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THICKENING AND DEWATERING CHARACTERISTICS OF ACTIVATED SLUDGE

CONTAINING METAL-PRECIPITATED PHOSPHORUS

BY

LYLE WAYNE MERRITT, 1942-

A THESIS

Presented to the Faculty of the Graduate School of the

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In Partial Fulfillment of the Requirements for the Degree

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Approved by

Sohini G. Gmpspah (Advisor)   _J. Charles Jennett_

L. M. Nicholson

ABSTRACT

The purpose of this research study was to investigate methods for the disposal of activated sludge containing metal-precipitated phosphorus. To accomplish this objective, chemically-treated activated sludge or a mixture of the secondary sludge with primary sludge were thickened and dewatered by vacuum filtration and centrifugation. The putrescibility of the dewatered secondary sludge was also evaluated, and since anaerobic digestion is the usual method of sludge treatment, a digestion study was conducted.

Secondary sludge for these studies was produced in five 38-gpd (144-1/day) activated sludge pilot plants operated at the Rolla Southeast Treatment Plant. Ferric chloride and alum were added directly to the aeration chambers of four of the plants, while the fifth served as a control; and the effectiveness of Fe^{+++} and Al^{+++} in removing phosphorus from wastewater was evaluated.

The addition of chemical precipitants to the activated sludge aeration chamber had a beneficial effect on the treatability of the sludge from the standpoint of vacuum filtration, but did not significantly alter its thickening and centrifuging characteristics; Al^{+++} had a greater effect than Fe^{+++} on all the sludge characteristics studied. The putrefactive characteristics of the dewatered metal-precipitated sludges were similar to those of a control sludge. Very little difference in gas production and composition was experienced during the anaerobic digestion of the chemically-treated sludges and the control sludge. Addition of either Al^{+++} or Fe^{+++} to the activated sludge system effectively reduced the concentration of phosphorus released in the effluent; however, greater removals were achieved with Al^{+++} than with Fe^{+++} when both were applied at equal M/P ratios.

ACKNOWLEDGMENT

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The author also wishes to acknowledge the Office of the City Engineer, Rolla, Missouri, for the outstanding cooperation which made this study easier, and the Department of Civil Engineering, University of Missouri-Rolla, for providing the facilities and equipment necessary for this investigation.

The author further wishes to acknowledge the patience and understanding shown by his wonderful family, without which this research could not have been possible.

To the U.S. Army Corps of Engineers, the author would like to express his gratitude for giving him the opportunity to attend civil schooling at the University of Missouri-Rolla.

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I. INTRODUCTION

Control of the discharge of excessive nutrients to surface waters, which is essential in preventing the accelerated eutrophication of lakes and other water bodies, has been the goal of sanitary engineers for the past several years. Phosphorus removal in wastewater treatment is now accepted as the most practical approach to the solution of this problem (1,2,3,4) and appears to be the direction in which enforcement agencies will move. This is exemplified by a recent action taken by the Water Resources Commission of the State of Michigan in response to demands made during the Lake Michigan Enforcement Conference held in January 1968 (5,6); the commission has ordered the removal of at least 80 percent of the phosphorus contained in wastewaters discharged to Lake Michigan (7). Similar action was expected to take place in the states of Wisconsin, Illinois, and Indiana (5).

There are a number of different methods for the removal of phosphorus from wastewaters and they may be grouped into two categories: biological uptake and chemical or physicochemical treatment. Phosphorus removal by algal uptake has been reported to range from as low as 19 percent to as high as 90 percent; however, a high pH was associated with the better removals and this would indicate that chemical precipitation was at least partially responsible for the values obtained (8,9,10). The removal of phosphorus by uptake in activated sludge is relatively ineffective and, in most cases, ranges between 20 and 30 percent (11). Values have been reported as high as 80 to 90 percent (12), however, these removals are extremely rare and, for the most part, chemical methods must be employed. Precipitation appears to be the most practical of the chemical methods to use.

Other physicochemical methods include electrodialysis, electrochemical treatment, sorption, and ion exchange (13). Many studies have been performed on phosphorus removal by chemical precipitation and they have fairly well shown that removals of 80 percent or greater can be achieved at costs that are not prohibitive (7,14,15,16,17,18,19). The chemicals most often employed are aluminum sulfate, sodium aluminate, calcium hydroxide, ferric chloride, and ferric sulfate and may be added before, during, or after biological treatment thus offering flexibility in operation. Calcium hydroxide is most efficiently utilized when added in primary treatment (14), while aluminum and iron salts are best used during or after biological treatment (16,17,18,19). When the chemicals are added to the aeration chamber of the activated sludge process or the dosing siphon of the trickling filter system, little more is required than the addition of a chemical feed system to the sewage treatment plant. There has been much information written on the use of Al^{+++} for precipitation of phosphorus, however, information on the use of Fe^{+++} is limited.

Chemical precipitation in the activated sludge aeration chamber results in the formation of a secondary sludge whose characteristics are different from those of the sludge produced by the conventional process. The quantity of sludge produced by chemical precipitation is increased greatly on a dry weight basis (20). This could be an important consideration as sludge handling and disposal amount to a considerable portion of the capital and operating expenses in sewage treatment operations. A second variance in the sludge character is the decrease in volatile content to approximately 50 percent of the total solids (20,21). Depending on the putrescibility of the sludge,

this fact would indicate that direct disposal of the dewatered sludge might be justified. A few investigators have reported on their observations of the sludge filterability and have stated that it dewatered easily, although no specific values or quantitative data were given (16,22). The settleability of the sludge is also improved greatly, as might be expected, with the addition of the metal precipitants (7,17,18,19).

An undesirable characteristic of any sludge, whether biological or biochemical, is that it must be disposed of. Studies have indicated that chemically-precipitated sludge produced with Al^{+++} can be successfully digested anaerobically. Gas production was not altered and the metal-phosphorus complex was not decomposed which would have allowed release of the metal or phosphorus in the digester supernatant (17,18,20,23). There are conflicting reports, however, pertaining to anaerobic digestion of Fe^{+++}-precipitated sludges. Two such reports state that trivalent iron would be reduced to its divalent state thereby allowing the iron and phosphorus to solubilize and be released in the supernatant (24,25). In contrast, at least one existing sewage treatment plant has experimented with the use of Fe^{+++} to precipitate phosphorus and experienced no such difficulty (7). In any event, anaerobic digestion is often a troublesome and costly operation requiring close and continuous control. Because of the changed characteristics of the biochemical sludge, a more efficient method of disposal might be feasible, however, specific information on the characteristics of the sludge is needed before an alternate disposal scheme can be developed.

The purpose of this research study was to investigate alternate methods for the disposal of activated sludge containing metal-precipitated phosphorus; emphasis was placed on dewatering by thickening, filtration and centrifugation, and on the putrefactive characteristics of the dewatered sludge. The chemically-treated sludge was not available and was produced in a pilot plant activated sludge system. An excellent opportunity was, therefore, afforded to additionally study the precipitation of phosphorus in the activated sludge aeration chamber. Use of ferric chloride and alum as the precipitants enabled the development of data pertaining to the effect of Fe^{+++}, thus adding to the limited information available in the literature, and the comparative evaluation of the effect of Al^{+++}, previously studied by Max (20) in the summer of 1969, at the winter season of the year. Since anaerobic digestion fits in the normal scheme of sludge disposal, anaerobic digestion studies were also conducted.

Five 38-gpd (144-1/day) continuous flow activated sludge pilot plant units were operated at the Rolla Southeast Sewage Treatment Plant and were fed settled domestic sewage. The sludge from these units, either alone or combined with an appropriate amount of primary sludge, was employed in the sludge disposal studies consisting of thickening with an especially designed and constructed multi-unit thickener rotating at 4 to 5 rph; vacuum filtration using a Buchner funnel; centrifugation with an International model UV centrifuge; and putrescibility in a closed gas collection system. The combined primary and secondary sludge was also used as feed for five 2-1 anaerobic digesters. The main parameters of the activated sludge study were influent and effluent total phosphorus and chemical oxygen demand,

metal to phosphorus ratio, and mixed liquor suspended and volatile suspended solids; those of the sludge disposal studies were solids concentration (thickening), specific resistance and filtrate chemical oxygen demand (filtration), cake solids concentration, percent solids capture and centrate chemical oxygen demand (centrifugation), and gas production and composition (putrescibility); and those of the digestion study were volatile acids, gas production and composition.

II. LITERATURE REVIEW

The purpose of this review was to examine the available litera-
ture on the subject of the disposal of activated sludge containing
metal-precipitated phosphorus, with emphasis on the thickening, de-
watering, and putrefactive characteristics of the sludge. Unfortu-
nately, the material reported on this subject was limited and, for
the most part, consisted only of personal observations made by dif-
ferent investigators while studying phosphorus removal. The evalu-
ation of the effectiveness of Al^{+++} and Fe^{+++} added directly to the
aeration chamber of the activated sludge process to precipitate and
remove phosphorus, and the effect of the precipitated metals on the
anaerobic digestion of the sludge produced were secondary objectives
of this thesis research. Since the available literature in these
areas had already been reviewed and summarized in two recent theses
by Max (20) and Vedder (21) at the University of Missouri-Rolla, a
review on these subjects is not presented in this section. However,
use will be made of these publications in later chapters of this
thesis in establishing experimental procedures and evaluating re-
search findings.

Barth, et al. (18) operated a 185-gpd (700-1/day) continuous
flow activated sludge plant employing three stages in series for
nitrogen and phosphorus removal. The first stage was a high-rate
activated sludge unit where sodium aluminate was added for phos-
phorus removal at an aluminum to phosphorus molar ratio (Al/P) of
1. The second and third stages were nitrification and anaerobic
denitrification units, respectively. Sodium aluminate was also
added to the third stage at an Al/P ratio of 0.2 in order to remove

any residual phosphorus present. The overall Al/P ratio actually averaged 1.5 throughout the study. Barth and associates reported that the sludge density index, a measure of sludge settleability, was increased from 0.44 to 1.12 by the weighting action of the aluminum.

Improved settling characteristics of the metal-precipitated sludge were also reported by Barth and Ettinger (17). They found that the mixed sludge produced by Al^{+++} or Fe^{+++} fed directly to the aeration chamber had better settling characteristics than either the biofloc or the metal hydroxides alone. The sludge was produced in a 100-gpd (378-l/day) continuous flow activated sludge plant which was fed raw domestic sewage with no primary clarification. One hundred percent of the settled sludge was returned to the aeration chamber and sludge wasting was between 3 and 5 percent of the influent flow. The secondary sludge was digested anaerobically and the digester supernatant was not recycled.

Eberhardt and Nesbitt (16) conducted studies on the removal of phosphorus with aluminum sulfate using a 60-l/day bench-scale activated sludge unit fed either a synthetic feed or settled domestic sewage. Aluminum to phosphorus ratios ranging from 1.87 to 2.44 were employed and the chemical was introduced either in the aeration chamber or in a mixing unit placed between the aeration chamber and the final clarifier. Filtration of the sludge from the aeration chamber was performed on a regular basis and the sludge was found to dewater easily; however, the method used in the filtration studies and the criteria employed in determining the sludge filterability were not discussed. Eberhardt and Nesbitt (16) also referred to studies conducted by Thomas (22) in which phosphorus precipitation with Fe^{+++} produced an easily filterable sludge.

Vedder (21) conducted studies on the removal of phosphorus by chemical precipitation using three laboratory-scale continuous flow activated sludge units with an average flow of 375 ml/hr (9 l/day). Settled domestic sewage was used as the feed and alum and sodium aluminate were added directly to the aeration chamber at Al/P ratios ranging from 0.8 to 1.75 and 0.45 to 1.9, respectively. The volatile content of the mixed liquor suspended solids in the units receiving chemicals decreased to approximately 50 percent, while it remained nearly 80 percent in the control unit. The sludge volume index, which is a measure of the settleability of the sludge,* varied from approximately 60 to well over 100; this variation was attributed by Vedder to changes in the strength of the sewage feed to the units, with the higher index values reflecting an increased food to micro-organism ratio.

A decrease in the volatile content of the chemically-treated sludge was also reported by Max (20) who investigated the fate of aluminum-precipitated phosphorus in activated sludge and anaerobic digestion. The addition of alum and sodium aluminate to the aeration chambers of four 38-gpd (144-l/day) activated sludge pilot plants pro- duced a sludge with better settling characteristics than those of the control and resulted in an increased amount of total mixed liquor sus- pended and volatile suspended solids; however, the volatile fraction of the sludge in the chemically-fed units decreased from 80 to about 50 percent of the total solids. When chemically-treated sludge mixed with primary sludge was anaerobically digested, little reduction in

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*Sludge Volume Index = 100/Sludge Density Index.

the volatile solids content occurred. Noting that the cost of treating the additional sludge produced in the chemical precipitation of phosphorus could be a major consideration in the application of this method of nutrient removal and that the volatile matter reduction in anaerobic digestion was low, Max (20) suggested that digestion of the chemically-treated activated sludge might not be necessary and recommended studies to determine the dewatering and offensive characteristics of the raw sludge.

III. DESCRIPTION OF THE STUDY

A. EQUIPMENT

1. Activated Sludge Pilot Plants

Five 38-gpd (144-1/day) continuous flow activated sludge pilot plants were operated in order to produce metal-precipitated sludge for use in the sludge disposal studies. A detailed drawing of one of the units, originally designed and constructed by Max (20), is presented in Figure 1. Each plant had a total capacity of 10.93 gal (41.4 1) separated by means of a baffle into an 8.67-gal (32.8-1) aeration chamber and a 2.26-gal (8.6-1) final clarification chamber. The position of this baffle could be adjusted as needed to prevent a buildup of solids in the clarification chamber. A trough with a V notch weir extending the width of the clarification chamber served as the effluent collection device. Air was supplied to the units by a 35-1/min vacuum-pressure pump* through a perforated plastic tubing distribution manifold located near the bottom of one side of the aeration chamber.

The activated sludge plants were operated at the Rolla Southeast (trickling filter) Treatment Plant and were fed settled domestic sewage. The waste was drawn by gravity from the dosing siphon through a 1/2-in. (1.27-cm) ID, 50-ft (15.3-m) long garden hose equipped at the inlet end with a screening structure consisting of a wooden frame wrapped in galvanized-metal screen with 1/8-in. (0.32-cm) openings. Screening was necessary to keep the larger solids from plugging the influent lines to the units. The sewage entered a distribution

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*Model PV-35, a product of the Precision Scientific Co., Chicago, Illinois.
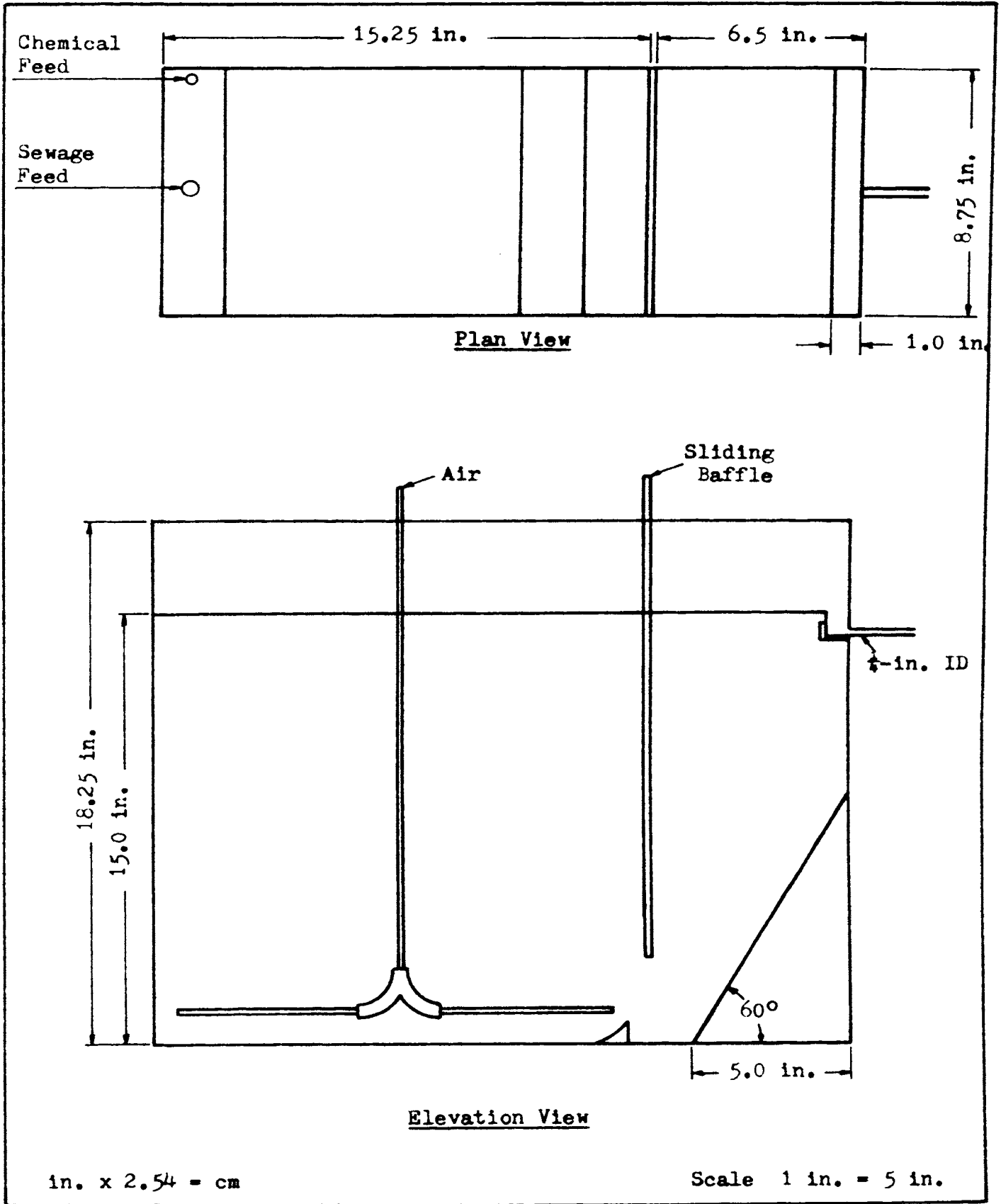
Figure 1. ACTIVATED SLUDGE PILOT PLANT UNIT [After Max (20)]

reservoir constructed of a 5-gal (18.9-1) metal can which had its interior surface coated with epoxy paint; it was then fed by gravity to each of the units through 1/4-in. (0.64-cm) ID flexible tubing. A 6-in. (15.2-cm) long weir cut along the side of the distribution reservoir provided an overflow and maintained, as near as possible, a constant hydraulic head in the feed lines to the units. The waste overflow entered a collection device and flowed through garden hose to the trickling filter. Significant sedimentation occurred in the distribution reservoir at the beginning of the study, and it was found necessary to provide mechanical mixing of the sewage in order to maintain the solids in suspension. A mixing Plexiglas propeller was connected to a vertical shaft supported at the top and bottom of the distribution reservoir, and was rotated through a pulley-and-belt system by an electric motor mounted at the side of the reservoir. The flow rate to the units was controlled by adjusting the discharge elevation of the feed lines.

Chemicals were supplied to four of the units by use of a Dekastaltic pump.* The fifth unit received no chemicals and served as a control throughout the study. Two 2.5-gal (9.45-1) bottles, one containing aluminum sulfate and the other ferric chloride, served as chemical reservoirs.

The study was conducted in the winter months which necessitated enclosing the activated sludge units and supporting equipment in a protective structure. A 1360-w thermostatically-controlled electric heater was placed within the structure to prevent freezing of the

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*A product of Buchler Instruments, Inc., Fort Lee, New Jersey.

chemical reservoirs and feed lines. The overall arrangement of the activated sludge pilot plants and the waste and chemical feed systems is shown in Figure 2.

2. Anaerobic Digesters

Anaerobic digestion of the sludges was conducted using five 1.0-gal (3.78-1) capacity anaerobic jars. The gas produced in digestion was directed through flexible tubing to 1-gal (3.78-1) graduated glass bottles filled with Rolla tap water where it displaced an equal amount of water which, in turn, flowed to a 5-gal (18.9-1) reservoir. As the water in the glass bottles was displaced and the fluid level dropped, a slight pressure resulted in the system. It was necessary, then, before taking gas volume measurements, to lower the ends of the water discharge lines and allow the pressure to equalize to that of atmospheric. The digesters were maintained at a constant temperature of 35°C in a walk-in incubator.* The arrangement of the anaerobic digesters and gas collection equipment is shown in Figure 3.

3. Thickening and Dewatering Equipment

a. Sludge Thickener

A five-unit thickener (Figure 4) was designed and constructed for use in conducting the thickening studies. The unit was powered by a 110-v electric motor with a 4-rpm drive shaft and was made of 3/4-in. (1.9-cm) plywood. A system of pulleys and belts was employed to reduce the turning speed of the mixing paddles to between 4 and 5 rph. The

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*Model 704, a product of Lab-Line Instruments, Inc., Melrose Park, Illinois.

