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PILOT PLANT STUDIES OF WASTEWATER CHEMICAL CLARIFICATION USING ALUM

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PILOT PLANT STUDIES OF WASTEWATER CHEMICAL CLARIFICATION USING ALUM

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ABSTRACT

The treatment effectiveness of the chemical clarification process using alum was evaluated through jar tests and pilot plant studies. Jar tests indicated that flocculation times of 15 minutes or greater resulted in the greatest phosphorus removal. Pilot plant studies were conducted using an alum dosage of 175 mg/l and a flowrate of 4 gpm. At a flocculation time of 16 minutes, 89 percent of the total phosphorus, 94 percent of the dissolved phosphorus, 76 percent of the turbidity, and 81 percent of the suspended solids were removed.

The pilot plant studies also indicated that a pH control or monitor system should be included in the process design to prevent periodic pH depressions below 6.0. The average pH and alkalinity of the clarified effluent were 6.3 and 35 mg/l as $CaCO_3$ respectively. Lower pH readings (below 6.0) were often recorded during the pilot plant studies.

As a result of alum addition, primary sludge production was estimated to be 2100 lbs/MG, or approximately double that expected of a conventional primary treatment facility. Percent solids were estimated to be 2.25.

The operating and amortized capital costs for alum addition to an existing primary treatment facility were estimated to total $.09/1000 gallons; of this, $0.06/1000 gallons represents the cost of alum.

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INTRODUCTION

Background

In order to curb eutrophication of surface waters, many existing and future wastewater treatment facilities will be required to remove a major portion of the algal nutrient, phosphorus. In most cases, phosphorus removal requirements range from 80 to 95 percent and, effluent concentration limits range from 0.1 to 2.0 mg/l as P. Massachusetts water quality standards require that "any existing discharge containing nutrients in concentrations which encourage eutrophication or growth of weeds or algae shall be treated to remove such nutrients to the maximum extent technically feasible." (1)

Phosphorus removal is usually accomplished by chemical precipitation with coagulants such as alum, lime, iron salts and polyelectrolytes. Of all these coagulants alum has proven to be one of the most effective and easily applied. The advantages of using alum include:

1) Removal of up to 90 percent of the phosphorus present in wastewater,
2) Increased removal efficiency of suspended solids and BOD in the clarification step,
3) Production of an effluent pH compatible with biological treatment (if sufficient alkalinity is present),
4) Provision for normal operation of anaerobic sludge digestion with production of a stable aluminum phosphate precipitate,
5) Convenient storage of alum and trouble-free feed through automatic control devices.

In contrast to the advantages of using alum, lime often elevates the pH beyond a range amenable to biological treatment. Moreover, the calcium phosphate precipitate thus formed redissolves under the acidic conditions of sludge digestion and returns phosphorus to the system. Ferric chloride reacts much like alum except that a highly colored effluent is produced if it is overdosed.

In spite of the many advantages of using alum, its acidic nature may cause a severe pH depression in typically soft, low alkalinity, New England wastewaters. A severe drop in pH would occur when alum is overdosed and all the alkalinity is depleted. Even if alum dosage is controlled, a pH adjustment may be required prior to further treatment such as chlorination or biological nitrification. Also, effluent pH values below 6.0 would violate the minimum level of effluent quality standards for secondary treatment (2) and would be less than the water quality standards for pH in Class C waters (1).

Other disadvantages of alum clarification include:

1) Difficulties in dewatering because of the light gelatinous sludge produced,
2) Unavailability of any proven technique to recover and reuse alum,
3) The higher cost of alum compared to other precipitants such as lime or ferric chloride.

Objectives

The basic objectives of this pilot plant study were as follows:

1) To demonstrate the application of alum as a chemical precipitant

in low alkalinity wastewaters,

2) To examine the effect of flocculation time on phosphorus removal,
3) To evaluate the overall effluent quality as measured by turbidity, suspended solids and total organic carbon (TOC),
4) To investigate sludge characteristics and sludge accumulation rate.

Scope

The investigative approach used in this study involved a series of jar tests followed by a pilot plant study. The jar tests were performed in order to determine general removal characteristics and to examine the effect of flocculation time as a single variable.

The pilot plant study was divided into two phases. Phase I was concerned with verifying the results of the jar tests on a continuous flow system. Three different flocculation times were investigated. Phase II was initiated to demonstrate the long term effectiveness of the process at the optimum flocculation time. All pilot plant studies were made at a flowrate of four gallons per minute (15.2 l/min.).

An alum concentration of 175 mg/l was used in all experiments. This dose was determined to be the most effective in a previous study of chemical treatment of Amherst wastewater performed by Bowen (3). With an average influent total phosphorus concentration of 6 mg/l as P, the aluminum to phosphorus mole ratio is 3 to 1.

Amherst primary effluent was used in both pilot plant experiments and in the jar tests. Raw sewage was not used because gross settleable solids would often clog pumps and pipes in the small pilot plant system. However, the use of primary effluent rather than raw sewage should not detract from the results of this investigation. This is because the Amherst Sewage Treatment Plant often discharges a strong effluent due to a chronic condition of hydraulic overloading. The strength of this effluent is shown in Table 1 for the period during which pilot plant studies were made.

The parameters analyzed during the jar tests and pilot plant studies include pH, alkalinity, turbidity, TOC, suspended solids, total and dissolved phosphorus. Percent volatile solids, specific gravity, and sludge accumulation rate were determined during the sludge accumulation studies.

TABLE 1

AMHERST PRIMARY EFFLUENT CHARACTERISTICS*

Parameter	Mean Value	Range of Values
Total Phosphorus (mg/l as P)	6.12	2.6 to 8.4
Dissolved Phosphorus (mg/l as P)	4.60	2.6 to 6.7
Suspended Solids (mg/l)	90	34 to 128
Turbidity (JTU)	48	20 to 70
Total Organic Carbon (mg/l)	62	16 to 89
pH	7.0	6.46 to 7.54
Alkalinity (mg/l as $CaCO_3$)	108	68 to 135

*Amherst primary effluent is the influent for all pilot plant experiments and jar tests.

CHEMICAL CLARIFICATION WITH ALUM

Chemical clarification with alum has long been used as a water purification process to remove fine suspended particles which would otherwise escape from the sedimentation process. The alum forms a flocculent precipitate which enmeshes the slowly settleable and colloidal particles to form rapidly settling aggregates or flocs. Added to wastewater, alum performs the same function causing greater removals of suspended solids, turbidity and organics. More importantly however, addition of aluminum ions removes phosphorus both directly by precipitation and indirectly, by enmeshment in an aluminum hydroxide floc. The combined results is the production of an effluent of sufficient quality to nearly match the performance of a good secondary treatment system.

There are many excellent publications available to the reader on the basic design considerations of the alum clarification process. The most comprehensive and useful from a practical application standpoint are those published by the EPA Technology Transfer Program. Some of these stress the phosphorus removal capability of alum while others are oriented towards the chemical clarification function of alum addition. An excellent example of the former is the "Process Design Manual for Phosphorus Removal" (4) which presents the latest techniques for removing phosphorus from various treatment processes; another report, entitled "Designing to Remove Phosphorus Using Metal Salts and Polymers in Conventional Plants" (5), deals with the application of alum and other chemicals to remove phosphorus in existing treatment facilities.

If the design emphasis is on physical-chemical treatment using alum, the reader should consult the EPA publication "Physical-Chemical Wastewater Treatment Plant Design" (6); all necessary plant design considerations are presented as well as case histories of applications. Another useful publication is "Physical-Chemical Processes" (7) by the Advanced Waste Treatment Research Laboratory in Cincinnati, Ohio. Design criteria are discussed and descriptions and performance evaluations of some physical-chemical pilot plants are presented.

Although these EPA publications, as well as the research literature, provide a wealth of information on phosphorus control strategies, there are few case histories of experience with low alkalinity wastewaters as to be encountered in the New England area. This report provides pilot plant data on removal of phosphorus from wastewater in Amherst, Massachusetts. Problem areas likely to be encountered in similar applications in New England are discussed. Moreover, this report deals with the effect of flocculation time on phosphorus removal, an area of process research often neglected.

JAR TESTS

Prior to conducting pilot plant studies of chemical clarification using alum, a series of jar tests were performed. Jar tests provided a method of singularizing the effect of flocculation time on turbidity, suspended solids, TOC, phosphorus, pH, and alkalinity. It also was a preliminary means of evaluating the overall removal effectiveness of alum.

The jar tests were accomplished using a six paddle, variable speed, stirring apparatus and one liter wastewater samples. Each sample was dosed with 175 milligrams of alum and mixed for 30 seconds at 100 rpm. The samples were then flocculated at 20 rpm for periods lasting between 0 and 24 minutes. After one hour of settling, samples of the supernatant were withdrawn for analysis. The analytical techniques used in both the jar test experiments and the pilot plant tests can be found in Appendix I.

