PILOT PLANT STUDIES OF WASTEWATER CHEMICAL CLARIFICATION USING LIME

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CHEMICAL CLARIFICATION USING LIME

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ABSTRACT

Lime clarification of raw wastewater was evaluated in jar tests
and extensive pilot plant operations. The relatively low alkalinity
of Amherst wastewater (averaging 149 mg/l during pilot plant tests)
required a lime dosage of 380 mg/l as CaO to produce an effluent
phosphorus of 1 mg/l or less. Because of low alkalinity, this lime
dosage resulted in a pH of approximately 11.5. These findings confirm
the importance of wastewater alkalinity in lime clarification.

Pilot plant studies demonstrated a need for longer flocculation
periods (approximately 15 minutes) to obtain maximum suspended solids
removal. Extensive pilot-scale testing with a flocculation time of
16 minutes produced an average effluent total phosphorus of 0.6 mg/l
as P, suspended solids of 33 mg/l, COD of 108 mg/l an a turbidity of
17 JTU. The sludge accumulation rate was 4000 lbs/MG, or approximately
four times the amount from primary sedimentation.

Lime sludge was shown to have good thickening and dewatering
characteristics; further improvement should be possible by adding
conditioning chemicals such as $FeCl_3$ or polymer. Approximately
60 percent of the total lime requirement was estimated to be recover-
able by recalcination if two-stage recarbonation is used.

Previous pilot plant studies of alum clarification at the UMASS
Wastewater Pilot Plant also produced effective treatment of low
alkalinity wastewater; lime sludge production was twice that of alum.

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This disadvantage is offset by the poorer dewatering properties of alum sludge. Economic analysis for a 10 MGD facility showed that alum clarification is less expensive than lime clarification. However, if anaerobic digestion of alum sludge is required, both alum and lime treatment costs are approximately the same.

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INTRODUCTION

Background

It has been well established that discharges from wastewater treatment plants often contain sufficient plant and algal nutrients to radically increase the eutrophication rate of receiving waters. It has also been shown that plant and algal growth can be controlled by limiting the supply of a single major nutrient. Of the major nutrients other than carbon, phosphorus is most easily controlled. It can be removed by a number of processes including lime clarification. Lime treatment of wastewater not only precipitates phosphorus but improves organic and suspended solids removal as well.

The addition of lime causes precipitation of calcium bicarbonate as follows:

$$Ca(OH)_2 + Ca(HCO_3)_2 \rightarrow 2CaCO_3\downarrow + 2H_2O$$
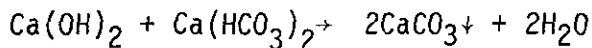
This reaction is dependent upon the presence of bicarbonate alkalinity. Remaining calcium ions will react with the orthophosphate ion to precipitate hydroxyapatite (an insoluble form of phosphorus) as shown below:

$$5Ca^{++} + 4OH^- + 3HPO_4^{--} \rightarrow Ca_5OH(PO_4)_3\downarrow + 3H_2O$$
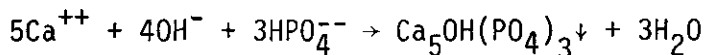
This insoluble hydroxyapatite complex will completely form around pH 9.5 and become increasingly insoluble as the pH rises.

At pH values above 10, magnesium hydroxide is precipitated from the wastewater according to the following reaction:

$$Mg^{++} + Ca(OH)_2 \rightarrow Mg(OH)_2 + Ca^{++}$$
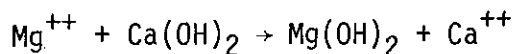
The magnesium hydroxide precipitate is important because it aids in liquid-solid separation (1). More detailed information on the reactions

involved in calcium precipitation of phosphorus can be found elsewhere
(2,3,4,5,6).

The chemical clarification process as applied to wastewater usually
involves rapid mixing of the chemical (in this case, lime) with the
wastewater, followed by flocculation and sedimentation. The rapid mix
must be turbulent enough to distribute the lime throughout the waste-
water for efficient phosphorus removal. The flocculation stage
promotes particle contact which allows the precipitation nuclei and
suspended particles to aggregate and settle out in the sedimentation
stage. The effluent from such a process typically has phosphorus
concentrations below 1.0 mg/l as P and organic and suspended solids
concentrations approaching secondary treatment quality. However, the
obvious drawbacks to this process are increases in both pH and hardness.
Moreover, calcium is unstable at a high pH and will precipitate out as
calcium carbonate causing inactivation of downstream filters and
scaling in pipes. This problem can be eliminated by recarbonation
which removes the calcium carbonate precipitate before it can effect
downstream processes.

Recarbonation can be accomplished in a single or two-stage system.
In a single-stage system, enough carbon dioxide is added to reduce the
pH to 7.0, or to any other desired value in one step. However, by
applying sufficient carbon dioxide in a single stage most of the
calcium remains in solution causing the calcium hardness of the
effluent to be quite high. Consequently, this system is used in high
alkalinity wastewaters where low lime dosages are adequate for
phosphorus removal. Single-stage recarbonation is also used when lime

recovery is not planned.

If lime is to be reclaimed or if calcium reduction in the effluent is required, then two-stage recarbonation is necessary. In two-stage treatment, sufficient lime is added to raise the pH of the wastewater to 11.0 and above. Low alkalinity wastewaters typically require high lime dosages for satisfactory floc formation. In the first stage of recarbonation, enough carbon dioxide is added to bring the pH down to approximately 9.3 where calcium carbonate precipitation results. This settled precipitate is a rich source of calcium oxide and may represent as much as one-third of the total recoverable lime (2). In the second stage, carbon dioxide is again added to reduce the effluent pH before discharge. Figure 1 illustrates the unit processes involved in lime clarification and single and two-stage recarbonation.

The lime clarification process can be included in several waste-water treatment schemes. Some of the more practical configurations, in terms of the present, state-of-the-art design practice are shown in Figure 2. Each scheme is intended to remove both phosphorus and organics to secondary treatment levels. The carbon adsorption and biological treatment steps remove the dissolved organics which are not adequately removed in the lime clarification process.

Objectives

The primary objectives of this study were:

1) To determine the lime dosage necessary to reduce effluent phosphorus concentrations below 1.0 mg/l as P in low alkalinity wastewater,

2) To examine the effect of flocculation time on the treatment efficiency of the process,

SINGLE STAGE RECARBONATION

RAW
WASTEWATER → RAPID MIX → FLOCCULA-TION → CLARIFICA-TION → RECARBONA-TION → EFFLUENT

TWO STAGE RECARBONATION

RAW
WASTEWATER → RAPID MIX → FLOCCU-LATION → CLARIFI-CATION → RECARBON-ATION → CLARIFI-CATION → RECARBON-ATION → EFFLUENT
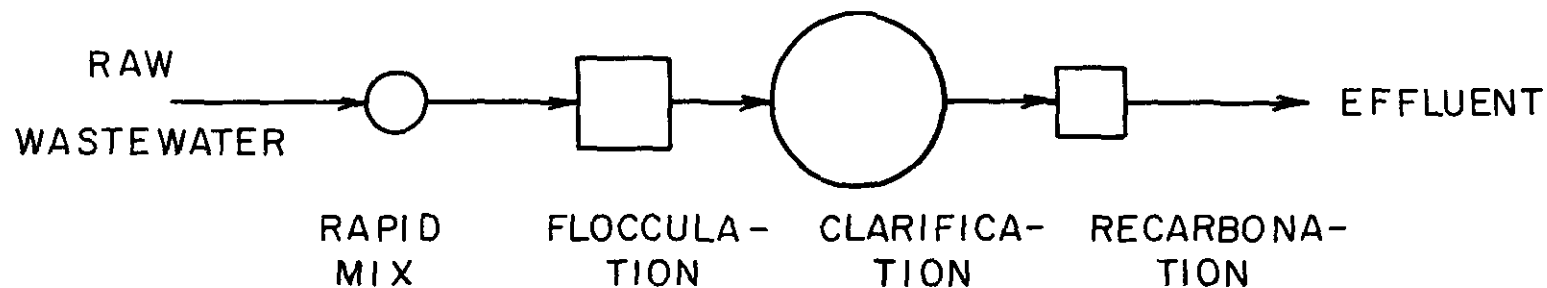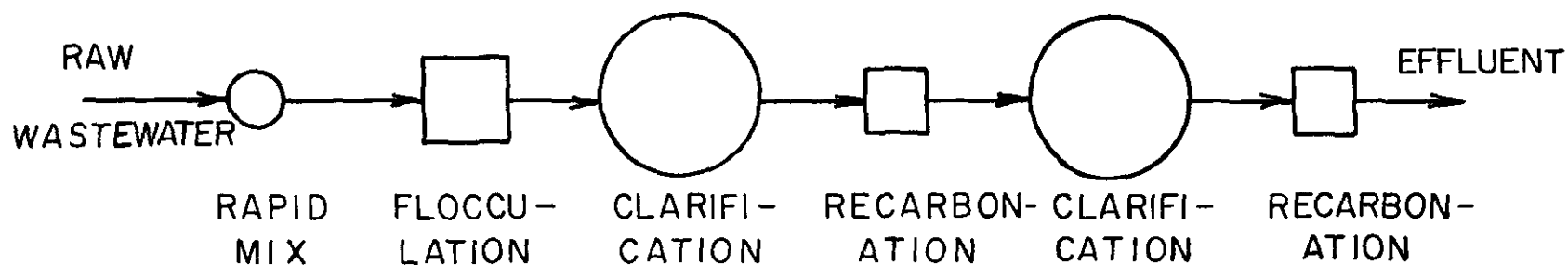
Figure 1.   Chemical Clarification with Single or Two-Stage Recarbonation.
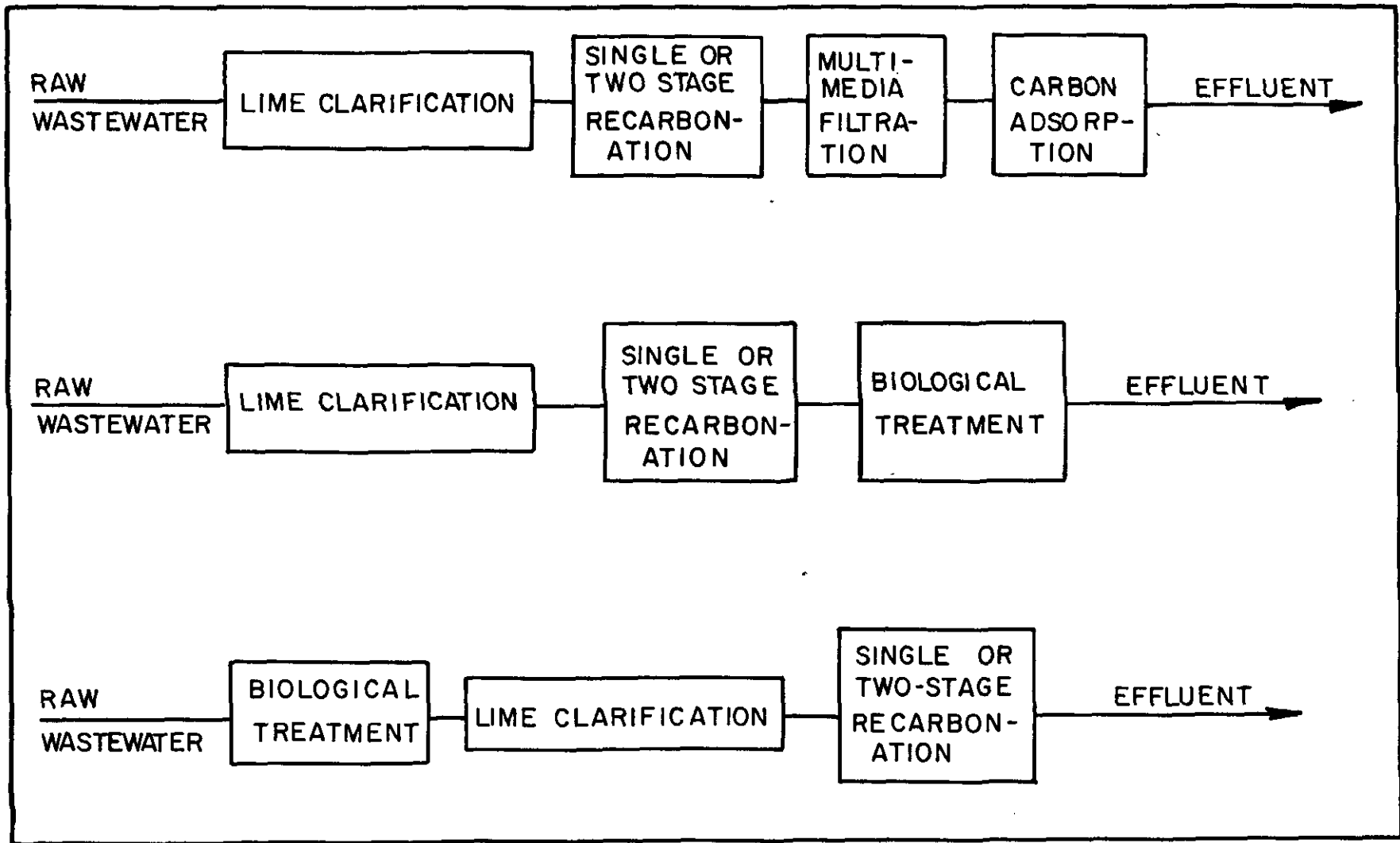
Figure 2.   Wastewater Treatment Schemes Using Lime Clarification.

3)   To demonstrate the treatment effectiveness of lime addition to raw wastewater through pilot-scale studies,

4)   To determine lime sludge characteristics, accumulation rate and dewaterability,

5)   To measure the quantity of recoverable lime (CaO) in the dewatered sludge,

6)   To examine the cost of chemical clarification with lime,

7)   To compare the treatment effectiveness and costs of lime clarification with alum clarification.

Scope

The investigative approach used in this study was to first establish the lime concentration required to reduce raw wastewater phosphorus concentrations to 1.0 mg/l as P or less. This information was obtained from jar tests. Jar tests were also used to examine the effect of flocculation time on the removal efficiencies of lime addition to raw wastewater.

Pilot plant studies were divided into two phases. Phase I was concerned with re-examining the effect of flocculation time on a continuous flow system. Three different flocculation times were investigated. Phase II was a longer duration study which measured the performance of the treatment process at the optimum flocculation time and dosage. Sludge characteristics and accumulation rate were also determined during this phase.

The unit processes used in the pilot plant treatment scheme included a hydrasieve, rapid mix, flocculators and a clarifier. Mixed media filtration was simulated by using a Whatman #2 filter on the

clarified effluent samples. Degritted raw Amherst wastewater and high quality (95 percent $Ca(OH)_2$) hydrated lime was used in all jar tests and pilot-scale investigations.

Using sludge generated from the pilot plant studies, various sludge handling methods were evaluated. These methods included gravity thickening, centrifugation and vacuum filtration. The supernatant, centrate, and filtrate from these processes were also analyzed. Specific resistance tests were conducted and the coefficient of compressibility was determined. Dewatered lime sludge samples were then recalcined to measure the amount of lime (CaO) available for reuse.

From previous investigations at the UMass Wastewater Pilot Plant on chemical clarification with alum (7) a comparison of the treatment effectiveness of lime and alum addition was obtained. Both studies were conducted using the same pilot scale units.

Parameters analyzed during the jar tests and pilot plant studies included pH, alkalinity, turbidity, chemical oxygen demand (COD), total organic carbon (TOC), suspended solids, total phosphorus, dissolved phosphorus and hardness. The frequency and type of sampling varied during the study and are explained in the body of the report. Analytical techniques and sample preservation methods are discussed in Appendix I.

