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"PHOSPHORUS REMOVAL USING CHEMICAL COAGULATION AND A CONTINUOUS COUNTERCURRENT FILTRATION PROCESS"

U.S. DEPARTMENT OF THE INTERIOR • FEDERAL WATER QUALITY ADMINISTRATION

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PHOSPHORUS REMOVAL USING CHEMICAL COAGULATION AND A CONTINUOUS COUNTERCURRENT FILTRATION PROCESS

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ABSTRACT

The Johns-Manville Moving Bed Filter, a continuous precipitation and countercurrent filtration process, was evaluated for the removal of phosphorus from municipal wastewater.

Using alum and an anionic polyelectrolyte, the process was found to effectively reduce total phosphorus (TP), orthophosphate (OP) and condensed phosphate (CP) over a wide range of influent phosphorus concentrations. Preliminary work using jar tests established an alum dose of 200 mg/l (17.4 mg/l Al, molar ratio of Al/P is 27/31) as effective for removal of 90 per cent TP from the secondary clarifier effluent of a trickling filter plant. This removal efficiency could not be sustained with an alum dose of 200 mg/l when higher TP levels were encountered. With total phosphorus concentrations on the order of 25 to 28 mg/l as P (Al/P = 0.6-0.7), the TP removal efficiency averaged 90 per cent. With lower total phosphorus concentrations, removal efficiency averaged 95 per cent and ranged up to 99 per cent (Al/P = 1.2-2.6).

Substantial reductions in final effluent total suspended solids (TSS) and 5-day biochemical oxygen demand (BOD_5) were also obtained. At an alum dose of 200 mg/l, TSS reduction averaged 70 per cent and BOD_5 reduction 80 per cent. If phosphorus removal were not a design consideration, the reduction of TSS and BOD_5 could be achieved with lower alum doses.

The 200 mg/l alum dose was also found to be equally effective for removal of phosphorus from raw sewage and primary effluent with the added capability for removing substantial portions of the TSS and BOD_5. In short studies on these streams, effluent as good or better than the final effluent from the trickling plant was obtained.

Costs for a 1.0 MGD plant are estimated to be $264,000 for capital and 12.0 cents per 1000 gal. for total operating cost. These costs would be about the same for raw sewage, final effluent or the two intermediate levels of prior treatment studied.

Ultimate disposal of the phosphorus-containing sludge could be achieved by a dewatering and landfill operation. Dewatering by means of a rotary vacuum precoat filter would require an estimated capital expenditure of $30,000 and total cost would be 3 cents per 1000 gal. of original wastewater treated.

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CONCLUSIONS

From the foregoing reported data, the following are concluded:

1. The MBF in combination with alum precipitation and an anionic polyelectrolyte effectively removed phosphorus from raw sewage, primary effluent, unsettled trickling filter effluent and final clarifier effluent.

2. The MBF under the same conditions effected substantial removals of TSS and BOD_5 from each of the above feed streams.

3. Preliminary data for raw sewage and primary effluent treatment indicate the capability for producing a filtered effluent as good or better in quality than the existing trickling filter plant with the added advantage of phosphorus removal.

4. The study program arrived at an alum dose of 200 mg/l which resulted in effective precipitation of phosphorus over a wide range of influent concentrations; however, even this dose was not sufficient to insure complete precipitation of phosphorus at the highest concentrations encountered and this is reflected in the residual phosphorus content of the MBF effluent.

    a. Initial TP concentrations below about 10-12 mg/l were reduced on the average about 95 per cent.

    b. Initial TP concentrations between about 12-15 and 20-25 mg/l were reduced at least 90 per cent with values to 95 per cent.

    c. Initial TP concentrations above 20-25 mg/l were reduced an average of 90 per cent with all values above 85 per cent for initial concentrations ranging up to 28 mg/l.

5. Removal of CP even at fairly high concentrations appeared to be particularly effective.

6. While an alum dose of 200 mg/l effectively reduced phosphorus over a wide range of Al/P ratios, it was found quite consistently for the limited number of data available that lower alum doses and the same Al/P ratios were much less effective.

7. In the treatment of final effluent to remove phosphorus, approximately 70 per cent of the TSS and 80 per cent of the BOD_5 were also removed. Average values in the treated effluent were 15 and 6.4 mg/l, respectively.

8. Alum doses as low as 100 mg/l removed on the average 50 per cent of the TSS and 70 per cent of the BOD_5 from the settled trickling filter effluent.

9. Capital costs of a 1.0 MGD installation in a mild climate location are estimated to be $264,000. Capital costs per million gallon would decrease with increasingly larger installations.

10. Total operating cost for a 1.0 MGD plant with a 200 mg/l alum dosage is estimated to be 12.0 cents per 1000 gal. treated. These costs would apply for treatment of raw sewage and primary effluent as well as trickling filter effluent.

11. Final concentrations of the phosphorus-containing sludge were not well established, but using a defensible 1.5 per cent solids in 10,000 gal. per day (from a 1.0 MGD plant), the phosphorus-containing solids can be reduced to a damp solid suitable for landfill by rotary vacuum precoat filtration for an estimated total cost of 3.0 cents per 1000 gal. of original wastewater treated.

RECOMMENDATIONS

The data from the processing of raw sewage and primary effluent appear to represent a significant advance in treatment capability with substantial removals of TSS and BOD_5 obtained simultaneously with phosphorus removal without prior biological treatment. However, the data base contained in this report for each of these types of wastewater feed is very limited.

The following are therefore recommended:

1. That additional one-month periods of operation of the pilot plant be carried out for primary effluent and for raw sewage to provide information on an extended range of influent conditions.

2. Moving Bed Filtration followed by granular carbon adsorption is a complete physical-chemical treatment system which could provide a high quality effluent. An additional study should be made in which:

    a. The effluent from a test series such as that proposed above be passed through beds of granular activated carbon to determine the extent of removal of the remaining organic matter.

    b. The filtering medium in the MBF be changed to granular activated carbon to determine its potential for a simultaneous continuous filtration and sorption medium. The treatment system described in Recommendation 2 represents a potentially important non-biological treatment alternative for the treatment of municipal wastewater.

INTRODUCTION

Objectives

This study was undertaken to evaluate the Johns-Manville Moving Bed Filter* process as a means for the continuous removal of phosphorus from typical municipal wastewater. Previous pilot plant studies by the contractor indicated the possibility for better-than-usual utilization of alum for phosphorus removal, possibly as the result of a depth-filtration mechanism, and also indicated a capability for handling wide variations in influent quality

Accordingly, the objectives of this program were:

(1) to operate on a pilot plant scale for a sufficient time to optimize precipitation, coagulation, flocculation and filtration for removal of phosphorus,

(2) to determine at what levels of prior wastewater treatment the process would be feasible, and

(3) to provide bases for estimates of capital and operating costs.

Background

Nutrients discharged to waterways are coming to be recognized as a major pollution problem. Traditionally "pollution" has been regarded as biodegradable materials which deplete oxygen in receiving waters and materials which have toxic or unsightly effects on these waters. More recently, as the emphasis has increased on providing better treatment to overcome this traditional pollution, there is a growing awareness on the role of nutrients as a different form of pollution generally not removed by present sewage treatment practices.[1]

"Nutrients" usually mean compounds of phosphorus and nitrogen which tend to fertilize receiving waters and thereby cause wild and uncontrollable growths of algae and other aquatic biota in a process called eutrophication. This not only results in unsightly appearance but causes important changes in the ecological balance in such waters and greatly decreases their utility. There is a growing demand for removal or at least reduction of the amount of these being discharged to waterways.[2, 3]

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*Johns-Manville patent pending.

Removal of phosphorus compounds has received initial emphasis for two reasons:

(1) phosphorus is easier to remove since it forms insoluble compounds, and the chemistry seems straightforward with a relatively limited number of options, and

(2) some blue-green algae have the capability of fixing nitrogen from the atmosphere so that phosphorus becomes the limiting nutrient in their life cycle.[3]

To date there appears to be no general agreement as to the level to which phosphorus must be reduced before the effluent can be discharged. Dryden[4] originally proposed a limit of 2 mg/l as PO_4 (0.65 mg/l as P) for a recreational lake supply but later revised this down to 0.5 mg/l as PO_4 (0.16 mg/l as P) as necessary to prevent regrowth of algae. On the other hand, an agreed upon clean-up program for Lake Michigan[2] recommended removal of at least 80 per cent of all phosphorus from treated wastewater. This permits substantially higher levels to be discharged than those cited above, presumably by allowing for dilution by the lake water to reduce overall concentrations below nuisance levels.

A recent summary[5] effectively covers the current state of the art with respect to both biological and chemical methods of phosphorus reduction placing the various options in perspective. The present studies were concerned only with chemical precipitation and more particularly with alum, i.e., aluminum sulfate, as the precipitant and the subsequent separation of the precipitated material and other solids which may have phosphorus associated with them from the substrate by filtration. A polyelectrolyte was used to facilitate the filtration step of the process.

MOVING BED FILTER PROCESS

Description of Process Operation

A treatment process employing the Moving Bed Filter, hereafter referred to as MBF, includes chemical precipitation and coagulation directly followed by filtration through a filter bed. The key component in the process is a unique filter designed to provide continuous countercurrent filtration even under high solids loading. Figure 1 is a schematic flow diagram of the MBF process. The principle of operation is as follows:

The chemicals are added directly to the influent wastewater line. Precipitation, coagulation and flocculation of solids occur in the head tank. The dosage of coagulant can be varied depending upon the nature of the waste to be treated and the quality of effluent desired. The head tank provides for four functions:

(1) it serves as a precipitation and flocculation chamber;

(2) it provides the necessary head for gravity feed through the filter bed;

(3) it provides some surge capacity; and

(4) the conical bottom of the head tank provides for collection of the spent filter medium and sludge.

The filter medium, usually sand, is contained in a tubular shell and is driven in one direction while the wastewater being treated passes through the filter bed in the opposite direction. The filtering action occurs throughout the depth of the bed as well as at its face. Filtered water flows out of the bed through discharge screens located on the side of the filter shell. Solids which have been removed are driven along with the filter medium toward the head tank and subsequently are removed from the filter face as rapidly as is required by their buildup. Movement of the filter medium is accomplished by means of an hydraulically operated diaphragm. The diaphragm pushes the bed as a plug toward the inlet, or filter face, end. As the diaphragm relaxes, clean sand feeds by gravity into the void left in the bed in front of the diaphragm. This cycle is then repeated with the next pulse of the diaphragm. The frequency of pulsing, and thus the rate of sand drive, can be varied depending upon optimizing the various filtration factors and is controlled by the rate of change of level in the head tank.