Figure 2. ACTIVATED SLUDGE PILOT PLANTS
AND WASTE AND CHEMICAL FEED SYSTEMS
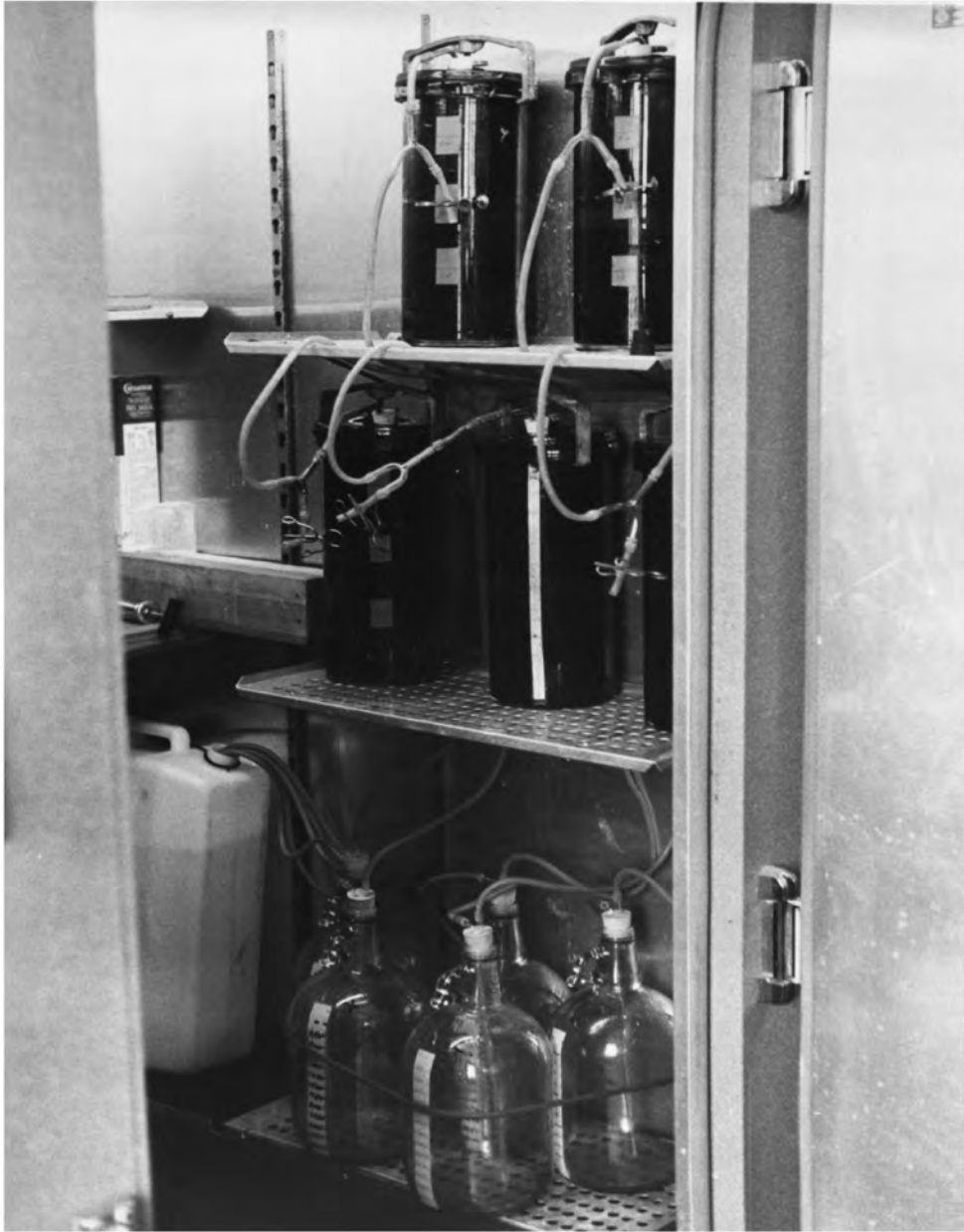
Figure 3. ANAEROBIC DIGESTERS AND GAS COLLECTION SYSTEM

Figure 4. THICKENING AND DEWATERING EQUIPMENT

mixing paddles were constructed of 1 x 3 x 3/16-in. (2.54 x 7.62 x 0.48-cm) Plexiglas with alternating 1/4-in. (0.64-cm) teeth and notches cut along the bottom edge. In addition, four 1 1/2 x 1/16-in. (3.81 x 0.16-cm) diam brass rods were inserted vertically in the top and bottom of the Plexiglas in order to effect mixing throughout the entire depth of the sludge. The paddles were suspended and rotated by drive shafts consisting of 3/16-in. (0.48-cm) diam brass rods which could be lifted vertically to withdraw the paddles from the sludge. Five paddles were employed so that thickening tests could be run concurrently on sludge from each of the five activated sludge units.

b. Vacuum Filtration System

The vacuum filtration system (Figure 4) was similar to that recommended by Eckenfelder (26, p.241) and Jones (27). It consisted of a 9.0-cm diam Buchner funnel connected by a glass tube equipped with a stopcock and rubber stoppers at both ends to a 100-ml graduated cylinder. The vacuum line, with branches leading to a vacuum gage and a vacuum control valve, was inserted in the rubber stopper at the top of the graduated cylinder. Vacuum was created by an aspirator connected to a water tap. To insure equal drainage over the entire area of the Buchner funnel, a piece of 16-mesh window screen was cut to fit over the bottom of the funnel, and the filter paper was then placed on top of the screen.

c. Centrifuge

An International model UV Centrifuge* (Figure 4) was used. It was equipped with a centrifuge head capable of handling at each

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*A product of the International Equipment Co., Needham Heights, Massachusetts.

spinning either four 250-ml centrifuge bottles at a maximum speed of 2000 rpm or sixteen 37-ml centrifuge tubes at a maximum speed of 1250 rpm, a timer, and a brake.

d. Putrefaction Units

Each putrefaction unit consisted of a closed system in which the gas produced by a sample of sludge could be measured and collected. A 500-ml Erlenmeyer flask served as the sample container and was connected through flexible tubing to a 250-ml Erlenmeyer flask filled with an acidic solution.* The displaced solution was routed through flexible tubing to a 100-ml graduated cylinder where it was measured. The arrangement of the putrefaction units is shown in Figure 5.

B. MATERIALS

1. Seed and Waste Feed for Activated Sludge Pilot Plants

Seed for the activated sludge plants was produced in laboratory fill-and-draw units. A 5-gal (18.9-1) Pyrex carboy and one of the pilot plant units with the sliding baffle removed were operated in the laboratory for approximately 30 days until a sufficient biological mass was produced to start the five field pilot plants. The fill-and-draw units were fed daily during the first part of this period and twice daily during the latter part with settled domestic sewage from the Rolla Southeast Treatment Plant. Ten gal (37.8 1) of sewage was transported to the laboratory on alternate days for this purpose and was stored at 10°C.

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*This solution contained 15 percent by volume of sulfuric acid in water saturated with sodium chloride.

Figure 5. PUTREFACTION UNITS

The feed for the activated sludge units consisted solely of settled domestic sewage obtained from the dosing siphon of the Rolla plant.

2. Seed and Sludge Feed for Anaerobic Digesters

Seed for the anaerobic digestion units was obtained from a sample cock located on the digester heat exchange unit at the Rolla Southeast Treatment Plant and consisted of 100 percent digester sludge. Three l of sludge was initially placed in each laboratory digestion unit, however, as gas was produced it caused the sludge to rise and plug the gas line at the top of each digester. Consequently, 1 l of sludge was withdrawn and the units operated with a 2-l capacity throughout the remainder of the study.

The feed for the anaerobic digesters consisted of 50 percent secondary sludge obtained from the activated sludge pilot plants and 50 percent primary sludge obtained from the primary clarifier at the Rolla plant. Secondary sludge was collected once a week in five 2.5-gal (9.45-l) plastic containers where it was allowed to consolidate overnight; it was then transferred to five 1000-ml beakers and stored in a refrigerator at 10°C. Primary sludge was also collected once a week; it was pumped from the bottom of the primary clarifier into the skim well located adjacent to the clarifier where it was removed by a bucket and placed in a 5-gal (18.9-l) plastic carboy. The sludge was then transported to the laboratory where it was allowed to consolidate; it was then transferred to a 1-gal (3.78-l) glass jar and stored in the refrigerator at 10°C. To insure that the sludge fed to the digesters did not contain any oxygen which would have been toxic to the anaerobic bacteria, appropriate volumes of sludge were

removed from the refrigerator and kept at room temperature for at least 8 hr prior to feeding.

3. Sludge for Thickening and Dewatering Studies

Chemically-treated activated sludges produced in the four pilot plant units and conventional activated sludge produced in the fifth, either alone or combined with primary sludge obtained from the Rolla Southeast Treatment Plant, were used for the thickening and dewatering studies. The activated sludges were obtained by saving the mixed liquor from the corresponding aeration chambers which would have normally been wasted in order to maintain the mixed liquor volatile suspended solids (MLVSS) at the 2000 mg/l level. The mixed liquors were collected in five 2.5-gal (9.45-l) containers and were transported to the laboratory. The sludge in each container was allowed to consolidate overnight; the supernatant was then decanted and wasted and the consolidated sludge was transferred to individual 1-gal (3.78-l) containers and stored in the refrigerator at 10°C until the tests were run. When primary sludge was used in combination with secondary sludge, it was obtained from the same supply that was used to feed the anaerobic digesters.

4. Chemical Precipitants

The chemicals used to precipitate phosphorus from the wastewater were reagent grade aluminum sulfate (alum) $[Al_2(SO_4)_3 \cdot 18H_2O]$ and ferric chloride $[FeCl_3 \cdot 6H_2O]$.

C. EXPERIMENTAL DETERMINATIONS

1. Total Phosphorus

Total phosphorus (rather than orthophosphate) was used as a parameter in this study because most of the complex organic and

inorganic forms of phosphorus can be broken down biologically to orthophosphate and thereby become available as nutrients for aquatic growths (28); consequently, all forms of phosphorus are important from the standpoint of nutrient control. In addition, use of total phosphorus facilitated the direct comparison of the findings of this study with the results obtained by Max (20) and Vedder (21).

Since a procedure for the determination of phosphorus in wastewater was not presented in Standard Methods (29), a method developed by Murphy and Riley (30) and modified by Jankovic, et al. (31) was used in this study. This method involved the formation of an ammonium phosphomolybdate complex under acidic conditions and subsequent reduction of this complex with ascorbic acid to produce a blue-colored solution. Measurement of the color intensity on a spectrophotometer and comparison of the percent transmittance obtained with a calibration curve prepared from known standards enabled the determination of the total phosphorus present in the sample.

The detailed procedure first involved the digestion of the sample using potassium persulfate as the oxidant. Two ml of 5N sulfuric acid and 1.0 g of potassium persulfate were added to a 300 ml COD* flask containing 10 ml of sample and a few boiling beads. The mixture was then diluted with 30 ml deionized water and digested on a COD apparatus for 30 min. This digestion period, which was longer than the 15 min prescribed by Jankovic, et al. (31), was recommended by Max (20) in order to allow maximum release of the complex organic phosphorus

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*Chemical oxygen demand.

present in the sample. After digestion, the sample was cooled and diluted to an appropriate volume. A Nessler tube containing 8 ml mixed reagent[*] was then filled to the 50-ml mark with the diluted sample and 10 min were allowed for color development. Color intensity was measured on a spectrophotometer[**] at 710 mµ[#] wavelength. A blank with deionized water in lieu of wastewater was prepared in the same manner and used to adjust the spectrophotometer to 100 percent transmittance.

2. Chemical Oxygen Demand

Chemical oxygen demand (COD) was used to determine the strength of the sewage feed flowing to the activated sludge pilot plants and as a measure of the efficiency of these units. The procedure employed was as set forth in Standard Methods (29, p.510). Influent COD was determined by mixing 20 ml of sample, 10 ml of 0.25N potassium dichromate solution, 30 ml of concentrated sulfuric acid,[##] and 0.4 g of mercuric sulfate in a 300-ml COD flask and digesting on a COD apparatus for 2 hr. The mixture was then diluted to approximately 140 ml, allowed to cool to room temperature, and titrated with a 0.10N ferrous ammonium sulfate solution using ferroin as an indicator. Effluent COD

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[*]Prepared by mixing 1.32 g of ascorbic acid dissolved in 75 ml of deionized water with 125 ml of 5N sulfuric acid and 37.5 ml of an ammonium molybdate solution (40 g/l), and then adding 12.5 ml of potassium antimonyl tartrate solution (0.2743 g/100-ml). This mixture was prepared daily.

[**]Hitachi Perkin-Elmer, Model 139 UV-VIS Spectrophotometer, a product of the Coleman Instrument Corporation, Maywood, Illinois.

[#]Although Jankovic, et al. (31) had recommended a wavelength of 882 mµ, the available spectrophotometer was not stable at that wavelength; however, a second peak had been reported by Murphy and Riley (30) at about 725 mµ and found by Max (20) to occur at 710 mµ for this particular spectrophotometer.

[##]This acid contained 22 g silver sulfate per 9-lb (4.09-kg) bottle.

values were determined in the same manner, except that a 0.025N potassium dichromate solution and a 0.01N ferrous ammonium sulfate solution were used. This allowed a more accurate determination of the low effluent COD values.

3. Total and Volatile Suspended Solids

Total and volatile suspended solids were determined in the mixed liquor of the activated sludge units in order to provide a measure of the microbial population in the aeration chambers; in the consolidated secondary and primary sludges used as feed for the anerobic digesters in order to compute the organic loading rates applied to these units; and in the settled sewage feed for the activated sludge plants in order to enable the determination of sludge age. The procedure employed in determining total and volatile suspended solids was that set forth in Standard Methods (29, p.424) with the exception that glass fiber filters were used in lieu of asbestos mats. An appropriate volume of sample* was vacuum-filtered through a 25-ml fired and preweighed Gooch crucible. The crucible and solids were dried for 1 hr at 103°C in an oven; they were then removed from the oven, cooled to room temperature in a desiccator, and weighed on an analytical balance to determine the total solids. The crucible and total solids were then fired in a muffle furnace at 600°C for 15 min, cooled in a desiccator, and reweighed to determine volatile solids.

Total suspended solids were also measured in the effluents from the activated sludge pilot plants in order to evaluate the efficiency of these units in removing suspended matter and detect any release of microbial floc. Effluent solids were determined by filtering from 50

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*Twenty ml of mixed liquor, 5 ml of consolidated sludge, and 25 or 50 ml of settled sewage were used.

to 150 ml of sample through a preweighed membrane filter;* the filter and solids were dried at 103°C for 30 min, cooled, and weighed on an analytical balance.

4. Total Solids

Total solids (TS) were one of the main parameters used in the thickening studies, and were determined using the procedure set forth in Standard Methods (29, p.534). An appropriate volume of sample was placed in a tared and preweighed evaporating dish and evaporated to near dryness on a water bath. The sample and dish were then placed in an oven at 103°C, dried for at least 1 hr, allowed to cool to room temperature in a desiccator, and reweighed. The volatile fraction of the TS was determined by firing the dish at 600°C for 1 hr, cooling to room temperature, and reweighing.

5. Sludge Volume Index

The sludge volume index (SVI) provided a measure of the settle-ability of the activated sludge, and was determined on the basis of the volume of sludge which had settled within 30 min in a 1-1 graduated cylinder and the MLSS concentration. The SVI was computed using the following formula (29, p.542):

$$SVI = \frac{\text{volume of sludge settled in 30 min, ml/l}}{\text{avg MLSS, mg/l}} \times 1000$$

6. Sludge Age

Sludge age (SA) was used in conjunction with the SVI as a control parameter in the operation of the activated sludge pilot plants. It

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*A Millipore type HA, 0.45-μ pore size filter, product of the Millipore Corporation, Bedford, Massachusetts, was used; the filter was placed in an aluminum weighing dish for drying and weighing purposes.

was determined as the ratio of the weight of sludge in the aeration chamber to the weight of suspended solids introduced daily using the following formula (32, p.550):

$$SA = \left[\frac{(\text{volume of aerator, mil gal}) \ (\text{avg MLSS or MLVSS,}^* \ \text{mg/l})}{(\text{sewage flow, mgd}) \ (\text{avg SS or VSS}^* \ \text{in influent waste, mg/l})}\right] \text{days}$$

A low SA (<3 days), in conjunction with a high SVI (>200), could be an indication of insufficient detention time in the aeration chamber, while a high SA (>6 days), in conjunction with a low SVI (<100), could result in nitrification or a cloudy effluent (32, p.550, 33, p.258).

7. Volatile Acids

The volatile acids concentration was used as a control parameter in the operation of the anaerobic digesters. A sudden or steady increase in volatile acids would be an indication of impending trouble and a "sour" digester could be the result. The procedure outlined in Standard Methods (29, p.538) was used in measuring volatile acids. This method consisted of passing an acidified aqueous sample containing organic fatty acids through a column of inert granular material; the acids were adsorbed on the column and then extracted with an organic solvent. Silicic acid was used as the granular material in the column and a n-butanol-chloroform mixture as the organic solvent. The procedure first involved extracting a sample of supernatant, usually 25 ml, from a sample of digester sludge by centrifugation. The supernatant sample was then acidified with 10N sulfuric acid to the thymol blue end point (pH = 1.2 to 2.8); however, because of the dark, almost black, color of the sample, which made indication of the color change

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*MLSS and SS were used with the control unit; MLVSS and VSS were used with the chemically-treated units.

impossible, a pH meter was used to determine the end point. Five ml of the acidified sample was then placed as evenly as possible over the surface of a 25-ml Gooch crucible filled with 10 g of 100-mesh silicic acid which had been previously slurried to remove the fines and dried in an oven at 103°C. The sample was drawn into the silicic acid column by vacuum and 50 ml of the solvent mixture* was immediately poured over the column. The vacuum was discontinued as soon as the last of the solvent entered the column. The solvent mixture containing the organic acids was then titrated in a carbon dioxide-free atmosphere** with 0.002N sodium hydroxide[#] using phenolphthalein as the indicator. It should be pointed out that Standard Methods (29, p.538) recommended use of a 0.02N sodium hydroxide solution, however, due to the low volatile acids content of the samples, less than 1 ml of this strength solution would be required to reach the end point. To increase the accuracy of the determination, the lower normality was used.

8. Volume and Composition of Digester Gas

The volume and composition of the gas produced by the anaerobic digesters served as a means of determining the efficiency of these units and evaluating the effects of the aluminum and iron contained in the feed sludges. The volume of gas produced was determined by

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*Prepared by mixing 300 ml of chloroform, 100 ml of n-butanol, and 80 ml of 0.5N sulfuric acid in a separatory funnel and drawing off the organic layer.

**This was accomplished by directing a stream of air, which had passed through a column of ascarite, into the titrating vessel.

[#]Prepared in absolute methanol from a concentrated sodium hydroxide stock solution in water.

measuring the amount of water displaced in the gas collection bottles. The composition of the gas was determined by passing a sample through a gas partitioner* equipped with a DEHS** and a molecular sieve# column in series. The sample was swept through the columns by a continuous flow of helium gas at a flow rate of 40 ml/min. The components of the gas emerged from the columns at different times and were sensed by a detector which sent an electrical signal to a recorder.## The concentration of the component gases was then determined by comparing the peak heights obtained to peak heights produced by calibration gases of known composition. Gas samples were collected using 10-ml syringes which were inserted through rubber stoppers located at the top of the digestion units. The gas partitioner and recorder are shown in Figure 6. (Also shown in this figure is a Beckman flat-bed 10-in. recorder which was not used.)

9. pH Value

The pH of the digester supernatant was used in conjunction with volatile acids as a control parameter in the operation of the anaerobic digesters; a low pH could be inhibitory to the methane-forming bacteria resulting in a "sour" digester. Also, because the solubility of the metal-phosphorus complexes could be affected by pH, measurements were performed periodically on the mixed liquor contained in the activated

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*Fisher Hamilton Model 29, a product of Fisher Scientific, Pittsburg, Pennsylvania.

**A 6-ft (1.83-m) long by 1/4-in. (0.64-cm) diam aluminum column packed with di-2-ethylhexylsebacate on 60-80-mesh chromosorb P.

#A 6.5-ft (1.98-m) long by 3/16-in. (0.48-cm) diam aluminum column packed with 40-60-mesh molecular sieve 13X.

##Speedomax W Recorder, a product of the Leeds & Northrup Company, Philadelphia, Pennsylvania.
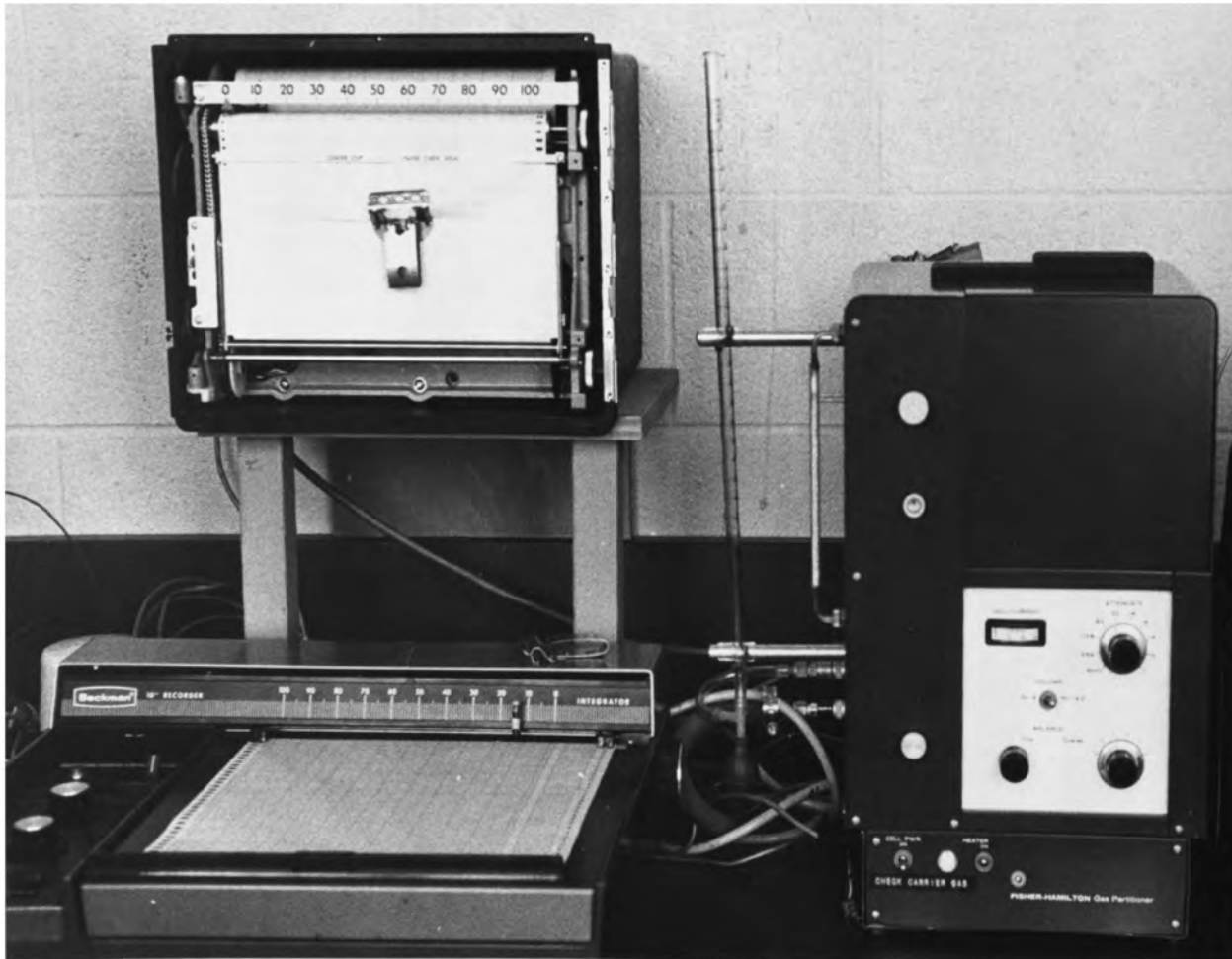
Figure 6. GAS PARTITIONER AND RECORDER

sludge units. All pH determinations were performed using a Zeromatic pH meter.*

D. EXPERIMENTAL PROCEDURES

1. Activated Sludge Study

All five activated sludge pilot plants were started with seed sludge produced in laboratory fill-and-draw units. The plants were operated for approximately 15 days without the addition of chemicals in order to create steady-state conditions, establish daily service procedures, and make necessary modifications and adjustments in the system. After this 15-day period, chemicals were added to four of the five units, while the fifth unit served as a control. The plants were serviced twice daily, once at around 9:00 AM and again at around 4:00 PM. The following procedure was employed when servicing the units:

a. Influent and effluent samples were collected for total phosphorus, COD, and solids determinations. [Analyses were performed on composite samples collected over an appropriate number of days. Phosphorus determinations were performed on 2-day composites for the first 25 days, 3-day composites for the next 48 days, and 4-day composites thereafter; COD determinations were performed on 4-day composites throughout the entire study; and influent SS and VSS and effluent SS were measured on 4-day composites during the latter-half of the study. Composite samples were stored in a refrigerator at 5°C until used.]

