NITRIFICATION AND HEAVY METAL REMOVAL
IN THE ACTIVATED SLUDGE TREATMENT PROCESS

A Dissertation

by

PAUL ALLEN RICHARDS

Submitted to the Graduate College of
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ABSTRACT

Nitrification and Heavy Metal Removal in the Activated

Sludge Treatment Process. (August 1976)

Paul Allen Richards, B.S., University of Southwestern Louisiana;

M.S., Texas A&M University

Chairman of Advisory Committee: Dr. Roy W. Hann, Jr.

A bench-scale, continuous flow, completely mixed activated sludge system was used to investigate the relationship of nitrification and other system parameters to heavy metal removal in the activated sludge waste treatment process.

The heavy metals studied were chromium, at concentrations ranging from 0.1 to 10.0 milligrams per liter, and silver, at concentrations ranging from 0.1 to 0.5 milligram per liter in settled primary domestic sewage. Analyses performed on the influent, mixed liquor, return sludge, and effluent included heavy metal concentration, pH, dissolved oxygen, temperature, suspended solids, chemical oxygen demand, nitrogen species, alkalinity, and other system control parameters.

Results indicate that the sludge wasting rate is directly related to heavy metal removal. Nitrification is only indirectly related, since sludge wasting controls sludge age which in turn determines the degree of nitrification.

A theory for the mechanisms contributing to heavy metal removal is developed. The capability of activated sludge to concentrate heavy metals is the main phenomenon involved. Sludge wasting is the key mechanism affecting heavy metal removal from the system.

ACKNOWLEDGEMENTS

DEDICATION

To Ann

for courage, bravery, endurance, and self-
sacrifice far above and beyond her vow to
me in the presence of The Almighty Father
of, "...for better, for worse, for richer,
for poorer, in sickness and in health...".

Herewith and in His presence, I
reaffirm my vow to you, "... until death
do us part."   Amen

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CHAPTER I

INTRODUCTION

This dissertation is a report of research conducted:

1. to investigate a potential relationship of nitrification to heavy metal removal in an activated sludge waste treatment system.

2. to compare heavy metal concentrations, at critical points within an activated sludge waste treatment system, to important waste characteristics and important system control parameters for the purpose of developing operating relationships which would be useful in optimum biological treatment of wastewater containing heavy metals.

Research reported in the literature and discussed in Chapter II has employed bench-scale, continuous flow, completely mixed activated sludge systems to study the effect of heavy metals on the treatment system or trace the fate of heavy metals through the system. Other recent research has employed batch-test systems to study the kinetics of heavy metal removal by the activated sludge process.

This research differs markedly from previous studies and is unique in that a bench-scale, continuous flow, completely mixed activated sludge system was used to study specific heavy metal removal by activated sludge treatment. The use of a continuous

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The *Journal Water Pollution Control Federation* has been used as a guide for format and style.

flow system permits more valid extrapolation of results to prototype activated sludge plants by allowing simulation of full-scale plant operation.

The activated sludge system employed consisted of separate aeration and sedimentation units with intermittent sludge recycle. Settled primary domestic sewage was used as the wastewater influent. The influent was spiked with chromium concentrations ranging from 0.1 milligram per liter to 10.0 milligrams per liter, and silver concentrations ranging from 0.1 milligram per liter to 0.5 milligram per liter. The duration of continuous operation and periodic sampling and testing was approximately four months for the chromium study and three weeks for the silver study.

Samples were taken of the influent, mixed liquor, return sludge, and effluent. The parameters monitored included heavy metal concentration, pH, dissolved oxygen, temperature, suspended solids, chemical oxygen demand, nitrogen species, alkalinity, and other system operation control parameters.

CHAPTER II

LITERATURE REVIEW

Concern for heavy metals in the nation's waters has been increasing rapidly. The toxicity of such heavy metals as mercury and lead with their associated crippling effects, and, in many cases, resultant death, has prompted concerted efforts to determine allowable, safe concentrations of heavy metals in waters used by man.[1-4]

Heavy metals occur naturally in surface waters because of chemical weathering, volcanic activity, and biochemical weathering.[5] Since background concentrations of heavy metals exist naturally, it is imperative to assure that any man-initiated process does not result in toxic concentrations of heavy metals. The heavy metals in question include aluminum, silver, arsenic, cadmium, chromium, copper, iron, mercury, manganese, lead, nickel, zinc, and cobalt.[6] The industrial processes which have heavy metals in their wastewater discharges include pulp and paper mills, organic chemical and petrochemical industries, fertilizer manufacture plants, basic steel works and foundries, basic non-ferrous metal-works and foundries, motor vehicle and aircraft-plating and finishing processes, and photochemical processing.[6] Treatment of wastewaters for removal of heavy metals, even in trace quantities, has presented a challenge to engineers.

As early as 1928,[7] problems associated with treating trade or industrial wastes in domestic sewage treatment plants have been reported. In this early account, Russel recommended treatment by the industry to prevent deleterious effects on the sewage treatment plant.

The literature associated with various effects of industrial wastes on domestic sewage treatment plants has steadily increased since 1928.[8-34] Heavy metals have been recently termed "the nemesis of any biological treatment plant".[35] Indeed, heavy metals have caused considerable problems with the operation of biological sewage treatment plants through the years; however, these plants were not designed or operated to handle heavy metal industrial wastes. In general, the trend has been to eliminate or at least reduce the strength of industrial wastes at the source prior to treatment at a domestic sewage treatment plant. Industry has recognized the problems associated with discharging toxic wastes directly into sanitary sewerage, and has expended great effort in attempting to pretreat its wastewater. The expense involved forced industrial plants to seek more economical means of treatment, and valuable waste material recovery logically followed.

Waste material recovery has largely been accomplished by physical-chemical treatment and through these efforts physical-chemical treatment has evolved as the most economically feasible means of treating or pretreating such wastes. The physical-chemical techniques currently used include chemical precipitation, electrodeposition, cementation, solvent extraction, ultrafiltration, ion exchange, and activated carbon adsorption among others.[6,36]

Heavy metal toxicity associated with biological treatment has been studied to gain a better understanding of the toxic effects to determine the feasibility of using biological treatment modified or designed to handle metal wastes.[37-74] In many cases, different

workers have reported different toxic levels for the same heavy metal. Abelson and Aldous[48] and MacLeod and Snell[49] found the toxicity to *Escherichia coli* and *Aerobacter aerogenes* to be markedly reduced by the presence of considerable amounts of magnesium. Moore, et al.[54] found that short of massive slug doses, hexavalent chromium (Cr^{+6}) did did not harm an activated sludge process such that it could not recover. In one test conducted, 500 milligrams per liter (mg/l) Cr^{+6} fed to an unacclimated activated sludge system for four hours did reduce system efficiency in terms of oxygen demand removal; however, recovery to normal performance occurred in four days. In this same study, nitrification was found to be inhibited even at lower Cr^{+6} concentrations, but after about ten days, nitrification returned to normal levels regardless of Cr^{+6} concentration; clearly demonstrating the ability of nitrifiers to acclimate to Cr^{+6}.

Thus, subtle differences in biological processes used by different workers could be a factor in the toxic level variations reported. The toxic level variations reported in the literature prompted Moulton and Directo[61] to formulate and publish a standardized procedure for determining toxicity to activated sludge. Therefore, with appropriate operation, the activated sludge process may be able to effectively treat a metal-bearing wastewater without deleterious effects to the system.

Studies of heavy metals removal by biological systems have been reported.[75-87] In these studies, the workers reported on the toxic level of a heavy metal or traced the fate of metals through a biological treatment system. Rudolfs and Zuber[75] concluded that the absorption

capacity of sludges may be used for heavy metal removal. Ruchhoft[76] reported that radioactive plutonium could be efficiently removed by absorption into the activated sludge zoogleal mass. Oliver and Cosgrove[77] concluded that heavy metal removal by activated sludge occurred in two stages: first, by primary settling; and second, by adsorption to the biological floc, with subsequent settling in secondary clarifiers. It was further concluded that all metals removed were concentrated in the sludge; and, accordingly, some method should be developed to recover the metals from the sludge. Stones[78-82] reported on removal efficiencies for several metals by an activated sludge process and concluded in each case that the metals were concentrated (removed) by the sludge. LeFebvre and Callahan[84], reporting on studies of activated sludge treatment of photoprocessing waste, concluded that the extreme toxicity of the waste to activated sludge organisms was caused by silver (Ag) accumulation in the sludge and further recommended that desilvered photoprocessing waste should not exceed 0.05 percent of the total waste influent. This waste concentration was equivalent to an upper limit of 0.03 mg/1 Ag. Thomas and LeFebvre[85] reiterated the same general conclusions. In this later report, biological sludge was found to be capable of concentrating silver at concentrations reaching 20.2 micrograms Ag per gram of sludge. Dagon[86] and most recently Bard, et al.[87] have reported on successful activated sludge treatment of photoprocessing waste at much higher concentrations. Silver concentrations greater than 250 mg/1 had no adverse effect on activated sludge systems. Only

in very recent published work have the kinetics of metal removal been reported.

Neufeld and Hermann[88] have very recently reported data on the kinetics of heavy metal interactions in the activated sludge process with an acclimated biomass. Their research specifically addressed itself to biomass production and respiration parameters, process design kinetics, and metal-sludge balance with the objective of determining the feasibility of aerobic, completely mixed treatment of industrial wastes containing high concentrations of heavy metals. The experimental procedures employed a batch-type laboratory reactor which was shock loaded up to 1,000 mg/l with a heavy metal in the soluble chloride form. Neufeld and Hermann concluded that an acclimated culture of high biomass concentration can be used to treat a waste with high food value (COD) which additionally contains high concentrations of heavy metals.

Cheng, et al.[89] conducted similar research to that of Neufeld and Hermann. Their experimental procedures also employed batch-type feed-and-draw laboratory reactors; however, the reactor was dosed with metal concentration of approximately 26 mg/l or less. The general objective of this work was to study the interactions of sludge and soluble heavy metals in wastewater and to determine relative adsorption of some metals onto a biological mass. As with most other reported studies, Cheng concluded that at low metal concentrations, adsorption onto the biomass occurs through metal-organic complexes; and at high metal concentrations, metal precipitation occurs through strictly chemical-physical precipitation in addition to biomass

adsorption. Heavy metal removal was determined to depend on several factors, such as pH, metal concentration, and concentration of organics within the biological system.

In the vast majority of earlier research on heavy metal inter-action with biological processes, the objectives have been to study the effects of heavy metals on the biological process with the specific purpose of determining the maximum metal concentration which can be accepted without deleterious effects to a biological process.

The most recent work has been an attempt to understand what parameters in a biological treatment process affect heavy metal removal efficiency without adverse effects on BOD removal.

Neither Neufeld and Hermann[88] nor Cheng, et al.[89] attempted a correlation of degree of nitrification associated with heavy metals removal. Although Neufeld and Hermann did correlate sludge age to metals removal, no specific discussion was presented concerning nitri-fication other than reference to work accomplished by the U. S. Public Health Service[90] (a collection of ten research papers including refer-ences 54, 59, 62, 63, 66, and 70 previously cited in this literature review) in which inhibition of nitrification in the aeration tanks of activated sludge processes was observed. In a personal communication, Dr. Ronald Neufeld, of the University of Pittsburgh, stated that con-tinued research to date in which he was involved had been confined to studies of carbonaceous parameters associated with metals removal. He indicated that thought had been given to studying nitrogenous parameters and it was, in fact, the next logical step to undertake in gaining a better understanding of metals behavior in the activated

sludge process. He further indicated that his laboratory has no plans to study nitrogenous parameters in the near future.

During the beginning stage of work accomplished at the Dallas Demonstration Plant, Dallas, Texas (currently The Henry J. Graeser Environmental Research and Training Facility), under EPA contract,[91] different metal removal characteristics were observed which appeared to be related to changing degrees of nitrification in the activated sludge process. Esmond and Petrasek[92] referred to this observation which was based on data obtained very early in the EPA project and emphasized that statistical analysis of the available data could be misleading. Increased metal removal resulting from increased nitrification was, at the time, unexpected; however, observations appeared to support a hypothesis that metals removal efficiency was a function of degree of nitrification. Subsequent, unpublished, more detailed analyses were performed as more data became available. However, because of wide variance in the statistical results and the many variables encountered, the analysis failed to confirm or deny that a well-nitrified effluent from an activated sludge process would have lower heavy metal concentrations. An additional observation was made in this detailed analysis which was related to an influent metal concentration effect. Heavy metal removal efficiencies were found to be highly scattered at very low influent concentrations, but as the concentration increased, the metal removal efficiency appeared to increase.

CHAPTER III

EXPERIMENTAL PROCEDURES

Description of Bench-Scale Activated Sludge Plant

A bench-scale, continuous flow, completely mixed activated sludge treatment system was used in this study. The basic flow diagram of the system is illustrated by FIGURE 1. The general system arrangement is shown in FIGURE 2.

Basic System Design

The mixed liquor suspended solids (MLSS), waste activated sludge (WAS), and return sludge recycle ratio required for near steady state system operation were approximated using Equation 1.

$$\Delta X = YS_r - k_d X \qquad \text{(Equation 1)}$$

where ΔX = Sludge produced per day (mg)

Y = Cell yield coefficient (mg cells produced/mg COD removed)

S_r = Chemical oxygen demand (COD) removed per day (mg COD removed/day)

k_d = Cell death coefficient (day^{-1})

X = Mixed liquor solids (mg)

Calculations were made by forcing the sludge produced per day (ΔX) to equal the WAS in order to approximate steady state at various sludge ages[1] ranging from 3 days to 15 days.

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[1]Sludge age is defined as the amount of total suspended solids in the mixed liquor divided by the amount of total suspended solids wasted per day.
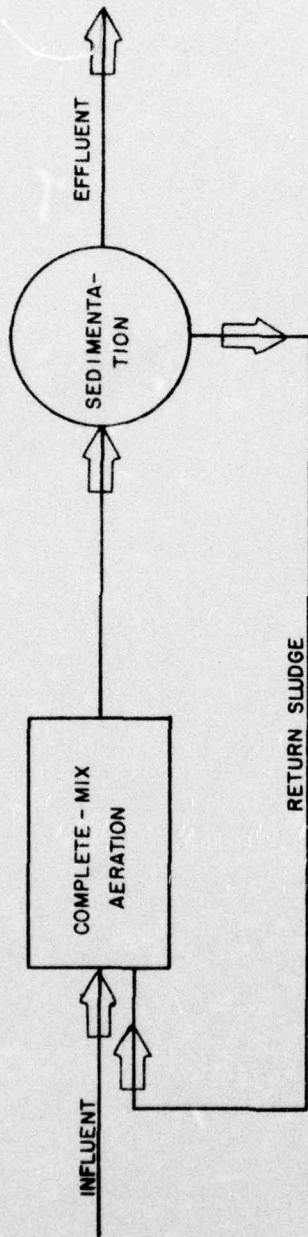
FIGURE I.—TREATMENT SCHEME FLOW DIAGRAM
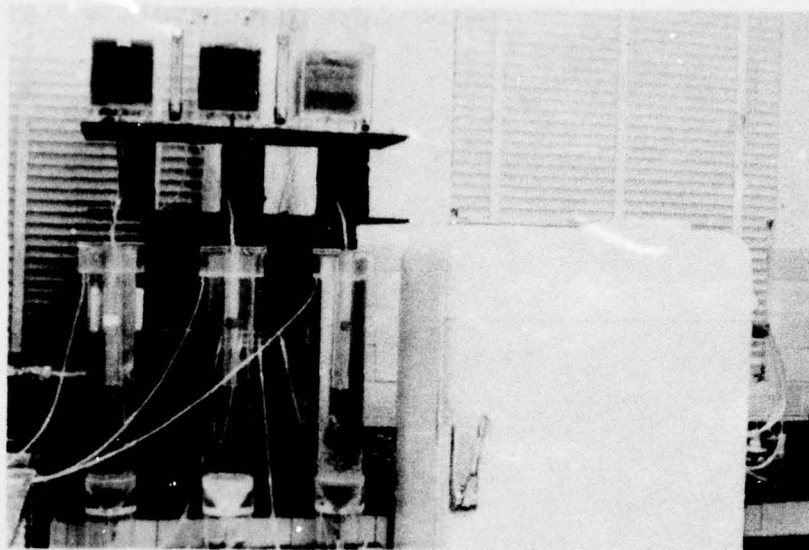
FIGURE 2.--General System Arrangement. The storage
refrigerator and clarifiers are in the foreground and
the aeration units are in the upper left. The center
clarifier was drained for contrast in this photograph.
Settling sludge in the lower half and compacted sludge
in the bottom cone of both end clarifiers may be ob-
served.