Results of the jar test experiments are summarized in Table 2. Turbidity and suspended solids showed only slight decreases with increasing flocculation time. Effluent TOC concentrations were scattered indicating that TOC is not a function of flocculation time. However, total and dissolved phosphorus concentrations were markedly decreased as the flocculation time increased. Total phosphorus decreased from a concentration of 1.2 mg/l as P without flocculation to a minimum of less than .1 mg/l as P after 15 minutes of flocculation. Flocculation times longer than 15 minutes also produced total phosphorus concentrations less than .1 mg/l as P. Dissolved phosphorus data

TABLE 2

EFFECT OF FLOCCULATION TIME ON JAR TEST RESULTS

Parameter	Influent Concen.	Flocculation Time (Min.)								
		0	3	6	9	12	15	18	21	24
		Effluent Concentration								
Turbidity (JTU)	39.0	13.5	9.5	6.5	5.0	3.0	2.0	2.0	2.0	2.0
Suspended Solids (mg/l)	117	9.0	7.5	6.5	6.0	4.5	5.0	-	-	-
TOC (mg/l)	63.5	27	23	23	22	24.5	21	24	20	27
Total Phosphorus (mg/l as P)	7.85	1.20	.85	.50	.30	.15	.10	.10	.10	.10
Dissolved Phosphorus (mg/l as P)	4.25	1.40	1.00	.60	.40	.27	.10	.10	.10	.10
pH	7.15	6.05	6.0	6.0	5.95	6.0	6.0	6.0	6.05	6.05
Alkalinity (mg/l as $CaCO_3$)	113	30	27.5	28.5	27	28.5	28.5	30	30	30

is almost identical to total phosphorus indicating the absence of any particulate matter in the supernatant. Alkalinity and pH remained relatively constant for all flocculation times.

Based on this data it appears that the primary justification for longer flocculation times is the significant increase in phosphorus removal. Maximum phosphorus removals occurred at flocculation times of 15 minutes or greater. The fact that greater phosphorus removals are achieved at longer flocculation times is probably due to promotion of a greater number of particle contacts. This permits the amorphous aluminum phosphate precipitate to aggregate and settle out.

The data also indicates that pH and alkalinity depression could be a problem in typical New England wastewaters. Initial pH and alkalinity of the Amherst wastewater sample used in jar tests was 7.15 and 113 mg/l as $CaCO_3$ respectively. After flocculation these values were reduced to approximately 6.0 and 30 mg/l as $CaCO_3$. While a treatment plant effluent containing pH and alkalinity values of this magnitude may be satisfactory most of the time, there will be occasions when the effluent pH and alkalinity may be further reduced. This is likely to occur during wet weather flows when the influent alkalinity is diluted.

PILOT PLANT STUDIES

Jar tests demonstrated that maximum phosphorus removals occurred at flocculation times of 15 minutes or greater. Further studies using a continuous flow system were needed to assess the effect of different flocculation times under actual plant operating conditions, and to evaluate the overall effluent quality produced.

Phase I of the pilot plant investigations was devoted to examining the overall effect of flocculation time on the treatment effectiveness of the chemical clarification process using alum. The pilot plant facility was operated at flocculation times of 5.0, 8.0, and 16.0 minutes. Data was collected continuously for three days at each flocculation time. The objective of this phase was to verify jar test results and to select the optimum flocculation time for further pilot plant testing.

Phase II consisted of data collection for 16 days at the optimum flocculation time determined from Phase I. The intent of the second phase was to evaluate the system for a sustained period. In addition, this extended study permitted measurement of sludge characteristics and accumulation rate.

Equipment

A schematic diagram of the pilot plant facility used during both phases is shown in Figure 1. The facility includes a rapid mix tank which provides a one minute detention time at 4 gpm (152 l/min.). It also includes two flocculation tanks with a full capacity of 32 gallons (121.6 l) each. Different flocculation times were obtained using

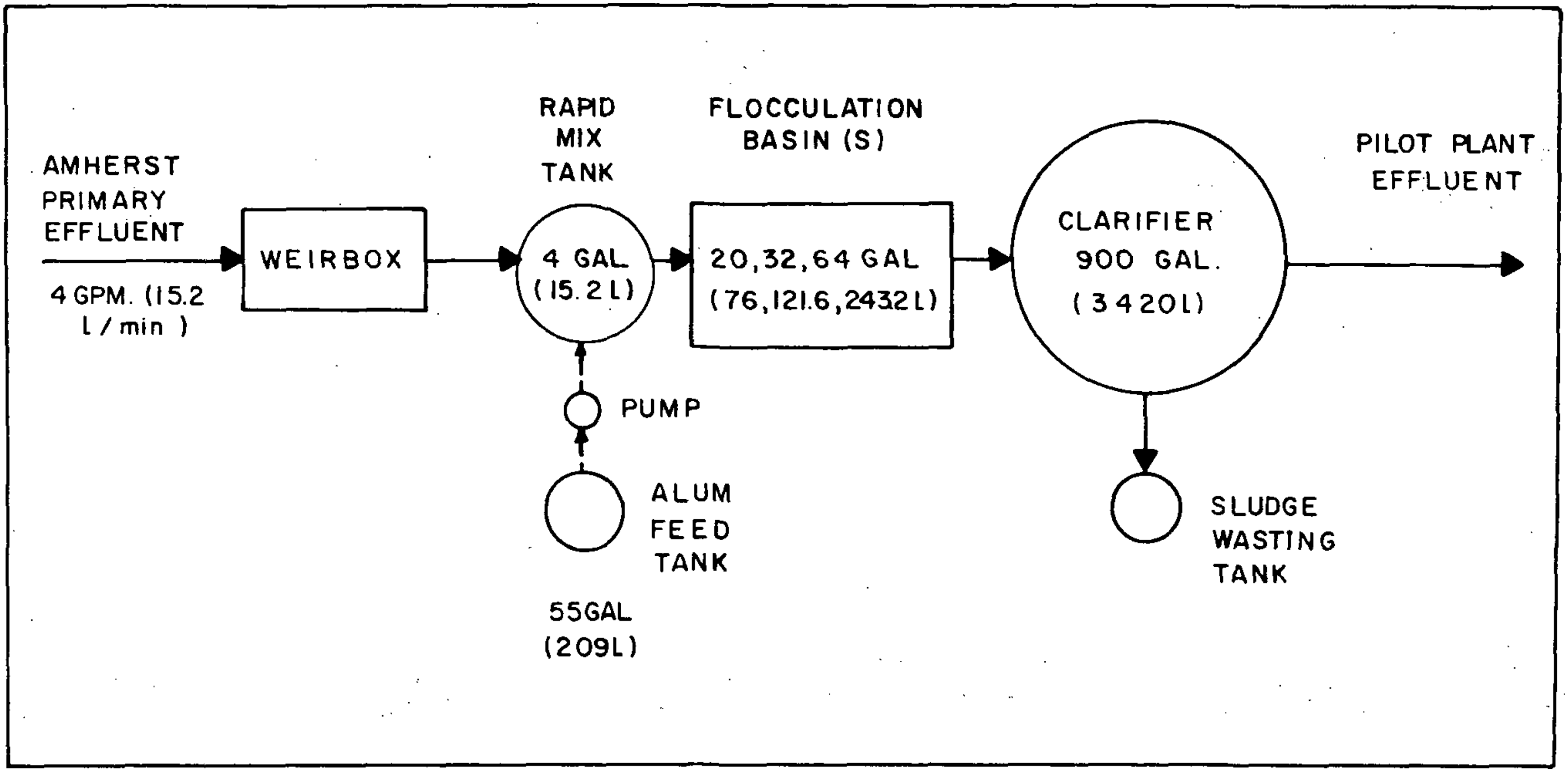

FIGURE 1. Schematic Diagram of Pilot Plant

various combinations of these two tanks. Effluent from the tanks flows to a 900 gallon (3420 l) circular clarifier which provides a 3.75 hour detention time at 4 gpm (15.2 l/min.). The clarifier has a rim inlet chamber and a center weir overflow. The cone shaped clarifier bottom contains a shaft mounted sludge scraper and a plexiglass window to monitor sludge accumulation.

In addition to these treatment units, the facility also includes a weirbox, an alum feed unit, and a sludge wasting tank. The weirbox is mounted at the influent end of the pilot plant and is used to monitor and maintain the desired 4 gpm (15.2 l/min.) flowrate. The liquid alum feed is controlled by a Sigmamotor metering pump. It was necessary to dilute the alum tenfold in order to accurately control the feed rate. By maintaining a constant flowrate at 41 ml/min. the desired concentration of 175 mg/l in the rapid mix tank was assured. The liquid alum was supplied by Holland Company of North Adams, Massachusetts. It contained 5.4 pounds of alum per gallon (0.74 kg/l).

Connected to the bottom of the clarifier is a 55 gallon (209 l) sludge wasting tank. Sludge sampling is accomplished by opening a connecting valve which allows accumulated sludge to flow into the wasting tank.

A more detailed listing of the pilot plant dimensions and design parameters is shown in Table 3.

Operating Procedure

After connecting the flocculation basin(s) required for the desired detention time, primary effluent was discharged into the weirbox and

TABLE 3

PILOT PLANT DIMENSIONS AND DESIGN PARAMETERS

Rapid Mix Tank	
Capacity	4 gal. (15.2 l)
Flowrate	4 gpm (15.2 l/min.)
Detention Time	1 min.
Flocculation Basin(s)	
Number of Basins	2
Dimensions of Each Basin	44 in. x 15 in. x 12 in. (110 cm. x 37.5 cm. x 30 cm.)
Liquid Depth	42 in. (105 cm.)
Flowrate	4 gpm (15.2 l/min.)
Capacities*	20 gal., 32 gal., 64 gal. (76 l, 121.6 l, 243.2 l)
Detention Times	5 min., 8 min., 16 min.
Paddle Area (full basin)	0.444 ft^2 (0.040 m^2)
Mean Velocity Gradient (G)	40 $sec.^{-1}$
Flocculation rpm	20
Clarifier	
Diameter	5.5 ft. (1.65 in.)
Volume	900 gal. (3420 l)
Detention Time (@ 4 gpm)	3.75 hours
Overflow rate (@ 4 gpm)	242 gpd/ft^2 (10, 218 lpd/m^2)

*The 20 gallon capacity was obtained by attaching a lower outlet in the 32 gallon flocculation basin.

adjusted to provide a flowrate of four gallons per minute. The alum feedrate was established at 41 ml/min. which provided a concentration of 175 mg/l alum in the rapid mix tank. The flocculator paddles were started and the rotational speed was set at 20 rpm. This produced a mean velocity gradient (G) of 40 $\sec^{-1}$ (see Appendix II). Finally, the sludge scraper mechanism was started and a plywood cover was placed over the top of the clarifier to reduce wind effects.