JAR TESTS

Before pilot-scale testing could begin, the proper lime dosage
and flocculation time had to be determined. The proper lime dosage,
in this case. is defined as the minimum amount of lime needed to
achieve phosphorus removals below 1.0 mg/1 as P. Phosphorus removal
was used as the main criteria for lime dosage selection because it
is the major function of the chemical clarification process. After
mixing lime with wastewater, adequate flocculation must take place
for particle aggregation. A 15 minute detention time is generally
regarded as sufficient for wastewater (8). However, jar tests were
conducted at various flocculation times to verify this design
condition.

Jar tests were accomplished using a six paddle, variable speed
stirring apparatus[1] and one liter wastewater samples. During jar
tests on the effect of lime dosage. each sample was mixed for one
minute at 100 rpm, flocculated for 15 minutes at 30 rpm and allowed
to settle for 30 minutes. After settling, a sample of the supernatant
was withdrawn for analysis of total phosphorus content and pH. This
procedure was repeated for three wastewaters of low to medium
alkalinity typical of Amherst. The results are shown in Figures 3
and 4.

Figure 3 indicates that lime concentrations between 300 and
400 mg/1 as CaO will reduce total phosphorus levels below 1.0 mg/1
as P for all alkalinities tested. As a conservative estimate, a

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[1] Phipps and Bird Incorporated, Richmond, Virginia.
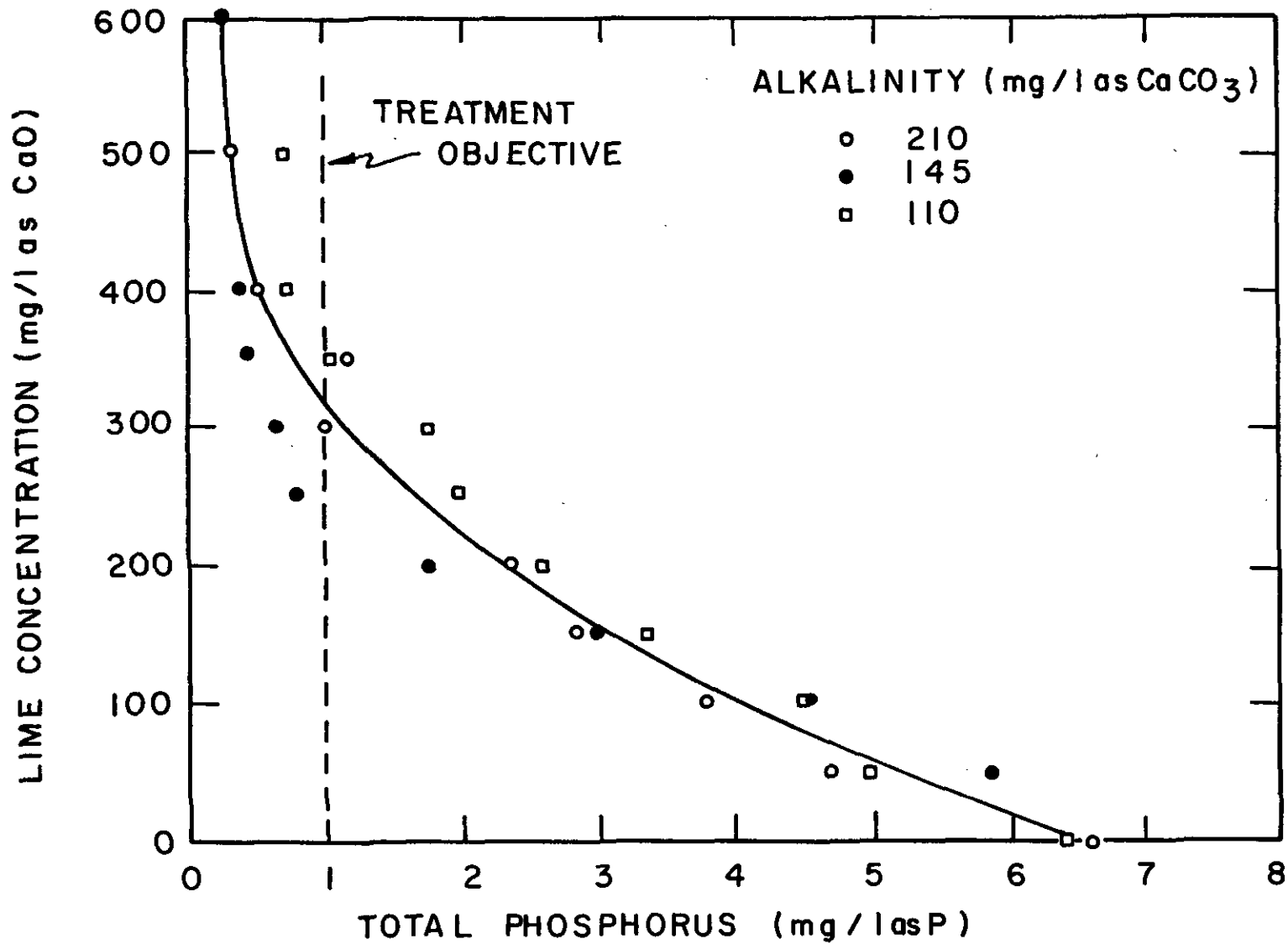
Figure 3. Total Phosphorus Concentration vs. Lime Dosage.

lime dosage of 380 mg/l as CaO should provide consistent phosphorus removals below 1.0 mg/l as P. This is in agreement with a previous study by Bowen (24) using Amherst wastewater. A high dosage requirement is characteristic of low alkalinity wastewaters where greater quantities of lime are needed to form enough calcium carbonate precipitate to produce a good-settling floc.

The pH of jar test samples with less than 1.0 mg/l total phosphorus concentration can be expected to remain in a narrow range between 11.0 and 12.0, as shown in Figure 4. Consequently, pH can be an effective measure of phosphorus removal and lime dosing can be paced by a pH control system. This fact should simplify process control and operation of a lime clarification system.

Jar tests conducted using a rapid mix time of 3 minutes, a settling time of 30 minutes and various lime slurry concentrations revealed that flocculation time had little effect on phosphorus removal (see Figure 5). However, further testing at a reduced rapid mix time of one minute and 14 percent slurry showed phosphorus removal to be significantly affected by flocculation time (see Figure 6). As a result, it appears that rapid mix time is as important as flocculation time in obtaining maximum phosphorus removal. A short rapid mix time may ineffectively disperse the lime slurry and longer flocculation times will be needed to obtain proper mixing. Increasing the rapid mix time results in better dispersion and maximum phosphorus removal is attainable at lower flocculation times. This finding suggests that
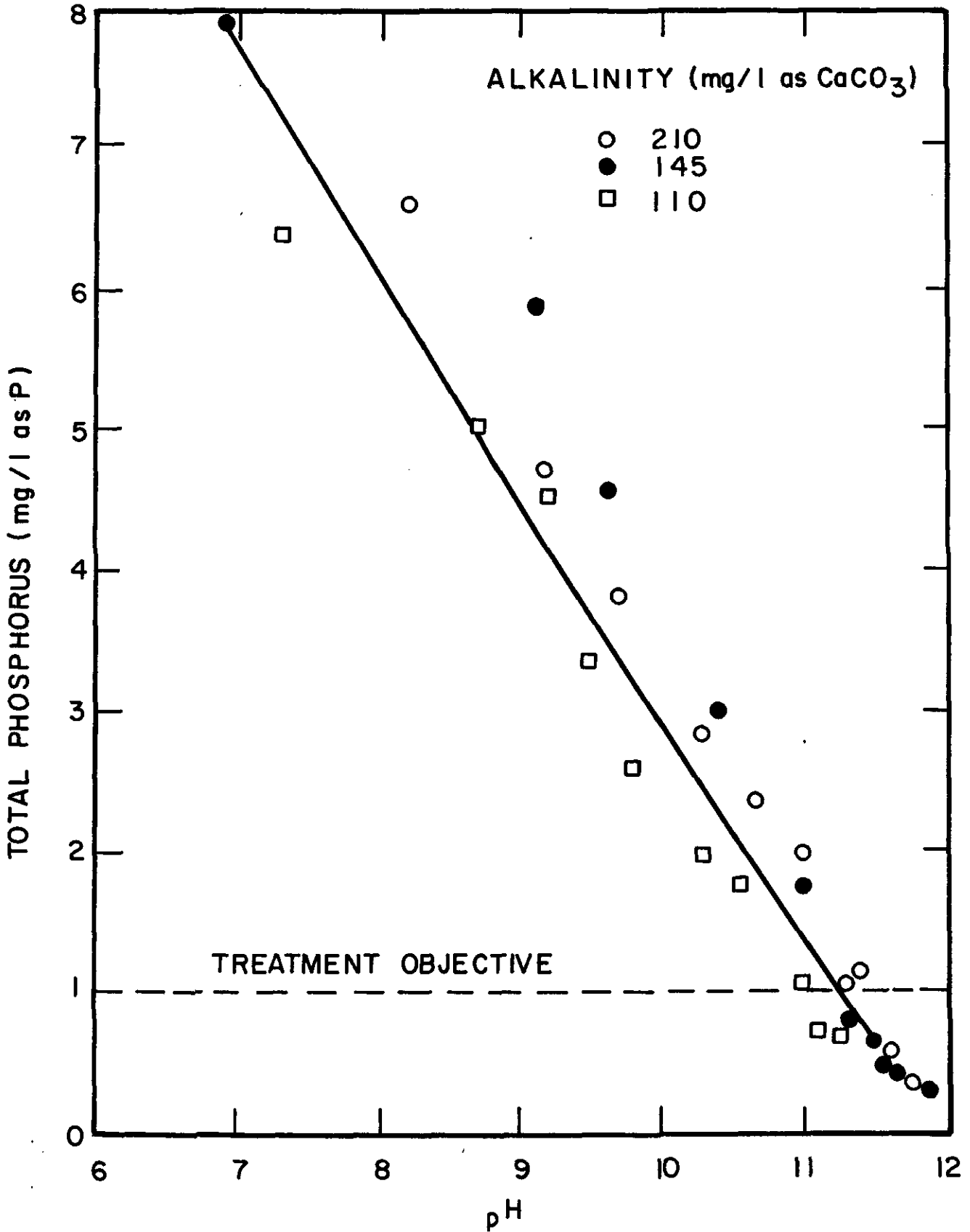
Figure 4.   Total Phosphorus Concentration vs. pH.
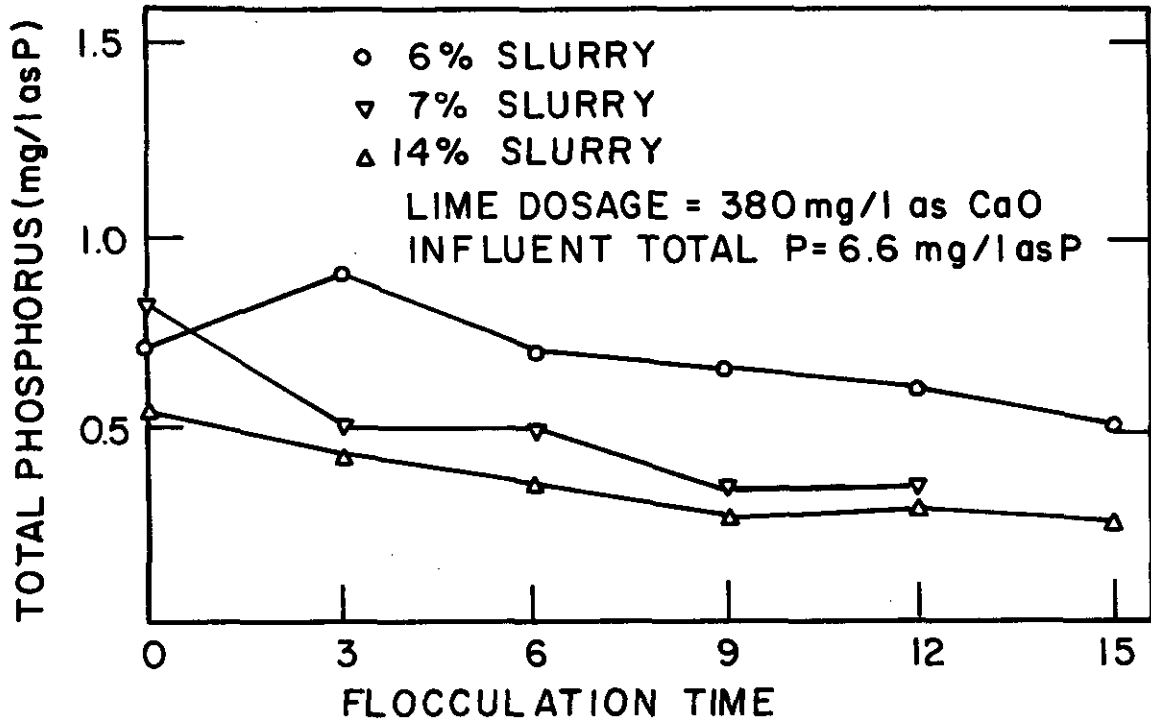
Figure 5. Effect of Flocculation Time on Phosphorus Removal (3 Minute Rapid Mix).
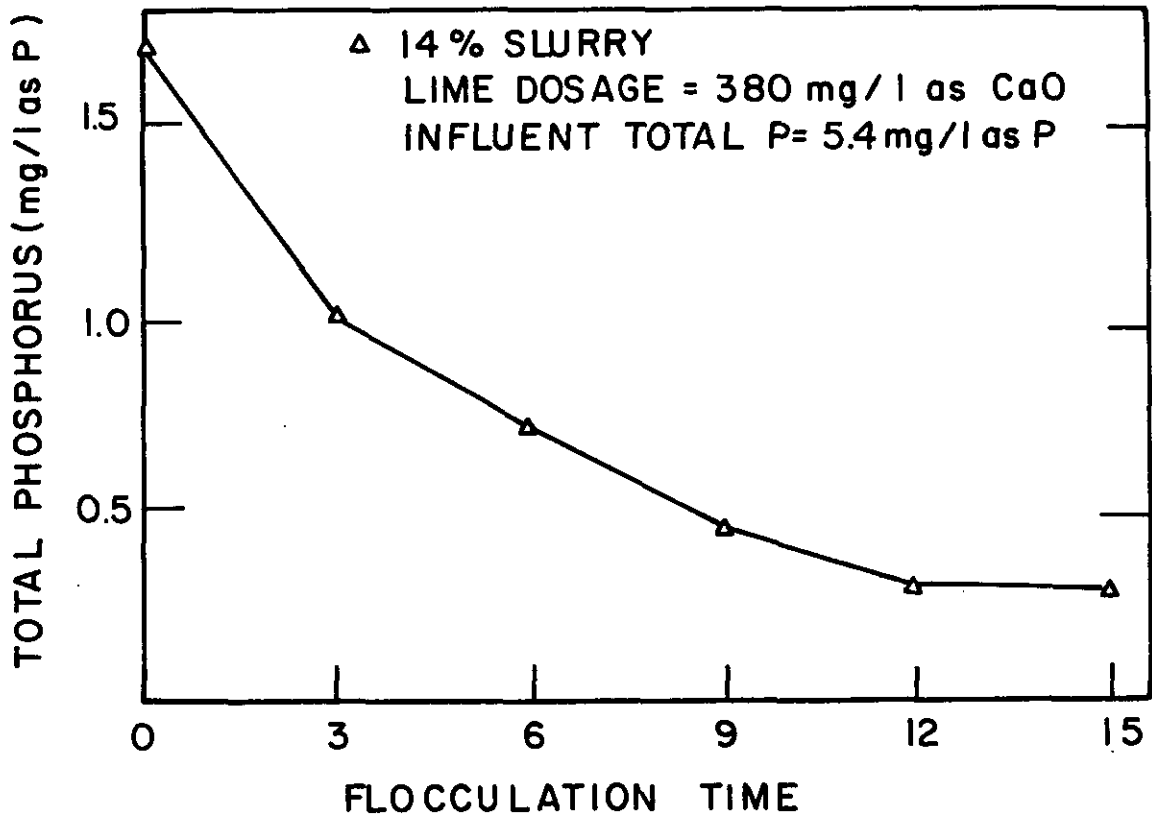
Figure 6. Effect of Flocculation Time on Phosphorus Removal (1 Minute Rapid Mix).

savings can be realized if the process design includes a rapid mix reactor capable of providing at least three minutes detention rather than building larger flocculation basins to make up for a lack of mixing in the rapid mix phase.