The sludge-sand mixture hydraulically or mechanically removed from the filtering face falls down into the hopper bottom of the head tank. This mixture is transferred to a washing column for cleaning. The clean sand

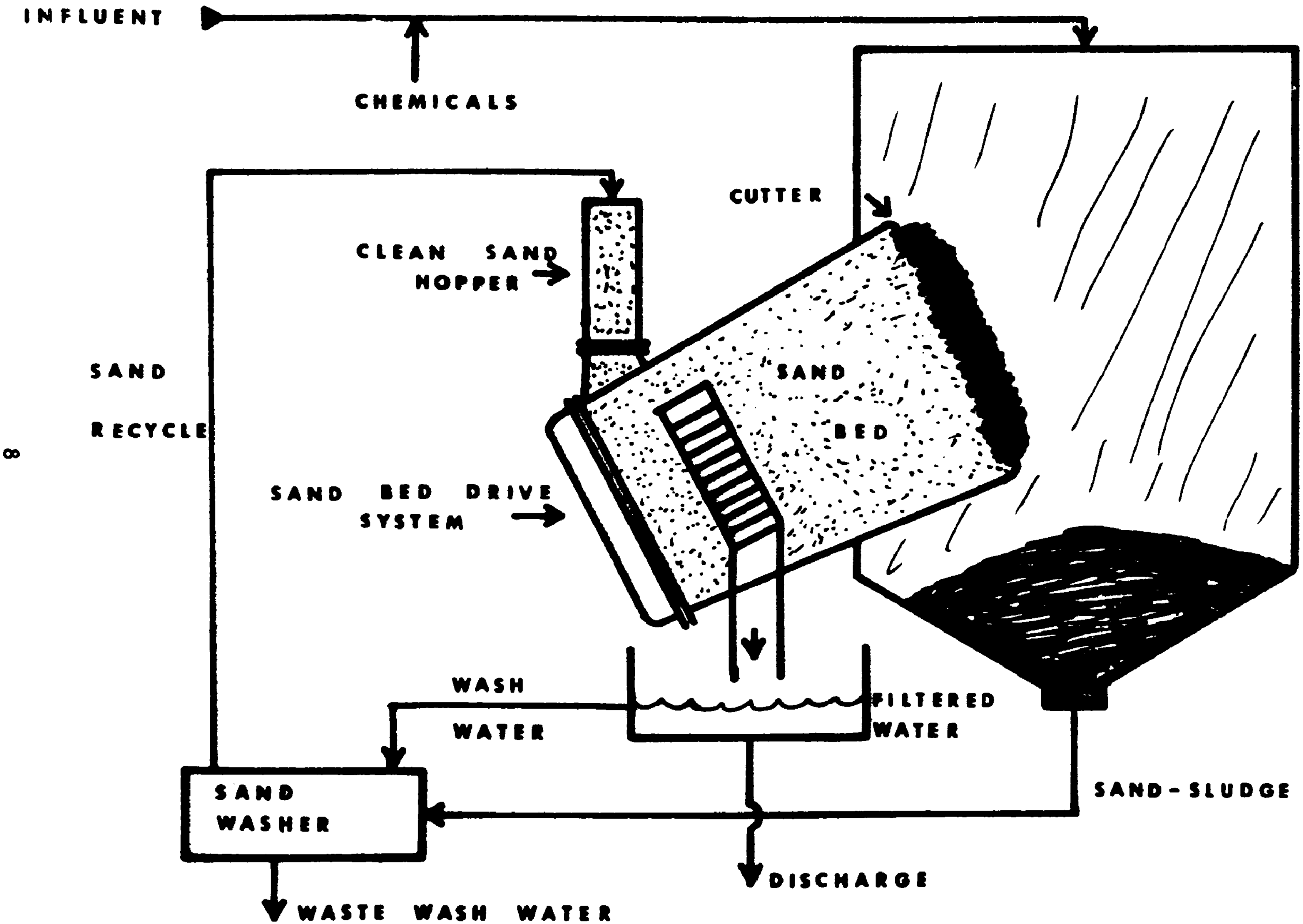

FIGURE 1. BASIC CONCEPT OF MOVING BED FILTER

is then returned by gravity to the hopper of the MBF. The removal and washing of the sand may be intermittent or continuous. Final washing of the sand is accomplished by means of filtered effluent. Since the sand is removed, cleaned and then returned to the system, the filtration process is not interrupted for backwashing as it is in conventional practice. The waste wash water flows into a settling tank where the sludge is concentrated prior to dewatering. The overflow, or supernatant, is recycled to the influent line of the MBF.

MBF Pilot Plant

The pilot plant unit used in this study consists of a single tubular filter bed having the following dimensions: diameter at water inlet end - 30 inches; average diameter of tube - 27 inches; total length of bed - 68 inches; bed depth, face to screen center - 50 inches; maximum cross-sectional area - 4.9 square feet; volume of sand contained within the shell - 20 cubic feet.

The filter medium used in all these studies was a commercially available filter grade sand. Grain size distribution of this sand was determined by screening through U. S. Standard sieves, and the sand was found to have a 10 per cent effective size of approximately 0.8 mm and a uniformity coefficient of 1.2. This is much coarser than the sand generally used in fixed bed rapid sand filtration.

Wastewater was delivered directly to the pilot plant unit by means of a self-priming centrifugal pump. The flow was determined by means of a variable area flow meter and the rate of flow was controlled by means of a valve on the discharge side of the pump. The waste was pumped to the top of the head tank where alum was injected into the influent line. Mixing and flocculation of the waste occurred within the head tank, prior to filtration. Figure 2 shows the MBF pilot plant during installation and prior to erection of the building around it.

A polyelectrolyte was used as a filter conditioner to control the depth of floc penetration. The flocculated waste passed down through the filter bed and out through the water outlet screens. The water outlet consisted of two screened slots, each 5-1/4 inches wide with a curved length of 17 inches, located along the sides of the filter shell.

Various auxiliary equipment included in the pilot plant installation were chemical solution tanks, mixers and feed pumps which allowed the application of two separate chemicals simultaneously. Also included was a 200-gallon storage tank for filtered water, part of which was reused for washing the spent sand and for the face cutting mechanism. The sand washing system was initiated by the frequency at which the bed was pulsed. The various steps within the wash cycle, that is, withdrawal of the sand and sludge, washing of the sand and sludge, return of the clean sand to the filter feed hopper, were automatically controlled by means of a program timer. The waste wash water was discharged to a 500-gallon steel tank for settling.

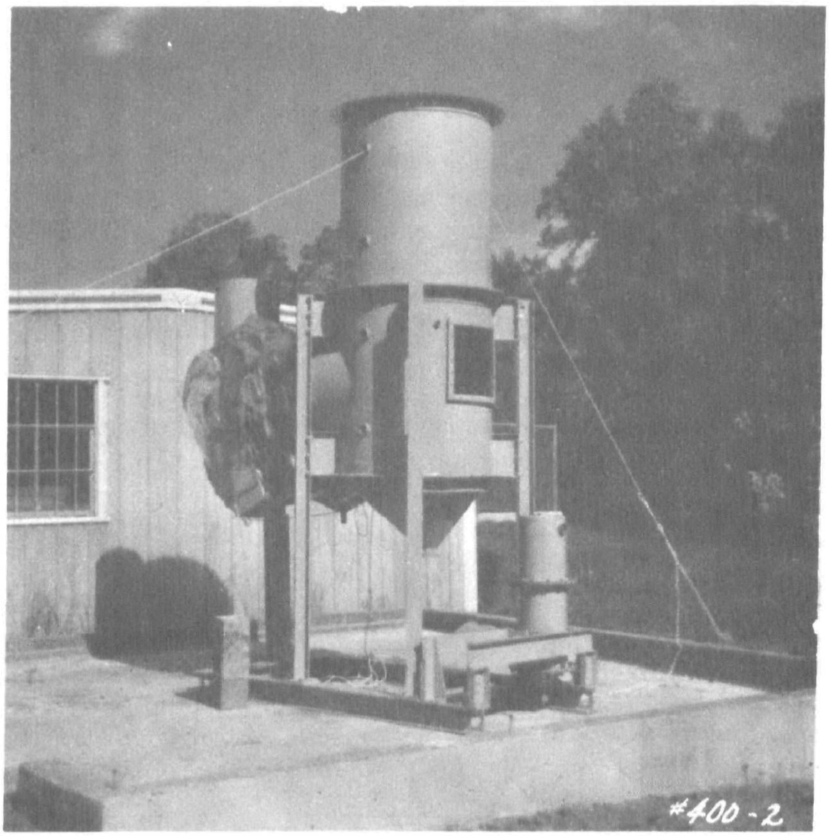

Figure 2. MBF PILOT PLANT UNDER CONSTRUCTION

MBF PILOT PLANT STUDIES

Test Location

The MBF pilot plant was set up at the Township of Bernards Sewerage Authority Treatment Plant at Liberty Corner, New Jersey. Placed in service in 1964 with a design flow of 0.55 MGD, this plant consists of coarse bar screens, comminutors, Clarigester*, high rate trickling filter, final settling tank and chlorine contact tank. During the study period (3/69 to 10/69), the flow in the plant ranged from 0.3 to 2.5 MGD. Heated sludge digestion is provided with disposal of the digested sludge to sand drying beds and then as landfill.

This plant was selected from the several available in the area on the basis of fairly typical trickling filter plant performance as well as its convenience to necessary analytical facilities at the Johns-Manville Research & Engineering Center.

A flow diagram of the Bernards Township Sewerage Authority Plant is shown in Figure 3. Also included is the location of the pilot plant and the alternative locations at which its feed streams were obtained for the study program. Most of the work was done with effluent from the final settling tank, which for convenience has been designated "final effluent."

Experimental Procedures

Pilot Plant Operation. Operation of the pilot plant was substantially as described in the preceding process description. After an initial period for shakedown of the equipment and testing of the various analytical procedures, the pilot plant was put into routine operation during April of 1969. Initially operated only on the day shift, it was later placed on 24-hour, around-the-clock operation with personnel present only during the day shift. The general operating procedure was to maintain constant influent flow conditions and set the frequency of push at a predetermined interval in order to maintain relatively constant hydraulic head.

Data regarding operational parameters, such as flow, cycle time for forward sand movement and diaphragm retraction, level fluctuations in the head tank and within the filter bed, and turbidity and pH of feed and filtered effluent, were recorded during each experimental run.

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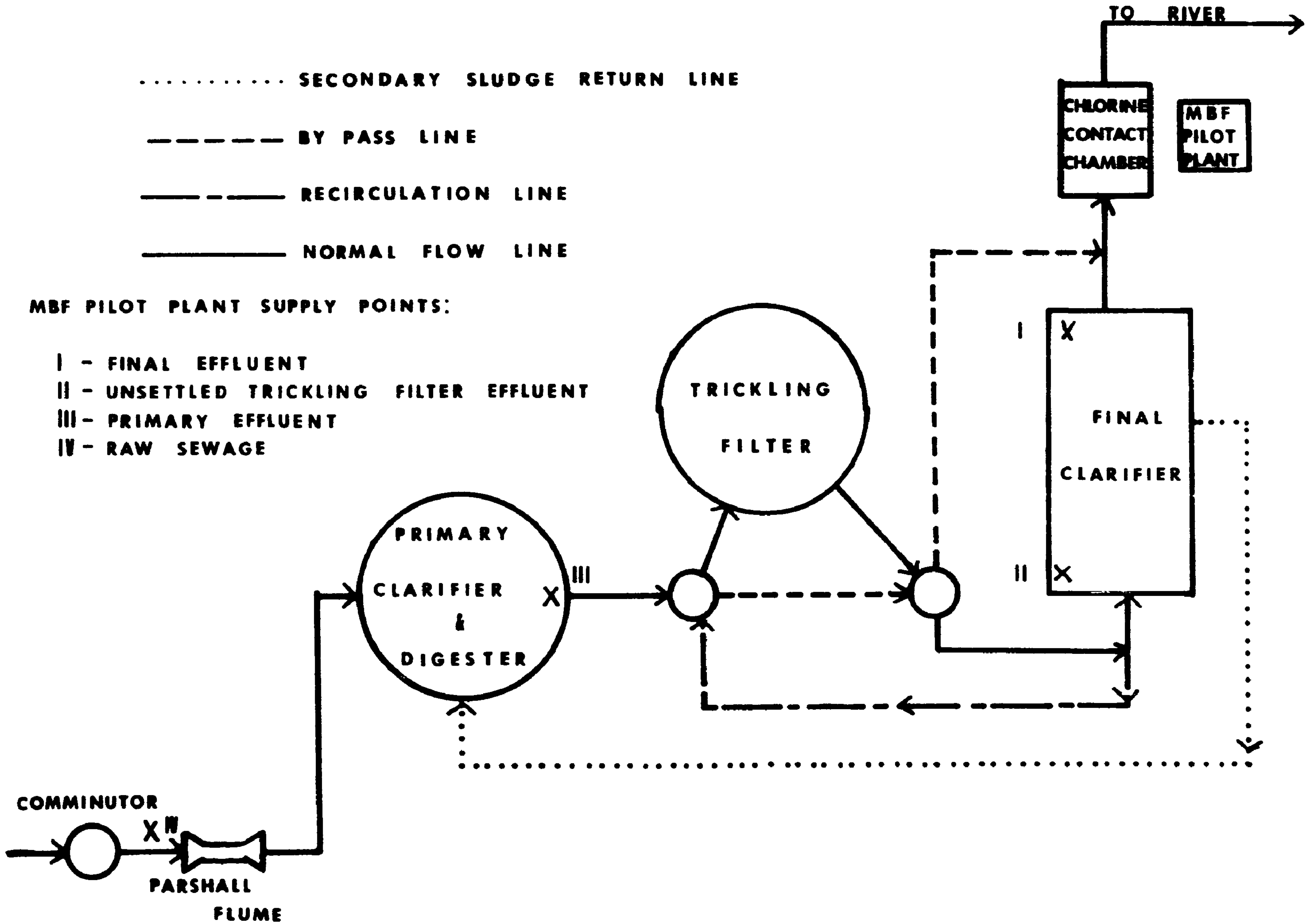

Figure 3. BERNARDS TOWNSHIP SEWAGE AUTHORITY PLANT

Chemicals Added. Alum was used as the primary coagulant throughout these studies. This was commercial filter grade aluminum sulfate with an Al_2O_3 concentration of 16.2 per cent by analysis. This corresponds to the formula $Al_2(SO_4)_3 \cdot 16H_2O$. To avoid possible problems due to evaporation or aging, alum feed solution of 5 per cent (wt) concentration was prepared approximately every other day. This solution was fed directly into the influent flow just before it discharged into the head tank. No attempt was made in this study to test other points of addition or means of mixing of the alum solution with the feed stream.