Equation 2 is a modification of Equation 1 which facilitates the com-
putation.

$$\frac{MLSS \times VOL}{\theta_c} = YS_r - k_d (MLSS \times VOL) \qquad \text{(Equation 2)}$$

where MLSS = Mixed liquor suspended solids (mg/l)

VOL = Volume of aeration

θ_c = Sludge age (days)

By selecting sludge age, the required MLSS may be determined, and the
remaining parameters of WAS and return sludge recycle ratio are
easily calculated assuming a reasonable value for the return sludge
concentration.

Initial calculations were based on the following assumptions:

Cell yield coefficient, Y = 0.54 mg cells produced/mg COD removed

Cell death coefficient, k_d = 0.07 day^{-1}

Influent flow rate, Q_o = 15 ml/min (21.6 l/day)

Influent COD, S_o = 200 mg/l

COD removal efficiency, E = 90%

These values were revised as experience was gained in operation of the laboratory system, and the following values reasonably reflect average system operation:

Y = 0.46 mg cells produced/mg COD removed

k_d = 0.07 day^{-1}

Q_o = 30 ml/min (43.2 l/day)

S_o = 125 mg/l

E = 75%

Influent Storage

A specially modified refrigerator (FIGURE 3) was used for influent waste storage under lowered temperature to reduce waste characteristic changes. The temperature varied from approximately 39°F (4°C) at the top of the refrigerator to 50°F (10°C) at the bottom. Three 15-gallon (57-liter) glass aquariums were used as waste storage containers within the refrigerator. Each aquarium was tightly fitted with a Plexiglas cover.
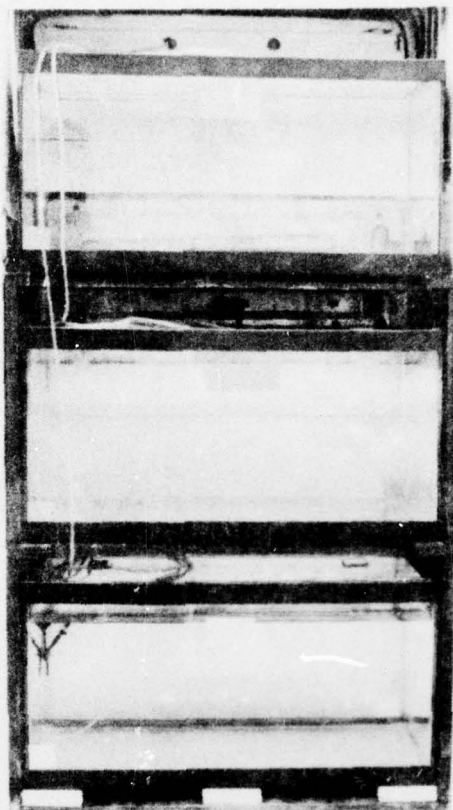
FIGURE 3.--Storage Refrigerator Interior.

Complete-Mix Aeration Tank

A Biooxidation Unit constructed of Plexiglas, manufactured by
BioDevelopment Associates, Austin, Texas, was used for the complete-
mix aeration units (FIGURES 4 and 5). The unit was operated without
a baffle to provide a completely mixed system. A standpipe overflow
weir was fitted in the unit (FIGURE 4) and was adjusted to the height
required for the design volume. The top of the Plexiglas overflow
tube had a small V-notch weir which was oriented on the side opposite
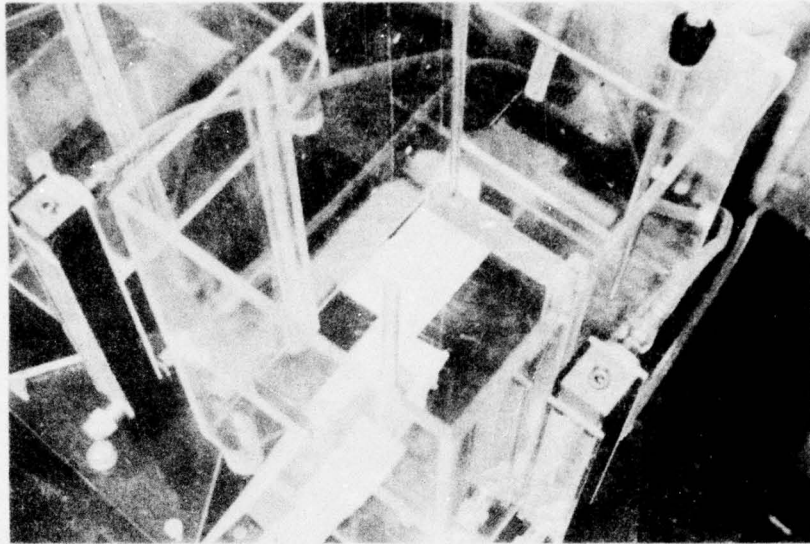
FIGURE 4.--Complete-mix Aeration Unit. The standpipe
overflow weir is located in the forward center of the
interior and the porous stone diffuser bar is located
in the rear bottom.
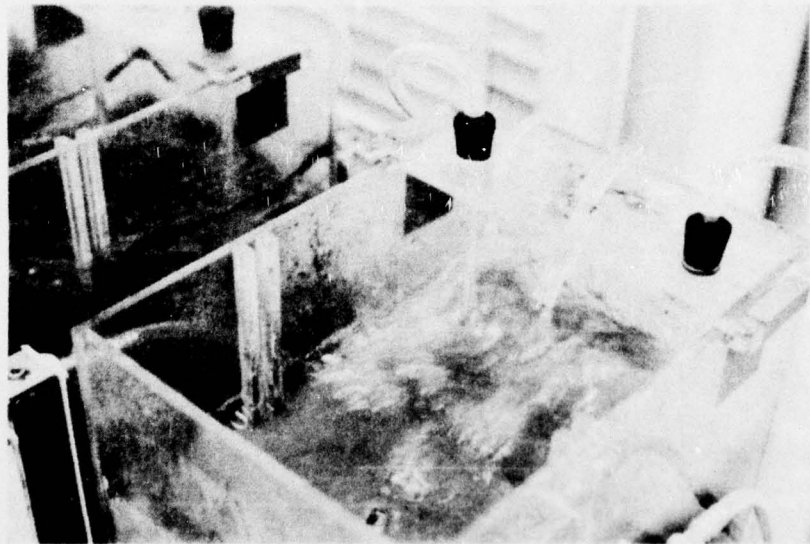
FIGURE 5.--Complete-mix Aeration Unit in Operation.
The smallest tube is the influent line and the largest
tube is the return sludge line. The tubes leading to
the rubber stoppers are air lines.

from the aeration device (therefore opposite the direction of roll of mixed liquor).

Overall dimensions.

Length - 10 inches (25.4 cm)

Width - 7 inches (17.78 cm)

Depth - 12 inches (30.48 cm)

Design capacity.

Volume - 8 liters

Hydraulic detention time (30 ml/min influent flow rate).

3.9 hours (13% return sludge rate)

3.5 hours (27% return sludge rate)

Clarifier

The clarifier simulated a center inlet, radial outlet, circular clarifier (FIGURES 6 and 7). The basic design for the clarifier was obtained from the Environics Branch, Civil Engineering Division, United States Air Force Weapons Lab., Kirtland Air Force Base, Albuquerque, New Mexico. This unit was also constructed of Plexiglas.

Overall dimensions.

See FIGURE 8.

Design capacity.

Volume - 6.66 liters

Hydraulic detention time.

3.7 hours @ 30 ml/min influent flow rate

Surface loading rate (overflow rate).

103.3 gallons/day-ft.^{2} @ 30 ml/min influent flow rate

(4208.6 liters/day-meter^2)
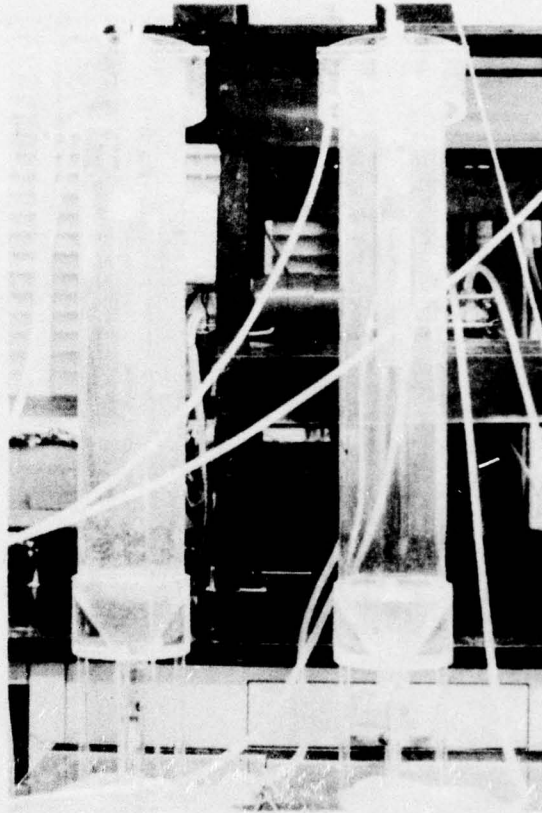
FIGURE 6.--Clarifiers. The clarifier on the right was drained for contrast in this photograph. Notice the hopper at the bottom of each cone. The tubes leaving the hoppers and coiled at the bottom of the photograph are the return sludge lines.
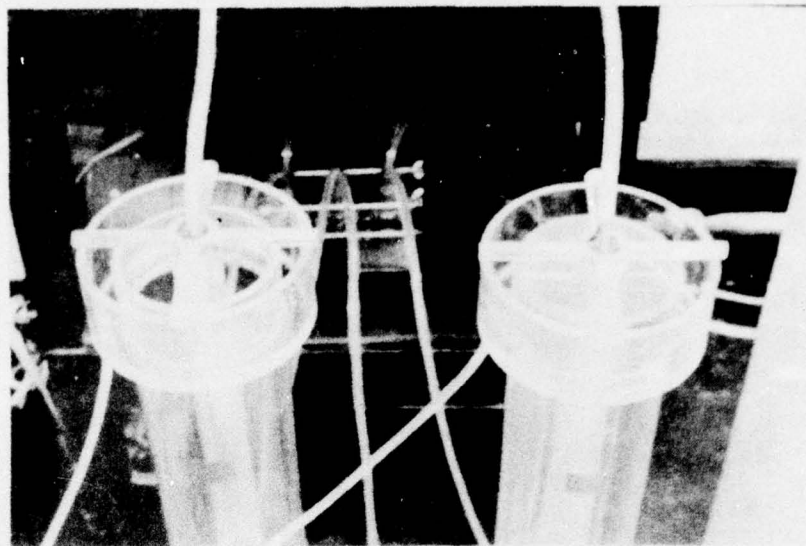
FIGURE 7.--Clarifier Overflow Weir and Weir Channel
Detail. The tubes leaving the bottom left of both
weir channels are the clarifier effluent lines and
the tubes entering the top of the clarifiers are the
aeration unit effluent lines.

Aeration and Mixing

Aeration and mixing was provided by passing compressed air
through a 0-125 psi air regulator and three 125-ml gas washing
bottles in series. Each gas washing bottle was partially filled
with approximately 75 ml of distilled water. This arrangement re-
moved compressor oil present in the air and also served to saturate
the air, thus minimizing evaporation losses in the aeration unit.
From the gas washing bottles, the air flowed through a Matheson Gas
Products Model 7631H Flowmeter with a No. 604 flow tube. Air subse-
quently entered the aeration unit through a porous bar provided with
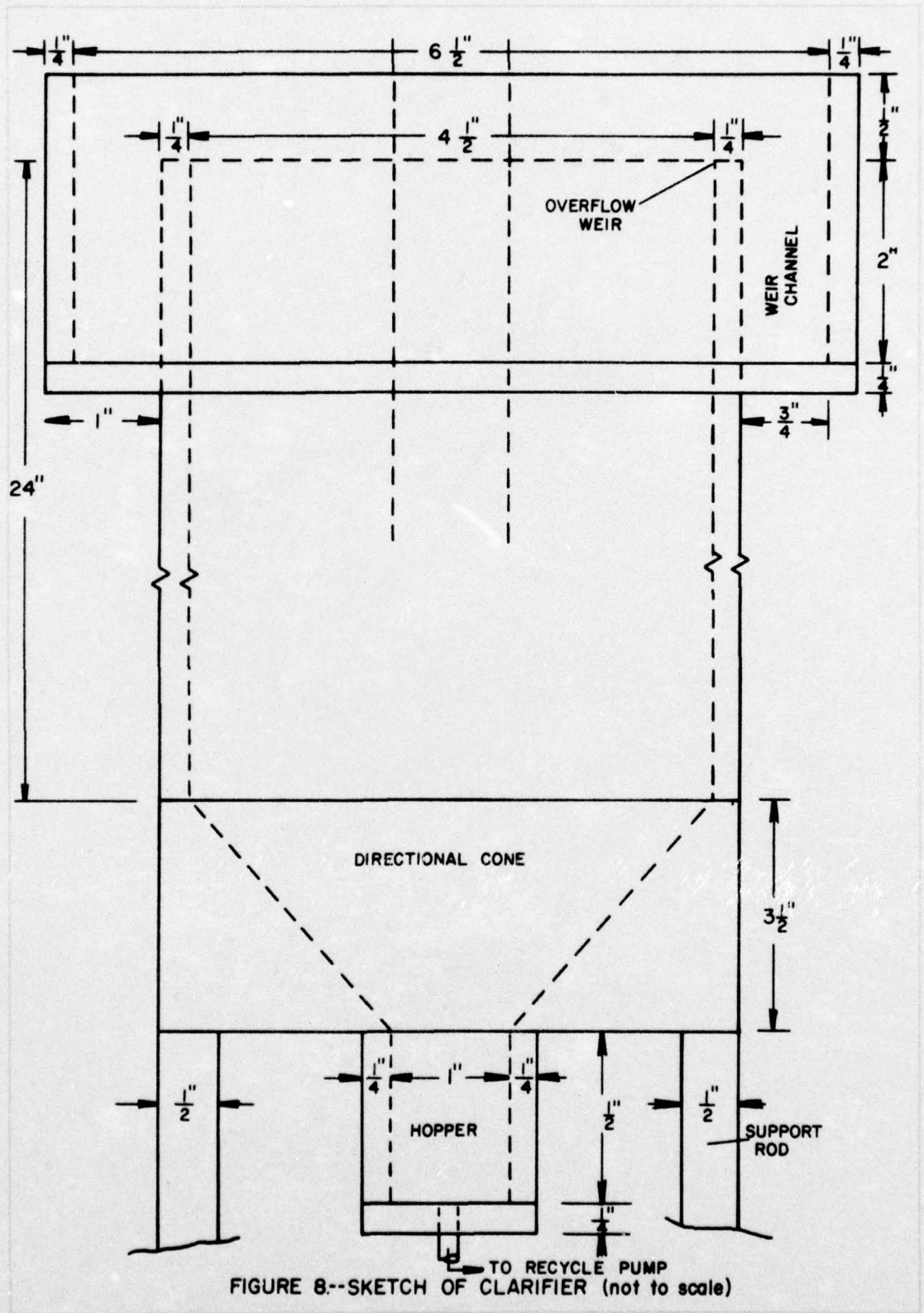
FIGURE 8.--SKETCH OF CLARIFIER (not to scale)

the Biooxidation Unit. However, at a sufficient air flow rate to provide adequate mixing in the aeration unit, the porous bar caused very high dissolved oxygen (DO) concentration (6-8 mg/l) in the mixed liquor. Therefore, a 1/4 inch Plexiglas tube with five 1/32 inch holes evenly spaced on the bottom was fabricated. This aeration device provided satisfactory mixing and, because of the larger air bubble size and resultant lower oxygen transfer rate, yielded lower DO concentrations (3-6 mg/l) in the mixed liquor. The air flow rate was maintained at 12.2 standard cubic feet per hour (SCFH) or 5,758 cubic centimeteres per minute (cm^3/min) with some deviations which are discussed in CHAPTER IV.

