological treatment. Low phosphorus residuals were attained, however, accompanying BOD removals were intermediate.

Lea _et al_. (32) and Owen (45) chemically treated secondary effluents. The former employed a third stage process whereas Owen cleverly introduced the chemical agent to the influent channel of the final clarifier. Overall BOD removals were excellent but in both cases filtration was required to produce low phosphorus residuals.

The groups of Bennet (3) and Garland (15) studied third stage chemical treatment of activated sludge plant effluents. Both employed short-term aeration processes to help offset the cost of the chemical treatment. Bennet, Eliassen, and McCarty achieved greater BOD removals because they maintained higher aeration tank MLSS concentrations and, therefore, lower solids loadings than did Garland and Shell. Similar to most of the reported process observations, the unfiltered effluent total phosphorus residuals were normally greater than 1.75 mg PO_4/L.

TABLE III

PHOSPHORUS AND BOD REMOVAL PERFORMANCES FOR REPORTED CHEMICAL PRECIPITATION PROCESSES

Ref. No.	Process Description	Coagulant Type	Coagulant Dosage (mg/L)	Phosphorus Data Eff. ($mgPO_4/L$)	Phosphorus Data[a] Removal (%)	BOD Removal[a] (%)
42	Coagulation, Precipitation, and Sedimentation of Raw Sewage--1.5 MGD Plant	"Alum" + Activated Silica	94+3.4	3.15[b]	81	70
"	" + Filtration	"	"	0.33[b]	98	--
48	Coagulation, Precipitation, and Sedimentation of Raw Sewage--Lab Glassware	$Ca(OH)_2$	300	1.8	93.5	71.3
"	"	"Alum"	400	0.8	97.0	73.2
32	Coagulation, Precipitation, and Sedimentation of STP effluent--10 GPM Pilot Plant	$Al_2(SO_4)_3 \cdot 14H_2O$	200[g]	2.23	85[c]	95[b,d]
"	" + Filtration	"	"	0.14	99[c]	--
45	HR Trick. Filter, Sed., LR Trick. Filter, Coagulation, Precip., and Sedimentation--0.77 MGD Plant	CaO	545	5.2	79.5[b,e]	94.5[b]
	" + Filtration	"	545	0.40	98.5[b,e]	--

TABLE III (continued)

Ref. No.	Process Description	Coagulant Type	Coagulant Dosage (mg/L)	Phosphorus Data Eff. ($mgPO_4/L$)	Phosphorus Data Removal[a] (%)	BOD Removal[a] (%)
3	HRAS, Sedimentation, Coagulation, Precipitation, and Sedimentation--10 GPM Pilot Plant	$Al_2(SO_4)_3 \cdot 14H_2O$	397[h]	4.90	89[c]	>86
"	" + Filtration	"	"	1.53	96.5[c]	≅95[b,f]
15	Modified Aeration, Sedimentation, Coagulation, Precipitation, and Sedimentation--10 GPM Pilot Plant	$Ca(OH)_2$+"Alum"	200+20	2.3	92[e]	83

[a] Except where indicated, reference is to all processes mentioned in description, i.e., where investigations were conducted on a secondary effluent, BOD removals resulting from this initial treatment are included.

[b] Calculated on basis of data presented.

[c] Biological phosphorus removal <u>not</u> included.

[d] Assumes 85 per cent removal by the sewage treatment plant.

[e] Biological phosphorus removal <u>is</u> included.

[f] Calculated assuming BOD removal across chemical stage was equal to COD removal reported by authors.

[g] Equivalent to 224 mg $Al_2(SO_4)_3 \cdot 18H_2O/L$.

[h] Equivalent to 444 mg $Al_2(SO_4)_3 \cdot 18H_2O/L$.

Combined Chemical and Activated Sludge Treatment

Stumm (63) in 1962 suggested the use of metal coagulants simultaneously for dispersed micro-organism flocculation and phosphorus precipitation. The idea was later investigated on a batch basis with success by Tenney and Stumm (64,65). Realizing that biological treatment with activated sludge occurs in two phases, substrate utilization and bioflocculation, they reasoned that by chemically aiding flocculation the entire process could be accomplished in a "high-rate, low-solids retention unit." The increased treatment costs for phosphorus removal and flocculation would then be partially compensated for by savings from the shortened biological phase. The continuous process hypothesized was not developed experimentally by the investigators.

Although no mention is made of using the coagulant for both cell flocculation and phosphorus precipitation, Thomas in Männedorf (67) and Uster (68) employed ferric chloride with a trace of ferric sulfate as an agent for phosphorus removal in combination with the activated sludge process. The chemical could be added either before or after the activated sludge basin (E. A. Thomas, personal communication). Total phosphorus residuals and removals across the activated sludge--final clarification basins using 10 mg Fe^{+++}/L were 1.85 mg PO_4/L and 92.4 per cent and 1.89 mg PO_4/L and 85.4 per cent at Männedorf and Uster, respectively. Filtered effluent phosphorus residuals, and BOD_5 residuals and removals were not reported. While the chemical process increased the weight of sludge produced, the total volume remained within the normal range experienced without chemical additions. In addition, the chemical

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Eberhardt and Nesbitt (12) presented results of synthetic sewage investigations on the chemical precipitation of phosphorus within a high rate activated sludge system. The details and complete findings of this work as well as those of follow-up domestic sewage studies are the subject of this dissertation.

Barth and Ettinger (1) added 10 mg Al^{+++}/L as sodium aluminate to the aeration basin of a conventional activated sludge (6 hours theoretical aeration) pilot plant. For 12 days of operation during which clarified sewage supplemented with sodium tripolyphosphate was treated, the average total phosphorus effluent concentration and per cent removal were 1.53 mg PO_4/L and 94.6. The average molar aluminum to phosphorus ratio over this period was 1.26. Filtered effluent phosphorus residual and sludge production data were not reported. Relative to a non-chemical control system, the addition of aluminate favorably dropped the sludge volume index from 200 to 77. The aluminate did not interfere with nitrification nor on the basis of microscopic observations did it effect any significant change in the population of higher biological forms. No change in precipitated phosphate identity occurred during anaerobic digestion studies.

OBJECTIVE OF THE PRESENT INVESTIGATION

It was the object of this research to develop and evaluate under continuous bench-scale operating conditions a combined chemical treatment short term activated sludge process capable of producing from sewage an effluent low in phosphorus, BOD, and suspended solids. Such a process would find application at existing activated sludge plants, including those presently overloaded, as well as for new facilities. The savings realized from the decreased requirement in aeration volume would at least partially offset the costs of chemical treatment.

PROCESS CONSIDERATIONS

CHEMICAL SELECTION

Selection of a metallic salt for use in the process was based on biological as well as chemical considerations. As indicated earlier, the major cations having an excellent capacity for phosphorus removal are Ca^{++}, Fe^{+++}, and Al^{+++}. While the latter two are also effective as bacterial flocculation agents, Ca^{++}, a non-hydrolyzable cation, is not (64). Use of calcium was undesirable from another point of view. Since the chemical was to be reacted in intimate contact with the activated sludge, calcium could not be employed at its optimum phosphorus removal pH, approximately 11 (45). Aluminum sulfate was chosen over ferric compounds because the pH of minimum $AlPO_4$ solubility, approximately pH 6, is about one pH unit higher than that of $FePO_4$ (63). The optimum insolubility pH of the latter was considered too close to that representing the lower limit of optimum biological oxidation (51).

ACTIVATED SLUDGE SELECTION

Two major alternatives existed for the selection of a short term aeration process. The first, modified aeration (57,58,69) is characterized typically by solids levels ranging from 300 to 1000 mg/L. As related by Sawyer (56), this scheme is often erroneously called high rate and is practiced extensively at Los Angeles, Miami, Mobile, Philadelphia and New York City. The second, high rate activated sludge

(HRAS), is commonly employed in Europe (2,25,46,47,72,73,75) and Great Britain (38) and is typified by solids concentrations ranging from 3,500 to 11,000 mg/L. In view of the foregoing and because both processes commonly have about the same aeration period (typically one to three hours) and, therefore, with sewage about the same volumetric BOD loading, they differ with respect to MLSS-BOD loadings and solids age. HRAS was selected for use over modified aeration since its higher solids age should lead to better bioflocculation, lower sludge production, and possibly more favorable removal or settleability of the precipitated phosphates by means of solids contact.

After selection of HRAS, it became apparent from a literature survey, the findings of which are summarized in Table IV, that the extent of linear alkylate sulfonate (LAS) degradation in this process has apparently never been reported. Therefore, LAS removals were extensively investigated and the findings are reported in this work.

TABLE IV

REPORTED LAS REMOVALS BY THE ACTIVATED SLUDGE PROCESS

Ref. No.	Type Plant	Theor. Aer. Period (hrs.)	Organic Loadings: lbs BOD_5 per 1000 ft^3/day	Organic Loadings: lbs BOD_5 per lbMLSS/day	MLSS (mg/L)	LAS or MBAS Removal %	BOD Removal %	Removal Ratio MBAS/BOD
(49)	Field, Full-scale	47	24-30	--	---	97.7	94.6	1.03
(17)	Field, Full-scale	24	---	--	2,200	93	90	1.03
(17)	" " "	13.4	---	--	1,560	70.2	59	1.19
(26)	Laboratory	--	---	--	---	70+	65	--
	Laboratory	5	---	--	1,500	94.7	91.4	1.04
	Laboratory	5	---	--	3,500	94.6	93.2	1.02
(27)	Field, Pilot Plant	8.5	28	0.28	1,600	94.3	85-90 (COD)	--
	Field, Pilot Plant	3.6	≅5.6	0.09	1,000	91.3	83 (COD)	--
	Field, Pilot Plant[a]	2.8	≅84	2.11	640	68.8	83 (COD	--
(10)	Field, Full-scale Pasveer Ditch	48	14	--	---	87	--	--
(28)	Field, Full-scale	17	21	--	---	85	92	0.92
(29)	Field, Full-scale	29	---	--	3,940	96.5	97.2	0.99

[a]Modified aeration.

EXPERIMENTAL APPROACH

GENERAL PLAN OF RESEARCH

The research was conducted and is reported herein as two major investigative programs:

Synthetic Sewage Investigations

Domestic Sewage Investigations

The synthetic sewage studies were designed to evaluate the influence of aluminum sulfate dosage and pH on process performance as measured by phosphorus and BOD residuals and removals. Consideration was also given to unit process requirements.

A follow-up program was undertaken to ascertain the applicability of the synthetic sewage findings to actual domestic sewage. Subsequent process and operational modifications to improve the observed performance were investigated.

APPARATUS

Bench-Scale Pilot Plant

Throughout this investigation the experimental pilot plant was modified periodically with regard to unit process basin and associated volume requirements. It is the purpose of this section to provide only a physical description of the laboratory apparatus using as a base the process scheme employed initially. Subsequent modifications and all pertinent operating conditions will be reported later.

A schematic diagram of the initial process design and a photograph of the actual laboratory pilot plant are shown, respectively, in Figures 1 and 2. In the order of flow, the process units included a complete-mixing aeration tank, a chemical mixing chamber, and flocculation and sedimentation basins. Other components of the plant included pH recorder--controller, pumping, and influent compressed air systems.

Unit Process Basins. The aeration tank and supporting structure were designed to allow volumetric flexibility by elevation changes and third-point sectioning. The tank walls and partitions were constructed of 1.27 and 0.65 cm clear lucite, respectively. The inside dimensions of each compartment in order of width, length, and height were 11.2, 14.0, and 35.6 cm. With all partitions removed the corresponsing dimensions were 34.8, 14.0, and 35.6 cm.

Each potential compartment contained influent ports for feed and return sludge, effluent ports for sludge wasting and outgoing mixed liquor, and two 2.54 cm dia. cylindrical gas diffuser stones. This assured uniform distribution of influent feed, return sludge, and air as well as uniform removal of waste sludge and mixed liquor. Figures 1 and 3a illustrate the aforesaid design. It can be observed in the latter that feed was so introduced as to minimize short-circuiting. Return sludge was added between the air diffusers.

The chemical mixing chamber, made of 1.27 cm clear lucite, had a width and length of 7.56 cm and a height of 20.3 cm. Two diffuser stones for both mixing and aeration were located on the bottom--one on each side of the influent mixed liquor port. pH control chemicals were added at the tank surface near the influent end; aluminum sulfate was

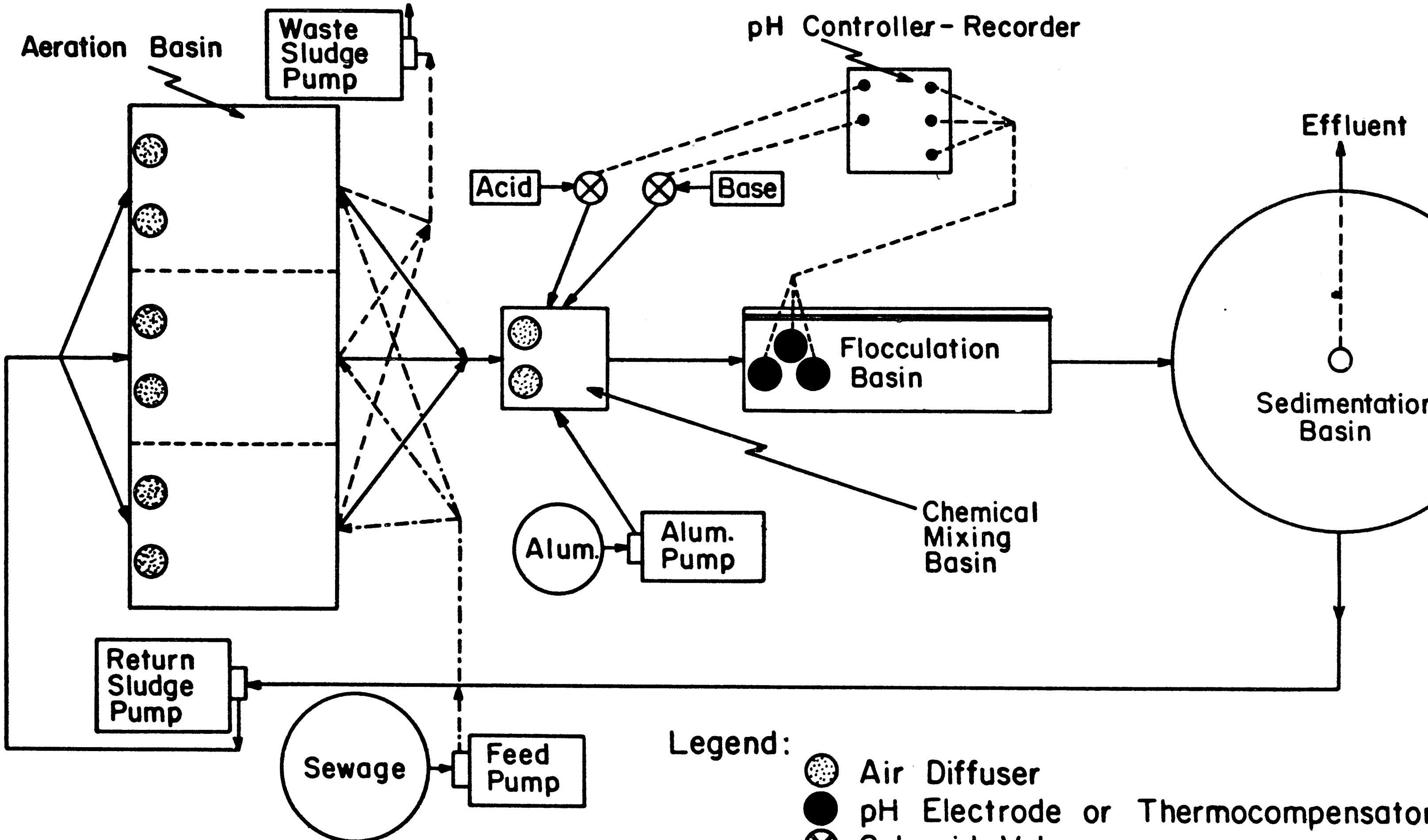

Figure 1. Schematic diagram of the bench-scale pilot plant--process scheme 1 (PS1)

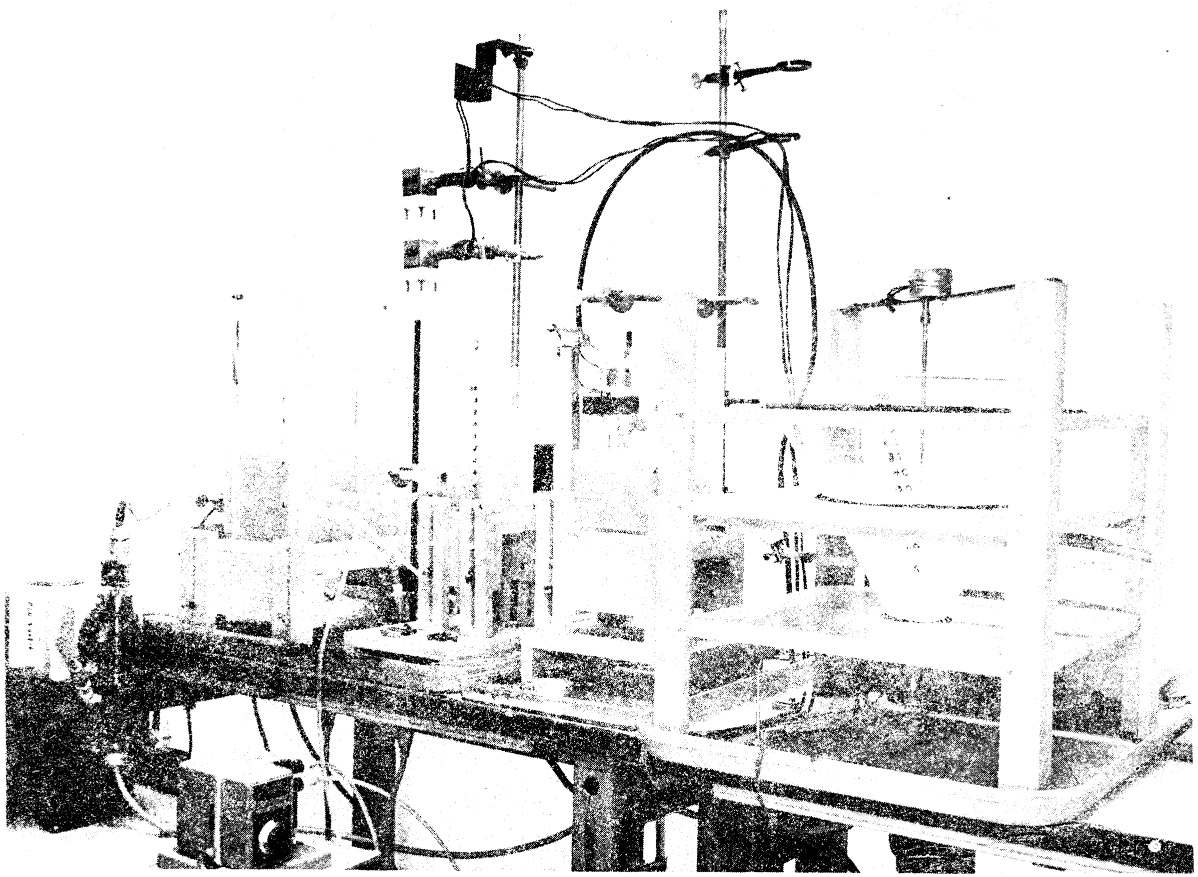

Figure 2. Bench-scale pilot plant.

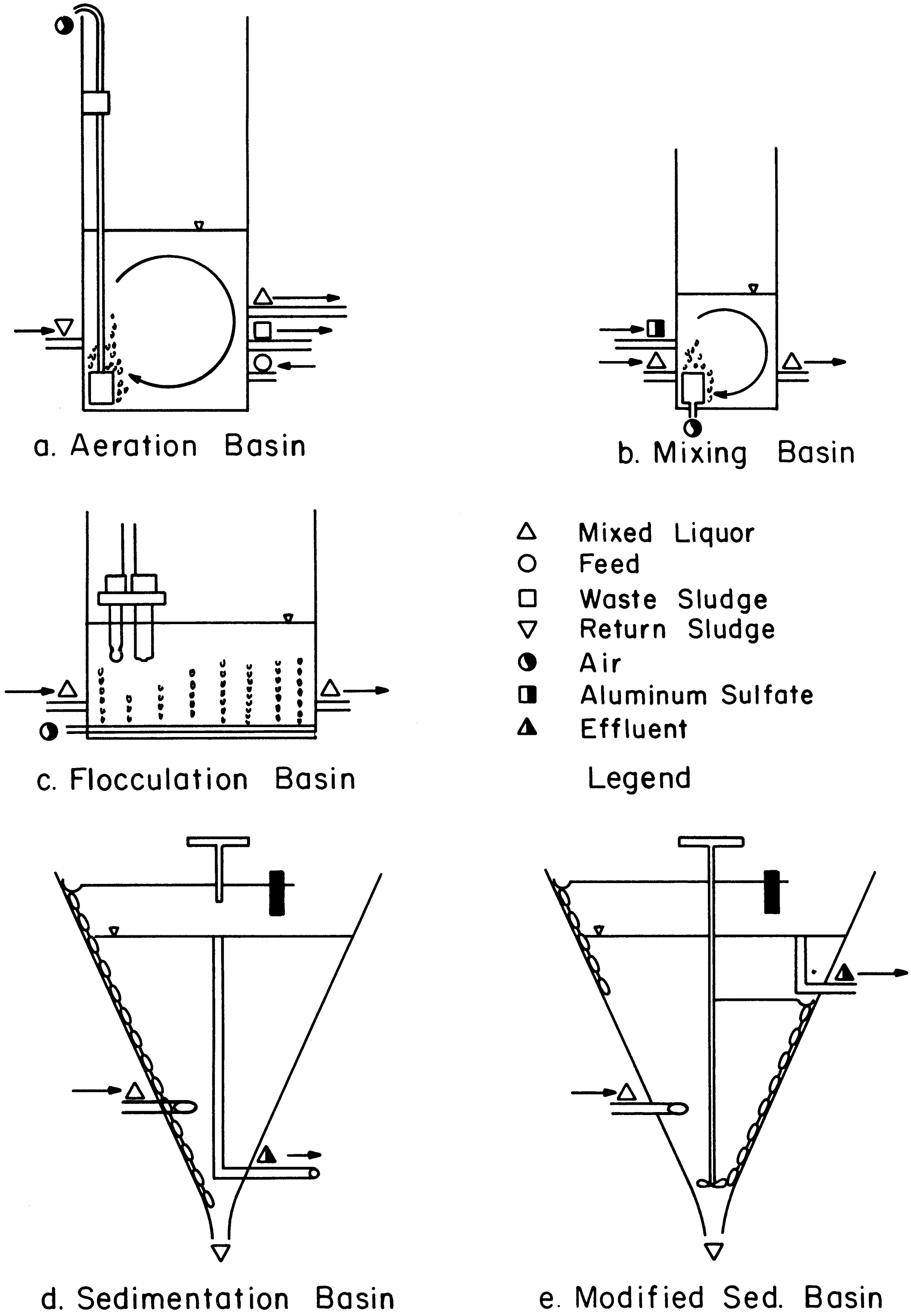

Figure 3. Unit process basin details--bench-scale pilot plant.

injected below the liquid surface just above the influent mixed liquor port. Figure 3b illustrates the design of this basin.

The inside measurement of the flocculation basin, also constructed of 1.27 cm lucite, were 6.98, 17.8, and 24.1 cm in width, length, and height. Mixing and aeration were provided by a perforated 0.45 cm I.D. vinyl tube located parallel to the direction of flow along the bottom left basin joint. The resultant cross current roll minimized short-circuiting. The measuring assembly of the pH recorder-controller was suspended at the head of this basin as shown in Figure 3c.

The sedimentation basin was constructed of 0.318 cm clear lucite. The conical unit had sides at a 60 degree angle to the horizontal. The diameter changed uniformly from 38.1 cm at the top to 3.80 cm at the base. A 5 cm-long transition section further decreased the cone apex to a 1.27 cm I.D. nipple which accommodated the return sludge tubing. Mixed liquor entered the basin tangentially via a port located approximately 8 cm up from the apex.

The effluent weir, the rim of a 1.27 cm I.D. lucite standpipe, was 3.99 cm in length. The clarifier volume was controlled by adjustments of the standpipe elevation. During the synthetic sewage control run the standpipe passed through the basin side 6.4 cm above the bottom of the cone transition sections as shown in Figure 3d. This placement, which produced periodic congestion at the exit with resultant sludge bridging and build-up, was improved as illustrated in Figure 3e at the start of the chemical precipitation experiments.

To prevent sludge accumulation on the sedimentation basin walls, a chain scraping device powered by a one-RPM clock motor was installed.

Depending on effluent clarity, the scraper was operated continuously or periodically on a timer controlled cycle. As illustrated in Figures 3d and 3e, a modification of the scraper was necessitated by the aforementioned standpipe rearrangement. Simultaneously, a small propellor was added to help prevent sludge bridging.