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*A product of Beckman Instruments, Inc., Fullerton, California.

b. Sewage feed lines were checked and cleaned as needed. Sludge accumu-
    lated on the walls of the aeration chamber above the mixed liquor
    was scraped back into the liquor.

c. Sewage flow rates were checked on alternating days and adjusted if
    required. Aeration rates were also adjusted when necessary.

d. Mixed liquor samples for MLSS and MLVSS determinations were col-
    lected in the morning on alternating days for the first 38 days
    and on every third day thereafter. Following the solids de-
    termination, an appropriate volume of mixed liquor was removed
    from each plant on the corresponding afternoons in order to main-
    tain the MLVSS level at 2000 mg/l; the excess mixed liquor was
    either used to provide sludge for the anaerobic digesters and/or
    sludge disposal studies, or was wasted to the adjacent trickling
    filter bed.

e. Chemical reservoirs were refilled with alum and ferric chloride
    solutions of an appropriate strength every fourth day.

2. Anaerobic Digestion Study

The anaerobic digesters were seeded with 100 percent digester
sludge obtained from the Rolla Southeast Treatment Plant. Feeding was
started 2 days later and during the first 26 days of operation, all
five units were fed a combination of 50 percent primary sludge and
50 percent secondary sludge obtained from the control activated sludge
pilot plant. Chemical sludge was not fed to the digesters during this
initial period in order to allow the volatile content of the activated
sludges to reach equilibrium, allow the digesters to undergo an accli-
mation period, and accumulate data for a gas-production base line.
From the 27th day to the end of the study, the digestion units were

fed a combination of 50 percent primary sludge and 50 percent secondary sludge from the corresponding activated sludge pilot plant units. The digesters were serviced daily and their contents shaken three times daily to simulate high-rate digestion. The following procedure was employed when servicing the units:

a. The discharge ends of the water lines leading from the gas measurement bottles to the reservoir were lowered and the gas pressure was allowed to equalize to that of atmospheric.

b. The gas lines were disconnected and the digesters removed from the incubator.

c. One hundred and thirty-three ml of supernatant was removed from each digester (sludge in lieu of supernatant was removed on Sundays), an equal amount of feed sludge was introduced, and the contents were mixed thoroughly. The pH of the supernatant was determined at frequent intervals; total phosphorus was measured in the sludge at weekly intervals during the latter part of the study, and volatile acids were determined at the same intervals in supernatant obtained by centrifuging the sludge.

d. Gas production was noted, the gas measurement bottles were refilled, and the water reservoir was emptied.

e. The units were repositioned in the incubator and the gas lines were connected.

3. Sludge Thickening and Dewatering Study

a. Thickening Tests

Five hundred ml of secondary sludge from each of the activated sludge pilot plants, or 250 ml of this sludge combined and thoroughly mixed with an equal amount of primary sludge, was placed in 600-ml

beakers. Samples were collected from each beaker for initial percent solids determinations, the thickener was started, and samples were taken at 2-hr intervals for solids determinations for a period of 8 hr. The thickener was then shut off, the supernatant in each beaker was decanted, and the thickened sludge was stored in a refrigerator at 10°C until vacuum filtration studies were conducted.

b. **Vacuum Filtration Tests**

The following procedure was employed in performing the vacuum filtration tests and, with slight modifications, was the same as that presented by Eckenfelder (26, p.240) and Jones (27).

a. A disc of filter paper* cut to the appropriate size was moistened with deionized water and placed over a wire screen resting at the bottom of a Buchner funnel.

b. The vacuum was turned on and the filter paper adjusted to obtain a seal.

c. An appropriate volume of sludge (either 100 or 200 ml) previously thickened on the multi-unit thickener was immediately poured into the Buchner funnel and spread to a uniform thickness.

d. After the desired vacuum had been reached, measurement and recording of the volume of filtrate collected at various time intervals was begun.

e. Filtration was continued until there was a vacuum break;** the vacuum was then released, the filtrate was collected for COD analysis, and percent solids determinations were performed on the filter cake.

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*Whatman No. 40, a product of W. & R. Balston Limited, England.

**The vacuum break was considered to have occurred when a drop in vacuum was noted.

f. The specific resistance* of the sludge was calculated from the filtration data.

c. Centrifugation Tests

Laboratory test procedures to determine the dewatering characteristics of sludge by centrifuging have not been well developed; because of the difficulty in correlating data obtained on a laboratory unit with expected centrifuge performance at full plant-scale level, geometrically-similar models have usually been employed (34). However, Vesilind (34) has recently proposed a method which, he felt, could be used to correlate laboratory data and plant performance. The experimental procedure employed in this study was, therefore, patterned after the method developed by Vesilind.

Laboratory centrifugation studies were conducted using either 100 percent secondary sludge or a mixture consisting of 50 percent primary and 50 percent secondary sludge; neither of the two sludges had been thickened on the multi-unit thickener. Sludge samples were centrifuged at various speeds and residence times, and the sludge cake and centrate were analyzed. Two types of studies were conducted. The first employed the small 37-ml centrifuge tubes; sludge consolidation and centrate turbidities were determined. The second study employed the larger 250-ml centrifuge bottles, with feed sludge, cake and centrate solids concentrations, and centrate COD values serving as major parameters.

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*Specific resistance is numerically equal to the pressure difference required to produce a unit rate of filtrate flow of unit viscosity through a unit weight of cake (26, p.237). A sample calculation is presented in Appendix A, p. 99.

d. Putrefaction Test

The putrefaction test consisted of placing a dewatered sample of secondary sludge in a closed system and measuring the gases produced both quantitatively and qualitatively. Two hundred and fifty ml of sludge from each of the activated sludge plants was vacuum-filtered. The dewatered samples were weighed and placed in the putrefaction units. Gas production was noted periodically and, after a sufficient volume of gas had been produced to displace the air originally contained in the system, the gas was analyzed on the gas partitioner.

IV. PRESENTATION OF RESULTS

The purpose of this research study was to examine methods for the disposal of activated sludge containing chemically-precipitated phosphorus. To accomplish this objective, metal-treated activated sludge or a mixture of secondary sludge with primary sludge were thickened and dewatered by vacuum filtration and centrifugation. Furthermore, the putrescibility of the dewatered secondary sludge was evaluated, as direct land disposal without any further treatment of this low volatile content sludge was felt to be a possibility. Since anaerobic digestion is the usual method of sludge treatment, a digestion study was also conducted.

Secondary sludge for these studies was produced in five 38-gpd (144-1/day) activated sludge pilot plants operated at the Rolla Southeast Treatment Plant. Ferric chloride and alum were added directly to the aeration chambers of four of the pilot plant units, while the fifth unit served as a control. Use of the two chemicals, both of which have been employed in the precipitation of phosphorus, enabled the comparative evaluation of the thickening and dewatering characteristics of the two activated sludges produced, and of the effectiveness of each chemical in removing phosphorus from wastewater.

A. ACTIVATED SLUDGE STUDY

The feed for the pilot plants consisted of settled sewage obtained from the dosing siphon at the Rolla plant. The flow was maintained as close as possible to 144 1/day, however, due to biological growths that became attached to the interior walls of the feed lines, the flow to most units was slightly less. Fluctuations in the elevation of sewage in the dosing siphon had little effect on the flow because of

the weir located along the side of the distribution reservoir (see Figure 2, p. 14). The average flow to each of the five plants, and the corresponding detention times in the aeration and clarification chambers are shown below.

Unit	Avg Flow l/day	Avg Detention Time, hr	
		Aeration Chamber	Clarification Chamber
1	142	5.55	1.51
2	143	5.51	1.50
3	142	5.55	1.51
4	144	5.47	1.49
5	145	5.43	1.48

The COD of the settled sewage feed averaged 229 mg/l over the three-month study period and ranged from 123 to 323 mg/l, while total phosphorus averaged 9.9 mg/l P and varied from 4.3 to 14.8 mg/l P.

Influent and effluent samples for phosphorus and COD determinations were taken twice daily and were combined over an appropriate number of days to form composites. Sampling times were approximately 9:00 AM and 4:00 PM, and to insure that the samples collected at these times when combined would represent average daily values, a phosphorus and COD profile of the settled sewage was prepared on two different days of the week, a Monday (January 18, 1971) and a Saturday (January 23, 1971). A sewage flow profile for the Rolla plant was also prepared from data obtained using a flow meter located at the Parshall flume at the entrance of the plant. This was done on Saturday, however, operational difficulties at the Rolla plant prevented the collection of flow data on Monday. Settled sewage samples for phosphorus and COD determinations were collected using a continuous flow sampler designed and constructed by Ford (35). The sampler consisted of a low capacity water pump which pumped a stream of settled sewage from

the distribution reservoir used in the activated sludge pilot plant system to a horizontal trough located within the sampler. The discharge end of the sample line was connected with a clothespin to a continuously rotating threaded rod, and as the rod turned the pin and discharge line moved along the length of the trough. The trough was sectionalized and each section was equipped with a discharge line leading to a sample bottle. The rotating speed of the threaded rod and the length of the sections were designed so that samples could be collected over periods of 15 min, 1 or 2 hr. For the purpose of this study, 1-hr samples were collected from 9:00 AM to 12:00 noon, and 2-hr samples were obtained thereafter until the end of the sampling run. The phosphorus and COD profiles and plant flow data are presented in Figure 7. Evaluation of the COD and phosphorus profiles, which followed the same trend on both sampling days, would indicate that the concentrations determined on the basis of the samples collected at the two sampling times used throughout the study closely represented the corresponding daily averages. Although equipment difficulties at the Rolla plant prevented collection of flow data on Monday, observation of the plant flow after the difficulties had been corrected indicated that the pattern shown for Saturday was fairly representative.

To effect the removal of phosphorus from the wastewater, ferric chloride and alum were added directly to the aeration chambers of pilot plants 2 and 3, and 4 and 5, respectively, while plant 1 was retained as a control. Based on previous studies conducted in the Rolla area (20,21), an Al/P ratio of 1.3 was selected. No data were available, however, on the use of Fe^{+++} and an Fe/P ratio of 1.0 was arbitrarily chosen; it was soon apparent that a higher ratio
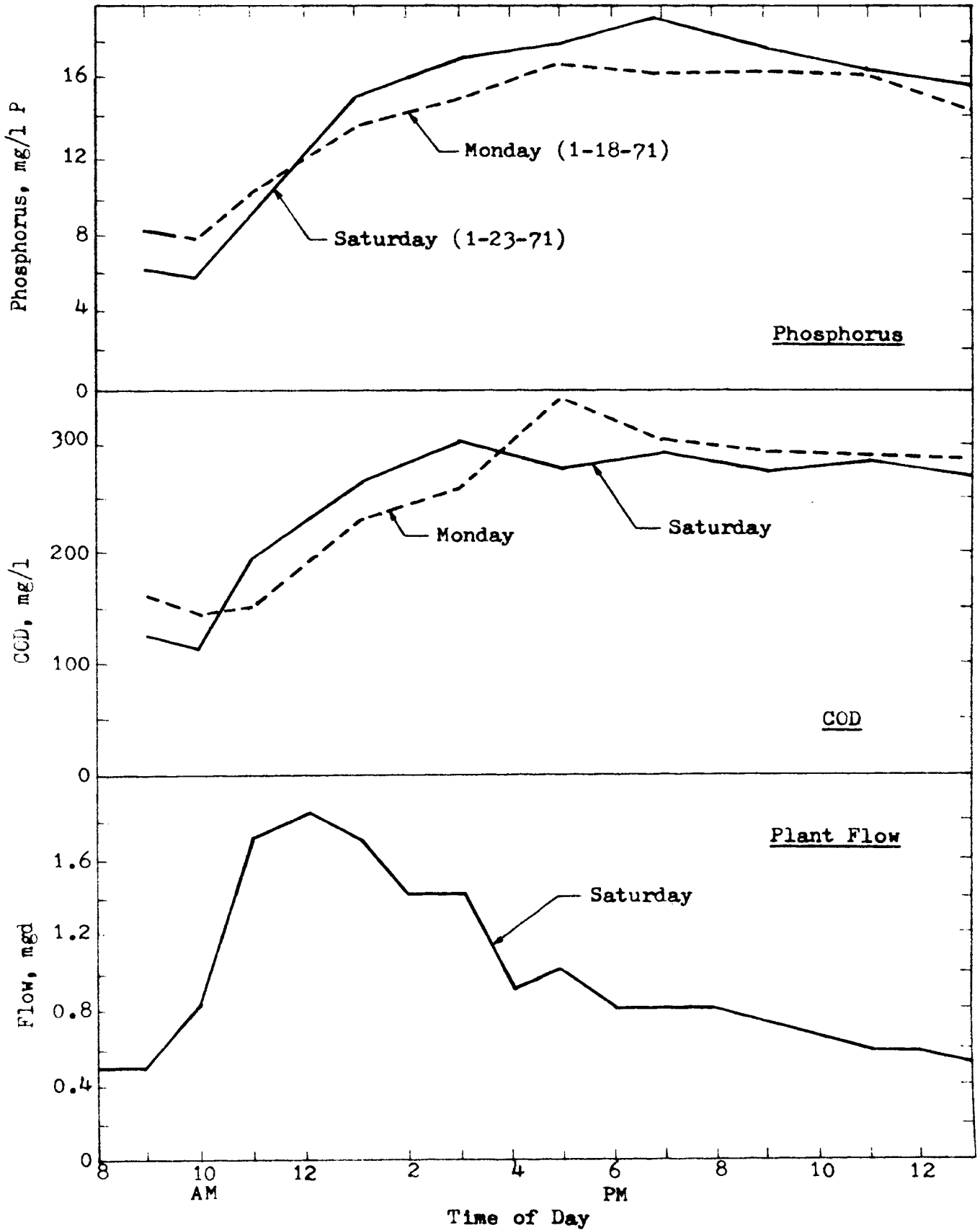
Figure 7. CHEMICAL OXYGEN DEMAND AND PHOSPHORUS PROFILES IN SETTLED
SEWAGE AND PLANT FLOW - ROLLA SOUTHEAST TREATMENT PLANT

was required for effective phosphorus removal and the Fe/P ratio was increased to 1.3. The Al/P and Fe/P ratios were kept equal until the last few days of the study when the Fe/P ratio was increased to 1.5. Due to fluctuations in the phosphorus content of the settled sewage (Table I), the actual metal to phosphorus (M/P) ratios applied varied widely and ranged from 0.7 to 3.8 for Fe^{+++} and 0.9 to 3.8 for Al^{+++}. Chemicals were fed to each unit at a rate of 1.0 l/day and the procedure for determining the feed concentration varied. For the first 31 days, feed concentrations were based on phosphorus levels in the settled sewage over the two previous determinations resulting in a change every 4 days. Because of the widely fluctuating phosphorus content of the sewage feed, it was felt that a constant M/P ratio was impossible to maintain, consequently, from the 31st day to the end of the study the chemical feed concentrations were changed only after a trend in the phosphorus level had been indicated.

Phosphorus data are presented in Table I and Figure 8. Also shown in Table I is an average flow for each sampling period. This flow represents the arithmetic mean of the flows to the five units, and its use was considered appropriate because the individual pilot plant flows varied by not more than 4 l/day (less than 3 percent). The residual phosphorus in the effluents from the four pilot plants treated with chemicals varied widely from Day 0, when chemical feed was begun, to the end of the study, however for the most part, they remained between 1 and 3 mg/l P. The higher residuals can be attributed in almost every case to a reduced M/P ratio actually applied. The very high phosphorus concentration in the effluent of Unit 5 near the 25th day was caused by a broken chemical feed line, and upon

Table I. ACTIVATED SLUDGE STUDY - PHOSPHORUS DATA

Date	Time Days*	Sewage Flow l/day	Influent mg/l P	Unit 1		Units 2&3		Unit 2		Unit 3		Units 4&5		Unit 4		Unit 5	
				Effluent mg/l P	% Removal	Fe+++ Added mg/day	Fe/P Ratio	Effluent mg/l P	% Removal	Effluent mg/l P	% Removal	Al+++ Added mg/day	Al/P Ratio	Effluent mg/l P	% Removal	Effluent mg/l P	% Removal
1-5-71	1	144	9.5	4.6	52	1150	0.9	4.0	58	4.8	50	1480	1.1	3.0	68	3.4	64
1-7-71	3	143	11.5	5.6	51		0.7	5.4	55	4.8	58		1.0	**	***	2.8	75
1-9-71	5	143	10.8	7.0	35	1870	1.2	1.8	83	2.8	74	1870	1.2	1.3	88	2.2	80
1-11-71	7	141	12.3	7.6	38		1.1	2.7	78	3.1	75		1.1	2.2	82	2.5	80
1-13-71	9	146	10.0	8.2	18	2060	1.4	2.3	77	2.2	78	2060	1.4	1.3	87	1.3	87
1-15-71	11	144	10.8	9.6	11		1.3	2.8	74	2.7	75		1.3	0.9	92	0.9	92
1-17-71	13	142	9.8	8.8	10	2150	1.5	1.5	85	2.3	77	2150	1.5	1.6	84	0.7	93
1-19-71	15	140	11.5	9.6	17		1.3	2.7	77	3.7	68		1.3	1.4	88	0.1	99
No phosphorus determinations made																	
1-23-71	19	144	12.3	9.6	22	1950	1.1	3.5	72	3.9	68	1950	1.1	2.2	82	2.4	80
1-25-71	21	144	12.1	11.4	6	1910	1.1	3.0	75	5.0	59	1910	1.1	2.2	82	3.4	72
1-27-71	23	143	8.0	8.4	-		2.0	2.7	66	3.8	53		2.0	1.3	84	3.5	56
1-29-71	25	142	14.8	12.2	18		1.1	5.1	65	5.3	64		1.1	2.5	83	8.6	42
2-1-71	28	144	13.5	11.4	16	2280	1.2	3.8	72	3.1	77	2280	1.2	2.4	82	1.3	90
2-4-71	31	143	8.8	7.8	11		2.1	2.8	68	2.2	75		2.1	1.4	84	1.4	84

*Run on composite samples, as follows: 2-day to day 25, 3-day to day 72, and 4-day to end of study.
**Phosphorus concentration below detection limit.
***Approximately 100% removal of phosphorus.

Table I (continued). ACTIVATED SLUDGE STUDY - PHOSPHORUS DATA

Date	Time Days*	Sewage Flow l/day	Influent mg/l P	Unit 1		Units 2&3		Unit 2		Unit 3		Units 4&5		Unit 4		Unit 5	
				Effluent mg/l P	% Removal	Fe+++ Added mg/day	Fe/P Ratio	Effluent mg/l P	% Removal	Effluent mg/l P	% Removal	Al+++ Added mg/day	Al/P Ratio	Effluent mg/l P	% Removal	Effluent mg/l P	% Removal
2-7-71	34	142	13.7	8.8	36		1.3	1.6	88	1.2	91		1.3	1.0	92	1.2	91
2-10-71	37	141	9.8	8.4	14		1.9	1.9	81	1.2	88		1.9	0.4	96	0.2	98
2-13-71	40	144	10.0	8.8	12	2660	1.8	1.4	86	1.9	81	2660	1.8	0.7	93	0.6	94
2-16-71	43	142	12.0	11.0	8		1.5	2.3	81	2.9	76		1.5	1.6	87	0.9	93
2-19-71	46	139	12.0	10.2	15		1.5	1.7	86	2.0	83		1.5	2.6	78	1.3	89
No samples taken - chemical feed pump inoperative																	
2-24-71	51	142	8.0	6.8	15	2660	2.3	0.6	92	0.7	91	2660	2.3	0.9	90	0.3	96
2-28-71	55	144	11.5	7.0	39	2660	1.6	1.4	88	1.0	91	2660	1.6	1.1	90	0.4	97
No samples taken - operational difficulties at the Rolla plant																	
3-8-71	63	144	4.8	4.4	8	2660	3.8	0.6	88	0.2	96	2660	3.8	1.2	75	0.9	81
3-11-71	66	141	6.3	6.8	-		2.9	0.4	94	**	***		2.9	1.0	84	0.2	97
3-14-71	69	139	6.5	6.4	2		2.8	0.1	99	**	***		2.8	0.6	91	**	***
3-17-71	72	144	11.3	8.2	27	1870	0.9	2.5	78	2.2	81	1870	0.9	1.4	88	1.7	85
3-21-71	76	142	10.8	8.8	19		1.0	5.3	55	4.3	62		1.0	2.2	80	3.2	70
3-25-71	80	140	10.3	9.0	13		1.3	4.4	57	2.8	73		1.3	1.7	84	1.4	87
3-29-71	84	144	11.0	8.8	20		1.4	1.7	85	1.2	89		1.3	1.5	86	1.7	84
4-2-71	88	144	9.0	8.0	11	2590	1.7	1.9	79	1.4	85	2240	1.4	1.3	86	0.8	91

*Run on composite samples, as follows: 2-day to day 25, 3-day to day 72, and 4-day to end of study.

**Phosphorus concentration below detection limit.

***Approximately 100% removal of phosphorus.
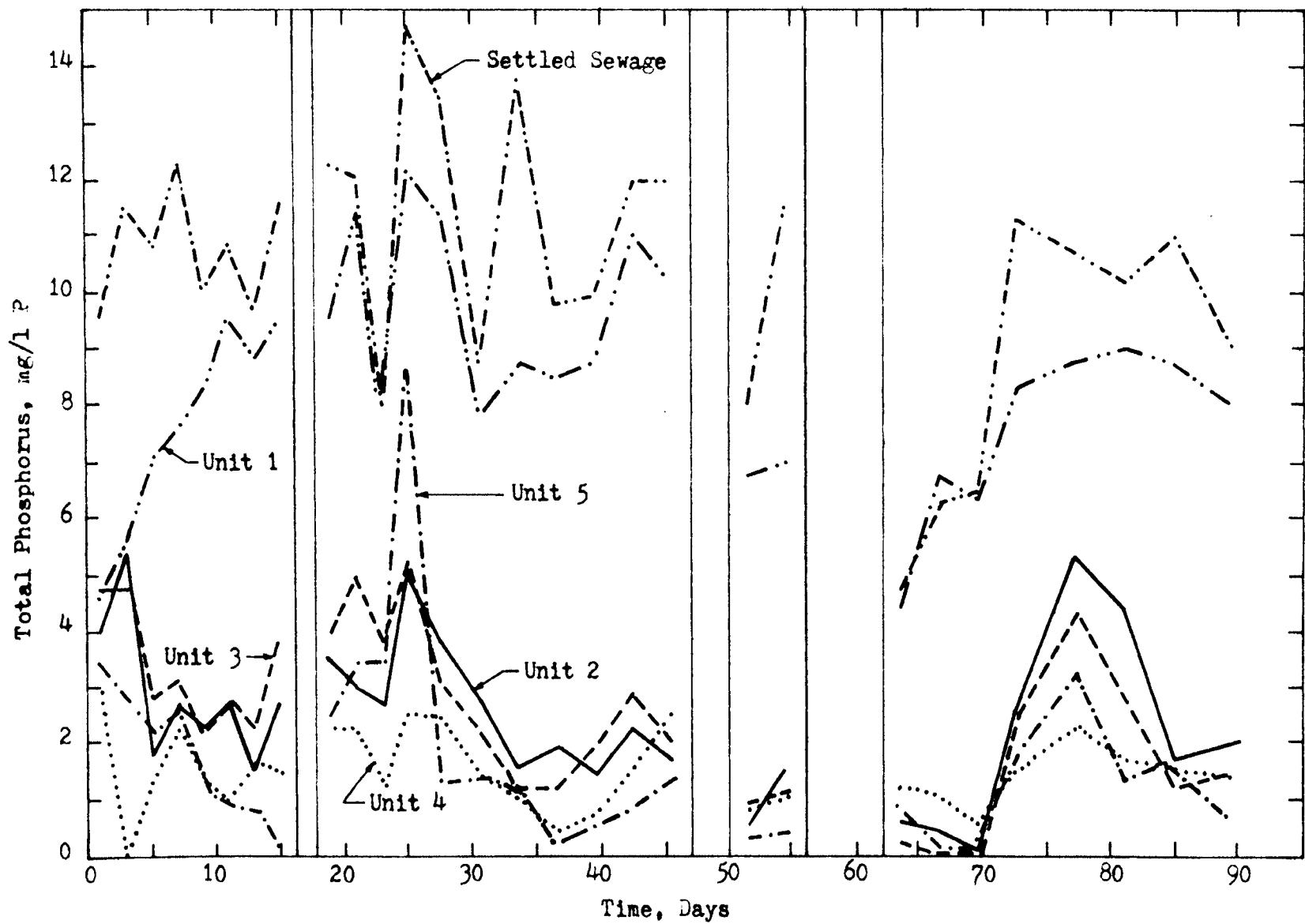
Figure 8. ACTIVATED SLUDGE STUDY - PHOSPHORUS DATA

repair of the line the residual decreased rapidly. On two separate
occasions, once on the 23rd day and again on the 66th day, the phos-
phorus contained in the effluent of the control unit was higher than
that in the sewage feed. The situation on the 23rd day may have been
caused by bulking sludge in the final clarifier resulting from an
oxygen deficiency in the aeration chamber; release of phosphorus in
the floc which escaped in the effluent during this period may explain
the situation. No explanation can be offered for the repeat occur-
rence on the 66th day. Samples for phosphorus determinations were not
collected between the 46th and 51st day because of operational diffi-
culties with the chemical feed pump. On the 56th day, sewage flow to
the Rolla plant was by-passed so that repairs could be made on the
primary clarifier. The units were fed on a fill-and-draw basis and
samples were not taken until the 62nd day when feed was siphoned from
the bar screen-grit chamber complex ahead of the by-pass gate. Plant
flow was started shortly thereafter and normal operations were resumed.
The average effluent phosphorus concentrations for each unit and the
corresponding phosphorus removals are presented below.