Alternatively, lower slurry concentrations such as the six percent slurry recommended in the EPA Process Design Manual for Phosphorus Removal (3) may not require as much rapid mixing as the higher slurry concentrations. The difference in rapid mix requirements between low and high slurry concentrations was not investigated because it would result in only minor differences in reactor sizing. Overdesigning the rapid mix reactor to provide five minutes detention time would assure dispersal of lime slurry at a minor increase in capital cost. However, more concern for the adequacy of flocculation basin design could result in some savings and a better effluent quality. Although jar tests did not show a strong relationship between phosphorus removal and flocculation time (at a rapid mix time of three minutes), it was decided that pilot plant studies should be conducted at different flocculation times in an attempt to verify jar test results under more realistic conditions.

PILOT PLANT STUDIES

Pilot plant studies were divided into two phases. Phase I was an extension of the jar test study in which the effect of flocculation time on the treatment effectiveness of the chemical clarification process was examined. The Phase II study was conducted using the optimum flocculation time determined from Phase I. Lasting for a period of 35 days, the Phase II study provided a basis for determining the reliability and performance of the clarification process using lime. In addition, this extended study permitted measurement of sludge characteristics and accumulation rate.

Phase I: The Effect of Flocculation Time

The Phase I pilot plant study was conducted in the summer of 1973 by Sweeney (9). Using many of the same pilot scale units described in the Phase II study, Sweeney evaluated flocculation times of 4.4, 7.5, and 17 minutes. During these tests, a 14 percent slurry of $Ca(OH)_2$ was fed into a rapid mix tank and mixed with raw wastewater for a period of three minutes. The lime slurry feed was adjusted to provide a concentration of 380 mg/l as CaO. After rapid mix and flocculation, the treated wastewater was allowed to settle in the clarifier for approximately 3.5 hours. Each flocculation time was evaluated over a period of three days of continuous operation. A total of 15 influent and effluent grab samples were taken. These samples were analyzed for pH, turbidity, suspended solids, total phosphorus and total dissolved organic carbon (TOC).

The results of their study appears in Table I. Mean influent, effluent and percent removal values are shown along with the effluent

TABLE 1

TREATMENT EFFICIENCY VS. FLOCCULATION TIME (9)

Parameter		Flocculation Time (Min)		
		4.4	7.5	17.0
Turbidity (JTU)	mean influent	69	57	62
	mean effluent	30	13	6
	mean % removal	56	77	90
	effluent stand.dev.	8.3	6.1	1.9
Suspended Solids (mg/l)	mean influent	147	155	124
	mean effluent	53	51	13
	mean % removal	64	67	89
	effluent stand.dev.	28.0	34.0	6.3
Total Phosphorus (mg/l)	mean influent	6.20	6.40	6.00
	mean effluent	1.25	.77	.57
	mean % removal	80	88	91
	effluent stand.dev.	0.44	0.20	0.19
Total Organic Carbon (dissolved) (mg/l)	mean influent	40	42	44
	mean effluent	34	30	29
	mean % removal	15	28	34
	effluent stand.dev.	3.9	5.7	5.2
pH	mean influent	7.3	7.2	7.1
	mean effluent	11.6	11.6	12.0
	effluent stand.dev.	0.08	0.07	0.09

standard deviation. All parameters displayed a decrease in concentra-
tion as flocculation increased except for pH which remained relatively
constant between 11.6 and 12.0. At the optimum flocculation time of
17 minutes, the effluent turbidity, suspended solids, total phosphorus
and total dissolved organic carbon (TOC) concentrations were 6 JTU,
13 mg/l, 0.57 mg/l as P, and 29 mg/l respectively.

Interpretation of the data in Table I can be simplified by
comparing the various parameters on the basis of percent removal
rather than effluent concentrations produced. In this way, differences
in influent concentration are taken into account. Figure 7 graphically
shows the effect of flocculation time on the removal efficiencies.
It is to be noted that the percent removals of all parameters are
greatest at a flocculation time of 17 minutes. Figure 7 also shows
that the greatest increase in phosphorus, turbidity and TOC removal
efficiency occurred when flocculation time was increased from 4.4 to
7.5 minutes. For example, phosphorus removal increased from 80 to 88
percent between the 4.4 and 7.5 minute flocculation time while
additional flocculation up to 17 minutes only increased the removal
efficiency to 91 percent - an increase of only three percent. Con-
sequently, it appears that if phosphorus removal is the primary
concern of the clarification process, a flocculation time of approxi-
mately eight minutes would be adequate. However, if downstream pro-
cesses such as carbon adsorption and nitrification are to be included
in the treatment system, longer flocculation times may be justified
for removal of suspended solids. As shown in Figure 7, the percent
removal of suspended solids increased almost linearly as the floccu-
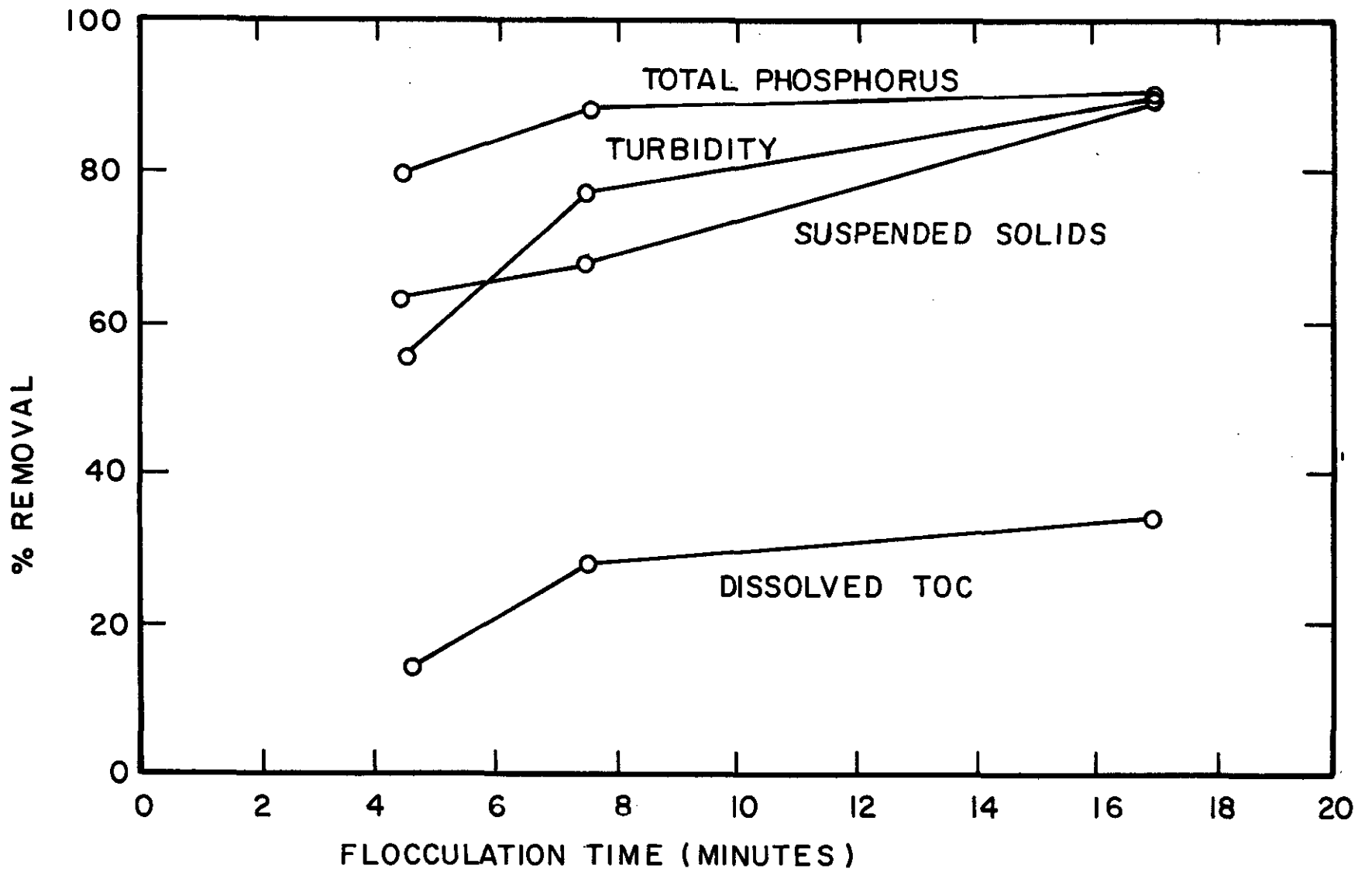
Figure 7.   Effect of Flocculation Time on Removal Efficiency of Pilot Plant.

lation time increased. A maximum removal of 80 percent was obtained at a flocculation time of 17 minutes. Higher suspended solids removals at the longer flocculation times were probably due to a greater opportunity for particle contact and aggregation.

The apparent discrepancy between jar test results, which showed no appreciable difference in effluent quality as a result of increasing flocculation time (using a rapid mix time of 3 minutes), and the pilot plant studies, could be due to a number of factors. In a pilot plant system, hydraulic short circuiting, reactor geometry, and diurnal variation in influent strength could have an overriding effect on the distribution and mixing of lime. Thus, more reactor time would be needed to compensate for this lack of mixing. Full-scale plants could be subject to even greater hydraulic variations which may justify conservative flocculation basin design.

Phase II. Pilot Plant Performance at Optimum Flocculation Time

Because the primary objective of this study was to demonstrate the treatment potential of the lime clarification process, it was decided that the Phase II studies should be conducted at a flocculation time which would insure an excellent overall removal of all wastewater pollutants. Alternatively, selection of an optimum flocculation time could be based on phosphorus removal only. Based on overall removal efficiency, the previous Phase I study indicated that longer flocculation periods produced a better quality effluent. Maximum removals for all parameters tested were obtained at a flocculation time of 17 minutes. However, in the Phase II study, a 16 minute rather than a 17 minute flocculation period was used because it facilitated flowrate control in the pilot plant system. The difference in treatment

efficiency between 16 and 17 minutes of flocculation, is considered minimal.

A schematic diagram of the pilot plant facility used during the Phase II study is shown in Figure 8. The degritted and comminuted wastewater was received from the neighboring Amherst Sewage Treatment Plant and pumped over a Bauer Hydrasieve[1]. The hydrasieve removed larger flotable solids which would otherwise cause blockages in the small conduits of the pilot plant while it allowed raw wastewater to pass. Cleaning the hyrasieve was accomplished twice daily by rinsing with a water hose.

Raw wastewater from the hydrasieve was directed to a weirbox where the flowrate was controlled at four gallons per minute. The wastewater then entered the rapid mix tank where it was mixed with lime. A six percent slurry (0.5 lbs $Ca(OH)_2$ per gallon) was used as recommended in the EPA Process Design Manual for Phosphorus Removal (3). By adjusting the slurry feedrate, a concentration of 380 mg/l as CaO was maintained in the wastewater. The lime used was 95 percent pure hydrated lime ($Ca(OH)_2$).

From the rapid mix tank the lime and wastewater mixture was flocculated for 16 minutes in two, in-series basins. Effluent from the basins flowed into a 900 gallon circular clarifier which provided a 3.75 hour detention time. The clarifier was equipped with a rim inlet chamber and a center weir overflow. The cone shaped clarifier bottom contained a shaft mounted sludge scraper and a plexiglass window to monitor sludge accumulation. A more detailed listing of the pilot plant

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[1]The Bauer Bros. Co., a subsidiary of Combustion Engineering, Springfield, Ohio.

LIME SLURRY
TANK

PUMP

HYDRASIEVE

DEGRITTED

AND
COMMINUTED
WASTEWATER

RAPID
MIX

FLOCCULATORS

CLARIFIER

EFFLUENT

PROCESS EVALUATIONS

· RECARBONATION
· MULTI-MEDIA
  FILTRATION

LARGE SOLIDS

SLUDGE

PROCESS EVALUATIONS

• GRAVITY THICKENING
• VACUUM FILTRATION
• CENTRIFUGATION
• LIME RECOVERY
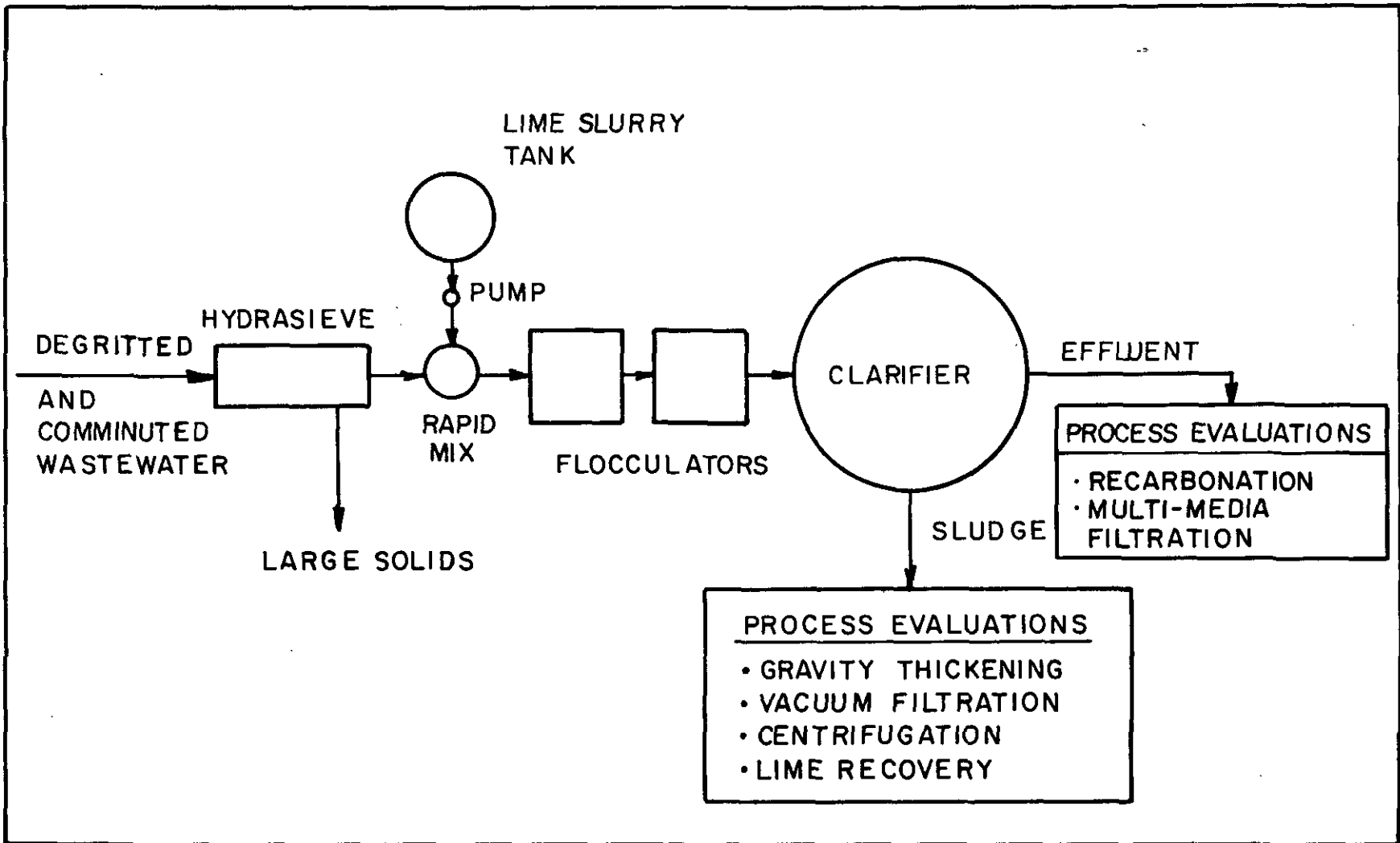
Figure 8. Schematic Diagram of Pilot Plant.

dimensions and design parameters are shown in Table 2. Calculations
of the mean velocity gradients (G) for both the flocculation basins
and rapid mix tank are shown in Appendix II.