Vinyl or Tygon tubing (0.793-1.27 cm O.D.) was used for all conduction and connecting lines. Connectors, tees and Y's were of polypropylene or polyethylene construction.

Compressed Air System. The compressed air system consisted in order of an oil trap, a pressure regulator, and a humidifier. Humidification was included to reduce evaporation losses from the aeration, mixing, and flocculation basins. Airflow to each of the aforementioned diffusers was controlled by a header composed of six needle valves.

Pumps. Feed was pumped to the aeration tank from a 103 liter carboy by a BIF Model 1210-04-9102 Simplex chemical feed pump equipped with a slurry head, flushing tee, and anti-siphon back loading valve. An identical pump was used for sludge recirculation.

Mixed liquor was wasted semi-continuously from the aeration tank by means of a timer operated (0-50% of the time of a 8'2" cycle) Model T-8 Sigmamotor peristaltic pump equipped with a Boston gear reductor.

A Beckman solution metering pump (0-2 ml/min Model) fed alum to the chemical mixing chamber. The accuracy and repeatability of this pump is specified as ± 0.04 ml/min and ± 0.01 ml/min., respectively.

pH Recorder-Controller System. This system consisted of a Bristol Dynamaster d-c millivoltmeter recorder, Model 1pH70GD2-TD110, integrally equipped with a Beckman Model 75 pH amplifier, a pH measuring circuit, and two solenoid valves for acid and alkali additions. Beckman industrial process electrodes (Reference No. 19565, Glass No. 19500, and Thermocompensator No. 19581) were used in the measuring circuit. Valcor No. 51C-19T-34-6 solenoid operated valves with glass stopcocks on the discharge sides controlled the acid and alkali additions. Both the body and diaphram of these valves were of teflon construction. Experience revealed that ASCO stainless steel bodied valves with teflon seats were corroded by the 0.1N H_2SO_4 and 0.1N NaOH solutions used.

Sewage Refrigeration System

A refrigeration system was employed throughout the investigative phase using clarified domestic sewage. The system consisted basically of a Tecumseh Type F12, 1HP compressor, a 50-ft. 1.27 cm O.D. copper immersion coil, and an insulated 55-gal. drum housing the 103 L feed carboy. Other essential hardware included a Type C083 drier, Type A3S1 solenoid valve, and GF1/2Z expansion valve (all Sporlan Valve Co.) and a White Rogers 263B thermostat. This system, pictured in Figure 4, dropped the temperature of 80 L of sewage from 25°C to 3.5°C in about 70 minutes. Continuous mixing was maintained by use of an air diffuser. Experience revealed that natural temperature elevation supplanted need for a heat exchanger following refrigeration.

EXPERIMENTAL PROCESS SCHEMES

Three basic process schemes--PS1, PS2, and PS3--were employed throughout the investigation. Schematic diagrams for all three are shown in Figure 5.

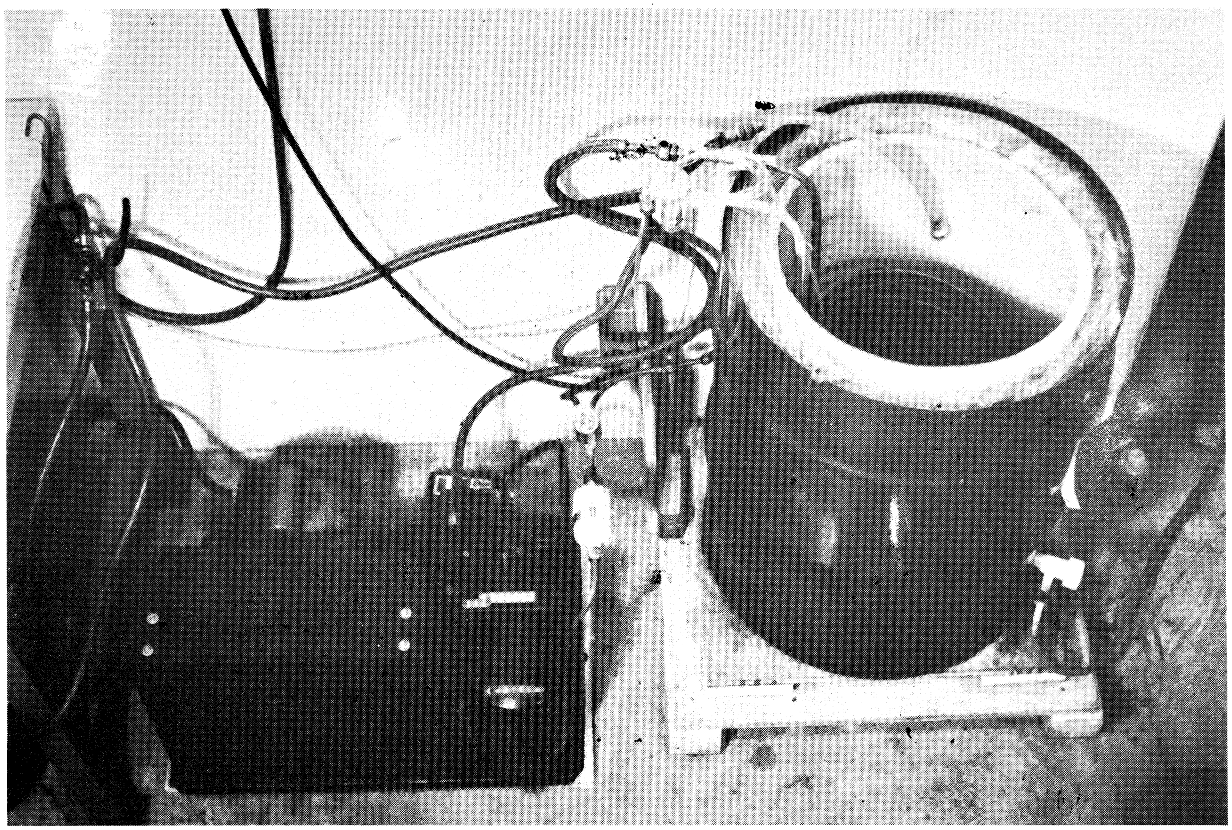

Figure 4. Refrigeration system--bench-scale pilot plant.

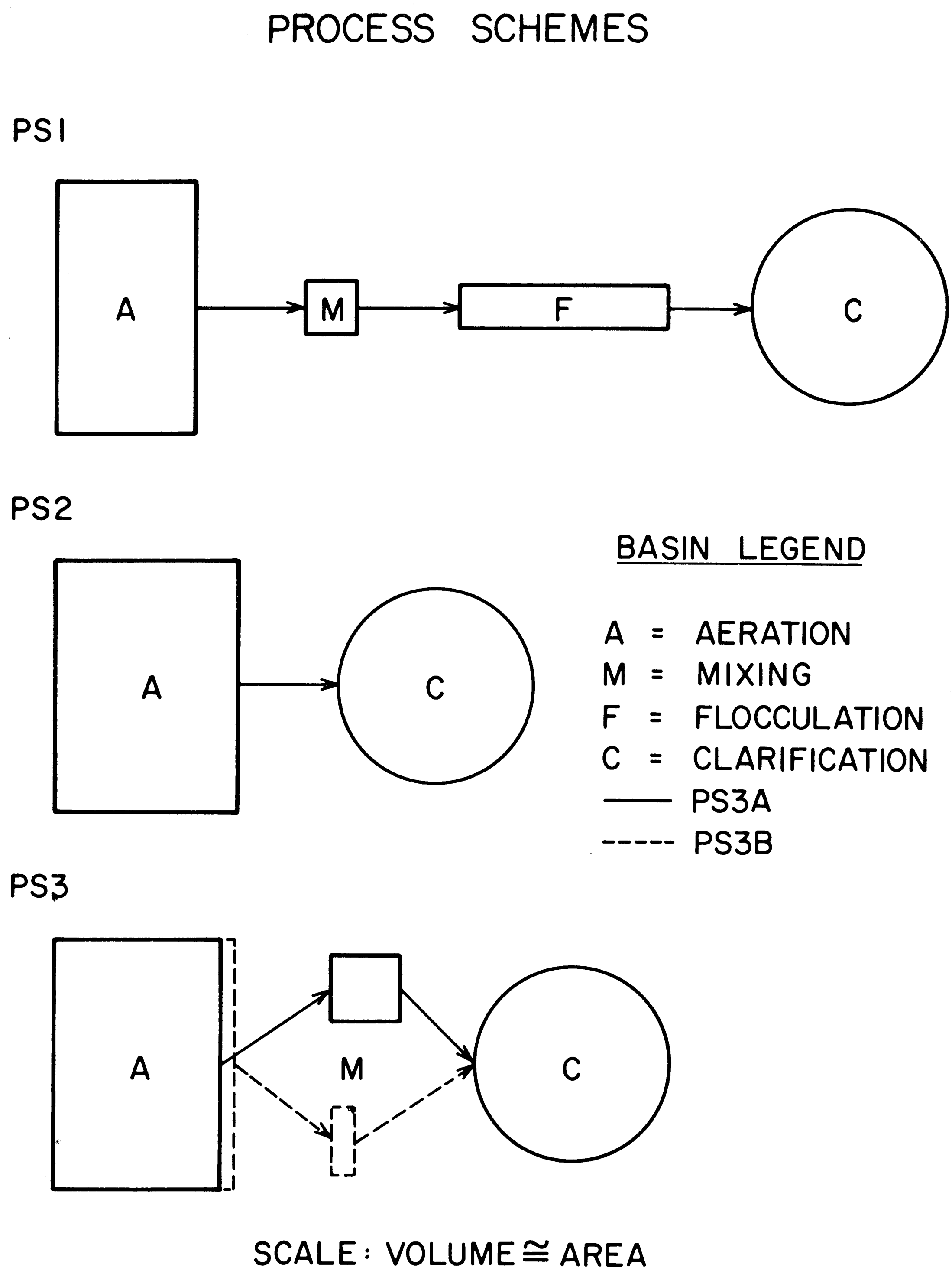

Figure 5. Experimental process schemes.

The total aeration and clarification volumes were held constant for the three designs. Because the mixing and flocculation basins were air agitated, total aeration volume (time) is defined in this investigation as the sum of those of the aeration, mixing, and flocculation basins. Therefore, the process modifications imposed by the use of several schemes involved only the chemical mixing and flocculation unit processes.

Table V will serve as a reference for the unit process volumes and theoretical detention times of the schemes investigated. All detention times are based on the 60 L/day flow rate used throughout the entire program of study.

During use of PS1, chemicals for both phosphorus removal and pH control were added to the mixing basin and the pH electrodes were located in the flocculation basin. With PS2 all chemical additions and pH monitoring occurred in the aeration basin. pH control was not maintained during employment of PS3 and aluminum sulfate was added to the mixing basin.

ANALYTICAL TESTS AND PROCEDURES

A summary of the tests performed and analytical procedures used throughout this investigation follows:

Biochemical Oxygen Demand--BOD was determined by the method given in Standard Methods (59). Ammonium chloride was excluded from the dilution water.

Chemical Oxygen Demand--COD was measured using the procedure developed at the Sanitary Engineering Research Laboratory (SERL) of the University of California (52).

TABLE V

PROCESS SCHEME VOLUMES AND THEORETICAL DETENTION TIMES

	Process Scheme			
	PS1	PS2	PS3A	PS3B
Unit Process Volumes, liters				
Aeration	5.00	6.66	6.00	6.40
Mixing	0.41	--	0.66	0.26
Flocculation	1.25	--	--	--
Clarification	3.75	3.75	3.75	3.75
Unit Process Theoretical Detention Times, hours				
Aeration	2.00	2.66	2.40	2.56
Mixing	0.16	--	0.26	0.10
Flocculation	0.50	--	--	--
Clarification	1.50	1.50	1.50	1.50
Total Aeration				
Volume, liters	6.66	6.66	6.66	6.66
Period, hours	2.66	2.66	2.66	2.66

Filtration--Filtration for solids determinations and, where indicated, prior to other analytical tests was performed using 5.5 cm dia. Reeve-Angel glass fiber filter pads.

Methylene Blue Active Substance--MBAS was determined by the Methylene Blue Method of Standard Methods (59).

Oxidized Nitrogen--The conversion of nitrite to nitrate and subsequent measurement of oxidized nitrogen was accomplished in accordance with the Phenoldisulfonic Acid Method of Standard Methods (59).

pH--pH measurements were made using a Beckman Zeromatic pH meter and the pH recorder-controller apparatus described earlier.

Phosphorus--The Stannous Chloride Method for Orthophosphate (59) was used for all phosphorus determinations. The test was conducted in an incubator controlled at 20°C. Ten minutes were allowed for color development and readings were taken at a wave length of 690 mu using a Beckman DB or Spectronic 20 spectrophotometer.

Several methods of sample preparation were employed. A modification of the alkaline ash procedure (23) was used to determine the total phosphate of the synthetic sewage and activated sludge. Allowance was made during the stannous chloride determination for the carried over strong acid molybdate solution used to pick up the ashed residue.

Preparation for the total phosphate test on the primary effluent sewage was made using a slight modification of the binary acid wet-ash procedure (70). The modification included a neutralization step prior to measurement using the stannous chloride technique. A comparison (see Table VI) between the binary acid wet-ash and Standard Methods hydrolysis (59) procedures revealed that for total phosphate determinations on sewage, the former consistently released more orthophosphate than the latter.

Effluent total phosphate determinations were made following preparation by either the binary acid wet-ash or Standard Methods hydrolysis procedures. Both techniques gave essentially identical results on effluent samples (see Table VII).

TABLE VI

COMPARISON OF THE BINARY ACID WET-ASH AND STANDARD METHODS HYDROLYSIS PHOSPHORUS ANALYSIS PREPARATION PROCEDURES ON CLARIFIED SEWAGE SAMPLES

Sewage Sample	Total Phosphate Measurement[a] (mg PO_4/L)		Per Cent BAW-A Exceeds SMH
	BAW-A	SMH	
1	52.0	51.2	1.5
2	41.0	40.3	1.7
3	42.4	39.6	7.1
4	44.3	43.9	0.9
5	62.9	60.2	4.5

[a]On the basis of six replicate samples.

TABLE VII

COMPARISON OF THE BINARY ACID WET-ASH AND STANDARD METHODS HYDROLYSIS PHOSPHORUS ANALYSIS PREPARATION PROCEDURES ON EFFLUENT SAMPLES

Effluent Sample	Total Phosphate Measurement[a] (mg PO_4/L)			
	Filtered		Unfiltered	
	BAW-A	SMH	BAW-A	SMH
1	0.21	0.18	5.8	5.8
2	0.28	0.29	7.3	7.3

[a]On the basis of three replicate samples.

Suspended and Volatile Solids--All SS and VS analyses were carried out using the procedure reported by Murphy *et al*. (41) with the following modifications:

1. The glass fiber filter pads were brought to constant weight at 104°C prior to taring.
2. The solids were dried at 104°C for 7-10 hours and ashed for 15 minutes at 600°C.
3. A correction was made for pad weight loss during ashing.

Sludge Volume Index--SVI of the mixed liquor was determined in accordance with Standard Methods (59).

Total Kjeldahl Nitrogen--Total Kjeldahl nitrogen was determined by the method given in Standard Methods (59).

SYNTHETIC SEWAGE INVESTIGATIONS

PROGRAM OF STUDY

In view of the non-reproducibility of domestic sewage, a synthetic substrate was used during the initial phases of this project to eliminate as variables both inorganic and organic feed composition. Following an extensive substrate and high rate acclimation period for the biological culture, the synthetic sewage investigations progressed in the following stages:

Biological Control Investigation--A control study of HRAS performance under PS1 with no chemical treatment.

Biological-Chemical Investigations--A two-phase study of phosphorus removal and biological performance under several aluminum sulfate dosages at operational pH's of 5.5 and 6.5.

Phase 1--The biological-chemical process employing PS1.

Phase 2--The biological-chemical process employing PS2.

Throughout the entire synthetic sewage program, the removal of LAS was closely followed to ascertain the degradability of this compound in a high rate biological system.

SYNTHETIC SEWAGE

A sewage formulation recommended by Butterfield (6) and used by Pasveer (47) for HRAS studies was chosen and modified to meet desired experimental requirements. The modifications included adjustments in the concentrations of organic components and use of tap water in place of the suggested salts solution. In addition, LAS and several forms of phosphate were included to provide a closer simulation of domestic sewage.

Composition

The composition of the complete synthetic sewage is shown in Table VIII. Where concentration ranges are given, quantitative data relative to these components will be given later where applicable.

TABLE VIII

SYNTHETIC SEWAGE COMPOSITION

Nutrient Broth[a]	365.0 mg
Urea	36.5 mg
LAS[b]	0 to 12.5 mg
Phosphate Buffer	variable
Sodium Tripolyphosphate[c] (STPP-$Na_5P_3O_{10}$)	0 to 3.23 mg
Tetrasodium Pyrophosphate (TSPP-$Na_4P_2O_7$)	0 to 3.45 mg
Water, Pennsylvania State University Tap	to 1000 ml

[a]Fisher, Lot 755896

[b]Compliments of the Soap and Detergent Association

[c]Food Grade, Compliments of FMC Corporation

Oxygen Demand and Biodegradability

Determinations of the oxygen demand and the biodegradability of the synthetic sewage were performed. During these tests the LAS and complex phosphates were omitted and 0.139 ml/L of a phosphate buffer[1] was added.

The findings of the BOD determinations are given in Table IX. Because a positive lag in BOD progression occurred, the rate constant (k), ultimate BOD (L), and BOD_5 were computed from the following relationship developed by Moore et al. (40):

$$y = L\ (1 - 10^{-k\ (t - t_o)}) \qquad (1)$$

where
- y = the BOD @ time t
- L = the ultimate BOD
- t_o = the lag period
- k = the rate constant

TABLE IX

SYNTHETIC SEWAGE BOD PROGRESSION

Period of Incubation (days)	BOD[a] @ 20°C (mg/L)
1	53.5
2	139.0
3	151.5
4	168.5
5	198.5

[a]Average of two determinations.

The characteristics of the synthetic sewage are summarized in Table X. In previous work by Eberhardt (11) using this synthetic sewage in a more concentrated form (BOD_5 = 365), a rate constant of 0.268 $days^{-1}$ was obtained.

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[1]Pasveers' buffer (47) -200 g K_2HPO_4/L and 50 g KH_2PO_4/L.

TABLE X

SYNTHETIC SEWAGE OXYGEN DEMAND AND BIODEGRADABILITY

k	0.229 $days^{-1}$
L	212 mg/L
BOD_5	194 mg/L
COD	372 mg/L

LAS Oxygen Demand

In view of the fact that concentrations of LAS ranging from 1 to 12.5 mg/L were to be present in the synthetic sewage, tests were conducted to determine the BOD_5 and COD contributed per mg of this substance. The COD was measured directly, whereas the BOD_5 was determined by adding known concentrations to samples of effluent from the pilot plant which had been consistently effecting LAS removals of greater than 90 per cent for a period of 45 days. The presence of a culture well acclimated to the LAS structure was thus assured.

The COD of LAS was determined to be 1.27 mg COD per mg LAS. The results of the BOD tests are shown in Table XI. NH_4Cl (2 mg/L) was added to one of the control effluent samples as well as to the LAS supplemented effluent samples to assure that nitrogen would not be limiting. The fact that the BOD_5 factors (0.34 and 0.33) are approximately equal for both LAS concentrations used indicates that an inorganic nutrient limiting condition was not present. The BOD factors were calculated using the nitrogen supplemented control to eliminate any apparent BOD contribution due to nitrification. The data indicate almost complete nitrification of the added nitrogen since the theoretical oxygen requirement for 2 mg NH_4Cl/L is about 2.39 mg/L which approximates the actual BOD increase of 2 mg/L.

TABLE XI

BOD_5 EQUIVALENT OF LAS

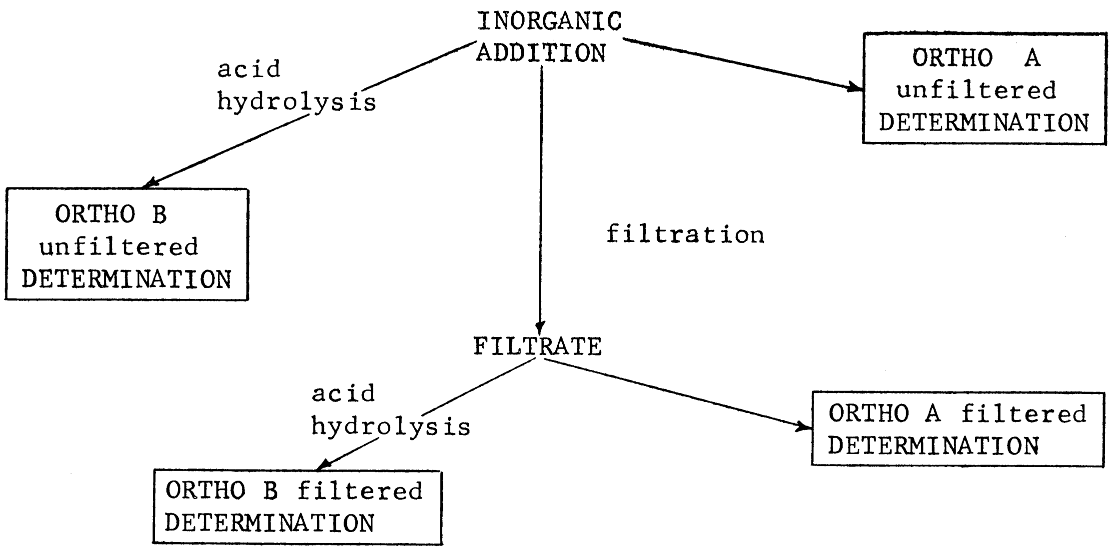
Sample	LAS mg/l	BOD_5 (mg/L)	LAS BOD_5 (mg/L)	mg BOD_5/mg LAS
A.S. Effluent	0	26	--	--
A.S. Effluent + NH_4	0	28	--	--
A.S. Effluent + NH_4	50	45	17	0.34
A.S. Effluent + NH_4	30	38	10	0.33

Phosphorus Concentrations

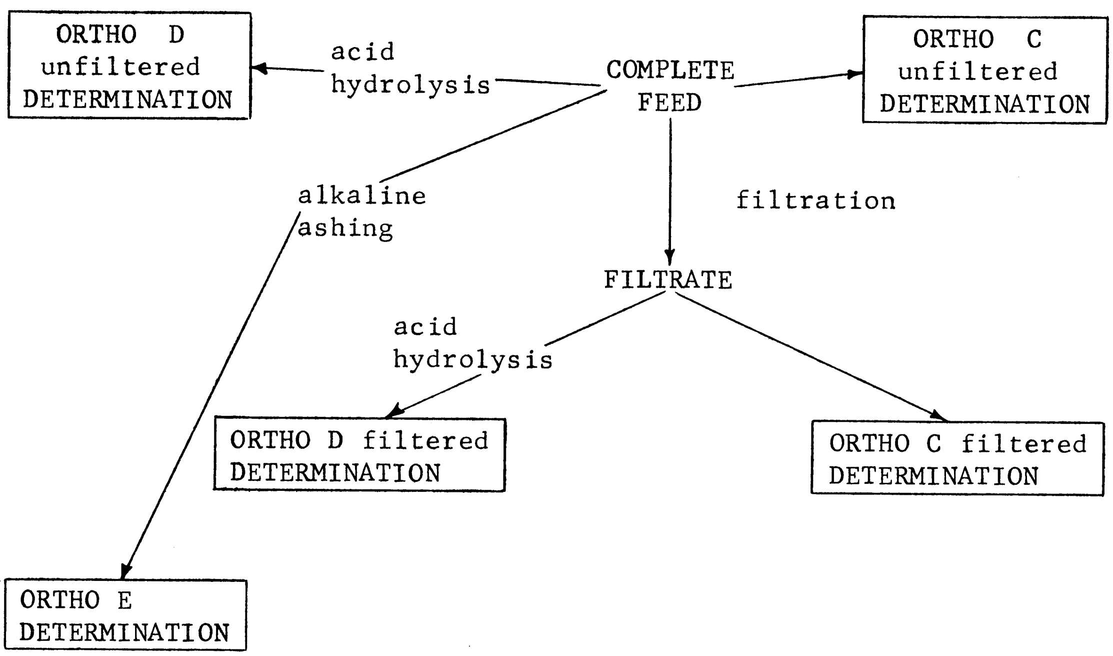
A quantitative study of the various forms of phosphorus in the complete synthetic sewage (all components listed in Table VIII) was undertaken to assure that the concentrations present were representative of a domestic waste as well as to provide control data for the phosphorus removal studies. In addition to the quantities given in Table VIII, the substrate contained per liter, 5 mg of LAS, 20 mg PO_4 (added as KH_2PO_4), 3.23 mg STPP and 3.45 mg TSPP.

To ascertain the sources of the phosphates, the substrate was analyzed in two steps. First, 10 liters of feed containing only the KH_2PO_4, STPP, and TSPP were prepared and analyzed. This batch is hereafter referred to as the inorganic addition. Second, 10 liters of the complete synthetic sewage were prepared and analyzed. The analysis schemes for each are shown in Figure 6.