As noted earlier, a polyelectrolyte was used as a filter conditioner to improve floc retention within the filter. Several polyelectrolytes were evaluated; however, most of the reported results were obtained with one product.* Each polyelectrolyte was made up as an unheated stock solution of 0.25-0.5 per cent by weight and refrigerated. The stock solution was stored for no longer than one week. Each day a fresh 0.01 per cent feed solution of the particular polyelectrolyte was prepared as feed solution. Polyelectrolytes were added to the body of the liquid in the head tank at a point just in front of the filter face.

Sampling. Initially, composite samples of the influent and effluent of the MBF were collected daily by means of an automated sampling technique. These samples were composited over a 2-hour period and were taken during different times of the day in order to determine diurnal fluctuations in performance. In addition, manually composited samples were taken from the head tank and from the waste wash water settler overflow. Turbidity measurements were routinely made on grab samples taken from within the filter bed at 12-inch intervals and from the filter effluent. After the basic operating characteristics were established for a given experiment, the system performance was continuously monitored for periods of up to three days. During these monitoring studies, analyses were made on 6-hour composite samples. All samples were refrigerated until transportation to the laboratory for analysis.

Analytical Tests and Procedures

Summary of the analytical tests performed and the procedures used throughout this investigation is as follows:

Biochemical Oxygen Demand - 5-day BOD was determined in accordance with the recommended procedure in Standard Methods.[6]

Alkalinity - Total alkalinity titrations were made using mixed bromcresol green methyl red indicator. Results are expressed as $CaCO_3$.

*Magnifloc 860A - Product of American Cyanamid Company.

Filtration - Laboratory filtrations were performed using 9-cm Reeve Angel glass fiber filter pads.

pH - pH measurements were made using a Leeds & Northrup Model 7664 pH meter.

Suspended and Volatile Solids - All suspended solids and volatile solids analyses were carried out according to *Standard Methods* with the following modification: the solids were dried at 104C for 14-16 hours.

Turbidity - Turbidity measurements were made at the pilot plant site on all samples which were collected. Turbidity measurements were made with a Hach Model 1860 laboratory turbidimeter and expressed as Jackson Turbidity Units (JTU).

Phosphorus - The stannous chloride method for orthophosphate was used for all phosphorus determinations. Ten minutes were allowed for color development and readings were taken at a wavelength of 690 mu using a Bausch and Lomb Spectronic 20 colorimeter.

Total phosphorus was determined by acidification and digestion of the samples to convert the condensed phosphates and organic phosphorus to orthophosphates. Persulfate was used as a catalyst. The following analytical scheme was used for the delineation of phosphorus forms of the various effluents:

Complete Sample

A	Filter sample through 9-cm Reeve Angel glass fiber filter pad	
Acid hydrolysis with persulfate then orthophosphate unfiltered determination	Filtrate	
	B	C
	Acid hydrolysis with persulfate then orthophosphate determination	Orthophosphate filtered determination

The analytical results are designated throughout this report as:

TP	Total Phosphorus	Scheme A
TFP	Total Filterable Phosphorus	Scheme B
OP	Orthophosphate, Soluble	Scheme C
CP	Condensed or Polyphosphates	Schemes B-C

The stannous chloride method for determination of phosphate was used because of its sensitivity at low levels (< 0.1 ppm) of orthophosphate. This method, however, is also highly sensitive to temperature, humidity and pH of the sample. As a result, two separate standard curves had to be generated; one for digested samples, one for undigested samples. Even with separate curves, there were in many instances discrepancies between the ortho and total filterable phosphorus values with OP greater than TFP (and in some cases greater than TP).

PHASE I - MBF TREATMENT OF FINAL EFFLUENT

Experimental Plan

Each of the various unit operations which make up the MBF process was given consideration in the initial experimental plan. Since this study is primarily concerned with phosphorus removal, the plan was set up in terms of this objective. However, other characteristics of the MBF feed and product (filtered) water were also determined to provide a broader evaluation of the process for treatment of trickling filter treated and untreated wastewater.

For this study, phosphorus removal was thought of as a series of interrelated steps:

(1) precipitation,

(2) coagulation-flocculation,

(3) filtration,

(4) removed solids-filter medium separation, and

(5) solids concentration for ultimate disposal.

A thorough analysis of phosphorus insolubilization and removal was possible with the pilot plant equipment. Factors of scale, however, precluded an intensive investigation of sludge characteristics and disposal.

The experimental plan for studying phosphorus removal from final effluent included several operations, some of which proceeded simultaneously, and which covered a period of four to five months:

1. Jar testing to:

   a. Determine the probable levels of alum addition required for various degrees of phosphorus insolubilization.

   b. Compare the pilot plant precipitation with that expected from laboratory procedures.

   c. Provide baseline data for various levels of the phosphorus forms designated in this report as TFP, OP, TP and CP.

   d. Determine probable levels of anionic polyelectrolyte addition required to produce filterable "floc" or filter conditioning needed for effective removal of the insoluble phosphorus.

2. Pilot plant operation to determine the level of phosphorus removal at various levels of alum addition.

3. Pilot plant operation at an alum feed level selected from Step 2 for a period of time to insure effective removal of phosphorus over a wide range of influent conditions.

4. Continuous operation of the pilot plant for two to three days to:

   a. Generate information on diurnal variations in the various plant and pilot plant parameters.

   b. Generate data for estimation of operating and capital costs.

Experimental Results

Jar Tests. Figure 4 illustrates the typical, and expected, relationship between levels of alum addition and OP and TP precipitation from final effluent. On the basis of an influent TP level of 8.2 mg/l, an alum dosage at least 150 mg/l (13 mg/l as Al) would be the expected requirement to reduce P to less than 1 mg/l, even though the alum demand was found to be somewhat lower to effect substantially complete precipitation of OP.

Also, as expected, other jar test and MBF operating data show that the alum requirement is influenced to some extent by the levels of phosphorus in the final effluent used as the MBF process feed. These levels were found to cover quite a wide range as an uncontrollable variable, as will be shown in later discussion.

Selection of MBF Alum Feed Level. Based on the jar tests, a number of replicate pilot plant runs were made covering alum feed levels from 100 to 250 mg/l. These runs, summarized in Table 1, also demonstrate the expected relationship between alum dose and phosphorus reduction. From these data, an alum dose of 200 mg/l (17.4 mg/l as Al^{+++}) was selected for longer-term study.

Jar Tests Versus MBF Performance. A number of simultaneous jar tests were made during MBF pilot plant runs at various alum feed levels. Purposes of these tests were:

(1) to compare MBF precipitation and removal with that obtained by laboratory jar test precipitation, and

(2) to provide some basis for delineation of phosphorus in the precipitation process as TP, TFP and OP.

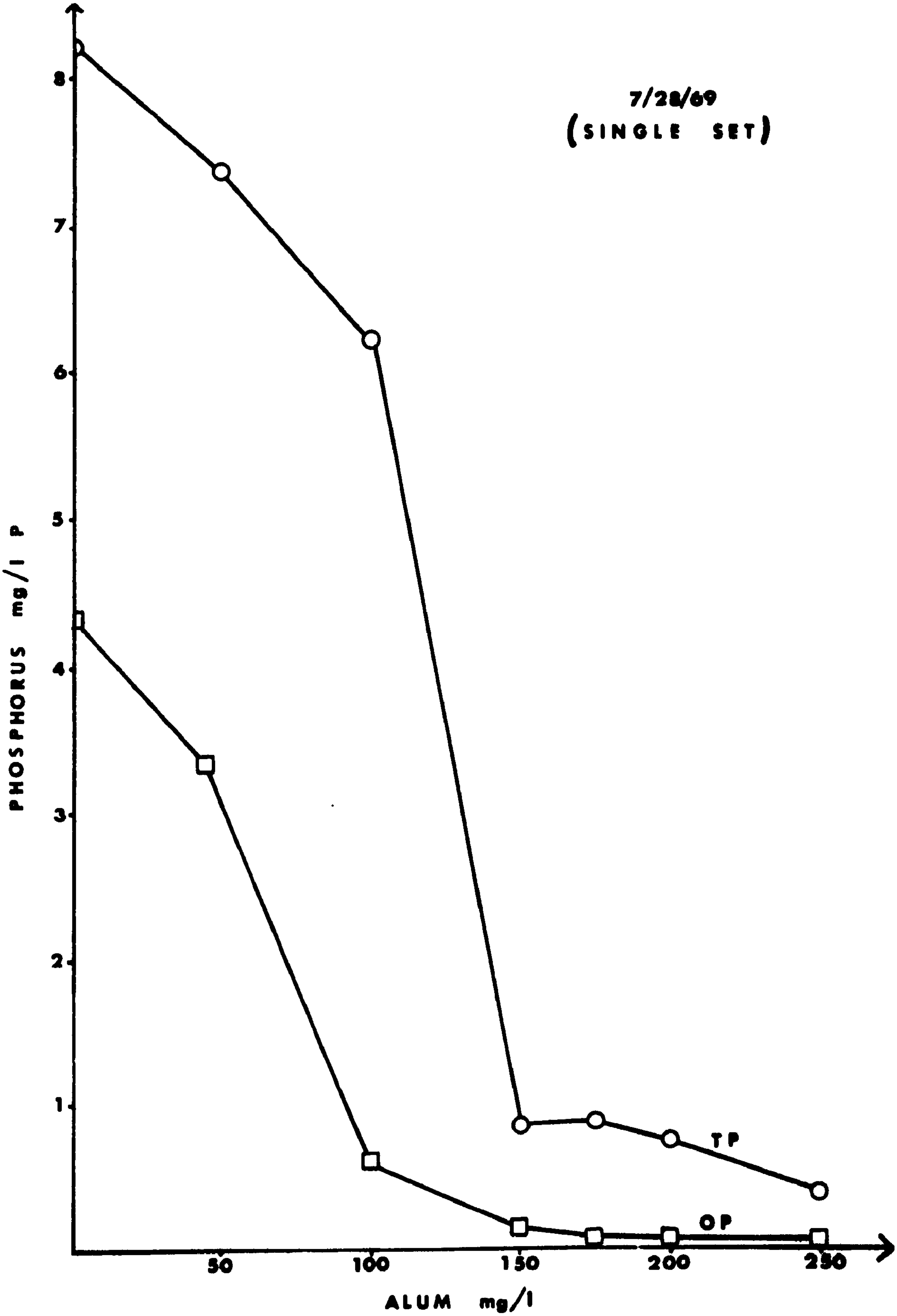

FIGURE 4. JAR TESTS ON SECONDARY CLARIFIER EFFLUENT

Table 1.