Unit	Control 1	Fe^{+++} 2	3	Al^{+++} 4	5
Avg Influent Phosphorus, mg/1 P	9.9	9.9	9.9	9.9	9.9
Avg Effluent Phosphorus, mg/1 P	8.0	2.3	2.1	1.4	1.4
Avg Phosphorus Removal, %	19	77	79	86	86

Chemical oxygen demand data are shown in Table II and Figure 9.
The effluent COD values obtained in all units were slightly higher than
those reported by other investigators employing activated sludge units
(16,20,21), however with few exceptions, the residuals remained below
50 mg/1. The adverse environmental conditions under which the pilot

Table II. ACTIVATED SLUDGE STUDY - CHEMICAL OXYGEN DEMAND DATA

Date	Time Days*	Influent mg/l	Unit									
			1		2		3		4		5	
			Effluent mg/l	% Removal	Effluent mg/l	% Removal	Effluent mg/l	% Removal	Effluent mg/l	% Removal	Effluent mg/l	% Removal
1-6-71	2	237	46	81	54	77	46	81	50	79	65	73
1-10-71	6	205	38	71	38	71	34	72	45	68	53	64
1-14-71	10	303	51	83	37	88	34	89	42	83	42	83
1-18-71	14	236	71	70	46	81	43	82	15	94	44	81
1-22-71	18	248	70	60	34	86	37	85	40	84	51	80
1-26-71	22	225	46	80	35	85	29	87	46	80	80	65
1-30-71	26	325	62	81	42	87	42	87	49	85	80	75
2-3-71	30	230	48	79	34	85	25	89	39	83	39	83
2-7-71	34	288	44	85	36	88	31	89	31	89	42	85
2-11-71	38	190	38	80	33	83	32	83	31	84	30	84
2-15-71	42	235	45	81	35	85	41	83	37	84	39	83
2-19-71	46	222	38	83	28	87	28	87	48	79	35	84
2-23-71	50	164	29	82	22	87	20	88	31	81	24	85
2-27-71	54	308	30	90	21	93	23	93	38	88	25	92
No samples taken - operational difficulties at the Rolla plant												
3-8-71	63	220	28	87	22	90	15	93	40	82	23	90
3-12-71	67	123	36	71	30	75	24	80	29	76	28	78
3-16-71	71	199	35	82	26	87	25	87	34	83	32	84
3-20-71	75	251	37	85	32	87	31	88	44	82	30	88
3-24-71	79	177	45	75	48	73	47	74	56	68	49	72
3-28-71	83	173	27	84	29	83	30	83	29	83	29	83
4-1-71	87	232	34	85	33	86	30	87	35	85	23	90
4-5-71	91	243	28	89	30	88	31	88	32	87	31	88

*Run on 4-day composite samples.
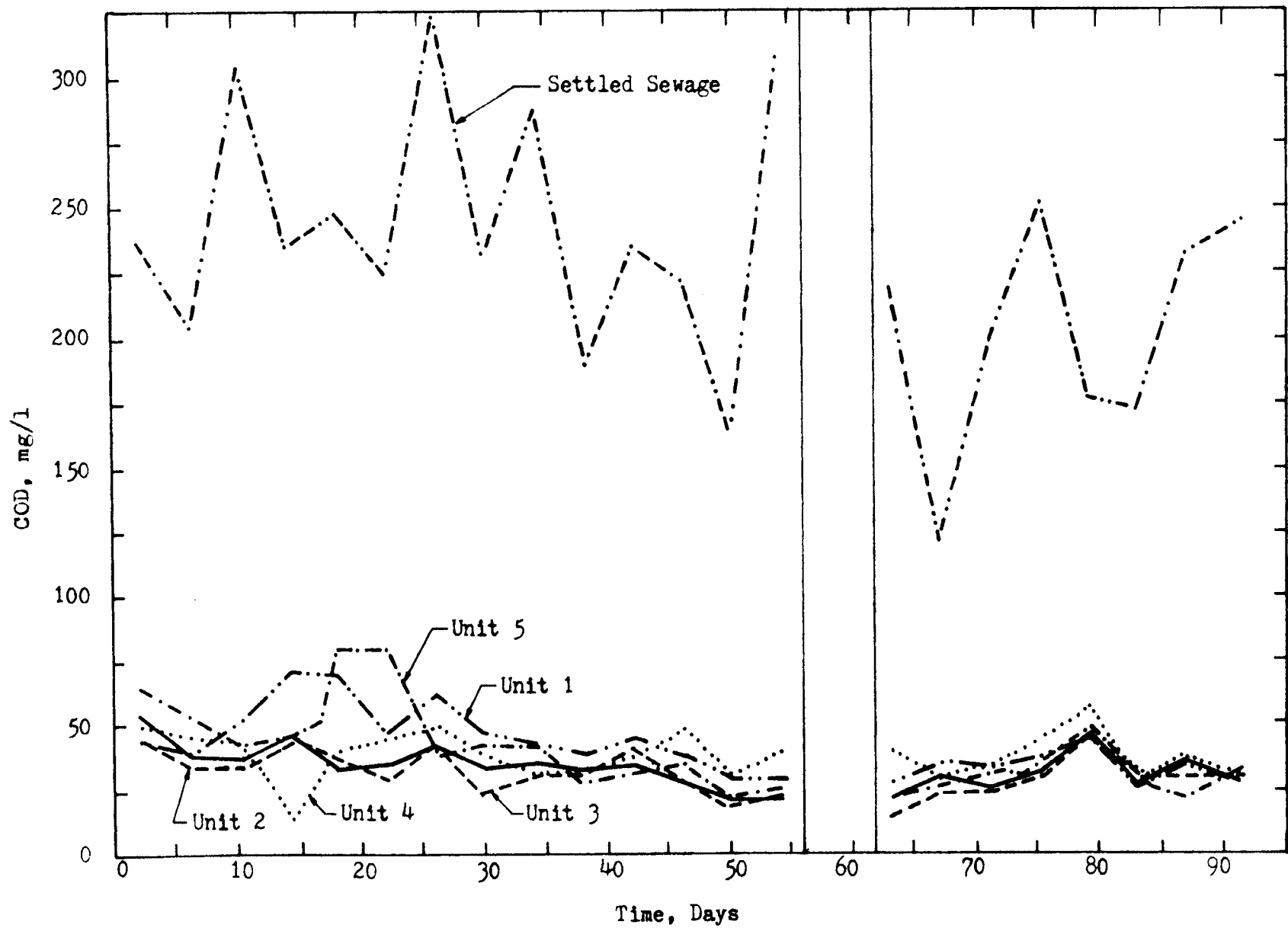
Figure 9. ACTIVATED SLUDGE STUDY - CHEMICAL OXYGEN DEMAND DATA

plants were operated could account for the higher effluent COD values observed (36), while the relatively low strength of the settled sewage feed further contributed to the lower COD removal efficiencies. Average COD values are given below.

Unit	Control 1	Fe^{+++} 2	3	Al^{+++} 4	5
Avg Influent COD, mg/l	229	229	229	229	229
Avg Effluent COD, mg/l	47	37	34	41	44
Avg COD Removal, %	80	84	85	82	81

Effluent SS were measured at varying intervals throughout the study and influent SS in the settled sewage feed were measured during the last 30 days. These values, along with the corresponding percent removals, are presented in Table III. The effluents from Units 4 and 5, which were treated with Al^{+++}, were clouded with pin-point floc over most of the study period. This is not necessarily reflected in the effluent SS values and would indicate that the suspended matter was very light in weight. The effluent of Unit 1, the control, and Units 2 and 3, which were treated with Fe^{+++}, remained crystal clear throughout most of the study.

The MLSS and MLVSS concentrations in the aeration chambers of the pilot plants served as a means of controlling the microbial population in the units. These data are presented in Table IV. The MLSS in Units 2 through 5 increased sharply immediately after the addition of chemicals to these plants had begun, while the volatile fraction progressively decreased. The average MLSS and MLVSS are shown on p. 51.

Table III. ACTIVATED SLUDGE STUDY - SUSPENDED SOLIDS DATA

Date	Time Days*	Influent mg/l	Unit									
			1		2		3		4		5	
			Effluent mg/l	% Removed	Effluent mg/l	% Removed	Effluent mg/l	% Removed	Effluent mg/l	% Removed	Effluent mg/l	% Removed
1-28-71	24	-	7	-	5	-	10	-	11	-	15	-
2-5-71	32	-	5	-	13	-	6	-	8	-	19	-
2-11-71	38	-	8	-	13	-	5	-	11	-	3	-
3-12-71	67	39	5	87	4	90	4	90	7	82	4	90
3-16-71	71	65**	3	95	6	91	9	86	19	71	16	75
3-20-71	75	120**	4	97	8	94	7	94	23	81	7	94
3-24-71	79	46**	18	61	13	72	3	94	10	78	8	83
3-28-71	83	112**	9	92	10	91	5	95	11	90	8	93
4-1-71	87	78**	8	90	16	80	15	81	21	73	7	91

*Run on grab samples through day 38 and on 4-day composites thereafter.
**The corresponding VSS values were 75, 40, 72, and 56 mg/l, respectively.

Table IV. ACTIVATED SLUDGE STUDY - MIXED LIQUOR SUSPENDED SOLIDS DATA

Date	Time Days	Unit 1 Total mg/l	Unit 1 Volatile mg/l	Unit 1 Volatile % of Total	Unit 2 Total mg/l	Unit 2 Volatile mg/l	Unit 2 Volatile % of Total	Unit 3 Total mg/l	Unit 3 Volatile mg/l	Unit 3 Volatile % of Total	Unit 4 Total mg/l	Unit 4 Volatile mg/l	Unit 4 Volatile % of Total	Unit 5 Total mg/l	Unit 5 Volatile mg/l	Unit 5 Volatile % of Total
1-3-71	-1	2840	2130	80	3100	2370	76	2860	2200	77	3550	2690	76	3230	2570	75
1-7-71	3	3310	2440	74	3260	2200	68	3070	2190	71	3720	2500	67	3290	2310	70
1-9-71	5	3130	2360	76	4390	2980	68	3890	2720	70	4210	2780	66	2620	1800	69
1-12-71	8	3710	2800	75	3780	2440	65	3770	2420	64	3630	2180	60	5510	3520	64
1-14-71	10	3380	2630	78	3720	2370	64	4190	2710	65	3730	2300	62	4160	2620	63
1-16-71	12	3250	2480	76	4240	2600	61	4030	2460	61	4520	2610	58	4350	2590	60
1-18-71	14	2620	2030	77	3880	2240	58	3690	2190	59	4150	2310	56	4040	2300	57
1-20-71	16	2740	2040	75	4460	2570	58	4050	2320	57	4630	2510	54	4830	2620	54
1-22-71	18	2790	2130	76	4770	2760	58	4510	2570	57	4990	2750	55	4770	2590	54
1-24-71	20	2940	2180	74	4020	2320	58	3915	2260	58	4170	2340	56	4150	2400	58
1-26-71	22	3030	2220	73	4590	2490	54	4290	2290	53	4100	2170	53	4080	2120	52
1-28-71	24	3110	2250	72	4490	2550	57	4300	2300	54	4150	2170	52	4500	2500	56
1-30-71	26	3000	2320	77	4440	2660	60	4510	2750	61	4270	2470	58	5930	3410	57
2-1-71	28	2590	1990	77	4540	2530	56	2990	1680	56	5010	2690	54	4960	2640	53
2-3-71	30	3900	3030	78	4790	2850	59	5270	3110	59	4340	2440	56	4970	2870	57
2-5-71	32	3100	2310	75	4510	2620	58	4770	2850	60	5350	3090	58	4650	2580	55
2-7-71	34	4010	2920	73	4520	2520	56	4060	2270	56	2940	1670	57	4880	2730	56
2-9-71	36	2610	1820	70	4460	2480	56	3170	1720	54	4450	2350	53	4430	2380	54

Table IV (continued). ACTIVATED SLUDGE STUDY - MIXED LIQUOR SUSPENDED SOLIDS DATA

Date	Time Days	Unit 1 Total mg/l	Volatile mg/l	% of Total	Unit 2 Total mg/l	Volatile mg/l	% of Total	Unit 3 Total mg/l	Volatile mg/l	% of Total	Unit 4 Total mg/l	Volatile mg/l	% of Total	Unit 5 Total mg/l	Volatile mg/l	% of Total
2-11-71	38	2780	2090	75	4780	2830	59	4290	2480	58	6940	3860	56	4850	2740	56
2-14-71	41	4190	3160	75	4520	2430	54	4830	2560	53	4230	2220	53	5880	3210	55
2-17-71	44	3370	2560	76	4620	2520	55	4740	2560	54	6190	3250	52	5620	2980	53
2-20-71	47	3400	2370	70	5240	2680	51	5210	2620	50	5320	2680	50	5560	2810	50
2-23-71	50	3070	2190	71	4640	2400	52	4270	2220	52	4450	2270	51	3980	2100	53
2-26-71	53	2770	2000	72	4840	2520	52	2290	1340	58	5190	2780	54	4060	2130	52
3-1-71	56	3350	2490	74	4620	2480	54	4860	2600	54	4750	2510	53	5000	2650	53
3-6-71	61	3320	2410	73	4830	2570	53	4670	2490	53	4450	2280	51	5350	2760	52
3-11-71	66	3170	2200	70	4770	2260	49	5650	2780	49	5510	2660	48	4870	2380	49
3-15-71	70	3080	2190	71	5660	2550	50	4560	2210	49	6440	3060	48	6110	3020	49
3-18-71	73	3405	2200	65	4970	2670	54	5430	2930	54	4765	2540	53	6310	3515	56
3-23-71	78	3540	2725	77	5470	3190	58	4675	2695	58	4935	2750	56	5175	3125	60
3-26-71	81	3075	1835	60	4600	2590	56	4730	2725	58	3985	2370	59	3300	2670	81
3-29-71	84	3100	2470	80	6925	4845	70	5085	2995	59	6900	4710	68	8275	6171	75
3-31-71	86	2590	1960	76	4350	2460	57	7155	4970	69	4610	2390	52	4640	2955	64
4-3-71	89	3390	2430	72	4625	2540	55	4200	2070	49	6475	3500	54	4785	2550	53
4-7-71	93	3295	2645	80	4730	2565	54	4635	2395	53	5360	2850	53	5060	2645	50

Unit	Avg MLSS mg/l	Avg MLVSS mg/l	% of MLSS
1	2940	2180	74
2	4020	2320	58
3	3920	2260	58
4	4180	2340	56
5	4140	2400	58

These values are generally in agreement with those reported by other investigators (20,21), however, there are some notable differences. The MLSS concentration maintained in the control unit was nearly 1200 mg/l greater than that maintained by Max (20), while the volatile fraction of the MLSS in the chemically-treated units was 5 to 6 percent higher. It is felt that these differences were due to the period of the year in which the studies were conducted, and that operation at a colder temperature resulted in the production of a greater amount of sludge (36,37).

Sludge volume index values were determined periodically and are given in Table V. The SVI in the control unit (Unit 1) remained higher than the recommended value of 100 (33, p.265; 38, p.35-22) throughout the study, however, even with the high values determined on the 34th, 70th, and 73rd days, bulking sludge was not experienced and there was no appreciable increase in the effluent SS (Table III). The SVI values of the activated sludges treated with Fe^{+++} (Units 2 and 3) were somewhat lower than those of the control, but still higher than the recommended value. The SVI associated with Units 4 and 5, which were treated with Al^{+++}, were high during the first two or three determinations, but then decreased sharply to values in the range reported by other investigators (18,21). Fluctuations in the SVI have been attributed by Vedder (21) to changes in the strength of the sewage

Table V. ACTIVATED SLUDGE STUDY - SLUDGE VOLUME INDEX DATA

Date	Time Days	Unit				
		1	2	3	4	5
1-28-71	24	180	150	160	200	150
2-7-71	34	237	195	210	340	110
2-11-71	38	180	170	175	200	90
2-17-71	44	140	123	124	70	75
2-26-71	53	180	110	115	50	80
3-1-71	56	190	120	117	45	62
3-6-71	61	170	147	112	55	53
3-15-71	70	250	175	115	36	44
3-18-71	73	250	182	165	46	47
3-26-71	81	150	153	171	51	55

Table VI. ACTIVATED SLUDGE STUDY - SLUDGE AGE DATA

Date	Time Days	Sludge Age, days Unit				
		1	2	3	4	5
Determined on the basis of total suspended solids						
3-8-71	63	12	17	19	18	18
3-12-71	67	15	28	26	31	30
3-16-71	71	12	15	16	15	17
Determined on the basis of total suspended solids for Unit 1 and volatile suspended solids for Units 2 through 5						
3-20-71	75	6	8	7	7	8
3-24-71	79	14	13	14	19	23
3-28-71	83	6	11	8	11	13
4-1-71	87	7	9	8	11	9

feed, with higher SVI values accompanying high feed strengths. Evaluation of the sewage strength (Table II) and SVI values obtained in this study does not support this statement. Rather, it is felt that the aeration rate was a greater factor in this study, as an increase in the air supplied to a unit with a high SVI resulted, in nearly every case, in a decrease in the SVI. The addition of chemicals to the aeration chambers of Units 2 through 5 improved the settling characteristics of these sludges over those of the control, with the most effect observed in the units treated with Al^{+++}.

Sludge age determinations were also conducted periodically during the latter part of the study, and in conjunction with SVI, were used as a control parameter in the operation of the pilot plant units. These values are presented in Table VI (p.52). The first three SA determinations were based on TSS, and because of the high MLSS present in the metal-treated units, the SA values for these units were abnormally high. Thereafter, the SA for the chemically-treated units was determined on the basis of VSS. By either method, the values were much greater (as much as 10 times as high) than the optimum of 3 to 5 days that has been reported for conventional activated sludge (32, p.550; 33, p.258). Unfortunately, little could be done to rectify this situation. More frequent wasting of the mixed liquor would have lowered the MLSS and thus lowered SA; however, a buildup of solids in the units was necessary in order to accumulate sufficient sludge for feeding the anaerobic digesters and for conducting the sludge disposal studies.

B. ANAEROBIC DIGESTION STUDY

Five 1.0-gal (3.78-1) digesters were employed in the anaerobic digestion study and were fed a mixture of 50 percent primary sludge obtained from the Rolla plant and 50 percent secondary sludge from the pilot plants, on the basis of a 15-day detention period. During the first 26 days of operation, all the digesters were fed secondary sludge collected from the control activated sludge unit. This allowed a sufficient acclimation period for the digesters while the volatile content of the mixed liquor in the chemically-treated units reached steady-state conditions. In addition, this period allowed sufficient data to be accumulated in order to formulate a gas production base-line so that the effects on gas production caused by the addition of the metal-treated sludge could be evaluated. From the 26th day to the end of the study, the digesters were fed secondary sludge from the corresponding pilot plant units. The organic loadings applied daily to the five digesters and the corresponding gas production are presented in Table VII, while average values are shown below.

| | Control | Fe^{+++} | | Al^{+++} | |
	1	2	3	4	5
Before Day 0					
Detention Time, days	15	15	15	15	15
Avg Organic Loading					
lb VS/day/cu ft	0.20	0.20	0.20	0.20	0.20
(kg VS/day/cu m)	(3.20)	(3.20)	(3.20)	(3.20)	(3.20)
Avg Gas Production					
ml/l	906	949	1010	948	1022
After Day 0					
Detention Time, days	15	15	15	15	15
Avg Organic Loading					
lb VS/day/cu ft	0.16	0.18	0.17	0.22	0.22
(kg VS/day/cu m)	(2.56)	(2.88)	(2.72)	(3.52)	(3.52)
Avg Gas Production					
ml/l	1112	1027	995	1027	975

Table VII. ANAEROBIC DIGESTION STUDY - GAS PRODUCTION DATA

Date	Time Days	Unit 1 Feed Rate *	Unit 1 Gas ml/l **	Unit 2 Feed Rate *	Unit 2 Gas ml/l **	Unit 3 Feed Rate *	Unit 3 Gas ml/l **	Unit 4 Feed Rate *	Unit 4 Gas ml/l **	Unit 5 Feed Rate *	Unit 5 Gas ml/l **
1-14-71	-26	0.28	750	0.28	800	0.28	875	0.28	850	0.28	850
1-15-71	-25		625		675		625		675		650
1-16-71	-24	0.19	925	0.19	700	0.19	750	0.19	875	0.19	850
1-17-71	-23		850		925		900		--		1000
1-18-71	-22		750		800		875		875		1000
1-19-71	-21		900		875		925		850		950
1-20-71	-20		950		950		875		1000		1000
1-21-71	-19	0.19	925	0.19	1000	0.19	1000	0.19	975	0.19	975
1-22-71	-18		--		--		--		--		--
1-23-71	-17		900		900		930		925		975
1-24-71	-16		925		875		900		925		950
1-25-71	-15		650		800		900		700		750
1-26-71	-14		--		--		--		--		--
1-27-71	-13		875		900		950		950		975
1-28-71	-12	0.15	900	0.15	975	0.15	925	0.15	1050	0.15	1075
1-29-71	-11		850		1025		1000		1150		1225
1-30-71	-10		750		800		925		850		1000
1-31-71	-9	0.20	975	0.20	1025	0.20	1000	0.20	1025	0.20	1000
2-1-71	-8		975		1000		950		1050		1050
2-2-71	-7		975		1025		1000		1100		1125
2-3-71	-6	0.24	1000	0.24	1050	0.24	1050	0.24	1050	0.24	1150
2-4-71	-5		1000		1125		1125		1075		1175
2-5-71	-4		1050		1175		1150		1150		1225
2-6-71	-3	0.25	1050	0.25	1050	0.25	1100	0.25	1200	0.25	1275
2-7-71	-2		1150		1250		1250		1300		1400
2-8-71	-1		1050		1125		1125		1150		1175
2-9-71	0		1100		1050		1100		1125		1175
2-10-71	1		1000		1000		925		1050		1050
2-11-71	2		1050		975		925		1075		925
2-12-71	3	0.14	800	0.13	800	0.13	725	0.14	825	0.13	800
2-13-71	4		900		850		825		925		850
2-14-71	5		--		--		--		--		--
2-15-71	6		900		950		925		950		900

*Expressed as lb VS/day/cu ft; to convert to kg VS/day/cu m multiply by 16.
**Expressed as ml gas produced/l digester capacity.