Within the accuracy limits of the analytical procedures, these analyses demonstrated that the synthetic substrate contained no insoluable forms of phosphate, i.e., A,B,C,D (all unfiltered) equaled



a: Procedure for Inorganic Addition Phosphate Analyses



b: Procedure for Complete Feed Phosphate Analyses

Figure 6. Synthetic sewage phosphorus analysis scheme.

respectively A,B,C,D (all filtered). The pertinent phosphate components were determined from the analytical data according to the scheme of Table XII.

TABLE XII

SCHEME FOR PHOSPHATE FORM DELINEATION OF COMPLETE SYNTHETIC SEWAGE

Total Phosphate	= ORTHO E
Total Orthophosphate	= ORTHO C
Inorganic Addition Contribution	= ORTHO A
Organic Component Contribution	= ORTHO C - ORTHO A
Inorganic Complex Phosphate	= ORTHO B - ORTHO A
Total Organic Phosphate	= ORTHO E - ORTHO C - (ORTHO B - ORTHO A)

By using this analysis and delineation system, the term Inorganic Complex Phosphate is completely descriptive. It does not include any of the complex organic phosphates which are reported (34,71) to undergo cleavage during acid hydrolysis. The term Total Organic Phosphorus includes all organic phosphates measurable following ashing of the sample as described under Analytical Tests and Procedures.

The results of two independently prepared and analyzed complete synthetic sewage batches are shown in Table XIII.

The orthophosphate measurements of the inorganic addition (avg. of $20.6 \pm .5$ mgPO_4/L) indicate that for the inorganic complex phosphate concentration of the synthetic feed, an extraction procedure for elimination of complex phosphate hydrolysis is not required. The small deviation from the 20.0mg/L of orthophosphate added might be attributed to experimental error, orthophosphate present in STPP (approx.0.4%) or TSPP

TABLE XIII

PHOSPHATE FORMS OF THE COMPLETE SYNTHETIC SEWAGE
(All expressed as mg PO_4/L)

Reported	Phosphate Form	Batch 1	Batch 2
42.2± .8	Total Phosphate	42.8± .9	41.6± .8
31.0± .6	Total Orthophosphate	31.0± .6	30.9± .6
---	Inorganic Addition Contribution	20.4± .5	20.8± .5
---	Organic Component Contribution	10.6± .2	10.1± .2
6.5± .1	Inorganic Complex Phosphate	6.5± .1	6.6± .1
4.7± .1	Total Organic Phosphate	5.3± .1	4.1± .1

(approx. 0.1%), and any complex phosphate hydrolysis prior to the initiation of the orthophosphate determinations.

Total Nitrogen

The total Kjeldahl nitrogen concentration of the complete synthetic sewage was 57.1 mg N/L.

ACTIVATED SLUDGE ACCLIMATION

Delays in arrival of equipment for the bench-scale pilot plant led to a decision to develop in advance a sludge acclimated to the synthetic sewage and high BOD loading rates. Need for the latter was suggested by the work of McNicholas and Tench (38) who during high rate activated sludge field studies found that a great deal of time was necessary to establish adequate purification after seeding with sludge from lower rate plants.

To simulate continuous operation, 2.5 L/day of concentrated feed were pumped into a five-liter aeration tank by means of the timer operated pump described for sludge wasting in the bench-scale plant.

Regular wasting of the mixed liquor was effected through overflow displacement caused by the incoming feed. The apparatus is shown in Figure 7.

The feed was a 24 fold concentration of the formulation presented in Table VIII minus the LAS, TSPP, and STPP. This strength was selected to produce in the acclimation unit both an organic loading and solids age approximating those to be used later in the 60 L/day pilot plant. In addition, 10 ml of Pasveers' buffer[1] were added per liter of concentrated feed.

Operation of the acclimation unit was started by adding to the aeration tank five liters of concentrated return sludge from the first stage aerator of The Pennsylvania State University activated sludge plant. Adaptation of the sludge was continued for 76 days before it was used for seeding the then completed pilot plant.

PILOT PLANT OPERATIONAL PROCEDURES

Synthetic Sewage and Chemical Preparation

Fresh feed was prepared every 24-36 hours. Any remaining sewage was wasted and the carboy was brushed and placed aside to dry. The new batch was made in a clean standby container. Polyphosphates were added to the feed in dry form to eliminate the hydrolysis which occurs in aging stock solutions.

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[1]Pasveers' buffer (47) -200 g K_2HPO_4/L and 50 g KH_2PO_4/L.

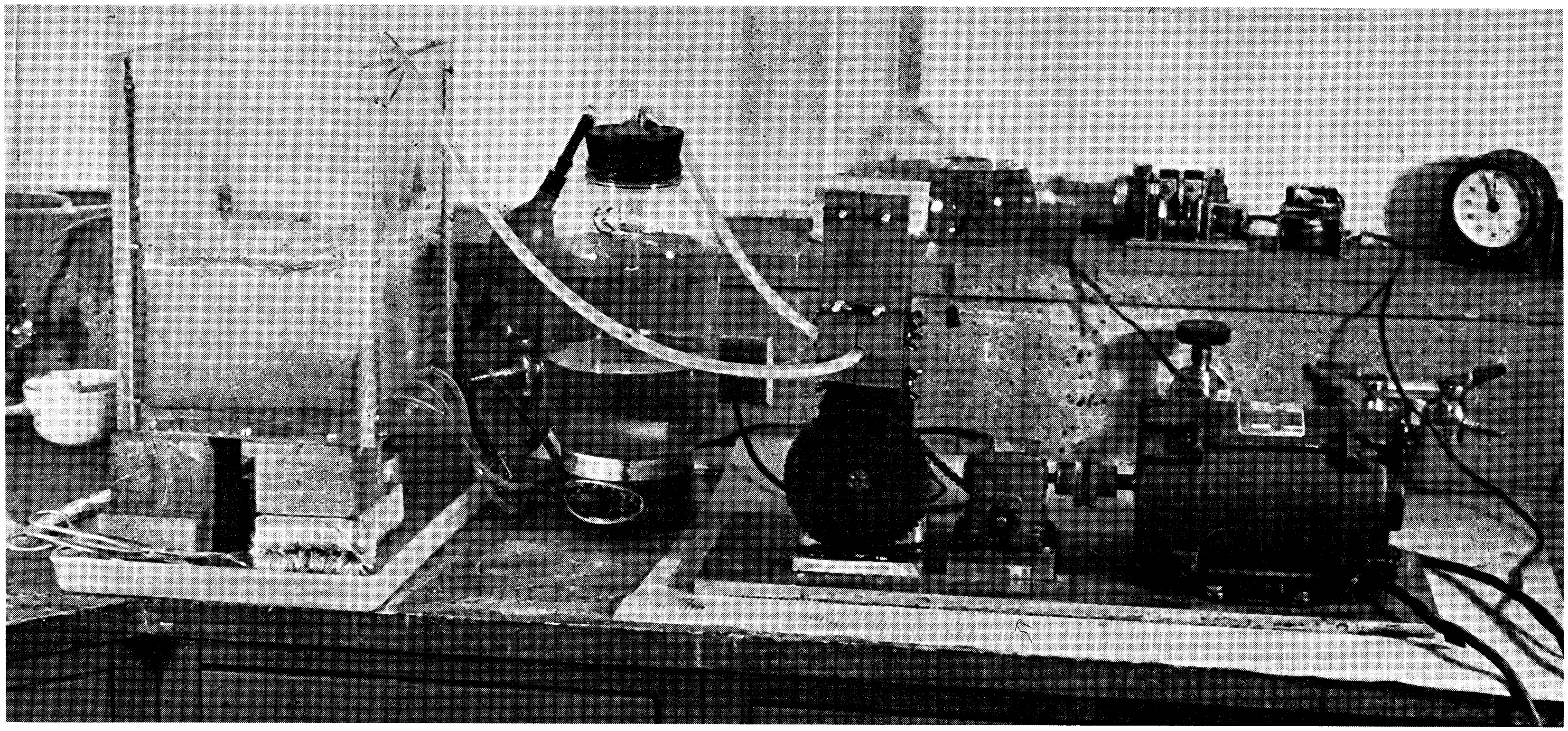

Figure 7. Activated sludge acclimation unit.

A new solution of reagent grade aluminum sulfate[1] ($Al_2(SO_4)_3 \cdot 18H_2O$) was made every two days since it has been reported (63) that aged aluminum stock solutions show a reduced tendency to react with phosphates. The acid and alkali used during periods of continuous pH control were, respectively, 0.1N reagent grade solutions of H_2SO_4 and NaOH.

pH Control

Where employed, pH control was maintained by a combination of feed adjustment and the continuous pH recorder-controller system. The pH amplifier of this system was standardized by suspending the electrodes of a standardized Beckman Zeromatic pH meter in the same basin housing the controller electrodes and adjusting the recorder to the pH indicated by the Zeromatic. The dead span of the recorder-controller was $\pm$ 0.25 pH units of the pH set point.

Sludge Wasting

Using the timer operated pump described earlier, excess sludge was, for purposes of control, semi-continuously wasted directly from the aeration tank. Because of complete mixing conditions, the accompanying supernatent was essentially identical to the clarified effluent. The weight of sludge wasted in this manner was computed from the daily volume of wasted mixed liquor and the average MLSS and MLVS concentrations over the wasting period.

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[1] Throughout this dissertation aluminum sulfate is $Al_2(SO_4)_3 \cdot 18H_2O$.

Mixed Liquor Solids Balance Procedure and Sludge Production Calculations

Procedure 1. Two different procedures for performing a system solids balance were used. In both, and where applicable, the mixed liquor solids concentrations in the aeration, mixing, and flocculation basins were assumed equal. The weight of solids contained in these basins was computed from the solids concentration and the measured working volumes. During the first 33 days of plant operation, the weight of solids in the sedimentation basin was assumed constant from balance to balance. Effluent solids losses were computed on the basis of effluent volume and average solids concentrations over the balance period. In this first procedure, solids production was calculated as the sum of the solids wasted, effluent solids, and solids lost through sampling plus or minus any net change in the weight of solids contained in the system. Because significant variation in production data resulted under conditions of almost constant BOD removal, a more refined procedure was used during the remaining 323 days of the synthetic sewage work.

Procedure 2. The new procedure, unlike the first, accounted for the actual weight of solids in the clarifier. An aeration basin sample was withdrawn for determining the solids concentration of the aeration, mixing, and flocculation basins. Thereafter, the aeration basin and, where applicable, the mixing and flocculation basins were isolated from the system by clamps and the clarifier solids were pumped to the aeration basin. Finally, a second sample was withdrawn from the aeration basin. By applying the appropriate volumes to the determined solids concentrations, the total system solids were calculated. Except for the fact that the total system solids included those in the clarifier, solids production was calculated as outlined in the first procedure. This improved technique produced more reliable production data.

Reported Mixed Liquor Solids and Solids Age

Because of significant variations in the weight of solids contained in the clarifier, two mixed liquor solids parameters are reported.

Theoretical MLSS, MLVS--The total weight of system solids divided by the total aeration volume (including mixing and flocculation basin volumes where applicable).

Working MLSS, MLVS--The concentrations measured prior to returning the clarifier solids to the aeration basin.

Theoretical values are used for run comparisons whereas the working parameter is used for kinetics.

Solids age is defined consistently throughout this study as the quotient of the total system volatile solids divided by the total volatile solids produced per day and, therefore, wasted at equilibrium.

BIOLOGICAL CONTROL RUN

Investigation Procedure

General. The activated sludge from the acclimation unit was transferred to the bench-scale pilot plant. Although there was no aluminum sulfate addition during this run, PS1 employing the mixing and flocculation basins was used.

There was no pH control during the first 84 days of the 93 day run. The pH, however, gradually stabilized at approximately 5.5. For the last nine days of the run, the pH control system was actuated to maintain this pH since operation at 5.5 was to be evaluated during the subsequent chemical precipitation investigations.

Analytical measurements performed during this run[1] included MLSS, MLVS, SVI, sludge production, system temperature and effluent SS, VS, COD, BOD_5, pH, LAS and oxidized nitrogen. In addition, the phosphorous content of the mixed liquor solids was determined to enable computation of the biological removal of phosphorus.

LAS Study. Table XV includes the applied LAS dosages. Starting on the eighth day of SS-CR, the influent concentration was incrementally increased from zero to 12.5 mg/L. A nine-day period of acclimation preceded the measurement of effluent residuals. Removal efficiencies were determined for influent levels of 3,5,7.5,10 and 12.5 mg/L.

A chloroform blank was used for effluent MBAS determinations. The effluent levels reported, therefore, may partially reflect the presence of MBAS substances other than LAS.

Synthetic Sewage. Relative to the composition of Table VIII, 0.139 ml of Pasveers' phosphate buffer[2] were added per liter and TSPP and STPP were omitted. Including all contributions, the total phosphate concentration of the feed was approximately 36 $mgPO_4/1$. The LAS concentration was varied as required for the LAS removal studies. Accordingly, the BOD_5's and COD's differed slightly from those given in Table 10 and ranged from 194-198 mg/L and 372-386 mg/L, respectively.

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[1]Hereafter coded SS-CR.

[2]Pasveers' buffer (47) -200 g K_2HPO_4/L and 50 g KH_2PO_4/L.

General Results and Discussion

Operation and Performance. Figure 8 reveals that although the plant received a constant rate of influent feed having little variation in strength, true steady-state operation was never achieved. The directly correlated and cyclic variations in SVI and effluent solids were regularly associated with changes in the activated sludge protozoan population. This is in accord with the conclusion of Cassel, et al. (7) that continuous mixed culture systems are dynamic in nature, contrary to the common assumption of steady-state.

Table XIV summarizes the organic loadings, effluent quality, and performance of SS-CR. The loadings of 110 lb. $BOD_5/1000\ ft^3$/day and 0.44 lbs BOD_5/lb MLSS/day are significantly higher than those for conventional activated sludge. The unfiltered BOD_5 removal of 87.7 per cent agrees favorably with the HRAS municipal sewage studies of Kehr and v.d. Emde (25). Removals of 87 and 86 per cent, respectively, would be predicted from their work for the above loadings.

The average oxidized nitrogen concentration of the effluent during the last 19 days of the run was 38.0 mgN/l. From the sludge production parameter for this run (see section on sludge production), the BOD_5 removal efficiency (filtered basis), and the assumption of 10 per cent nitrogen in the sludge (Eckenfelder & O'Connor [13] reported a range of 6-15 per cent for active metabolizing sludges), it is approximated that 10.2 mgN/l were removed for synthesis from the synthetic sewage. Therefore, with an influent concentration of 57.1 mgN/l, about 81 per cent nitrification was achieved.

Sludge production data for SS-CR are reported in a later section.

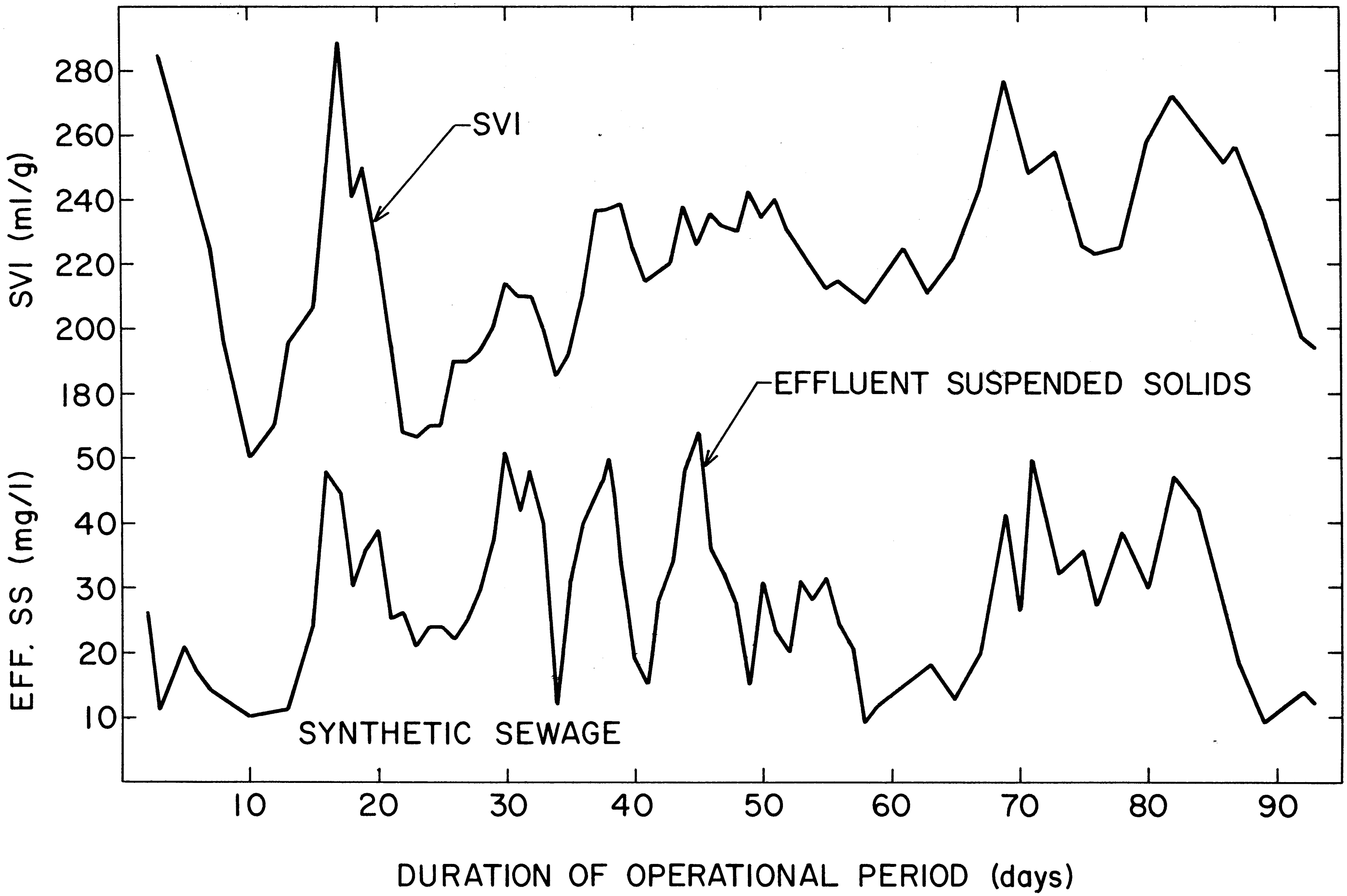

Figure 8. Mixed liquor sludge volume index and effluent suspended solids variations--synthetic sewage biological control run.

TABLE XIV

GENERAL OPERATION AND PERFORMANCE--RUN SS-CR
RUN CODE SS-CR

	Average	Range
Mixed Liquor		
MLSS, mg/L[a]	4,060	---
MLVS, mg/L[a]	3,750	---
%VS	92.4	---
Solids, age, days	5.02	---
SVI, ml/g	220	160-289
Temperature, °C	≅ 23	---
Organic Loadings		
lb BOD_5/1000 ft^3/day	110	109-111
lb BOD_5/lb MLSS/day[b]	0.435	0.431-0.439
lb COD/1000 ft^3/day	213	209-217
lb COD/lb MLSS/day[b]	0.841	0.825-0.857
Effluent Quality and Performance		
Suspended Solids, mg/L	28	9-54
Volatile Solids, mg/L	28	8-54
BOD_5		
Unfiltered, mg/L	24	8-52
% Removal	87.7	---
Filtered, mg/L[c]	4	---
% Removal	98.0	---
COD		
Unfiltered, mg/L	83	21-126
% Removal	78.1	---
Filtered mg/L[d]	43	---
% Removal	88.7	---

[a]Working concentrations.

[b]Based on working concentrations.

[c]Calculation of on page 68.

[d]Unfiltered COD −(1.42)(Eff. VS).

Biological Phosphorus Removal. Using two different methods of analysis, the phosphorus content of the sludge on a volatile solids dry weight basis was found to be 1.68 and 1.72 per cent P. These values are within the range of the experimental findings reported in Table I. On the basis of a 1.70 per cent P content, the BOD_5 removal (filtered), and sludge production during SS-CR, 5.31 mg PO_4/L were removed via synthesis. Considering the influent phosphorus concentration of approximately 36 mg PO_4/L, a removal of 14.7 per cent was possible. With 28 mg/L of effluent solids, however, the actual removal was reduced to 3.85 mg PO_4/L or approximately 10.7 per cent.

LAS Removal Findings

Results and Discussion. Complete LAS and associated BOD_5 data for SS-CR are reported in Table XV. The graphical presentation in Figure 9[1] of these data as well as that for later runs reveals an independence between effluent residual and influent concentration. With reference to SS-CR data only, 76 per cent of the residuals lie within $\pm$ one standard deviation of the mean, 0.25 mg/L. The experimentally determined standard deviation, 0.06 mg/L, agrees with that given by Standard Methods (59) for the concentration range measured.

LAS reductions over SS-CR ranged from 90.0 to 99.2 per cent with a mean of 96.5 per cent. Thus with a theoretical aeration period of only 2.66 hours, and a volumetric organic loading 110 lb BOD_5/1000 ft^3/day, the HRAS process effected LAS removals which compare favorably

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[1] Note that Figures 9 and 10 include all the biological and biological-chemical experimental data for both the synthetic and domestic sewage investigations.

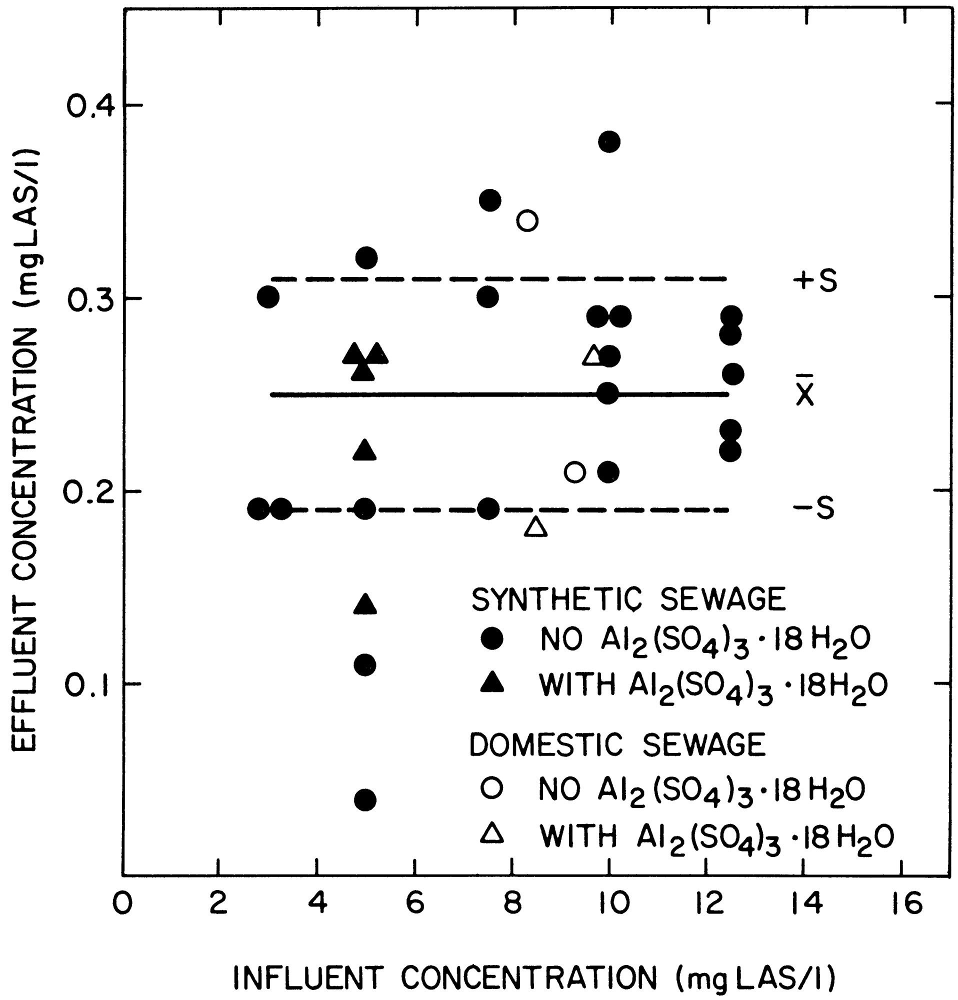
TABLE XV

LAS AND ASSOCIATED BOD_5 PERFORMANCE DATA--RUN SS-CR

Date (1966) Major LAS Study Period[b]	LAS Data			BOD_5[a]	
	Inf. (mg/L)	Eff. (mg/L)	Removal (%)	Eff. (mg/L)	Removal (%)
4/14-19	1.0	--	--	11	94.2
4/20-21	3.0	--	--	16	91.8
4/22	"	0.30	90.0	--	--
4/23-24	"	--	--	--	--
4/25	"	0.19	93.7	--	--
4/26	"	0.19	93.7	37	81.0
4/27	5.0	--	--	--	--
4/28	"	0.04	99.2	20	89.8
4/29	"	--	--	--	--
4/30	"	0.11	97.8	17	91.3
5/1	"	--	--	--	--
5/2	"	0.19	96.2	--	--
5/3	7.5	0.35	95.3	18	90.9
5/4	"	0.19	97.5	--	--
5/5	"	0.30	96.0	28	85.8
5/6	10.0	0.27	97.3	--	--
5/7	"	0.29	97.1	18	90.9
5/8	"	--	--	--	--
5/9	"	0.38	96.9	--	--
5/10	"	0.25	97.5	--	--
5/11	"	--	--	--	--
5/12	"	0.21	97.9	--	--
5/13	"	0.29	97.1	--	--
5/14-24	"	--	--	16	91.8
5/25	12.5	0.22	98.3	--	--
5/26	"	0.23	98.2	--	--
5/27	"	0.29	97.7	16	91.9
5/28	"	0.26	97.9	--	--
5/29	"	0.28	97.8	--	--
7/2	5.0	0.32	93.8	24	88.7

[a]Unfiltered effluent.