The system required a minimum of four hours to reach steady state. Usually the units were allowed to run overnight before taking the first samples. The influent flowrate and alum feedrate were checked periodically throughout the day. Only minor flow adjustments were ever required.

During Phase II of the pilot plant study, the accumulated sludge in the clarifier was also measured and wasted daily. The sludge blanket level was readily observable thru a plexiglass window at the bottom of the clarifier. In order to obtain a uniform sample, sludge was wasted into an adjacent tank and manually stirred.

Sampling Procedure

Both grab and composite samples were taken during Run No. 1 at a flocculation time of five minutes and Run No. 2 at eight minutes. The grab samples were gathered during the daytime hours of 9, 10, 11, 1, 2, 3, while the composite samples were taken during the off-duty hours between 5PM and 8AM. A Serco[1] automatic sampler provided hourly influent

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[1] Sonford Products Corporation, Dain Tower, Minneapolis, Minnesota 55402

samples which were later combined into four-hour composites. A Surveyor[1] automatic sampler furnished a 15 hour composite of the effluent. The total number of samples taken over each of the runs included 30 influent samples (18 grab samples and 12 composites) and 21 effluent samples (18 grab samples and 3 composites).

Composite samples were not taken during Run No. 3 at 16 minutes flocculation time because the automatic samplers were not available. Consequently, only 18 influent and effluent grab samples were taken. This should not seriously effect a comparison of results because the grab samples were collected during the periods associated with the highest influent pollutional levels and therefore provide the main test of removal effectiveness.

During Phase II, 24 hour composites were taken of the influent and effluent using a Durram Dial-A-Pump[2]. The pump operated continuously over the 24 hour period and provided a gallon of sample. No samples were taken over the weekends. Ten composite samples were taken over the 16 day period.

Precautions were taken to maintain sample integrity. Turbidity, alkalinity, pH and suspended solids were measured immediately after sampling. The samples were then acidified and refrigerated at 4°C. Total phosphorus, dissolved phosphorus, and TOC were determined at the end of the week when all samples had been gathered. The analytical

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[1] N-CON Systems Company, Incorporated, Larchmont, New York.

[2] Durrum Instrument Corporation, 925 East Meadow Drive, Palo Alto, Calif.

methods and techniques used are discussed in Appendix I.

Phase I: The Effect of Flocculation Time

The effect of flocculation time on the treatment efficiency of the pilot scale chemical clarification system using alum is summarized in Table 4. Mean influent and effluent values are given along with the effluent standard deviation. The mean percent removal is also calculated for all wastewater treatment parameters.

An examination of the data shown in Table 4 indicates that phosphorus removal is strongly dependent on flocculation time while turbidity, suspended solids and TOC removals are not. This agrees well with the previous jar test results. During the pilot plant study the mean percent removal of turbidity varied slightly with 58, 51 and 56 percent noted for flocculation times of 5, 8, and 16 minutes respectively. The clearest effluent (19 JTU) was produced during Run No. 1 at a flocculation time of five minutes.

The highest removal of suspended solids was achieved with a flocculation time of eight minutes (Run No. 2); an average of 83 percent of the suspended solids were removed. Ironically, the lowest removals were obtained during Run No. 3 at the longest flocculation time of 16 minutes. However, the suspended solids concentration of the influent was generally higher during this period and probably contained many floatables. This floatable material (grease, garbage, etc.) is able to pass over the effluent weir because the pilot plant clarifier is not equipped with a skimming device. Consequently it is expected that effluent samples would sometimes contain a higher amount of suspended

TABLE 4

TREATMENT EFFICIENCY VS. FLOCCULATION TIME

Parameter		Flocculation Time (Minutes) Run No. 1 5.0	Run No. 2 8.0	Run No. 3 16.0
Turbidity (JTU)	mean influent	45	45	50
	mean effluent	19	22	22
	mean % removal	58	51	56
	effluent stand.dev.	4.0	7.5	5.3
Suspended Solids (mg/l)	mean influent	87	80	95
	mean effluent	26	14	39
	mean % removal	70	83	59
	effluent stand. dev.	10.9	14.0	11.6
TOC (mg/l)	mean influent	50	63	65
	mean effluent	26	33	36
	mean % removal	48	48	45
	effluent stand.dev.	7.0	7.4	8.0
Total Phosphorus (mg/l as P)	mean influent	5.22	6.15	6.20
	mean effluent	1.36	1.75	1.11
	mean % removal	74	72	82
	effluent stand.dev.	0.23	0.54	0.40
Dissolved Phosphorus (mg/l as P)	mean influent	4.65	5.03	4.01
	mean effluent	1.45	1.57	0.08
	mean % removal	68	69	98
	effluent stand.dev.	0.40	0.57	0.07
pH	mean influent	6.83	6.96	7.22
	mean effluent	6.24	5.83	5.20
	effluent stand.dev.	0.16	0.54	0.54
Alkalinity	mean influent	96	111	117
	mean effluent	42	37	15
	effluent stand.dev.	9.8	17.0	11.6

solids than normal. Later results obtained during Phase II of the pilot plant studies will show that 81 percent of the suspended solids were removed at the 16 minute flocculation time.

TOC removal remained relatively constant for all flocculation times. Forty-eight percent of the TOC was removed during Run No. 1 and Run No. 2 and 45 percent during Run No. 3.

Unlike turbidity, suspended solids and TOC, phosphorus concentration decreased with increasing flocculation times. This is especially noticeable at a flocculation time of 16 minutes where 82 percent of the total phosphorus was removed, producing a mean effluent concentration of 1.11 mg/l as P. Dissolved phosphorus was also decreased by 98 percent to a mean effluent concentration of 0.08 mg/l. The differences in phosphorus removals between the five and eight minutes of flocculation were minimal. Figures 2, 3, and 4 show the variation in phosphorus removal observed using alum for flocculation times of five, eight and sixteen minutes respectively. It is to be noted that fluctuations in daily influent phosphorus concentrations were effectively dampened by the pilot plant process. The uniformity of the effluent phosphorus concentrations is also indicated by the small standard deviation values shown in Table 4.

The effect of flocculation with alum on the low alkalinity wastewater found in Amherst and throughout most of New England is also shown in Table 4. The mean effluent pH and alkalinity decreased as the flocculation time increased. This decrease is contrary to the results obtained in the jar tests where effluent pH and alkalinity remained