Flow Conditions and Pumping Equipment

Flow of mixed liquor from the aeration unit to the clarifier, and final effluent flow from the clarifier to a laboratory drain was by gravity through Tygon tubing.

The basic pumping system employed for this study was a Cole-Parmer Masterflex Variable Speed Drive System, No. 7545-00. One system, equipped with No. 7014 Pump Heads, was used for the waste influent and was operated continuously. The influent flow rate initially was 15 milliliters per minute (ml/min), but was increased to 30 ml/min for reasons discussed in CHAPTER IV. A second system, equipped with No. 7015 Pump Heads, was used for return sludge. The return sludge flow was intermittent with a rate of approximately 60 ml/min during each pumping cycle which was repeated every 30 minutes. Duration of pumping was varied to meet system operation

requirements and is also discussed in CHAPTER IV. A Dayton Percentage Cycle-Type Timer, No. 2E210, 0-30 minute range, was used to control the pumping cycle. Tygon tubing was used for both pump systems.

Operation of Plant

The original intent in this study was to operate three separate systems as previously described using a laboratory synthesized waste consisting of glucose, peptone, monosodium glutamate, urea, yeast extract, and several other compounds for nutrient requirements. One system was to be operated as a control, and two systems were to be spiked with a heavy metal.

After two months of operating the three systems, the synthetic waste proved too difficult to manage under the experimental design conditions necessary to meet the objectives of this research. Problems of poor settling, bulking sludge, rising sludge, and growth of micro-organisms in the waste feed storage tanks were experienced. Many operational parameters were changed during this two-month period to no avail. Acclimation of biological seed to the synthesized waste was practiced at the outset by slowly increasing the food-to-micro-organism ratio; however, because of the characteristics of the waste, large populations of filamentous microorganisms (FIGURES 9 and 10) developed regardless of system operation management. The use of the synthesized waste was therefore abandoned.

Because of the problems associated with the glucose-based synthe-sized waste, as well as recognition of the potential for selective microbial population development with use of other synthesized wastes,
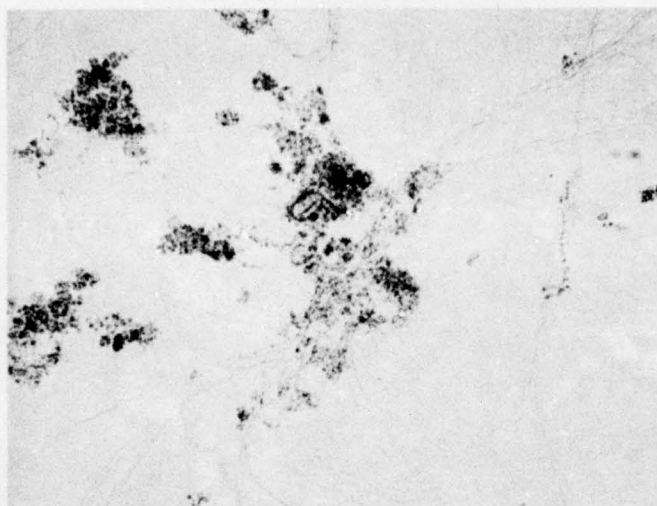
FIGURE 9.--Control Clarifier Contents, 8/28/75.
Magnification-100X, showing typical filamentous
forms of microorganisms present.
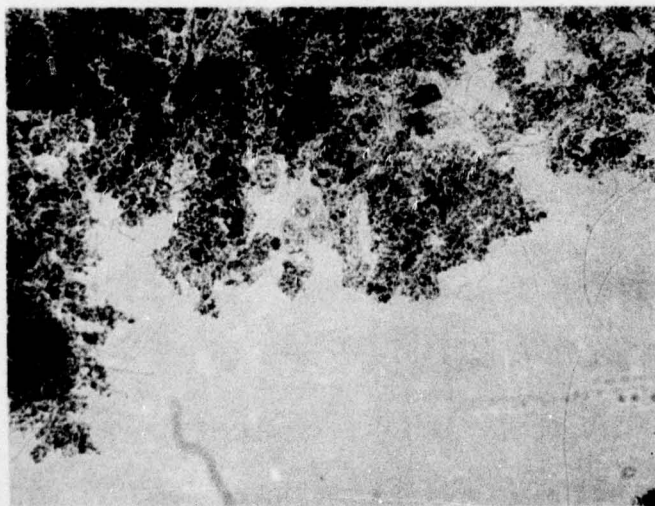
FIGURE 10.--Control System Mixed Liquor, 9/25/75.
Magnification-100X, showing typical filamentous
forms of microorganisms present.

settled domestic sewage was selected as the waste to be used in this study. Use of domestic sewage has several advantages over laboratory synthesized wastes which outweigh the logistic disadvantages of collection, transportation, and storage, and the variations in waste characteristics. The advantages include elimination of an acclimation phase to the waste when domestic sewage seed is used for development of the microbial population. Further, and most important, extrapolation of results obtained from the laboratory study to field application in domestic sewage treatment is much more valid.

Return activated sludge from the College Station, Texas sewage treatment plant was used for the biological seed in starting the laboratory system. The College Station plant is an extended aeration activated sludge plant. The return sludge from the final clarifier was obtained by grab sample from the return line just prior to entering the reaeration basin. This return sludge was strained through several layers of cheeze cloth to remove large solids and appropriate volumes were placed in the laboratory aeration units to achieve the approximate desired MLSS concentration.

Settled primary domestic sewage was used throughout this study with no modification other than addition of a heavy metal source as described later in this chapter. Because of the weak strength of the domestic sewage available, further modification of the original experimental design was necessary. This modification, discussed in detail in CHAPTER IV, led to deletion of two of the three systems. The capability to obtain sufficient data to meet the original research objective was not jeopardized.

The Bryan, Texas sewage treatment plant from which the settled primary domestic sewage was obtained is a two-stage, high-rate, trickling filter plant. Preliminary treatment consists of screening and aerated grit removal. The settled primary sewage was pumped from the primary clarifier effluent weir channel into 5-gallon plastic containers (FIGURE 11). Sewage was collected at approximately 9:30 a.m. on weekdays, usually 24 hours prior to the time required for resupply of the laboratory system. The sewage was temporarily placed in a walk-in refrigeration chamber which was maintained at approximately 34°F (1°C); then transferred to the influent storage refrigerator. This allowed sufficient cooling of the sewage prior to transfer to the refrigerator which was then able to maintain sufficient cooling to minimize waste characteristic change.

Each of the three aquarium storage containers within the refrigerator was marked at a volume of 43.2 liters. Each was filled to the mark with sewage for final volume after addition of the heavy metal stock solution.

By rapidly filling the aquariums after addition of the appropriate volume of metal stock solution, vigorous agitation and mixing was obtained, thus providing even distribution of the heavy metal. The aquariums were rinsed thoroughly with tap water between each resupply of sewage. Occasionally, the interior of the aquariums was wiped with 10% (by volume) hydrochloric acid (HCl) to remove minor films which developed, and thoroughly rinsed with tap water.

During each sewage resupply cycle, the influent tube was removed from the aeration unit and about 150 ml of 10% HCl was pumped through

FIGURE 11.--Collection of Settled Primary Domestic Sewage. This photograph illustrates the delivery of settled primary domestic sewage into plastic containers used for transporting the sewage to the laboratory.

the tube, followed by 300-400 ml of distilled water. About 50 ml of the fresh sewage was allowed to flow through the tube prior to reestablishing flow to the aeration unit. This procedure reduced microbial growth in the tubing. The influent flow rate was determined by allowing flow into a 100-ml graduated cyclinder for exactly two minutes, reading the resultant volume, and returning the influent

to the aeration unit. By repositioning the tube in the pump head at least every three days and adjusting the variable speed pump controller as required, the influent flow rate was maintained from 27.5 ml/min to 31.0 ml/min. On two isolated occasions, the flow rate was measured at 25.75 ml/min when a bearing in the pump head froze and at 25.5 ml/min when the tube became pinched in the pump head.

The return sludge pump was actuated by an automatic timer every 30 minutes. Since this pump was not in continuous operation and was fitted with a larger size tubing, it was unnecessary to reposition the tube in the pump head or vary the controller setting to maintain a relatively constant flow rate. Pumping time for each 30-minute cycle was varied occasionally depending upon the amount of sludge contained in the clarifier. By visual inspection of the amount of sludge present at the beginning and end of a cycle, the pumping time was varied to allow withdrawal of about 3/4 of the sludge present. This procedure was followed to prevent sludge from remaining in the clarifier for longer than 1 to 1-1/2 hours (2 to 3 cycles), and to prevent total sludge withdrawal. Sludge detention time in the clarifier in excess of 1 to 1-1/2 hours frequently resulted in MLSS depletion and unstable operating conditions. Generally, the system remained very stable.

Other minor system management procedures were followed. The aeration unit interior walls were scraped twice daily by hand using a plastic stirring rod with a flattened end. The clarifier interior wall and bottom cone sloped surface were gently rodded with a glass rod to dislodge adhered sludge as required. In general, the entire

system was kept free of sludge buildup on any surfaces and within any tubing by scraping, rodding, or replacing tubing as required.

Experimental Testing and Sampling Procedures

Preparation of Laboratory Ware

All laboratory glass and plastic (polyethylene) ware used for sampling and storage were acid cleaned with HCl, 10% by volume. Nitric acid (HNO_3), 10% by volume, was used on storage containers for samples on which silver analyses were performed. The laboratory ware with which samples for subsequent metal analyses came into contact was rinsed three times with distilled-deionized water. All other laboratory ware was rinsed three times with distilled water. Filtering apparatus was pretreated in the same manner.

Heavy Metal Stock Solutions

Heavy metal stock solutions used for influent spiking and standards were prepared using potassium chromate (K_2CrO_4), chromium trioxide (CrO_3), and silver sulfate (Ag_2SO_4), with distilled-deionized water. The solubilities of these compounds in parts by weight per 100 parts by weight of water are:[93] K_2CrO_4, 36 @ 20°C; CrO_3, 166 @ 15°C; and Ag_2SO_4, 0.57 @ 0°C. The stock solutions were prepared in concentrations such that appropriate volumes, easily and accurately measured in graduated cylinders, could be added to each aquarium storage tank which, when filled to the 43.2-liter mark,

would yield the desired concentration of hexavalent chromium (Cr^{+6}) or silver (Ag).

Sampling

Complete sampling was accomplished at approximately the same time every other day excluding weekends, with some exceptions. Samples of the influent waste were taken from the influent tube at the point it entered the aeration unit. Samples of the return sludge were taken from the recycle tube in the same manner. Grab samples of the mixed liquor were taken directly from the aeration unit. Effluent samples were taken from the end of the effluent tube leaving the clarifier weir channel.

First, effluent samples were taken by placing the effluent tube into the top of a 500-ml erlenmeyer flask. Slightly more than 400 ml were collected. Care was exercised to insure the tube did not contact the volume collected.

Next, the mixed liquor was sampled by dipping a 150-ml beaker into the aeration tank and rinsing the beaker with the mixed liquor. About 150 milliliters were collected and transferred into a 500-ml erlenmeyer flask. Immediately thereafter, an in-situ determination of mixed liquor temperature and DO was made.

Last, the influent was sampled in the same manner as the effluent. At the same time, the return sludge was sampled by placing the recycle tube into the top of a 500-ml erlenmeyer flask prior to the beginning of a return sludge pumping cycle. The entire volume for the pumping cycle was collected; thus allowing an average measurement for that

cycle of any return sludge parameter subsequently analyzed. Again, care was exercised to insure the tube did not contact the volume collected.

After the effluent and mixed liquor had been sampled and during influent and return sludge sampling, sample separation was begun for individual parameter analysis. A 30-ml aliquot of the effluent and mixed liquor were transferred into 125-ml polyethylene bottles for subsequent total[1] metal analysis. Slightly more than 50 milliliters of effluent were transferred into a 125-ml polyethylene bottle for subsequent Total Kjeldahl Nitrogen (TKN) analysis. Next, 20 milliliters of the effluent and mixed liquor were vacuum filtered through glass-fiber filters and the filtrate was transferred into 125-ml polyethylene bottles for subsequent soluble[2] metal analysis.

At this point in the sampling procedure, influent and return sludge sampling had been completed and the above sample separation techniques were repeated for the influent and return sludge.

Two replicate 100-ml aliquots of the influent and effluent were then vacuum filtered for suspended solids determinations. The filtrate was retained and slightly more than 50 milliliters of each were trans-ferred into 125-ml polyethylene bottles for subsequent soluble TKN analyses, and about 20 milliliters of each were transferred into small

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[1]For the purpose of this research, analyses for heavy metal, TKN, and COD performed on unfiltered samples or sample aliquots yield the total concentration of the parameter analyzed.

[2]For the purpose of this research, analyses for heavy metal, TKN, and COD performed on the filtrate of samples or sample aliquots which was filtered through glass-fiber filters yield the soluble fraction of the total concentration.

glass dram bottles for subsequent nitrite (NO_2^-) and nitrate (NO_3^-) analyses. At this time, the TKN and NO_2^- - NO_3^- samples were placed in a deep freeze for storage.

Chemical oxygen demand analyses were then initiated. Aliquots of 20 milliliters each of the unfiltered influent and effluent samples were taken for total COD, and 20 milliliters each of the filtered influent and effluent were taken for soluble COD. The COD flasks were placed on the refluxing apparatus and refluxing was initiated. While this step of the COD analysis was proceeding, further sample separation and testing proceeded.

The remainder of the unfiltered mixed liquor and return sludge samples, and 50-ml aliquots of the unfiltered influent and effluent samples were transferred into 150-ml beakers for pH and ammonia (NH_3) analyses. Determinations of pH were made on each of the four samples. Two 25-ml aliquots of the mixed liquor and two 10-ml aliquots of the return sludge samples were then vacuum filtered for replicate suspended solids determinations. The remainder of the mixed liquor and return sludge samples was returned to the system by pouring each into the aeration unit. Although these were volumes less than 50 ml, it was considered advisable to return these samples containing high cell concentrations to the system to minimize MLSS depletion. This technique also permitted knowledge of the exact amount of mixed liquor and return sludge withdrawn from the system, thus allowing determination of sludge age. Next, the NH_3 concentrations of the influent and effluent aliquots were determined.

Each separated sample for metal analysis was then preserved by adding, dropwise, the appropriate amount of concentrated HNO_3 to yeild a 0.5% HNO_3 solution in the sample.

Lastly, as soon as time permitted, a full volume of return sludge over a recycle period was collected in a beaker. The DO of the return sludge was determined and the sludge was immediately returned to the system by pouring into the aeration unit. As the return sludge was being collected for DO analysis, the influent waste flow rate was measured. Final weight determinations for suspended solids and titrations for COD results were made at the end of the day.