Effluent from the clarifier was not subjected to further treatment.
However, the degree of recarbonation required and probable quality of
effluent as a result of multi-media filtration were evaluated by labora-
tory tests. Recarbonation requirements were evaluated for both single
and two-stage systems according to the method presented by Culp and
Culp (2). Multi-media filtration was simulated by filtering a
clarified sample through a Whatman #2 filter paper prior to analysis.
Past experience has shown that the quality of the filtrate will be
about the same as that achieved with a multi-media filter (8).

During the Phase II study, accumulated sludge in the clarifier
was wasted and measured daily. The sludge level was readily observable
through a plexiglass window. In order to obtain a uniform sample,
sludge was wasted into an adjacent tank and manually stirred. Samples
of the clarifier sludge were then collected and preserved for later
thickening, vacuum filtration. centrifugation and lime recovery
evaluations. These sludge dewatering processes will be discussed in
the next section.

The results of the 35 day, Phase II pilot plant study are shown in
Table 3. During this study grab samples of the raw wastewater influent,
and clarifier effluent were taken at 9 AM. 10 AM 11 AM, 1 PM, 2 PM.
3 PM and composited. Analytical techniques and procedures are discussed
in Appendix I.

Throughout the 35 day study, excellent removals of phosphorus,

TABLE 2

PILOT PLANT DIMENSIONS AND DESIGN PARAMETERS

Rapid Mix Tank

Capacity	20 gal.
Detention Time	5 min.
Mean Velocity Gradient (G)	463 sec^{-1}

Flocculation Basin

Number of Basins	2
Dimensions	3.66 ft x 1.25 ft x 1.0 ft
Volume	32 gal.
Detention Time (2 basins)	16 min.
Paddle Area	0.444 ft^2
Flocculation rpm	30
Mean Velocity Gradient (G)	73 sec^{-1}

Clarifier

Diameter	5.5 ft.
Volume	900 gal.
Detention Time (@ 4 gpm)	3.75 hours
Overflow rate (@4 gpm)	242 gpd/ft^2
Weir loading (@ 4 gpm)	1834 gpd/ft

TABLE 3

PILOT PLANT PERFORMANCE AT OPTIMUM FLOCCULATION TIME

Parameter	Average Influent	Average Effluent (% Removal)	Average Multi-Media Effluent(+ % Removal)
pH	7.5	11.6	--
Alkalinity* (mg/1 as $CaCO_3$)	149	495	--
Total Phosphorus (mg/1 as P)	8.5	0.60 (93)	0.38 (+3)
Dissolved Phosphorus (mg/1 as P)	5.9	0.24 (96)	--
Suspended Solids (mg/1)	174	33 (81)	5.0 (+16)
COD (mg/1)	440	108 (75)	89 (+5)
Turbidity (JTU)	75	17 (77)	4 (+18)
Hardness (mg/1 as $CaCO_3$)	45	370	--

*The average phenolphthalein alkalinity of the effluent was 453 mg/1 as $CaCO_3$.

suspended solids, chemical oxygen demand (COD), and turbidity were obtained. Total and dissolved phosphorus concentrations were effectively removed below 1.0 mg/l as P during the entire experiment. With an average influent phosphorus concentration of 8.5 mg/l as P and an effluent concentration of 0.6 mg/l as P, the mean percent removal of phosphorus was 93 percent. An additional three percent removal could be obtained by multi-media filtration. Daily variations in influent and effluent total phosphorus concentrations are shown in Figure 9. Effluent phosphorus concentrations remained low despite large variations in influent values.

Influent suspended solids were reduced by 81 percent as a result of the lime clarification process. Another 16 percent reduction is predicted by multi-media filtration thereby producing a final effluent containing only 5.0 mg/l suspended solids. Herein lies the value of multi-media filtration in preventing solids build-up in subsequent treatment steps such as carbon contactors.

Like suspended solids, a large fraction of turbidity (18 percent) can be removed by multi-media filtration. Clarification alone removed another 77 percent for a total removal of 95 percent. The effluent turbidity after both clarification and filtration processes was only 5 JTU.

COD removals were not greatly improved by simulated multi-media filtration (5.0 percent). However, chemical clarification alone removed 75 percent leaving 108 mg/l in the effluent. Because secondary treatment standards are usually stated in terms of biochemical oxygen demand (BOD), and not COD, it is not possible in this case to clearly
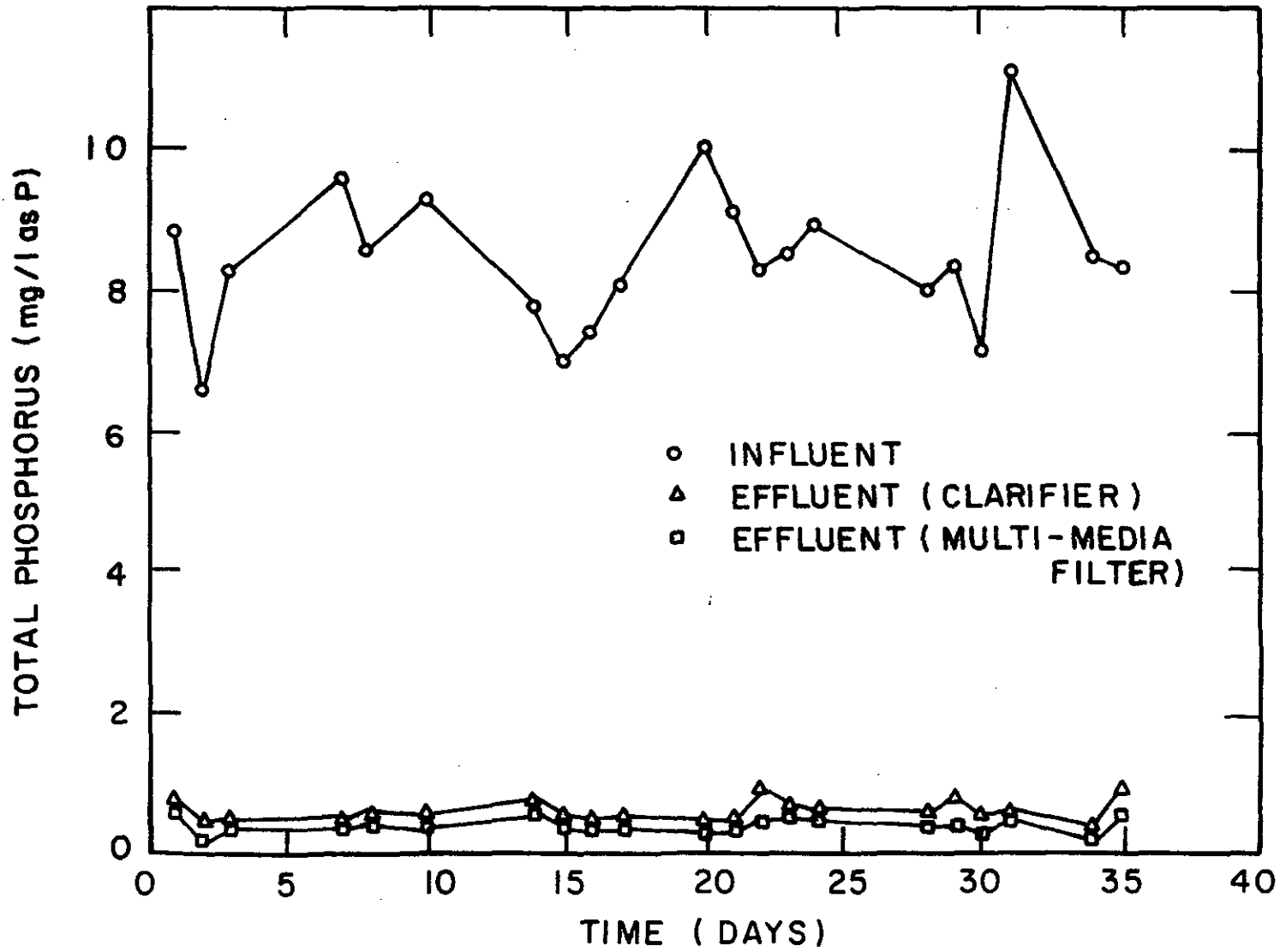
Figure 9.   Influent and Effluent Phosphorus Concentrations During Phase II Study.

establish whether chemical clarification alone would meet secondary standards. In most cases, further treatment (e.g. by carbon adsorption or activated sludge) would be necessary to consistently remove an additional fraction of dissolved organics.

Due to the high pH and hardness of the effluent, recarbonation will be necessary. Calculations shown in Appendix III indicate that a total of approximately 1830 lbs/MG of CO_2 will be necessary for a two-stage recarbonation system. For single-stage recarbonation where lime recovery is not planned approximately 3350 lbs/MG of CO_2 will be required. More carbon dioxide is needed in single-stage recarbonation because the calcium carbonate precipitate is not removed and must therefore be converted to soluble calcium bicarbonate. Potential sources of CO_2 gas include stack gas from a lime reclaiming or sludge incineration furnace, commercial liquid carbon dioxide and natural gas.

Lime sludge characteristics and accumulation rates are shown in Table 4. Four thousand pounds per million gallons (4,000 lbs/MG) of lime sludge were produced during the pilot plant study. This figure is in close agreement with estimates of sludge quantities calculated from precipitation reactions and suspended solids removal. These calculations are shown in Appendix IV. Higher sludge accumulation rates would occur if two-stage recarbonation were included in the process because of the additional calcium carbonate precipitate produced. The lime sludge did not have an offensive odor and could be stored indefinitely at 4°C.

TABLE 4

SLUDGE CHARACTERISTICS AND PRODUCTION USING LIME

Percent dry solids   2.75

Percent volatile   33.0

Volume of sludge   17,360
(gal/MG)

Pounds of dry sludge   4,000
(lbs/MG)

Specific gravity   1.012

Operational problems encountered during the 35 day lime study included:

1) Buildup of $CaCO_3$ precipitate on the rapid mix propeller and shaft. Air agitation instead of mechanical mixing would probably solve this problem.

2) Scaling of both flocculators and the clarifier with 1/50 inch of $CaCO_3$ precipitate.

3) Occasional clogging of slurry feed line.

SLUDGE DEWATERABILITY

One of the most important aspects of wastewater treatment is sludge dewatering and disposal. In addition, recovery and reuse of available lime is also a necessary consideration. As part of this study, gravity thickening, vacuum filtration, centrifugation and recalcination processes were evaluated.

Thickening

Sludge that is not thick enough for efficient and economical dewatering by processes such as vacuum filtration and centrifugation requires a "thickening" step. Such is the case with the lime sludge produced during the Phase II study which averaged only 2.75 percent dry solids. The aim of lime sludge thickening is to increase the concentration of dry solids to a more workable range of four to ten percent while greatly reducing sludge volume.

In this study, the gravity thickening process was evaluated according to the graphical method of Talmage and Fitch (10). Five gallon samples of clarifier sludge were placed in 5.5 inch diameter plexiglass columns (filled to a water column height of 4 ft) and the position of the sludge interface was recorded over a 24 hour period. No stirring devices were used. A plot of sludge interface versus time resulted in the settling curves shown in Appendix V.

From each settling curve, representing a given feed solids concentration, solids loading rates to the thickener were calculated for achieving various underflow solids concentrations according to the

method outlined in Appendix V. This procedure resulted in the relationship shown in Figure 10 where thickener solids loading rates versus underflow solids concentration are plotted for each feed solids concentration investigated. A more generalized form of this relationship is given by the thickener design curves shown in Figure 11. Here, thickener solids loading rates can be determined for a variety of feed and thickener underflow concentrations. For example, if the average feed solids concentration is 3 percent the thickening process can be expected to produce a sludge of 6 to 9 percent solids. Solids loading rates should range between 9 and 17 $lbs/day-ft^2$. Burns and Shell (11) reported similar results in their study where a 3 percent lime sludge was thickened to 8 percent solids using a solids loading rate of 11.2 $lbs/day-ft^2$.