Table VII (continued). ANAEROBIC DIGESTION STUDY - GAS PRODUCTION DATA

Date	Time Days	Unit 1		Unit 2		Unit 3		Unit 4		Unit 5	
		Feed Rate *	Gas ml/l **	Feed Rate *	Gas ml/l **	Feed Rate *	Gas ml/l **	Feed Rate *	Gas ml/l **	Feed Rate *	Gas ml/l **
2-16-71	7		925		950		950		950		925
2-17-71	8		900		925		950		950		950
2-18-71	9	0.16	900	0.16	800	0.16	750	0.16	825	0.16	800
2-19-71	10		750		625		550		600		625
2-20-71	11		1100		625		800		600		650
2-21-71	12		950		925		675		675		675
2-22-71	13		1100		925		825		825		875
2-23-71	14		1000		850		1000		875		900
2-24-71	15		950		800		950		850		850
2-25-71	16		1450		1200		1000		1125		1000
2-26-71	17		1000		1050		950		1075		950
2-27-71	18	0.08	--	0.14	--	0.13	--	0.15	--	0.15	--
2-28-71	19		950		950		950		1000		850
3-1-71	20		1000		1000		950		925		900
3-2-71	21		1250		1225		1050		1125		1000
3-3-71	22		1000		950		900		925		950
3-4-71	23		950		975		925		900		925
3-5-71	24		975		950		975		1000		950
3-6-71	25		1100		950		950		1050		925
3-7-71	26		1150		900		925		1000		1000
3-8-71	27	0.10	750	0.13	625	0.14	550	0.18	650	0.16	600
3-9-71	28		950		900		850		925		825
3-10-71	29		1000		950		900		950		900
3-11-71	30		1125		1125		1050		1100		1050
3-12-71	31		1150		1125		1050		1125		1000
3-13-71	32		1400		1350		1300		1450		1200
3-14-71	33	0.20	1075	0.21	1050	0.19	1000	0.22	1050	0.21	950
3-15-71	34		1200		1225		1150		1175		900
3-16-71	35		925		950		925		950		875
3-17-71	36		1375		1375		1350		1300		1250
3-18-71	37		1550		1175		1250		1150		1200
3-19-71	38	0.23	1500	0.21	1300	0.22	1300	0.28	1150	0.27	1125
3-20-71	39		1350		1150		1200		1100		1000
3-21-71	40		--		--		--		--		--
3-22-71	41		1000		875		850		1050		800

*Expressed as lb VS/day/cu ft; to convert to kg VS/day/cu m multiply by 16.
**Expressed as ml gas produced/l digester capacity.

Table VII (continued). ANAEROBIC DIGESTION STUDY - GAS PRODUCTION DATA

Date	Time Days	Unit 1 Feed Rate *	Unit 1 Gas ml/l **	Unit 2 Feed Rate *	Unit 2 Gas ml/l **	Unit 3 Feed Rate *	Unit 3 Gas ml/l **	Unit 4 Feed Rate *	Unit 4 Gas ml/l **	Unit 5 Feed Rate *	Unit 5 Gas ml/l **
3-23-71	42		1125		1000		1000		1175		1050
3-24-71	43		875		750		700		800		750
3-25-71	44		1300		1100		1200		1250		1100
3-26-71	45	0.17	1200	0.19	1200	0.20	1200	0.22	1150	0.23	1050
3-27-71	46		1250		1450		1300		1250		1250
3-28-71	47		1225		1375		1250		1250		1225
3-29-71	48		1250		1250		1225		1225		1150
3-30-71	49		1300		1175		1125		1325		1100
3-31-71	50		1550		1375		1375		1550		1450
4-1-71	51		1300		1200		1200		1225		1350
4-2-71	52		1275		1275		1250		1175		1150
4-3-71	53		800		850		750		800		750
4-4-71	54		1100		1000		900		1050		1000
4-5-71	55		1125		1050		950		950		1025
4-6-71	56	0.20	--	0.25	--	0.21	--	0.35	--	0.37	--
4-7-71	57		1500		1425		1475		1450		1375
4-8-71	58		1000		900		925		850		950
4-9-71	59		1050		975		950		925		1000
4-10-71	60		750		800		775		825		750
4-11-71	61		900		975		950		1000		1000
4-12-71	62		1000		1075		1050		1000		975

*Expressed as lb VS/day/cu ft; to convert to kg VS/day/cu m multiply by 16.

**Expressed as ml gas produced/l digester capacity.

The lack of any substantial decrease in gas production associated with Units 2 through 5 further substantiates similar findings reported by other investigators (7,17,18,20,23). Gas production in all the units was within the expected range for high-rate digestion (1.0 1 gas/day/1 digester capacity).

The volatile acids content of digester sludge is an important control parameter in anaerobic digestion, consequently, volatile acids determinations were made periodically throughout the study. These values, along with the pH of the digester supernatant, are presented in Table VIII. The volatile acids were very low, at all times determinations were conducted, with the lowest and highest values of 7 and 72 mg/l as CH_3COOH occurring in Unit 3. Samples were collected at the end of the 24-hr feeding period, and if a large and active microbial population was present in the digesters, these low volatile acids values could be expected. In any event, there existed no sudden increase in volatile acids after the addition of the chemically-treated secondary sludges. The pH remained well within the range of 6.6 to 7.6 in which the methane organisms are able to function (26, p.220).

The composition of the digester gas was determined by use of the Fisher Hamilton gas partitioner on three different days during the latter part of the study, and the values obtained are presented below.

	Gas Content, % by Volume					
	50th Day		54th Day		60th Day	
Unit	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
1	58	36	59	35	62	35
2	60	36	62	34	57	35
3	62	34	58	37	61	35
4	61	34	57	39	61	33
5	63	35	61	36	57	34

Table VIII. ANAEROBIC DIGESTION STUDY - VOLATILE ACIDS AND pH DATA

Date	Time Days	Unit 1 Volatile Acids mg/l*	pH	Unit 2 Volatile Acids mg/l*	pH	Unit 3 Volatile Acids mg/l*	pH	Unit 4 Volatile Acids mg/l*	pH	Unit 5 Volatile Acids mg/l*	pH
1-11-71	-29		7.5		7.3		7.4		7.4		7.3
1-12-71	-28		7.3		7.3		7.3		7.3		7.3
1-14-71	-26		7.2		7.2		7.2		7.2		7.2
1-15-71	-25		7.1		7.1		7.2		7.2		7.1
1-16-71	-24		7.1		7.1		7.1		7.1		7.1
1-18-71	-22		7.1		7.1		7.1		7.1		7.1
1-19-71	-21		7.3		7.2		7.3		7.3		7.3
1-24-71	-16	48	7.2	12	7.2	24	7.3	12	7.3	18	7.2
1-28-71	-12		7.2		7.2		7.2		7.2		7.2
1-31-71	- 9	38	7.4	24	7.3	7	7.2	38	7.3	14	7.3
2-5-71	- 4		7.2		7.2		7.3		7.3		7.2
2-7-71	- 2	19	7.3	41	7.3	14	7.3	26	7.3	41	7.2
2-11-71	2		7.1		7.2		7.2		7.2		7.3
2-14-71	5	28	7.1	46	7.4	20	7.3	30	7.3	38	7.2
2-18-71	9		7.2		7.3		7.1		7.3		7.3
2-21-71	12		7.2		7.3		7.2		7.1		7.1
2-28-71	19	40	7.1	50	7.4	46	7.1	28	7.2	52	7.2
3-3-71	22		7.1		7.3		7.1		7.2		7.3
3-7-71	26	38	7.2	45	7.2	50	7.2	42	7.3	36	7.2
3-14-71	33		7.3		7.2		7.3		7.2		7.3
3-18-71	37		7.1		7.3		7.3		7.3		7.3
3-21-71	40	68	7.2	38	7.2	72	7.2	54	7.3	62	7.3
3-28-71	47	50	7.2	62	72.	48	7.2	48	7.2	50	7.4
4-1-71	51		7.3		7.1		7.0		7.1		7.3

*As CH_3COOH.

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The gas composition was essentially identical in all five units. Methane and carbon dioxide averaged 60 and 35 percent, respectively, with the remaining 5 percent consisting of nitrogen and other undeterminable gases. The fraction of methane produced was slightly lower than average values reported (65 to 70 percent), while carbon dioxide was within the reported range (30 to 35 percent) (39, p.18).

The volatile matter and total phosphorus content of the digester sludge were determined on three different occasions during the last 30 days of operation. The volatile content of the sludge in the control unit averaged 53 percent, while in Units 2, 3, 4, and 5 it averaged 50, 50, 49, and 50 percent, respectively. The total phosphorus values obtained are shown below.

	Total Phosphorus, mg/l P		
Unit	25th Day	33rd Day	50th Day
1	1200	1180	1050
2	2080	2100	2150
3	1720	2070	2400
4	2140	2480	2600
5	2140	2420	2900

The phosphorus values in all five units were much higher than those reported by Max (20), however, they did agree with the data reported by Zenz and Pivnicka (23). The increase in phosphorus content of the digester sludge over that reported by Max was believed to be due to the higher organic loadings applied to the digesters in this study. The phosphorus content in Units 2 and 3 was consistently less than that in Units 4 and 5; however, considering the lower phosphorus removals from the wastewater effected by the addition of Fe^{+++} and corresponding decreased phosphorus content of the feed sludge, and the lower loading rates applied to digesters 2 and 3, lower values would be expected.

C. SLUDGE THICKENING AND DEWATERING STUDY

Sludge for the thickening and dewatering studies consisted of secondary sludge either alone or mixed with an equal volume of primary sludge. A total of five tests were conducted employing thickening and vacuum filtration with sludges collected on five separate occasions. The first two tests were made using 100 percent secondary sludge from each of the pilot plant units. The thickened sludges from these tests were used as digester feed, and vacuum filtration was performed on fresh sludge held in reserve. The last three tests employed mixed primary and secondary sludges and the thickened mixture was then used in vacuum filtration. Centrifugation tests were performed on three separate occasions on sludge from the same supply used in the last three thickening and filtration tests. Both secondary and combined secondary and primary sludges were centrifuged in each test. The sludge cakes used in the putrefaction test were obtained by vacuum filtration of 250 ml secondary sludge from each of the activated sludge pilot plants.

1. Thickening Tests

The data obtained from the thickening tests are presented in Table IX and Figure 10. All thickening runs were conducted using the five-unit thickener (Figure 4, p.16) with paddle arms which rotated at between 4 and 5 rph; however, the construction of the paddles was modified twice during the study. Originally, each paddle consisted only of a 1 x 3-in. (2.54 x 7.62-cm) piece of Plexiglas placed near the bottom of the vessel containing the sludge. This resulted in little or no stirring action at the upper regions of the sludge; consequently, 3-in. (7.62-cm) long brass rods were inserted vertically

Table IX. SLUDGE THICKENING AND DEWATERING STUDY - THICKENING DATA

Time hr	100% Secondary Sludge				50% Primary-50% Secondary Sludge				
	Run 1	Run 2	Average		Run 3	Run 4	Run 5	Average	
	% Total Solids			%*	% Total Solids				%*
Unit 1									
0	2.2	1.7	2.0	0	2.5	3.6	2.6	2.9	0
2	2.6	2.1	2.4	20	3.3	4.0	3.5	3.6	24
4	2.8	2.4	2.6	30	4.8	5.3	4.0	4.7	62
6	3.1	2.8	3.0	50	5.2	5.7	4.6	5.2	79
8	3.2	3.0	3.1	55	5.3	5.7	4.9	5.3	83
Unit 2									
0	2.4	2.4	2.4	0	3.6	4.5	3.0	3.7	0
2	2.6	2.7	2.7	13	4.6	4.9	4.0	4.5	22
4	2.7	3.0	2.9	21	4.9	5.2	4.5	4.9	32
6	2.7	3.1	2.9	21	5.2	5.3	4.8	5.1	38
8	2.9	3.1	3.0	25	5.2	5.4	5.0	5.2	41
Unit 3									
0	2.4	2.2	2.3	0	3.5	4.1	3.0	3.5	0
2	2.7	-	-	-	4.0	4.4	3.7	4.0	14
4	2.6	2.6	2.6	13	4.5	4.6	4.1	4.4	26
6	2.9	2.8	2.9	26	4.8	4.7	4.3	4.6	31
8	3.1	2.9	3.0	30	4.9	4.8	4.7	4.8	37
Unit 4									
0	3.9	5.1	4.5	0	3.9	4.8	3.5	4.1	0
2	4.1	5.5	4.8	7	4.5	5.5	4.5	4.8	17
4	4.0	5.7	4.9	9	4.6	6.0	5.1	5.2	27
6	4.1	5.8	5.0	11	4.9	6.0	5.4	5.4	32
8	4.2	5.8	5.0	11	5.2	6.1	5.8	5.7	39
Unit 5									
0	3.5	4.1	3.8	0	3.3	4.3	3.4	3.7	0
2	3.7	4.4	4.1	8	4.1	4.6	4.0	4.2	14
4	3.7	4.5	4.1	8	4.5	4.9	4.5	4.6	24
6	3.8	4.5	4.2	11	4.6	4.9	5.2	4.9	32
8	4.0	4.9	4.5	18	5.0	5.2	5.3	5.2	41

*Increase in total solids, % of initial value.
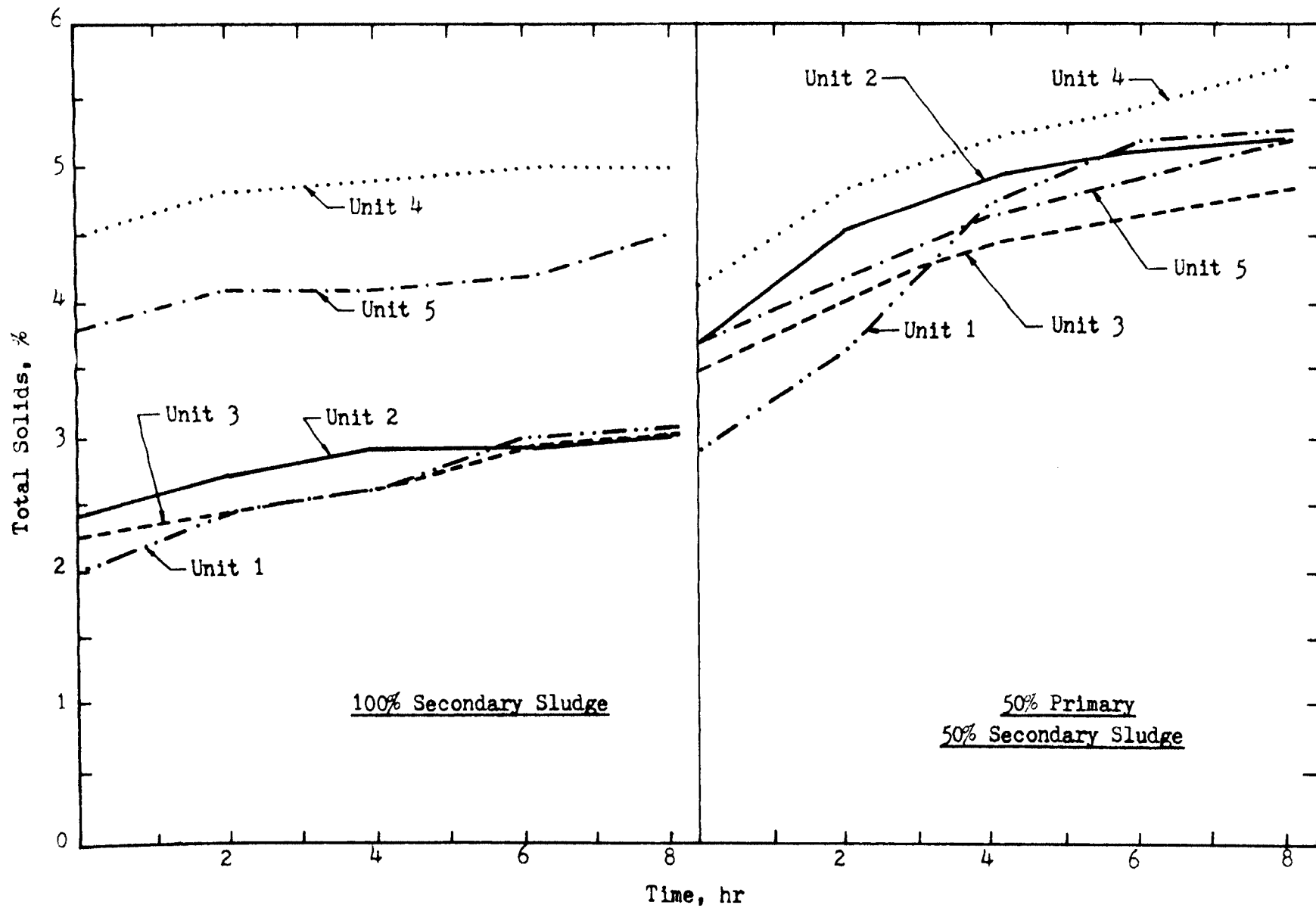
Figure 10. SLUDGE THICKENING AND DEWATERING STUDY - THICKENING DATA
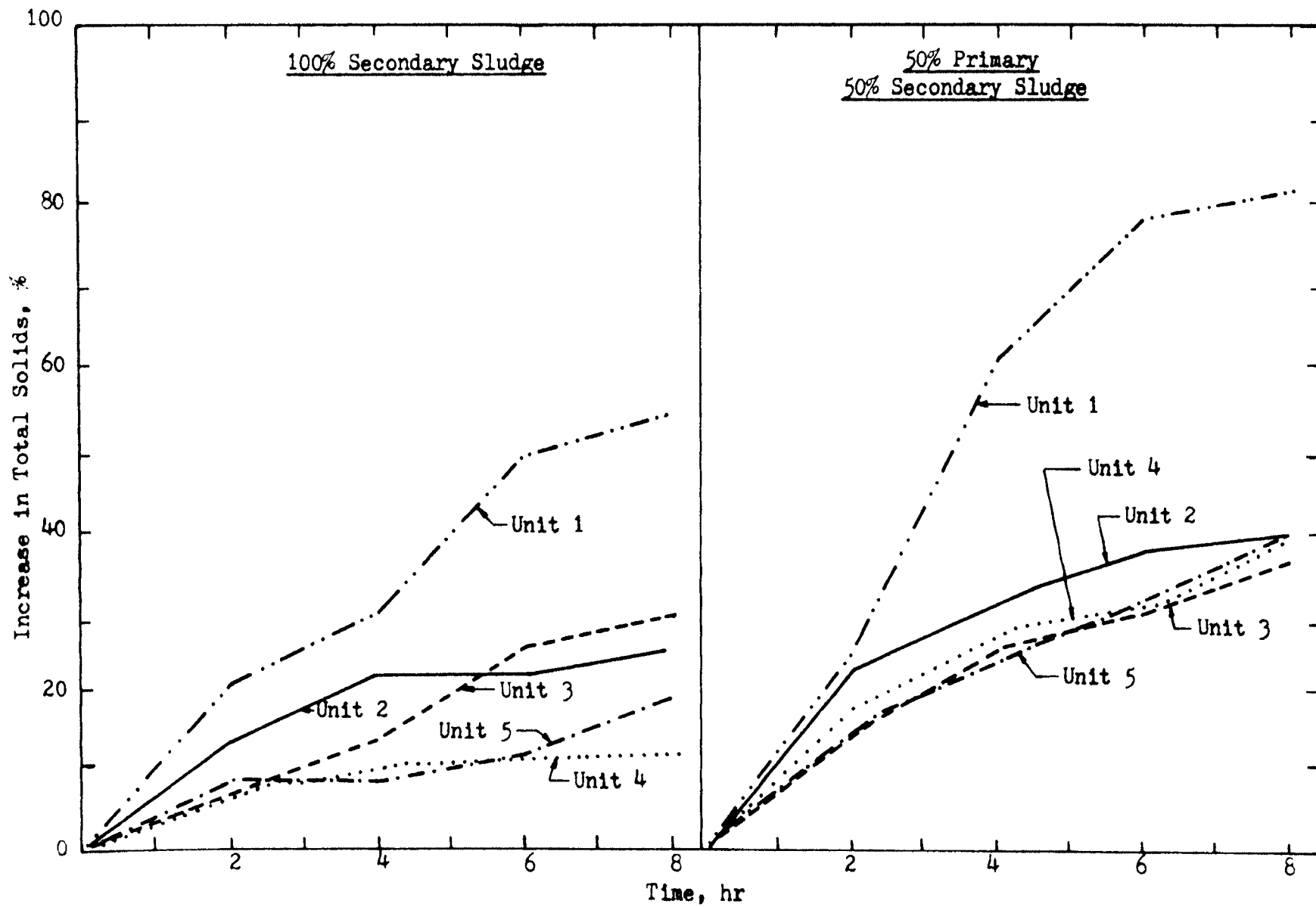
Figure 10 (continued). SLUDGE THICKENING AND DEWATERING STUDY - THICKENING DATA

along the top edge of the paddles to simulate the pickets which are employed in many full-scale thickeners. This configuration was used for Runs 2 and 3, however, during Run 3 the coarse mixture created by the addition of the primary sludge would not flow freely over the paddle surface and was simply pushed around the vessel. In an attempt to rectify this situation, the paddles were again modified and the configuration shown in Figure 4 was employed during Runs 4 and 5. The problem was somewhat relieved, but a certain amount of sludge still collected in front of the leading paddle surface.

The thickening ability of the paddles was not changed by the various modifications, and excellent results were obtained in all the runs. This is exemplified by comparing the results obtained with findings reported by other investigators (40,41,42). Sparr and Grippi (40) conducted thickening tests on conventional activated sludge, either alone or mixed with primary sludge, and employed 3-ft (0.9-m) long cylinders containing an elaborate stirring mechanism (details of the system were not presented). They reported that the total solids (TS) content of thickened secondary sludge ranged from 2.8 to 3.3 percent, and of the mixed sludge (at a 1 to 1 volume ratio of secondary to primary) varied between 5 and 6 percent. These values are comparable to those obtained in the present study. At plant-scale level, Torpey (41) obtained over a 7-month period at the Bowrey Bay Plant in New York City an average TS value of 6 percent for thickened secondary and primary sludge (40 percent secondary and 60 percent primary on a TS basis). Finally, values of 3 to 3.5 percent TS have been reported by Jordan and Scherer (42) for thickened conventional activated sludge at the Amarillo River Road Water Reclamation Plant in Texas.