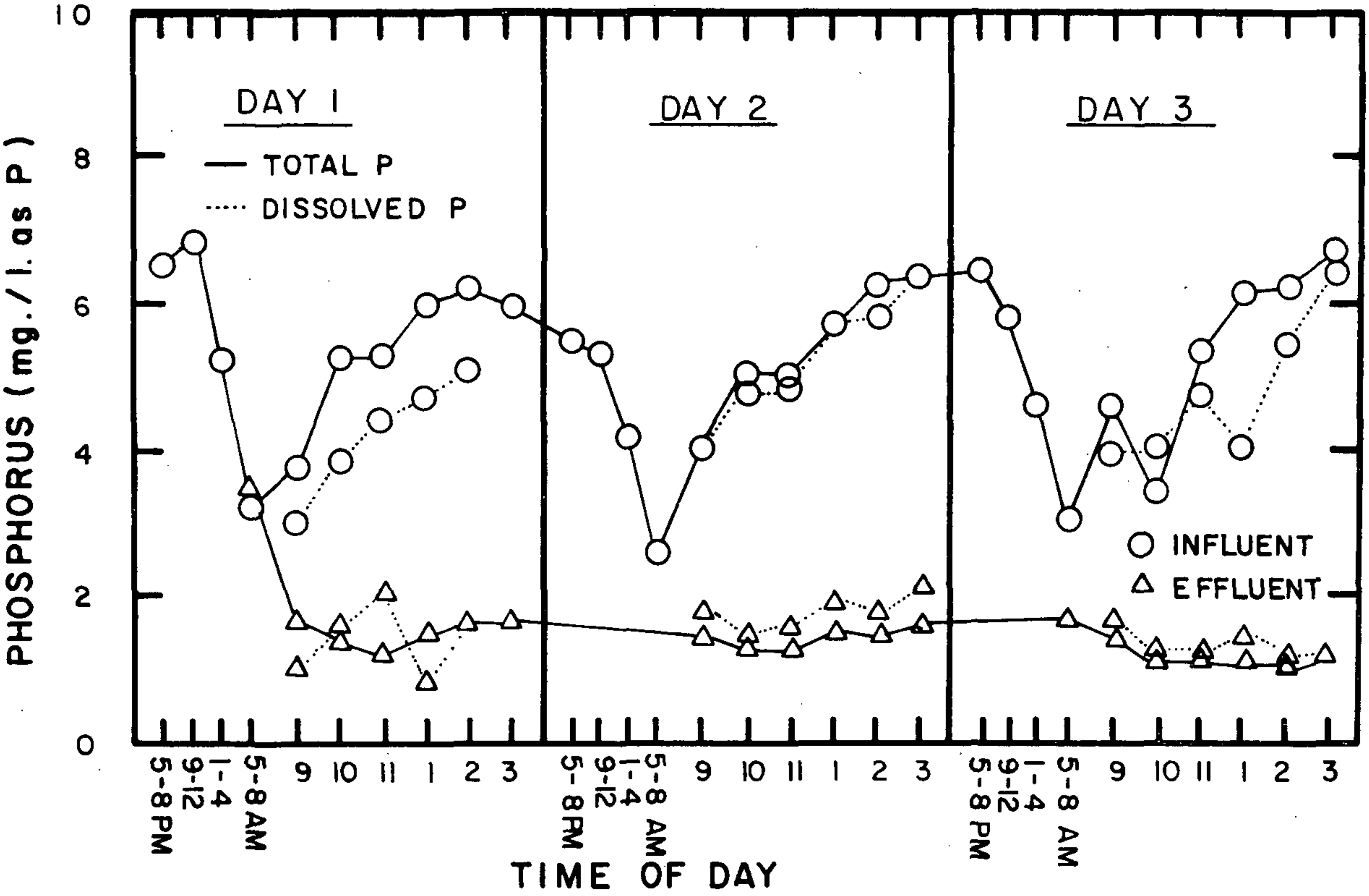

FIGURE 2. Influent and Effluent Phosphorus Concentrations for a Flocculation Time of 5.0 Minutes.

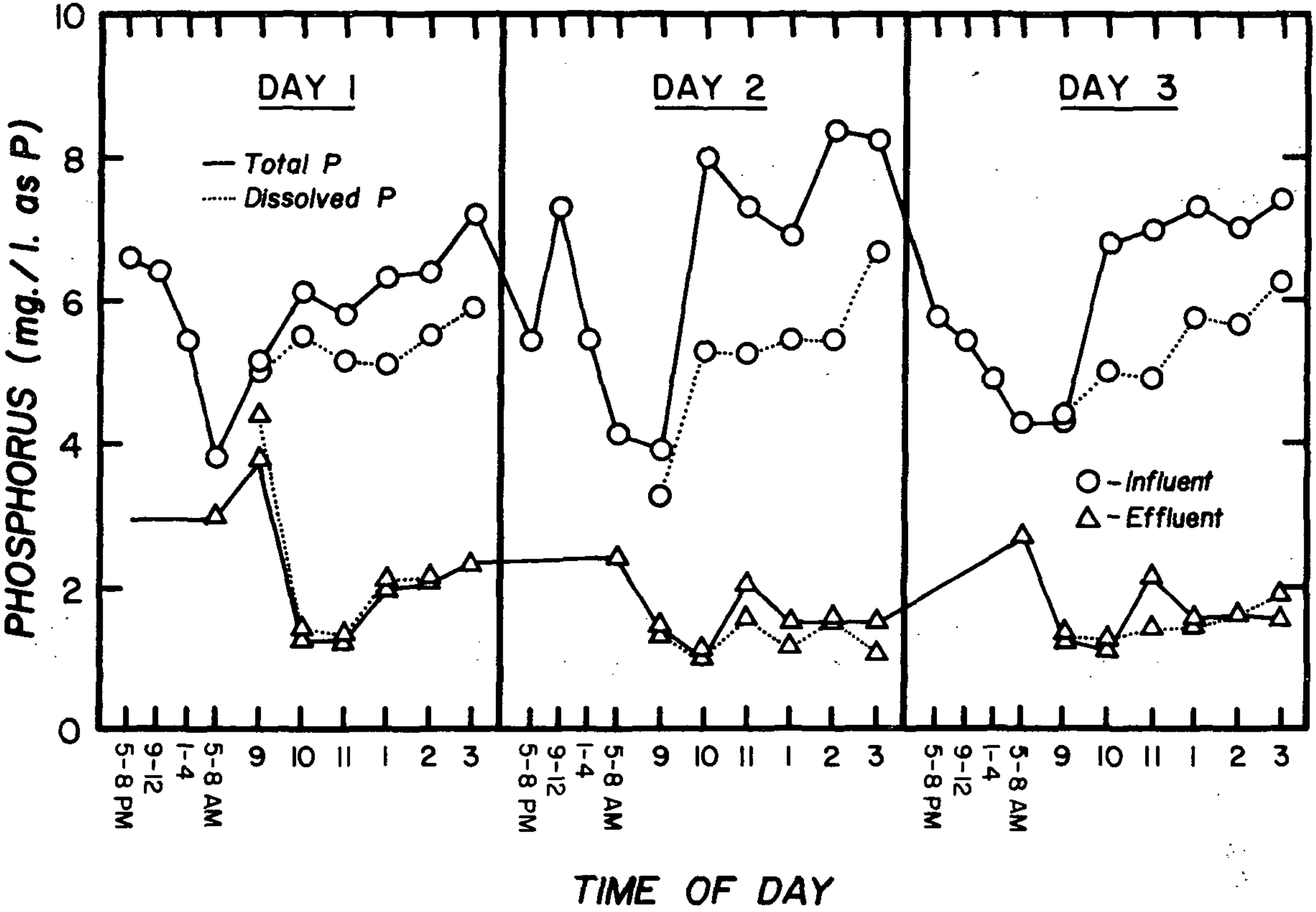

FIGURE 3. Influent and Effluent Phosphorus Concentrations for a Flocculation Time of 8.0 Minutes.

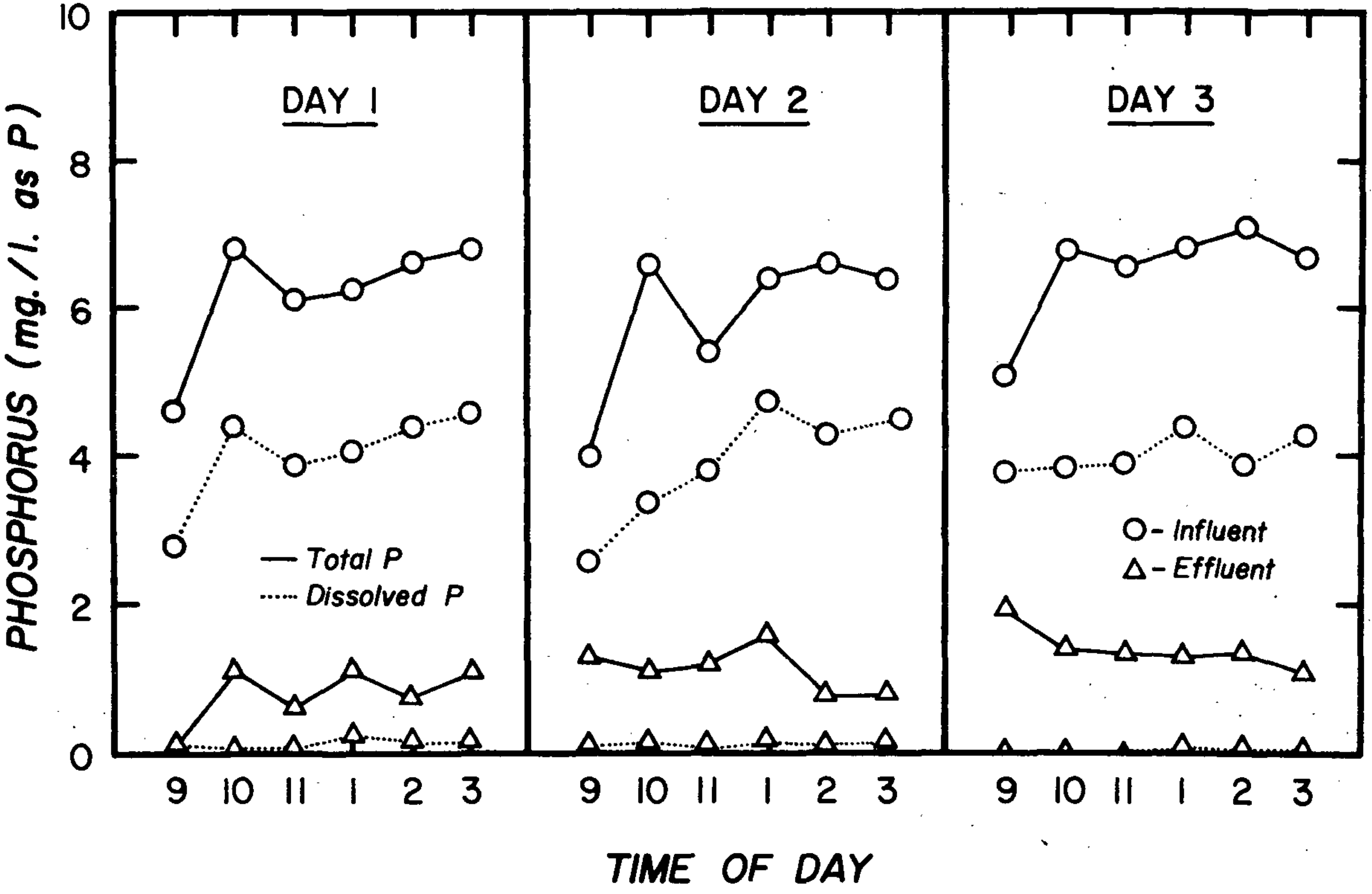

FIGURE 4. Influent and Effluent Phosphorus Concentrations for a Flocculation Time of 16.0 Minutes.

relatively constant. It is also to be noted that the mean effluent pH values were below 6.0 at the 8 and 16 minute flocculation times. The probable cause of this result is a temporary overdosing of alum. Consequently, it appears that a pH monitoring or control system is necessary in order to avoid temporary overdoses which may cause serious pH reductions or alkalinity depletions.