Partial sampling was accomplished at the same time of day on "off days" (days when complete sampling was not accomplished). Samples of the influent, effluent, and mixed liquor were collected in the same manner as previously described. Two replicate 20-ml aliquots of the influent and effluent were subjected to analysis for total COD. Next, 50-ml aliquots of each were transferred into 150-ml beakers for pH and total alkalinity analyses. Two 25-ml aliquots of the mixed liquor and two 100-ml aliquots of the effluent were vacuum filtered for volatile and total suspended solids determination. Influent flow rate was measured and, frequently, mixed liquor temperature and DO were determined as previously described. Other parameters were occasionally determined.

Cursory microscopic examinations were frequently made of the mixed liquor by preparing a simple, wet slide with a cover glass. Using this technique, protozoa were the lowest form of microorganism distinguishable, with the exception of bacterial masses (zoogloeal

masses), termed sludge floc. The total microbial population is referred to as activated sludge in this dissertation. All magnifications reported in this dissertation are the product of the occular power (10) times the objective power.

Analytical Techniques and Procedures

Filtration Techniques

Vacuum filtration through glass-fiber filters was used for solids separation.

Influent and effluent suspended solids, soluble TKN, and COD. The filtration apparatus consisted of 500-ml glass vacuum flasks fitted with rubber stoppers and plastic funnels (termed hereinafter the sample retention apparatus), Sargent No. 2 rubber crucible holders, and Gooch porcelain crucibles. Glass-fiber filters, 2.4 centimeters in diameter, were set in the crucibles by vacuum filtering 10 milliliters of distilled water. The crucibles with filter mats were then dried at 103°-105° for one hour and placed in a dissicator until used. Each crucible was tared just prior to use. A crucible was then fitted into a crucible holder and placed into a plastic funnel. The sample was well mixed by swirling; a volume was measured into a graduated cylinder and poured into the Gooch crucible with vacuum applied. After filtration was complete, the crucible was removed and placed into a standard Gooch crucible holder fitted in another vacuum flask (termed hereinafter the washdown apparatus). The graduated cylinder was then washed with 10 milliliters of distilled water and this wash volume was filtered through the crucible. A second crucible was

fitted into the same sample retention apparatus and a replicate sample volume was filtered. The crucible was removed and placed onto the washdown apparatus and the graduated cylinder wash procedure was repeated. Separate sample retention apparatus were used for the influent and effluent and the same washdown apparatus was used for both. This technique includes all procedures prescribed by Standard Methods[94] and, with the separate sample filtration and graduated cylinder washdown modification, allowed suspended solids determination as well as subsequent analyses on the filtrate, and use of a minimum amount of laboratory ware.

Mixed liquor and return sludge suspended solids. The filtration apparatus consisted of 1000-ml glass vacuum flasks (no pretreatment required) fitted with Millipore filter heads, Sargent No. 2 rubber crucible holders placed in an inverted position on top of the Millipore head, and A.S.T.M. - Bitumen, porcelain crucibles, 3.7 centimeters in diameter. The use of this filter head arrangement was suggested by Dr. Tom D. Reynolds, Professor, Civil Engineering Department, Texas A&M University, and a member of the author's Graduate Committee. Dr. Reynolds has previously used this type of filtration apparatus and has found that larger volumes of high solids content samples may be filtered much more rapidly than with standard Gooch crucibles. Glass-fiber filters, 3.7 centimeters in diameter, were set in the crucibles by vacuum filtering 10 milliliters of distilled water. The crucibles with filter mats were then dried at 103°C-105°C for one hour and placed in a dissicator until used. Each crucible was tared just prior to use. A crucible was tightly fitted into a crucible

holder on the top of a Millipore filter head. The sample was well mixed by swirling; a volume was measured into a graduated cylinder and poured into the bitumen crucible with vacuum applied. The graduated cylinder was then washed with 10 milliliters of distilled water and this wash volume was filtered through the crucible. Since retention of the filtrate was not required there was no need for separate sample filtration and graduated cylinder wash down as was the case with the influent and effluent samples.

Influent and effluent heavy metals. Three sample retention apparatus, identical to those previously described, each completely acid washed and rinsed as previously discussed, were used. One was used as a blank reference, one for influent samples, and one for effluent samples. In this case, glass-fiber filters were set in the Gooch crucibles by vacuum filtering 10 milliliters of 10% HCl followed by a minimum of 10 milliliters of distilled-deionized water. The crucibles and filter mats were dried at 103°C-105°C for one hour and placed in a dissicator until used. Since no solids determinations were to be made with these crucibles, there was no need for taring prior to use. Distilled-deionized water blanks, influent, and effluent volumes of 20 milliliters each were thoroughly mixed by swirling and measured into 25-ml graduated cylinders. These blank and sample volumes were then vacuum filtered through each corresponding apparatus.

Mixed liquor and return sludge heavy metals. Three filtration apparatus identical to those previously described were used. Each was completely acid-washed and rinsed. Glass-fiber filters were set in the bitumen crucibles using 10% HCl and distilled-deionized water and

the crucibles and filter mats were dried and stored as before. No taring was required. Distilled-deionized water blanks, mixed liquor, and return sludge samples were thoroughly mixed by swirling, and volumes of 20 milliliters each were measured into 25-ml graduated cylinders. Blank and sample volumes were vacuum filtered through each corresponding apparatus.

Alkalinity

Alkalinity determinations were made by the potentiometric titration method prescribed by Standard Methods[94], except that titration was only made to a pH of 4.5. Standard 0.02N acid titrant was standardized each day immediately before use by titrating against 0.0200N sodium carbonate to a pH of 4.5.

Chemical Oxygen Demand

Determinations of both total and soluble COD were made in accordance with Standard Methods[94], using the dichromate reflux method.

Dissolved Oxygen and Temperature

Dissolved oxygen and mixed liquor temperature readings were made using a Yellow Springs Instrument, Model 51A, Oxygen Meter. The meter was calibrated at an elevation reading of 200 feet on the calibration dial with the probe in O_2 saturated air over standard O_2 saturated biochemical oxygen demand (BOD) dilution water in a 300 milliliter BOD bottle. Mixed liquor DO and temperature were determined by

consistently placing the probe approximately 2 inches below the surface of the mixed liquor, immediately adjacent to the aeration tank over-flow weir standpipe. Return sludge DO was determined by collecting a full recycle volume in a beaker as described previously. The probe was placed into the beaker at about one-half the return sludge depth and the reading was taken. Refrigerator temperature was measured using a standard laboratory mercury thermometer.

Heavy Metals

Standard solutions. Heavy metal standard solutions were prepared using the metal stock solutions of K_2CrO_4, CrO_3, and Ag_2SO_4 previously mentioned under Experimental Testing and Sampling Procedures - Heavy Metal Stock Solutions. Appropriate volumes were diluted with HCl, 0.5% by volume, for the Cr standards and HNO_3, 0.5% by volume, for the Ag standards in volumetric flasks. A volume of 100 milliliters of each standard was subjected to the same digestion (wet ashing) procedure (to be described later) as the samples for total metal analysis. These digested standards were then placed in plastic bottles, tightly capped, and stored as was the remainder of each original standard as prepared.

Total metal analysis - chromium. This procedure, used for un-filtered sample preparation prior to atomic absorption spectrophoto-metric analysis for Cr, is a slight modification of that used by Oliver and Cosgrove.[77] To a carefully measured 25-ml aliquot of a preserved, unfiltered sample in a 125-ml erlenmeyer flask, 5 milli-liters of concentration HCl and 1.5 milliliters of concentrated HNO_3 were added. The flasks were placed on a hot plate under a fume hood

and the mixture was digested by boiling to a volume of 1 to 2 milli-
liters. The flasks were removed from the hot plate and allowed to
cool under the fume hood. The concentrate was made up to the original
volume with distilled-deionized water and the digestion procedure was
repeated. In all cases, after the second digestion, a white ash was
observed in each flask. These white solids were barely detectable
in the influent and effluent samples, but were very obvious in the
mixed liquor and return sludge samples. After the second cooling, the
concentrate was carefully made up to the original 25-ml volume and a
sub-aliquot of approximately 10 milliliters was centrifuged at 3000
revolutions per minute (rpm) for 10 minutes. Approximately 7 milli-
liters of the supernatant were decanted after centrifugation and the
chromium concentration of this supernatant was determined by atomic
absorption (AA) analysis. In most cases, the mixed liquor and return
sludge samples required dilution to reach a concentration in the linear
range of AA analysis. This was accomplished by serial dilution as
required prior to centrifugation, using distilled-deionized water.
Chromium standard volumes of 100 milliliters, with 20 ml HCl and 6 ml
HNO_3, were digested by boiling to a concentration of 5-10 milliliters
in the same manner. After the second digestion, the concentrate was
made up to the original 100-ml volume with distilled-deionized water.
Centrifugation was not required since no solids were present.

Total metal analysis - silver. Since use of HCl as one of the
digestion aids for silver causes silver chloride (AgCl) formation and
subsequent precipitation, a second digestion procedure was required.
This procedure, used for unfiltered sample preparation prior to AA

analysis for Ag, is similar to that previously described for Cr. To a carefully measured 25-ml aliquot of a preserved, unfiltered sample in a 125-ml erlenmeyer, 2.5 ml of concentration HNO_3 and 0.5 ml of 30% hydrogen perioxide (H_2O_2) were added. The flasks were placed on a hot plate under a fume hood and the mixture was digested by boiling to a volume of 1-2 milliliters. The flasks were removed from the hot plate and allowed to cool under the fume hood. The concentrate was made up to the original volume with distilled-deionized water and the digestion procedure was repeated. In all cases, after the second digestion, solids had been converted to a white ash. After the second cooling, the concentrate was carefully made up to the original 25-ml volume and a sub-aliquot of approximately 10 ml was centrifuged at 3000 rpm for 10 minutes. Approximately 7 milliliters of the supernatant were decanted after centrifugation and the silver concentration of this supernatant was determined by AA analysis. Only a few samples required dilution to reach a concentration in the linear range of AA analysis. This was accomplished by a single dilution of the supernatent as required. Silver standard volumes of 100 milliliters, with 10 ml HNO_3 and 2 milliliters H_2O_2 were digested by boiling to a concentrate of 5-10 milliliters and readjusted to the original 100-ml volume in the same manner. Centrifugation was not required.

Soluble metal analysis. Filtered samples were subjected to AA analysis directly from their storage bottles.

Atomic absorption spectrophotometric instrumentation and techniques. A Perkin-Elmer AA Spectrophotometer, Model 303, equipped with a Perkin-Elmer Digital Concentration Readout, Model DCR 1 and a

Fisher Recordall, Series 5000, strip chart recorder was used for all direct aspiration, flame analyses. A Perkin-Elmer AA Spectrophotometer, Model 403, equipped with a graphite furnace, and a Perkin-Elmer, Model 165, strip chart recorder was used for chromium concentrations of 0.1 mg/l and less. Sample injections of 50 microliters were used for analysis with the graphite furnace. Standard conditions as prescribed in the Perkin-Elmer operation manual were used for all AA work with the single exception that, with chromium concentrations between 5 to 10 mg/l, sufficient linearity could be obtained with a lean, oxidizing flame such that samples in this concentration range did not require dilution. Samples of higher concentrations did not require further dilution beyond this range; thus the errors inherent with dilution were minimized.

A minimum of three standard concentrations was used for each standardization plot. Undigested standards were used for soluble metal (undigested sample) determinations and digested standards were used for total metal (digested sample) determinations. Distilled-deionized water used for dilution was carried through each digestion as a blank, and several selected concentrations of undigested standards were also carried through each sample digestion run using volumes of each equal to sample volumes. These were continually monitored to insure accuracy of analysis.

Nitrogen Species Analyses

Ammonia (HN_3). Influent and effluent 50-ml samples, separated as previously described, were analyzed for ammonia concentration using an

Orion Research Ammonia Electrode, Model 95-10, with a Corning Digital 110 Expanded Scale pH Meter. The known addition method as described in the ammonia electrode instruction manual supplied by the manufacturer was employed. Ammonia standard solutions were prepared using A.C.S. certified reagent grade ammonium chloride. The ammonia electrode was checked for proper operation immediately prior to sample analysis by measuring the NH_3 concentration of a 50-ml aliquot of 10.0 mg/l NH_3 standard using 5 milliliters of 100.0 mg/l NH_3 standard as the known addition.

Nitrite (NO_2^-) and nitrate (NO_3^-). Filtered influent and effluent samples, separated and stored as previously described, were analyzed for NO_2^- and NO_3^- concentration using a Technicon Auto Analyzer System with the method prescribed by the U.S. Environmental Protection Agency.[95] Samples were removed from deep-freeze storage and allowed to thaw at room temperature immediately prior to analysis. Effluent samples were diluted with distilled-deionized water by a factor of 20 for NO_3^- analysis.

Total Kjeldahl Nitrogen (TKN). Samples were removed from deep-freeze storage and thawed in a warm water bath. Immediately after complete thawing, 50-ml aliquots were carefully measured and transferred into standard Kjeldahl Flasks containing Hengar Granules for boiling safety. Next, 30 milliliters of digestion reagent, prepared in accordance with Standard Methods[94], Section 135, were added. The mixtures were digested on a standard Kjeldahl digestion apparatus by boiling for one hour. This time allowed sufficient boiling beyond the evolution of SO_3 fumes. After cooling for 1 hour, the digested syrup

was carefully diluted to 250 milliliters with distilled water. Two 100-ml aliquots of the diluted volume were carefully measured and transferred into separate 150-ml beakers for replicate NH_3 concentration analysis by the known addition method using an ammonia electrode. A blank and 10.0 mg/l NH_3 standard were carried through the entire digestion and dilution procedure. Using one blank replicate, sufficient alkaline reagent (10M NaOH + 2M NaI) was added to adjust the pH to above 10. The volume of alkaline reagent required was measured and this same volume was subsequently used for all remaining blank, standard, and sample replicates. The appropriate volume of alkaline reagent was added to a sample while gently mixing with a magnetic stirrer. Immediately thereafter, the ammonia electrode was placed into the mixture and the millivolt (mv) potential was read to the nearest 0.1 mv upon stabilization of the reading. Immediately after taking this initial reading, 10 milliliters of an ammonia standard was added to the mixture as the known addition. The mv potential was again read to the nearest 0.1 mv upon reading stabilization. It was found that excellent, reproducible results were obtained with a millivolt change (ΔE) of -5 mv to -30 mv between the initial and final readings. The ammonia standards used as known additions were 1.0 mg/l NH_3 for blank determinations, 10.0 mg/l NH_3 for effluent samples, 30.0 mg/l NH_3 for influent samples, and 10.0 mg/l NH_3 for 10.0 mg/l standards. The following will serve to illustrate how final NH_3 concentrations were calculated:

$$DF = \frac{V_1}{V_0} \times \frac{V_a + V_k + V_r}{V_a} \qquad \text{(Equation 3)}$$

$$NH_3(mg/l) = Q \times DF \times C \qquad \text{(Equation 4)}$$

where DF = Dilution factor

V_o = Original sample volume taken for digestion (ml)

V_1 = Diluted sample volume after digestion (ml)

V_a = Aliquot volume of diluted sample taken for measurement of NH_3 concentration (ml)

V_k = Volume of known addition (ml)

V_r = Volume of alkaline reagent (ml)

Q = Factor read from TABLE II, values for Q vs. ΔE (25°), contained in the ammonia electrode instruction manual

C = Concentration of known addition (mg/l NH_3)

pH

All pH determinations were made using a Corning Digital 110 Expanded Scale pH Meter with a glass-calomel electrode.