Evaluation of Figure 10 would indicate that the separate thicken-
ing of the chemically-treated sludges would be of questionable value.
Considering the secondary sludges alone, the TS content of the Al^{+++}-
and Fe^{+++}-treated sludges after 8 hr of thickening was increased by
only 11 to 18, and 25 to 30 percent, respectively, while that of the
control was increased by 55 percent. With the addition of primary
sludge, the increase in TS improved to around 40 percent in Units 2
through 5, while it averaged 83 percent in Unit 1. Although the per-
cent increase in TS is a valuable tool in evaluating the effectiveness
of thickening, initial and final TS values must also be considered. The
secondary sludges containing Al^{+++} (Units 4 and 5) consolidated before
thickening to approximately 4 to 4.5 percent TS, while the sludges con-
taining Fe^{+++} (Units 2 and 3) and the control sludge (Unit 1) consoli-
dated to between 2 and 2.5 percent TS. These relatively high values
were obtained by allowing the sludge to settle under quiescent condit-
ions for at least 12 hr prior to conducting tests. It is doubtful
whether under normal plant operating conditions these values could be
achieved. Considering thickener feed sludge concentrations of between
0.5 and 1.5 percent TS, which may be more realistic at plant level, the
benefits realized, especially with Al^{+++}-treated sludges, would be much
greater. The TS concentration of the mixed primary and secondary
sludges was again much higher than would be expected under actual con-
ditions. It should be noted that the average thickener influent SS
concentration at the Bowrey Bay Plant was only 2880 mg/l (41). Al-
though this concentration may be low, even considering an influent
concentration of 2 percent (20,000 mg/l) TS and the values of thickened
sludge obtained in this study, the increase would be nearly 150 percent.

In any event, when the chemically-treated sludges were mixed with primary clarifier sludge, the degree of thickening was not significantly different from that of the control waste activated sludge mixed with primary sludge. However, when the secondary sludges alone were thickened, the Al^{+++}-treated sludge was more noticeable because of both its higher initial and final TS concentrations.

2. Vacuum Filtration Tests

The data obtained from the filtration tests are summarized in Table X and the volume of filtrate collected at various time intervals in each filter test, along with a sample calculation of specific resistance, are presented in Appendix A, p. 99. It should be pointed out that the time for the vacuum break to occur was in some cases longer than what has been presented in the appendix. In those instances, values were not recorded past the last entry listed as sufficient data had already been acquired for a specific resistance determination. It was necessary, however, to carry out filtration until a vacuum break did occur so that the final moisture content of the sludge could be determined.

One hundred ml samples of sludge were used for all tests with the exception of Unit 1 in Run 1 and Units 4 and 5 in Run 2. It was initially planned to use 200-ml samples throughout the study, however, after the sludge from Unit 1 required approximately 5 hr for the vacuum break to occur, the sample size was reduced. The sample size for Units 4 and 5 was again increased to 200 ml in Run 2 because the exceptionally fast filter time experienced in Run 1 indicated a need for a greater size sample. The specific resistance of the sludges increased significantly after Run 1, and consequently the sample size was again reduced during Runs 3 through 5.

Table X. SLUDGE THICKENING AND DEWATERING STUDY - VACUUM FILTRATION DATA

Run	Vacuum in. Hg	100% Primary Sludge				50% Primary-50% Secondary Sludge			
		% Total Solids		Filtrate COD, mg/l	$R^* \times 10^{-7}$ sec^2/g	% Total Solids		Filtrate COD, mg/l	$R^* \times 10^{-7}$ sec^2/g
		Initial	Final			Initial	Final		
Unit 1									
1	20	1.5	14.2	378	740	--	--	--	--
2	25	1.7	50.0	400	780	--	--	--	--
3	20	--	--	--	--	5.6	15.4	5450	190
4	20	--	--	--	--	6.9	29.0	3935	120
5	20	--	--	--	--	5.6	20.6	4840	510
Unit 2									
1	20	--	--	--	--	--	--	--	--
2	25	2.4	15.3	589	340	--	--	--	--
3	20	--	--	--	--	5.6	16.4	3720	400
4	20	--	--	--	--	6.3	27.5	3050	240
5	20	--	--	--	--	4.0	17.8	4390	110
Unit 3									
1	20	2.4	12.0	318	230	--	--	--	--
2	25	2.3	14.7	240	400	--	--	--	--
3	20	--	--	--	--	5.6	16.7	3570	330
4	20	--	--	--	--	5.3	16.8	2810	190
5	20	--	--	--	--	4.3	16.9	4100	120
Unit 4									
1	20	4.9	14.9	400	16	--	--	--	--
2	25	4.9	17.3	392	79	--	--	--	--
3	20	--	--	--	--	6.4	17.4	3600	330
4	20	--	--	--	--	6.3	15.5	3030	220
5	20	--	--	--	--	5.4	15.7	3920	120
Unit 5									
1	20	3.6	13.1	389	8.9	--	--	--	--
2	25	4.1	16.9	450	240	--	--	--	--
3	20	--	--	--	---	5.8	15.0	3570	250
4	20	--	--	--	---	6.4	21.0	3015	370
5	20	--	--	--	---	5.2	15.6	3770	140

*Specific resistance (for computations see Appendix A).

The final filter cake TS concentration (Table X) remained relatively constant for all the tests. The extremely high value determined for Unit 1 in Run 2 was not indicative, and it is felt that a sampling error or an error in reading the analytical balance may have been the cause of this value. However, recalculation of the specific resistance based on a TS concentration of 20 percent changed this value very little from 780×10^7 to 735×10^7. This would indicate that even a gross change in the filter cake moisture content had little effect on the specific resistance and that the major factor involved was the slope of the t/V versus V plot (see Figure A-1, Appendix A), or the dewatering rate.

The filtrate COD values (Table X) were relatively high in the tests where 100 percent secondary sludge was employed, and increased many fold with the addition of primary sludge. The COD must have been exerted primarily by soluble organics as little suspended matter was observed in the filtrate. A very strong putrid odor accompanied the high COD values.

The specific resistance values (Table X) fluctuated from run to run with the greatest change occurring between Runs 1 and 2. The low values determined in Run 1 could be attributed to a high (2.9 to 3.8) M/P ratio applied to the pilot plant units just prior to collection of the sludge on the 66th day (see Table I). The excess chemicals applied to the wastewater would have been free to act as sludge conditioners after precipitation of the phosphorus had taken place. Sludge for Run 2, which was collected on the 73rd day, reflected the low (0.9 to 1.0) M/P ratio applied to the units between Runs 1 and 2 with resulting higher sludge specific resistance values. The addition of

primary sludge to the secondary sludges resulted in decreased specific resistance of the control sludge and generally increased values for the other four sludges, although this was not always the case.

3. Centrifugation Tests

The laboratory method employed for sludge centrifugation was essentially the same as proposed by Vesilind (34). This investigator evaluated each variable that might have affected full-scale centrifuge performance and eliminated those that had little effect. By doing so, Vesilind limited the list to three: the relative centrifugal force (G), the residence time (t), and the scrolling characteristics of the sludge. The first two were easily controlled on a laboratory machine and by determining the TS concentration in the feed sludge and the centrate, the recovery efficiency, which is a measure of the settling characteristics of the sludge, could be determined for a given rotating speed* and residence time. The scrolling characteristic was defined by Vesilind as the consistency of the sludge cake, or how much body or strength it exhibited. It was measured by use of a penetrometer with the depth of penetration within the sludge cake as the variable. This particular variable was not measured quantitatively during these tests, as it was felt that for the purpose of this study visual evaluation and comparison of sludge cake body and strength would be sufficient.

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*The relative centrifugal force may be computed from the rotating speed and radius using the following formula (43).

$$G = 0.00001118 \times r \times N^2$$

where, G = relative centrifugal force, gravities
r = rotating radius, cm
N = rotating speed, rpm

The data obtained from the centrifugation tests are tabulated in Table XI and average values of the initial and final TS concentrations for each Gt value[*] are presented graphically in Figure 11. Most of the sludge samples collected for testing in the first run were used to standardize test procedures and to assist in selecting rotating speeds and residence times for use in the remaining runs. Twenty-four combinations of various rotating speeds and residence times were employed in Run 1 using 37-ml test tubes, and the percent sludge consolidation and centrate turbidities were measured. These data have not been presented in this thesis as they were of little value other than that already mentioned. It was concluded from these tests, however, that very little, if any, difference in sludge consolidation occurred during separate tests as long as the Gt values were equal. From this observation, it was decided that a residence time of 10 min would be used for the remainder of the study. This choice minimized the effects of start-up and shut-down on the test results and did not require a long waiting period between spinnings. To insure that the Gt value, and not the residence time, was the only major variable affecting the final TS concentration, a 3.8-min time and a 680 G-force (2000 rpm) were employed during Run 3 along with the standard 95, 170, and 260 G-forces (750, 1000, and 1250 rpm) and 10-min machine time. Slightly higher final TS concentrations were experienced at the higher G-force, however, the differences were not considered significant. The range of Gt values employed (950 to 2600 G-min) was based on an article by Albertson and Guidi (44) in which they reported that Merco Bowl

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[*]The Gt value was obtained by multiplying the relative centrifugal force (G) by the residence time in the machine (t); it was expressed in G-min.

Table XI. SLUDGE THICKENING AND DEWATERING STUDY - CENTRIFUGATION DATA

Run	G Force	Gt* G-min	100% Secondary Sludge					50% Primary-50% Secondary Sludge				
			% Solids				Centrate COD, mg/l	% Solids				Centrate COD, mg/l
			Initial	Final	Centrate	Capture		Initial	Final	Centrate	Capture	
Unit 1												
1	260	2600	1.4	4.4	0.25	94	660	3.6	11.2	0.36	97	3950
2	95	950	1.6	3.6	0.28	92	1470	3.8	8.6	0.29	97	5410
	170	1700	1.6	4.6	0.25	95	721	3.8	9.9	0.25	97	5210
	260	2600	1.6	5.5	0.24	96	695	3.8	11.8	0.24	98	5490
3	95	950	1.2	3.4	0.29	91	1410	2.6	8.0	0.28	97	3940
	170	1700	1.2	4.6	0.26	95	800	2.6	10.4	0.25	97	3940
	260	2600	1.2	5.4	0.25	95	675	2.6	10.6	0.24	98	3680
	680	2600	1.2	5.5	0.25	95	905	2.6	11.4	0.27	98	4100
Unit 2												
1	260	2600	2.6	5.3	0.21	96	575	4.3	9.4	0.36	96	3940
2	95	950	2.8	3.6	0.26	93	486	4.3	7.5	0.27	96	3840
	170	1700	2.8	4.6	0.25	95	535	4.3	8.6	0.26	97	4160
	260	2600	2.8	5.4	0.23	96	551	4.3	10.0	0.24	98	4400
3	95	950	2.5	3.6	0.28	92	680	3.1	6.6	0.24	96	3120
	170	1700	2.5	4.5	0.25	94	608	3.1	8.1	0.25	97	3190
	260	2600	2.5	5.2	0.23	96	545	3.1	8.9	0.24	97	2710
	680	2600	2.5	5.4	0.23	96	700	3.1	9.5	0.25	97	3510
Unit 3												
1	260	2600	2.5	5.0	0.20	96	535	4.6	9.8	0.35	96	3950
2	95	950	2.4	3.4	0.25	93.	423	4.3	7.8	0.25	97	3840
	170	1700	2.4	4.4	0.23	95	455	4.3	9.0	0.25	97	4550
	260	2600	2.4	5.1	0.22	96	551	4.3	10.4	0.22	98	4860
3	95	950	2.2	3.4	0.27	92	455	3.1	6.3	0.24	96	2990
	170	1700	2.2	4.1	0.25	94	410	3.1	8.1	0.22	97	3170
	260	2600	2.2	5.2	0.22	96	470	3.1	8.8	0.24	97	2840
	680	2600	2.2	5.3	0.21	96	605	3.1	8.6	0.26	97	3510
Unit 4												
1	260	2600	3.4	6.8	0.22	95	715	5.0	10.5	0.28	97	3950
2	95	950	3.8	5.7	0.28	95	611	4.6	8.0	0.30	96	3880
	170	1700	3.8	6.5	0.25	96	628	4.6	9.6	0.27	97	4080
	260	2600	3.8	7.5	0.23	97	710	4.6	10.6	0.25	97	4510
3	95	950	3.4	5.0	0.29	94	715	3.7	8.6	0.29	97	3840
	170	1700	3.4	6.8	0.25	96	685	3.7	9.6	0.27	97	3710
	260	2600	3.4	8.0	0.24	97	670	3.7	9.8	0.27	97	3180
	680	2600	3.4	8.2	0.24	97	710	3.7	11.2	0.25	98	3660

*A 10-min residence time was used with all tests, except that a 3.8-min time was used in Run 3 when a 680 G-force was employed.

Table XI (continued). SLUDGE THICKENING AND DEWATERING STUDY – CENTRIFUGATION DATA

Run	G Force	Gt* G-min	100% Secondary Sludge					50% Primary-50% Secondary Sludge				
			% Solids				Centrate COD, mg/l	% Solids				Centrate COD, mg/l
			Initial	Final	Centrate	Capture		Initial	Final	Centrate	Capture	
Unit 5												
1	260	2600	3.1	5.5	0.22	96	683	4.8	8.7	0.26	97	3940
2	95	950	2.8	4.3	0.26	94	753	4.0	7.4	0.28	96	3840
	170	1700	2.8	5.1	0.24	95	752	4.0	8.7	0.25	97	4200
	260	2600	2.8	5.4	0.21	96	883	4.0	10.0	0.24	98	4430
3	95	950	2.5	4.5	0.27	94	780	3.5	7.6	0.29	96	3940
	170	1700	2.5	5.0	0.25	95	653	3.5	9.1	0.23	97	3500
	260	2600	2.5	6.0	0.23	96	600	3.5	9.6	0.23	98	2940
	680	2600	2.5	6.1	0.24	96	690	3.5	9.3	0.23	98	3780

*A 10-min residence time was used with all tests, except that a 3.8-min time was used in Run 3 when a 680 G-force was employed.
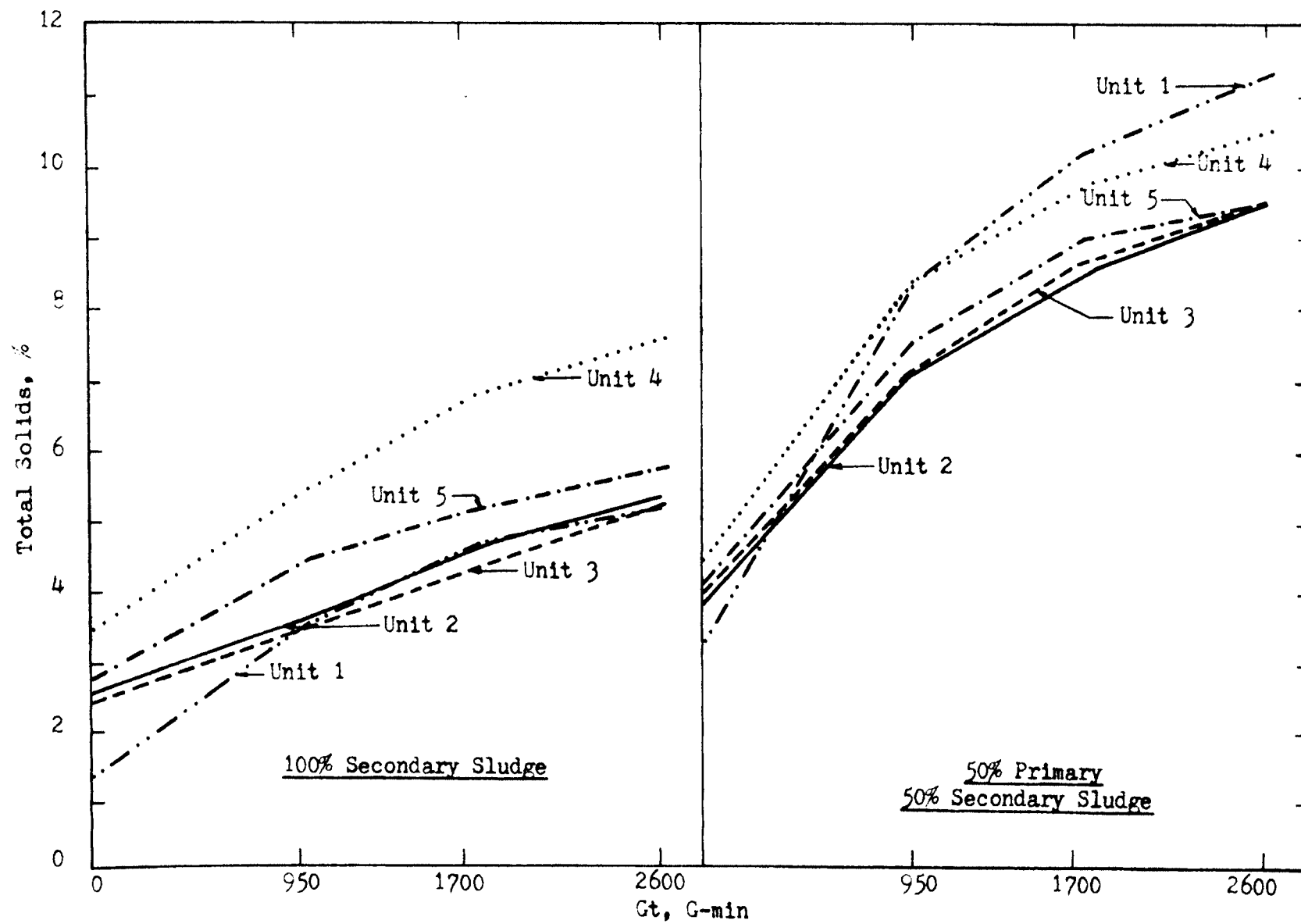
Figure 11. SLUDGE THICKENING AND DEWATERING STUDY - CENTRIFUGATION DATA

centrifuges operated at residence times varying between 0.25 and 1.25 min and G-forces ranging from 3,000 to 3,750; the resulting Gt values were 930 to 4,600 G-min. An error in determining the relative G-force associated with the rpm of the laboratory centrifuge, which was not detected until after the test runs had been completed, resulted in a lower Gt value actually being employed than originally planned. Consequently, the higher Gt limit used in actual practice was not reached.

The solids capture in mixed primary and secondary sludge during centrifugation in all tests, including those conducted on the control sludge, was at least 96 percent and exceeded the 80 to 95 percent values normally reported for full-scale operation (45, p.98). Solids capture values obtained in tests employing 100 percent secondary sludges were slightly lower and ranged from 91 to 96 percent. In neither case was there a significant difference between values obtained with the control sludge and the chemically-treated sludges.

The final sludge cake TS concentrations were lower than the 15 to 30 percent encountered in plant operation (45, p.98), both when 100 percent secondary sludge and combined primary and secondary sludge were tested. This was probably due to the lower Gt values employed during the laboratory tests. The addition of primary sludge caused a significant increase in cake solids, especially in the mixture containing the control sludge. In contrast, when 100 percent secondary sludge was tested, the Al^{+++}-treated sludge achieved the highest TS concentration, with the control and Fe^{+++}-treated sludges reaching almost identical values.

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The firmness or strength of the filter cakes was evaluated by attempting to pour or shake the samples from the centrifuge bottles. In all tests employing mixed sludges, the cakes could neither be poured or shaken from the centrifuge containers, irregardless of the G-force which had been employed. When 100 percent secondary sludge was tested, the sample from Unit 1 would flow after a Gt value of 950 G-min and could be shaken loose after a Gt value of 1700 G-min. None of the chemically-treated sludges would either flow or be shaken loose, however, irregardless of the Gt value.

4. Putrefaction Test

The gas production data obtained from the putrefaction study are presented in Table XII and shown graphically in Figure 12. No significant amounts of gas were produced until approximately the 7th day from Units 1, 3, 4, and 5, while a longer period of 12 days was required for Unit 2. The initial delay in gas production was believed to be due to a period of change from a predominantly aerobic bacterial population to an anaerobic population. The weight of VS contained in each putrefaction unit was computed on the basis of the total weight of the filtered sludge sample, an estimated TS concentration based on values obtained in previous vacuum filtration tests, and the volatile content of the MLSS contained in the pilot plant units prior to sludge collection. These computed values are shown below.

Unit	Control 1	Fe^{+++} 2	3	Al^{+++} 4	5
Cake VS, g	5.2	4.9	5.1	9.4	9.4

Table XII. SLUDGE THICKENING AND DEWATERING STUDY - PUTREFACTION DATA

Date	Time Days	Temper-ature* °C	Cumulative Gas Production, ml				
			Unit				
			1	2	3	4	5
3-29-71	0	-	0	0	0	0	0
4-1-71	3	24	28	14	0	19	28
4-3-71	5	23	28	14	0	19	28
4-5-71	7	23	28	14	5	34	28
4-6-71	8	24	38	14	15	49	36
4-10-71	12	26	61	14	46	105	64
4-12-71	14	26	82	32	70	156	89
4-13-71	15	24	89	38	76	173	97
4-19-71	21	25	116	79	105	235	194
4-24-71	26	22	175	139	161	308	280
4-26-71	28	24	186	157	178	338	308
4-28-71	30	23	187	165	184	349	318
4-30-71	32	23	193	173	192	355	327
5-31-71	63	-	251	253	312	477	463

*Ambient temperature in the laboratory.