[b]Major LAS study period (4/14-5/29)



$\bar{x}$ = mean value of all effluent concentrations

+s,-s = one standard deviation of the mean

Figure 9. Effluent LAS residual as related to influent LAS concentration--complete synthetic sewage and domestic sewage investigations.

with those reported (see Table IV, p. 20) for processes having greater aeration periods (3.6-48 hours) and lower loadings (5.6-30 lb BOD_5/1000 ft^3/day). It is apparent that the high performance resulted from the maintenance of high MLSS concentrations. This is illustrated by a comparison with the data of Klein and McGauhey (27). Under operating conditions of about 84 lb BOD/1000 ft^3/day and 2.8 hours aeration, they reported MBAS reductions of only 68.8 per cent. Their solids loading, however, was approximately 2.11 lb BOD/lb MLSS/day in comparison to 0.44 for SS-CR.

With the near constancy of effluent residuals during SS-CR, percentage removals generally increased directly with influent concentrations. This is shown in Figure 10 where the curve drawn represents percentage removal for a constant effluent level of 0.25 mg/L. Associated BOD_5 removals averaged 89.8 (unfiltered) and 98.0 (filtered) per cent. The filtered effluent per cent removal ratio, LAS/BOD_5, was, therefore, 0.98 indicating that LAS and BOD_5 removals are essentially identical. This observation is in accord with the work of others (see Table IV) who reported unfiltered ratios ranging from 0.9 to 1.2.

That LAS removals generally approximate those of BOD explains the consistency of effluent LAS residuals during the present study. While greater than a four-fold increase in influent LAS was experienced, the peak LAS BOD_5 contribution represented only about two per cent of the total load. With the system consistently assimilating about 98 per cent of the influent BOD_5, it should have had little difficulty in effecting near-complete loss of surfactant identity as well as degradation of the imposed additional organic loads.

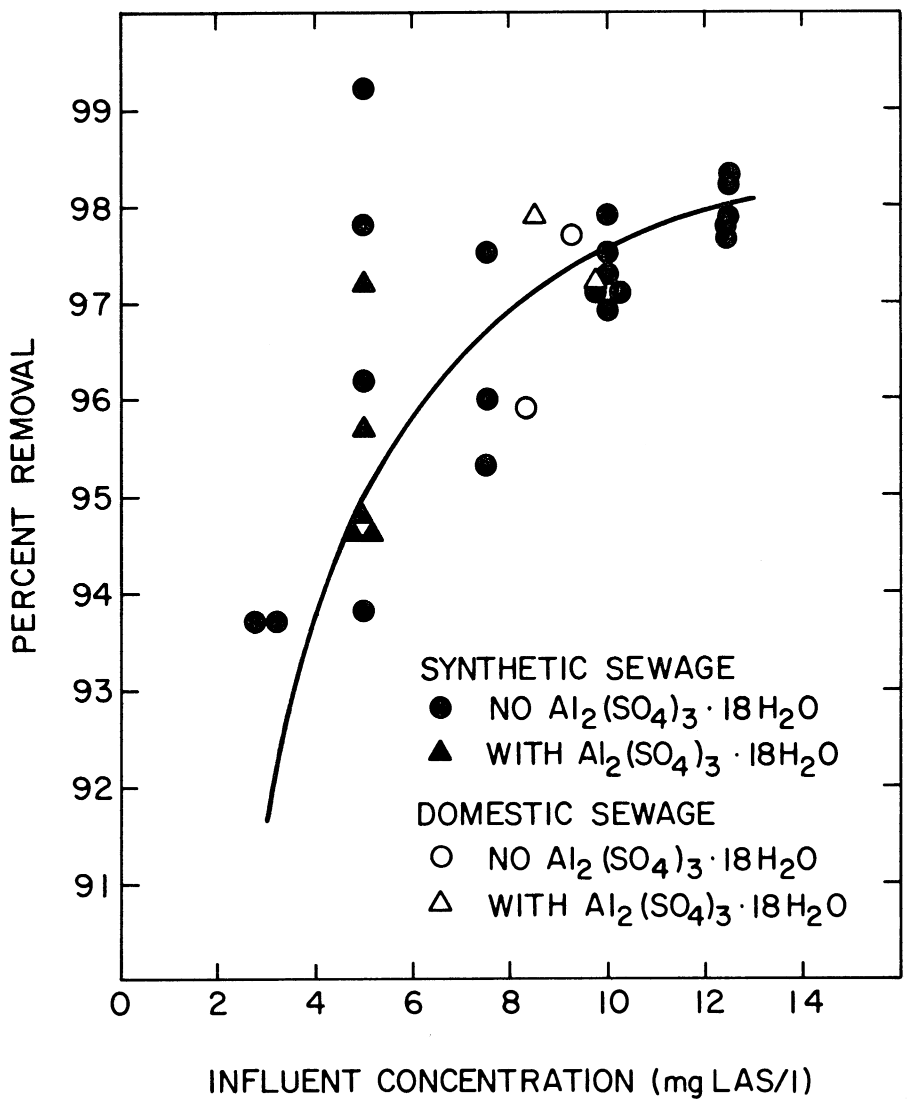


Figure 10. A comparison of observed per cent LAS removals with calculated removals based on a constant residual of 0.25 mgLAS/L--complete synthetic sewage and domestic sewage investigations.

At no time during the investigation did the LAS cause significant foaming. Apparently the combination of a complete mixing system coupled with the high MLSS concentrations resulted in an almost instantaneous uptake of influent LAS.

BIOLOGICAL-CHEMICAL RUNS

Investigation Procedure

As indicated earlier, there were two phases to this work--SS Phase 1 employing PS1, and SS Phase 2 employing PS2.

SS Phase 1. Aluminum sulfate addition was started after 93 days of biological operation during SS-CR. The investigations were initiated at a flocculation pH of 5.5 since the activated sludge had been previously acclimated to this pH during SS-CR. It is emphasized that during employment of PS1, the pH referred to is always that of the flocculation basin. Aeration tank pH's were higher by approximately 0.5-1.0 units. During the pH 5.5 operation, Al:P (molar ratio) dosages of 1:1 and 1.5:1 (149 and 224 mg aluminum sulfate per liter, respectively) were investigated.

An increase in pH to 6.5 was carried out in 0.5 pH unit steps. The complete adaptation period covered 30 days or approximately 10 solids ages. At pH 6.5, Al:P dosages of 1.5:1 and 1.75:1 (224 and 261 mg aluminum sulfate per liter) were studied. Successful results at the latter application suggested a need for a similar study at pH 5.5.

The pH was reduced in 0.5 units to 5.5 over a 22-day period or about six solids ages. Following the 1.75 Al:P study at pH 5.5, SS Phase 2 was initiated.

SS Phase 2. As noted earlier, during employment of PS2 chemicals were added directly to the increased volume aeration tank and the mixing and flocculation basins were by-passed. The Al:P ratio and operation pH were maintained, respectively, at 1.75 and 5.5. Under PS2, the pH differential of PS1 was eliminated.

General. With one exception, all the SS-pH-Al:P[1] runs were of 30 or more days duration. The exception, SS-PS1-5.5-1:1[1], was ended after nine days of equilibrium because the chemical dosage was obviously inadequate.

Analyses performed included MLSS, MLVS, SVI, sludge production,[2] system temperature, and effluent oxidized nitrogen, LAS, BOD_5 (unfiltered), COD (unfiltered and filtered), SS, VS, and ortho and total phosphorus on both unfiltered and filtered samples.

Synthetic Sewage. Component concentrations not indicated in Table VIII, but used throughout all the chemical precipitation runs follow:

LAS, mg/L	5.0
Phosphate Buffer (KH_2PO_4), mg/L	28.66
STPP, mg/L	3.23
TSPP, mg/L	3.45

The resulting phosphorus concentrations were those given in Table XIII. The BOD_5 and COD were 196 and 378 mg/L, respectively.

[1]This designation will hereafter be used for run identification, i.e., Synthetic Sewage, Process Scheme 1, pH 5.5, and Al:P=1.5:1 will be coded SS-PS1-5.5-1.5:1. The Domestic Sewage runs will later be coded DS-etc. This coding is explained in greater detail in the List of Symbols.

[2]Improved solids balance procedure used.

Results and Discussion--SS Phase 1

Organic Loadings. It will be later illustrated, particularly in the section on sludge production, that the chemical precipitation produced an increase in both inorganic and volatile mixed liquor solids. It was considered desirable, however, to report organic solids loadings on the same basis used commonly in the literature and during SS-CR--i.e., lb BOD_5/lbMLSS/day where the MLSS represents primarily biological solids. This was accomplished using EQ. 9 derived as follows:

Conditions and Assumptions.

1. Total aeration volume constant for the biological and biological-chemical systems.
2. Biological solids production versus solids age relationship identical for both systems.
3. Mixed liquor and wasted solids relative to each system are identical homogeneous mixtures of biological and chemical solids.

Let

$$LF = \frac{\text{Wt. } BOD_5 \text{ applied per unit time}}{\text{Wt. system } MLSS_{Biol.}} \qquad (2)$$

where Wt. BOD_5 applied per unit time = B

Wt. system $MLSS_{Biol.}$ = M

$$SA = \frac{\text{Wt. solids in system}}{\text{Wt. solids prod. per unit time}} \qquad (3)$$

where because of homogeneity, the solids parameter used may be MLSS or MLVS

and $SA_{Biol.} = SA_{Chem.} = SA$ (4)

Therefore

$$LF = \frac{B}{SA \times \text{Wt. } MLSS_{Biol.} \text{ prod. per unit time}} \qquad (5)$$

Now

Wt. $MLSS_{Biol.}$ prod. per unit time per Wt. BOD_5 removed can be approximated over a short SA range by

$$c_1 SA^n \qquad (6)$$

where n = slope of Figure 16 = 0.379
c_1 = intercept of Figure 16

Then

$$c_1 SA^n R = \text{Wt. } MLSS_{Biol.} \text{ prod. per unit time} \qquad (7)$$

where R = Wt. BOD_5 removed based on filtered effluent

Therefore

$$LF = \frac{B}{SA \times c_1 SA^n R} = \frac{B}{c_1 R SA^{1+n}} \qquad (8)$$

Finally

$$\frac{LF_{CPR}}{LF_C} = \frac{B_{CPR}\ R_C}{B_C\ R_{CPR}} \times \left(\frac{SA_C}{SA_{CPR}}\right)^{1+n} \qquad (9)$$

where CPR = Biological-chemical system
C = Biological system

Now

for the synthetic sewage investigations

$B_{CPR} = B_C$

$R_{CPR} = R_C$

$SA_C = 5.02$

$LF_C = 0.435$

Substituting

$$LF_{CPR} = 0.435 \left(\frac{5.02}{SA_{CPR}}\right)^{0.62} \qquad (10)$$

The conditions and assumptions listed were met or approximated during the biological and biological-chemical runs. Accordingly, the organic solids loadings listed in Tables XVI and XXI were computed using EQ. 10.

TABLE XVI

ORGANIC BIOLOGICAL LOADINGS--SS PHASE 1

Run Code	Organic Loading: Volumetric ($lbBOD_5/1000ft^3/day$)	Organic Loading: Solids ($lbBOD_5/lbMLSS_{Biol}/day$)
pH 5.5		
SS-PS1-5.5-1:1	110	0.53
SS-PS1-5.5-1.5:1A	110	0.56
SS-PS1-5.5-1.5:1B	110	0.62
SS-PS1-5.5-1.75:1	110	0.52
pH 6.5		
SS-PS1-6.5-1.5:1	110	0.52
SS-PS1-6.5-1.75:1	110	0.58

Table XVI reveals that the organic solids loadings during the chemical precipitation runs were all significantly greater than conventional loadings. In addition, they exceeded that of SS-CR because of the lower solids ages maintained.

Pilot Plant Operating Conditions. The operating conditions for the SS Phase 1 runs are shown in Table XVII. It is seen that high MLSS concentrations (6,080-9,110) were maintained. This resulted not only from HRAS operation but, also from a build-up of chemically precipitated solids. Figure 11, representing the first chemical run (SS-PS1-5.5-1:1) subsequent to SS-CR, illustrates the increase in inorganic suspended solids (IS) which followed the start-up of chemical feeding. The inorganic solids during SS Phase 1 ranged from 29.1 to 34.6 per cent as

TABLE XVII

AVERAGE PILOT PLANT OPERATING CONDITIONS--SS PHASE 1

Run Code	Days of Operation	MLSS[a] (mg/L)	MLVS[a] (mg/L)	Per Cent Volatile Solids	Solids Age (days)	SVI[b] (ml/g)	System[c] Temperature (°C)
pH 5.5							
SS-PS1-5.5-1:1	9	6,080	4.310	70.9	3.63	35	26.6
SS-PS1-5.5-1.5:1A	44	7,420	4,950	66.8	3.35	65	26.2
SS-PS1-5.5-1.5:1B	20	6,940	4.610	66.4	2.85	--	22.7
SS-PS1-5.5-1.75:1	30	9,110	6.130	67.2	3.81	25	21.8
pH 6.5							
SS-PS1-6.5-1.5:1	31	7,990	5,230	65.4	3.72	33	23.1
SS-PS1-6.5-1.75:1	31	8,270	5,600	6.77	3.19	113	22.2

[a]Theoretical--Calculated on the basis of total solids in system and 6.66 liters total aeration volume.

[b]Spot-check determinations.

[c]Recorded between 9 and 11 a.m.

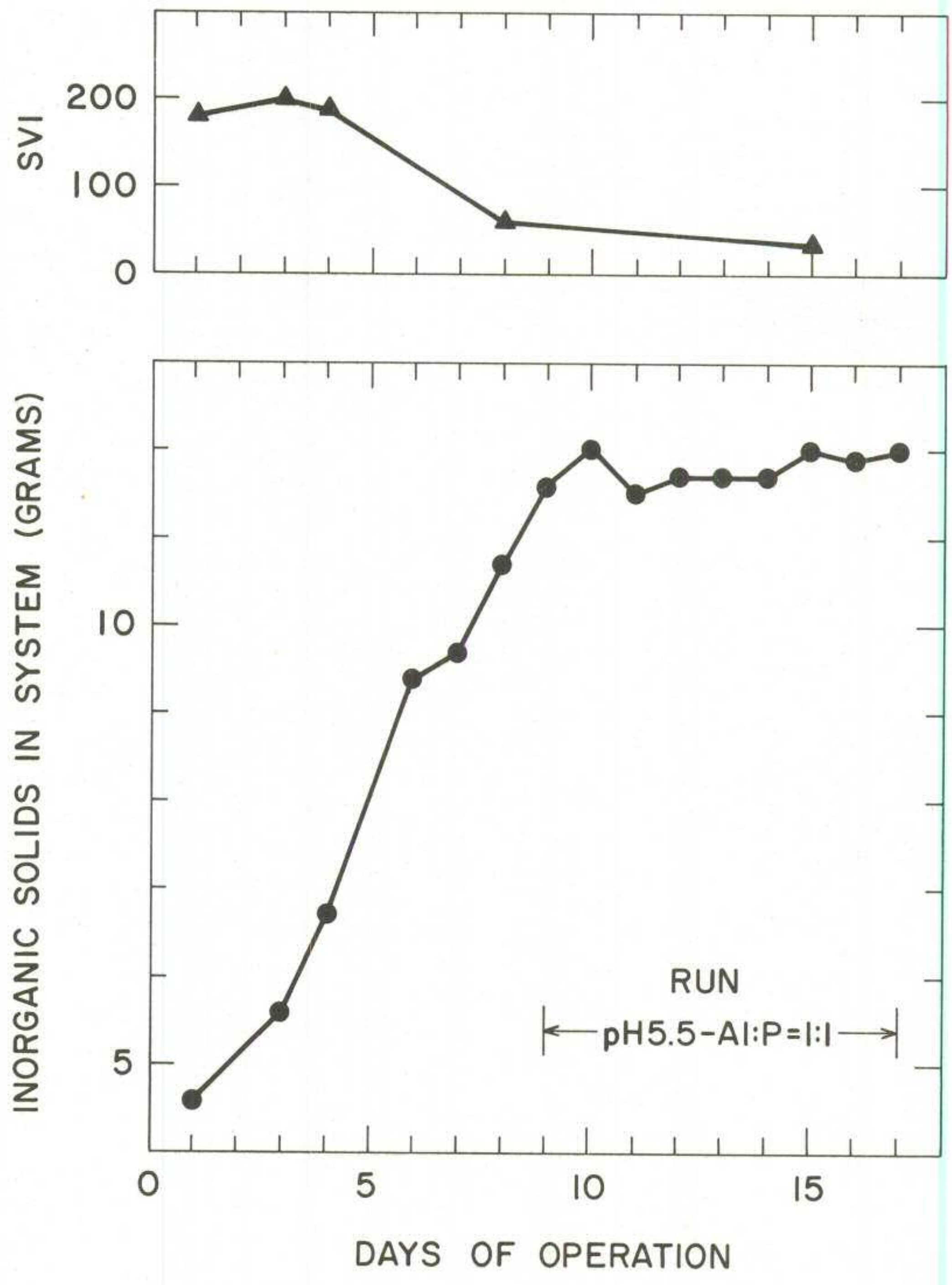


Figure 11. Mixed liquor inorganic solids and sludge volume index changes upon addition of aluminum sulfate--Run SS-PS1-5.5-1:1, SS Phase 1.

compared to 7.6 per cent during SS-CR. In addition, as will be discussed later in the section on sludge production, there was an increase in apparent non-biological volatile solids.

Figure 11 also shows that the addition of aluminum sulfate and subsequent IS build-up decreased the SVI from 180 to 35. Table XVII reveals that throughout the chemical runs the SVI remained significantly below the average of 220 for SS-CR. In general, the compactness of the settled sludge was greater at pH 5.5 than at 6.5. This was evidenced by an increased accumulation of clarifier solids during the latter runs. During SS-PS1-6.5-1.75:1, the high MLSS concentration and relatively high SVI produced a build-up which submerged the basin inlet, thus converting the clarifier into a modified solids contact unit.

General Effluent Quality. The data of Table XVIII reveal that the effluent suspended solids concentrations were highly variable for several runs. As experienced during SS-CR, this variation was frequently cyclic and usually associated with observed protozoan population dynamics. Figure 12 illustrates the effluent solids variation for SS-PS1-5.5-1.5:1A. As shown, the fluctuations were decreased during SS-PS1-5.5-1.5:1B when the solids age was reduced by one half day. Effluent solids levels were also reduced throughout SS-PS1-5.5-1.75:1 and SS-PS1-6.5-1.75:1 by increased aluminum sulfate. Biological fluctuations, however, were still apparent. During SS-PS1-6.5-1.75:1, the extremely low average concentration (6.0 mg SS/L) was believed to be partially a result of filtration by the aforementioned clarifier solids blanket.

TABLE XVIII

GENERAL PERFORMANCE AND EFFLUENT QUALITY--SS PHASE 1

Run Code	Suspended Solids: Total Avg. (mg/L)	Suspended Solids: Total Range (mg/L)	Suspended Solids: Volatile Avg. (mg/L)	BOD_5 Unfiltered Range (mg/L)	BOD_5 Unfiltered Avg. (mg/L)	BOD_5 Unfiltered % Rem	COD Filtered[a] Avg. (mg/L)	COD Filtered[a] % Rem	Oxidized Nitrogen Avg. (mgN/L)
pH 5.5									
SS-PS1-5.5-1:1	38	23-57	29	7-20	15	92.3	22[b] (52)	94.2	2.4
SS-PS1-5.5-1.5:1A	53	12-161	38	7-20	13	93.3	26 (60)	93.1	2.3
SS-PS1-5.5-1.5:1B	20	9.0-37	16	8-13	11	94.4	17 (37)	95.5	1.8
SS-PS1-5.5-1.75:1	21	9.0-40	15	4-16	11	94.4	10 (23)	97.3	1.3
pH 6.5									
SS-PS1-6.5-1.5:1	62	7.0-97	41	11-34	23	88.3	29 (75)	92.3	40.9
SS-PS1-6.5-1.75:1	6.0	0.5-31	4.5	2-10	5	97.4	6 (8)	98.4	38.9

[a]Unfiltered average COD's are shown in brackets.

[b]Soluble COD for this run only was estimated.

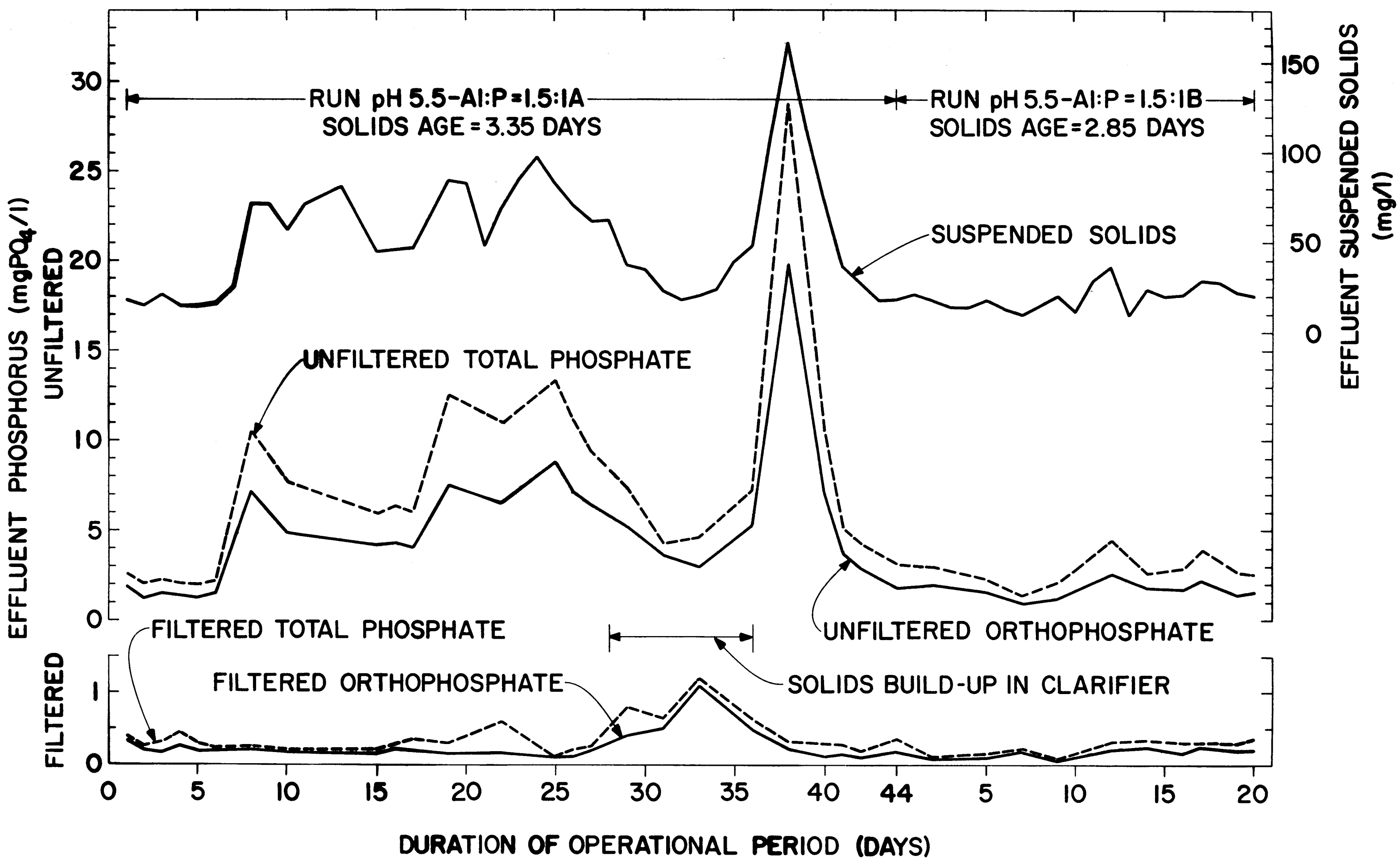


Figure 12: Effluent phosphorus and suspended solids variations during runs SS-PS1-5.5-1.5:1A and SS-PS1-5.5-1.5:1B--SS Phase 1.