Phase II: Pilot Plant Performance at Optimum Flocculation Time

Phase I study confirmed jar test findings in that greater phosphorus removals were possible using a longer period of flocculation. However, in order to more fully evaluate the performance of the chemical clarification process using alum, it was decided to extend the study period to 16 days. The Phase I study only provided a three day evaluation period at the optimum 16 minute flocculation time. Information was also needed in Phase II, on the sludge characteristics and accumulation rate. Studies of longer duration will be conducted in conjunction with the upcoming ammonia removal investigations with activated carbon. This information will be contained in a subsequent report.

The data obtained from the Phase II study is summarized in Table 5. During the Phase II study, the mean influent concentrations were slightly lower than those experienced in the Phase I study. This can be seen by comparing the mean influent values in Table 4 with those in Table 5. The cause of this discrepancy is the improved treatment efficiency of the Amherst plant during the summer months when the student population is minimal. That is, the clarifiers of the Amherst plant are able to

TABLE 5

PILOT PLANT PERFORMANCE AT OPTIMUM FLOCCULATION TIME

Parameter	Mean Influent	Mean Effluent	Mean % Removal	Effluent Stand. dev.
pH	7.1	6.3	--	0.34
Alkalinity (mg/l as $CaCO_3$)	103	35	--	35.0
Total Phosphorus (mg/l as P)	4.98	0.55	89	0.23
Dissolved Phosphorus (mg/l as P)	4.63	0.27	94	0.15
Turbidity (JTU)	33	8	76	2.80
Suspended Solids (mg/l)	43	8	81	4.84

effectively treat the lower summer flows. As in Phase I, the Amherst plant effluent was used as the pilot plant influent.

The only parameter significantly affected by the improved performance of the Amherst clarifiers was the influent suspended solids concentration. It ranged between an average of 80 to 95 mg/l during the Phase I study while Phase II produced an average value of only 43 mg/l. Although higher suspended solids concentrations would provide better test of the system, the main concern of this study is the effectiveness and suitability of alum for removing phosphorus in low alkalinity wastewaters. It is already well known that alum addition enhances suspended solids removal. Even with this low influent concentration, the average removal of suspended solids during Phase II was 81 percent with a mean effluent concentration of 8 mg/l being produced. Figure 5 shows the influent and effluent suspended solids concentrations during the study period.

As shown in Table 5, 89 percent of the total phosphorus and 94 percent of the dissolved phosphorus was removed during the Phase II study. The individual total and dissolved sample concentrations are shown in Figure 6. The mean effluent concentrations were 0.55 and 0.27 mg/l as P for total phosphorus and dissolved phosphorus respectively. This treatment efficiency should satisfy most phosphorus removal requirements. However, it may be possible to reduce total phosphorus concentrations even further by injecting an anionic polymer into a lower energy mixing zone following alum addition. The polymer would aid in settling suspended matter which contains much of the residual phosphorus.

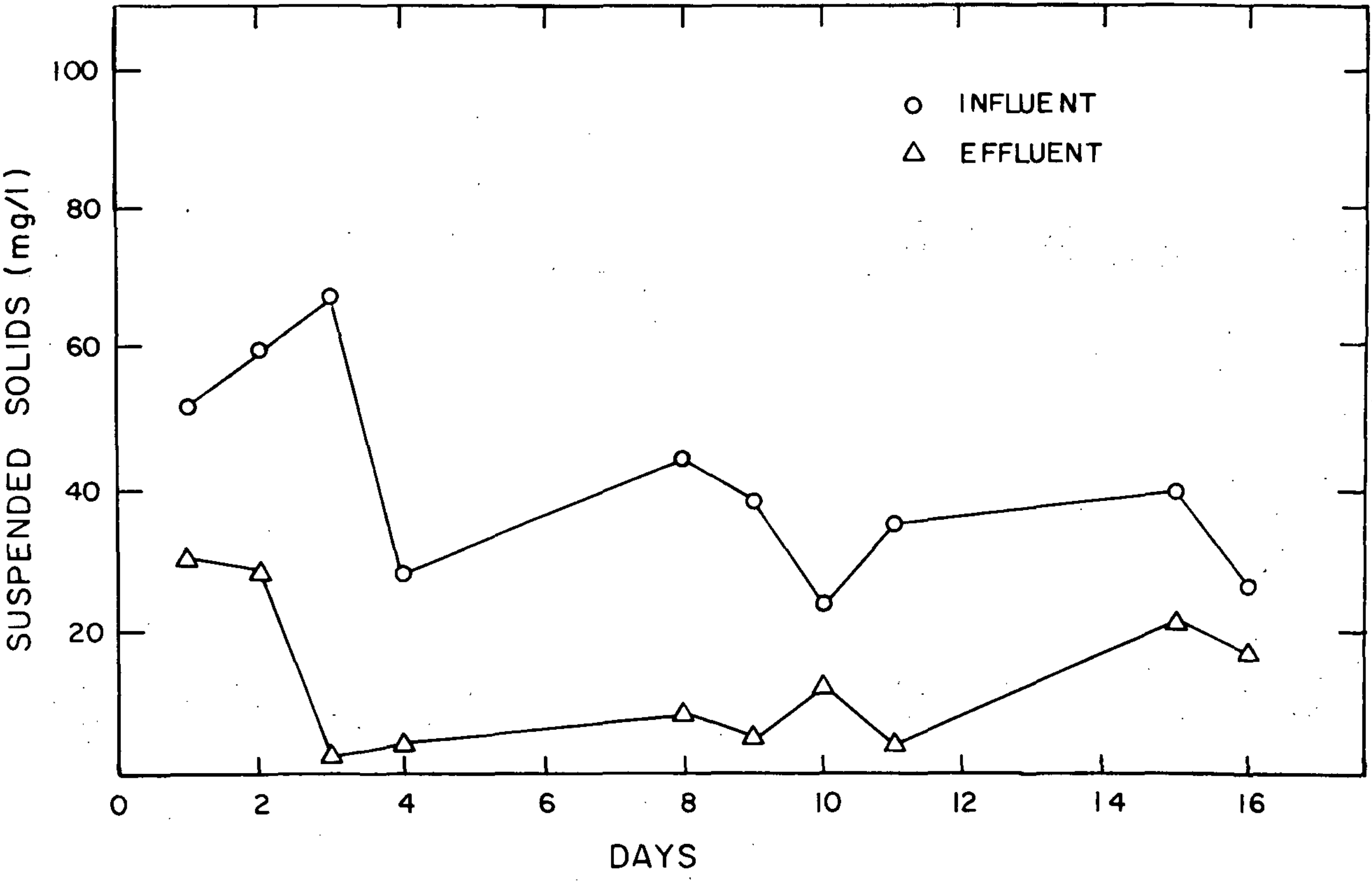

FIGURE 5. Variation in Suspended Solids During Phase II Study.