The quality of the thickener supernatant is shown in Table 5. Alkalinity, pH, suspended solids, turbidity and hardness were approximately equivalent in concentration to the clarification process effluent (refer to Table 3). However, total phosphorus and COD concentrations increased to values characteristic of the untreated wastewater. Because suspended solids concentrations were low, it seems that these high COD and phosphorus levels were due to the dissolved fraction. The presence of dissolved COD and phosphorus could result from the break-up of floc aggregates during settling and compression which would release enmeshed colloidal particles to the supernatant. However, return of this supernatant to the plant influent should not affect COD and phosphorus removals because of the relatively small volume
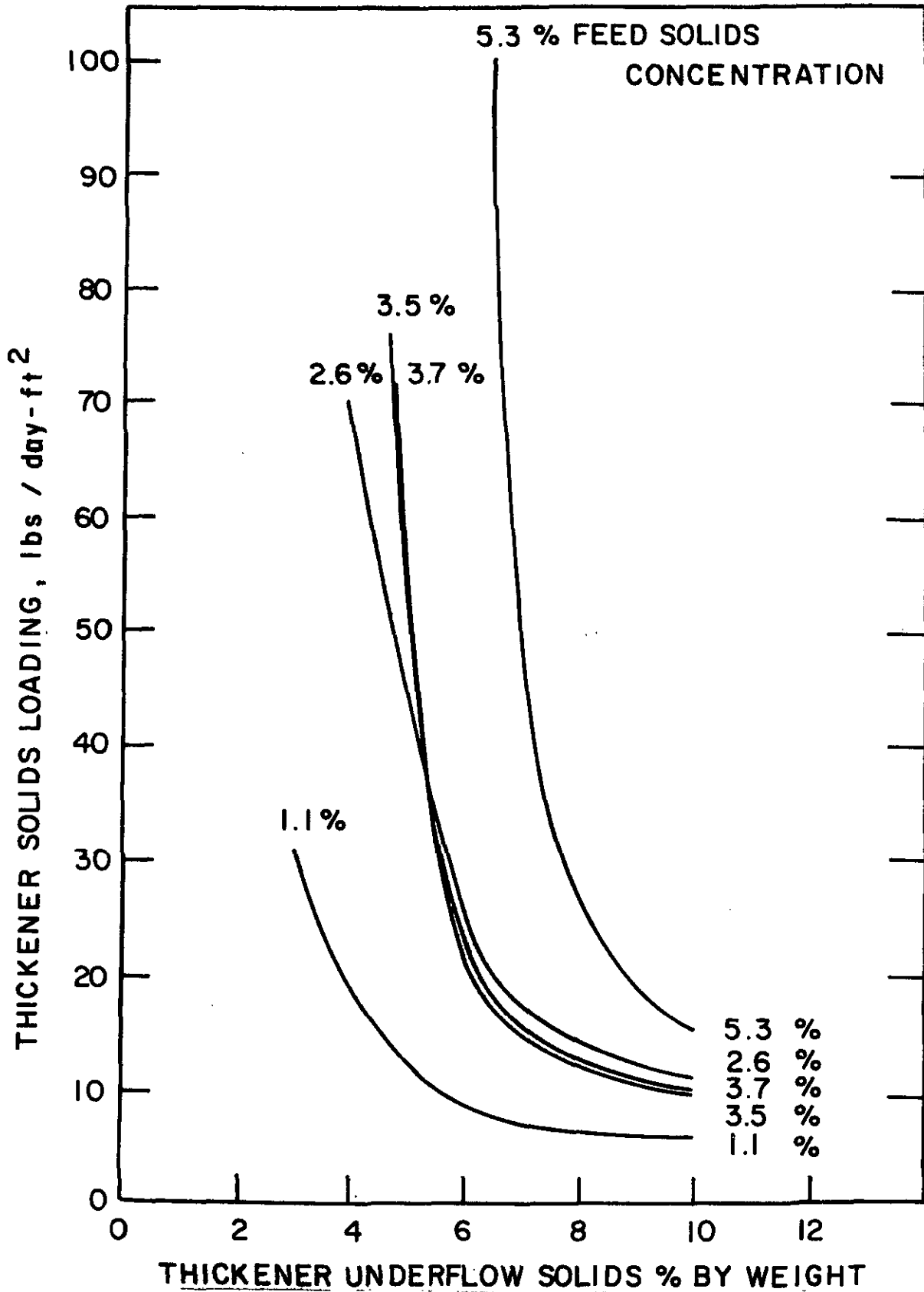
Figure 10.   Lime Sludge Thickening Curves.
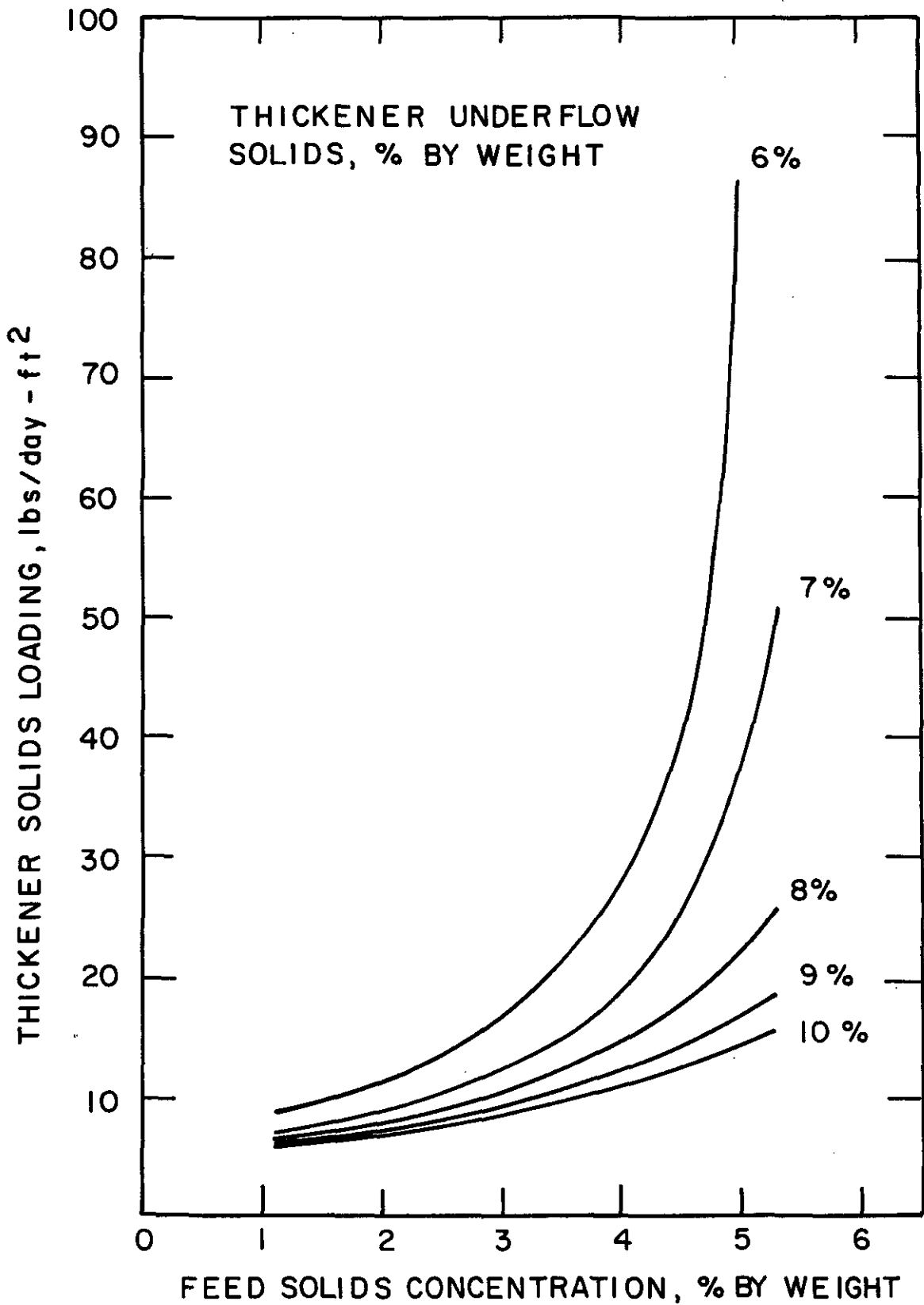
Figure 11. Thickener Design Curves.

TABLE 5

THICKENER SUPERNATANT

Parameter	Thickener[1] Supernatant
pH	11.7
Alakalinity (phenolphthalein) (mg/l as $CaCO_3$)	429
Alkalinity (total) (mg/l as $CaCO_3$)	493
Suspended Solids (mg/l)	24
COD (mg/l)	374
Turbidity (JTU)	18
Total Phosphorus (mg/l as P)	8.4
Hardness (mg/l as $CaCO_3$)	438

[1] Average of 8 determinations.

produced; of the 100 gallons of sludge wasted daily from the pilot

plant, approximately 50 gallons or 0.8 percent of the total plant flow,

would return as supernatant.

Vacuum Filtration

The dewaterability of lime sludge by vacuum filtration was measured

by specific resistance determinations and filter leaf tests. Specific

resistance (R) is a measure of the ease with which water may be drained

from a given volume of sludge when subjected to a driving force such

as gravity or vacuum. Hence a sludge with a high specific resistance

would be difficult to dewater. If three or more specific resistance

tests are performed at different pressures, a plot of specific resis-

tance versus pressure on bi-logarithmic paper will result in a straight

line. The slope of the straight line is dimensionless and represents

the coefficient of compressibility (σ). A sludge with a high coefficient

of compressibility indicates that the filter cake is easily compressed

and therefore reduced in volume. Typical literature values of specific

resistance and coefficient of compressibility are shown in Table 6.

From these values it can be seen that wastewater sludges are generally

more difficult to dewater than water treatment sludges. Water treatment

sludges are also more compressible.

The results of specific resistance tests using thickened lime sludge

are shown in Figure 12. At 38.1 cm Hg, the specific resistance is

24.0×10^9 sec^2/gm which is within a range typical of wastewater sludges.

The coefficient of compressibility is 1.056 which is characteristic of

water treatment sludges. Consequently, the lime sludge can be expected

TABLE 6

TYPICAL SPECIFIC-RESISTANCE AND COEFFICIENT OF COMPRESSIBILITY

VALUES FOR VARIOUS SLUDGES

Sludge	Specific Resistance @ 38.1 cm Hg(sec^2/gm)	Coefficient of Compressibility
Primary Wastewater (13)	15 - 50 x 10^9	--
Digested Wastewater (12)	14 - 70 x 10^9	0.51 - 0.74
Water Treatment (12)	1 - 10 x 10^9	0.8 - 1.3
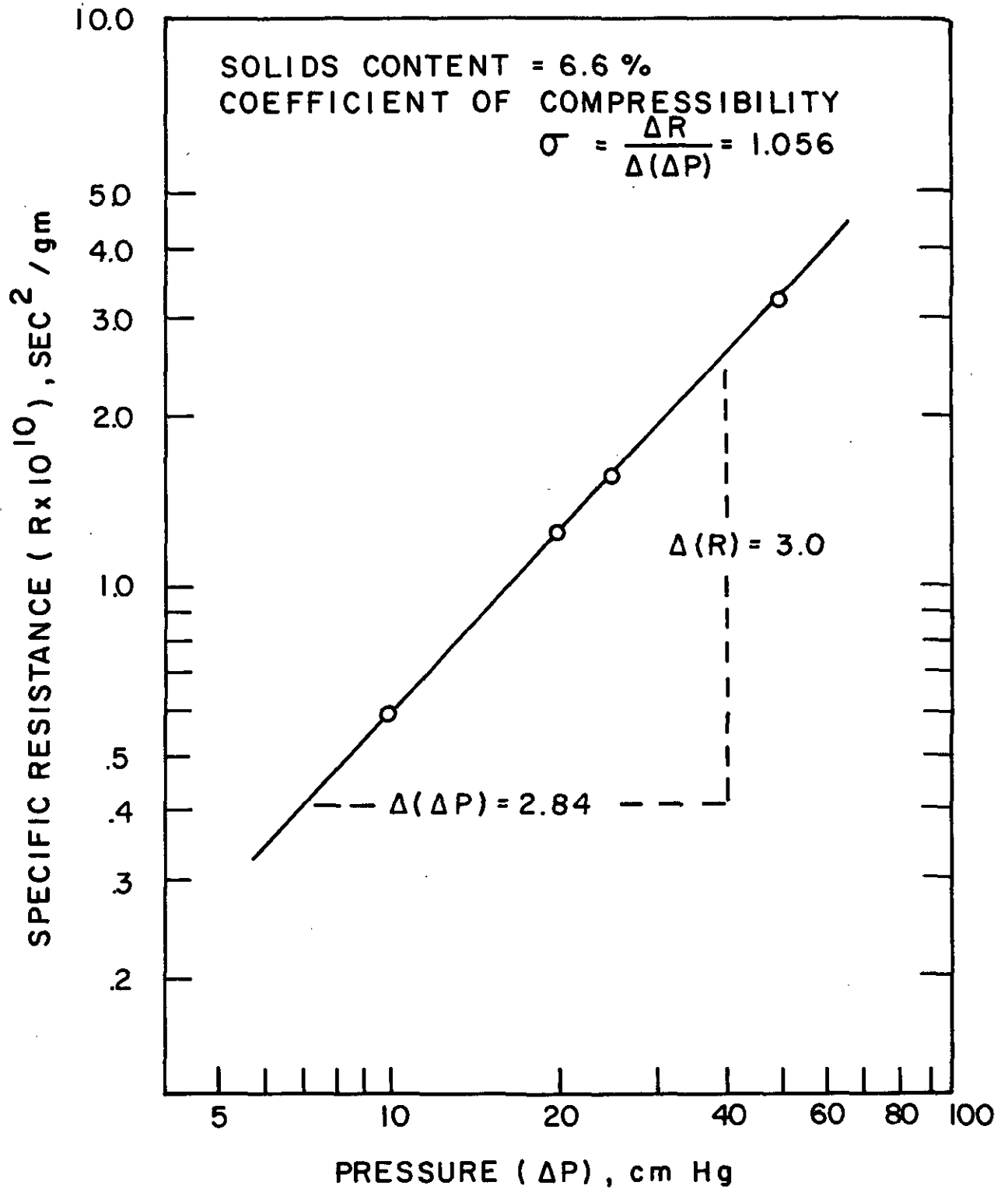
Figure 12. Specific Resistance and Coefficient of Compressibility for Lime Sludge.

to display dewatering characteristics similar to both types of sludge
i.e. moderately difficult to dewater but easy to compress. The method
used for determining both specific resistance and coefficient of
compressibility is described in a report by Adrian et al. (12).

Although vacuum filter yield rates can be determined from specific
resistance measurements, filter leaf tests provide a more realistic
method of specifying operational characteristics of the vacuum filter.
Not only are test results more accurate with respect to yield rate,
cake moisture and filtrate clarity but they offer a visual demonstration
of cake texture, cracking and dischargeability from the filter medium.
The filter leaf tests discussed in this report were performed at the
UMASS Wastewater Pilot Plant facility using equipment and procedures
of the Komline-Sanderson Company.[1]

A twill cloth (#C-528) with a porosity of 20 CFM was chosen as
the filter medium. Three other cloths were tried (#C-509, C-525,
C-2022) with varying degrees of success. Overall, the nylon twill
cloth produced the most easily discharged cake and a filtrate of
acceptable clarity. Based upon preliminary experiments, a vacuum of
20 in Hg and 37.5 percent submergence was used in all tests. Five
thickened sludges ranging from 5.2 to 10 percent solids concentration
were evaluated. Selection of the optimum yield rate for each sludge
was based on the maximum drum speed which produced an acceptable cake
discharge. No conditioning chemicals were used during any of these
tests.

[1] Komline-Sanderson Engineering Corporation, Peapack, New Jersey.

The results of the filter leaf tests are shown in Figure 13. From this figure, the vacuum filter yield can be calculated for various thickener underflow concentrations. For example, with a typical thickener underflow concentration of 7 percent, the filter yield would be approximately 2.7 lbs/hr-ft^2. Greater yields should be possible with the addition of conditioning chemicals such as ferric chloride or polymers. The average thickness of the lime sludge cake was 1/8 inch and the solids content ranged from 26 to 32 percent. A scraper discharge with blowback is recommended for cake removal.

The quality of the vacuum filtrate is shown in Table 7 together with that of the thickener supernatant. Alkalinity, pH and hardness remained at effluent levels while suspended solids, COD, turbidity and total phosphorus concentrations were significantly higher. The high COD concentration (1220 mg/l average) was the most surprising characteristic of the filtrate. As was the case with thickener supernatant, the break-up of floc aggregates during filtration could be the chief factor. Returning this filtrate to the head of the plant should not overload the lime clarification process because of the small volumes involved. Of the 100 gallons of clarifier sludge produced daily at the pilot plant approximately 10 gallons would return as filtrate, or 0.2 percent of the total flow.