Suspended Solids

Volatile and total suspended solids were determined in accordance with Standard Methods[94], with only slight modifications in filtration as previously discussed. Influent and effluent sample volumes of 100 ml, mixed liquor sample volumes of 25 ml, and return sludge sample volumes of 10 ml were used.

CHAPTER IV

RESULTS AND DISCUSSION

The literature contains only sparse accounts of operating a bench-scale, continuous flow, activated sludge system similar to the one used in this research, and these accounts are limited in detail. Accordingly, especially in consideration of the recommendations for further research which are given in CHAPTER V, a chronological account of system operation is presented below. Pertinent observations affecting the results and conclusions are briefly noted. Detailed discussions are contained in subsequent sections of this chapter as noted in the account.

System Operation Account

Chromium Studies (TABLE 1, page 104)

The activated sludge systems were successfully placed in operation on 10/10/75, using settled primary sewage as the influent. Each system was charged with approximately 3000 mg/1 MLSS. Initially, the activated sludge systems operated well within the anticipated parameters, and reasonable steady state conditions, in terms of MLSS, were achieved by the sixth day. A microscopic examination of the control system and test system mixed liquors on 10/15/75 revealed an excellent, mixed population, good floc formation, and no observable filamentous forms; indicating a good quality activated sludge. Benedict and Carlson[96] similarly defined a well-developed, activated sludge and used similar microscopic examinations to compare separate activated sludge cultures.

On 10/16/75, the return sludge recycle time was reduced to prevent total sludge blanket withdrawal. This was one of the first variations required in operation parameters and was attributed to the difficulties associated with intermittent recycle of return sludge instead of continuous recycle. (System size, flow rate, tubing size, and low rate pumping capability dictated intermittent recycle of return sludge.)

The amount of sludge produced per day did not meet expectations. Two reasons were immediately recognized. First, the influent COD was significantly lower than had been anticipated (based on earlier COD determinations), and only occasionally approached estimated values. Second, the COD removal efficiency was not as high as expected. The problem of less-than-expected sludge production contributed to the necessity for return sludge time reduction and also contributed to modification of the experimental design as will be discussed later.

Acclimation of test system 1 and 2 to chromium was begun on 10/18/75 when each was spiked to 0.1 mg Cr/l. On 10/21/75, the chromium concentration was increased to 1.0 mg/l. A microscopic examination of the control and test system 1 mixed liquors on 10/22/75 indicated an excellent quality activated sludge. No significant differences between the two systems were observed.

On the morning of 10/23/75, a large amount of risen sludge was present in the control system clarifier. Upon gentle rodding of the sludge at the top of the clarifier, immediate release of small gas bubbles occurred followed by rapid settling of the sludge. Within one hour, the clarifier was operating normally with excellent settling and sludge compaction. Because of the size of the clarifier model

and the associated side-wall effects, this rising sludge problem occurred periodically; however, for each occurrence under normal conditions, the procedure of gently rodding the surface to allow escape of N_2 was followed by rapid sludge settling and return to normal operation within a few hours. By gently rodding the clarifier interior wall and the sloped surface of the bottom cone as a daily preventive, rising sludge was held to a minimum. In addition, it was found that setting the return sludge recycle time such that almost all the sludge was removed during each cycle aided in preventing rising sludge. Therefore, for the clarifier design used, a sludge detention time of 1 to 1-1/2 hours should not be exceeded.

A microscopic examination of the mixed liquor from each system on 10/23/75 indicated similar excellent activated sludge. FIGURES 12 and 13 are typical of the mixed liquor in each system. Subsequent to the microscopic examination, test systems 1 and 2 were spiked to 2.0 mg Cr/l. On 10/25/75, test systems 1 and 2 were spiked to 4.0 mg Cr/l.

As operation and sampling of the three systems along with sample analyses proceeded through 10/27/75, it became very apparent that a change in the experimental approach was dictated. The problem of low sludge production was becoming increasingly apparent. Although sample sizes were rigidly held to the absolute minimum which would allow subsequent analyses, the amount of suspended solids removed by sampling exceeded the amount which could be withdrawn as waste activated sludge to maintain steady state conditions. Mixed liquor suspended solids were depleted to unacceptable levels after full sampling days, and
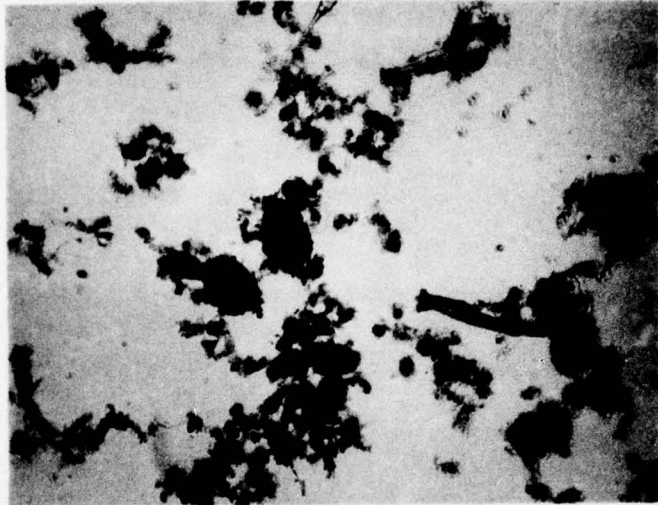
FIGURE 12.--Control System Mixed Liquor, 10/23/75. Magnification-35X, showing excellent sludge floc formation and a species of Rotifer.
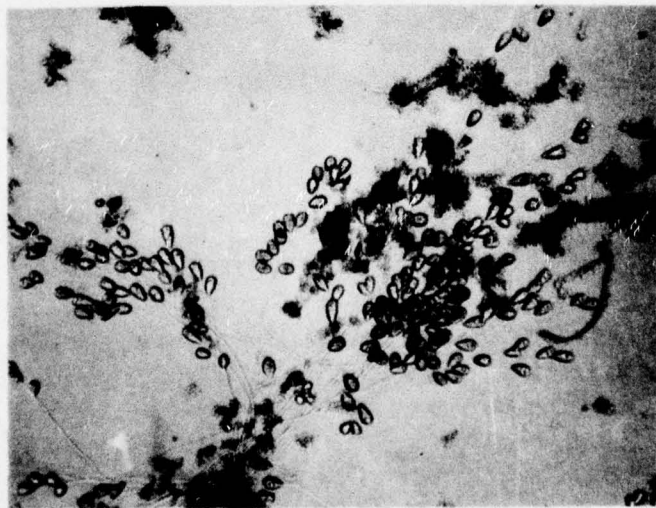
FIGURE 13.--Test System 1 Mixed Liquor, 10/28/75. Magnification-35X, showing a typical large colony of stalked Ciliates.

recovery was far too slow. After appropriate consultation, the decision was made to increase the influent flow rate which would, in turn, increase the sludge production rate. Because of equipment limitations, it was necessary to delete two systems to provide sufficient influent storage capacity to meet the increase in flow rate.

Deletion of one of the test systems did not significantly affect test results. Two test systems were included in the original experimental design to permit a paired analysis of results; however, the logistics simply would not permit operation of two test systems.

Several alternatives were considered in an attempt to maintain a control system along with a test system; however, the alternatives available were not feasible. Operation of the control system was, however, continued through chromium acclimation of test system 1. This provided the necessary data for comparison of system performance under chromium loading conditions versus system performance under no chromium loading.

No significant performance differences between the test systems were observed through 10/28/76. Accordingly, test system 2 was removed from service, and test system 1 was spiked to 7.0 mg Cr/l. On 10/30/75, test system 1 was spiked to the final Cr concentration of 10.0 mg/l. On this same day, rising sludge again occurred in the control system clarifier; the condition was rectified by rodding the sludge. Complete sampling was resumed on 10/31/75. On 11/01/75, the control system was removed from service and the flow rate to the remaining system, test system 1, was increased. Reference to the

single system remaining as test system 1 has been deleted after 11/02/75 in TABLE 1 and the following text.

On 11/02/75, the influent flow rate was increased. On 11/03/75, the mixed liquor contained an excellent mixed population; however, sludge floc formation was not as good as it had been. Flocs consisted mainly of masses about one-half the size previously observed with only a few larger masses. The influent flow was increased to the desired rate of 30 ml/min and was maintained at this rate, with minor variation, for the remainder of this research.

System operation and sampling proceeded smoothly through 11/13/75; however, sludge settling characteristics were decreasing in quality. Microscopic examinations of the mixed liquor on 11/08/75, 11/12/75, and 11/13/75 revealed poor floc formation as well as a decline in variety and number of the protozoan population. Very few stalked ciliates were present on 11/12/75, and in fact the stalk remains of dead colonies were evident (FIGURES 14 and 15). Initially, these remains appeared to be a form of filamentous organism; however, closer examination and subsequent observation of identical remains in an earlier lysed state with the ciliate bell still attached confirmed their general identity.

The sludge age of the system, through 11/13/75, (individual values are given in TABLE I), ranged from 4 days to 76 days with a median of 19 days and an average value of 27 days. This is a relatively high value compared to sludge ages of 2-5 days at which most activated sludge plants are operated. This high sludge age was the most probable cause of poor floc formation and the decrease in
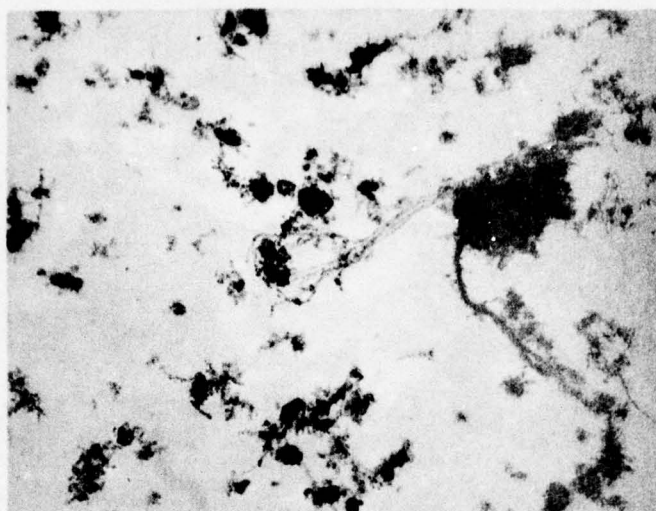
FIGURE 14.--Mixed Liquor, 11/12/75. Magnification-35X.
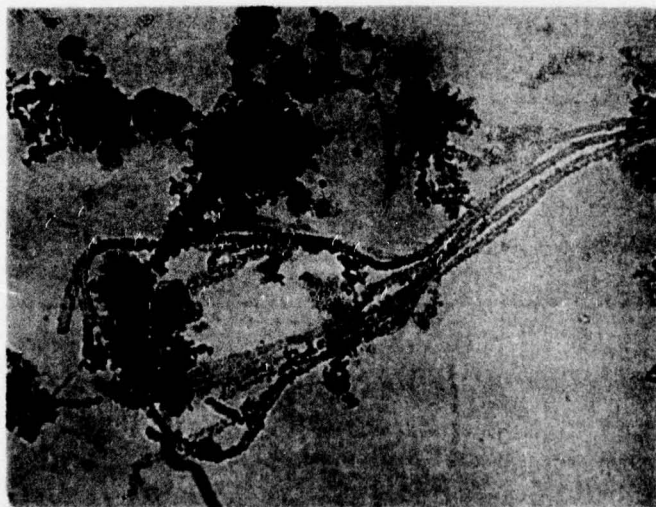
FIGURE 15.--Mixed Liquor, 11/12/75. Magnification-100X, showing enlarged view of FIGURE 14.

activated sludge quality observed.

Because the degree of nitrification was still suspected to have a potential effect on metal removal, a decrease in the high nitrifying system performance was desired. Therefore, for the first time in 13 days, sludge was wasted in addition to that removed by sampling. On 11/15/75, microscopic examination of the mixed liquor revealed a marked increase in the number and variety of protozoans present. On 11/15/75 and 11/20/75, additional sludge was again wasted. On 11/21/75, the mixed liquor contained the most dynamic, mixed protozoan population to date, and the sludge floc had increased in size. During the period from 11/14/75 through 11/21/75, sludge age ranged from 9 days to 38 days with a median value of 16 days and an average value of 17 days. The increase in quality of the activated sludge and the better sludge floc formation was, therefore, attributed to the decrease in sludge age.

On 11/22/75, during preventive rodding of the clarifier, the glass rod used was inadvertently broken. An 8 inch piece of rod fell into the clarifier which hindered proper return sludge flow. On 11/23/75, the clarifier was replaced with an identical clarifier used for one of the previously deleted systems. The contents of the obstructed clarifier were transferred into the replacement clarifier and, in the process, only one return sludge recycle period was missed. Within two hours, clarification was proceeding normally, with little, noticeable effects on overall system operation other than an increase in effluent total suspended solids concentration the following day.

By 11/24/75, it was obvious that metal removal was not being affected by varied system operation to date. The DO concentration was suspected to have an effect on metal-sludge interaction and; thus, metal removal. Therefore, in an attempt to reduce the DO concentration in the return sludge by lowering the mixed liquor DO concentration, the air flow rate was reduced from 5,758 cm^3/min to 4,531 cm^3/min.

On 11/25/75, microscopic examination of the mixed liquor (FIGURE 16) indicated a high quality activated sludge similar to that observed on 11/21/75.

On 11/29/75 and 11/30/75, large quantities of sludge were wasted to decrease the sludge age in a further attempt to reduce nitrification. Microscopic examination of the mixed liquor on 11/30/75 revealed an increase in number and diversity of the microbial population, excellent floc formation, and the reappearance of higher life forms (FIGURE 17).

The sludge wasting practiced on 11/29/75 and 11/30/75 obviously lowered MLSS concentration which, in turn, lowered the amount of sludge in the clarifier. This condition required a decrease in return sludge recycle time on 12/02/75 to prevent total sludge withdrawal from the clarifier.

Observations and results obtained through 12/04/75 made it obvious that no metal removal was occurring within detection limits. Thus, at the influent concentration of 10 mg/l Cr, operation of this activated sludge system under high nitrifying conditions did not affect metal removal. However, since the total metal concentration of the return sludge was approximately eight times that of the influent concentration,

FIGURE 16.--Mixed Liquor, 11/25/75. Magnification-35X, showing typical large colony of stalked ciliates.
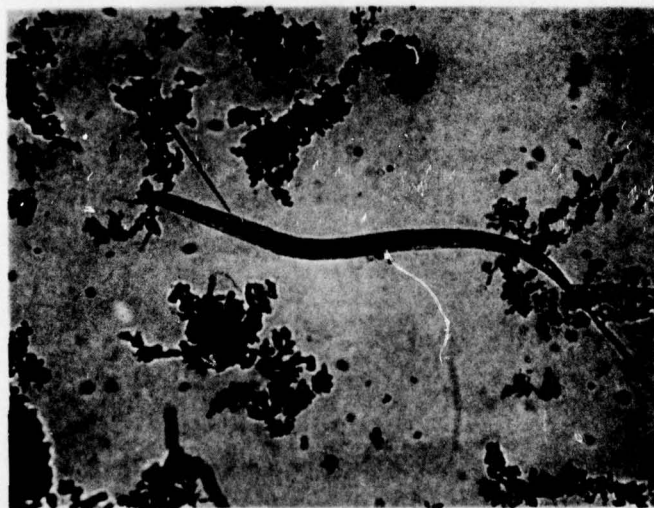
FIGURE 17.--Mixed Liquor, 11/30/75. Magnification-100X, showing excellent floc and the presence of a species of nematode.

chromium uptake by the sludge was obvious. The total mass of metal concentrated in the sludge was, however, insignificant in comparison to the total mass of metal continuously entering and leaving the system.

Because of the potential influent metal concentration effect on metal removal which was indicated by analysis of the Dallas data[91], a different approach for this study was developed. The continued study was conducted in three phases.