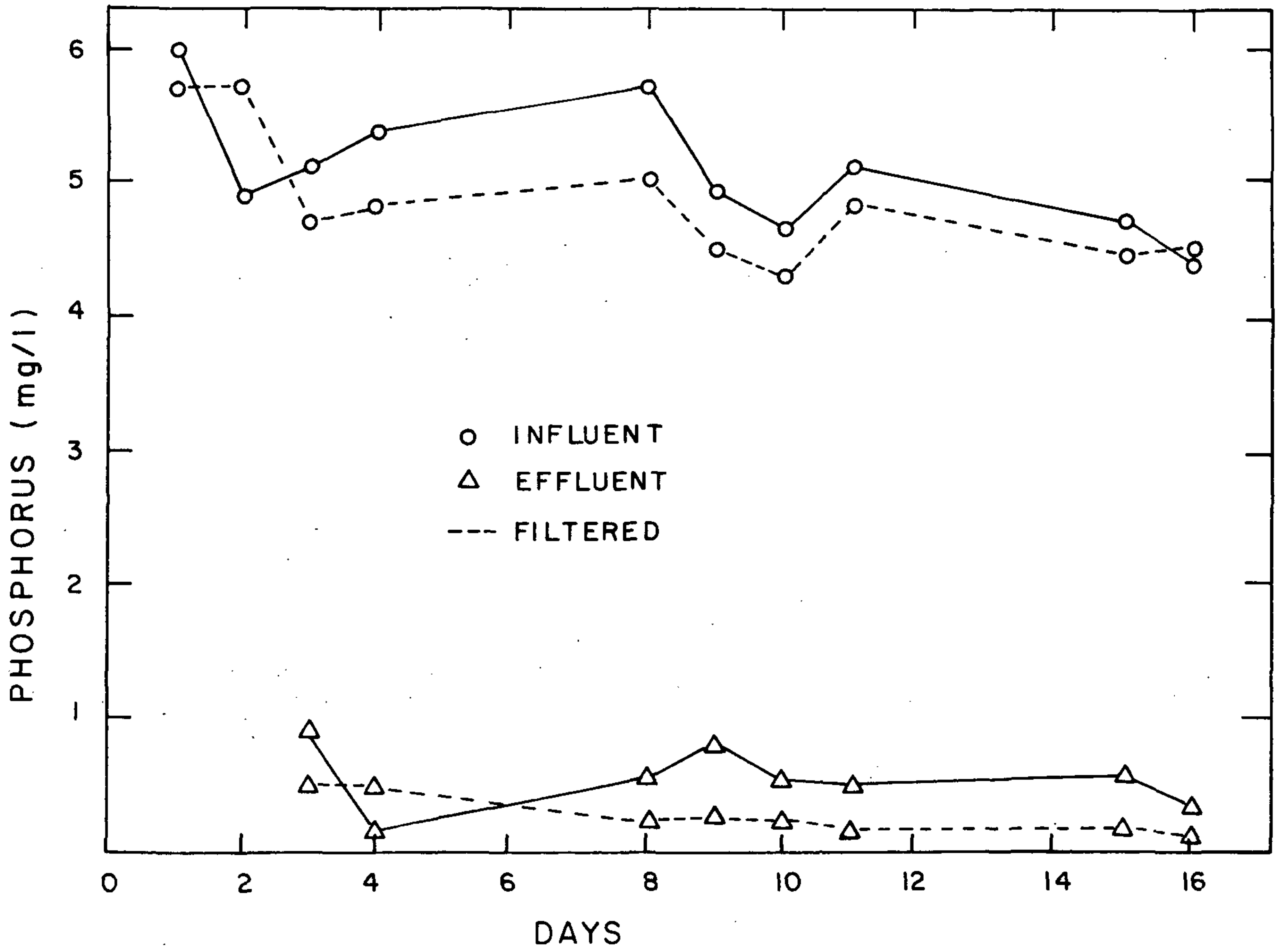

FIGURE 6. Variation in Phosphorus Concentrations During Phase II Study.

The total phosphorus concentration of this effluent would then be nearly equal to dissolved phosphorus concentrations.

On the average, alkalinity and pH were not severely depressed during the Phase II study even though 2.76 inches of rain fell during the 16 day period. Alkalinity and pH readings are shown in Figures 7 and 8. The mean effluent pH was 6.3 and the alkalinity was reduced to 35 mg/l as $CaCO_3$ from an influent of 103 mg/l as $CaCO_3$. However, as shown in Figure 7 the lowest alkalinity recorded during the Phase II study was only 7 mg/l and the pH was 5.4. Similar low pH values were recorded during the Phase I study. The occurrence of occasional pH depressions as noted in both pilot plant studies reinforces the conclusion that some degree of pH control or monitor system is necessary. Such a system would warn the operator of any malfunction in the alum feed system and maintain the effluent pH above 6.0.

The use of alum in the chemical clarification process produces a very clear effluent as revealed by the turbidity removal data. Seventy-six percent of the turbidity was removed; the average effluent turbidity was 8 JTU. Daily influent and effluent concentrations of turbidity are shown in Figure 9.

Sludge Production

Sludge collected during the Phase II study was usually black near the bottom of the clarifier and grey near the top of the sludge blanket. It had an objectionable odor and often times contained sludge worms if not wasted daily. The most notable sludge characteristics measured were specific gravity (1.0045) and total volatile dry solids (58 percent).

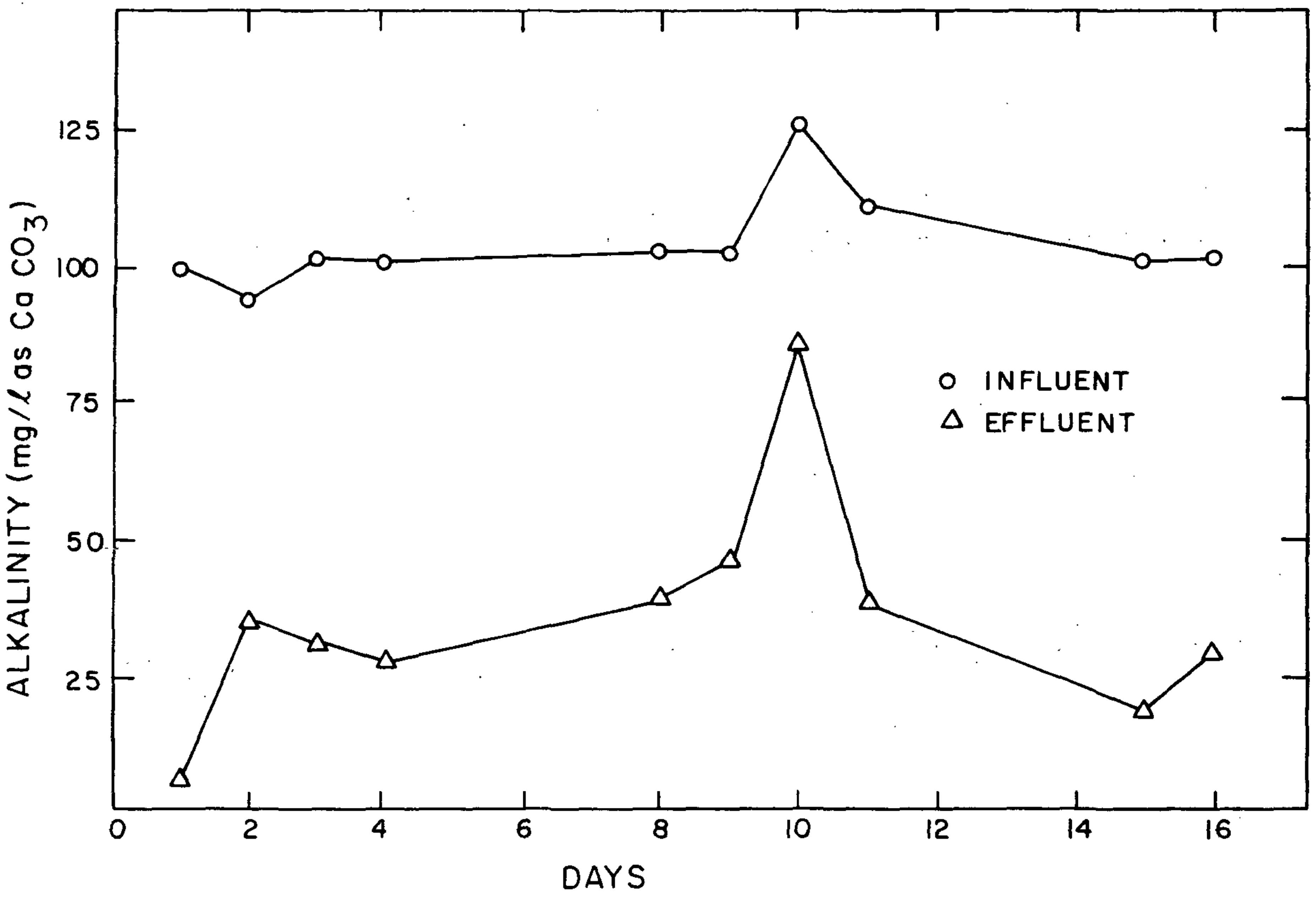

FIGURE 7. Variation in Alkalinity During Phase II Study.