Of the six runs shown in Table XVIII, the ranges of average unfiltered BOD_5 and soluble COD removals were 88.3-97.4 per cent and 92.3-98.4 per cent, respectively. The BOD_5 removals all exceeded the 87.7 per cent of SS-CR.

It was considered of value to closely estimate the soluble BOD_5 residuals which had not been determined. A plot of effluent unfiltered BOD_5 versus effluent biological solids was constructed. The VS values in Table XVIII were not considered a good measure of biological mass for reasons indicated under Sludge Production. A reasonable parameter calculated as follows was used:

$$\text{Eff. } VS_{Biol} \cong (\text{Eff. } COD_{Total} - \text{Eff. } COD_{Soluble})/1.42^{1} \qquad (11)$$

Figure 13 includes the average data for all the SS Phase 1, SS Phase 2 and SS-CR runs. It is evident that a good approximation of the average soluble BOD_5 for all the synthetic sewage investigations is 4 mg/L. Accordingly, the BOD_5 removal (filtered basis) for all the runs was approximately 98 per cent and a significant fraction of each of the reported unfiltered BOD_5's resulted from effluent biological solids.

It can also be concluded from Figure 13 that the aluminum sulfate addition did not effect any appreciable soluble BOD removal. This is further evidenced in Table XVIII which indicates that only a small fraction of the soluble COD was possibly removed chemically. This is in agreement with observations by Tenney (64).

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[1] 1.42 mg oxygen are required for the complete carbonaceous oxidation of one mg of typical activated sludge cells (13).

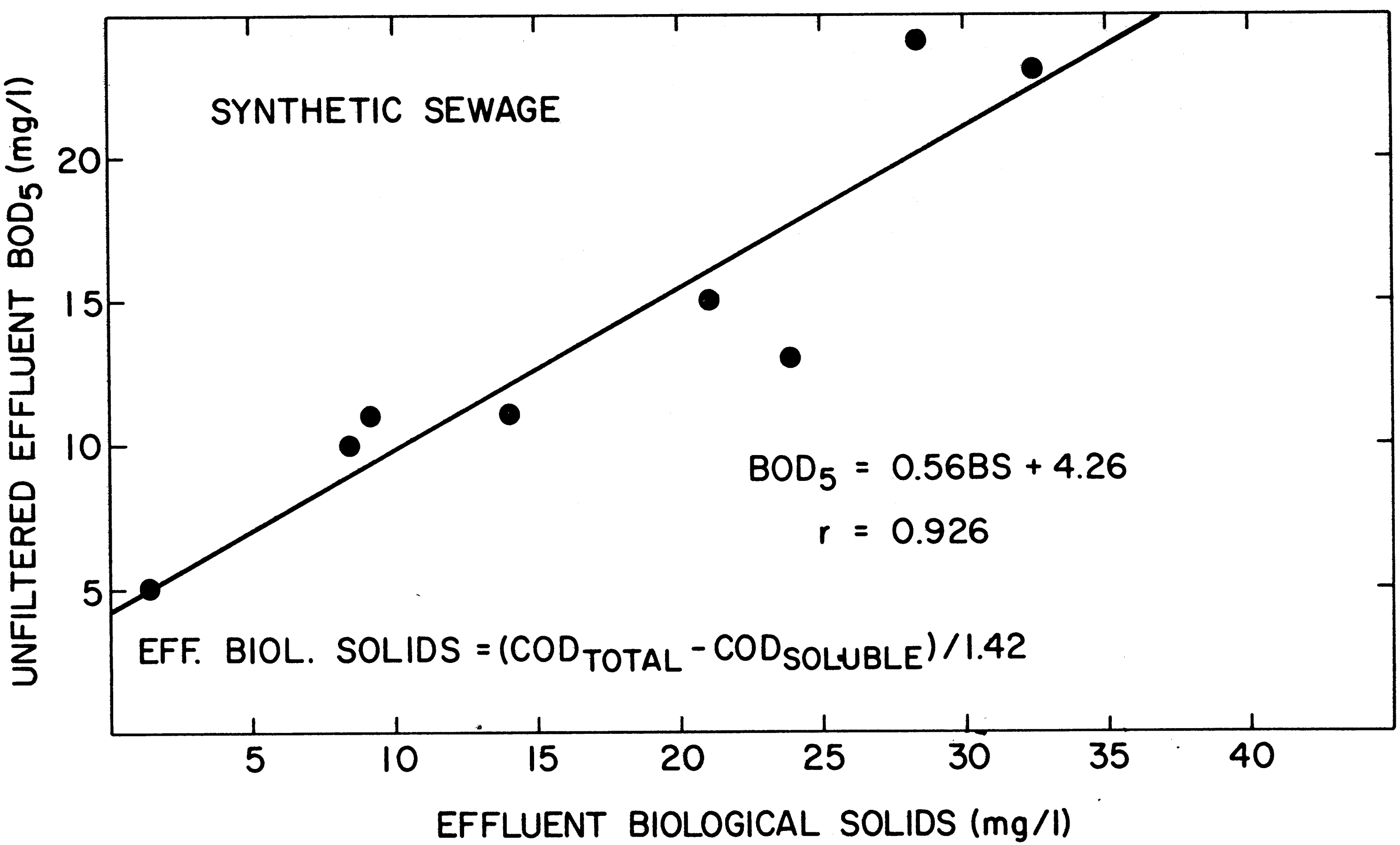

Figure 13. Unfiltered effluent BOD_5 as a function of effluent biological solids--complete synthetic sewage investigations.

It is seen in Table XVIII that whereas a highly nitrified effluent was produced during the pH 6.5 runs, nitrification was retarded during the pH 5.5 work. In addition, intra-pH data reveal a trend of decreasing nitrification with increasing aluminum sulfate dosage. Further, it will be recalled that during the last 19 days of SS-CR with no chemical precipitation and a pH range of 5.25-5.74, the average effluent oxidized nitrogen concentration was 38.0 mgN/L. An integrated analysis of all these data as well as those of SS Phase 2 and the pH acclimation periods, suggests a possible inhibitory synergistic effect between pH and aluminum sulfate on nitrification.

Performance data on LAS removal during both SS Phases 1 and 2 are found together in a later section.

<u>Filtered Effluent Phosphorus</u>. The data in Table XIX reveal the capability of this process operating at pH 5.5 with Al:P equal to or exceeding 1.5:1 and followed by filtration to remove consistently more than 99 per cent of the total influent phosphorus. Not only is the percentage removal high, but effluent residuals approximate the minimum attainable for the chemical equilibria involved. For example, on the basis of an assumption that $AlPO_4$ represents the bulk of the phosphate precipitate present and the six equilibria $AlPO_4$ solubility diagram by Stumm (63), the minimum attainable orthophosphate concentration is approximately 0.05 $mgPO_4$/L. The average orthophosphate residual of SS-PS1-5.5-1.75:1 was 0.08 $mgPO_4$/L.

Considering the influent concentration of inorganic complex phosphorus, 6.5 $mgPO_4$/L, it is evident from the data that excellent hydrolyzable phosphate removals were effected. For Al:P ratios of 1.5:1 or higher, the efficiencies were 98 per cent or greater.

TABLE XIX

FILTERED EFFLUENT PHOSPHORUS AND RELATED PERFORMANCES--SS PHASE 1

Run Code	$Al_2(SO_4)_3 \cdot 18H_2O$ (mg/L)	Orthophosphate Range ($mgPO_4/L$)	Orthophosphate Avg. ($mgPO_4/L$)	Total Phosphate Range ($mgPO_4/L$)	Total Phosphate Avg. ($mgPO_4/L$)	Per Cent Removal
pH 5.5						
SS-PS1-5.5-1:1	149	2.5-4.7	3.8	2.9-5.7	4.5	89.3
SS-PS1-5.5-1.5:1Aa	224	0.10-1.1	0.25	0.21-1.2	0.38	99.1
SS-PS1-5.5-1.5:1Ab[a]	224	0.10-0.37	0.18	0.21-0.60	0.29	--
SS-PS1-5.5-1.5:1B	224	0.06-0.25	0.17	0.07-0.36	0.25	99.4
SS-PS1-5.5-1.75:1	261	0.02-0.22	0.08	0.07-0.29	0.14	99.7
pH 6.5						
SS-PS1-6.5-1.5:1	224	0.26-0.85	0.58	0.26-0.95	0.65	98.4
SS-PS1-6.5-1.75:1	261	0.20-0.46	0.37	0.26-0.64	0.49	98.8

[a]Excludes data for nine-day clarifier solids build-up period.

In Table XIX two sets of data are given for SS-PS1-5.5-1.5:1A to demonstrate the effect of clarifier sludge retention time on soluble phosphorus residuals. During a nine-day period, solids accumulated in the clarifier because of sludge bulking. As a result, the soluble phosphorus residual increased markedly--see Figure 21 as well as Table XIX. This observation is in agreement with Levin, et al. (33). In the discussion which follows, the data excluding this period will be used.

Figure 14[1] demonstrates the effect of aluminum dosage on the filtered or soluble phosphorus residuals. It is apparent that for the conditions of this work an Al:P ratio significantly greater than one was required for essentially complete removals. This observation is in accord with findings of others. Work reported by Tenney (64) during simultaneous removal of phosphate and microorganisms by aluminum indicates that an Al:P ratio of approximately 3.5 was required to produce a soluble orthophosphate residual of 0.5 $mgPO_4/L$. Campbell (Campbell, Rensselaer Polytechnic Institute, personal communication) working with phosphorus solutions observed need for Al:P ratios significantly greater than one to effect low residuals. Henrikson (21) reported that molar capacity ($mMPO_4$ removed per mM coagulant cation added) decreases rapidly for removal efficiencies greater than 90%. Aluminum hydrolysis (61), the requirement of aluminum hydroxo-polymers for cell flocculation (64), and the formation of aluminum hydroxy phosphates having Al:P molar ratios greater than one (see section on sludge production) were probably

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[1]Figure 14 includes the data of SS-PS2-5.5-1.75:1--SS Phase 2.

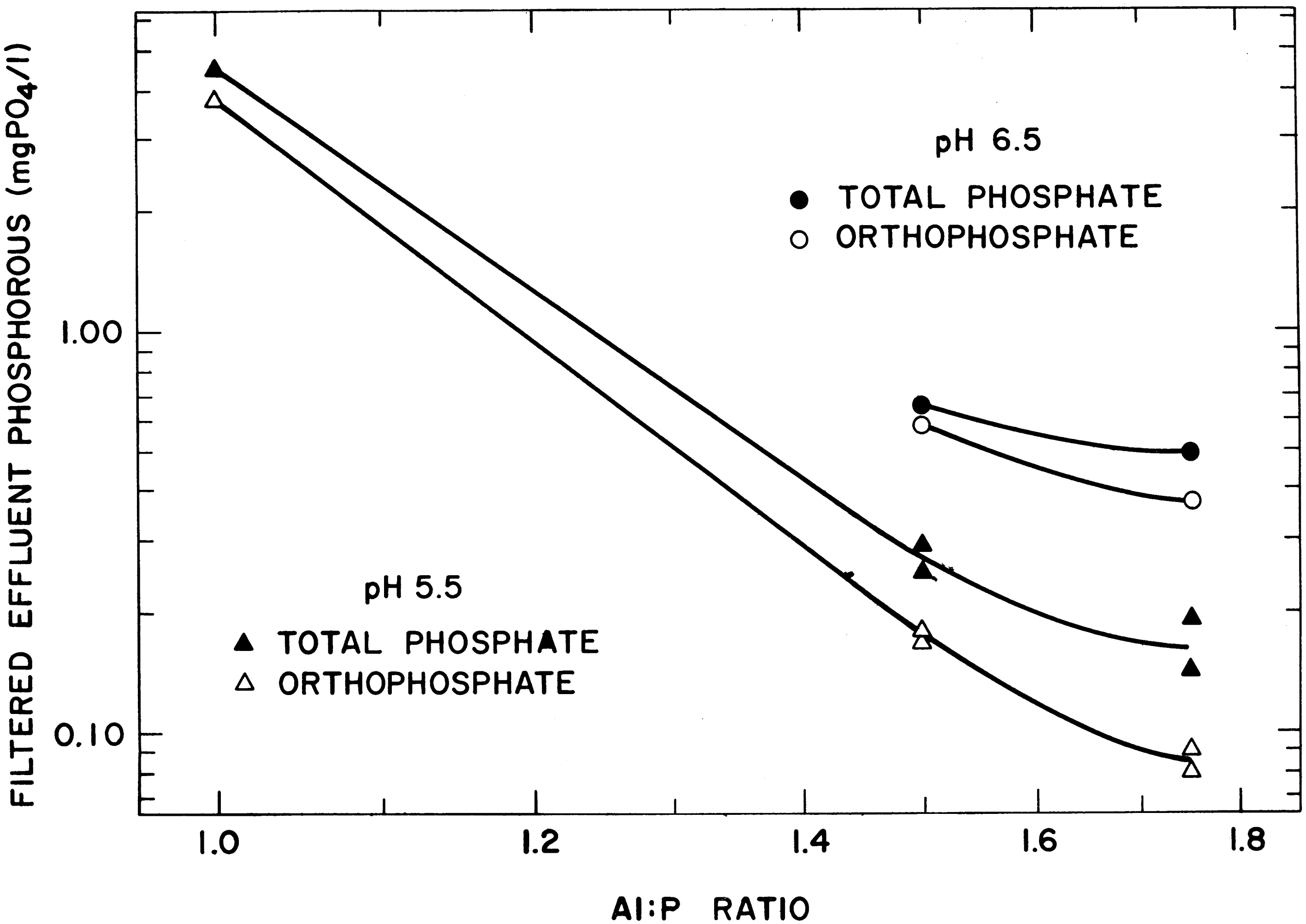

Figure 14. Filtered effluent phosphorus as a function of molar Al:P ratio and pH--SS Phases 1 and 2.

significant factors contributing toward the observed requirement during the present work for ratios greater than one.

It is also seen in Figure 14 that for a constant Al:P ratio, effluent residuals were lower at pH 5.5 than at pH 6.5. Several investigators have reported that phosphorus removal by various cations is influenced by pH (21,32,36,64). The pH dependence of the aluminum ion-phosphate interaction can be explained by considering the solubility product of the aluminum phosphate and the hydrolysis and acid base equilibria of the metal and phosphate ions, respectively (64). The interaction complexity is intensified by the presence of several forms of phosphate and the possible formation of multiple compounds such as aluminum hydroxy phosphates.

Unfiltered Effluent Phosphorus. Figures 12 and 15[1] depict a relationship between effluent unfiltered phosphorus and suspended solids. It is seen in Table XX, a summary of the unfiltered phosphorus data, that the lowest residuals were obtained during SS-PS1-6.5-1.75:1 when clarification was apparently jointly aided by the increased alum dosage over SS-PS1-6.5-1.5:1 and a clarifier solids blanket. Likewise, the effluent of SS-PS1-5.5-1.5:1A was improved by a reduced solids age during SS-PS1-5.5-1.5:1B and increased aluminum sulfate during SS-PS1-5.5-1.75:1, both of which improved clarification. The high phosphorus residual of SS-PS1-5.5-1:1 resulted both from low soluble removals and poor clarification.

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[1]The curves in Figure 15 include data from the SS Phase 2 run--SS-PS2-5.5-1.75:1.

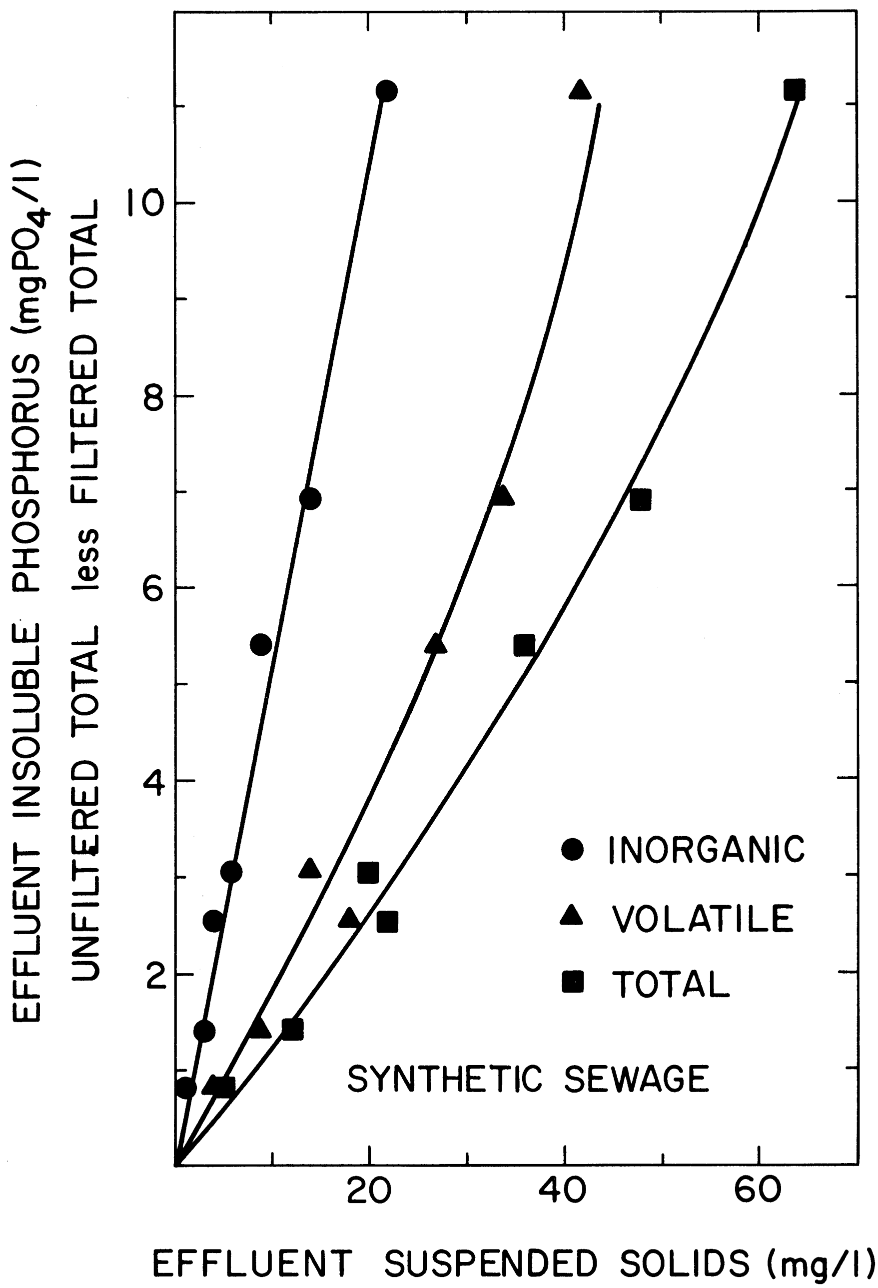


Figure 15. Effluent insoluble phosphorus as a function of effluent suspended solids--SS Phases 1 and 2.

Results and Discussion--SS Phase 2

Organic Loadings and General Operating Conditions. The pilot plant employing PS2 was operated for 35 days under the loadings and conditions given in Table XXI.

TABLE XXI

ORGANIC LOADINGS AND GENERAL OPERATING CONDITIONS--SS PHASE 2

Run Code SS-PS2-5.5-1.75:1

Organic Loadings	
Volumetric, lb BOD_5/1000 ft^3/day	110
Solids, lb BOD_5/lb $MLSS_{Biol}$/day	0.53
Mixed Liquor	
MLSS[a], mg/L	8,890
MLVS[a], mg/L	6,020
%MLVS	67.7
SVI, ml/g	22
Solids Age, days	3.70
Temperature, °C	21.0

[a]Theoretical--calculated on the basis of average weight of system solids and 6.66 L aeration volume.

It is evident from a comparison of Table XXI with Tables XVI and XVII that, with the sole exception of the pilot plant process schemes, the performance of SS-PS2-5.5-1.75:1 was evaluated under essentially the same conditions as SS-PS1-5.5-1.75:1.

Effluent Quality and Performance. Table XXII summarizes the effluent quality and performance of SS-PS2-5.5-1.75:1 which generally speaking were similar and in some respects better than those of its

TABLE XXII

EFFLUENT QUALITY AND PERFORMANCE--SS PHASE 2

Run Code SS-PS2-5.5-1.75:1

	Average	Range
Suspended Solids, mg/L		
Total	12	4.0-28
Volatile	9	4.0-20
BOD_5, mg/L		
Unfiltered	10	6-15
% Removal	94.8	----
Filtered[a]	4	----
% Removal	98.0	----
COD, mg/L		
Unfiltered	36	26-65
% Removal	90.5	----
Filtered	24	11-34
% Removal	93.6	----
Oxidized Nitrogen, mgN/L	1.1	0-2.7
Phosphorus, $mgPO_4/L$		
Filtered		
Ortho	0.09	0.04-0.19
Total	0.19	0.13-0.29
% Removal	99.5	----
Unfiltered		
Ortho	1.1	0.34-3.2
Total	1.6	0.61-3.9
% Removal	96.2	----

[a] See Figure 13 and related discussion--SS Phase 1.

SS Phase 1 counterpart (Tables XVII-XIX). The major difference was reduced effluent solids during SS Phase 2--12 mgSS/L as compared to 21 mgSS/L. As a result, the average unfiltered total phosphorus residual was proportionately lower--1.6 $mgPO_4/L$ versus 3.2 $mgPO_4/L$. It is possible that the increased pH stability afforded by PS2 promoted a more stable biological system with resultant improvement in bioflocculation and clarification. Considering other factors involved, particularly the closeness of the filtered effluent orthophosphate levels, the slight increase during SS Phase 2 in filtered total phosphorus is not considered significant.

It is to be recalled that the effluent filtered BOD_5 and filtered and unfiltered phosphorus discussions (see also Figures 13, 14, and 15) under SS Phase 1 include the data from SS-PS2-5.5-1.75:1 of SS Phase 2.

LAS Removals--SS Phases 1 and 2

LAS and associated BOD_5 data are shown for both SS Phases 1 and 2 in Table XXIII. As seen in Figures 9 and 10 (pp. 55 and 57) the LAS residuals and removals conform to the findings of SS-CR. It appears that the aluminum sulfate did not effect additional LAS elimination. In light of its failure to reduce significantly the soluble BOD_5 and COD residuals, this is not surprising. The data further reveal an LAS/BOD_5 (unfiltered) removal ratio of 1.0.

SLUDGE PRODUCTION

Results and Discussion

Biological Run. Complete sludge production data for all the synthetic sewage investigations are found in Table XXIV. Although somewhat high, the volatile solids production of SS-CR fell within the range of experimental findings of others. This is shown in Figure 16 where a least square line relating biological solids production and solids age has been constructed. It is realized that this relationship deviates

TABLE XXIII

LAS AND ASSOCIATED BOD_5 DATA--BIOLOGICAL-CHEMICAL RUNS

Run Code	Las Data[a]			BOD_5[b]	
	Inf. (mg/L)	Eff. (mg/L)	Removal (%)	Eff. (mg/L)	Removal (%)
SS-PS1-5.5-1:1	5.0	0.14	97.2	15	92.4
SS-PS1-5.5-1.5:1B	5.0	0.26	94.8	--	--
SS-PS1-6.5-1.5:1	5.0	0.22	95.7	--	--
SS-PS1-6.5-1.75:1	5.0	0.27	94.6	3	98.3
SS-PS1-5.5-1.75:1	5.0	0.27	94.6	--	--
SS-PS2-5.5-1.75:1	5.0	0.25	95.0	8	96.0

[a]Data represents only a spot-check for each run.

[b]Unfiltered.

from linearity over a wide range of solids age, however, the following equation reasonably describes the data reported:

$$\log (100VS_P/BOD_{5,R}) = -0.379 \log SA + 1.8761 \quad (12)$$

where

VS_P = Weight VS produced.

$BOD_{5,R}$ = Weight BOD_5 removed.

SA = Solids age in days over a range of approximately 1.5-8 days.

and

$r = 0.805$

Biological-Chemical Runs. The weight and volume ratios in Table XXIV compare sludge production during the biological-chemical runs with that expected under biological operation only. The expected biological value (not shown) for each run was obtained by computing the

TABLE XXIV

SLUDGE PRODUCTION--COMPLETE SYNTHETIC SEWAGE INVESTIGATIONS

Run Code	Sludge Production (lb/lb BOD_5 Removed[a])			Solids Age	Production Weight Ratio[b]	SVI	Production Volume Ratio[c]
	VS	IS	SS	(days)	Act. SS_{CPR}/Exp'd. $SS_{Biol.}$	(ml/g)	$SS_{CPR}/SS_{Biol.}$
SS-CR[d]	0.531	0.031	0.562	5.02	1.00	220	1.00
SS-PS1-5.5-1:1	0.707	0.278	0.985	3.63	1.55	35	0.25
SS-PS1-5.5-1.5:1A	0.879	0.418	1.30	3.35	1.98	65	0.58
SS-PS1-5.5-1.5:1B	0.955	0.460	1.42	2.85	2.03	--	--
SS-PS1-5.5-1.75:1	0.955	0.462	1.42	3.81	2.27	25	0.26
SS-PS1-6.5-1.5:1	0.835	0.433	1.27	3.72	2.02	33	0.30
SS-PS1-6.5-1.75:1	1.04	0.491	1.53	3.19	2.29	113	1.18
SS-PS2-5.5-1.75:1	0.967	0.455	1.42	3.70	2.25	22	0.22

[a]On the basis of a constant BOD_5 influent, a constant effluent (see Figure 13) and constant flow, 11.2 grams/day of BOD_5 were removed for all runs.