The possibility that lowering the return sludge DO concentration may result in metal precipitation within the clarifier (hence, metal removal) remained. Accordingly, the first phase of continued study required maintaining the influent chromium concentration at 10 mg/l and further depressing the return sludge DO concentration. System operation under these conditions would continue until sufficient data was obtained to confirm or deny the potential return sludge DO concentration effect. The second and third phases required influent metal concentration reduction with continued system operation under the same conditions of low return sludge DO concentration and high nitrification. Influent metal concentrations of 1.0 mg/l for the second phase and 0.1 mg/l for the third phase were selected. This range of concentrations was considered sufficient to determine the existence of a concentration effect.

On 12/05/75, air flow rate was reduced from 4,531 cm^3/min to 1,510 cm^3/min. This lower air flow rate was chosen arbitrarily to determine the feasibility of this technique in reducing return sludge DO concentration.

Return sludge recycle pumping time was increased on 12/06/75 from 2 minutes to 2-1/2 minutes as a rising sludge preventive based solely on the observed amount of sludge remaining in the clarifier after each recycle period. On 12/07/75, the pumping time was reduced to 2 minutes based on the realization that a longer sludge detention time would assist in reducing the return sludge DO concentration. Since the increase in pumping time on the previous day had been made only as a preventive, this reduction in pumping time was justified. System operation through 12/09/75, with close monitoring of mixed liquor and return sludge DO concentrations, revealed that DO concentration was not reaching the desired lower level. In addition, poor mixing in the aeration unit was evident. Therefore on 12/09/75, the porous stone bar air diffusion device was replaced by the fabricated tube diffusion device previously described. Air flow rate was returned to 5,758 cm^3/min to provide adequate mixing in the aeration tank. Within, a few hours, a significant reduction in mixed liquor DO concentration was detected. The return sludge DO concentration responded more slowly; however, by the next day, 12/10/75, was approaching the low level desired. Air flow was reduced to 4,531 cm^3/min on 12/12/75 and 3,917 cm^3/min on 12/13/75 with only minimal reduction of return sludge DO concentration. Further reduction of the return sludge DO by reducing air flow rate would have resulted in inadequate mixing in the aeration unit; therefore, the air flow rate of 3,917 cm^3/min was maintained for the first phase of continued study.

Microscopic examinations of the mixed liquor accomplished periodically during the period 12/01/75 through 12/11/75 revealed

a well established, high quality activated sludge. Other system parameters monitored through 12/15/75 substantiated normal performance.

On 12/15/75, complete sampling was resumed to begin the first phase of the influent metal concentration effect study. During sampling, the return sludge filtrate for soluble metal analysis was observed to have a much less yellowish color than had been noted previously. This observation indicated a relatively low soluble chromium concentration. (Subsequent metal analysis substantiated a significantly lower chromium concentration). Therefore, all system parameters monitored for the period 12/09/75 through 12/24/75 were examined. A direct relationship was found between the return sludge soluble metal concentration and return sludge DO concentration, indicating that low DO concentrations in the return sludge does have an effect on heavy metal uptake by the sludge; and therefore may affect heavy metal removal. Detailed analysis of this observation is contained under a subsequent, separate section of this chapter. The minor changes in return sludge recycle pumping time on 12/15/75 and 12/16/75 were made because of the amount of sludge contained in the clarifier. Since the duration of increased pumping time was approximately 15 hours, this action was not considered to have had any significant effect regarding the soluble metal - DO relationship. The return sludge DO concentration increase from 12/16/75 through 12/24/75 was attributed to the depletion of return sludge solids caused by resumption of complete sampling.

On 12/24/75, after 55 days of system operation with an influent chromium concentration of 10 mg/l, microscopic examination of the

mixed liquor indicated an excellent quality activated sludge (FIGURE 18). The mixed liquor total chromium concentration was in excess of 30 mg/l and the return sludge total chromium concentration had reached levels in excess of 260 mg/l.
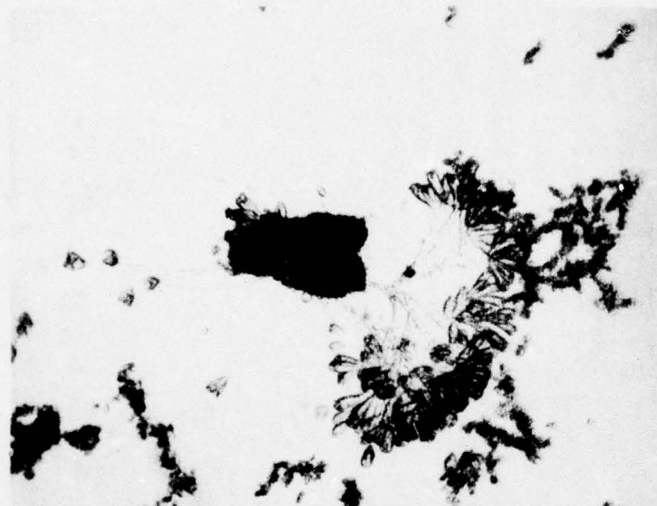
FIGURE 18.--Mixed Liquor, 12/24/75. Magnification-35X, showing a large colony of one species of stalked ciliates on the right and several individual stalked ciliates of a different species on the left.

On 12/24/75, after sampling was completed, the influent chromium concentration was reduced to 5.0 mg/l. The reduction to 1.0 mg/l for the second phase of the influent metal concentration effect study was not made immediately to minimize any potential shock effect to the system.

On 12/26/75, at 4:45 p.m., a large amount of risen sludge in the clarifier was rodded and rapidly settled. Again at 10:40 p.m.,

rodding was required to break up a large amount of risen sludge; rapid settling again followed with development of a large sludge blanket in the clarifier. The return sludge pumping time was increased to 5 minutes and allowed to operate for one cycle to adequately withdraw the sludge; thereafter, pumping time was reset at 2 minutes.

On 12/27/75, the air flow rate was increased to 5,758 cm^3/min because of inadequate mixing in the aeration tank. The MLSS concentration appeared to be greater which accounted for the less-than-adequate mixing. This higher air flow rate did not significantly increase the return sludge DO concentration and was therefore justified.

On 12/30/75, the influent chromium concentration was reduced to 1 mg/l. On 1/04/75, microscopic examination of the mixed liquor indicated an excellent quality activated sludge.

On 1/05/76, complete sampling was resumed for the second phase of the influent metal concentration effect study. Sampling and system operation proceeded smoothly through 1/15/76 with normal operation and system behavior.

After sampling was completed on 1/15/76, the influent chromium concentration was reduced to 0.1 mg/l in preparation for the third phase of this study on the influent metal concentration effect. Complete sampling was resumed on 1/19/76. Microscopic examination on this date indicated a typical, high quality activated sludge. On 1/20/76, the compressed air system malfunction, and the system was without air for approximately one hour. This condition probably contributed to a severe rising sludge problem wich occurred the following day, 1/21/76. The risen sludge was rodded and rapid settling followed

immediately. Because such a large volume of sludge was present in the clarifier, return sludge pumping time was increased to reduce the sludge volume to a normal level. After three hours (six pumping cycles), the sludge volume had returned to normal, and the pumping time was reduced to the previous duration. A small amount of risen sludge was rodded on 1/22/76 with good results. On 1/23/76, microscopic examination of the mixed liquor indicated a high quality activated sludge. Sludge settling characteristics in the clarifier were better than had been observed in several weeks. However, on the following day, sludge withdrawal from the clarifier was not satisfactory. Sludge in the bottom cone was rodded which liberated a significant amount of N_2. Some sludge began to rise during the rodding action, but resettled upon release of N_2. The clarifier returned to normal operation within one hour.

On 1/26/76, a severe rising sludge condition again occurred. The corrective measures which had been employed on 1/21/76 were repeated. Increased pumping time spanned a four-hour period (eight cycles), after which the previous pumping time was resumed. Microscopic examination of the mixed liquor on 1/29/76 indicated a high quality activated sludge. The influent metal concentration effect study was completed on this date.

After sampling was completed on 1/29/76, the system was spiked to 1 mg Cr/l. The potential for a change in system performance associated with a different source of chromium existed. Therefore, as preplanned, chromium trioxide, CrO_3, was used as the new chromium source. Initially, the influent metal concentration was increased to

1 mg/l using potassium chromate, K_2CrO_4. This concentration was chosen because of the relative speed in AA analysis by the flame technique in comparison to the graphite furnace technique. However, in retrospect, a somewhat higher concentration should have been selected because of the difficulties experienced in comparing influent and effluent soluble metal concentration to the corresponding total concentration.

On 1/29/76, when settled primary sewage was obtained from the Bryan Sewage Treatment Plant, the primary clarifier effluent weir channel was nearly inundated. This condition had not been observed to date and was the result of pumping down the wet well in the sewage lift station located ahead of preliminary treatment. This pumping practice was normally conducted at about 7:30 a.m. several times each week; however, on this day, pumping had been delayed such that its effect on the primary clarifier was still evident at 9:30 a.m. The sewage obtained was used to resupply the system influent waste on 2/01/76. Because the COD of the settled primary sewage very likely would be higher under the primary clarifier conditions observed on 1/29/76, the sharp increase in system influent COD on 2/02/76 through 2/04/76 is a logical consequence.

On 2/01/76, the system was spiked to a chromium concentration of 1 mg/l using CrO_3 as the metal source. The system was operated normally through 2/04/76 with no significant changes in performance. Microscopic examinations on 2/01/76, prior to changing the chromium source, and on 2/02/76, 16 hours after changing the chromium source, indicated equally high quality activated sludge (FIGURES 19 and 20).
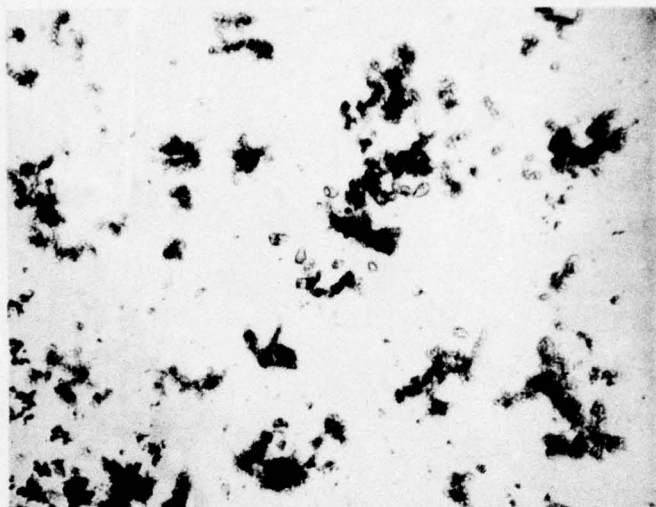
FIGURE 19.--Mixed Liquor, 2/01/76. Magnification-
35X, showing activated sludge under conditions of
1.0 mg/l influent chromium concentration with
K_2CrO_4 as the chromium source.
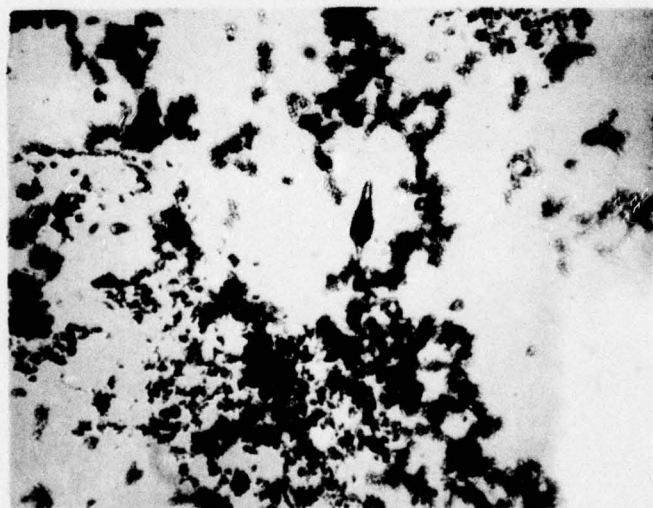
FIGURE 20.--Mixed Liquor, 2/02/76. Magnification-
35X, showing activated sludge under conditions of
1.0 mg/l influent chromium concentration with
CrO_3 as the chromium source.

Silver Study (TABLE II, page 115)

The system used for the previous chromium studies was drained, cleaned, and re-started on 2/06/76 for the silver study. In general, system operational parameters were the same as those for the chromium study.

Return sludge from the College Station sewage treatment plant was obtained on 2/06/76 and strained through cheese cloth. The aeration tank was charged with a volume of the strained sludge sufficient to obtain a MLSS concentration of approximately 2,000 mg/l. System balance was achieved on 2/09/76 by increasing the return sludge recycle pumping time, wasting the appropriate volume of mixed liquor based on the MLSS concentration, and then reducing the pumping time for return sludge to prevent complete sludge withdrawal from the clarifier.

Microscopic examinations of the mixed liquor from 2/06/76 through 2/09/76 initially indicated a stressed, poorly-mixed microbial population; however, a steady increase in the number and diversity of the population was observed. The initial, poor quality activated sludge was a direct result of aeration problems experienced at the College Station plant for several weeks prior to collection of the return sludge used to charge the laboratory system. Because of the aeration difficulties, the College Station plant was also experiencing poor sludge settling and compaction in the final clarifier. Sludge settled volumes were running as high as 800 ml. This sludge rapidly recovered after being placed into the laboratory system. After approximately 60 hours of operation with this initially poor quality

activated sludge, mixed liquor wasted on 2/07/76 was found to have a sludge settled volume of 200 ml and a sludge volume index of 87 ml/gram. Microscopic examination of the mixed liquor on 2/10/76 indicated a very high quality activated sludge.

On 2/10/76, the system was spiked to a silver concentration of 0.1 mg/l using silver sulfate (Ag_2SO_4) as the metal source. Complete sampling was begun on 2/12/76. Microscopic examinations of the mixed liquor on 2/15/76 and 2/18/76 indicated a very high quality activated sludge. The microbial population diversity was excellent (FIGURES 21 and 22). A previously unobserved protozoan (FIGURES 21 and 23) was abundant, and higher life forms were present (FIGURE 24).

On 2/18/76, after sampling was completed, the influent silver concentration was increased to 0.2 mg/l. On 2/20/76, very few Amphileptidae were present and another protozoan (FIGURE 25) was becoming predominant; however, the activated sludge quality remained typically high.

On 2/23/76, the influent pump head developed a bad bearing and was replaced. Only minor effect on influent flow rate for a short period of time resulted. On 2/25/76, microscopic examination revealed a similar population (FIGURE 26) to that observed 2/20/76.

After sampling was completed on 2/25/76, the influent silver concentration was increased to 0.5 mg/l. The system continued to function normally through 2/27/76 when system operation was terminated. Activated sludge quality remained high through termination.

63
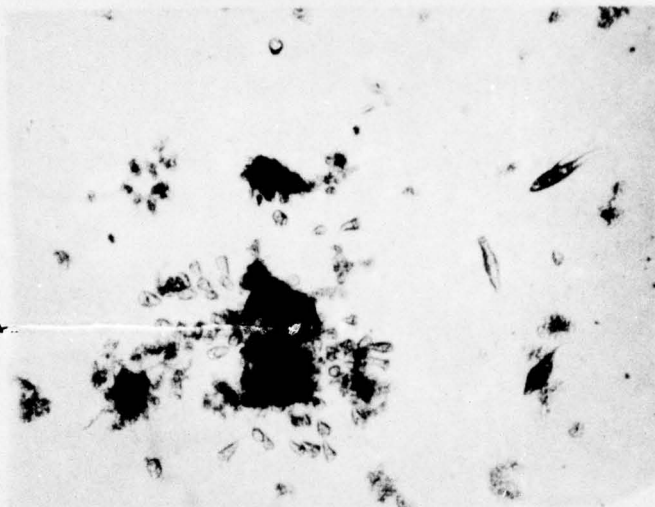
FIGURE 21.--Mixed Liquor, 2/15/76. Magnification-
35X, showing the microbial population diversity.