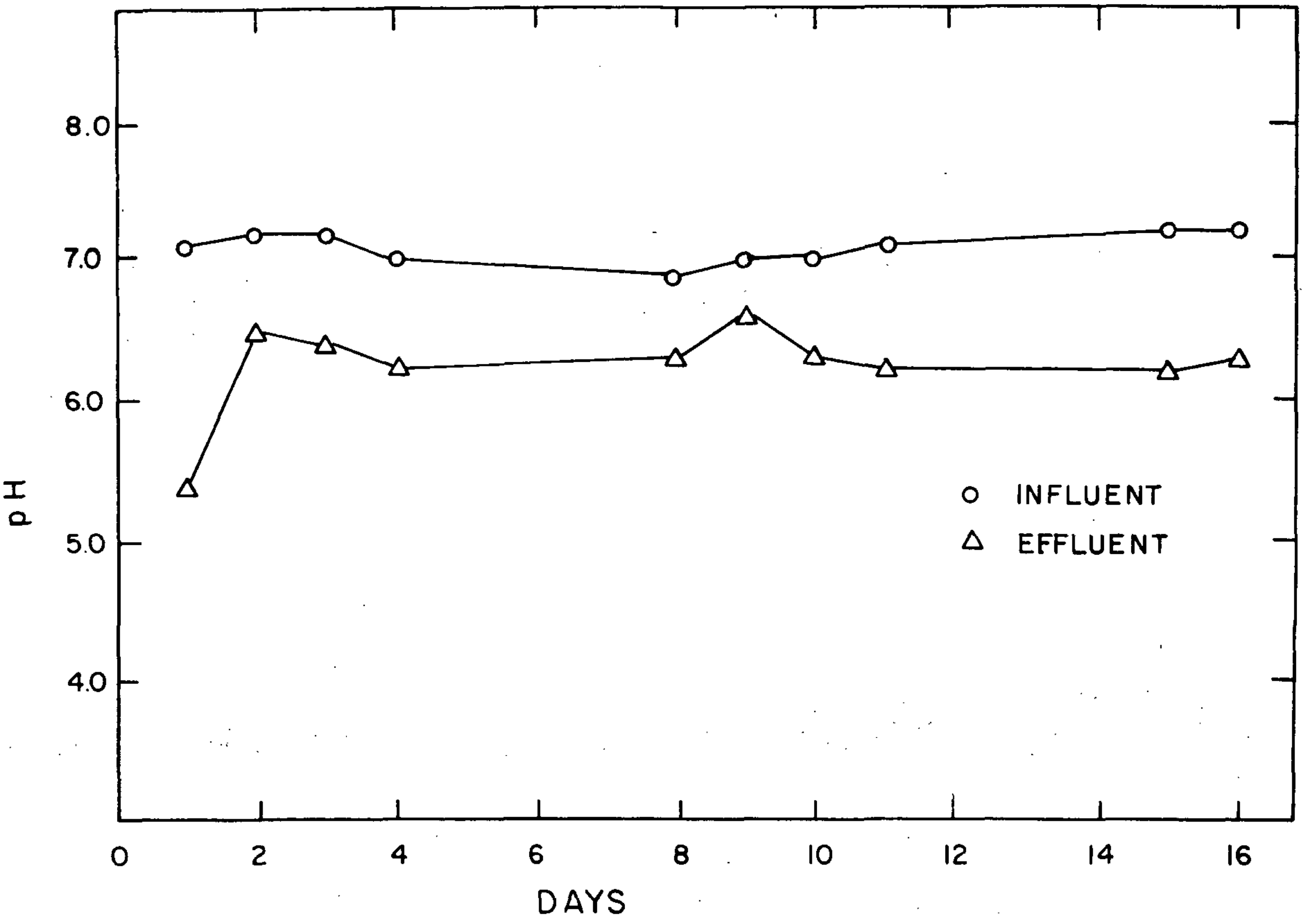

FIGURE 8. Variation in pH During Phase II Study.

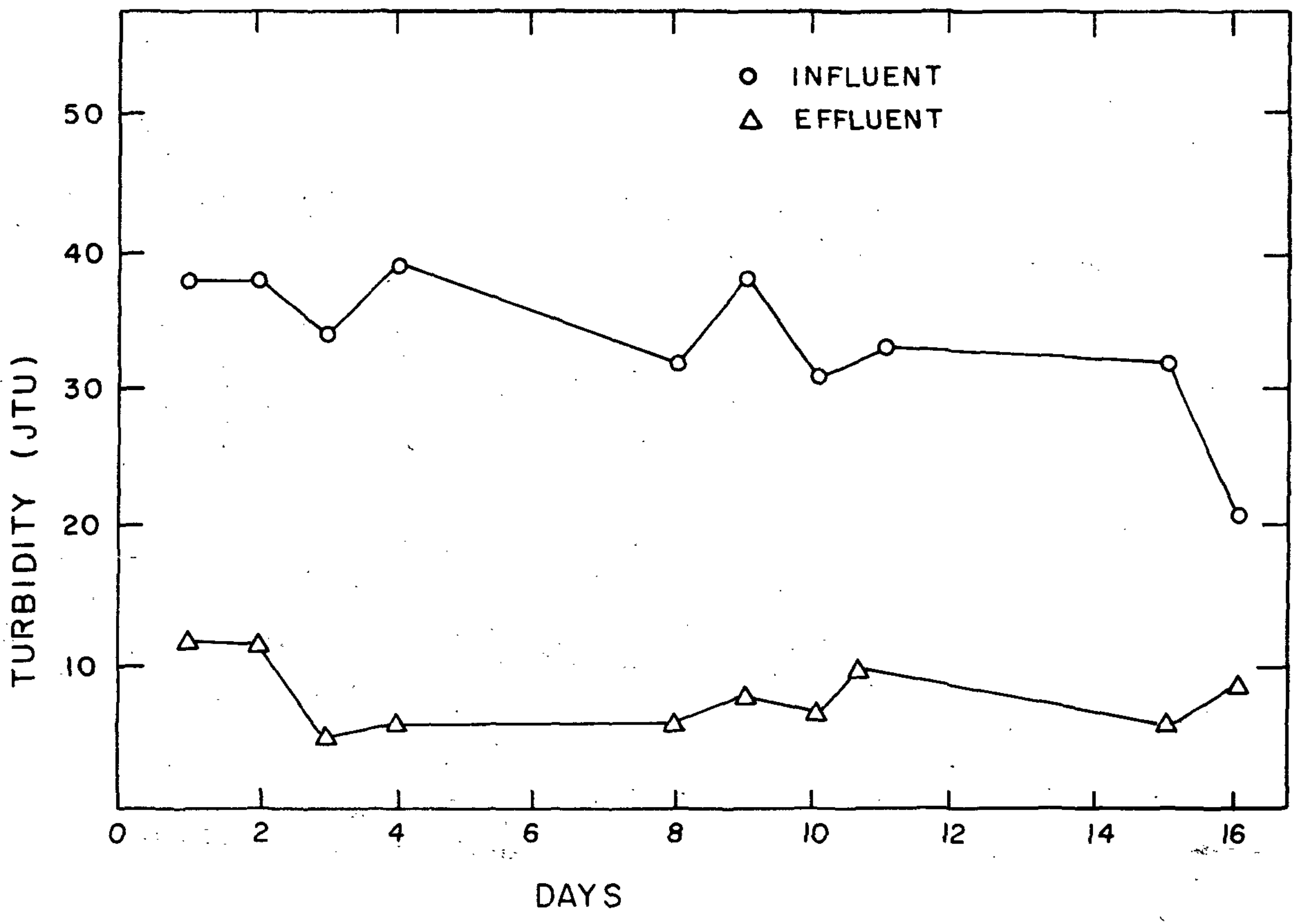

FIGURE 9. Variation in Turbidity During Phase II Study.

Approximately 50 gallons (190 l) of wet sludge were wasted daily from the 5760 gallon per day pilot plant. Scaled up accordingly, this is equivalent to 8680 gallons per million gallons. Assuming that the total wet sludge accumulation rate is equivalent to the sum of the Amherst STP and pilot plant sludge accumulation rates, the total wet sludge accumulation rate is therefore 11,225 gallons per million gallons (Amherst STP sludge wastage rate - 2545 gallons per million gallons). This large volume is not surprising considering the light gelatinous nature of alum sludges as evidenced by the average dry solids concentration of 1.25 percent obtained in this study. These results are similar to those reported in the EPA Process Design Manual for Sludge Treatment and Disposal (8) where the percent sludge solids averaged 1.2 percent and the sludge volume production rate varied between 10,000 and 36,000 gallons per million gallons.

The dry solids accumulation during the Phase II study is shown in Figure 10. Both the cummulative pounds of total and fixed solids wasted over the 16 day period are represented. From this data the average dry solids accumulation rate was determined to be 5.3 pounds (2.4 kg) per day or 920 pounds (414 kg) per million gallons of sewage. Similar results were obtained in a study by Burns and Shell (9) where 930 pounds per million gallons was obtained from a wastewater of comparative strength. If the dry solids accumulation rate resulting from the Amherst primary clarifiers (1180 pounds per million gallons) is added to the alum generated sludge (920 pounds per million gallons) the total sludge accumulation rate is then 2100 pounds per million gallons. From