[b]Corrected for solids age.

[c]Ratio of SVI_s times weight ratio.

[d]Last 60 days of operation (period of improved solids balance procedure).

Figure 16. Volatile solids production as a function of BOD_5 removal and solids age--literature and complete synthetic sewage investigation data.

Biological Sludge

Present Investigation

- ○ SS-CR
- △ DS-CR

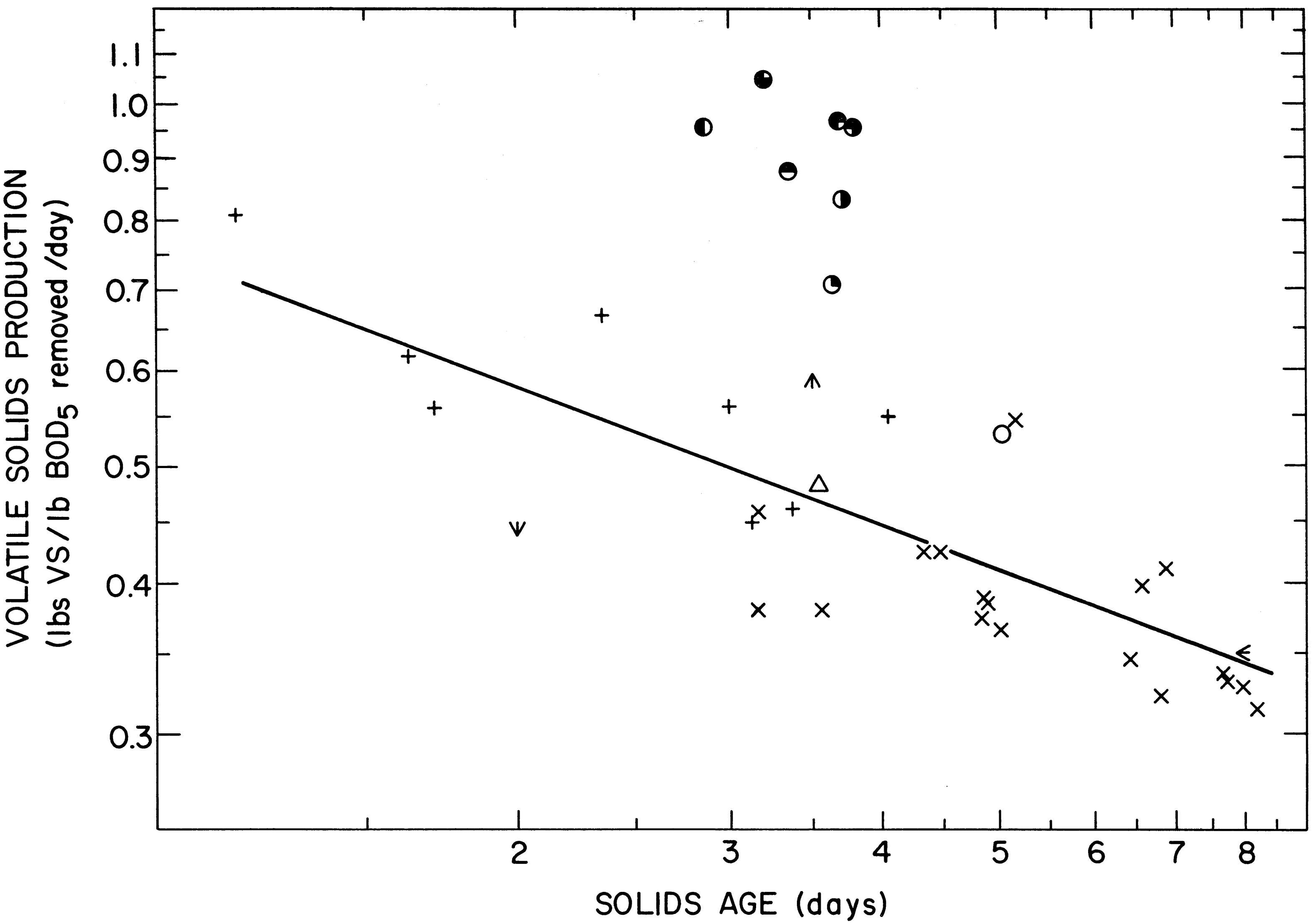
Literature

- + Wuhrmann (75)
- × McCarty & Broderson (37)
- Kehr & v.d. Emde (25,72)
- Blain (4)
- Lamb (30)

Biological-Chemical Sludge

Synthetic Sewage Investigations

- ◔ SS-PS1-5.5-1:1
- ◑ SS-PS1-6.5-1.5:1
- ◒ SS-PS1-5.5-1.5:1A
- ◐ SS-PS1-5.5-1.5:1B
- SS-PS1-5.5-1.75:1
- SS-PS2-5.5-1.75:1
- SS-PS1-6.5-1.75:1


VOLATILE SOLIDS PRODUCTION
(lbs VS/lb BOD_5 removed /day)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
2
3
4
5
6
7
8
SOLIDS AGE (days)

$VS_P/BOD_{5,R}$ value from EQ. 12, dividing this by the per cent VS of SS-CR to obtain $SS_P/BOD_{5,R}$, and finally multiplying this value by the ratio of the actual to expected $VS_P/BOD_{5,R}$ of SS-CR. The weight ratio of actual to expected production for the biological-chemical run was then determined. The advantage of this ratio over the more easily obtainable $(SS_P/BOD_{5,R})CPR$ / $(SS_P/BOD_{5,R})_C$ is that solids age is considered. The volume ratio is the product of the chemical to control SVI ratio and the weight ratio.

The data indicate that chemical precipitation significantly increased SS weight production. This is illustrated in Figures 17 and 18. The curve through the control point of Figure 17 represents the expected total biological solids production. The dashed family of curves was constructed under the assumption that chemical precipitation contributions are constant with solids age.

Of greater importance from a practical viewpoint, however, is the volume of sludge produced. The volume ratios in Table XXIV clearly indicate with one exception reduced sludge volumes for the biological-chemical process. This resulted from the SVI reductions consistently effected by the aluminum sulfate.

It is evident from Table XXIV that the increase in production of inorganic solids was accompanied by an increase in the production of volatile solids. Figure 16 reveals that VS production was not only a function of BOD_5 removal and solids age but also the Al:P ratio or chemical dosage. This is not surprising as Cole and Jackson (8) reported that the formation of sterrettite (molar ratio=$3Al_2O_3:2P_2O_5:9H_2O$) is favored during the reaction of aluminum and dihydroxy phosphate at pH

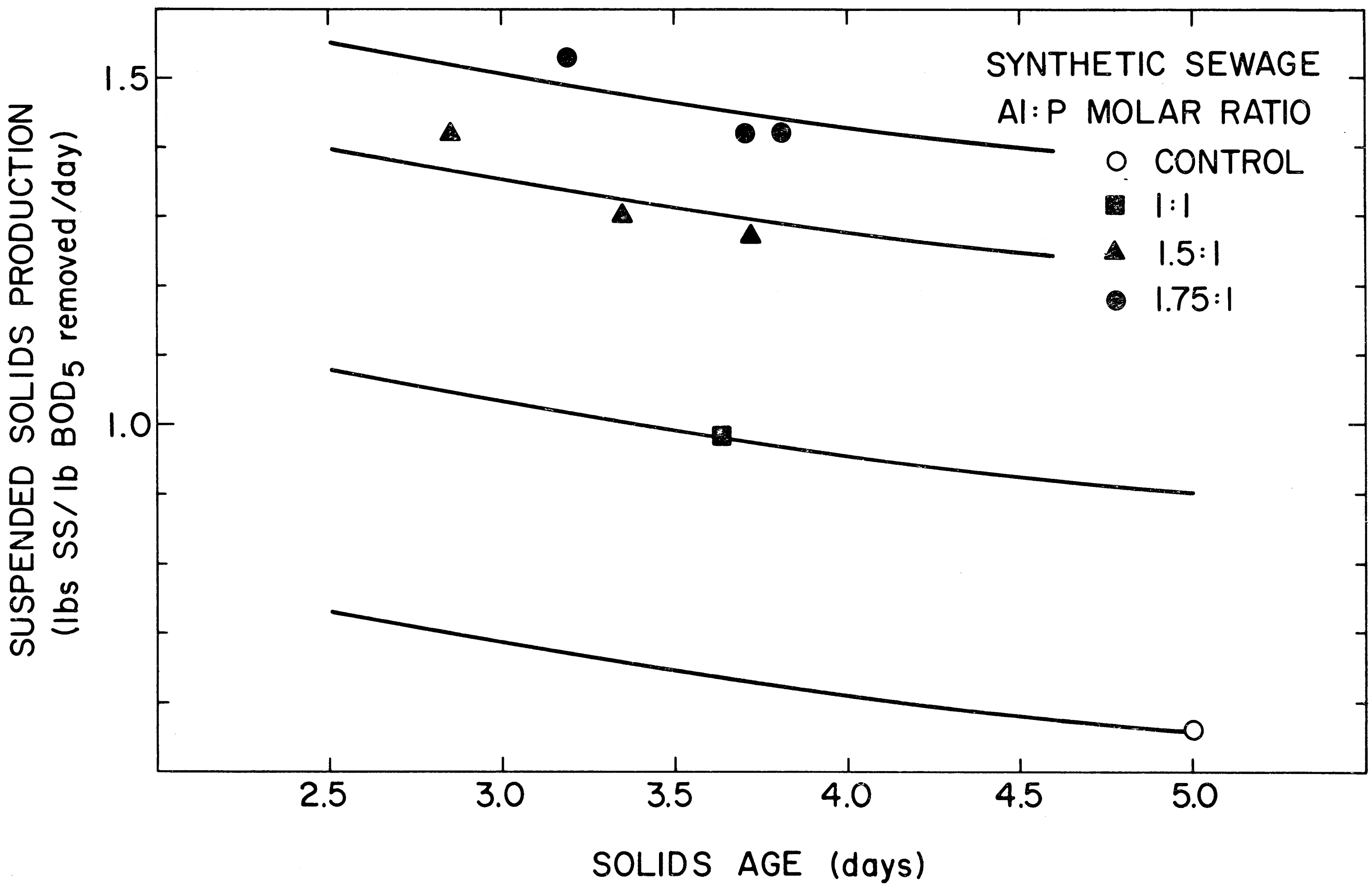


Figure 17. Total solids (sludge) production as a function of BOD_5 removal and solids age--complete synthetic sewage investigations.

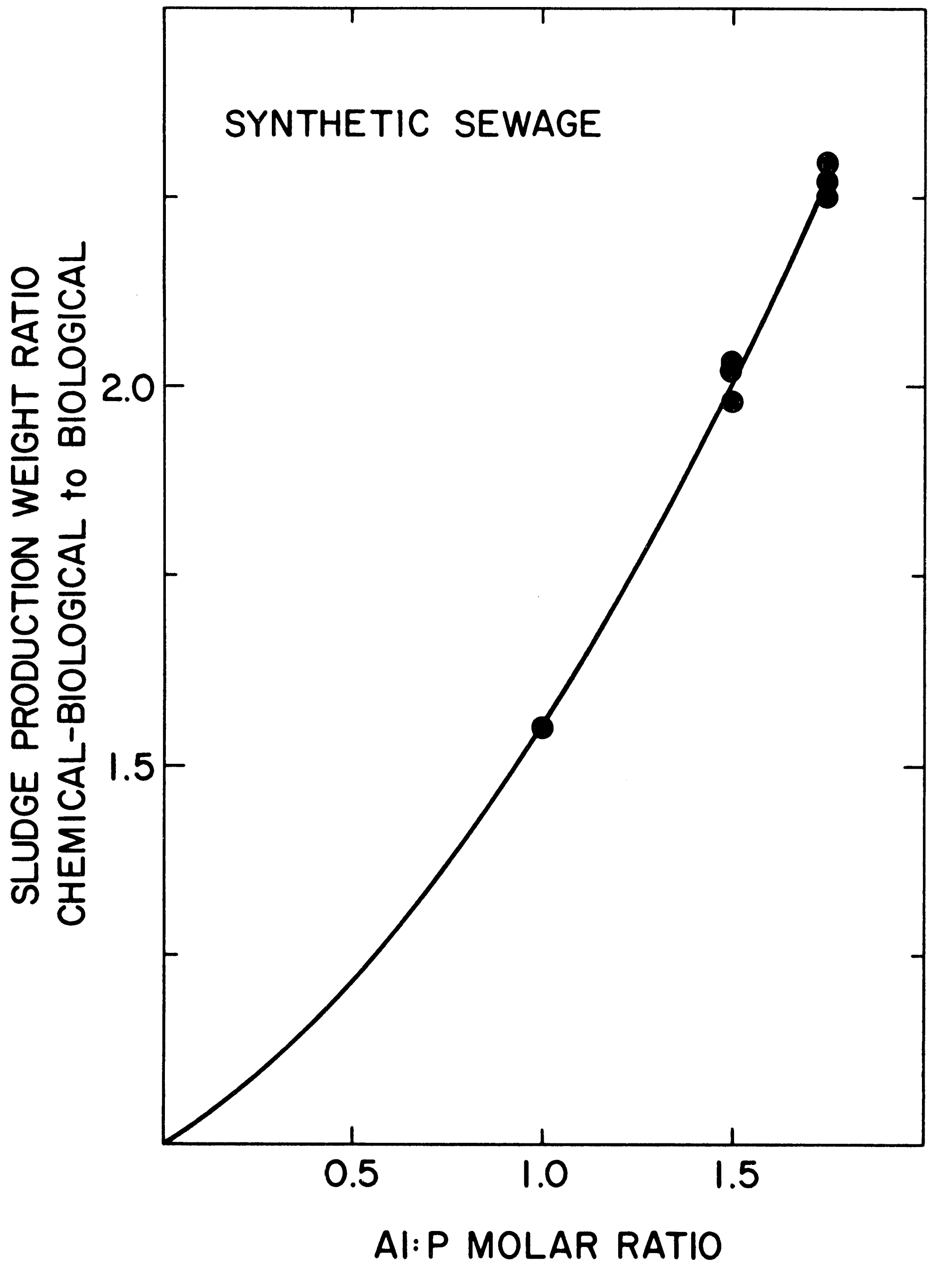


Figure 18. Total sludge production as affected by chemical treatment for phosphorus removal (Al:P Molar Ratio)--complete synthetic sewage investigations.

values of 5 to 6. Their ignition tests revealed sterrettite weight losses as high as 21.6 per cent at 105 to 800°C. The presence of a phosphate compound of this nature would, therefore, provide explanation for an increase in volatile solids production. In addition, it would provide additional explanation for the observed requirement for Al:P ratios significantly greater than one.

DOMESTIC SEWAGE INVESTIGATIONS

PROGRAM OF STUDY

Clarified sewage from The Pennsylvania State University treatment plant was employed as a substrate for a 113-day period. Pilot plant performance was evaluated in two stages:

Biological-Chemical Investigations--A two-phase evaluation of phosphorus removal and biological performance with varying aluminum sulfate dosage.

DS Phase 1 -- The biological-chemical process employing PS2.

DS Phase 2 -- The biological-chemical process employing PS3.

Biological Control Investigation--A study of HRAS performance with no chemical treatment.

In addition, throughout the program spot-checks of LAS removal were made to complement the related findings of the synthetic sewage investigations.

NATURE OF THE DOMESTIC SEWAGE USED

Sewage was collected from the effluent launder of the University treatment plant primary clarifier. With the exception of routine dairy and occasional laboratory discharges, this plant receives what might be classified as a domestic sewage. Digester supernatant is pumped to the head of the primary clarifier.

Table XXV reveals the character of the sewage employed. The data represent the entire investigative period. Statistics for the individual runs are given later or can be obtained from the respective

TABLE XXV

CHARACTER OF THE SEWAGE EMPLOYED--COMPLETE DOMESTIC SEWAGE INVESTIGATIONS

	University Clarified Sewage Range	University Clarified Sewage Average	Synthetic Sewage
BOD[a]			
5-day, mg/L	65-585	223	194
k, $days^{1}$	---	0.217	0.229
COD[a]	162-918	368	372
SS	80-220	134	0
pH	6.6-7.7	7.1	---
Total Kjeldahl N, mgN/L	17.9-53.5	33.8	57.1
Phosphorus, $mgPO_4/L$			
Ortho	---	20.2	31.0
Complex	---	19.4	11.2
Total	24.5-54.8	39.6	42.2

[a]On the basis of the average value over storage.

performance data. As indicated by the ranges shown, significant variations in quality were experienced despite a somewhat routine collection schedule. These resulted primarily from an irregular supernatant return schedule and the University calendar.

A comparison between the domestic and synthetic sewages reveals both similarities and dissimilarities. Although the COD's were essentially equal, the University sewage had significantly higher BOD's. Naturally, the relative forms of these organic parameters differed greatly due to the absence of solids in the synthetic sewage. Likewise, while the total phosphorus concentrations were similar, the forms varied significantly. The University sewage had a considerably higher concentration of complex phosphorus. For the synthetic sewage, 6.5 $mgPO_4/L$ of the complex forms were inorganic polyphosphates--i.e., TSPP and STPP. Assuming the soluble organic complex forms equal for both substrates and a sewage suspended solids phosphorus concentration of 0.65 per cent as P (23), the complex inorganic phosphorus content of the University sewage was approximately 12 $mgPO_4/L$ or almost double that of the synthetic sewage.

PILOT PLANT OPERATIONAL PROCEDURES

Substrate Changeover

The pilot plant remained in continuous operation during the transition from synthetic to domestic sewage. The activated sludge was retained and the substrate change was effected completely in less than an hour. Subsequently, seventeen days or approximately six solids ages of acclimation preceded the start of the investigations. Throughout the entire transition period, aluminum sulfate was dosed at a rate equal to both that of the preceding run (SS-PS2-5.5-1.75:1) and the first domestic sewage run.

General Operation

In general, the pilot plant was operated as described for the synthetic sewage investigations. The improved solids balance procedure was used and pH control was eliminated.

Sewage Procurement, Storage, and Analysis

A new batch of sewage was trucked to the lab daily. That remaining from the previous day was wasted and the storage carboy was brushed, rinsed, and refilled. The refrigeration system described earlier lowered the sewage temperature to approximately 3.5°C in about an hour and held it there continuously. The total time elapsed from collection to attainment of the aforesaid temperature was less than two hours.

Phosphorus, BOD_5, COD, suspended solids, pH, and total Kjeldahl nitrogen analyses were performed on the sewage immediately upon its arrival at the lab. Systematic observations revealed that despite the temperature depression, a significant BOD and COD exertion occurred over the 24-hour storage period. Therefore, BOD_5 and COD analyses were also performed each day prior to wasting. The average of the initial and final determinations is reported herein. In the event of an invalid test or no determination at all, BOD_5 values were obtained from the relationship in Figure 19 which was developed from data covering the entire investigation period.

BIOLOGICAL CONTROL RUN

Investigation Procedure

Although the domestic sewage control run, DS-CR, followed the chemical precipitation investigations, it is being reported first. To assure wastage of the majority of the chemical sludge accumulated in the mixed liquor, seven days or approximately two solids ages of continuous operation without addition of aluminum sulfate preceded the start of DS-CR.

The major objective of this run was to obtain reference BOD_5 removal and sludge production data. Analytical measurements performed in addition to the sewage analyses included mixed liquor SS, VS, SVI and

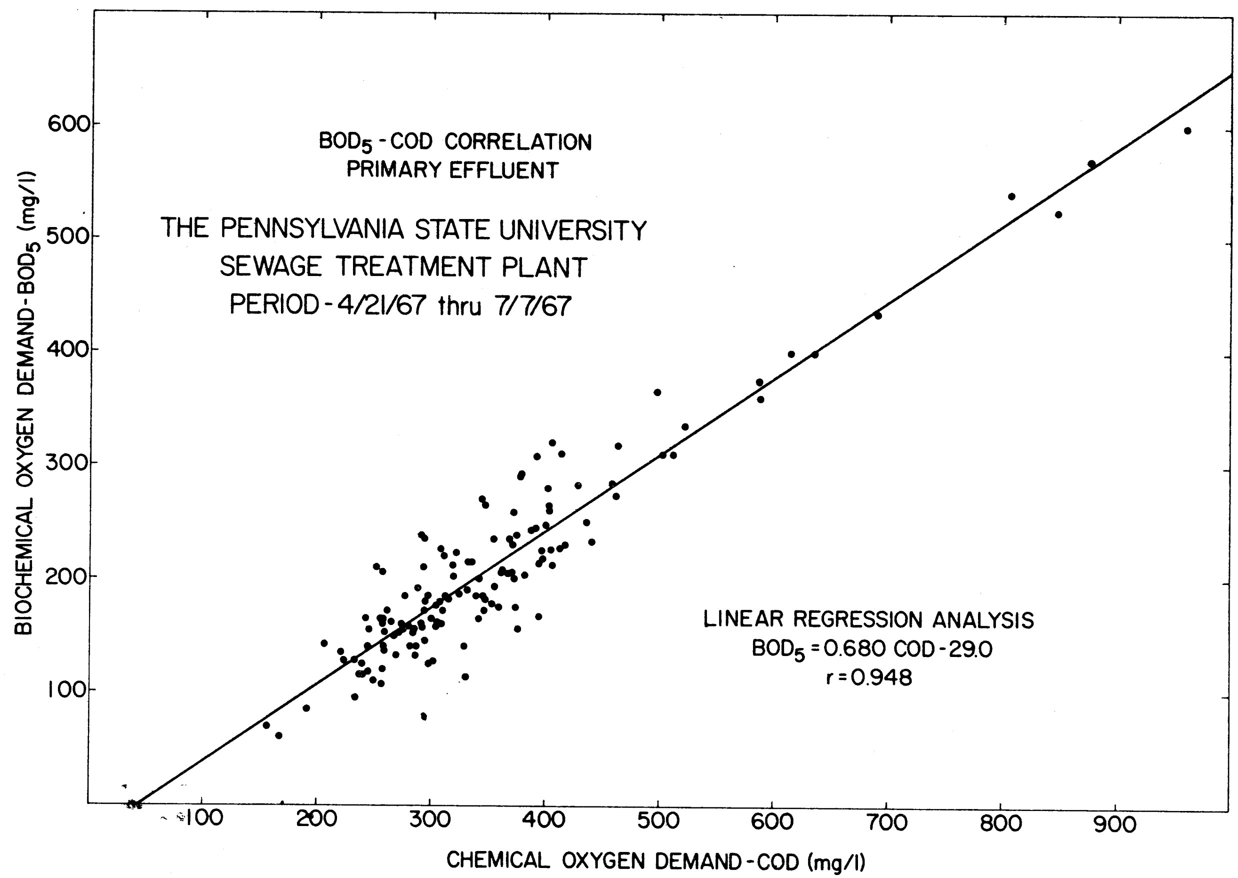


Figure 19. BOD$_5$ versus COD correlation, primary effluent of The Pennsylvania State University treatment plant--complete domestic sewage investigations.

pH and effluent SS, VS, BOD_5 (filtered and unfiltered), COD (filtered), oxidized nitrogen, and MBAS.

Results and Discussion

Table XXVI summarizes the operation, loadings, and performance of DS-CR. The 0.62 lb BOD_5/lb MLSS/day loading is about three times that of a typical conventional loading. It is to be noted that a loading range of about 56-160 per cent of the mean was experienced. The subsequent average BOD_5 removal efficiency agrees well with the 86 and 85.5 per cent values predicted by the high rate curves of Kehr and v.d. Emde (25) for the average volumetric and solids BOD_5 loadings encountered.

Despite the variable loadings, operation was steadier than that of SS-CR. Apparently the continuous seeding by the sewage sustained a more stable biological system. The nitrifying population which on the basis of oxidized nitrogen effluent analyses underwent sporadic fluctuations appeared to be an exception. A reasonable explanation for this, however, is not apparent from the available data. Taking into consideration the influent total Kjeldahl nitrogen (avg. of 32.3 mgN/L), that required for synthesis (about 13.4 mgN/L), and the average effluent oxidized nitrogen, approximately 33 per cent of the potential nitrification was averaged during DS-CR.

Using the average influent phosphorus concentration for the investigations (39.6 mgPO_4/L), the quantity of sludge produced, and a phosphorus content for the sludge of 2.62 per cent, it is estimated that 26.5 per cent of the phosphorus was removed biologically leaving an effluent concentration of 29.1 mgPO_4/L (21.2 per cent and 31.2 mg PO_4/L considering effluent volatile solids).