FIGURE 22.--Mixed Liquor, 2/18/76. Magnification-
35X, showing a typical large colony of stalked
ciliates.

64
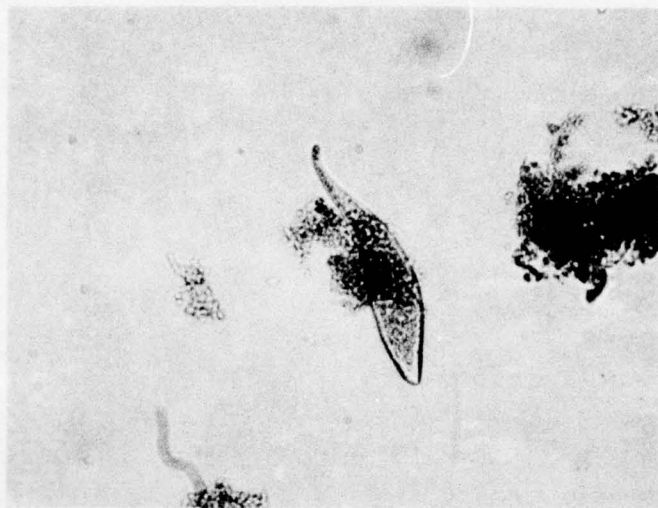
FIGURE 23.--Mixed Liquor, 2/18/76. Magnification-100X, showing a protozoan, conditionally identified to be of the Family Amphileptidae.[97]

FIGURE 24.--Mixed Liquor, 2/18/76. Magnification-35X, showing higher life form, conditionally identified to be of the Phylum Nemertea.[98]
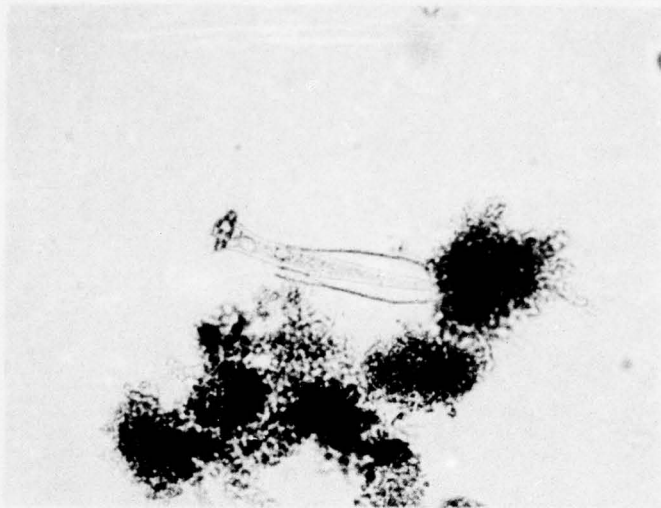
FIGURE 25.--Mixed Liquor, 2/20/76. Magnification-
100X, showing a typical protozoan, conditionally
identified to be of the tribe Loricata.[99]
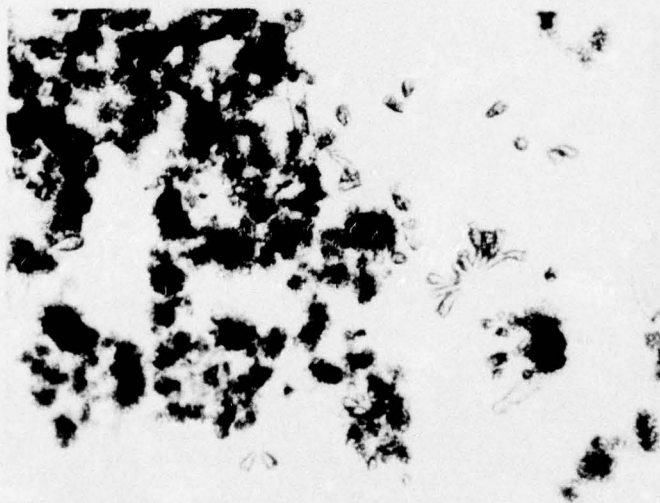
FIGURE 26.--Mixed Liquor, 2/25/76. Magnification-
35X, showing the well-mixed, high quality activated
sludge present. In the center-life of the photograph,
a loricate may be observed with the animal contracted
inside the lorica.

System Performance Data

All system performance parameters are chronologically tabulated. Significant parameter observations are emphasized under the corresponding parameter sub-heading.

Chromium Studies

pH (TABLE III, page 117). Values are reported to the nearest 0.1 for the influent, mixed liquor, return sludge, and effluent. There were no significant differences between the control and test system(s) during the chromium acclimation period from 10/13/75 through 11/01/75. Thereafter, through all phases of the chromium study, pH remained relatively stable. Variations in the influent pH were, in general, reflected by corresponding variations in mixed liquor, return sludge, and effluent pH. The influent pH ranged from 7.2 to 8.1, with a median value of 7.5; mixed liquor pH ranged from 7.4 to 8.0, with a median value of 7.7; return sludge pH ranged from 7.3 to 7.8, with a median value of 7.5; and effluent pH ranged from 7.4 to 8.3, with a median value of 7.8. Based on frequency of observations, the median pH values correspond to the most frequently observed value, with the exception of the influent pH. The most frequently observed influent pH was 7.6; however, the median influent pH was within 2 observations of the most frequent value. There were an equal number of observations for return sludge pH values of 7.4 and 7.5.

Therefore, the only pH observation worthy of note is a slight internal system variation in pH, with a general increase in the

order: return sludge, influent, mixed liquor, and effluent.

Dissolved oxygen and temperature (TABLE IV, page 121). Values are reported to the nearest 0.1 mg/l DO for the mixed liquor and return sludge, and to the nearest 0.1°C for the mixed liquor. No significant differences in DO between the control and test system(s) were observed during the chromium acclimation period from 10/13/75 through 11/01/75.

Variations in DO concentrations reflect the changes in air flow rate and type of aeration device used as discussed in the previous section of this chapter. In addition, fluctuations in the total suspended solids are generally reflected by DO concentrations, but to a lesser degree.

As noted in the preceding section of this chapter, a significant reduction of soluble chromium in the return sludge, detected on 12/15/75, was attributed to a DO effect. A detailed analysis of this effect is discussed under a separate section included later in this chapter.

Mixed liquor temperature ranged from 16.4°C to 22.5°C (62°F - 73°F). Temperature fluctuations reflected the temperature of the influent. Although influent temperature was not monitored, the temperature was known to vary depending upon the location, within the refrigerator, of the aquarium storage container from which the influent was pumped. Thus, influent storage temperature accounted for the variations in mixed liquor temperature observed. No temperature effect on system performance was observed.

Suspended solids (TABLE V, page 124). Values are reported to the nearest 1 mg/l for the influent, mixed liquor, return sludge, and effluent. Influent total suspended solids varied according to primary clarifier performance at the sewage treatment plant from which the settled primary was collected. Mixed liquor, return sludge, and effluent total suspended solids varied according to laboratory system operation and management.

Because of the large number of analyses considered critical for evaluation of this unique study which were included in the experimental design, volatile suspended solids analyses were necessarily limited. Hence, the volatile suspended solids data available are insufficient in scope for adequate evaluation; but are reported to permit comparison in future similar research.

Chemical oxygen demand (TABLE VI, page 134). Values are reported to the nearest 1 mg COD/l for the influent and effluent. COD removal efficiencies are reported to the nearest 0.1%. Although the settled primary sewage used as the laboratory system influent was collected at the same time of day and only on weekdays, large variations of influent COD frequently occurred. Some of these variations were explainable, such as that which occurred on 2/02/76 through 2/04/76 which was discussed in the previous section of this chapter; others, which are readily observed in TABLE VI, cannot be explained with authority. Suffice it to mention that prototype sewage treatment plants experience similar loading variations, which serves to give more validity to extrapolation of these laboratory results to prototype treatment plants.

Total and soluble COD removal efficiencies followed one another very closely in most instances; soluble COD removal efficiency was, generally, slightly higher.

A statistical analysis, using mean and standard deviation, of the COD removal efficiencies confirmed similar system performance between the control and test system(s) prior to and during chromium acclimation from 10/13/75 through 11/01/75. During pre-acclimation system operation, 10/13/75 through 10/17/75, the mean COD removal efficiency was 64.4% (±20.8%), if all 12 COD observations on these dates are included in the calculation. However, if the three lowest values (test system 2, 10/15/75; control system, 10/16/75; and test system 1, 10/16/75) are considered as questionable values and are disregarded in the calculation; the mean COD removal efficiency was 74.3% (±3.6%). During acclimation, 10/20/75 through 11/01/75, the control system mean COD removal efficiency was 75.1% (±4.5%) and the mean COD removal efficiency for the tests systems was 72.9% (±6.8%). The mean COD removal including each system for the entire period 10/13/75 through 11/01/75, disregarding the three low values, was 74.0% (±5.1%). Using the higher value for the pre-acclimating period, all mean COD removal efficiences as calculated are statistically the same.

A relationship between COD removal efficiency and influent chromium concentration was indicated and is discussed in detail in a separate section included later in this chapter.

Influent nitrogen species (TABLE VII, page 141) and effluent nitrogen species (TABLE VIII, page 144). Values are reported to the

nearest 0.1 mg/l as N. When the determined or calculated value was
less than 0.5, the value was reported as 0.0; an entry of 0 corresponds
to an undetected parameter when analysis was performed, or no difference
for calculated values. Values were determined for TKN, HN_3-N, NO_2^--N,
and NO_3^--N. Organic nitrogen (ORG-N) was calculated as the difference
in total TKN and NH_3-N, and total nitrogen represents the sum of
total TKN, NO_2^--N, and NO_3^--N.

The data readily exhibit a consistently high reduction in NH_3-N.
The influent NH_3-N mean concentration was 20.0 mg/l (±4.8 mg/l) for
the entire period of study, 10/03/75 through 2/04/76. On two consecu-
tive days, 11/03/75 and 11/05/75, the effluent NH_3-N concentration was
inordinately high and no significant variation in influent nitrogen
occurred. The only system operation parameter which varied signifi-
cantly during this period was the influent flow rate. Flow rate was
increased from 15 ml/min to 20 ml/min on 11/01/75; from 20 ml/min to
25 ml/min on 11/02/75; and from 25 ml/min to 30 ml/min on 11/03/75.
Therefore, a temporary shock effect on system nitrification evidently
occurred as a direct result of the influent flow rate increase.
Thereafter, the system rapidly adjusted to the increased loading and
returned to normal performance. Disregarding these two effluent
NH_3-N values, the effluent NH_3-N mean concentration was 0.1 mg/l
($\pm$ 0.1 mg/l). Thus, the mean removal efficiency for NH_3-N was 99.4%.
The mean removal efficiency for total TKN was 90.1%.

The influent soluble TKN mean concentration was 86% of the
influent total TKN mean concentration, and the effluent soluble TKN
was 52% of the effluent total TKN (disregarding the effluent TKN

values on 11/03/75 and 11/05/75).

Alkalinity (TABLE IX, page 147). Values are reported to the nearest 1 mg/l as $CaCO_3$. The data readily exhibit relatively stable values for the influent and the effluent. The influent mean concentration was 457 mg/l ($\pm$24 mg/l), and the effluent mean concentration was 329 mg/l ($\pm$30 mg/l).

Alkalinity determinations were used as a simple means of indirectly monitoring system NH_3-N reduction performance on off-sampling days. A relationship has been reported[100] which results in an alkalinity decrease of 7.2 mg/l per 1.0 mg/l of NH_3-N oxidized based on stoichiometry. Based on available data[100], it was also reported that 6.0 mg/l of alkalinity (as $CaCO_3$) were removed per 1.0 mg/l of TKN removed.

In this research, based on the calculated mean concentrations of alkalinity, NH_3-N, and TKN observed during the chromium study, 6.4 mg/l of alkalinity were removed per 1.0 mg/l of NH_3-N removed, 4.4 mg/l of alkalinity were removed per mg/l of total TKN removed, and 5.0 mg/l of alkalinity were removed per mg/l of soluble TKN removed. A detailed explanation for the difference in the relationships obtained in this research and the reported relationships is not within the scope of this research. Presumably, these relationships would vary with different sewages; therefore, caution is indicated in applying these relationships to a wide range of conditions.

Chromium (TABLE X, page 149). Values are reported to the nearest 0.1 mg Cr/l for the influent, mixed liquor, return sludge, and effluent. Frequently, soluble chromium concentration was determined to be

greater than total chromium concentration for the influent and effluent.

The difference in total and soluble chromium compared to the total values as a percentage ranges from 2% to 100% for the influent and effluent. The lower range of differences, 2% to 10%, corresponds to those analyses performed at the 10 mg Cr/l level, and are considered to be within acceptable experimental error. The upper range of differences, 11% to 100%, corresponds to those analyses performed at the 1 mg/l and 0.1 mg/l levels.

A check on the filtration technique was made by duplicating all filtration procedures with distilled-deionized water. Analysis for chromium concentration was performed using the graphite furnace AA technique. The chromium concentration of the distilled-deionized water prior to filtration was 0.0015 mg/l, and on 12 separate filtrates was less than 0.001 mg/l. Therefore, the filtration technique employed in this research is not considered to have contributed to these errors.

Chromium is known for its difficulty of analysis at a concentration range of 0.1 mg/l to 1.0 mg/l. At 0.1 mg/l, the upper limit of graphite furnace analysis has been approached; and at 1.0 mg/l, the lower limit of flame analysis is being approached. Because of the inherent errors associated with dilution, and the relatively small sample volume available for dilution, these errors were accepted with due caution exercised in subsequent data analysis.

A significant trend, associated with an increase in the mixed liquor and return sludge chromium concentration as the study progressed,

is readily observed in the data. This trend and its associated impli-
cations are considered to be the most important observation of this
research. Accordingly, a complete discussion is contained under a
subsequent separate section of this chapter.

Silver Study

pH (TABLE XI, page 153). Values are reported to the nearest 0.1
for the influent, mixed liquor, return sludge, and effluent. pH
remained relatively stable throughout this study. Variations in the
influent pH were, in general, reflected by corresponding variations
in mixed liquor, return sludge, and effluent pH. The influent pH
ranged from 7.4 to 7.7, with a median value of 7.6; mixed liquor pH
ranged from 7.5 to 7.6, with a median value of 7.6; return sludge pH
ranged from 7.3 to 7.5, with a median value of 7.4; and effluent pH
ranged from 7.6 to 8.0, with a median value of 7.7. In all cases the
median values and the most frequently observed values were the same.

Therefore, the only pH observation worthy of note is a slight
internal system variation in pH, with a general increase in the order:
return sludge, influent, mixed liquor, and effluent.

Dissolved oxygen and temperature (TABLE XII, page 154). Values
are reported to the nearest 0.1 mg DO/l for the mixed liquor and
return sludge, and to the nearest 0.1°C for the mixed liquor. Varia-
tions in DO concentrations reflect, in general, fluctuations in the
total suspended solids. Mixed liquor temperature ranged from 19.2°C
to 21.5°C (67°F to 71°F). No DO or temperature effect on system per-
formance was observed.

Suspended soilds (TABLE XIII, page 155). Values are reported to
the nearest 1 mg/l for the influent, mixed liquor, return sludge, and
effluent. Influent total suspended solids varied according to primary
clarifier performance at the sewage treatment plant from which the
settled primary was collected. Mixed liquor, return sludge, and ef-
fluent total suspended solids varied according to laboratory system
operation and management. Volatile suspended solids analyses were
limited by experimental design and are reported only for comparison
in future similar research.