SUMMARY OF PHOSPHORUS REMOVAL FROM FINAL EFFLUENT

	Phosphorus Concentration - mg/l as P				Avg. Reduction (%)	No. of Obs.	Avg. Al/P Molar Ratio
	Secondary Effluent		MBF Effluent				
	Range	Avg.	Range	Avg.			
Alum Dosage - 100 mg/l; Anionic Polyelectrolyte - 0.5 mg/l to 0.75 mg/l						17	
Total	4.2 - 19.4	12.0	0.35 - 9.5	5.40	59.0		0.83
Filterable	3.4 - 17.8	10.5	0.13 - 7.2	3.29	63.0		0.94
Ortho	2.8 - 14.6	8.5	0.07 - 7.1	2.88	72.2		1.16
Alum Dosage - 150 mg/l; Anionic Polyelectrolyte - 0.5 mg/l to 0.75 mg/l						21	
Total	13.5 - 21.6	16.5	2.2 - 10.0	5.35	67.2		0.90
Filterable	13.0 - 19.8	15.5	1.7 - 7.1	3.25	79.0		0.96
Ortho	12.3 - 17.1	13.6	1.4 - 6.9	3.07	75.7		1.09
Alum Dosage - 200 mg/l; Anionic Polyelectrolyte - 0.5 mg/l to 0.75 mg/l						34	
Total	6.3 - 15.0	9.4	0.09 - 1.2	0.51	94.6		2.10
Filterable	4.0 - 13.1	8.0	0.01 - 0.30	0.11	98.6		2.47
Ortho	4.1 - 11.6	7.8	0.01 - 0.30	0.10	98.9		2.54
Alum Dosage - 250 mg/l; Anionic Polyelectrolyte - 0.5 mg/l						7	
Total	16.1 - 21.9	17.8	0.41 - 3.4	1.24	93.4		1.38
Filterable	11.9 - 13.9	13.2	0.11 - 0.31	0.23	98.2		1.87
Ortho	11.4 - 13.9	12.9	0.08 - 0.26	0.20	98.5		1.91

The data summarized in Table 2, while showing the previously discussed relationship between alum dosage and phosphorus removal, also show significantly lower levels of TP in the MBF effluent than in the jar tests. This is intriguing, but the range of influent phosphorus concentrations where comparative data are available is too limited to permit any conclusions as to mechanism.

Phosphorus Removal at 200 mg/l Alum. Table 3 presents data for TP, TFP and OP reductions over a broad range of conditions encountered during a period of almost four months. These data cover only the single alum dosage of 200 mg/l (17.4 mg/l as Al) and the same anionic polyelectrolyte* throughout, dosed at 0.5 to 0.75 mg/l.

As shown in Table 3, the reduction in total filterable phosphorus (TFP) might be considered as the degree to which the influent TFP was insolubilized by the alum addition. For 34 composite samples, the average per cent removal was 98.6, the maximum 99.8 and the minimum reduction 95.9, respectively. Since alum feed was held constant, the range of 4.00 to 13.10 mg/l of influent phosphorus reflected Al/P ratios between 1.33 and 4.35. These levels could be expected to cause high levels of precipitation.

A more important measure of overall process performance, perhaps, is total phosphorus (TP) removed. In addition to effective precipitation, low values of TP require retention in the MBF of both precipitated phosphorus and that associated with solids in the final effluent. For the 34 composites tabulated, the average TP reduction was 94.6 per cent while the maximum was 98.82 and the minimum 88.35. To give an idea of distribution, only two of the 34 values were less than 90 per cent.

When Al/P ratios are considered in the light of TP content, rather than TFP, the range of 1.16 to 2.76 to 1 represents efficient chemical utilization.

The two samples which had TP reductions of less than 90 per cent illustrate that retention in the filter rather than precipitation was less than optimum. Composite 3-6A had a TFP removal of 98.8 per cent but the corresponding TP removal was only 88.35 per cent. Similarly, composite 3-7A had 99.0 per cent of the TFP removed and only 89.5 per cent of the TP. This indicates that TFP was almost completely precipitated, but the resulting precipitate was not as adequately retained in the filter. The reasons for the decreased removal in these instances are not known, but they could be associated with either a chemical parameter such as the polyelectrolyte feed or with some mechanical problem. Despite these lapses, the overall performance of the MBF process was very high.

*Magnifloc 860A - Product of American Cyanamid Company.

Table 2.

COMPARISON OF THE MBF PROCESS AND JAR TESTS FOR PHOSPHORUS REMOVAL

	Alum ppm	860A ppm	pH	Al/P OP	Al/P TFP	Al/P TP	OP mg/l P	TFP mg/l P	TP mg/l P
TEST SERIES 1									
Clarifier Effluent	0	0	7.0				8.0	9.6	10.9
MBF Effluent	100	0.75	6.8	1.09	0.91	0.80	2.0	2.3	4.4
Jar Test Effluent	100	0.75	6.8	1.09	0.91	0.80	1.9	2.1	7.5
Jar Test Effluent	150	0.75	6.7	1.63	1.35	1.19	0.45	0.58	2.1
TEST SERIES 2									
Clarifier Effluent	0	0	7.2				6.6	5.8[(1)]	6.6
MBF Effluent	200	0.75	6.3	2.64	2.64	2.64	0.02	0.04	0.30
Jar Test Effluent	200	0.75	6.2	2.64	2.64	2.64	0.04	0.08	0.42
TEST SERIES 3									
Clarifier Effluent	0	0	7.1				8.0	8.5	9.7
MBF Effluent	200	0.75	6.5	2.18	2.05	1.79	0.04	0.09	0.50
Jar Test Effluent	200	0.75	6.4	2.18	2.05	1.79	0.24	0.30	1.44

[(1)] See note on page 16

Table 3.

PHOSPHORUS REMOVAL FROM FINAL EFFLUENT

Conditions: Alum Dosage - 200 mg/l (17.4 mg/l Al); Anionic Polyelectrolyte - 0.5-0.75 mg/l

Composite		Total Phosphorus (mg/l)				Total Filterable Phosphorus (mg/l)			Orthophosphate (mg/l P)		
		Infl.	MBF	% Red.	Al/P	Influent	MBF	% Red.	Influent	MBF	% Red.
3-3	AM	7.93	0.75	90.54	2.19	7.18	0.25	96.52	7.93	0.25	96.85
	PM	15.00	0.45	94.33	1.16	10.00	0.29	95.96	8.90	0.22	97.23
3-4	PM	8.50	0.56	93.41	2.05	7.70	0.24	96.88	8.80	0.22	97.50
3-5	AM	7.10	0.32	95.49	2.45	6.30	0.12	98.10	6.70	0.10	98.51
	PM	9.30	0.77	91.72	1.87	8.20	0.10	98.78	7.20	0.09	98.75
3-6	AM	7.70	0.27	96.49	2.26	7.10	0.05	99.30	8.10	0.05	99.38
	PM	10.30	1.20	88.35	1.69	9.50	0.11	98.84	9.20	0.09	99.02
3-7	AM	6.85	0.48	92.99	2.54	5.97	0.06	98.99	4.50	0.06	98.67
	PM	8.00	0.84	89.50	2.17	7.20	0.07	99.03	4.80	0.04	99.17
3-13	AM	7.90	0.74	90.63	2.20	7.30	0.18	97.53	8.00	0.16	98.00
3-18	AM	7.50	0.70	90.67	2.32	6.60	0.04	99.39	7.80	0.03	99.62
	PM	10.00	0.49	95.10	1.74	8.70	0.05	99.43	8.80	0.05	99.43
3-19	AM	6.60	0.30	95.45	2.64	5.80	0.04	99.31	6.60	0.02	99.70
	PM	9.70	0.50	94.85	1.79	8.50	0.09	98.94	8.00	0.04	99.50
3-20	AM	7.20	0.09	98.75	2.42	6.30	0.01	99.84	6.70	0.01	99.85
	PM	8.40	0.15	98.21	2.07	8.10	0.03	99.63	7.60	0.04	99.47
4-8	AM	7.70	0.29	96.23	2.26	7.00	0.01	99.86	7.30	0.01	99.86
	PM	11.30	0.82	92.74	1.54	10.30	0.02	99.81	9.00	0.01	99.89

Table 3. (Cont'd)

PHOSPHORUS REMOVAL FROM FINAL EFFLUENT

Conditions: Alum Dosage - 200 mg/l (17.4 mg/l Al); Anionic Polyelectrolyte - 0.5-0.75 mg/l

Composite		Total Phosphorus (mg/l)				Total Filterable Phosphorus (mg/l)			Orthophosphate (mg/l P)		
		Infl.	MBF	% Red.	Al/P	Influent	MBF	% Red.	Influent	MBF	% Red.
4-9	AM	6.80	0.09	98.68	2.56	5.60	0.02	99.64	6.60	0.02	99.70
	PM	9.30	0.11	98.82	1.87	8.80			9.80	0.02	99.80
4-10	AM	7.00	0.10	98.57	2.49	4.00	0.02	99.50	4.10	0.02	99.51
	PM	8.00	0.10	98.75	2.17	5.00	0.01	99.80	5.00	0.01	99.80
4-15	AM	11.50	0.46	96.00	1.51	9.20	0.15	98.37	9.20	0.09	99.02
	PM	12.30	0.88	92.85	1.41	10.90	0.28	97.43	10.00	0.23	97.70
4-16	AM	9.20	0.50	94.57	1.89	8.60	0.22	97.44	8.60	0.20	97.67
	PM	11.20	0.63	94.37	1.55	10.40	0.15	98.56	8.50	0.10	98.82
4-17	AM	6.30	0.31	95.08	2.76	5.60	0.06	98.93	4.90	0.02	99.59
	PM	9.50	0.31	96.74	1.83	7.30	0.06	99.18	7.20	0.02	99.72
6-17	AM	7.80	0.30	96.15	2.23	6.60	0.10	98.48	7.50	0.10	98.67
	PM	13.20	0.90	93.18	1.32	12.80	0.10	99.22	8.70	0.10	98.85
6-18	AM	8.30	0.40	95.18	2.10	7.30	0.10	98.63	7.60	0.20	97.37
	PM	12.20	0.90	92.62	1.43	11.00	0.10	99.09	9.20	0.10	98.91
6-19	AM	14.00	0.50	96.43	1.24	8.90	0.30	96.63	10.80	0.20	98.15
	PM	14.90	1.00	93.29	1.17	13.10	0.30	97.71	11.60	0.30	97.41
Avg.		9.37	0.51	94.60	1.97	8.03	0.11	98.60	7.80	0.10	98.86
Min.		6.30	0.09	88.35	1.16	4.00	0.01	95.96	4.10	0.01	96.85
Max.		15.00	1.20	98.82	2.76	13.10	0.30	99.86	11.60	0.30	99.89

Other Parameters. In Table 4 data for parameters other than phosphorus removal at various levels of alum addition are summarized.

These data show that on the average 100 mg/l alum in final effluent reduced total suspended solids (TSS) about 47 per cent while doubling the alum dose to 200 mg/l increased average TSS removal to about 67 per cent. Table 4 also indicates that the remaining TSS in the MBF effluent are significantly different in character having a much higher level of fixed solids at all levels of alum addition, indicating that there was a substantial removal of volatile matter.

Additions of 100 mg/l alum reduced BOD_5 on the average about 71 per cent, and at 200 mg/l the reduction was about 80 per cent.

This indicates that where phosphorus removal is not an objective substantial improvement in the quality of the final effluent could be attained with much lower lower chemical consumption.

Extended Pilot Plant Runs

Objectives. Extended runs were made on final effluent to demonstrate the performance and reliability of the MBF system under variable load conditions and to develop cost information.

Limitations. The cyclic nature of sewage flows and strength is well known and does not require explanation here. However, any pilot plant program which can also be substantially affected by uncontrollable factors, such as the weather, may end up well outside of the planned experimental limits. Such problems did arise. First, when after several months of "normal" rainfall the period preselected for an extended run turned out to be one of the wettest periods in many years causing very high flows and diluted wastewater through the plant; second, when a new extended run was attempted to have substantially higher phosphorus values than had been encountered except for an occasional sample in the previous several months of the study; and finally when a third attempt was made to find phosphorus values still substantially higher than expected. The resulting data from the three extended runs provide a broader diversity of results than had been planned. They also raise several questions, noted below, for which answers are not apparent.

Experimental Conditions. An alum feed level of 200 mg/l was used during all three extended runs. During the first extended run (Run I), 0.2 mg/l of a special anionic polyelectrolyte* was used. The dose of Magnifloc

*Atlas Flocculant 110 - Product of Atlas Chemical Industries, Inc.

Table 4.