TABLE XXVI

GENERAL OPERATION AND PERFORMANCE--RUN DS-CR

Run Code DS-CR

	Average	Range
Mixed Liquor		
MLSS, mg/L[a]	3,650	---
MLVS, mg/L[a]	3,090	---
%VS	84.6	---
Solids Age, days	3.46	---
SVI, ml/g	181	174-193
Temperature, °C	23.7	---
pH	7.3	7.1-7.4
Organic Loadings		
lb $BOD_5/1000ft^3$/day	140	78-357
lb BOD_5/lbMLSS/day[b]	0.617	---
lb $COD/1000ft^3$/day	231	140-357
lb COD/lbMLSS/day[b]	1.02	---
Effluent Quality and Performance		
Suspended Solids, mg/L	29	14-58
% Removal	75.8	---
Volatile Solids, mg/L	26	13-52
BOD_5		
Unfiltered, mg/L	31	16-62
% Removal	87.6	---
Filtered, mg/L	5.6	5.5-5.8
% Removal	97.8	---
COD		
Unfiltered, mg/L[c]	90	55-156
% Removal	78.2	---
Filtered, mg/L	53	32-82
% Removal	87.1	---
Oxidized Nitrogen, mgN/L	6.2	0-17.2
LAS, mgMBAS/L	0.28	0.21-0.34
% Removal	96.8	---
Run duration, days	12	---

[a]Working concentration.

[b]Based on working concentration.

[c]Filtered COD + (1.42)(Eff. VS).

The DS-CR sludge production data which were used as a basis for synthesis in the foregoing calculations are presented in a later section.

It is seen in Table XXVI that as found during the synthetic sewage work, essentially all the MBAS was removed. The data for DS-CR are plotted in Figures 9 and 10 for comparison. Likewise, the removal ratio MBAS/BOD_5 (filtered), 0.99, again approximated unity.

BIOLOGICAL-CHEMICAL RUNS

Investigation Procedure

It will be recalled that Figure 5 and Table V present the design schematics and unit process volumes and detention times for PS2, PS3A, and PS3B which were employed during DS Phases 1 and 2.

DS Phase 1. DS-PS2-6.6-1.88:1,[1] using the process scheme and aluminum sulfate dosage (261 mg/L) found successful during the synthetic sewage work, followed the 17-day domestic sewage acclimation period. Unsatisfactory flocculation and clarification led to increases in aluminum sulfate to 298 and 335 mg/L. Continued poor performance prompted modification of the pilot plant to PS3.

DS Phase 2. PS3A and PS3B were evaluated at an aluminum sulfate addition of 335 mg/L. Because employment of PS3 resulted in a significant improvement in effluent quality, the dosage was dropped back to 261 mg/L for evaluation.

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[1]The coding system is explained on p. 59 as well as in the List of Symbols. The coded pH is the run average for the basin receiving the aluminum sulfate.

General. The duration of the investigative periods was dependent primarily on process performance. Two runs were terminated after four days because applied operational changes had obviously failed to effect effluent improvement. The others lasted from 10 to 20 days.

Analyses performed included mixed liquor SS, VS, SVI, pH, and temperature and effluent ortho and total phosphorus (filtered and unfiltered), BOD_5 (filtered and unfiltered), COD (filtered), SS, VS, oxidized nitrogen, and MBAS.

Results and Discussion--Unfiltered Data of DS Phases 1 and 2

The results of the chemical precipitation runs are presented in three sections--Unfiltered Data, Filtered Data, and Sludge Production. The filtration classification was made because of the clarification difficulties encountered and the strong dependency of phosphorus and BOD_5 removals on this unit process. The influent sewage characteristics and pilot plant operational parameters for each run are included in the present section.

Influent Sewage Characteristics. Table XXVII presents the average influent sewage characteristics for each run.

Pilot Plant Operating Conditions. The plant organic loadings are given in Table XXVIII. The volumetric parameter ($lbBOD_5/1000\ ft^3/day$) is as usual based on the total aeration volume. The solids loadings were computed using EQ. 9 modified as follows:

TABLE XXVII

AVERAGE INFLUENT SEWAGE CHARACTERISTICS--DS PHASES 1 AND 2

Run Code	Phosphorus ($mgPO_4/L$)			BOD_5 (mg/L)	COD (mg/L)	SS (mg/L)	Total Kjeldahl Nitrogen (mgN/L)	pH
	Ortho	Complex	Total					
DS Phase 1								
DS-PS2-6.6-1.88:1	21.1	18.5	39.6	191	324	148	36.5	7.2
DS-PS2-6.5-2.37:1	20.0	15.9	35.9	200	314	141	36.4	7.2
DS-PS2-6.6-2.08:1	23.8	22.0	45.8	185	323	166	37.4	7.2
DS Phase 2								
DS-PS3A-6.1-2.42:1	20.5	18.9	39.4	212	346	130	34.8	7.0
DS-PS3B-6.0-2.44:1	18.1	21.0	39.1	260	421	123	31.6	7.0
DS-PS3B-6.8-1.87:1	19.8	19.9	39.7	241	401	130	29.6	7.0

TABLE XXVIII

ORGANIC BIOLOGICAL LOADINGS--DS PHASES 1 AND 2

Run Code	Volumetric ($lbBOD_5/1000\ ft^3/day$)	Solids ($lbBOD_5/lbMLSS_{Biol}/day$)
DS Phase 1		
DS-PS2-6.6-1.88:1	107	0.60
DS-PS2-6.5-2.37:1	112	0.63
DS-PS2-6.6-2.08:1	104	0.77
DS Phase 2		
DS-PS3A-6.1-2.42:1	119	0.59
DS-PS3B-6.0-2.44:1	146	0.64
DS-PS3B-6.8-1.87:1	135	0.63

For the domestic sewage investigations

$$B_{CPR} \neq B_C = 250 \text{ mg/L}$$

$$R_{CPR} \neq R_C = 244 \text{ mg/L}$$

$$SA_C = 3.46 \text{ days}$$

$$LF_C = 0.617 \text{ lbBOD}_5\text{/lbMLSS/day}$$

and mg/L are used for B and R since the feed rate to both systems was identical

Substituting into EQ. 9

$$LF_{CPR} = 0.602 \frac{B_{CPR}}{R_{CPR}} \left(\frac{3.46}{SA_{CPR}}\right)^{0.62}$$

It is seen that the solids loadings among the runs did not vary greatly and, further, that these loadings were generally about 10 per cent higher than those of the synthetic sewage investigations.

The plant operational parameters are presented in Table XXIX. As also observed during the synthetic sewage work, the addition of aluminum sulfate produced a significant increase in the fraction of mixed liquor inorganic solids (40.9-34.6 per cent IS in comparison to 15.4 per cent IS during DS-CR). It will be later demonstrated that as before, VS production was also increased as a result of the formation of non-biological forms. Recalling the average SVI of 181 during DS-CR, it is seen that favorable decreases in this parameter occurred with progressive increases in aluminum sulfate dosage.

Unfiltered Effluent Quality and Related Performances. The effluent quality and performance for each set of experimental conditions exclusive of filtration are summarized in Table XXX. The dependency of both total phosphorus and BOD_5 removals on clarification is apparent. Figure 20 reveals that the relationships between effluent insoluble phosphorus and the various forms of effluent solids are similar to those of the synthetic sewage work. Significant differences in performance among the separate runs are discussed in the following sections.

DS Phase 1. Despite the unsatisfactory flocculation and clarification during DS-PS2-6.6-1.88:1, analyses revealed as will be shown later that the aluminum sulfate dosage was effecting a near complete soluble phosphorus removal. Therefore, the run was continued under the assumption that the problem was biological in nature and would be corrected with further acclimation. Prospects for this were dim, however, as microscopic observations revealed an excellent protozoan population. After 19 days of operation (actually 36 days total acclimation) with an average unfiltered phosphorus removal of about 50 per cent, the chemical

TABLE XXIX

AVERAGE PILOT PLANT OPERATING CONDITIONS--DS PHASES 1 AND 2

Run Code	Days of Operation	$Al_2(SO_4)_3 \cdot 18H_2O$ (mg/L)	MLSS[a] (mg/L)	MLVS (%)	Solids Age (days)	SVI[b] (ml/g)	System Temp.[c] (°C)
DS Phase 1							
DS-PS2-6.6-1.88:1	19	261	7,510	59.1	3.54	110	20.5
DS-PS2-6,5-2.37:1	4	298	8,320	56.9	3.27	54	21.9
DS-PS2-6.6-2.08:1	4	335	7,030	56.3	2.34	---	22.6
DS Phase 2							
DS-PS3A-6.1-2.42:1	20	335	7,700	58.3	3.56	48	21.6
DS-PS3B-6.0-2.44:1	15	335	8,020	61.0	3.21	64	23.8
DS-PS3B-6.8-1.87:1	10	261	7,370	65.4	3.36	125	23.0

[a]Theoretical--Calculated on the basis of total system solids and 6.66 total aeration volume.

[b]Periodic determination.

[c]Recorded between 9 and 11 a.m.

TABLE XXX

UNFILTERED EFFLUENT QUALITY AND RELATED PERFORMANCES--DS PHASES 1 AND 2

Run Code	Suspended Solids Range (mg/L)	Suspended Solids Avg. (mg/L)	Suspended Solids Removal (%)	BOD_5 Range (mg/L)	BOD_5 Avg. (mg/L)	BOD_5 Removal (%)	Phosphate Ortho Avg. ($mgPO_4$/L)	Phosphate Total Range ($mgPO_4$/L)	Phosphate Total Avg. ($mgPO_4$/L)	Phosphate Total Removal (%)
DS Phase 1										
DS-PS2-6.6-1.88:1	50-220	125	15.5	25-87	58	69.6	12.7	7.9-27.6	19.6	50.5
DS-PS2-6.5-2.37:1	96-192	139	1.4	40-51	45	77.5	11.4	14.5-30.5	20.8	42.1
DS-PS2-6.6-2.08:1	170-286	226	-36.1	48-73	58	68.7	20.5	28.8-48.4	38.8	15.3
DS Phase 2										
DS-PS3A-6.1-2.42:1	7-104	26	80.0	6-20	10	95.4	2.1	1.1-16.2	3.5	91.1
DS-PS3B-6.0-2.44:1	5-28	18	85.4	5-100[a]	20	92.3	0.90	0.24-3.9	1.6	95.9
DS-PS3B-6.8-1.87:1	10-82	30	76.9	4.5-22	14	94.2	3.2	1.3-9.3	4.8	87.9

[a]Maximum was associated with an influent BOD_5 of 585.

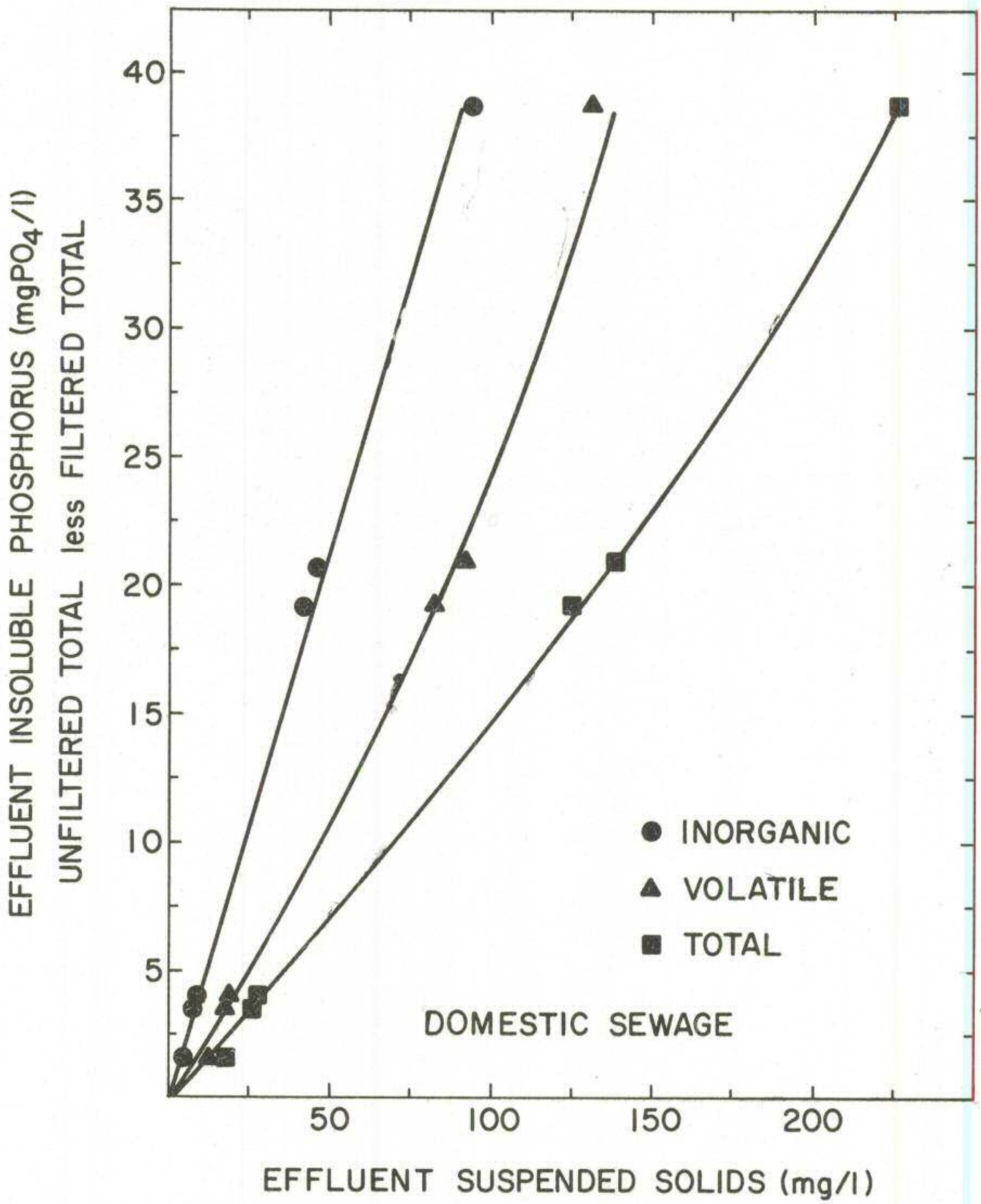

Figure 20. Effluent insoluble phosphorus as a function of effluent suspended solids--DS Phases 1 and 2.

dosage was increased in two steps from 261 to 335 mg/L over an eight-day period. As indicated in Table XXX, performance worsened.

Since work by Tenney (64) on dispersed cell-phosphorus batch systems had indicated an absence of peptization with aluminum sulfate dosages significantly exceeding flocculation requirement, it was decided to investigate by means of jar tests increased coagulant dosages to the aeration tank mixed liquor. Additions of 0, 25, 50, 75, and 100 mg/L (all systems had the base dosage of 335 mg/L from the pilot plant) were made. With the exception of the control, almost instantaneous flocculation with a resultant clear supernatant occurred in all systems. With continued stirring, however, the flocs deteriorated. These observations suggested that the lengthy flocculation period afforded by the aeration basin under PS2 was responsible for the poor clarification observed.

On the basis of the foregoing, the pilot plant was modified to PS3A. Immediate improvement in clarification was evident upon resumption of operation at the same rate of aluminum sulfate application. Within a three-hour period, the clarifier was clear. Figure 21 graphically depicts the change.

DS Phase 2. The change from PS2 to PS3A marked the start of DS Phase 2 and DS-PS3A-6.1-2.42:1. The average unfiltered removals for this 20-day run were excellent--80.0, 95.4, and 91.1 per cent, respectively, for SS, BOD_5, and total phosphorus.

It was considered of interest at this point to investigate the effect of a further reduction in flocculation time. PS3B with a theoretical mixing and flocculation basin detention period of only six minutes (two minutes considering recirculation) was employed for a period

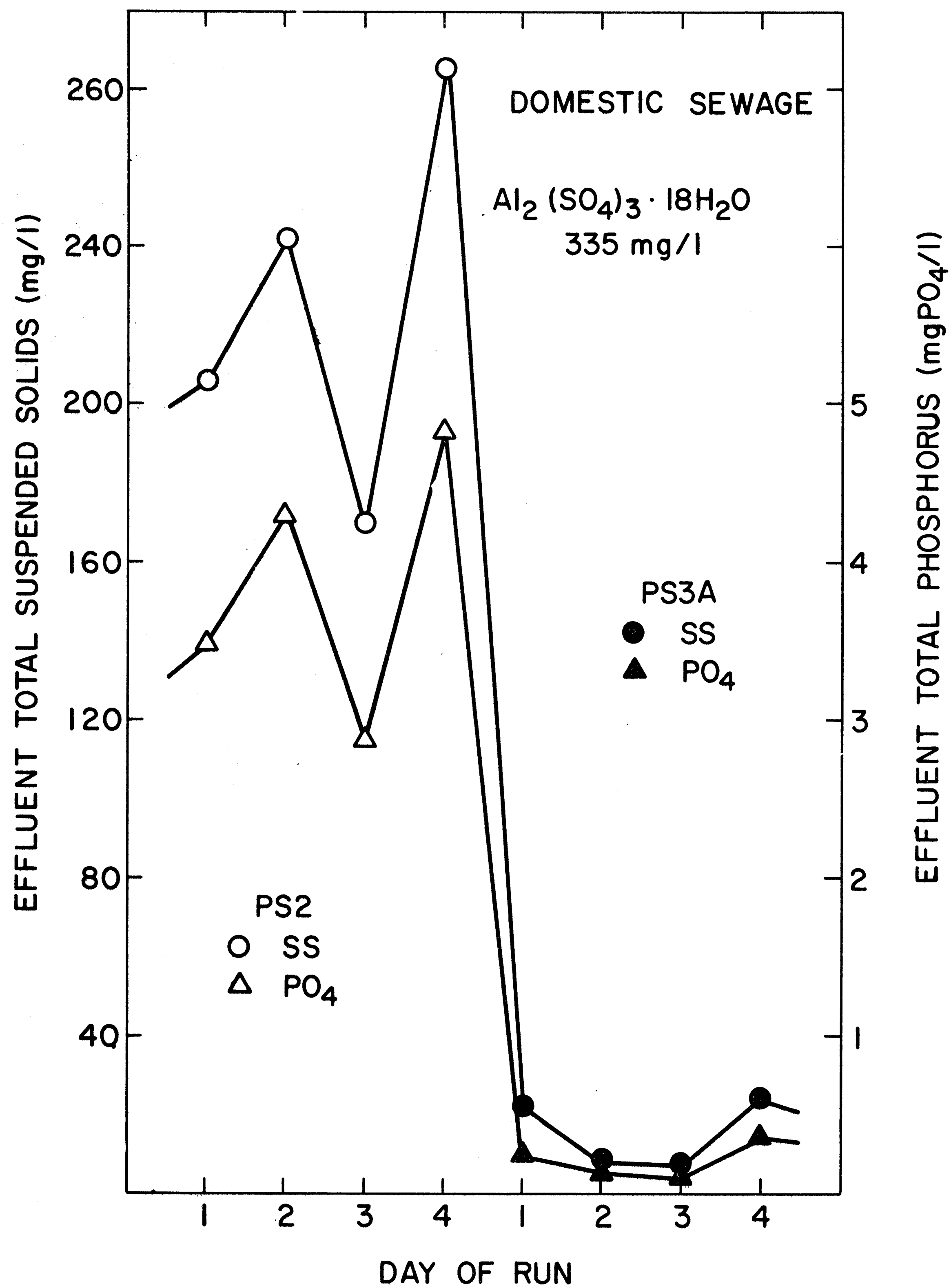

Figure 21. Suspended solids and phosphorus effluent quality as affected by the change from PS2 to PS3A--runs DS-PS2-6.6-2.08:1 and DS-PS3A-6.1-2.42:1.

of 20 days. Five consecutive days of operation were discredited as a result of back-to-back clogging, power failure, and aeration disruption occurrences. In comparison to the performance under PS3A, there was an increase in suspended solids and phosphorus removals and a slight decrease in BOD_5 removals. The latter resulted largely from two days of operation during which influent BOD_5's were 585 and 532 mg/L. The average 95.9 per cent phosphorus removal and 1.6 $mgPO_4/L$ residual approach the best unfiltered performance of the synthetic sewage investigations--96.9 per cent and 1.3 $mgPO_4/L$ for SS-PS1-6.5-1.75:1. Figure 22 illustrates the compactness of the settled MLSS and the clarity of the supernatant after 30 minutes of settling during DS-PS3B-6.0-2.44:1. In addition, the influent settled sewage and effluent quality are compared.

Finally, DS-PS3B-6.8-1.87:1 was conducted to determine whether or not a comparable performance could be obtained with an aluminum sulfate reduction back to 261 mg/L. Although generally favorable results were attained, the phosphorus treatment deterioration to 87.9 per cent removal and a residual of 4.8 $mgPO_4/L$ was significant.

Results and Discussion--Filtered Data of DS Phases 1 and 2

General Effluent Quality and Performance. Exclusive of phosphorus data, Table XXXI summarizes the filtered effluent quality and performance of each chemical precipitation run including those of DS-CR. It should be realized that while the unfiltered data of the two four-day runs, DS-PS2-6.5-2.37:1 and DS-PS2-6.6-2.08:1, were helpful toward ascertaining the conditions necessary for acceptable flocculation and

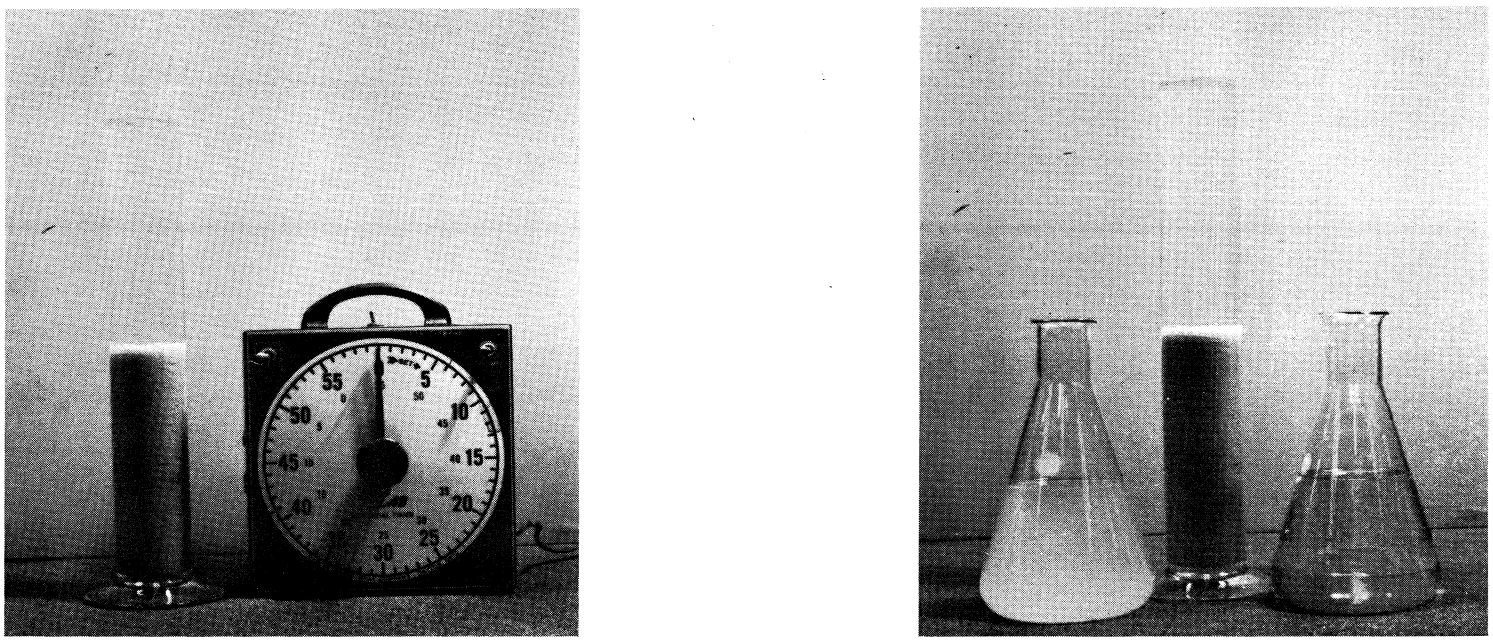

Figure 22. Mixed liquor compaction after 30 minutes of settling and a comparison of influent and effluent clarity--Run DS-PS3B-6.0-2.44:1*

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*6/27/67--MLSS = 7,200 mg/L, SVI = 68 ml/g, influent clarified domestic sewage suspended solids = 105 mg/L, final clarified effluent suspended solids = 5 mg/L.