The low filter yield rates obtained in this study are consistent with those obtained by other investigators. For a primary lime sludge (3.6 percent solids) flocculated at pH 11.0, Parker, et al. (14)
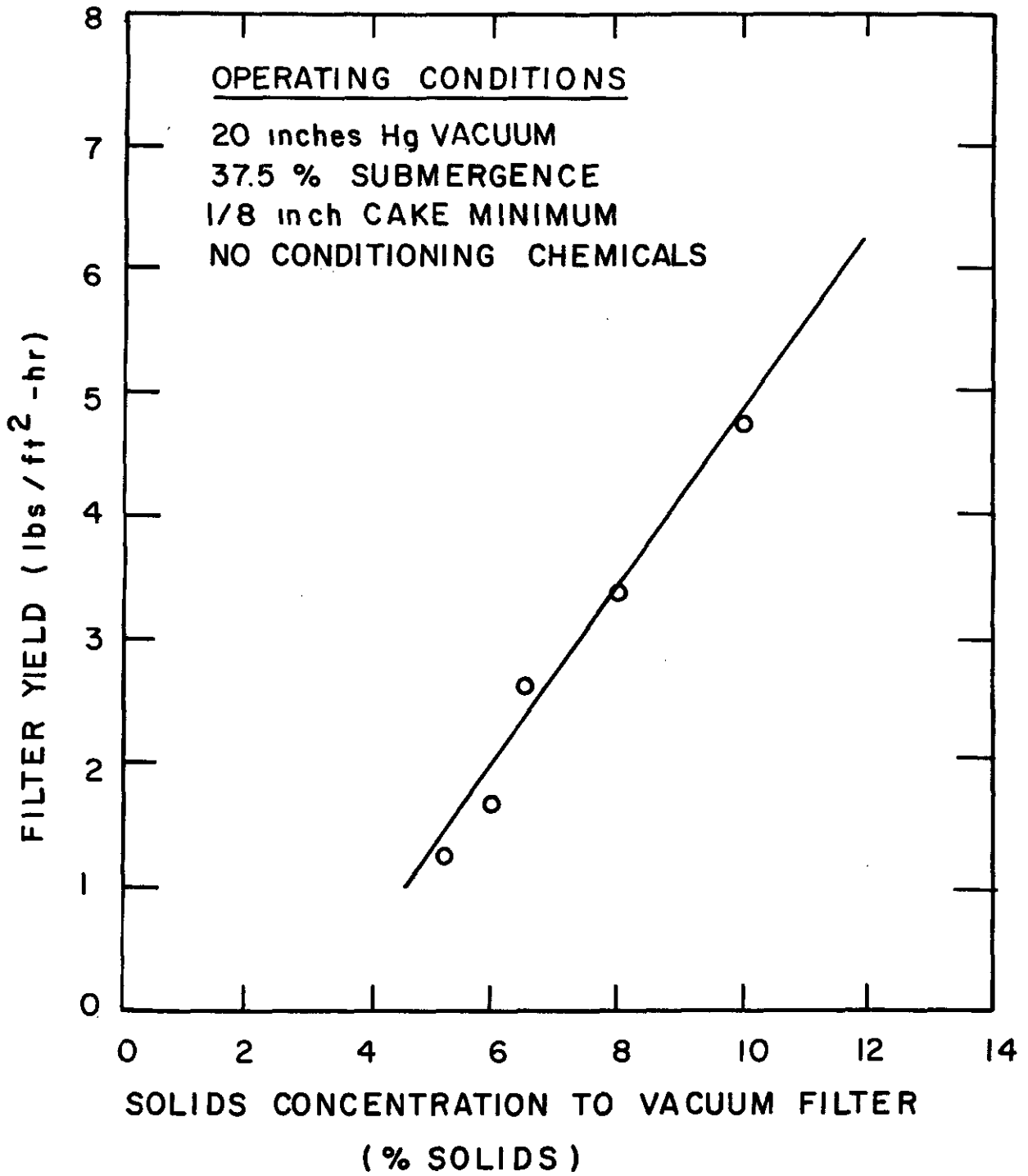
Figure 13.   Vacuum Filter Yield for Various Feed Solids Concentrations.

TABLE 7

COMPARISON OF THICKENER SUPERNATANT AND VACUUM FILTRATE QUALITY

Parameter	Thickener[1] Supernatant	Vacuum[2] Filtrate
pH	11.7	11.6
Alkalinity (phenolphthalein) (mg/l as $CaCO_3$)	429	398
Alkalinity (total) (mg/l as $CaCO_3$)	493	543
Suspended Solids (mg/l)	24	68
COD (mg/l)	374	1220
Turbidity (JTU)	18	30
Total Phosphorus (mg/l as P)	8.4	9.6
Hardness (mg/l as $CaCO_3$)	438	467

[1] Average of 8 determinations.

[2] Average of 6 determinations.

reported a filter yield rate of 1.5 lbs/hr-ft^2. From the data presented by Burns and Shell (11), a 7 percent sludge would produce a 2.4 lbs/hr-ft^2 filtration rate. They also conducted tests with anionic polyelectrolyte flocculation aid (Dow Chemical, AP-30) which increased vacuum filter yields by 30 to 70 percent.

Centrifugation

Three gallons of thickened lime sludge were sent to Bird Machine Company[1] for preliminary centrifuge tests. From laboratory spin tests they predicted that a production model machine would produce a cake containing solids "in the 30 percent range". They also indicated that a clear centrate may result without the use of chemical aids. Lime recovery by "wet classification" is also possible using a series of two or three centrifuges. The letter reporting the results of the centrifuge test is shown in Appendix V.

Recalcination and Lime Re-Use

If the lime sludge can be disposed of satisfactorily on land, then this may be the most economical alternative. However, if this is not the case, recovery and re-use of the lime fraction in the sludge may be the cheapest arrangement. In this way sludge volumes would be reduced and savings could be realized not only in disposal costs but chemical costs as well.

Lime recovery or recalcination is a relatively simple process consisting of incinerating the sludge at temperatures of about 1850°F.

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[1]Bird Machine Company. Incorporated. South Walpole, Massachusetts 02071.

This procedure drives off water and carbon dioxide leaving only calcium oxide or quicklime. The organic fraction of the sludge is oxidized leaving an inert ash. Calculations shown in the EPA Manual on Physical-Chemical Wastewater Treatment Plant Design (8)reveal that lime sludge quantities would be reduced by approximately 45 percent by this process and that nearly 60 percent of this amount would be reuseable quicklime. Estimates of incinerator ash composition for this study, shown in Appendix VI, agree within one percentage point of these values.

To check these estimates lime recalcination was simulated using a high temperature muffle furnace according to the procedure outlined by Mulbarger et al. (15). Dried sludge samples from the filter leaf tests were placed in a porcelain crucible and inserted into the oven where the temperature was gradually raised to $1850^{o}F$. This temperature was held for 1.5 hours after which the resulting lime as CaO and ash was allowed to cool. A portion of this incinerated sludge was titrated against a known lime concentration using 0.5 N H_2SO_4. This procedure was carried out twice using a composite of 11 dried sludge samples. These titrations indicated that the average lime (as CaO) content of the incinerated sludge was 63 percent which is quite close to the EPA estimate cited previously. The weight of dry sludge was also reduced by 50 percent as a result of incineration.

After the sludge is recalcined, a portion of the ash which contains both quicklime (CaO) and inerts must be wasted before it can be re-used.

Wasting is necessary to reduce the buildup of inerts due to recycling into the clarification process. The actual wastage rate of percent blowdown will depend on how fast inerts accumulate in the system. Usually a 25 percent blowdown rate is assumed for theoretical calculations (8).

With a 50 percent reduction in sludge weight due to recalcination and a lime (as CaO) content of 63 percent and 25 percent blowdown rate, the lime available for re-use can be calculated as follows:

Dry sludge production	=	4000 lbs/MG
Recalcined sludge (50% reduction)	=	2000 lbs/MG
Available CaO (63% recalcined sludge)	=	1260 lbs/MG
Available CaO (after 25% blowdown)	=	945 lbs/MG

The lime used during clarification was 380 mg/l as CaO or 3170 lbs/MG. If 945 lbs/MG are recycled into the chemical clarification process, 2225 lbs/MG of make-up lime will be required or 70 percent of the total lime requirement. Clearly, the recalcination and re-use of lime in this case would not be economically attractive. However, if the effluent is recarbonated, substantial quantities of calcium carbonate could be precipitated out and recalcined along with the clarification process sludge. Calculations in Appendix VI show that an additional 1260 lbs/MG of lime (as CaO) could be recovered which is equal to the amount obtained from the clarification process. The total available lime (as CaO) including recarbonation, is then 1890 lbs/MG (assuming 25 percent blowdown of recarbonated sludge). Consequently, the make-

up lime requirement is now reduced to approximately 40 percent, or 1280 lbs/MG. Whether lime recovery and re-use would be economically justifiable in this case is not clear. Only an orderly economic evaluation would provide the answer. The cost of lime clarification including lime recovery is discussed in the section entitled "Cost Comparison of Lime and Alum Chemical Clarification".

PERFORMANCE COMPARISON OF LIME AND ALUM CLARIFICATION

Prior to this study, a similar pilot plant investigation of
alum clarification was conducted. These results are summarized in
a report entitled "Pilot Plant Studies of Wastewater Chemical
Clarification Using Alum" (7). While the same pilot-scale units
were used in both studies, Amherst primary effluent was used during
the alum study rather than raw wastewater. Hence, a direct compar-
ison of alum and lime clarification is not possible. Because primary
effluent was used in the alum study, it would be reasonable to expect
lower effluent turbidity, suspended solids and TOC concentrations
than in the lime study. However, phosphorus removals should not
be greatly affected because primary treatment does not remove
significant amounts of phosphorus.

A comparison of the mean effluent quality of alum and lime clari-
fication is shown in Table 8. The low pH and alkalinity of alum
treated effluent and the high pH and alkalinity due to lime treatment
is predictable considering the respective acidic and caustic character
of alum and lime. Because of the low pH produced by alum addition,
it was concluded that a pH control or monitor system would be required.
On the other hand, because of the high pH produced by lime treatment
recarbonation is necessary. Excellent total and dissolved phosphorus
removals were achieved using both chemicals. Effluent phosphorus
concentrations were approximately equivalent using either alum or lime.
Turbidity and suspended solids concentration were slightly lower using
alum. However, this may be due to lesser concentrations of these

TABLE 8

COMPARISON OF MEAN EFFLUENT QUALITY USING ALUM OR LIME*

Parameter	Alum	Lime
pH	6.3	11.6
Alkalinity (mg/l as $CaCO_3$)	35	495
Total Phosphorus (mg/l as P)	0.55	0.60
Dissolved Phosphorus (mg/l as P)	0.27	0.24
Turbidity (JTU)	8	17
Suspended Solids (mg/l)	8	33

*It should be noted that raw wastewater was used in the lime study whereas primary effluent was used during the alum study.

parameters in primary effluent which reduces the loading on the alum
clarification process.

Not shown in Table 8 are organic removals obtained by each
process. A direct comparison was not possible because total organic
carbon (TOC) was measured in the alum study and chemical oxygen demand
(COD) in the lime study. The TOC of the alum treated effluent was 36
mg/l and the COD of the lime clarification effluent was 108 mg/l.

A comparison of alum and lime sludge characteristics is shown in
Table 9. Alum sludge characteristics were adjusted to reflect a raw
wastewater feed system. From this data it is evident that lime
clarification will produce more sludge than alum clarification both in
volume and dry solids. However the lime sludge was more dense than the
alum sludge and should dewater more easily. Also, the lime sludge had
very little odor and would remain in this stable condition for long
periods of time.

In conclusion, it would appear that on the basis of effluent
quality, either chemical would produce equivalent results. Both
chemicals also produced large quantities of sludge which must be
dewatered and ultimately disposed. The dewaterability of lime sludge
was investigated in this report and satisfactory results were obtained.
In contrast, no dewaterability tests were performed using alum sludge.
These tests will be conducted as part of another study. Other investi-
gators (11,16) have already demonstrated the dewaterability of alum
sludges with conventional equipment. Consequently, the primary
determinant in selecting either lime or alum clarification will depend
on costs, which are discussed in the next section.

TABLE 9

COMPARISON OF ALUM AND LIME SLUDGE CHARACTERISTICS

Characteristic	Alum	Lime
Percent dry solids	2.25	2.6
Percent volatile solids	58	33
Specific gravity	1.0045	1.012
Volume of sludge (gal/MG)	11,225	17,361
Pounds of dry sludge (lbs/MG)	2,100	4,000

COST COMPARISON OF LIME AND ALUM CHEMICAL CLARIFICATION

One of the more uncertain areas concerning chemical clarifi-
cation of wastewater is the cost of the process. Accurate cost data
will not be available until many plants have been built and operated
for several years. Even cost estimates are often outdated and mis-
leading because of recent increases in fuel, electrical and chemical
costs. For example it is a common misconception that one of the main
advantages of using lime is that it costs less than other chemical
coagulants. However, the cost of fuel needed to convert limestone
to lime has increased dramatically over the last two years, causing
a threefold increase in lime costs. Consequently the economic
advantage of lower chemical cost has been largely eliminated and
lime recovery becomes more of a necessity.

Despite the lack of actual cost data from full-scale treatment
facilities, up-to-date cost estimates can be determined from a number
of publications (11,20,21,22,23). This cost information was used to
generate comparative cost data based on the treatment requirements
of Amherst wastewater and a flow of 10 MGD. These costs are conceptual
in nature and do not involve extensive investigation of site, construc-
tion or hydraulic details. Moreover, the cost comparison includes
only the chemical clarification and sludge handling portions of a
total treatment scheme.

All costs presented in this analysis were based on March 1975
price levels (ENR Construction Cost Index = 2200· EPA-STP Index
(Boston) = 240). Capital costs were ammortized at 7 percent for 20

years. Operation and maintenance costs were based on a 10 MGD design capacity, an alum cost of $80/ton, and a lime cost of $60/ton as $Ca(OH)_2$.

The costs of a chemical clarification treatment scheme using alum is shown in Table 10. The processes included were preliminary treatment (bar screens and comminution) solids contact, chemical feed system (including chemical costs), vacuum filtration and sanitary landfill. Anaerobic digestion is shown separately in the event that sludge stabilization is required. The total cost of this system is approximately 18¢/1000 gallons without anaerobic digestion and 20¢/1000 gallons with anaerobic digestion. A major portion of this cost is the chemical cost of alum.

The estimated costs of chemical clarification using lime, with and without lime recovery, are shown in Tables 11 and 12, respectively. The processes included in the lime clarification scheme are the same as the alum clarification scheme except that single-stage recarbonation was included in the lime clarification scheme without recovery; two-stage recarbonation and recalcination were incorporated in the lime clarification scheme with recovery. The total cost of lime treatment without recovery (see Table 11) was estimated at 25¢/1000 gallons. The large quantities of lime required (21 tons/day as $Ca(OH)_2$) account for the high cost of this treatment method. In comparison, the cost of lime treatment with recovery is only 20¢/1000 gallons (Table 12) and indicates the economic desirability of a lime recovery system

TABLE 10

COST OF ALUM TREATMENT

Process*	Design Condition	Capital Cost ¢/1000 gal	O & M Cost ¢/1000 gal	Total Cost ¢/1000 gal
Bar Screens & Comminution (11,23)	10 MGD	.02	0.11	0.13
Solids Contact (20)	600 gpd/ft^2	2.02	2.55	4.57
Chemicals & Feed System (11,20)	175 mg/1 alum	.19	6.89	7.08
Vacuum Filter (21)	1 lb/hr-ft^2	1.78	1.55	3.33
Sanitary Landfill (21)	42 wet tons/day	.47	2.31	2.78
TOTAL (w/o Anaerobic Digestion)		4.48	13.41	17.89
With Anaerobic Digestion	200,000 ft^3	1.25	0.56	1.81
TOTAL (with Anaerobic Digestion)		5.73	13.97	19.70

*
Appropriate references for cost calculations are shown in parentheses.

TABLE 11

COST OF LIME TREATMENT WITHOUT RECOVERY

Process*	Design Condition	Capital Cost ¢/1000 gal	O & M Cost ¢/1000 gal	Total Cost ¢/1000 gal
Bar Screens & Comminution (11.23)	10 MGD	0.02	0.11	0.13
Solids Contact (20)	1500 gpd/ft^2	1.19	1.64	2.83
Chemicals & Feed System (20)	380 mg/l as CaO	0.47	14.10	14.57
Single-Stage Recarbonation (22)	1/3 cost of two-stage system	0.25	0.33	0.58
Vacuum Filter (21)	4.0 lbs/hr-ft^2	0.85	2.09	2.94
Sanitary Landfill (21)	67 wet tons/day	0.62	3.07	3.69
TOTAL		3.40	21.34	24.74

*
Appropriate references for cost calculations are shown in parentheses.