SUMMARY OF TREATMENT PERFORMANCE - FINAL EFFLUENT

Alum Dosage	Secondary Effluent Range	Secondary Effluent Avg.	MBF Effluent Range	MBF Effluent Avg.	Avg. Reduction (%)
			pH		
100	6.8 - 7.2	7.1	6.6 - 7.1	6.9	
150	7.0 - 7.3	7.2	6.7 - 7.2	7.0	
200	6.9 - 7.4	7.2	5.7 - 7.1	6.7	
250	7.3 - 7.4	7.3	6.6 - 6.9	6.8	
		Total Alkalinity - mg/1 $CaCO_3$			
100	105 - 270	178	55 - 212	134	
150	189 - 238	206	114 - 177	141	
200	134 - 237	180	13 - 168	95	
250	174 - 225	189	59 - 104	80	
		Total Suspended Solids - mg/1			
100	41 - 135	64	8 - 64	34	46.9
150	33 - 67	48	9 - 46	20	58.4
200	22 - 118	50	1 - 57	15	66.6
250	31 - 55	44	5 - 12	8	73.0
		Fixed Suspended Solids - % of Total			
100	1.0 - 38	19.9	10 - 83	40.4	
150	0.1 - 26	13.5	0.1 - 67	36.6	
200	0.5 - 46	15.6	0.0 - 85	42.8	
250	11 - 23	18.1	33 - 67	48.3	
		Turbidity - JTU			
100	28 - 60	42	5.0 - 36	19	54.8
150	24 - 40	30	5.0 - 18	8.7	71.0
200	13 - 54	33	1.4 - 27	6.4	78.5
250	22 - 36	27	2.8 - 13	4.5	83.2
		BOD_5 - mg/1			
100	40 - 75	58	5 - 29	17	70.8
150	-- --	--	- --	--	
200	14 - 97	65	3 - 30	12	80.2
250	-- --	--	- --	--	

860A was 0.5 to 0.75 mg/l during all of the other reported work on final effluent.

The pilot plant was manned around the clock during these runs to insure that adequate operating and analytical data would be obtained. Chemical feed rates, head loss profiles along the filter bed and influent and effluent turbidity values were monitored hourly. Six-hour composites of the final effluent and MBF effluent were taken by automatic samplers.

These samples were analyzed for OP, TFP and TP. In addition, pH, total alkalinity, total suspended solids (TSS) and fixed suspended solids (FSS) also were determined.

Attempts were made also to collect the settled sludge from the sand wash water settling tank. Since the volume of sludge accumulated in any reasonable sampling period turned out to be quite small (probably 10-15 gallons or less in a 400-gallon tank) it proved impractical to withdraw sludge without substantial volumes of supernatant causing dilution. Subsequent work has established that solids concentrations of 1.5 per cent by weight are readily attainable and that concentrations of 2.0 per cent or more are possible.

Experimental Results. Phosphate removal data for the three extended runs on final effluent are presented in Figures 5, 6 and 7. Corresponding total plant flows are given in Table 5.

Run I was initiated just after an extended period of excessive rainfall. Flow through the plant had decreased from over six times the design flow to about three times the design flow (1.65 MGD). Relatively low phosphorus levels were observed during this period of high flow. There does not appear to be any explainable reason for the relatively high levels of TFP observed and the correspondingly high levels of "condensed phosphates" (TFP-OP). It would appear that almost no conversion of CP occurred at the highest level of TP encountered during this run, but in the absence of CP values for the raw sewage this cannot be verified.

With 200 mg/l alum feed, the MBF reduced TP from an average of 5.67 to 0.28 mg/l or a reduction of 94.8 per cent despite the relatively high proportion of CP. OP was reduced from an average of 2.97 to 0.005 mg/l or 99.8 per cent.

Phosphorus data for Run II (Figure 6) present quite a different picture. The expected diurnal variations are evident and the peaks correspond to a lag of 5 to 6 hours behind the lift pumps at the wet well. Unexpected, however, were peak TP concentrations ranging up to 25.7 mg/l, and also the relatively large amount of TFP, particularly toward the end of the run. The high degree of removal (90 per cent) of TFP and TP at an Al/P ratio of about 0.7 appears to be particularly worthy of note (1700 hr, 9/23, Fig. 6).