TABLE XXXI

FILTERED EFFLUENT QUALITY AND RELATED PERFORMANCES--DS PHASES 1 AND 2

Run Code	$Al_2(SO_4)_3 \cdot 18H_2O$ (mg/L)	COD Range (mg/L)	COD Avg. (mg/L)	COD Removal (%)	BOD_5[a] Avg. (mg/L)	BOD_5[a] Removal (%)	Oxidized Nitrogen Avg. (mgN/L)	MBAS[a] Avg. (mg/L)	MBAS[a] Removal (%)
DS-CR	0	32-82	53	87.1	5.6	97.8	6.2	0.28	96.8
DS Phase 1									
DS-PS2-6.6-1.88:1	261	2-50	20	93.8	3.4	98.2	12.4	--	--
DS-PS2-6.5-2.37:1	298	2-29	13	95.8	--	--	11.9	--	--
DS-PS2-6.6-2.08:1	335	6-36	23	92.9	--	--	8.8	--	--
DS Phase 2									
DS-PS3A-6.1-2.42:1	335	0-34	19	94.5	0.7	99.7	7.9	--	--
DS-PS3B-6.0-2.44:1	335	4-166[b]	37	91.2	3.0[c]	98.8	3.5	0.22	97.7
DS-PS3B-6.8-1.87:1	261	19-79	37	90.8	--	--	1.5	--	--

[a] Spot-check determinations.

[b] Maximum is associated with an influent COD of 918 mg/L.

[c] Median value reported because of the magnitude of the maximum extreme.

clarification, they are of limited value as representative performance indicators due to the brevity of the observation periods.

Considering the insignificant variation in COD loadings and the influence of the maximum extreme COD residual on the mean of DS-PS3B-6.0-2.44:1, the data reveal that the addition of aluminum sulfate was responsible, at best, for only slight soluble COD removals. Although the related data are spotty, it would appear, further, that BOD_5 and MBAS removals were not significantly affected by the chemical dosage. These observations are in accord with the findings of the synthetic sewage investigations.

The BOD_5 removals for all the chemical precipitation runs exceeded 98 per cent. The MBAS residuals and removals of DS-PS3B-6.0-2.44:1 are included in Figures 9 and 10 and are seen to conform with earlier findings. As expected, the ratio of the filtered MBAS and BOD_5 removals of the run approached unity.

Unlike those experienced during the synthetic sewage investigations, the observed variations in effluent oxidized nitrogen are not readily explainable. There is no apparent correlation with pH, aluminum sulfate dosage, or influent total Kjeldahl nitrogen.

<u>Phosphorus Residuals and Removals</u>. Table XXXII reveals that with filtration the complex and total phosphrus removals were essentially equal and were, with one exception, 98.8 per cent, consistently equal to or greater than 99 per cent.

An intra-comparison of two essentially constant Al:P ratio pairings, DS-PS2-6.6-1.88:1 and DS-PS3B-6.8-1.87:1; and DS-PS3B-6.0-2.44:1 and DS-PS3A-6.1-2.42:1, strengthens the observation made during the

TABLE XXXII

FILTERED EFFLUENT PHOSPHORUS AND RELATED PERFORMANCES--DS PHASES 1 AND 2

		Orthophosphate		Total Phosphate			
						Per Cent Removals	
Run Code	$Al_2(SO_4)_3 \cdot 18H_2O$ (mg/L)	Range (mg/L)	Avg. (mg/L)	Range (mg/L)	Avg. (mg/L)	Complex	Total
DS Phase 1							
DS-PS2-6.6-1.88:1	261	0-1.1	0.29	0-1.2	0.41	99.4	99.0
DS-PS2-6.5-2.37:1	298	0-0.10	0.04	0.09-0.17	0.14	99.4	99.6
DS-PS2-6.6-2.08:1	335	0.02-0.11	0.04	0.08-0.19	0.12	99.6	99.7
DS Phase 2							
DS-PS3A-6.1-2.42:1[a]	335	0-0.14	0.05	0-0.35	0.13	99.6	99.7
DS-PS3B-6.0-2.44:1	335	0-0.05	0.01	0-0.10	0.04	99.9	99.9
DS-PS3B-6.8-1.87:1	261	0.09-1.1	0.37	0.14-1.4	0.49	99.4	98.8

[a]Excludes 5/24/67 data. pH dropped to 4.6 due to failure of feed pump.

synthetic sewage studies and likewise by other investigators that pH influences the phosphorus removal reactions. In addition, pH influence on the opposite or lower side of the pH optimum was observed during DS-PS3A-6.1-2.42:1. Because of a sewage pump failure, an excess of aluminum sulfate lowered the mixed liquor pH to 4.6. Despite a consequentially high Al:P ratio, the soluble phosphorus level increased significantly.

A comparison among the data of runs DS-PS2-6.6-1.88:1, DS-PS3B-6.8-1.87:1 and SS-PS1-6.5-1.75:1 (see Table XIX for the latter), with consideration given to the small differences in pH's and Al:P ratios, reveals that, unlike the finding of Henriksen (21) of an upward shift in optimum pH for sewage over phosphorus solutions, there appears to be reasonable agreement between the domestic and synthetic sewage investigations. This is illustrated in Figure 23 which relates effluent residual, Al:P ratio, and pH. The curves shown have been constructed over the data ranges within which a reasonable approximation was considered possible. Little consideration was given to the data of the two four-day runs. Likewise no attempt was made to define a pH 6 curve since only two extreme values were available. The general shape of the curves is similar to that obtained by Tenney (64) and is in accord with the finding of Henriksen (21) that molar capacity decreases with increasing removal efficiency or decreasing residual. The lowest average total soluble phosphorus residual attained was 0.04 mg PO_4/L.

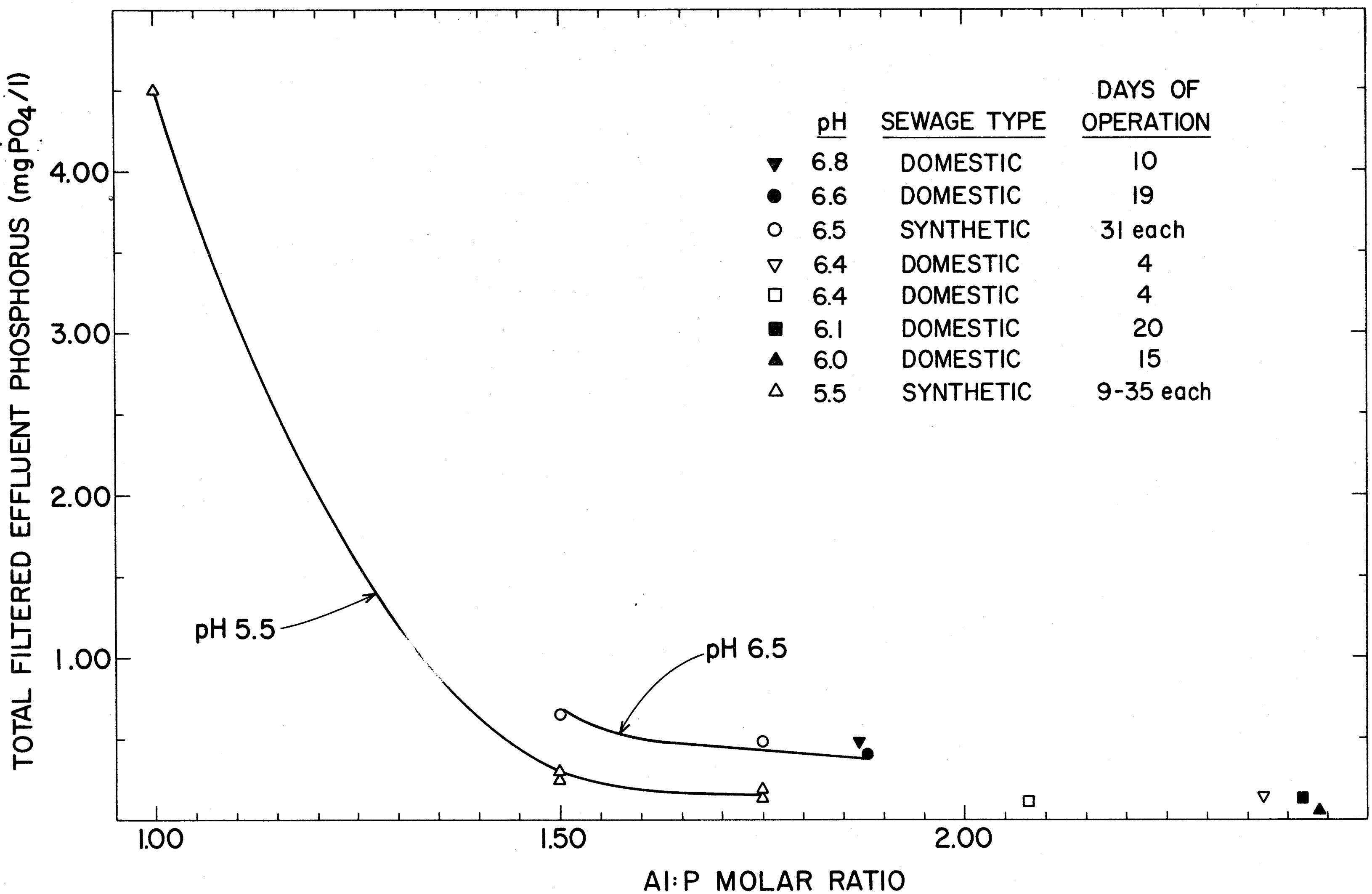


Figure 23. Filtered effluent total phosphorus as a function of molar Al:P ratio and pH--synthetic sewage and domestic sewage investigations.

SLUDGE PRODUCTION

Results and Discussion

Sludge production observations from the domestic sewage investigations are presented in Table XXXIII and Figure 24. It is illustrated in the latter that solids production during the control, DS-CR, fell well within the range of values reported by others.

The weight and volume ratios for the chemical precipitation runs again take solids age into consideration. Increases in both IS and VS production resulted from chemical treatment. The VS increases which are shown in Figure 24 provide further indication of the formation of a phosphate compound such as sterrettite which loses OH from its lattice upon ignition. While significant total suspended solids production weight increases did occur, they were generally lower than those realized during the synthetic sewage investigations. This is particularly evident when chemical dosage is taken into consideration.

Favorable SVI decreases were again experienced from the addition of aluminum sulfate. With dosages of 335 mg/L, the total sludge production volumes were consistently less than 70 per cent of those expected from comparable biological systems.

TABLE XXXIII

SLUDGE PRODUCTION--COMPLETE DOMESTIC SEWAGE INVESTIGATIONS

Run Code	Sludge Production ($lb/lb\ BOD_5$ Removed[a]) VS	IS	SS	Solids Age (days)	Production Weight Ratio[b] Act. SS_{CPR}/Exp'd $SS_{Biol.}$	SVI (ml/g)	Production Volume Ratio[c] $SS_{CPR}/SS_{Biol.}$
DS-CR[d]	0.482	0.080	0.562	3.55	1.00	181	1.00
DS Phase 1							
DS-PS2-6.6-1.88:1	0.641	0.375	1.02	3.54	1.81	110	1.10
DS-PS2-6.5-2.37:1	0.753	0.466	1.22	3.27	2.11	54	0.63
DS-PS2-6.6-2.08:1	0.963	0.702	1.66	2.34	2.53	---	---
DS Phase 2							
DS-PS3A-6.1-2.42:1	0.627	0.427	1.05	3.56	1.88	48	0.50
DS-PS3B-6.0-2.44:1	0.658	0.410	1.07	3.21	1.84	64	0.65
DS-PS3B-6.8-1.87:1	0.603	0.319	0.922	3.36	1.68	125	1.16

[a] BOD_5 removal based on BOD_5 at beginning of storage (initial BOD_5) and filtered effluent BOD_5.

[b] Corrected for solids age.

[c] Ratio of SVI_s times weight ratio.

[d] Sludge production was measured over last 11 days. The solids age over this period was 3.55 days in comparison to 3.46 for the entire 12-day period.

Figure 24. Volatile solids production as a function of BOD_5 removal and solids age--literature and complete synthetic sewage and domestic sewage investigation data.

Biological Sludge

Present Investigation

- ○ SS-CR
- △ DS-CR

Literature

- + Wuhrman (75)
- × McCarty & Broderson (37)
- Kehr & v.d. Emde (25,72)
- Blain (4)
- Lamb (30)

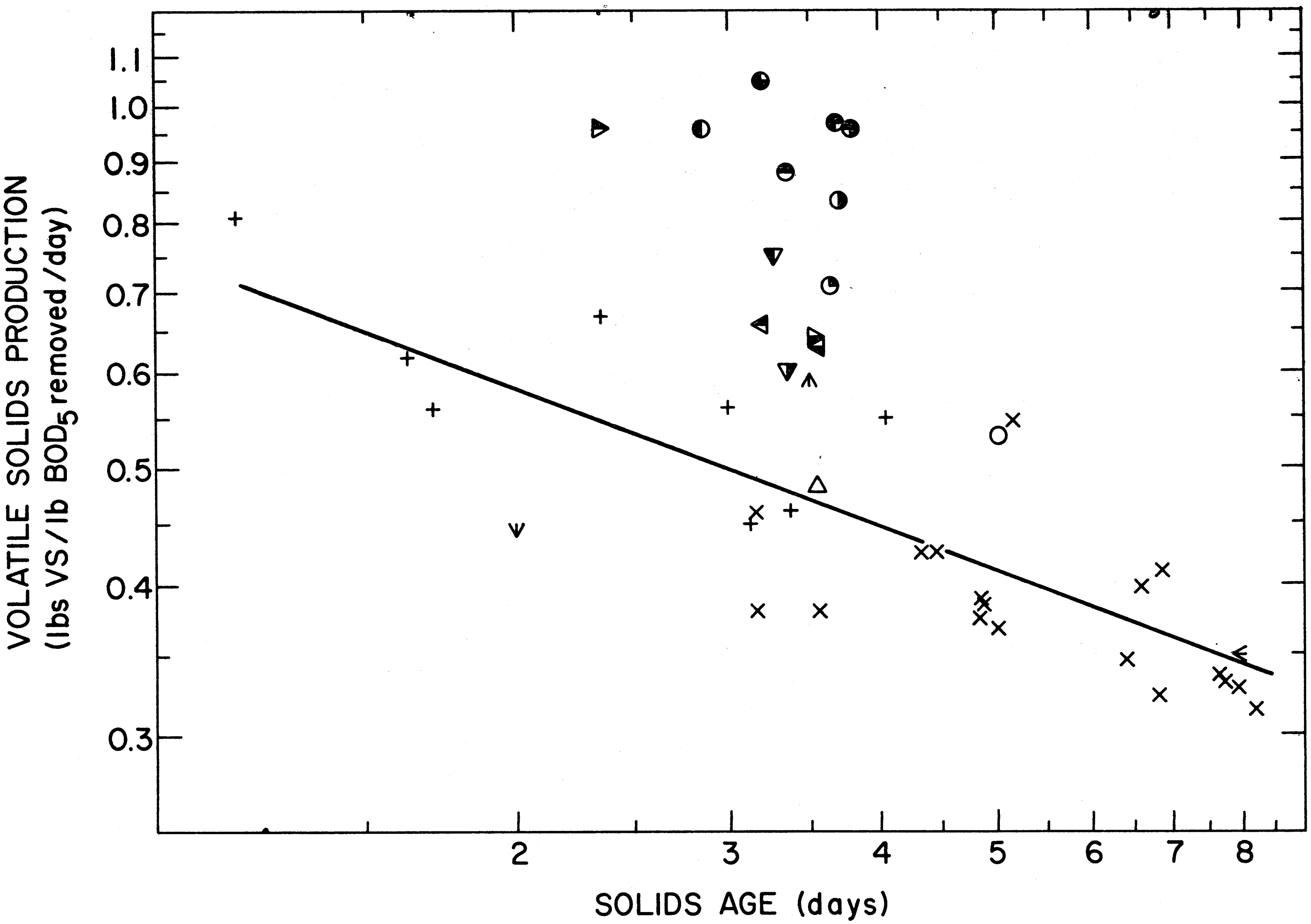
Biological-Chemical Sludge

Synthetic Sewage Investigations

- SS-PS1-5.5-1:1
- SS-PS1-6.5-1.5:1
- SS-PS1-5.5-1.5:1A
- SS-PS1-5.5-1.5:1B
- SS-PS1-5.5-1.75:1
- SS-PS2-5.5-1.75:1
- SS-PS1-6.5-1.75:1

Domestic Sewage Investigations

- DS-PS3B-6.8-1.87:1
- DS-PS2-6.6-1.88:1
- DS-PS2-6.6-2.08:1
- DS-PS2-6.5-2.37:1
- DS-PS3A-6.1-2.42:1
- DS-PS3B-6.0-2.44:1


VOLATILE SOLIDS PRODUCTION
(lbs VS/lb BOD_5 removed/day)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
2
3
4
5
6
7
8
SOLIDS AGE (days)

GENERAL DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

GENERAL DISCUSSION

Detailed discussions of the results of these investigations and comparisons of the findings with those of earlier works have been included in previous sections of this dissertation. The general discussion at hand will avoid repetition of this material and will deal primarily with the overall performance and applicability of the investigated process.

The unit process studies were most revealing with respect to the delineation of a final process schematic. Both the synthetic and domestic sewage investigations indicated that a separate flocculation basin as included in PS1 is not necessary. The former work suggested that both mixing and flocculation could be satisfactorily accomplished in a complete mixing aeration basin, whereas the latter indicated that they should be effected shortly before entrance of the mixed liquor to the final clarifier. It is interesting to note that Thomas (E. A. Thomas, personal communication) on the basis of full-scale studies found it usually better to add $FeCl_3$-$FeSO_4$ to the transmission line between the aeration and final clarification basins than to the influent line of the aerator. The indicated difference in the flocculation characteristics of the synthetic and domestic sewages cannot be explained from the work reported herein although one major difference between the two substrates--the greater inorganic complex phosphate content of the domestic sewage--may have been a contributing factor. The work completed, however, does suggest that the most favorable point of chemical application would be to the effluent line of the aeration basin or perhaps with plug flow, which exists with most conventional activated sludge plants, to the aeration basin near the effluent end.

Employment of the foregoing scheme with a combined aeration, mixing-flocculation, and clarification theoretical detention time of only 4.16 hours and 335 mg/L of aluminum sulfate produced phosphorus, BOD_5 and suspended solids residuals and removals, respectively of 1.6 mg PO_4/L and 95.9 per cent; 20 mg BOD_5/L and 92.3 per cent; and 18 mg SS/L and 85.4 per cent. In comparison, conventional activated sludge treatment with a combined aeration and clarification theoretical detention period of 8-10 hours might produce from the same domestic sewage primary effluent residuals and removals of 32 mg PO_4/L and 18 per cent; 22 mg BOD_5/L and 92 per cent; and 18 mg SS/L and 85 per cent. The only significant difference in performance between the two processes would be the greater phosphorus removal resulting from chemical treatment. Accordingly, the savings realized from a reduction in required basin volume for the biological-chemical process can be applied directly toward offsetting chemical treatment costs.

Sludge production is a most important consideration in the evaluation of a waste treatment process. The data of Table XXXIII compare production during the biological-chemical process with that expected for a biological process having an equivalent solids age. Therefore, the ratios given are not directly applicable for a comparison between the biological-chemical process and conventional activated sludge since the latter is typically operated at higher solids ages. Using the data given for DS-PS3A-6.1-2.42:1 with a solids age of 3.56 days and an aluminum sulfate dosage of 335 mg/L, the sludge production versus solids age relationship (EQ. 12), and a solids age and SVI for conventional activated sludge of five days and 100 (typical of very satisfactory operation [18]), it is calculated that the biological-chemical to conventional total sludge weight and volume production ratios are 2.13 and 1.02, respectively, and that the <u>biological</u> sludge weight production ratio is 1.14. Accordingly, under the conditions stated, the volumes of sludge produced would be about equal. This is similar to the finding of Thomas (67) who reported that sludge volume production following ferric chloride -ferric sulfate addition was within the normal range experienced without chemical additions. The biological volatile solids production ratio of 1.14 would not significantly increase digester organic loadings. Assuming that 65 per cent of the weight of organic sludge entering a digester originates at the primary clarifier, the organic loading would increase by approximately five per cent.

Two other important considerations relative to the sludge produced by the biological-chemical process are its ability to be dewatered and the effect of anaerobic digestion on the forms of bound phosphorus. Regularly performed filtration of the sludge revealed it dewatered easily. This was likewise observed for the iron containing sludge of Thomas (67). Barth and Ettinger (1) reported that the identity of phosphorus precipitated using aluminum did not change during anaerobic digestion and, therefore, precipitated phosphorus was not released. Finally, the finding of Thomas (68) that the anaerobic digester supernatant from the biological-chemical sludge contained less phosphorus than that of a control, apparently because any unreacted iron present precipitated the phosphorus released biologically, would most likely apply during digestion of the sludge discussed herein.

The total phosphate residual attained without filtration, 1.6 mg PO_4/L, compares favorably with the corresponding values of the processes summarized in Table III. In addition, although produced from significantly higher influent levels, it is essentially equivalent to the residuals obtained by other combined biological-chemical processes--1.85 and 1.89 mg PO_4/L by Thomas (67, 68) at Männedorf and Uster, respectively, and 1.53 mg PO_4/L by Barth and Ettinger (1). Its acceptability with respect to minimizing eutrophication, however, depends not on its relative standing with residuals produced by others, but on the type and local nature of the receiving water, its existing phosphorus background level, and the dilution factor involved.

Assuming a receiving water total available phosphorus concentration of 0.03 mg PO_4/L or less is desired, a background level of 0.01 mg PO_4/L exists, and a dilution of one part effluent to nine parts receiving water is available, an effluent total available phosphorus concentration of approximately 0.2 mg PO_4/L is required. It is evident that, under these conditions and the equivocal assumption that the majority of the phosphorus present is available for algal and aquatic plant growth, the unfiltered effluent concentration of 1.6 mg PO_4/L would be unacceptable. However, the effluent level with filtration, approximately 0.08 mg PO_4/L (average of DS-PS3A-6.1-2.42:1 and DS-PS3B-6.0-2.44:1), would safely meet the requirement. This example illustrates that a prerequisite for the judicious employment of this process is knowledge of the receiving water permissible phosphorus concentration, the existing background level, and the availabilities of the various forms of effluent phosphorus as nutrients. This approach would provide a quantitative basis for deciding whether the process can be applied successfully, if so, whether or not filtration is required, and finally, with filtration, what precipitant dosage is necessary. With respect to the latter, not only aluminum sulfate but other biologically compatible chemicals such as ferric chloride, ferric sulfate, and sodium aluminate should be given consideration.

CONCLUSIONS

In view of the experimental findings of the present study and of previous related work it can be concluded that:

1. Essentially complete soluble phosphorus removals are attainable by the combined biological-chemical process studied. The removal efficiency is dependent upon pH and the Al:P molar ratio. In this study an Al:P ratio of 1.5 to 2:1 was necessary to effect almost complete removals.
2. Without filtration, the phosphorus content of the combined process effluent is dependent both upon soluble levels and suspended solids concentrations. For the domestic sewage investigative conditions an aluminum sulfate dosage in excess of that necessary to produce a low soluble residual was required to effect satisfactory flocculation and clarification.

3. The biological performance of the activated sludge as measured by soluble organic substrate removal was not adversely affected by additions of aluminum sulfate as high as 335 mg/L. Moreover, the aluminum sulfate itself did not effect significant removals of soluble BOD_5 or LAS.
4. The addition of aluminum sulfate favorably decreased the SVI of the HRAS mixed liquor.
5. In addition to significantly increased phosphorus removals, the biological-chemical process investigated offers the advantages of increased BOD_5 (unfiltered effluent) and suspended solids removals over those of a HRAS process operating under similar conditions without aluminum sulfate addition. In comparing sludge production between the two, the former at optimum chemical dosage would produce more sludge by weight and less sludge by volume.
6. The BOD_5 (unfiltered effluent) and suspended solids removals of the combined process under the conditions of the present study and a typical conventional activated sludge process would be approximately the same. The volumes of sludge produced by the two would likewise be approximately identical, whereas the former process would produce a greater weight of sludge. The combined process, naturally, would produce significantly lower phosphorus residuals.
7. The combined process does not require a separate flocculation basin for effective performance. With domestic

sewage, however, the point of chemical application and time of flocculation require consideration.

8. The theoretical aeration period required by the biological-chemical process investigated is from one-third to one-half that employed typically with conventional activated sludge. The savings realized from the decreased detention time will at least partially offset the costs of chemical treatment.
9. The conventional MLVS parameter was not an acceptable measure of biological mass in the biological-chemical system investigated.
10. In both the HRAS and combined biological-chemical systems studied, the LAS removals were excellent and essentially equal to the associated BOD_5 removals.

RECOMMENDATIONS FOR FURTHER RESEARCH

Several areas for future investigation are warranted by the observations and findings of this study.

1. Performance under biological loading factors (LF) significantly higher than those of this study should be investigated.
2. The influence of the process variables--chemical dosage, pH, and solids age--on nitrification should be evaluated.
3. The capability of the various forms of effluent phosphorus to support algal and aquatic plant growth should be determined.

4. Performance of the process under field conditions, pilot plant or full-scale, should be evaluated. The field studies should consider methods of sludge treatment and disposal.

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