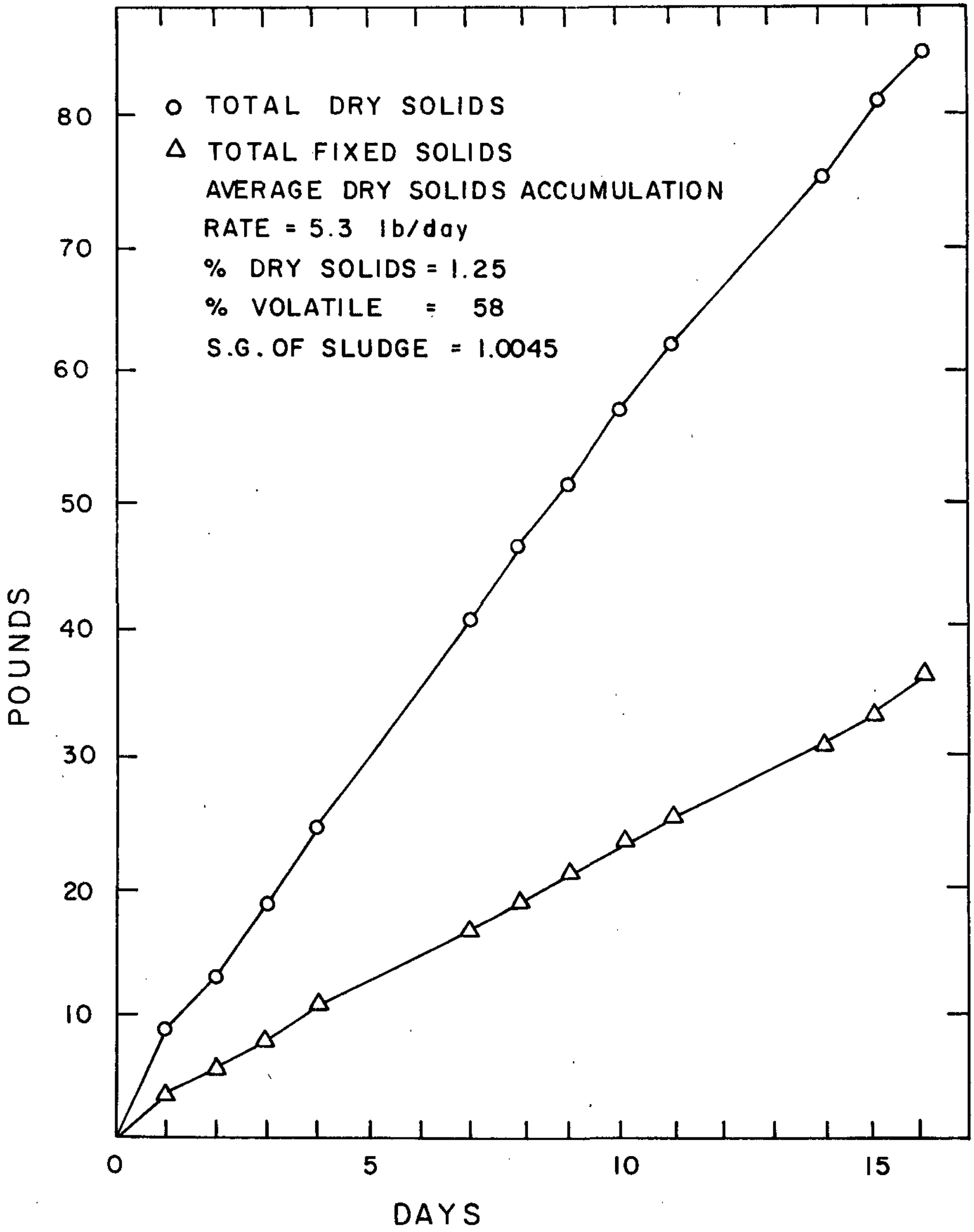

FIGURE 10. Dry Solids Accumulation During Phase II.

this data it is apparent that the use of alum in the chemical clarification process will nearly double the dry solids accumulation rate of primary sedimentation alone.

Table 6 summarizes the findings obtained for alum sludge production in treatment of primary effluent and the estimated production of sludge in a raw wastewater feed system.

Future studies will be aimed at measurement of sludge accumulation when raw wastewater is used as the influent to the chemical clarification system. Moreover, these later studies will focus attention upon pilot scale testing of alternative methods of sludge handling.

TABLE 6

ESTIMATED SLUDGE PRODUCTION FOR ALUM ADDITION TO RAW WASTEWATER

Sludge Production Parameter	Amherst Primary Sludge	Pilot Plant Alum Sludge (Amherst Primary Effluent Feed)	Estimated Total Sludge Using Raw Wastewater
% Solids	5.5	1.25	2.25*
gal./M.G.	2,545	8,680	11,225
lbs/M.G.	1,180	920	2,100

*Calculated from volume and pounds of sludge produced, assuming specific gravity of 1.0.

COST OF CHEMICAL CLARIFICATION WITH ALUM

It is beyond the scope of this study to present detailed cost analyses for chemical clarification with alum. These costs will vary according to the size of the treatment facility and the degree of removal required. Costs will also differ between new plants and upgraded facilities. The most detailed and usable cost information can be found in EPA Technology Transfer Publications (4,5,6,7). Publications by Cecil (10), Minton and Carlson (11), and Geinopolos and Vilen (12) also present valuable cost information.

A major portion of the total cost of chemical clarification with alum is the cost of alum itself. Using Amherst as an example, almost 6600 pounds of alum would be required daily (average flowrate = 4.5 MGD). Based on a cost of $0.04 per pound of dry alum (dry alum is 49 percent by weight of liquid alum) the cost of alum treatment is then approximately $0.06 per 1000 gallons. Including the cost of a storage and feeding system at $0.02 per 1000 gallons (5) and a supplementary sludge handling cost of $0.01 per 1000 gallons (5) the total cost of chemical clarification would be approximately $0.09 per 1000 gallons of which 66 percent would be the cost of alum. Pending the development of a viable method of alum recovery, the chemical cost of alum will continue to be a major cost item in the clarification process.

CONCLUSIONS

1) The chemical clarification process using alum can be applied to low alkalinity wastewaters provided a pH control or monitor system is included in the process design.

2) Chemical clarification with alum can produce an effluent of sufficient quality to meet most secondary treatment requirements. During the pilot plant demonstrations at optimum flocculation time 89 percent of the total phosphorus, 94 percent of the dissolved phosphorus, 76 percent of the turbidity, and 81 percent of the suspended solids were removed. These removals were achieved using an alum dosage of 175 mg/l. The average pH and alkalinity of the effluent was 6.3 and 35 mg/l as $CaCO_3$ respectively.

3) Flocculation time has a significant effect on the amount of phosphorus removed from wastewater. Jar tests and pilot studies indicate that flocculation times of 15 minutes or greater produced the least effluent phosphorus concentrations.

4) Removal of turbidity, suspended solids, and TOC did not appear to be a function of flocculation time.

5) The dry solids accumulation rate doubled as a result of alum addition. Fifty-eight percent of the dry solids were volatile.

6) The resulting chemical sludge produced in the clarification process had a moisture content of 98 percent. A denser sludge should be produced by the combined removal of primary and chemical sludge in a full-scale clarifier. More tests are needed to determine sludge dewaterability.

7. A major portion of the total cost of the chemical clarification process is the high cost of alum. Based on a cost of $0.04 per pound of dry alum, the total cost of alum addition would be approximately $0.09 per 1000 gallons of which $0.06 per 1000 gallons would be the cost of alum.

REFERENCES

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3. Bowen, S. P., "Evaluation of Process Design Parameters for Phosphorus Removal from Domestic Wastewater by Chemical Clarification," Doctoral Dissertation, University of Massachusetts, Department of Civil Engineering (1974).

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5. Laughlin, J. E., "Designing to Remove Phosphorus Using Metal Salts and Polymers in Conventional Plants," presented at EPA Technology Transfer Design Seminar for Wastewater Treatment Facilities, Boston, Ma. (Sept. 1974.)

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7. "Physical-Chemical Processes," prepared for the U. S. Environmental Protection Agency Technology Transfer Design Seminar, NERC, Cincinnati, Ohio, (September 1974).

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11. Minton, G. R. and Carlson, D. A., "Combined Biological-Chemical Phosphorus Removal," Jour. Water Poll. Control Fed., 44, 1736 (1972).

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APPENDIX I - ANALYTICAL TECHNIQUES

All analyses were performed in accordance with the 13th Edition of Standard Methods for the Examination of Water and Wastewater. The method of analysis selected for each measured parameter is discussed below.

Phosphorus - Total phosphorus was determined by both the Vanadomolybdophosphoric acid and Ascorbic Acid methods. The former method was used during the jar tests and Phase I pilot plant studies were relative concentrations and were of primary concern. The latter method was used during the Phase II pilot plant studies where the lowest effluent phosphorus concentrations were experienced. The persulfate digestion preceeded both methods.

All glassware was washed in hot 1 + 1 hydrochloric acid and filled with distilled water until use. At least two standards were analyzed with every test and colorimetric determinations were made on a Bausch and Lomb Spectronic 20.

Soluble phosphorus was determined by filtration through a 0.45 micron membrane filter prior to analysis.

Alkalinity - Alkalinity was measured by titrating each sample with .01N H_2SO_4 to an endpoint of 4.5. Potentiometric titrations were carried out using an Orion expanded scale pH meter. Results are expressed in mg/l as $CaCO_3$.

Total Organic Carbon - A Beckman Model 915A Organic Carbon Analyzer was used in analyzing 20 microliter samples. Replicate injections were made until reproducible results were obtained. A calibration curve was generated before each use.

Turbidity - Turbidity measurements were obtained using a Hach Model 2100A Turbidimeter. The meter was standardized before each use and the data was expressed in Jackson Turbidity Units.

Suspended Solids - The glass fiber filter technique with a membrane filter holder was used throughout the study. The volatile portion was determined by ignition at 550°C for 15 minutes.

Total Solids - Fifty milliliters of sample was evaporated on a dried and tared dish. The residue was dried at 103°C, cooled in a dessicator, and weighed.

Total Volatile and Fixed Residue - The residue from the total solids determination was ignited at 550°C for 15 minutes, cooled and weighed.

APPENDIX II

DETERMINATION OF THE MEAN VELOCITY GRADIENT (G)

The mean velocity gradient (G) can be determined from the equation:

$$G = \left(\frac{C_d A \rho \ v^3}{2 \mu \ V}\right)^{1/2} \qquad \text{(ref. 7, p. 281)} \qquad (1)$$

where:

G = mean velocity gradient, ft/sec/ft = 1/sec.

C_d = drag coefficient of flocculator paddles moving perpendicular to fluid.

A = paddle area, ft^2

ρ = mass fluid density, $slugs/ft^3$

v = relative velocity of paddles in fluid, ft/sec, usually 70 to 80 percent of the paddle tip speed.

μ = absolute fluid viscosity, lb force-sec/ft^2

V = flocculator volume, ft^3

For the flocculation units used during the pilot plant studies, the value of the above the parameters are:

C_d = 1.8 for rectangular paddles

A = 1 in. x 32 in. x 2 = 64 $in.^2$ = 0.444 ft^2

ρ = 1.938 lb-sec^2/ft^4 @ 60°F

v = $.75\ v_p = .75(2\pi\ nR/60)$, where v_p = paddle-tip speed

n = rpm = 20

R = radius of paddles = .375 ft.

$\mu = 2.36 \times 10^{-5}$ lb-sec/ft^2

$V = 32$ gal. $= 4.278$ ft^3

Substituting in equation 1, the mean velocity gradient G is 40 sec^{-1}. This is well within the range of 20 to 75 sec^{-1} recommended in "Wastewater Engineering" (ref. 7, p. 282).