Note: Each putrefaction unit was loaded with the cake obtained by vacuum filtration of 250 ml sludge from the corresponding activated sludge plants. The volatile solids content of each cake was as follows:

Unit	Cake VS, g
1	5.2
2	4.9
3	5.1
4	9.4
5	9.4
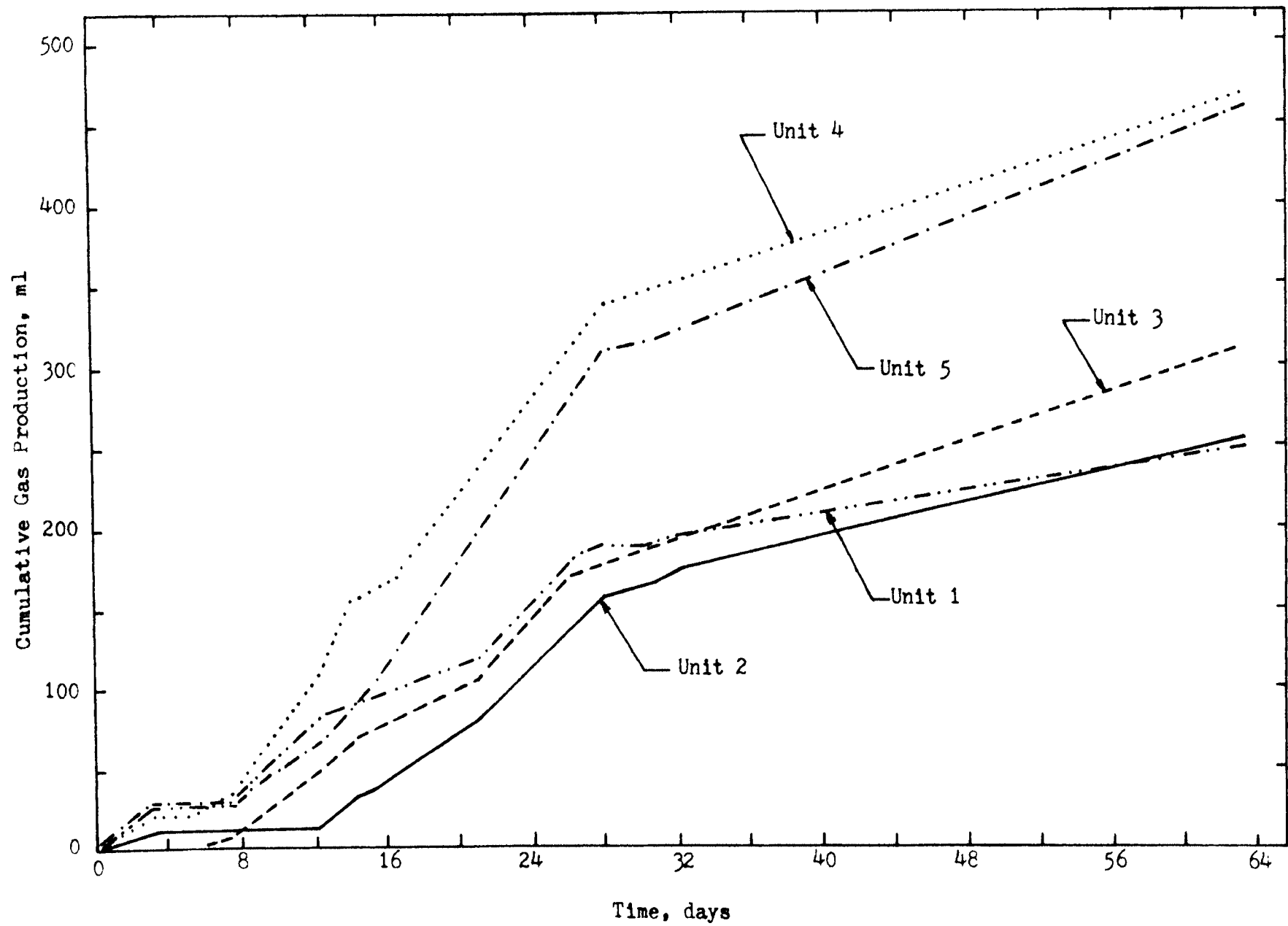
Figure 12. SLUDGE THICKENING AND DEWATERING STUDY - PUTREFACTION DATA

The higher total gas production associated with Units 4 and 5 (Figure 12) reflected the greater amounts of VS initially placed in those units. The quantities of gas which had been produced at the end of 63 days per unit weight of VS in the cake placed in each putrefaction unit were as follows:

Unit	Control 1	Fe^{+++} 2	3	Al^{+++} 4	5
Gas Produced, ml/g VS	48.3	51.6	61.2	50.8	49.3

Gas samples, collected by inserting the needle of a 10-ml syringe through the rubber stopper in each putrefaction unit, were analyzed on the Fisher Hamilton gas partitioner. Analyses were performed on two separate occasions and the results are shown below.

	Gas Content, % by Volume			
	26th Day		30th Day	
Unit	CH_4	CO_2	CH_4	CO_2
1	4	21	8	22
2	6	26	7	23
3	13	23	10	22
4	36	32	32	32
5	24	26	28	24

V. DISCUSSION

The direct addition of aluminum and iron salts to the activated sludge aeration chamber is today considered to be a practical approach in removing phosphorus from wastewater and thereby abating the nutrient enrichment of the receiving waters. This addition of chemicals has been reported to result in the formation of a sludge with characteristics which differ widely from conventional activated sludge. The weight of sludge produced is increased greatly, while its volatile content is decreased and its settleability and filterability are enhanced. The method normally employed in disposing biological sludge is anaerobic digestion followed by sludge drying, and studies have been conducted to investigate the feasibility of anaerobic treatment of the chemically-precipitated sludge. The results have been favorable, however, the increased weight of the sludge might necessitate additional digester capacity. The characteristics of the metal-treated sludge would indicate that consideration of other, perhaps more efficient, disposal methods may be warranted, yet little has been done to evaluate this possibility. Alternate disposal methods involve primarily dewatering by either vacuum filtration or centrifugation, followed by incineration or lagooning. The primary purpose of this research study was, therefore, to evaluate the thickening and dewatering characteristics of the chemically-treated sludge; and to determine the putrefactive characteristics of the dewatered sludge, an important factor in considering lagooning or direct land disposal.

Sludge for the disposal studies was produced in a five-unit activated sludge pilot plant system which was operated entirely in the field and duplicated, as closely as possible, conditions that would

exist in actual plant operation. The units, which were located at the Rolla Southeast Treatment Plant, were fed settled sewage drawn from the plant on a continuous basis and, consequently, were subjected to constantly changing feed strength and characteristics. Sludge developed in this system could, therefore, be expected to have characteristics which would be comparable to sludge produced in a plant-scale activated sludge unit. The primary advantage then of the pilot plant system was that it approximated prototype operation far better than a laboratory system could. Its use was not without certain liabilities; the smoothness, uniformity, and reproducibility of data possible in laboratory studies was not present in this research, and this made evaluation more difficult. Location of the equipment at the plant site subjected the system to uncontrollable environmental conditions and made it dependent upon the continued operation of the Rolla treatment facility; it also restricted the amount of supervision that could be exerted by the investigator. None the less, it is felt that the advantages associated with the field study far outweighed the inherent difficulties.

The experimental procedures used in the sludge disposal studies followed standardized techniques whenever possible. If appropriate methods were not available, procedures were developed as part of the study. The use of the Buchner funnel for vacuum filtration studies is well established and the procedure is relatively straightforward. Dewatering by centrifugation on a laboratory centrifuge has not been widely performed and the method used was fairly new. Although a number of thickening studies have been reported in the literature, descriptions of the laboratory test units which were employed were limited; it was, therefore, necessary to design and construct a

thickener especially for this study, and by trial and error modify it so that effective performance could be obtained. Likewise, the putrefaction equipment was designed and assembled for use in this research.

Test procedures were designed to enable as complete an investigation as was possible. The sludge disposal studies considered the major methods normally employed, and evaluated the thickening and dewatering characteristics of both chemically-treated secondary sludge and a mixture of primary and secondary sludge. Operation of the activated sludge pilot plants, necessary to provide metal-treated sludge for the disposal studies, was extended to allow the comparative evaluation of the effectiveness of Al^{+++} and Fe^{+++} in removing phosphorus from wastewater by chemical precipitation. Finally, the use of a control unit throughout the study made possible the comparison of the characteristics, including amenability to physical and biological treatment, of the chemical sludges with those of conventional activated sludge.

An evaluation of the results reported in the preceding chapter would indicate that the addition of chemical precipitants to the activated sludge aeration chamber had a beneficial effect on the treatability of the sludge from the standpoint of vacuum filtration, but did not significantly alter its thickening and centrifuging characteristics. Aluminum had a greater effect than Fe^{+++} on all the sludge characteristics studied. Very little difference in gas production and composition was experienced during the anaerobic digestion of the chemically-treated sludges and a control sludge. Addition of either Al^{+++} or Fe^{+++} to the activated sludge system effectively reduced

the concentration of phosphorus released in the effluent; however, greater removals were achieved with Al^{+++} than with Fe^{+++} when both were applied at equal M/P ratios.

Major findings obtained in the sludge disposal studies are summarized in Table XIII. As can be seen from the data presented in this table, the secondary sludges containing the metal precipitants consolidated to a greater initial TS concentration than the control, and this was also reflected in the mixtures of primary with secondary sludges. Thickening and centrifugation, however, had a more pronounced effect on the control sludge and the final TS concentrations achieved with the control and metal-treated sludges were essentially the same; this was true of both the biological and the combined sludges, although the degree of consolidation of the mixed sludges was greater. An exception was the Al^{+++}-precipitated secondary sludge which reached a higher final TS level, but this could be attributed to the initial TS content of this sludge which was greater. It should be noted that the presence of metals in the sludge resulted in centrifuge cakes which had improved scrolling characteristics; the firmness of the cake could be a deciding factor in this method of sludge dewatering and this is an area where additional research is needed.

Chemical treatment also enhanced the filterability of the activated sludge, evaluated in terms of specific resistance, with the greatest improvement found in the Al^{+++}-treated sludge. Addition of primary sludge apparently negated the beneficial effects of the chemicals and the specific resistance values of the metal precipitated and control sludges were essentially the same.

Table XIII. SLUDGE THICKENING AND DEWATERING STUDY - AVERAGE OPERATING CONDITIONS AND EXPERIMENTAL DATA

Characteristic	100% Secondary Sludge			50% Primary-50% Secondary Sludge		
	Secondary Sludge From Unit					
	1	2 & 3	4 & 5	1	2 & 3	4 & 5
	Metal Precipitant Used in Activated Sludge Aeration Chamber					
	Control	Fe^{+++}	Al^{+++}	Control	Fe^{+++}	Al^{+++}
Sludge Thickening Tests (at 4 to 5 rph)						
Total Solids, %						
Initial	2.0	2.4	4.2	2.9	3.6	3.9
Final (after 8-hr thickening)	3.1	3.0	4.8	5.3	5.0	5.4
Total Solids Increase, % of initial	55	28	14	83	39	40
Vacuum Filtration Tests at 20 to 25 in. Hg (508 to 635 mm Hg)						
Total Solids, %						
Initial	1.6	2.4	4.4	6.0	5.2	5.9
Final (at vacuum break)	14.2	14.0	15.5	21.6	18.7	16.7
Total Solids Increase, % of initial	790	483	252	260	260	183
Specific Resistance x 10^{-7}, sec^2/g	760	323	86	273	232	238
Filtrate COD, mg/l	389	382	408	4741	3606	3484
Centrifugation Tests (at 2600 G-min)						
Total Solids, %						
Initial	1.4	2.5	3.1	3.3	3.7	4.1
Final	5.2	5.2	6.7	11.2	9.4	10.0
Total Solids Capture, % of initial	95	96	96	98	97	98
Centrate						
COD, mg/l	734	567	708	4305	3715	3800
Total Solids, mg/l	2500	2200	2300	2800	2700	2500
Putrefaction Test (at 22 to 26°C)						
	Obtained by Vacuum Filtration of 250 ml Secondary Sludge					
Cake						
VS Content, g	5.2	5.0	9.4	--	--	--
Gas Produced (after 63 days), ml/g VS	48.3	56.5	50.0	--	--	--

The filtrate COD values were high, especially when primary sludge had been combined with the biological sludge; consequently, recycling of the filtrate would be necessary. High COD values were also determined in the centrate which, in addition, had a high total solids content; it may be noted that despite the release of solids in the centrate, the solids capture was excellent and was well above the normally anticipated range of 80 to 95 percent (45, p.98).

Evaluation of the putrefaction data indicated that all sludges produced essentially equal quantities of gas. A closed system was utilized in this study to simulate conditions that would exist when the dewatered sludge is disposed of by lagooning or land fill and is subjected to anaerobic microbial action.

The data obtained in the activated sludge and anaerobic digestion studies are summarized in Table XIV. The lower gas production rates associated with the digestion of the metal-treated sludges, compared to the production of the control sludge, were thought to reflect the presence of more stable organics in those sludges as a result of the chemical additions, and were not attributed to any inhibitory effects of the aluminum and iron in the sludge. Although the concentration that these metals reached in the digester sludge was not determined, based on the buildup of phosphorus in the digester (see p.60), it was assumed that no substantial release of metals occurred in the supernatant.

The removal of phosphorus in the activated sludge pilot plants was satisfactory, both when Fe^{+++} and Al^{+++} were added. The higher effluent residual associated with Units 2 and 3 (2.2 mg/l P), compared to that of Units 4 and 5 (1.4 mg/l P), indicates that Fe^{+++} was less

Table XIV. ACTIVATED SLUDGE AND ANAEROBIC DIGESTION STUDIES -
AVERAGE OPERATING CONDITIONS AND EXPERIMENTAL DATA

Characteristic	Unit		
	1	2 & 3	4 & 5
	Metal Precipitant Used		
	Control	Fe^{+++}	Al^{+++}
Activated Sludge Study			
Influent Settled Sewage			
Flow, l/day	142	142	144
Total Phosphorus, mg/l P		9.9	
COD, mg/l		229	
TSS, mg/l		77	
Metal to Phosphorus Ratio, M/P	-	1.6	1.6
Detention Time, hr			
Aeration Chamber	5.6	5.6	5.5
Clarification Chamber	1.5	1.5	1.5
Organic Loading, lb COD/day/cu ft	0.062	0.062	0.063
(kg COD/day/cu m)	(0.99)	(0.99)	(1.01)
MLSS, mg/l	2940	3970	4160
MLVSS, mg/l	2180	2290	2370
SVI	193	149	93
Settled Effluent			
Total Phosphorus, mg/l P	8.0	2.2	1.4
COD, mg/l	47	36	42
TSS, mg/l	7	8	12
Removal, %			
Total Phosphorus	19	78	86
COD	80	84	82
TSS	87	88	83
Anaerobic Digestion Study			
Sludge Feed	50% Primary-50% Secondary		
Organic Loading, lb VS/day/cu ft	0.16	0.18	0.22
(kg VS/day/cu m)	(2.56)	(2.80)	(3.52)
Detention Time, days	15		
Volatile Acids, mg/l as CH_3COOH	41	37	37
Gas Production, ml/day/l	1112	1011	1001

effective in precipitating phosphorus than Al^{+++}. This is further shown by the curves presented in Figure 13, which has been prepared to evaluate the effect of the M/P ratio on the removal of phosphorus. The values obtained in every phosphorus determination performed in this study are plotted in this figure and the curves shown were developed by means of the least squares method of curve fitting and an appropriate computer program; although all data points were used as input for the computer program, the curves have not been plotted past the M/P ratio of 3.0 because it was felt that insufficient data were available beyond that ratio. The curves, which represent 3rd degree polynomials, were selected as the best fit after attempts were made with linear, 2nd, 4th, and 5th degree polynomial, and logarithmic equations. It is interesting to note that the average phosphorus residuals and corresponding removals shown in Table XIV are essentially the same as the values which would be obtained from Figure 13. On the basis of the average M/P ratio of 1.6 which was applied in this study, phosphorus residuals of 2.3 and 1.2 mg/l P, and removals of 80 and 88 percent for iron and aluminum, respectively, were read from Figure 13, while the corresponding average values presented in Table XIV were 2.2 and 1.4 mg/l P, and 78 and 86 percent.

The performance of the activated sludge pilot plant units was excellent throughout the study. The quality of the effluents from the five units, both in terms of COD and SS, was better than the levels suggested in the effluent guidelines proposed by the Missouri Water Pollution Board (46) for streams other than the Missouri and Mississippi Rivers; the proposed effluent values are 80 mg/l COD and 20 mg/l SS. Although no limits have yet been established for the
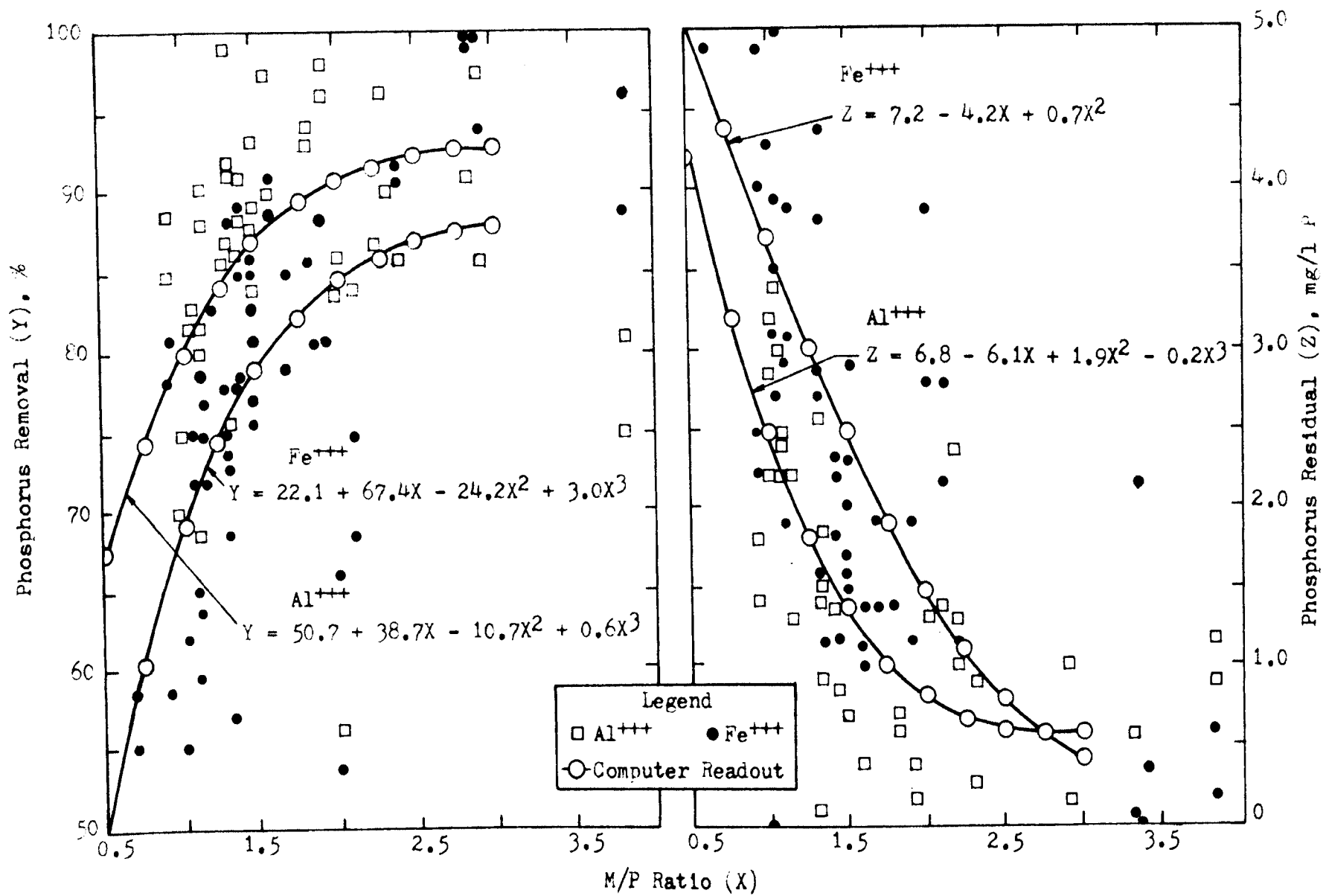
Figure 13. EFFECT OF THE METAL TO PHOSPHORUS RATIO ON PHOSPHORUS REMOVAL
BY CHEMICAL PRECIPITATION IN THE ACTIVATED SLUDGE AERATION CHAMBER

discharge of nutrients to Missouri waters, a minimum phosphorus removal of 80 percent is being considered in other states (5,7); this value was well exceeded when alum was employed, but was not quite reached when ferric chloride was used.

The selection of chemical feed (Fe^{+++} and Al^{+++}) concentrations used in this research was based solely on phosphorus removal considerations; it depended upon the influent phosphorus concentration to the activated sludge plants and a desired M/P ratio. The specific resistance values obtained in the vacuum filtration tests would indicate that, to a certain extent, M/P ratios greater than the optimum value for phosphorus removal resulted in vastly improved sludge filterability (see p.69). The determination of the chemical doses to be applied should, therefore, reflect not only the requirements for effective phosphorus removal, but also the optimum operation of the entire treatment plant, including the sludge disposal section.

This study has provided a valuable insight into the thickening and dewatering characteristics of the metal-containing sludge resulting from the removal of phosphorus by chemical precipitation and has attempted to consider the place of sludge disposal in the overall treatment scheme; additional work is needed, however, in order to further evaluate the sludge disposal methods, especially in the areas of incineration and direct land disposal of the dewatered sludge. The removal of phosphorus from wastewater will be required more and more in the future as regulatory standards become more stringent, and chemical precipitation in the activated sludge aeration chamber offers many advantages over other potential methods. It is, therefore, imperative that the design engineer be provided with the information

which will enable him to evaluate and select a method of disposal for the metal-treated sludge which would best fit in the overall treatment scheme, thereby allowing optimum plant operation and performance.

VI. CONCLUSIONS

On the basis of the findings of this investigation, the following conclusions may be drawn.

1. Ferric chloride and alum added directly to the aeration chamber of the activated sludge process effectively decreased the concentration of phosphorus released in the effluent; Fe^{+++} was not as effective a precipitant as Al^{+++}, and when both metals were applied at M/P ratios of 1.6, effluent phosphorus was reduced to 2.2 and 1.4 mg/l P, respectively.

2. The performance of the activated sludge pilot plants was excellent, even under the adverse environmental conditions encountered in the field, especially during the winter months; effluent COD and SS values averaged 47 and 12 mg/l or less, respectively, throughout the three-month study period.

3. The addition of Fe^{+++} and Al^{+++} resulted in an increased concentration of MLSS which had a decreased volatile fraction; the metal-treated sludges consolidated to a greater TS concentration than a control sludge which received no chemicals.

4. The metal-treated sludges, when combined with an equal volume of primary sludge, were effectively digested anaerobically; gas production and composition and volatile acids concentration were not significantly altered by the presence of the metals.

5. Thickening of the control sludge, either alone or mixed with an equal volume of primary sludge, was more effective than thickening of the chemically-treated sludges under the same experimental conditions; the multi-unit thickener was an effective and inexpensive

laboratory unit which was capable of developing reliable data comparable to those expected in plant operation.

6. Vacuum filtration of activated sludge was facilitated by the presence of the metal precipitants, especially Al^{+++}, as indicated by the corresponding specific resistance values; when primary sludge was combined with the secondary sludges, no appreciable difference was found in the filterability of the control and metal-treated sludges.

7. Centrifugation of the Al^{+++}-treated activated sludge produced a cake with a higher TS concentration than was obtained with the control of Fe^{+++}-treated sludge; when primary sludge was combined with the secondary sludges, the cake TS concentration increased and all sludges attained essentially the same final TS level.

8. The filtrates and centrates resulting from the vacuum filtration and centrifugation of the different sludges exhibited high COD values, especially when primary sludge was mixed with secondary sludge.

9. The dewatered metal-precipitated sludges demonstrated putrefactive characteristics which in terms of cumulative gas production were comparable to the characteristics of the control sludge.

10. The dewatering characteristics of the secondary sludge were enhanced by the presence of the metal precipitants, especially aluminum, but little improvement was obtained in the thickening characteristics; when the secondary sludges were combined with the primary sludge, very little difference was noted in the final characteristics attained by the metal-treated sludges and the control.

VII. RECOMMENDATIONS FOR FUTURE STUDY

On the basis of the findings of this investigation, the following areas are recommended for further study.