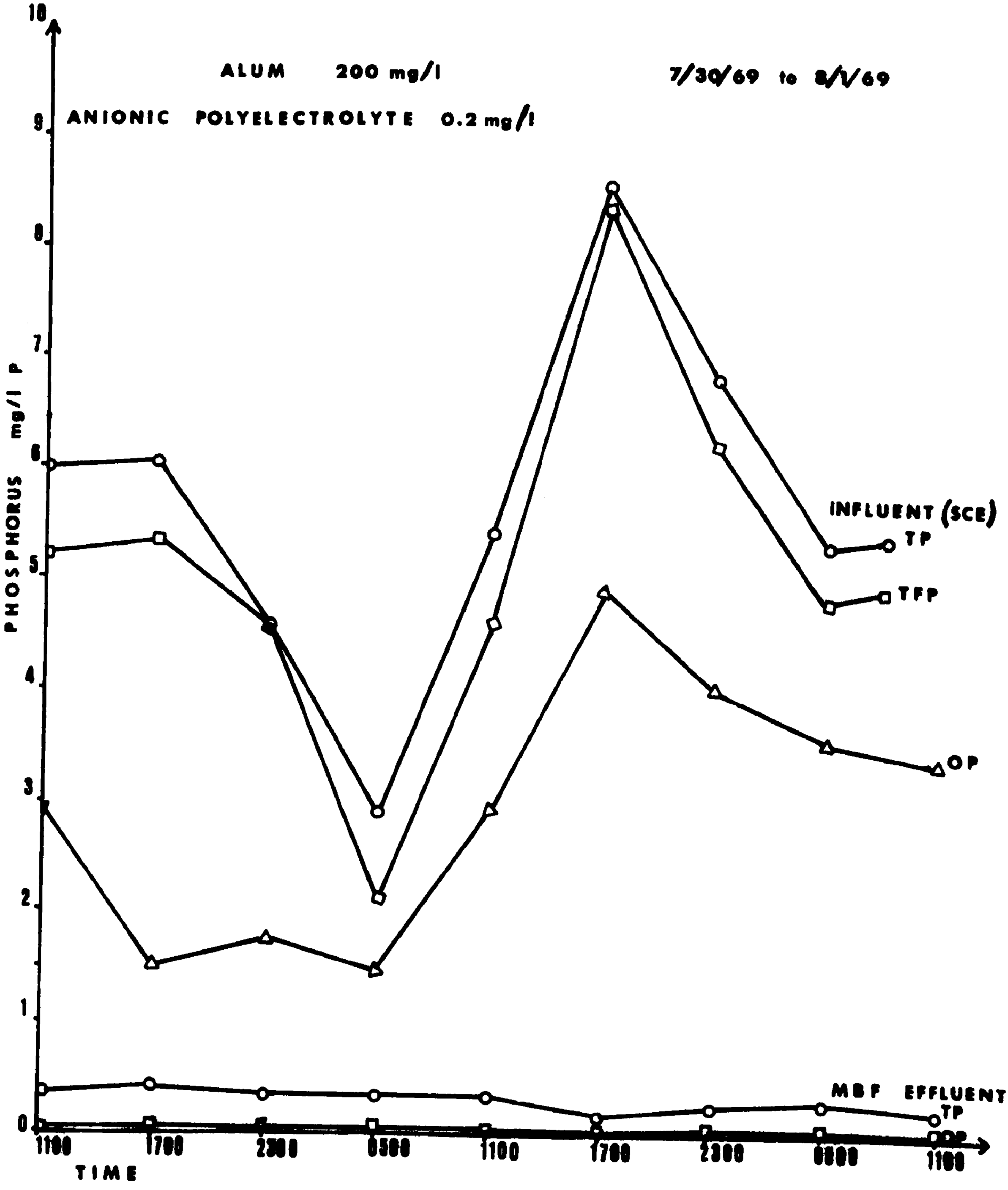

FIGURE 5. PHOSPHORUS LEVELS RUN I

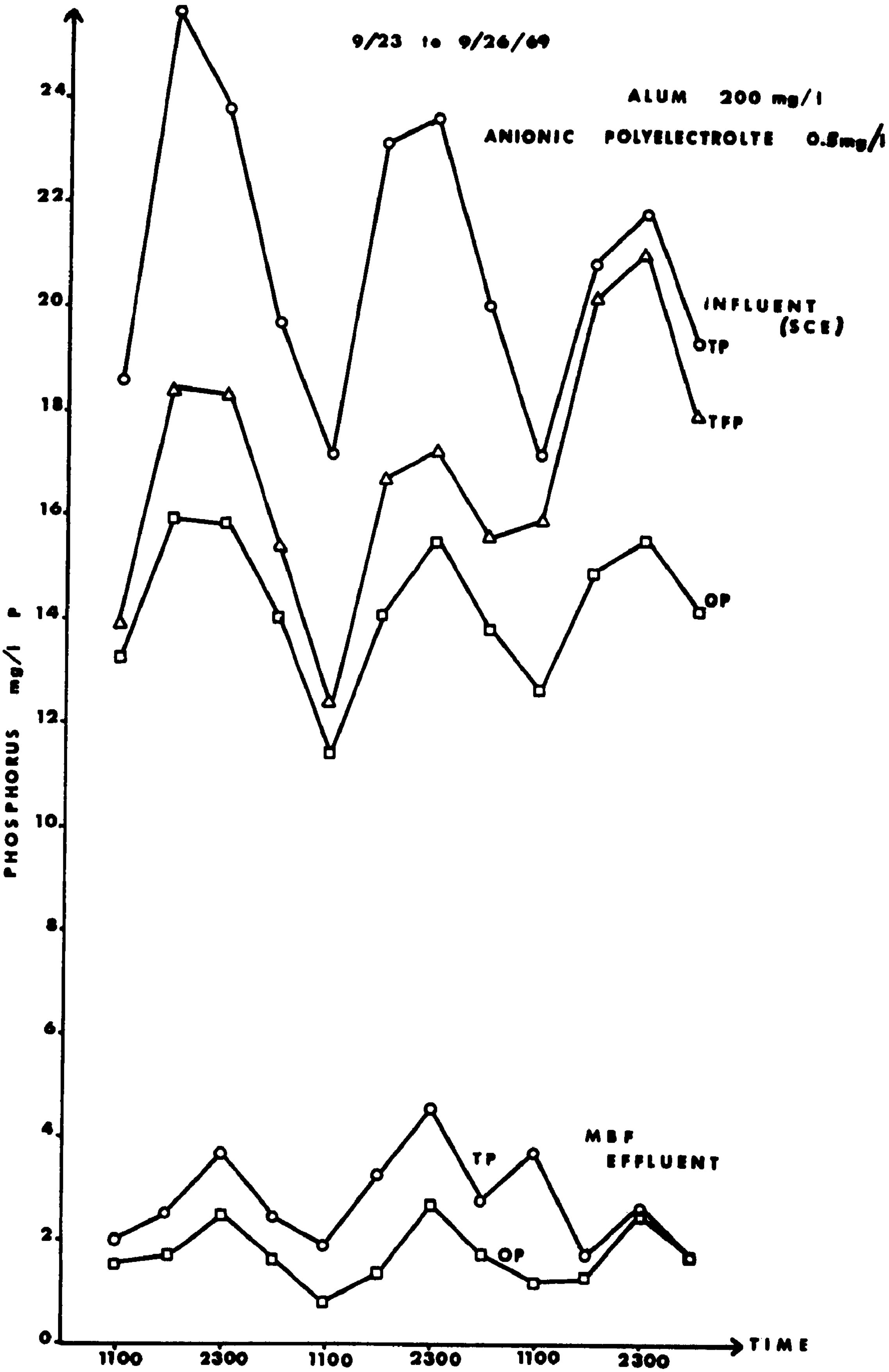

FIGURE 6. PHOSPHORUS LEVELS RUN II

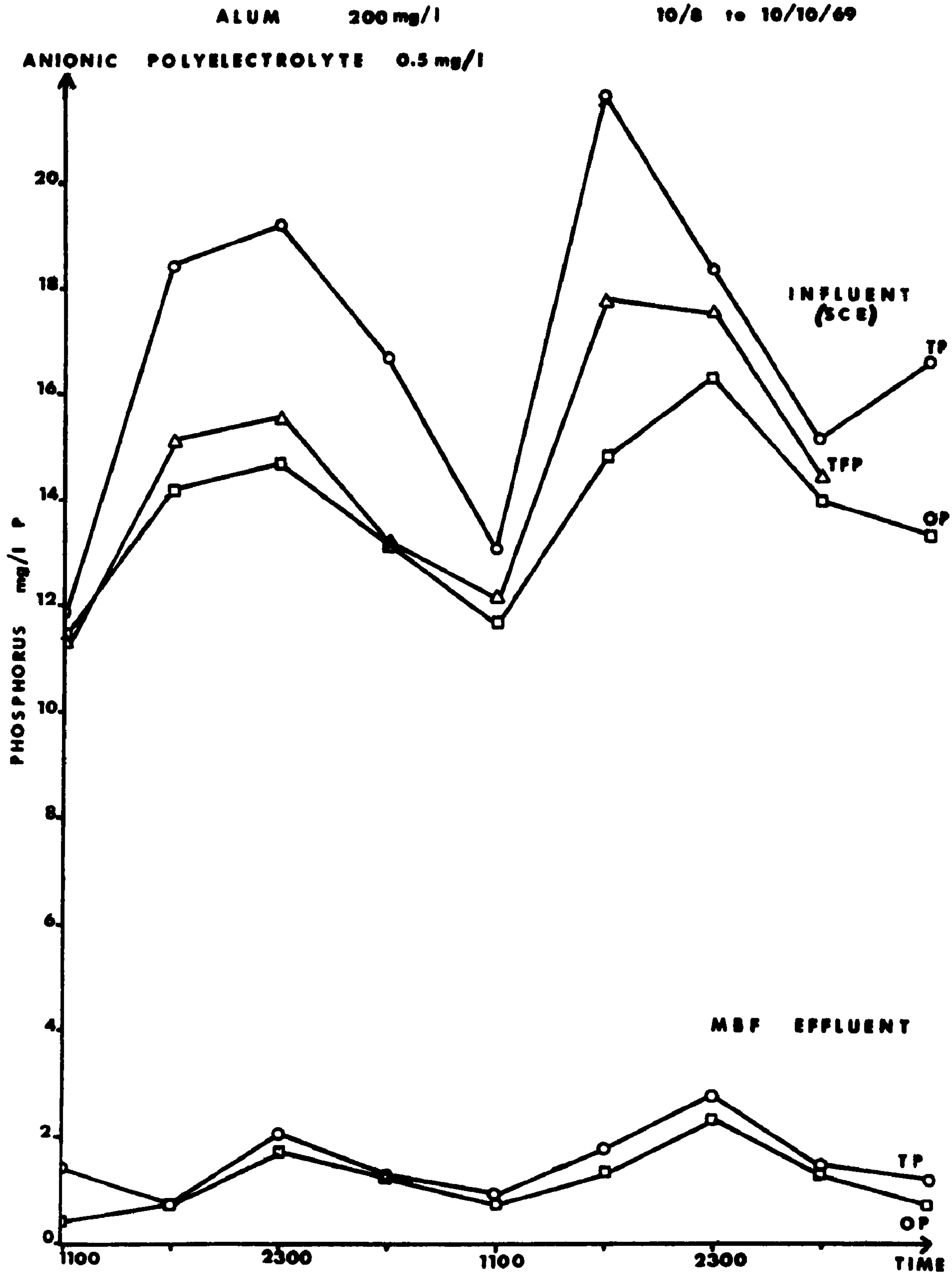

FIGURE 7. PHOSPHORUS LEVELS RUN III

Table 5.

PLANT FLOWS DURING EXTENDED RUNS ON FINAL EFFLUENT

Time	FLOWS (MGD) Run I (7/30 - 8/1/69)	Run II (9/23 - 9/26/69)	Run III (10/8 - 10/10/69)
0200-0800	1.87	0.28	0.30
0800-1400	2.41	0.66	0.67
1400-2000	2.08	0.54	0.53
2000-0200	1.78	0.58	0.62
0200-0800	1.32	0.27	0.31
0800-1400	1.52	0.61	0.70
1400-2000	1.29	0.50	0.55
2000-0200	1.23	0.57	0.62
0200-0800	0.89	0.26	0.30
0800-1400	1.12	0.59	----
1400-2000		0.50	
2000-0200		0.56	
0200-0800		0.23	

The constant alum feed of 200 mg/l and high influent phosphorus concentrations resulted in residual phosphorus concentrations which were considerably higher than those obtained during the preliminary studies. This difference can be attributed to the low Al/TP ratios which averaged 0.85 and ranged between 0.68 and 1.01. The average TP removal was 87 per cent. The removal of TFP (89.9 per cent) and OP (88.2 per cent) was slightly better than the removal of TP, as shown in Table 6.

In Run III, influent phosphorus levels were still quite high compared with earlier baseline work but slightly lower than the levels of Run II. Higher degrees of removal were obtained for TP (91 per cent), TFP (92 per cent) and OP (92 per cent), as shown in Table 6. These removals were achieved with average Al/P ratios of 1.08 for TP, 1.22 for TFP and 1.28 for OP, again indicating quite efficient utilization of alum.

The results of these experiments demonstrate the performance reliability of the MBF system under a wide range of influent conditions. During this run, the TP removal efficiency was never less than 85 per cent and only two OP and two TFP values were less than 90 per cent removed.

Other Parameters. Table 7 summarizes data on alkalinity, pH, TSS and FSS for all three extended runs. BOD_5 data are included for two of these runs.

Total suspended solids removals were comparable to those previously reported with average reductions ranging from 60 to 75 per cent and TSS values in the processed final effluent averaging between 9 and 13 mg/l.

Average BOD_5 reductions were 88 and 72 per cent with average residual BOD_5 values of 3 and 8 mg/l. It was observed that the highest percentages of removal, as might be expected, were associated with the largest amounts of TSS and BOD_5 available in the final effluent.

Table 6.

SUMMARY OF PHOSPHORUS REMOVAL FOR CONTINUOUS RUNS

		TP				TFP				OP			
Run No.		In	Al/P	Out	% Red.	In	Al/P	Out	% Red.	In	Al/P	Out	% Red.
Run I	Avg.	5.67	3.07	0.28	94.8	5.09	3.42	<0.005	99.9	2.97	5.86	<0.005	99.8
	Min.	2.92	1.95	0.14	88.6	2.11	2.08			1.45	3.57		
	Max.	8.91	5.96	0.40	99.0	8.38	8.25			4.88	12.00		
Run II	Avg.	20.9	0.83	2.8	86.8	16.9	1.03	1.7	89.9	14.3	1.22	1.7	88.2
	Min.	17.2	0.68	1.7	78.5	12.4	0.83	0.7	84.3	11.4	1.09	0.8	82.6
	Max.	25.7	1.01	4.6	91.8	21.0	1.40	2.8	94.5	15.9	1.53	2.7	93.0
Run III	Avg.	16.75	1.08	1.50	91.0	13.88	1.22	1.22	92.0	13.73	1.28	1.15	91.9
	Min.	11.59	0.81	0.61	85.1	11.14	0.98	0.40	87.0	11.73	1.07	0.39	85.6
	Max.	21.57	1.50	2.75	96.7	17.72	1.53	2.31	96.4	16.30	1.53	2.34	96.5

Table 7.

SUMMARY OF TREATMENT PERFORMANCE FROM EXTENDED RUNS

Run No.		pH		Alkalinity		Total Suspended Solids			% Fixed Suspended Solids		BOD		
		In	Out	In	Out	In	Out	% Red.	In	Out	In	Out	% Red.
Run I	Avg.			90	17	36	10	61	32	60	25	3	88
	Min.	6.7	5.9	79	12	11	8	0	20	30	12	2	80
	Max.	7.1	6.3	98	24	77	12	84	45	100	46	4	96
Run II	Avg.	7.3	6.8	170	98	32	13	60	11	41	31	8	72
	Min.	7.2	6.7	155	83	18	5	34	3	0	13	4	46
	Max.	7.4	7.0	194	116	40	25	83	30	63	40	14	84
Run III	Avg.	7.2	6.8	186	111	37	9	75	11	17			
	Min.	7.1	6.7	164	89	19	3	50	0	0			
	Max.	7.3	6.8	220	139	65	20	91	22	46			

PHASE II - MBF TREATMENT OF UNSETTLED TRICKLING FILTER EFFLUENT

Experimental Plan

The satisfactory filtration of secondary effluent with 200 mg/l of alum, without presettling per se, demonstrated the capability of the MBF system for handling high solids loadings. Filtration of unsettled trickling filter effluent was evaluated to achieve greater utilization of this removal capability. If feasible, comparable removals of phosphorus, TSS and BOD_5 could be achieved with greater economy through elimination of the need for final clarifiers in the design of future trickling filter plants.

The pilot plant was run for two 1-week periods in August and September. Jar tests indicated that the alum dosage could be maintained at 200 mg/l. This also permitted comparison of the performance and operation with the results obtained on final effluent. Except for some minor difficulties in maintaining constant flow for extended periods of time, no exceptional operation problems were encountered.

Experimental Results

Phosphorus Removal. The phosphorus removal results and other performance parameters evaluated during the two weeks of operation are summarized in Table 8. As expected, the concentrations of wastewater constituents were generally higher than had been observed in the final effluent. The total influent phosphorus averaged 19.1 mg/l P and had a maximum concentration of 28.6 mg/l P. These values are comparable to those observed during Runs II and III. The concentration of particulate phosphorus in the unsettled trickling filter effluent (4 mg/l P) was significantly higher than it was in the settled effluent (1.4 mg/l P). The trickling filter effluent data also appear to differ from the settled effluent data in that a higher degree of hydrolysis of CP may have occurred, based on the average values for OP and TFP. However, when TP and TFP concentrations were unusually high, the degree of hydrolysis may have been less complete. Absence of data on the corresponding levels of TFP, OP and CP in the raw sewage preclude more definite conclusions on this. Regardless of the form of the phosphorus, however, MBF removals were good.

During this limited period of study, the average phosphorus removal efficiencies were better than those obtained during treatment of the final secondary effluent. As summarized in Table 8, phosphorus removals ranged between 90 and 98 per cent with averages of about 95 per cent.

Comparison of the removal of the filterable phosphorus at approximately equivalent influent levels to those in final effluent showed that treat-

Table 8.

SUMMARY OF TREATMENT PERFORMANCE - UNSETTLED TRICKLING FILTER EFFLUENT

Parameter	TF Effluent		MBF Effluent		Avg. Reduction (%)
	Range	Avg.	Range	Avg.	
Phosphorus - mg/l P					
Total	10.1 - 28.6	19.1	0.25 - 2.70	0.99	95.1
Filterable	8.2 - 21.3	14.9	0.01 - 2.60	0.62	96.2
Ortho	7.2 - 16.7	12.4	0.01 - 2.00	0.53	96.1
pH	7.1 - 7.3	7.2	6.3 - 7.0	6.7	----
Total Alkalinity - mg/l as $CaCO_3$	151 - 208	183	29 - 121	89	
Total Suspended Solids	63 - 212	86	0.3 - 17	7.1	91.4
Fixed Suspended Solids - % of Total	3 - 22	8.3	9 - 50	24.7	----
Turbidity - JTU	22 - 83	43	1.0 - 8.8	3.73	91.3
BOD_5	30 - 223	55	1.0 - 9.0	3.8	91.9

ment of the unsettled effluent was slightly more effective. The average filterable phosphorus concentration was reduced from 14.9 mg/l P to 0.62 mg/l P in the treatment of the unsettled trickling filter effluent. The same degree of removal was evident for the ortho fraction.

Thus, it is indicated that the higher solids loading did not interfere with the chemical reaction of the aluminum and phosphorus. It is possible that a slight benefit may have been derived from formation of a greater amount of floc which may also have served to remove some of the phosphorus through sorption.

Other Parameters. As shown in Table 8, the amount of alkalinity consumed by the aluminum was slightly higher during the period of treatment on the unsettled trickling filter effluent. On the average, total alkalinity was reduced by 94 mg/l as $CaCO_3$ as compared to 70 mg/l as $CaCO_3$ from the final effluent data. This is also shown in the slightly lower pH values of the MBF effluent although the difference is only 0.1 unit.

As expected, higher suspended solids were encountered in the unsettled trickling filter effluent, averaging 86 mg/l whereas the final secondary effluent values averaged about 50 mg/l. A greater portion of the unsettled effluent solids was organic in nature with the fixed suspended solids being only 8.3 per cent of the total. The suspended solids were reduced to an average of 7 mg/l with the fixed suspended solids about 25 per cent of the total.