TABLE 12

COST OF LIME TREATMENT WITH RECOVERY

Process*	Design Condition	Capital Cost ¢/1000 gal	O & M Cost ¢/1000 gal	Total Cost ¢/1000 gal
Bar Screens & Communition (11,23)	10 MGD	.02	0.11	0.13
Solids Contact (20)	1500 gpd/ft^2	1.19	1.64	2.83
Chemicals & Feed System (20)	60% lime recovery	0.47	6.50	6.97
Two-Stage Recarbonation (22)	10 MGD	0.75	1.00	1.75
Vacuum Filtration (21)	4.0 lbs/hr-ft^2	0.85	2.09	2.94
Recalcination (22)	20 tons/day dry sludge	2.96	2.29	5.25
Sanitary Landfill ($6/Ton)	4.4 tons/day	–	0.26	0.26
TOTALS		6.24	13.89	20.13

*
Appropriate references for cost calculations are shown in parentheses.

even for relatively small plants, The use of a 60 percent lime
recovery factor was based on laboratory recalcination tests (see
section entitled "Lime Recalcination and Re-Use").

The results of this cost analysis indicate alum clarification
to be the least expensive alternative. provided that anaerobic
digestion is not required. If digestion is required alum treatment
becomes as expensive as lime treatment with recovery. Lime treatment
without recovery is by far the most expensive alternative.

CONCLUSIONS

1) Jar tests indicated that a lime dosage of 380 mg/l as CaO
    will reduce the total phosphorus concentration in raw Amherst
    wastewater to 1.0 mg/l or less. A relatively constant pH of
    approximately 11.5 can be expected from such a dosage.

2) Phosphorus removal did not improve significantly with longer
    flocculation times in either jar tests or pilot plant studies.
    However, the jar tests showed that if the rapid mix time was
    reduced from 3 minutes to 1 minute, longer flocculation times were
    needed for equivalent phosphorus removals.

3) Pilot plant studies conducted at different flocculation times
    demonstrated a need for longer flocculation periods (approximately
    15 minutes) to obtain maximum suspended solids removal.

4) Lime clarification of raw wastewater can consistently reduce
    phosphorus concentrations below 1.0 mg/l as P. Extended pilot
    plant studies also demonstrated that suspended solids, turbidity,
    and chemical oxygen demand (COD) can also be reduced by 81, 77
    and 75 percent respectively. Multi-media filtration is most
    effective in further reducing suspended solids and turbidity.

5) The sludge accumulation rate as a result of lime addition can be
    expected to increase dramatically. During the pilot plant studies,
    4000 lbs/MG were produced which is approximately four times the
    amount from primary sedimentation alone. An additional 2250 lbs/MG
    of $CaCO_3$ sludge would be produced by two-stage recarbonation.

6) Thickening characteristics of lime sludge are good. Laboratory
    tests show that thickener sludge concentrations in the 6 to 9

percent range can be expected for a solids loading rate of 9
to 17 lbs/day-ft^2.

7) A conditioning chemical such as $FeCl_3$ or a polymer will be
needed to increase vacuum filter yield rates to more acceptable
levels of 5 or 6 lbs/hr-ft^2. Filter leaf tests using thickened
lime sludge and no conditioning chemicals typically produced yield
rates of 3.0 lbs/hr-ft^2.

8) Dewatering by centrifugation should produce cake solids in the
30 percent range. A clear centrate may also result without the
use of coagulant aids.

9) Because of the volume of supernatant and vacuum filtrate produced
is small, their high COD content should not severely affect the
treatment efficiency of the process.

10) Approximately 60 percent of the total lime requirement can be
recovered by recalcination if two-stage recarbonation is used.

11) With proper dosing, alum or lime clarification are equally effec-
tive in treating low alkalinity wastewater. The main difference
in the two processes is that alum clarification lowers pH and
alkalinity such that provisions for upward pH adjustment are
required while lime addition raises pH and alkalinity, and downward
pH adjustment is necessary. Also sludge production in the lime
system is greater than alum but lime sludge is easier to handle.

12) Comparative cost studies show that chemical clarification of raw wastewater is less expensive using alum than lime. The cost of a 10 MGD clarification scheme using alum is approximately 18¢/1000 gallons. However, if anaerobic digestion of alum sludge is required, this cost is increased to 20¢/1000 gallons which is equivalent to the estimated cost of lime clarification with lime recovery. Lime treatment without recovery is by far the most expensive alternative at 25¢/1000 gallons.

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18) Methods for Chemical Analysis of Water and Wastes, U.S. Environmental Protection Agency, Office of Technology Transfer, EPA-625/6-74-003 (1974).

19) Sawyer, C. N. and McCarty, P. L., Chemistry for Sanitary Engineers, McGraw-Hill, 2nd Edition (1967).

20) Process Design Manual for Suspended Solids Removal, U.S. Environmental Protection Agency Technology Transfer, EPA 625/1-75-003a (January 1975).

21) Process Design Manual for Sludge Treatment and Disposal, U.S. Environmental Protection Agency Technology Transfer, EPA 625/1-74-006, (October 1974).

22) Advanced Wastewater Treatment as Practiced at South Tahoe, U. S. Environmental Protection Agency, Project 17010 ELQ (WPRD 52-01-67), (August 1971).

23) Estimating Manpower Requirements for Conventional Wastewater Treatment Facilities, EPA 17090 DAN 10/71, (1971).

24) 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).

APPENDIX I

ANALYTICAL TECHNIQUES

All analyses were performed in accordance with the 13th Edition

of Standard Methods for the Examination of Water and Wastewater (17)

and Methods for Chemical Analysis of Water and Wastes (18). Most

samples were analyzed immediately after sampling, but when preservation

was necessary, it was done according to EPA guidelines (18).

Phosphorus - Total phosphorus was determined according to the

EPA single reagent method. Dilutions were made as necessary. The

persulfate digestion was used and colormetric determinations were

carried out with a Bausch and Lomb Spectronic 20.

At least two standards and a reagent blank were analyzed with

every set of samples. Glassware was washed with hot 1 + 1 hydrochlo-

ric acid, and filled with distilled water until use.

Soluble phosphorus was determined by immediate filtration

through a 0.45 micron membrane filter prior to analysis.

Alkalinity - Alkalinity was measured by titrating each sample

with .01 N H_2SO_4 to the respective endpoints of 4.5 for total

alkalinity and 8.3 for phenophthalein alkalinity. Electrometric

titrations were carried out on a Radiometer model 28B pH meter and

results expressed in mg/l as $CaCO_3$.

Chemical Oxygen Demand (COD) - The samples including a blank

were refluxed for two hours and titrated with standardized .01 N

ferrous ammonium sulfate.

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

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 - The water was boiled off an appropriate volume of sewage or sludge in a dried and tared dish. The residue was dried at 103°C and weighed.

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

Hardness - A 25 ml sample was titrated against standardized EDTA titrant.

APPENDIX II

DETERMINATION OF THE MEAN VELOCITY GRADIENT (G)

Flocculation Tanks

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

$$G = \left(\frac{C_d A \rho v^3}{2 \mu V}\right)^{1/2} \tag{1}$$

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 assumed and calculated values of the above 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(2π nR/60), where v_p = paddle-tip speed

n = rpm = 30

R = radius of paddles = .375 ft.

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

$V = 32$ gal $= 4278$ ft^3

Substituting these values in Equation 1, the mean velocity gradient (G) is 73 sec^{-1} which is within the range of 20 to 75 sec^{-1} recommended for flocculation (13). A high velocity gradient was used to prevent settling of the heavy lime floc in the flocculation basins.

Rapid Mix Tank

The velocity gradient in a rapid mix tank must be greater than that in a flocculation basin to insure proper mixing. Culp and Culp (2) recommend a velocity gradient of at least 300 sec^{-1}. For a rapid mix tank with an electrically driven propeller and shaft, the mean velocity gradient (G) can be determined from the equation:

$$G = (\frac{HPW \times 550}{\mu\, V})^{1/2}$$

where HPW is the water horsepower.

For a rapid mix tank with a volume of 20 gallons and a stirrer with a 1/30 HP, 75 percent efficient motor, the mean velocity gradient (G) is 463 sec^{-1}. This velocity gradient with a 5-minute detention time should be adequate for dispersing the lime slurry in the wastewater.

APPENDIX III

## CARBON DIOXIDE REQUIRED FOR RECARBONATION

In the recarbonation process, one molecule of CO_2 is required to convert calcium hydroxide ($Ca(OH)_2$) to calcium carbonate ($CaCO_3$) according to the following chemical reaction:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad (1)$$
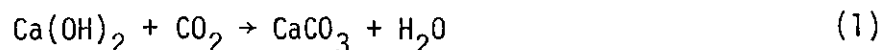
This reaction is essentially complete at a pH of 9.3 and results in the formation of a heavy, rapidly settling floc is principally calcium carbonate. The amount of CO_2 required in lbs/MG to complete this reaction can be calculated from the relationship:

$$CO_2 \text{ (lbs/MG)} = 3.7 \times \text{(OH alk. in mg/l as } CaCO_3) \text{ (ref. 2)} \qquad (2)$$

If more CO_2 is added calcium carbonate is converted to calcium-bicarbonate according to the reaction:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2 \qquad (3)$$
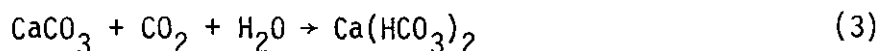
This reaction is complete at a pH of 8.3 . The amount of CO_2 needed to convert carbonates to bicarbonates is then

$$CO_2 \text{(lbs/MG)} = 3.7X \text{ (}CO_3 \text{ alk. in mg/l as } CaCO_3) \text{ (ref. 2)} \qquad (4)$$

If calcium hydroxide is converted to calcium bicarbonate in a single step, the amount of CO_2 required is:

$$CO_2 \text{(lbs/MG)} = 7.4X \text{ (OH alk. in mg/l as } CaCO_3) \text{ (ref. 2)} \qquad (5)$$

Assuming that at a pH of 11.5 the lime clarification effluent is composed of hydroxide-carbonate alkalinity, the carbonate and hydroxide alkalinity can be calculated as follows:

$$CO_3 \; alk(mg/l \; CaCO_3) = 2X(total \; alk(mg/l \; CaCO_3) -$$

$$phenol. \; alk \; (mg/l \; (CaCO_3)) \qquad\qquad (ref.[19]) \quad (6)$$

$$OH \; alk(mg/l \; CaCO_3) = total \; alk. \; (mg/l \; CaCO_3) -$$

$$CO_3 \; alk. \; (mg/l \; CaCO_3) \qquad\qquad (ref. \; 19) \quad (7)$$

From Table 5 the phenolphthalein alkalinity is 453 mg/l as $CaCO_3$ and the total alkalinity is 495 mg/l as $CaCO_3$. Thus, from Equations 6 and 7, the carbonate alkalinity can be calculated to be 84 mg/l as $CaCO_3$ and the hydroxide alkalinity is 411 mg/l as $CaCO_3$.

Two-Stage Recarbonation

In the first stage, CO_2 is added to convert calcium hydroxide to calcium carbonate precipitate. According to Equation 2, the amount of CO_2 required is then:

$$CO_2 \; (lbs/MG) = 3.7X \; (411 \; mg/l \; as \; CaCO_3) = \underline{1521}.$$

After precipitation of $CaCO_3$ additional CO_2 is added in the second stage to further reduce the pH from approximately 9.3 to 8.3 or below. According to Equation 4, the CO_2 required can be calculated as follows:

$$CO_2(lbs/MG) = 3.7X \; (84 \; mg/l \; as \; CaCO_3) = \underline{311}.$$

The total carbon dioxide requirement for both stages of recarbonation is then $\underline{1832 \; lbs/MG}$.

Single-Stage Recarbonation

If lime is not to be reused, single-stage recarbonation may be employed. However, by applying all the carbon dioxide in a single step, little calcium is precipitated and the hardness of the effluent is increased. To change all the hydroxide and carbonate alkalinity to bicarbonate, the CO_2 required is:

$$CO_2(lbs/MG) = 7.4X \ (411 \ mg/l \ as \ CaCO_3) = 3041$$

$$CO_2(lbs/MG) = 3.7X \ (84 \ mg/l \ as \ CaCO_3) = 311.$$

The total CO_2 required for single-stage carbonation is then 3352 lbs/MG.
The greater CO_2 requirement in single-stage recarbonation is due to
the fact that all carbonates must be converted to bicarbonates, where-
as in a two-stage system, the carbonates are settled out and removed.

APPENDIX IV

ESTIMATES OF LIME SLUDGE PRODUCTION

The method used for calculating the amount of dry sludge pro-
duced is outlined in Physical-Chemical Wastewater Treatment Plant
Design. (8) The results of the lime clarification study are summa-
rized below (see also Table 3):

	Influent	Effluent
Suspended Solids (mg/l)	174	33
Total Phosphorus (mg/l as P)	8.5	0.6
Total Hardness (mg/l as $CaCO_3$)	45	370
Ca^{++} (mg/l)	14	148
Mg^{++} (mg/l)	2.5	0

Estimated Dry Sludge from Suspended Solids Removal.

(174-33) mg/l X 8.34 X 1 MGD = 1176 lbs/MG

Estimated Dry Sludge from PO_4 Precipitation.

Hydroxyapatite $Ca_5OH(PO_4)_3$ is formed according to the reaction,

$5Ca^{++} + 4OH^- + 3HPO_4^{--} \rightarrow Ca_5OH(PO_4)_3 \downarrow + 3H_2O$.

Accordingly, 1 mole $Ca_5 OH(PO_4)_3$ is formed per 3 moles P.

$\frac{8.5 - 0.6}{31}$ = 0.255 moles P removed

$\frac{0.255}{3}$ = 0.085 moles $Ca_5 OH(PO_4)_3$ formed; M.W. is 502 and

0.085 x 502 = 43 mg/l $Ca_5 OH(PO_4)_3$ precipitate formed

43 mg/l X 8.34 X 1 MGD = 359 lbs/MG

Estimated Dry Sludge from $CaCO_3$ Precipitate.

Lime Dosage = 380 mg/l as CaO or 271 mg/l as Ca^{++}

Influent Ca^{++} (mg/l) = 271 + 14	= 285
Effluent Ca^{++} (mg/l)	= 148
Total Ca^{++} (mg/l) in sludge	= 137
Less Ca^{++} in hydroxyapatite ppt.	= 17
Ca^{2+} in calcium carbonate sludge	= 120

Dry sludge from $CaCO_3$ = $\frac{100}{40}$ X 120 = 300 mg/l

300 mg/l X 8.34 x 1 MGD = 2502 lbs/MG

Estimated Dry Sludge Due to $Mg(OH)_2$ Precipitation

Magnesium hydroxide $(Mg(OH)_2)$ is formed according to the reaction,

$$Mg^{++} + Ca\ (OH)_2 \rightarrow Mg(OH)_2 + Ca^{++}$$
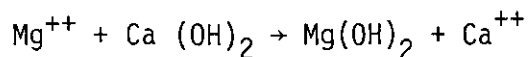
With one mole of $Mg(OH)_2$ formed per mole of Mg^{++}, the amount of magnesium hydroxide sludge produced is:

$$\frac{2.5}{24.31} = 0.1\ X\ 58.31 = 6\ mg/l\ as\ Mg\ (OH)_2$$

6 mg/l X 8.34 X 1 MGD = 50 lbs/MG

Summary of Dry Sludge Production

Sludge Species	lbs/MG
Sewage solids	1176
$Ca_5\ OH(PO_4)_3$ precipitate	359
$CaCO_3$ precipitate	2502
$Mg(OH)_2$ precipitate	50
Total	4087

APPENDIX V

GRAVITY THICKENING AND CENTRIFUGE DATA

Gravity Thickening

The gravity thickening characteristics of lime sludge were
determined by the following test procedure:

1) A 5-gallon sample of the wasted lime sludge from the
   clarifier was set aside. The characteristics of this
   sludge are shown in Table 4. Some samples were diluted
   or concentrated to obtain various initial sludge concen-
   trations (C_I).