1. The selection of an optimum M/P ratio necessary to obtain both effective phosphorus removal and enhanced sludge dewatering characteristics should be investigated in order to maximize the overall plant performance.

2. The fate of the iron-precipitated phosphorus in anaerobic digestion, the effect of iron on the digestion process, and the potential release of iron in the digester supernatant should be further evaluated.

3. Thickening and dewatering studies should be conducted on a pilot-plant scale to further substantiate the laboratory findings obtained in this investigation.

4. The incineration of the dewatered sludge and potential subsequent recovery and reuse of the metal precipitants warrants additional study.

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VITA

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The author is an associate member of the Society of Sigma Xi and a student member of the Water Pollution Control Federation and the Missouri Water Pollution Control Association. He is an Engineer-in-Training in Michigan.

He was married to the former Deanna B. Appelget in 1964 and they have two boys, Delbert L. and Christopher W.

APPENDIX A

VACUUM FILTRATION DATA

AND SAMPLE CALCULATION OF SPECIFIC RESISTANCE

Vacuum filtration tests were performed using both 100 percent secondary sludge from the activated sludge pilot plants (Runs 1 and 2) and a mixture consisting of 50 percent secondary and 50 percent primary sludge from the Rolla plant (Runs 3, 4, and 5). The volume of filtrate obtained at different time intervals is given in Table A-1, and the initial and final TS concentrations and filtrate COD values are presented in Table X, p. 68. These data were employed in computing the specific resistance of the various sludges using the procedure described by Eckenfelder (26, p.240), and the values obtained are listed in Table X.

A sample computation of specific resistance, using data obtained for Unit 4 in Run 2, is outlined below. Specific resistance was determined from the following equations:

$$R = \frac{2bPA^2}{uc}$$

where, R = specific resistance, sec^2/g
b = slope of the plot of t/V versus V, sec/sq cm
t = filtration time, sec
V = volume of filtrate, ml
P = vacuum applied to filter, g/sq cm
A = area of filter, sq cm
u = viscosity of filtrate = 0.01 poises
c = weight of solids per unit volume of filtrate, g/ml

and

$$c = \frac{1}{C_i/(100-C_i) - C_f/(100-C_f)}$$

where, C_i = initial moisture content of sludge, %
C_f = final moisture content of sludge, %

From the t/V versus V plot shown in Figure A-1, the slope of the straight line portion was computed as:

$$b = \frac{6.4}{84.0} = 0.0762 \text{ sec/sq cm}$$

and from the initial and final moisture contents (Table X) c was computed as:

$$c = \frac{1}{95.1/4.9 - 82.7/17.3} = 0.0685 \text{ g/ml}$$

Knowing the area of the filter (63.6 sq cm) and the vacuum applied (25 in. Hg = 879 g/sq cm), the specific resistance was then computed:

$$R = \frac{(2)(0.0762)(879)(63.6)^2}{(0.01)(0.0685)} = 79 \times 10^7 \text{ sec}^2/\text{g}$$
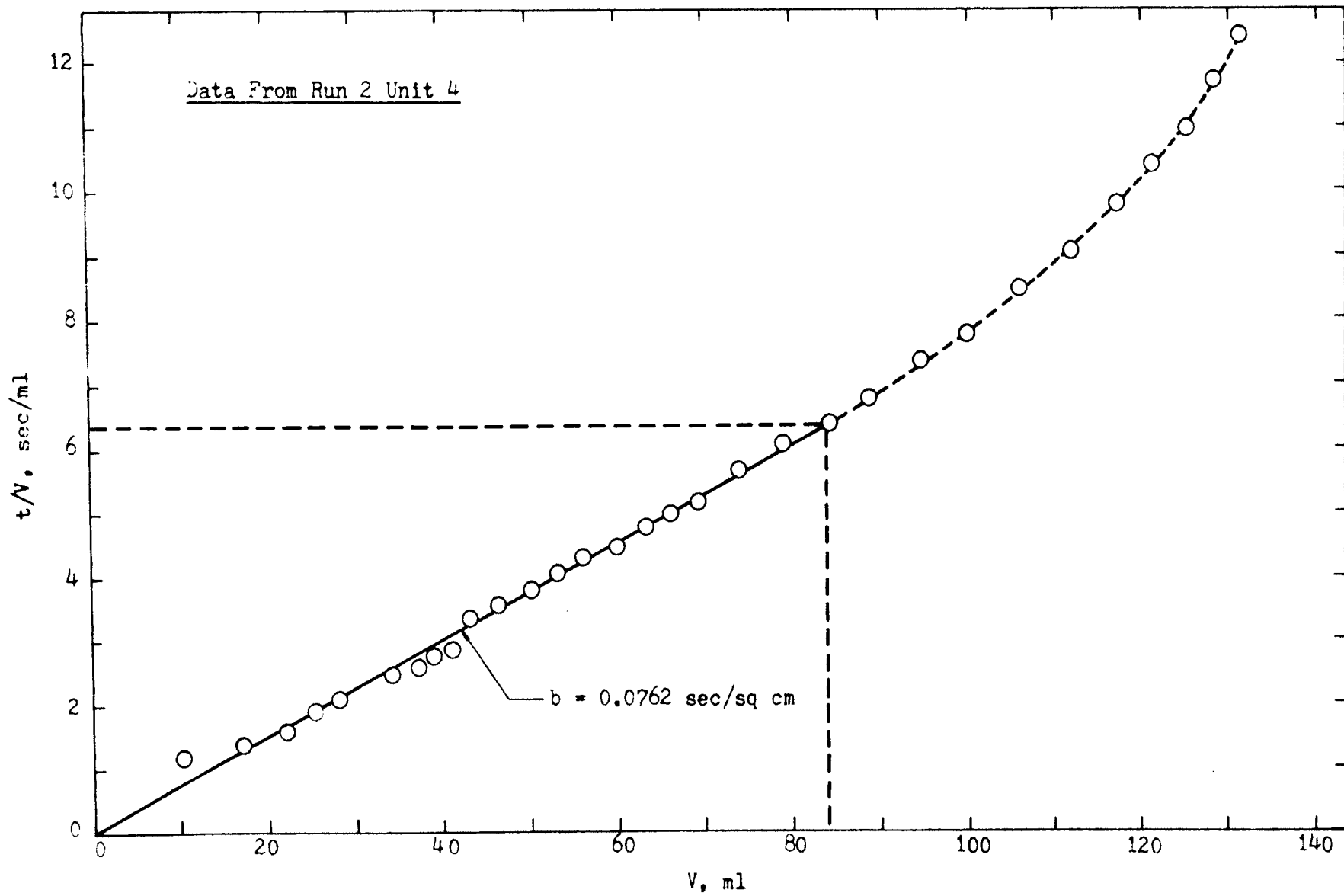
Figure A-1. VACUUM FILTRATION STUDY - DEVELOPMENT OF "b" FOR COMPUTATION OF SPECIFIC RESISTANCE

Table A-I. SLUDGE THICKENING AND DEWATERING STUDY - VACUUM FILTRATION DATA

Unit 1

Time (t)		Filtrate Volume (V), ml				
Min	Sec	Run 1	Run 2	Run 3	Run 4	Run 5
0	0	0	0	0	0	0
0.2	12	8.0	8.0	-	9.0	-
0.4	24	12.0	-	6.0	-	-
0.5	30	13.0	-	-	14.0	12.0
0.6	36	14.0	19.0	-	-	-
0.8	48	-	22.0	11.0	17.0	-
1.0	60	19.0	24.0	-	19.0	14.0
1.2	72	20.5	26.0	13.0	21.0	-
1.4	84	22.0	28.0	-	23.0	16.0
1.6	96	23.5	30.0	16.0	25.0	-
1.8	108	25.0	31.0	-	26.0	-
2.0	120	27.0	32.5	19.0	27.5	18.5
2.4	144	29.0	35.0	-	-	-
2.5	150	30.0	-	-	30.0	20.5
2.8	168	31.5	37.0	-	-	-
3.0	180	32.5	-	24.0	32.5	22.0
3.2	192	33.5	39.0	-	-	-
3.5	210	35.0	-	-	35.0	24.0
3.6	216	36.0	41.0	-	-	-
4.0	240	37.5	43.0	29.0	36.5	25.0
4.5	270	40.0	45.0	-	38.5	27.0
5.0	300	42.0	47.0	33.0	40.0	28.0
5.5	330	43.5	49.0	-	-	-
6.0	360	45.5	51.0	35.0	43.0	31.0
6.5	390	47.0	52.5	-	-	-
7.0	420	49.0	54.0	38.5	45.0	33.5
7.5	450	50.0	55.5	-	-	-
8.0	480	52.0	57.5	41.5	48.0	35.0
8.5	510	53.5	-	-	-	-
9.0	540	54.5	60.0	44.0	50.0	38.0
10.0	600	57.5	62.0	47.0	52.0	40.0
12.0	720	63.0	67.0	-	55.0	-
14.0	840	67.5	71.0	-	58.0	-
15.0	900	69.5	-	55.0	59.0	-
17.0	1020	74.0	75.0	-	-	51.0
20.0	1200	80.5	77.5	60.0	64.5	55.0
25.0	1500	89.0	81.0	64.0	68.0	61.0
30.0	1800	96.0	83.5	67.0*	70.5	65.0
35.0	2100	-	85.0		72.5	-
40.0	2400	110.0	86.0		74.0	73.0*
45.0	2700	116.0	-		75.0	
50.0	3000	122.0	88.0		76.0	
55.0	3300	127.0	-		76.5	
60.0	3600	131.0	90.0		77.0	
70.0	4200	139.0	-		78.0	
80.0	4800	146.0	92.0*		78.5*	
90.0	5400	150.0				
120.0	7200	162.0				
143.0	8580	166.5				

*Vacuum break.

Table A-I. SLUDGE THICKENING AND DEWATERING STUDY –
VACUUM FILTRATION DATA

Unit 1

Time (t)		Filtrate Volume (V), ml				
Min	Sec	Run 1	Run 2	Run 3	Run 4	Run 5
0	0	0	0	0	0	0
0.2	12	8.0	8.0	–	9.0	–
0.4	24	12.0	–	6.0	–	–
0.5	30	13.0	–	–	14.0	12.0
0.6	36	14.0	19.0	–	–	–
0.8	48	–	22.0	11.0	17.0	–
1.0	60	19.0	24.0	–	19.0	14.0
1.2	72	20.5	26.0	13.0	21.0	–
1.4	84	22.0	28.0	–	23.0	16.0
1.6	96	23.5	30.0	16.0	25.0	–
1.8	108	25.0	31.0	–	26.0	–
2.0	120	27.0	32.5	19.0	27.5	18.5
2.4	144	29.0	35.0	–	–	–
2.5	150	30.0	–	–	30.0	20.5
2.8	168	31.5	37.0	–	–	–
3.0	180	32.5	–	24.0	32.5	22.0
3.2	192	33.5	39.0	–	–	–
3.5	210	35.0	–	–	35.0	24.0
3.6	216	36.0	41.0	–	–	–
4.0	240	37.5	43.0	29.0	36.5	25.0
4.5	270	40.0	45.0	–	38.5	27.0
5.0	300	42.0	47.0	33.0	40.0	28.0
5.5	330	43.5	49.0	–	–	–
6.0	360	45.5	51.0	35.0	43.0	31.0
6.5	390	47.0	52.5	–	–	–
7.0	420	49.0	54.0	38.5	45.0	33.5
7.5	450	50.0	55.5	–	–	–
8.0	480	52.0	57.5	41.5	48.0	35.0
8.5	510	53.5	–	–	–	–
9.0	540	54.5	60.0	44.0	50.0	38.0
10.0	600	57.5	62.0	47.0	52.0	40.0
12.0	720	63.0	67.0	–	55.0	–
14.0	840	67.5	71.0	–	58.0	–
15.0	900	69.5	–	55.0	59.0	–
17.0	1020	74.0	75.0	–	–	51.0
20.0	1200	80.5	77.5	60.0	64.5	55.0
25.0	1500	89.0	81.0	64.0	68.0	61.0
30.0	1800	96.0	83.5	67.0*	70.5	65.0
35.0	2100	–	85.0		72.5	–
40.0	2400	110.0	86.0		74.0	73.0*
45.0	2700	116.0	–		75.0	
50.0	3000	122.0	88.0		76.0	
55.0	3300	127.0	–		76.5	
60.0	3600	131.0	90.0		77.0	
70.0	4200	139.0	–		78.0	
80.0	4800	146.0	92.0*		78.5*	
90.0	5400	150.0				
120.0	7200	162.0				
143.0	8580	166.5				

*Vacuum break.

Table A-I (continued). SLUDGE THICKENING AND DEWATERING STUDY -
VACUUM FILTRATION DATA

Unit 2

Time (t)		Filtrate Volume (V), ml				
Min	Sec	Run 1	Run 2	Run 3	Run 4	Run 5
0	0		0	0	0	0
0.2	12		12.0	-	12.0	-
0.4	24		17.0	-	-	-
0.5	30		-	-	-	28.0
0.6	36		21.0	10.0	18.0	-
0.8	48		23.0	11.0	20.0	-
1.0	60		26.0	12.0	22.0	36.0
1.2	72		28.0	-	23.0	-
1.4	84		30.0	-	24.0	-
1.5	90		-	14.0	-	41.0
1.6	96		32.0	-	25.0	-
1.8	108		33.0	-	26.0	-
2.0	120		35.0	16.0	27.5	47.0
2.4	144		37.5	-	-	-
2.5	150		-	18.5	30.5	50.0
2.8	168		40.0	-	-	-
3.0	180		-	20.0	33.0	54.0
3.2	192		43.0	-	-	-
3.5	210		-	21.5	34.5	58.0
3.6	216		45.0	-	-	-
4.0	240		47.0	23.0	37.0	61.0
4.5	270		50.0	24.5	39.0	63.0
5.0	300		52.0	25.5	41.0	65.0
6.0	360		56.0	28.0	44.5	69.0
7.0	420		60.0	30.0	47.5	71.0
8.0	480		63.5	32.0	50.0	73.5
9.0	540		66.0	33.5	52.0	75.0
10.0	600		69.0	35.0	53.5	76.5
11.0	660		-	-	56.0	78.0*
12.0	720		73.0	-	57.0	
13.0	780		76.0*	-	58.5	
14.0	840			-	60.0	
15.0	900			42.0	61.0	
20.0	1200			48.0	66.5*	
25.0	1500			52.0		
30.0	1800			56.0		
35.0	2100			59.0		
40.0	2400			62.0		

Run 1: Incomplete vacuum seal - sludge lost to filtrate

*Vacuum break.

Table A-I (continued). SLUDGE THICKENING AND DEWATERING STUDY -
VACUUM FILTRATION DATA

Unit 3

Time (t)		Filtrate Volume (V), ml				
Min	Sec	Run 1	Run 2	Run 3	Run 4	Run 5
0	0	0	0	0	0	0
0.2	12	-	10.0	-	-	-
0.4	24	-	19.0	-	-	-
0.5	30	5.0	23.0	-	-	10.0
0.6	36	-	26.0	-	17.0	-
0.8	48	-	29.0	11.0	20.0	-
1.0	60	10.0	31.0	12.0	22.0	19.0
1.2	72	-	34.0	-	24.0	-
1.4	84	-	35.0	14.5	25.0	-
1.5	90	14.0	37.0	-	-	24.0
1.6	96	-	39.0	-	26.0	-
1.8	108	-	41.0	16.5	27.0	-
2.0	120	17.0	44.0	-	28.5	28.0
2.2	132	-	-	18.0	-	-
2.4	144	-	47.0	-	-	-
2.6	156	-	-	19.0	31.5	32.0
2.8	168	-	49.0	-	-	-
3.0	180	23.0	-	20.5	33.5	38.0
3.5	210	26.5	51.0	-	35.5	41.0
4.0	240	29.0	54.0	23.5	37.0	44.0
4.5	270	32.0	56.0	-	39.0	47.0
5.0	300	34.5	60.0	26.0	41.0	50.0
5.5	330	37.0	-	-	-	-
6.0	360	39.0	64.0	28.0	44.0	52.0
6.5	390	41.5	-	-	-	-
7.0	420	43.5	67.0	30.0	47.0	56.0
7.5	450	45.5	-	-	-	-
8.0	480	47.5	70.0	32.0	49.0	60.0
8.5	510	49.5	-	-	-	-
9.0	540	51.5	72.0	33.0	51.0	62.0
9.5	570	53.0	-	-	-	-
10.0	600	54.5	75.0	35.5	53.0	65.0
11.0	660	57.0	-	-	55.0	67.0
12.0	720	59.5	78.0	-	56.5	69.0
13.0	780	61.5	-	-	58.5	71.0
14.0	840	63.0	79.5	-	60.0	72.0
15.0	900	65.0	-	42.0	61.0	73.0*
16.0	960	66.0	81.5	-	-	
17.0	1020	67.0	-	-	-	
18.0	1080	68.5	83.5*	-	-	
19.0	1140	69.5		-	-	
20.0	1200	70.0*		47.0	66.5	
25.0	1500			52.0	70.5*	
31.0	1860			56.0		
38.0	2280			60.0		
42.0	2520			62.0		

*Vacuum break.

Table A-I (continued). SLUDGE THICKENING AND DEWATERING STUDY - VACUUM FILTRATION DATA

Unit 4

Time (t)		Filtrate Volume (V), ml				
Min	Sec	Run 1	Run 2	Run 3	Run 4	Run 5
0	0	0	0	0	0	0
0.1	6	10.0	-	-	-	-
0.2	12	20.0	10.0	3.0	-	-
0.3	18	25.0	-	-	-	-
0.4	24	30.0	17.0	6.0	-	12.0
0.5	30	35.0	-	-	-	-
0.6	36	37.0	22.0	9.0	9.0	-
0.7	42	41.0	-	-	-	-
0.8	48	43.0	25.0	10.0	15.0	17.0
0.9	54	47.0	-	-	-	-
1.0	60	50.0	28.0	-	23.0	-
1.2	72	56.0	-	12.0	24.0	22.0
1.4	84	60.0	34.0	12.5	25.0	-
1.5	90	-	-	-	-	-
1.6	96	62.0	37.0	14.0	26.0	26.0
1.8	108	65.0	39.0	15.0	28.0	-
2.0	120	67.0*	41.0	15.5	28.0	29.0
2.4	144		43.0	-	-	-
2.5	150		-	-	30.0	32.0
2.8	168		46.5	-	-	-
3.0	180		-	19.0	32.0	35.0
3.2	192		50.0	-	-	-
3.5	210		-	-	34.0	37.0
3.6	216		53.0	-	-	-
4.0	240		56.0	22.0	35.0	40.0
4.5	270		60.0	-	37.0	43.0
5.0	300		63.0	25.0	38.0	45.0
5.5	330		66.0	-	-	-
6.0	360		69.0	27.5	41.0	47.0
7.0	420		74.0	29.5	44.0	50.0
8.0	480		79.0	31.0	45.0	54.0
9.0	540		84.0	33.0	47.0	56.0
10.0	600		88.5	35.0	49.0	59.0
11.0	660		-	-	50.5	61.0
12.0	720		97.0	-	52.0	63.0
13.0	780		100.0	-	53.5	65.0
14.0	840		-	-	54.5	67.0*
15.0	900		106.0	42.0	56.0	
17.0	960		112.0	-	-	
19.0	1020		117.0	-	-	
20.0	1080		-	47.0	59.0*	
21.0	1140		121.0	-		
23.0	1260		125.0	-		
25.0	1500		128.0	51.0		
27.0	1620		131.0	-		
29.0	1740		133.0	-		
30.0	1800		135.0	55.0		
35.0	2100		138.5	58.0		

*Vacuum break.

Table A-I (continued). SLUDGE THICKENING AND DEWATERING STUDY -
VACUUM FILTRATION DATA

Unit 5

Time (t)		Filtrate Volume (V), ml				
Min	Sec	Run 1	Run 2	Run 3	Run 4	Run 5
0	0	0	0	0	0	0
0.1	6	13.0	-	-	-	-
0.2	12	27.0	-	2.0	-	-
0.3	18	37.0	-	-	-	-
0.4	24	43.0	10.0	5.0	0	15.0
0.5	30	50.0	-	-	-	-
0.6	36	56.0	14.0	8.0	4.0	-
0.7	42	60.0	-	-	-	-
0.8	48	65.0	-	10.0	5.0	18.0
0.9	54	68.0	-	-	-	-
1.0	60	71.0*	20.0	12.0	6.0	-
1.2	72		-	13.5	-	22.0
1.4	84		25.0	14.0	8.5	-
1.6	96		-	15.0	-	25.0
1.8	108		28.0	15.5	10.0	-
2.0	120		-	16.0	11.0	28.0
2.2	132		32.0	-	-	-
2.5	150		-	19.0	13.0	31.0
2.6	156		34.0	-	-	-
3.0	180		36.0	21.0	15.0	33.0
3.5	210		39.5	23.0	16.0	36.0
4.0	240		42.0	25.0	17.5	38.0
4.5	270		44.5	26.0	19.0	40.0
5.0	300		47.0	28.0	20.0	42.0
6.0	360		51.0	31.0	23.0	45.0
7.0	420		54.5	33.0	25.0	49.0
8.0	480		58.0	36.0	27.0	52.0
9.0	540		61.0	38.0	29.0	55.0
10.0	600		64.0	40.0	30.0	57.0
11.0	660		-	-	31.0	59.0
12.0	720		69.5	43.5	33.0	61.0
13.0	780		-	-	34.0	63.0
14.0	840		74.5	-	35.5	65.0
15.0	900		-	48.0	36.5	67.0*
18.0	1080		84.0	52.5	-	
20.0	1200		88.0	-	41.5	
23.0	1380		92.0	57.5	-	
25.0	1500		96.0	60.0*	46.5	
30.0	1800		105.0		51.0	
35.0	2100		113.5		54.0	
40.0	2400		120.5		57.0	
45.0	2700		126.5		-	
50.0	3000		131.0		60.0*	
60.0	3600		136.0			
65.0	3900		143.5			

*Vacuum break.

APPENDIX B

ABBREVIATIONS

The following abbreviations, in use by the Journal Water Pollution Control Federation (47), have been employed in this thesis.

afternoon	PM
average	avg
before noon	AM
centimeter	cm
chemical oxygen demand	COD
cubic foot (feet)	cu ft
cubic meter (s)	cu m
degree (s) Celsius	^{o}C
diameter	diam
foot (feet)	ft
gallon (s)	gal
gallons per day	gpd
gram (s)	g
gravity, force due to	G
hour (s)	hr
inch (es)	in.
inside diameter	ID
kilogram (s)	kg
liter (s)	l
meter (s)	m
micron (s)	μ
milligrams per liter	mg/l
millimicron (s)	mμ
milliliter (s)	ml
million gallons	mil gal
million gallons per day	mgd
minimum and minute (s)	min
mixed liquor suspended solids	MLSS
mixed liquor volatile suspended solids	MLVSS
normal	N
number (s)	No.
pound (s)	lb
pounds per day per cubic foot	lb/day/cu ft
revolutions per minute	rpm
revolutions per hour	rph
second (s)	sec
sludge density index	SDI
sludge volume index	SVI
sludge age	SA
suspended solids	SS
total solids	TS
total suspended solids	TSS
volatile solids	VS
volatile suspended solids	VSS
volt	v
watt	w