The reduction of BOD_5 in unsettled trickling filter effluent had been expected to be greater than for final effluent because of the larger amount of suspended solids with which BOD could be associated. However, the degree of removal, an average of 92 per cent versus an average of 80 per cent for final effluent, was better than expected, and average BOD_5 values in the MBF processed effluent were 3.8 mg/l for unsettled and 12 mg/l for final effluent, respectively. It should be noted that the figure for final effluent encompasses a substantially larger number of samples and wider range of wastewater treatment plant flows and strengths.

During one 24-hour period of operation, a record was kept of the volumes of sludge pumped and per cent solids of the resulting sludge. Based upon these measurements, the sludge volume was 2.8 per cent of the treated flow. The per cent solids of the sludge was 0.48 and the fixed solids content was 66.6 per cent of the dry solids. However, these values are subject to the same limitations discussed earlier in connection with sludge collection and are not suitable for design purposes.

PHASE III - MBF TREATMENT OF PRIMARY EFFLUENT

Experimental Plan

Success of MBF treatment of unsettled trickling filter effluent gave added interest to the study in which primary settled wastewater was processed. This was a two-week study, during which the influent to the MBF was taken from the effluent channel of the primary settling tank. The objective of this study was to determine the feasibility of applying the MBF ahead of the biological secondary treatment. The plan included evaluation of the other treatment parameters as well as the removal of phosphorus. Besides operational feasibility, the difference in the relative character of the various phosphorus forms would also be evaluated.

Again, the pilot plant was operated at a constant alum dosage of 200 mg/l and an anionic polyelectrolyte dosage of 0.5 to 0.75 mg/l. These conditions were determined by comparing MBF pilot plant operation with jar testing shown in Table 9. They also permitted comparison with the earlier work on unsettled trickling filter and final effluent.

Experimental Results

Phosphorus Removal. The data collected from this period of operation are summarized in Table 10. The general levels of phosphorus, with the average of 14.6 mg/l, were within the same range as those found for final effluent. However, the relative forms were markedly different. Orthophosphate was about 92 per cent of the TFP in the final effluent. In the primary effluent, OP comprised only 73 per cent of the TFP. This is to be expected due to some subsequent hydrolysis of CP as it passes through the trickling filter. The relative percentage of phosphorus associated with the solids was similar to that found in the final effluent.

Total phosphorus removal averaged 93.1 per cent under a wide range of influent concentrations (7.0 to 20 mg/l as P). At influent concentrations of less than 10 mg/l, the TP removal averaged 96.6 per cent. The data showing average removals of 95.8 per cent for OP and 96.1 per cent for TFP are equally promising. The latter result indicates fairly complete precipitation and removal of a relatively high proportion of CP. These removals are better than those obtained in the treatment of the final effluent although there is no obvious reason that this should be so.

If appearance is any indication, the MBF was substantially effective in the clarification of primary effluent as shown in Figure 8.

The character of the primary effluent varied widely during the test with TSS ranging between 51 and 114 mg/l and BOD_5 between 50 and 103 mg/l.

Table 9.

COMPARISON OF JAR TESTS AND MBF PROCESSING OF PRIMARY EFFLUENT

	Primary Effluent	MBF Effluent	Jar Test Effluent		
			1	2	3
Date - 8/21/69					
Alum Dosage - mg/l	--	200	200	200	225
Anionic Polyelectrolyte Dosage - mg/l	--	0.5	0.5	0.5	0.5
pH	7.3	6.8	6.7	6.7	6.7
Total Alkalinity - mg/l $CaCO_3$	164	51	84	84	76
Turbidity - JTU	36	0.6	1.5	2.5	1.5
Orthophosphate - mg/l P	6.31	0.03	0.04	0.05	0.02
Per Cent Removal	--	97.9	--	--	--
Total Phosphate - mg/l	9.7	0.12	0.25	0.34	0.19
Per Cent Removal	--	99.6	--	--	--

Table 10.

SUMMARY OF TREATMENT PERFORMANCE - PRIMARY EFFLUENT

Parameter	Primary Effluent Range	Primary Effluent Avg.	MBF Effluent Range	MBF Effluent Avg.	Avg. Reduction (%)
Phosphorus - mg/1 P					
Total	7.0 - 20.3	14.6	0.08 - 4.00	1.13	93.1
Filterable	5.5 - 18.1	13.2	0.02 - 2.80	0.58	96.1
Ortho	4.1 - 15.0	9.76	0.02 - 2.80	0.38	95.8
pH	7.0 - 7.3	7.2	6.5 - 6.8	6.7	--
Total Alkalinity - mg/1 $CaCO_3$	127 - 229	179	51 - 145	99	44.6
Total Suspended Solids	51 - 114	77	1 - 27	11	86.5
Turbidity - JTU	33 - 83	53	0.65 - 8.5	3.8	92.5
BOD_5 - mg/1	50 - 103	67	3 - 25	12	81.9
BOD_5 (filterable)	10 - 36	23	-- --	--	--

Figure 8. COMPARISON OF UNTREATED AND MBF PROCESSED PRIMARY EFFLUENT

Other Parameters. As shown in Table 10, the average suspended solids and BOD of the primary effluent were 77 and 67 mg/l, respectively, which may be considered to be lower than the levels generally found in primary settled domestic sewage. The resulting MBF effluent had a suspended solids concentration of 11 mg/l and a BOD_5 of 12 mg/l. These removals are extremely encouraging for a chemical coagulation-filtration system.

In considering removals of suspended solids and BOD_5, filterable BOD_5 was run on the primary effluent and these data are also included in Table 10. Since the MBF effluent BOD was lower than the filterable BOD of the influent to the MBF, it seems likely that some of the BOD associated with colloidal materials was being removed by the chemical treatment.

Within the limits of measurement, these results were obtained with no apparent decrease in flow rate through the MBF pilot plant system, which indicates that the alum-reaction products (i.e., Al-colloid precipitates, $Al(OH)_3$, $Al\ PO_4$, etc.) are probably still the rate-governing factor.

Attempts to accumulate and measure the volume and concentration of sludge were again unsuccessful so a new tack was taken. Estimations of the volumes of the resultant alum sludge were made from settling tests using 2-liter graduated cylinders carried out on the waste wash water. On the basis of these tests, the volume of sludge was approximately 0.9 per cent of the treated volume. After one-hour settling, the sludge density was about 0.65 per cent with a 48.9 per cent of the dry solids being ash. This concentration of solids is probably slightly lower due to wall effects and other inhibitions than that which would be obtainable from steady-state operation, but it appears to have better validity than the intermittent data from the pilot plant.

PHASE IV - MBF TREATMENT OF RAW SEWAGE

Experimental Plan

The successful treatment of primary effluent created increased interest in establishing the potential of the MBF to process raw sewage. While the primary emphasis was still on phosphorus removal, evaluation of suspended solids and BOD removal in the light of the experience with primary effluent assumed almost equal importance.

Since alum at the 200 mg/l level had proven effective for primary effluent, this same level was used for the work with the raw wastewater. This had the advantage of making data from all of the levels of wastewater treatment studied comparable. The same anionic polyelectrolyte also was used at the 0.5 to 0.75 mg/l level.

Problems and Limitations. Because of limitations requested by the host plant staff, MBF operation during this period was limited to 8 to 12 hours when raw sewage was available. Filtration of raw sewage was attempted for two weeks, although usable data were only obtained for the second week of operation.

During the initial operation on raw sewage, difficulties in obtaining a reliable flow to the pilot plant unit were encountered. The main problem was the clogging of the suction lines and pump. After rearrangement of the piping and shifting the point of withdrawal, operation of the unit was maintained over a period of one week. The raw sewage was taken from the influent channel after the comminutor and just ahead of entrance to the Parshall flume. A coarse screen was placed across the suction inlet.

Experimental Results

Phosphorus Removal. The performance data collected over the week of operation on raw sewage are presented in Table 11. The total phosphorus level of the raw sewage varied between 11.6 and 41.1 mg/l P with an average of 21.5 mg/l P. Only 57 per cent of the TP was in the OP form and about 25 per cent was associated with the suspended solids. Removal of TP averaged 91 per cent and for OP was 95.2 per cent. A single high effluent value of 5.40 mg/l was observed. Of this, 4.0 mg/l was associated with the effluent suspended solids. For no apparent reason, very poor flocculation was noted during this period. The average ratio of Al/TFP was 1.01. The Al/TP ratio, which was even lower at 0.81, looks extremely promising.

Other Parameters. A very substantial reduction in BOD was concurrently obtained as shown in Table 11. The influent level was reduced from an average of 115 mg/l down to 19 mg/l. The maximum influent level of 153 mg/l

Table 11.

SUMMARY OF TREATMENT PERFORMANCE - RAW SEWAGE

Parameter	Raw Sewage Range	Raw Sewage Avg.	MBF Effluent Range	MBF Effluent Avg.	Avg. Reduction (%)
Phosphorus - mg/l P					
Total	11.6 - 41.1	21.5	0.49 - 5.40	2.16	91.1
Filterable	9.1 - 39.7	18.6	0.07 - 1.50	0.79	95.8
Ortho	8.8 - 20.4	13.2	0.04 - 1.30	0.57	95.2
pH	7.1 - 7.2	--	6.8 - 7.1	--	--
Total Alkalinity - mg/l $CaCO_3$	170 - 217	185	82 - 131	106	42.7
Total Suspended Solids	110 - 214	156	7 - 69	27	82.6
Fixed Suspended Solids - % of Total	6.9 - 25.0	12.6	14.3 - 50	35.4	--
Turbidity - JTU	63 - 200	119	4.5 - 48	16	86.5
BOD_5 - mg/l	84 - 153	115	7 - 46	19	83.5
BOD_5 (filterable)	19 - 41	32	-- --	--	--

was reduced by the MBF treatment to 28 mg/l. In all samples, the chemical filtration process removed more than just the BOD associated with the suspended solids. The filterable BOD of the raw sewage, which averaged 32 mg/l, was about 60 per cent higher than the MBF effluent BOD. It is believed that most of the additional BOD removal was associated with colloidal materials which were coalesced by the chemical addition and subsequently removed by filtration.

Comparable reductions in TSS were obtained with the influent average of 156 being reduced to 27 mg/l. The character of the solids in the latter was also different with 35 per cent fixed solids as opposed to 12.6 per cent in the influent, again demonstrating a substantial removal of organic matter.

These levels of removal were of considerable interest since they were at least as good as those being effected by the present trickling filter plant with the additional benefit of better than 90 per cent TP removal.

Physical Observations. A very significant difference in the operational characteristics of the system was observed with the raw sewage as compared to operation on either the secondary or primary effluents. The variations in filter outflow and head in relation to the face cutting sequence were very pronounced. Upon removal of the clogged filter interface, the outflow rapidly increased and the head sharply decreased. An outflow of 3 gpm to 17 gpm was observed and resultant changes in head of as great as 12 inches were common. As the frequency of cutting (as often as every two pushes of the filter bed) was increased, the fluctuations appeared to level off. The clogging of the filter bed under these conditions was probably a result of the buildup on the interface of the macerated paper and other fibrous solids contained in the raw influent.

During this short period of operation, there was no visible buildup of grease within the system.

Required Alum Dose for Phosphorus Reduction. It has been reported[5] that Al/P ratios of 1.25 to 1.75 mg/l are needed to precipitate soluble phosphorus and that, therefore, the required dose of alum is reasonably proportional to the soluble phosphorus concentration. Other literature references support this theory.

The work at Bernards Township tends to show that this theory is somewhat oversimplified. It was noted in Figure 4 that the orthophosphate concentration was 4.4 mg/l as P. Taking an Al/P ratio of 1.5 as a median value, an alum dose of 75 mg/l should have been sufficient to remove 90 per cent or more of the soluble phosphorus. However, 90 per cent removal did not occur until a dose of 125 mg/l (Al/P = 2.5) alum was applied.