2) The 5-gallon sample was poured into a 5.5 inch graduated
   plexiglass column and the interface height recorded with
   time. No mixing was provided. The height of the interface
   was recorded over a period of 24 hours. The settling curves
   of 5 sludges of various initial concentrations are shown
   in Figure AV-1.

3) The supernatant was siphoned off and preserved for analysis
   (see Table 5). The remaining thickened sludge was drained
   from the column into one-gallon containers and a sample
   withdrawn for percent solids analysis. The gallon containers
   of sludge were refrigerated and used later in filter leaf
   tests.

4) By the method of Talmage and Fitch (10) a "working line"
   was developed tangent to the settling curve at the com-
   pression point. Figure AV-2 shows a typical sludge thickening
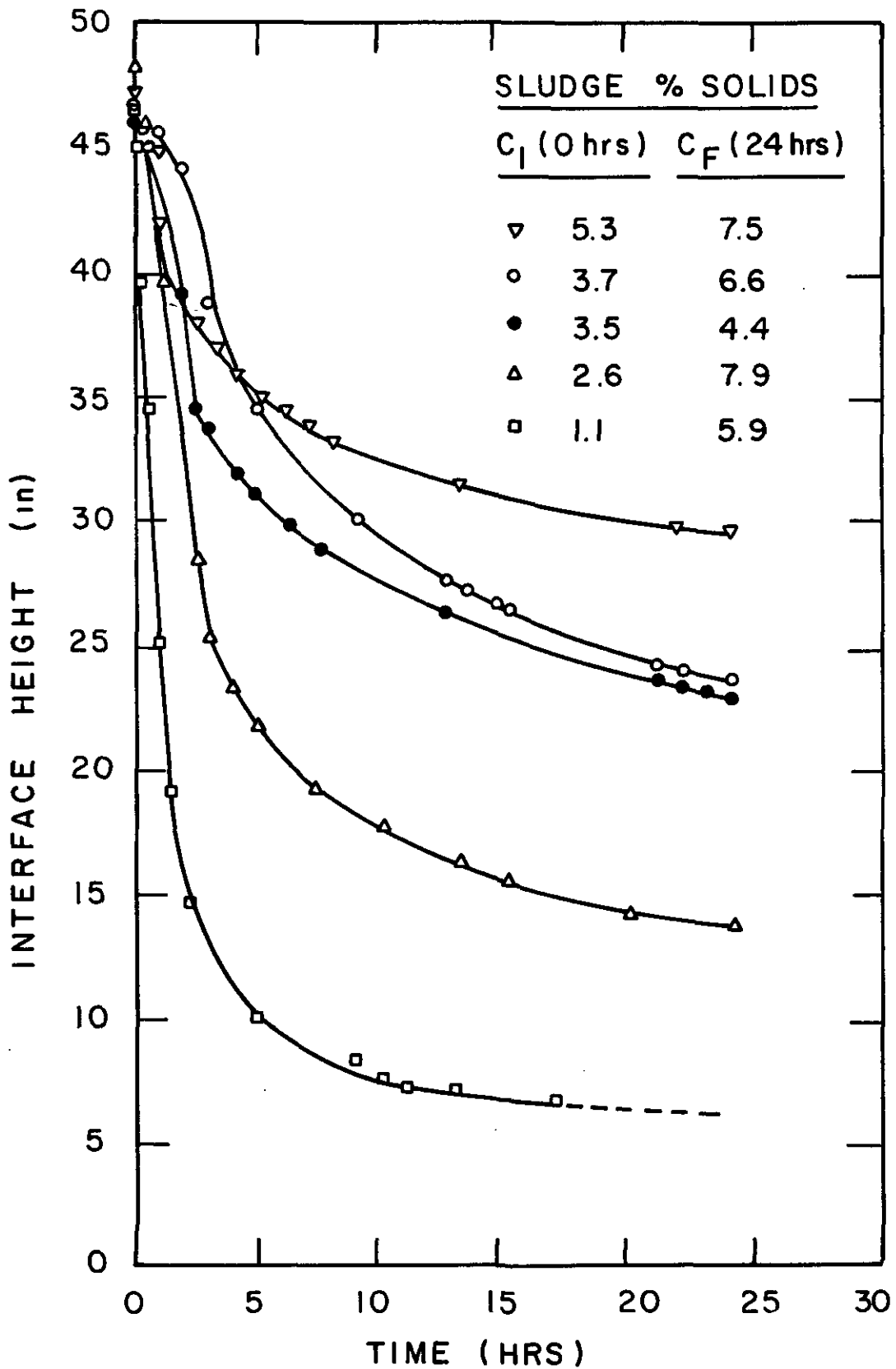   curve with a "working line" which will be used to compute
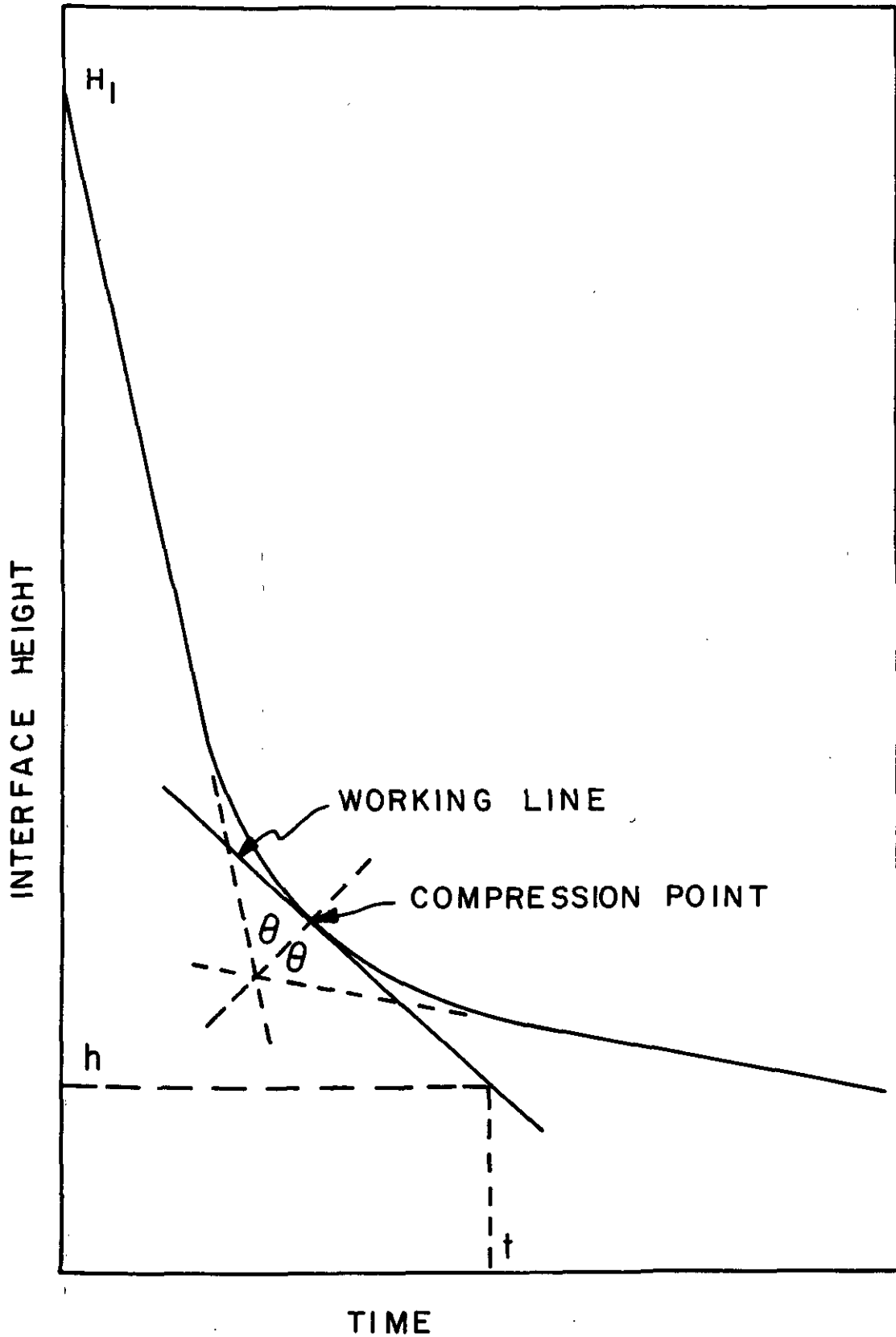
Figure AV-1. Laboratory Settling Curves.

Figure AV-2. Typical Sludge Thickening Curve.

a thickener solids loading at a given underflow concentration (C_u).

5) A desired thickener underflow concentration (C_u) in percent solids was selected.

6) Knowing the specific weight of the solids (SW_s) and supernatant (SW_ℓ) and the weight of solids (W_s), the volume of slurry (Vsl) associated with an assumed thickener underflow concentration (C_u) was computed according the the relationship:

$$Vsl = \frac{W_s}{SW_s} + \frac{W_\ell}{SW_\ell} \qquad (1)$$

where W_ℓ = weight of liquid in underflow

$$= \frac{W_s(100)}{C_u} - W_s \qquad (2)$$

The weight of solids (W_s) can be calculated from the initial sludge concentration (C_I) and the volume of sludge used. By drying a measured volume of sludge at 103°C and relating the weight of dried sludge solids to an equivalent weight of water, the specific gravity of the dry sludge was determined to be 1.785. The specific weight (SW_s) is then 111.38 lb/ft^3. The specific weight of liquid in the underflow (SW_ℓ) was assumed to be the same as water (62.4 lbs/ft^3).

7) The sludge interface height (h) associated with the computed volume of slurry (V_{sl}) was calculated and the time (t) for thickening was determined from the working line (see Figure AV-2).

8) Knowing t, C_I and H_I the predicted thickener loading (U) can be calculated from the relationship,

$$U = \frac{C_I H_I}{t}$$

9) Steps 5 through 8 were repeated for several thickener under-flow concentrations. The plotted data generated by this procedure resulted in a smooth curve relating thickener solids loading vs. underflow solids concentration for a given feed solids concentration. Laboratory thickening test results shown in Figure 10 were developed in this manner.

Centrifugation

The results of laboratory centrifuge tests are presented in the following letter from the Bird Machine Company.

BIRD MACHINE COMPANY, INC., SO. WALPOLE, MASS. 02071

PHONE: 617 668-0400   /   TELEX: 92 4428   /   CABLE: BIRDMACHIN SOWALPOLEMASS

BIRD

January 29, 1975

University of Massachusetts
Department of Civil Engineering
Amherst, MA   01002

Attention: Mr. C. James Martel

Subject: Sludge Sample #291
            BMC Lab Report #8168

Dear Mr. Martel:

I am enclosing a copy of the above referenced lab report
covering the results of the sludge sample as described in
your letter of December 17, 1974.

The preliminary spin tests are encouraging in that dewatered
cake products in the low 20% range were produced, and high
solids recovery (clear centrate) was realized with extremely
low polymer dosage. The lab work, therefore, indicates that
a sludge of this nature would be handled extremely satisfactory
in a production model machine, and I would predict cake products
in the 30% range and a possibility of accomplishing centrate
clarity without chemical aids.

Concerning the recalcining of the lime for reclamation, I
would appraise you of the South Lake Tahoe installation in
California. This project has received wide spread notoriety
as a tertiary treatment plant, and has been written up in
various publications. Specifically I would direct your attention
to the manual on "Advanced Waste Water Treatment" by Culp & Culp,
Van Nostrand Reinhold, Publishers. In addition, the publication
by the U.S. Government Printing Office entitled "Advanced Waste
Water Treatment as Provided at Lake Tahoe" would be of interest,
and this publication carries Research Series No. 17010ELQ-08/71.

Basically, the dewatering application at Tahoe consists of three
centrifuges, with Unit No. 1 handling the straight organic
sludge from which the cake product is incinerated for final
disposal. The second machine is used in the recalcining process
and functions in the following manner.

422 N. N.W. Hwy., PARK RIDGE, ILL. 60068   7 Dunwoody Park, ATLANTA, GA. 30341   6415 S.W. Canyon Court, PORTLAND, ORE. 97221   1354 Creekside Drive, WALNUT CREEK, CALIF. 94596

30 Galesi Drive, WAYNE, N.J. 07470   P O. Box 484, DUNBAR, W VA. 25064   2721 Mine & Mill Road, LAKELAND, FLA. 33603

BIRD MACHINE COMPANY, INC.

University of Massachusetts
Department of Civil Engineering
Amherst, MA
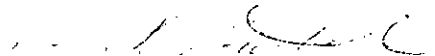Mr. C. James Martel
January 29, 1975

- 2 -

The lime slurry fed to the second unit is operated in a
"classifying" manner, wherein only the calcium carbonate
is precipitated and removed from the centrifuge, with the
centrate containing the other impurities such as metal
hydroxides, etc. In this manner, almost pure calcium carbonate
is recovered from the system prior to being sent to the
recalcining unit. The cake product from this machine is
normally in the 40% solids region.

In the event that you are considering such a program or
process, I would recommend that you utilize an additional
centrifuge to handle the centrate from the initial lime
slurry machine. In this manner, the second machine would
dewater the impurities to approximately 12-15% solids and
then process for further disposal either by landfill or
incineration.

Please review the attached data and if we can be of any
further assistance to you, do not hesitate to contact us
accordingly.

Very truly yours,

BIRD MACHINE COMPANY, INC.

A.S. Nisbet
Sales Engineer
Environmental Control Equipment

ASN:pjt/23

Enc.

APPENDIX VI

ESTIMATES OF LIME RECOVERY

Incinerated Sludge Production

Assuming a 60 percent volatile content of the sewage as calculated in Appendix IV and complete conversion of $CaCO_3$ to CaO the sludge (ash) composition after incineration would be:

Sludge Species	lbs/MG
Sewage solids	470
$Ca_5 OH(PO_4)_3$ precipitate	359
CaO	1401
$Mg(OH)_2$ precipitate	50
Total	2280

Estimated sludge weight reduction = 44 percent

Percent of quicklime (CaO) = 61 percent

Additional Lime Sludge Due to Recarbonation

If two stage recarbonation is added to the lime clarification process, substantial quantities of calcium carbonate could be precipitated out and recalcined for re-use. Assuming that the effluent can be discharged at a moderate hardness concentration of 100 mg/l as $CaCO_3$ (40 mg/l as Ca^{2+}) the estimated quantity of lime sludge recovered from recarbonation is calculated as follows:

Influent to first stage recarbonation	= 148 mg/l as Ca^{2+}
Effluent from first stage of recarbonation =	40 mg/l as Ca^{2+}
Ca^{2+} in sludge	= 108 mg/l as Ca^{2+}
or $CaCO_3$ precipitate	= 270 mg/l as $CaCO_3$
270 mg/l X 8.34 X 1 MGD	= 2252 lbs/MG

If this calcium carbonate sludge is incinerated along with the chemical clarification sludge, approximately 1260 lbs/MG of additional quicklime (CaO) will be recovered.