Figure 9 shows the relationship of Al/P ratio to orthophosphorus removal at various alum doses. From this it can be seen that removals of 90 per

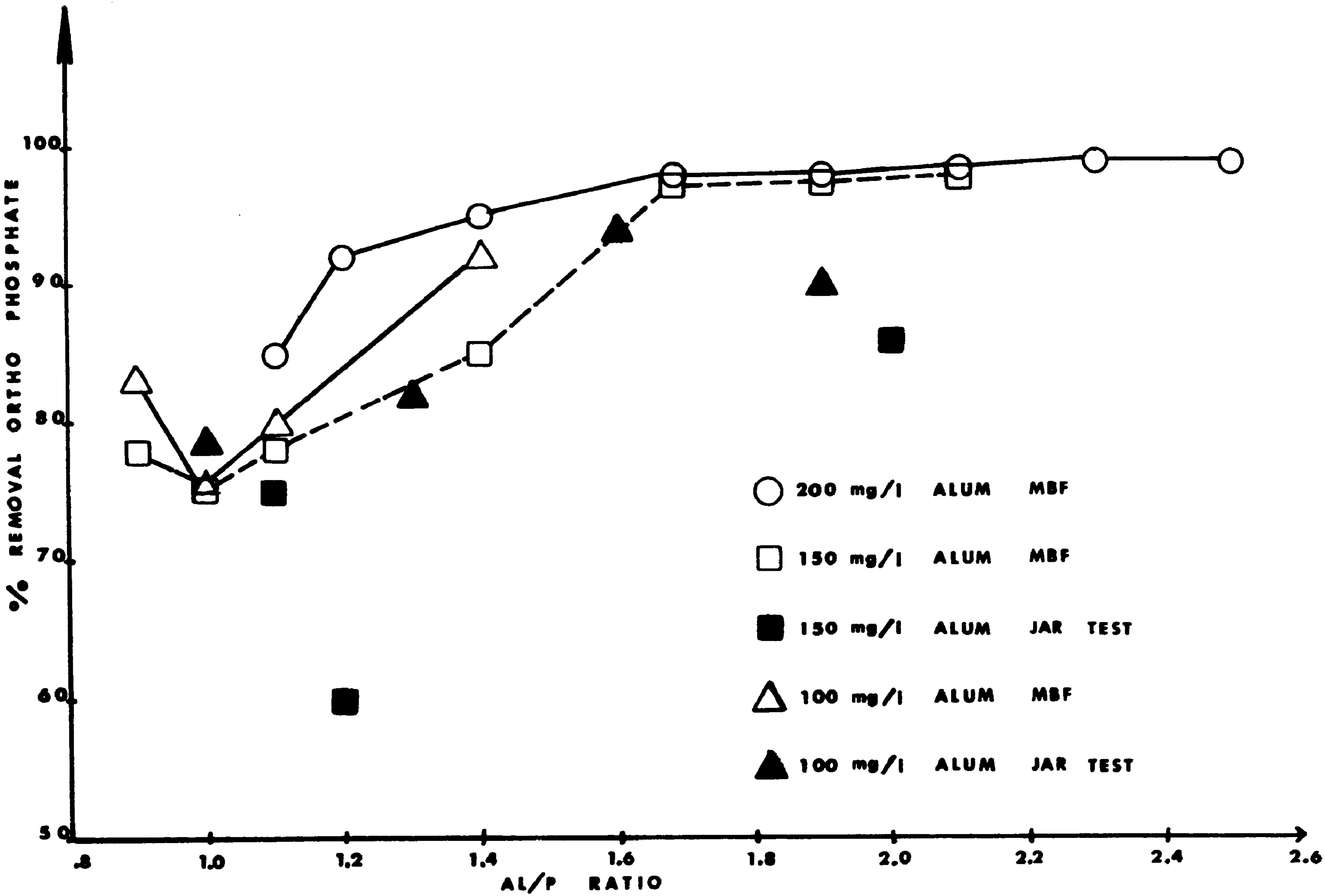

FIGURE 9. RELATIONSHIP OF ALUM DOSAGE TO REMOVAL EFFICIENCY

cent or better at an Al/P ratio of 1.25-1.5 cannot be achieved with a dose of 100 mg/l alum while 90 per cent removal is achieved at a ratio of 1.2 with 200 mg/l alum.

This phenomenon was observed with all of the sources, i.e., final effluent, primary effluent, etc., at the Bernards plant. Parenthetically, it can be noted that similar effects have been observed at other treatment plants having either trickling filters or the activated sludge process.

It would appear, then, that two conditions must be met to insure some specific level of soluble phosphorus precipitation with alum: (1) an Al/P ratio of 1.2 or more for 90 per cent reduction, and (2) a minimum alum dose of the order of 200 mg/l (for Bernards). These data lead to a hypothesis that sewage has an "alum demand" which must be satisfied before soluble phosphorus can be effectively removed.

COST ESTIMATES

General Considerations of MBF Capital Costs

All cost estimates in this report are based on a 1.0 MGD MBF system. Typically, the cost per million gallon of installed capacity will be less in larger installations and more in smaller installations.

A "system" consists of all of the components, i.e., moving bed filters, pumps, chemical feed systems, sand washers, wash water reclaim tank, etc., to make an operating system, F.O.B. shipping point. Sludge dewatering equipment, when required, is supplied as a separate equipment package on the same basis.

While the cost of system components can be established with precision as of the date of this report, installed costs are of necessity less precise. The equipment has been designed to minimize installation costs. Even so, these have been found to vary widely based on local construction labor costs; whether housing is needed or not and, if so, the type building specified by the owners; and the cost of connecting into the rest of the system, i.e., whether wet wells and lift pumps are required, etc.

The cost of housing is probably the most difficult to estimate since in some climates no housing except a shed covering of the main control panel and chemical feed system would be required. In intermediate climates, these components should be housed and some exposed piping and metal surfaces would require insulation or heat tracing. In climates having long periods of extreme cold weather full housing would be required. For this report, the first alternative has been used for estimating installed costs.

Amortization

Recent publications of the FWQA(7) have used amortization of capital costs at 4-1/2 per cent and a 25-year period. This same basis has been used so as to permit direct comparison with other processes.

Operating Costs

Chemicals. Similar considerations arise with respect to operating costs but these are more easily resolved. Where it is available commercial liquid alum (48 per cent solution) may be as much as $10 to $12 less per ton of alum content than dry alum. At the 200 mg/l level, this represents savings of 0.8 to 1.0 cents per 1000 gal. processed. For the purposes of this report, the cost of alum has been assumed to be $0.025 per pound.

Anionic polyelectrolytes also have a broad cost spread. Two of the several polyelectrolytes used in this study were found to work well, but the one which could be applied at 0.2 mg/l and thereby halve the polyelectrolyte costs is not yet commercially available. So, costs are based on use of 0.5 mg/l of commercially available material at $1.50 per pound.

Power. The installation has approximately 65-hp connected load, excluding two 10-hp and one 5-hp standby pumping units, and the equivalent of 42-hp continuous load. Power cost has been assumed at $0.01 per kw-hr.

Operation and Maintenance. Since the equipment is automated on a fail-safe basis, a 1.0 MGD installation requires only two man-hours per day. Chemical tanks must be refilled, recorder charts changed and pumps and general operating conditions reviewed daily. All labor costs were estimated on a $3 per hour rate.

Non-routine maintenance requirements were estimated to be one man-hour per day. Maintenance material is estimated at 30 per cent of operating and maintenance labor.

Cost Summary

Capital, dollars

MBF Process Equipment	$188,000
Installation (erection, piping, wiring on slab with shed roof covering key components)	36,000
MBF Process Total	$224,000
Outside Work (lift pumps, piping, etc.)	40,000
TOTAL ESTIMATED COST	$264,000

Process Cost, cents/1000 gal.

Amortization - 4½% and 25 yr	4.9¢
Alum - 200 mg/l @ 2.5¢/lb	4.2
Polyelectrolyte - 0.5 mg/l @ $1.50/lb	0.6
Power	0.8
(Subtotal)	10.5

Process Cost, cents/1000 gal. (cont'd)

(Subtotal)	10.5
Operating and Maintenance Labor @ $3/hr	0.9
Supervision and Payroll Overhead	0.3
Maintenance Material	0.3
TOTAL ESTIMATED PROCESS COST	12.0¢

Ultimate Disposal of Sludge

With approximately 95 per cent of the phosphorus originally present in the wastewater fixed and concentrated in the underflow from the wash water reclaim tank, an unusual opportunity is provided for "ultimate" disposal of phosphorus. One such method involves dewatering with a rotary precoat filter to a damp solid which can then be used as landfill, for example.

Data from the present study have been supplemented with data from other larger-scale operations to enable preparation of preliminary estimates of the cost of such a dewatering operation. All of the operating costs are given in terms of the volume of the original wastewater. To these estimates would have to be added the cost of trucking and landfill operations which will be governed by local considerations.

Basis. This estimate assumes the dewatering of 10,000 gpd (1.0 per cent of throughput) of sludge containing 1.5 per cent solids by weight.* The dewatering requires a 75-sq ft rotary vacuum precoat filter on a 24-hr per day basis with two hours off stream for washup and precoating and requires an operator only during that time. HYFLO SUPER-CEL** is the filter medium and will be consumed at the rate of 0.156 lb/hr/ft^2. The damp cake, containing about 30 per cent solids, can be deposited directly in a hopper body for trucking to a disposal site. The filtrate from the dewatering operation is suitable for addition to the MBF processed effluent stream without recycling.

*These estimates will be favorably influenced by increases in feed solids concentration and decreases in volume of sludge since rotary vacuum precoat filtration rates are not linearly decreased with increased solids concentration. The above estimates are based on the best currently available information.

**Product of Johns-Manville.

Cost Summary

Capital, dollars

Equipment	$22,000
Installation	8,000
TOTAL INSTALLED COST	$30,000

Process Cost, cents/1000 gal.

Amortization - 4½% and 25 yr	0.55¢
Filter Aid @ 4.5¢/lb	1.3
Power	0.2
Operating and Maintenance Labor	0.6
Supervision and Payroll Overhead	0.2
Maintenance Material	0.1
TOTAL ESTIMATED PROCESS COST	2.95¢

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ACCESSION NO.

Johns-Manville Products Corporation, Phosphorus Removal Using Chemical Coagulation and a Continuous Countercurrent Filtration Process, Final Report FWQA Contract No. 14-12-154, June 1970

ABSTRACT:

The Johns-Manville Moving Bed Filter, a continuous precipitation and countercurrent filtration process, was evaluated for the removal of phosphorus from municipal wastewater.

Using alum and an anionic polyelectrolyte, the process was found to effectively reduce total phosphorus (TP), orthophosphate (OP) and condensed phosphate (CP) over a wide range of influent phosphorus concentrations. Preliminary work using jar tests established an alum dose of 200 mg/l (17.4 mg/l Al, molar ratio of Al/P is 27/31) as effective for removal of 90 per cent TP from the secondary clarifier effluent of a trickling filter plant. This removal efficiency could not be sustained with an alum dose of 200 mg/l when higher TP levels were encountered. With total phosphorus concentrations on the order of 25 to 28 mg/l as P (Al/P = 0.6-0.7), the TP removal efficiency averaged 90 per cent. With lower total phosphorus concentrations, removal efficiency averaged 95 per cent and ranged up to 99 per cent (Al/P = 1.2-2.6).

Substantial reductions in final effluent total suspended solids (TSS) and 5-day biochemical oxygen demand (BOD_5) were also obtained. At an alum dose of 200 mg/l, TSS reduction averaged 70 per cent and BOD_5 reduction 80 per cent. If phosphorus removal were not a design consideration, the reduction of TSS and BOD_5 could be achieved with lower alum doses.

The 200 mg/l alum dose was also found to be equally effective for removal of phosphorus from raw sewage and primary effluent with the added capability for removing substantial portions of the TSS and BOD_5. In short studies on these streams, effluent as good or better than the final effluent from the trickling plant was obtained.

Costs for a 1.0 MGD plant are estimated to be $264,000 for capital and 12.0 cents per 1000 gal for total operating cost. These costs would be about the same for raw sewage, final effluent or the two intermediate levels of prior treatment studied.

Ultimate disposal of the phosphorus-containing sludge could be achieved by a dewatering and landfill operation. Dewatering by means of a rotary vacuum precoat filter would require an estimated capital expenditure of $30,000 and total cost would be 3 cents per 1000 gal of original wastewater treated.

This report was submitted in fulfillment of Contract No. 14-12-154 under the sponsorship of the Federal Water Quality Administration.

KEY WORDS:

Phosphorus Removal

Moving Bed Filter

Sand Filtration

Solids Removal

BOD Removal

Alum Coagulation

Chemical Treatment

Treatment Costs