Chemical oxygen demand (TABLE XIV, page 157). Values are reported
to the nearest 1 mg COD/l for the influent and effluent. COD removal
efficiencies are reported to the nearest 0.1%. Variations in influent
COD occurred in a similar manner to that which was previously dis-
cussed for the chromium study. Total and soluble COD removal effi-
ciencies correlated well; soluble COD removal efficiency was, generally,
slightly higher.

A relationship between COD removal efficiency and influent silver
concentration was not observed in this study. However, the relatively
high COD removal efficiency observed in comparison to the chromium
study is significant. A detailed analysis of this effect is included
in a separate, subsequent section of this chapter.

Influent nitrogen species (TABLE XV, page 159) and effluent nitro-
gen species (TABLE XVI, page 160). Values are reported to the nearest
0.1 mg/l as N. When the determined or calculated value was less than
0.5, the values was reported as 0.0; an entry of 0 corresponds to an
undetected parameter when analysis was performed, or no difference for

calculated values. Values were determined for TKN, NH_3-N, NO_2^--N, and NO_3^--N. Organic nitrogen (ORG-N) was calculated as the difference in total TKN and NH_3-N, and total nitrogen (Total-N) represents the sum of total TKN, NO_2^--N, and NO_3^--N. The data readily exhibit a consistently high reduction in NH_3-N for the entire study duration.

The influent NH_3-N mean concentration was 16.7 mg/l ($\pm$2.4 mg/l), and the effluent NH_3-N mean concentration was less than 0.1 mg/l. Thus, the mean removal efficiency for NH_3-N was greater than 99.4%. The mean, total TKN removal efficiency was 93.3%.

The influent soluble TKN mean concentration was 91% of the influent total TKN mean concentration; and the effluent soluble TKN was 50% of the effluent total TKN.

Alkalinity (TABLE XVII, page 161). Values are reported to the nearest 1 mg/l as $CaCO_3$. The data indicate relative stability in system performance. The influent mean concentration was 461 mg/l ($\pm$8 mg/l) and the effluent mean concentration was 335 mg/l ($\pm$18 mg/l). For the silver study, 7.5 mg/l of alkalinity were removed per 1.0 mg/l of NH_3-N removed; 4.1 mg/l of alkalinity were removed per 1.0 mg/l of total TKN removed; and 4.3 mg/l of alkalinity were removed per 1.0 mg/l of soluble TKN removed.

Silver (TABLE XVIII, page 162). Because of the increased sensitivity and reliability of AA analysis for silver, values are reported to the nearest 0.01 mg/l Ag for the influent, mixed liquor, return sludge, and effluent.

An important observation was made regarding the background silver concentration of the settled primary domestic sewage used as the

influent for this study and the primary clarifier return sludge used for the microbial seed in charging the laboratory system. The silver concentration data reported for 2/10/76 were silver concentrations determined on samples taken prior to spiking the system with silver. Insufficient data was available to determine whether this background silver concentration originated from the settled primary sewage or the primary clarifier return sludge.

Regardless of the source in this case, the importance of this observation is its relation to the detection of heavy metals in any domestic sewage. Analyses performed on the influent or effluent of a domestic sewage treatment plant may fail to show the presence of a heavy metal because of low concentration and detection limits. However, the microbial mass of any type of biological treatment system may serve to concentrate a heavy metal. Accordingly, analyses for both total and soluble heavy metal, as defined in this dissertation, should be performed to confirm or deny the presence of heavy metals in bio-logical treatment systems and the influent or effluent wastewater thereof.

A significant trend, associated with an increase in the mixed liquor and return sludge silver concentration as the study progressed, may be readily observed in the data. A complete discussion is con-tained under a subsequent, separate section of this chapter.

Analysis of Nitrification and Heavy Metal Relationship

Early observations in the Dallas project[91] appeared to support a hypothesis that high nitrification led to more efficient heavy

metal removal from wastewater. However, as more data was collected, further detailed analysis failed to confirm or deny the hypothesis.

The results of this research demonstrated that high nitrifying conditions prevailed throughout both the chromium and silver studies. In the chromium study, no significant chromium removal was determined regardless of the influent concentration. In the silver study, significant removal of silver did occur at the 0.1 mg/l and 0.2 mg/l influent Ag concentrations; however, when the influent silver concentration was increased to the 0.5 mg/l level, a marked reduction in silver removal occurred.

Because low nitrifying conditions were never achieved in any phase of this research, definite denial of a nitrification effect cannot be made. However, the results strongly lead to the conclusion that an indirect relationship of nitrification to metal removal exists.

Under given system operational conditions, the amount of sludge wasted will determine the degree of nitrification which takes place. A high rate of sludge wasting will result in young sludge age, which in turn yields lower degrees of nitrification. Conversely, low-rate sludge wasting will result in relatively older sludge, which in turn yields higher degrees of nitrification. It is the sludge wasting rate which appears to be the main mechanism affecting heavy metal removal. Therefore, nitrification appears indirectly related to heavy metal removal. This sludge wasting affect or mechanism will be discussed in more detail in a later section of this chapter.

The ability of nitrifying organisms to acclimate to high levels of a heavy metal has been documented in the literature.[54] Heavy

metal shock loads have reduced nitrification for a period of time, but recovery of system nitrification and subsequent relative insensitivity to changes in metal loading has followed. As previously mentioned, high nitrification prevailed through all phases of this research. Therefore, the capability of nitrifying organisms to readily acclimate to high levels of chromium, and low levels of silver, without inhibition of nitrification has been demonstrated.

Analysis of Heavy Metal and COD Relationship

TABLE XIX (page 163) presents corresponding influent chromium concentration and COD removal efficiency data. TABLE XX (page 167) presents the same relationships for silver.

The mean COD removal efficiencies during the chromium study were 74.0% ($\pm$5.1%) during the pre-acclimation and acclimation period, 10/13/75 through 11/01/75; 54.6% ($\pm$10.7%) at the 10 mg Cr/l level, 11/02/75 through 12/24/75; 63.4% ($\pm$5.8%) at the 1 mg/l level, 1/05/76 through 1/15/76; and 51.2% ($\pm$11.1%) at the 0.1 mg/l level, 1/16/76 through 1/29/76. During the chromium source comparison study at 1 mg Cr/l, the mean COD removal efficiencies were 51.7% ($\pm$14.1%) when K_2CrO_4 was used as the Cr source, 1/30/76 through 2/01/76, and 57.5% ($\pm$7.6%) when CrO_3 was used as the Cr source, 2/02/76 through 2/04/76.

The mean COD removal efficiencies during the silver study were 71.9% ($\pm$6.0%) at the 0.1 mg Ag/l level, 2/10/76 through 2/18/76; 74.9% ($\pm$3.9%) at the 0.2 mg/l level, 2/19/76 through 2/27/76.

A marked reduction in COD removal efficiency is readily observed in TABLE XIX from 11/02/75 through 11/04/75. Although the available

data are insufficient to attempt a definitive explanation for this rapid decrease, some pertinent data relationships are noteworthy.

During the period 11/02/75 through 11/04/75, the influent flow rate was increased from 15 ml/min to 30 ml/min which would appear to have been the cause for reduction in COD removal efficiency. However, the COD removal efficiency for the silver study was as high as that for the pre-acclimation and acclimation phases of the chromium study. Therefore, because the influent flow rate for the silver study was 30 ml/min and the influent flow rate for the pre-acclimation and acclimation phases of the chromium study was 15 ml/min, the increased flow rate alone is not considered to have been the major cause for the reduction in COD removal efficiency. Further, considering the COD removal efficiency achieved during the silver study, system recovery during the chromium study in terms of COD removal efficiency would be expected if the flow rate alone was the major factor involved; observations readily show that this did not occur during three months of continued operation.

Accordingly, the increased chromium loading which resulted from the increased flow rate is hypothesized to be the major factor contributing to the rapid reduction in COD removal efficiency observed from 11/02/75 through 11/04/75. A general data analysis indicates that as system chromium concentrations increase, the COD removal efficiency decreases. Because of the conditions under which the system was operated for the chromium study, system failure did not occur.

Reduction in COD removal efficiency for the silver study was not observed. However, continued system operation under the low influent silver level probably would have resulted in decreased COD removal efficiency occurring more gradually than that observed during the chromium study.

Analysis of Return Sludge Dissolved Oxygen and
Soluble Metal Concentration Relationship

Because of the significant reduction in the return sludge soluble chromium concentration observed on 12/15/75, all system parameters monitored for the period 12/09/75 through 12/24/75 were examined. A direct relationship was found between the return sludge soluble chromium concentration and return sludge DO concentration. (See entries for these values on 12/15/75 through 12/24/75 in TABLE IV, page 121 and TABLE X, page 149). This relationship indicates that low DO concentration in the return sludge does affect chromium uptake by the sludge; and, accordingly, may affect heavy metal removal. However, with an influent Cr concentration of 10 mg/l; the decrease in soluble metal, or increase in sludge associated metal, was not sufficient in total metal mass to affect the overall system chromium removal under the existing operation conditions. The minor changes in return sludge recycle pumping time on 12/15/75 and 12/16/75 were made because of the amount of sludge contained in the clarifier. Since the duration of increased pumping time was only approximately 15 hours, this action was not considered to have had any significant effect regarding the soluble chromium - DO relationship. The return sludge DO concentration

increase from 12/16/75 through 12/24/75 was attributed to the depletion
of return sludge solids caused by resumption of complete sampling.

Unfortunately, Eh was not monitored. However, it is believed
that an Eh-pH diagram analysis during this period would have revealed
significant insight into the cause of this observation. If the Eh
changed enough to effect the solubility of the chromium such that
metal complexing with the sludge was enhanced, the soluble metal con-
centration would obviously decrease.

Analysis of Heavy Metal and Suspended Solids Relationship

TABLE XXI (page 168) presents a relationship of suspended chromium
concentration and suspended solids for the influent, mixed liquor, return
sludge, and effluent. TABLE XXII (page 171) presents the same rela-
tionships for silver. Suspended metal is considered to be that metal
which is physically, chemically, or biologically associated with the
sludge solids. Suspended metal concentrations were calculated as the
difference in total metal and soluble metal, each of which were pre-
viously defined in CHAPTER III, page 29. Where the soluble chromium
concentration was greater than the total chromium concentration, nega-
tive values were calculated and are reported in TABLE XXI (page 168).
These negative values occurred only for the influent and effluent and
are attributed to a combined effect of relatively low suspended solids
concentrations and experimental error. Therefore, influent and effluent
values for the metal-solids relationship are reported only to illustrate
that regardless of influent or effluent total metal concentration,
the corresponding suspended metal concentration did not exhibit a

time-related trend.

The experimental errors experienced were several orders of magnitude less than the mixed liquor and return sludge suspended chromium concentrations determined and these errors undoubtedly occurred in each determination. Therefore, these experimental errors may be disregarded in an analysis of the important time-related trend of increasing suspended metal concentrations.

FIGURES 27 and 28 graphically illustrate the concentration of chromium with time in the mixed liquor and return sludge respectively. An attempt to fit a curve to the data was not considered necessary.

FIGURES 29 and 30 graphically illustrate the concentration of silver with time in the mixed liquor and return sludge, respectively. The silver study data covered a much shorter time in comparison to the chromium study and significant data scatter occurred. A rough silver balance on the system for the period 2/11/76 through 2/18/76 was made based on influent and effluent flow rates of 43.2 l/day, average total metal concentrations, and the average daily withdrawal of mixed liquor and return sludge. Calculations show that 4.3 mg Ag/day entered the system, 0.9 mg/day exited the system in the effluent, and only 0.2 mg/day was removed from the system by sludge wasting. Obviously, the amount of silver entering the system exceeded the combined amount which exited or was removed from the system.

Considering this system balance and the data reported by Thomas and LeFebver[85] specifically regarding increasing silver concentration with time in activated sludge, it appears that silver is concentrated by activated sludge in a manner similar to that demonstrated for chromium.
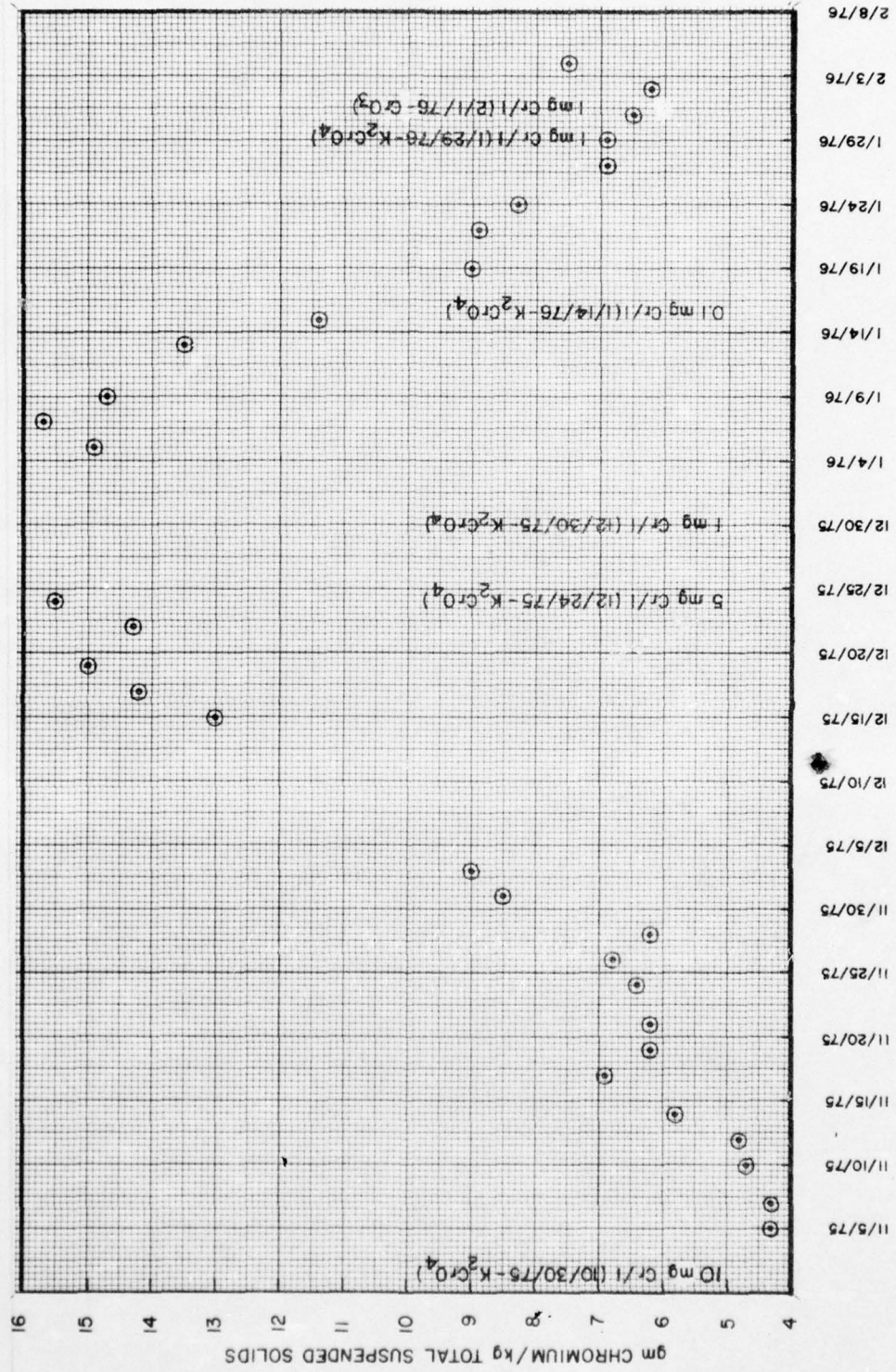
FIGURE 27.--MIXED LIQUOR CHROMIUM-SOLIDS WEIGHT RATIO vs. TIME
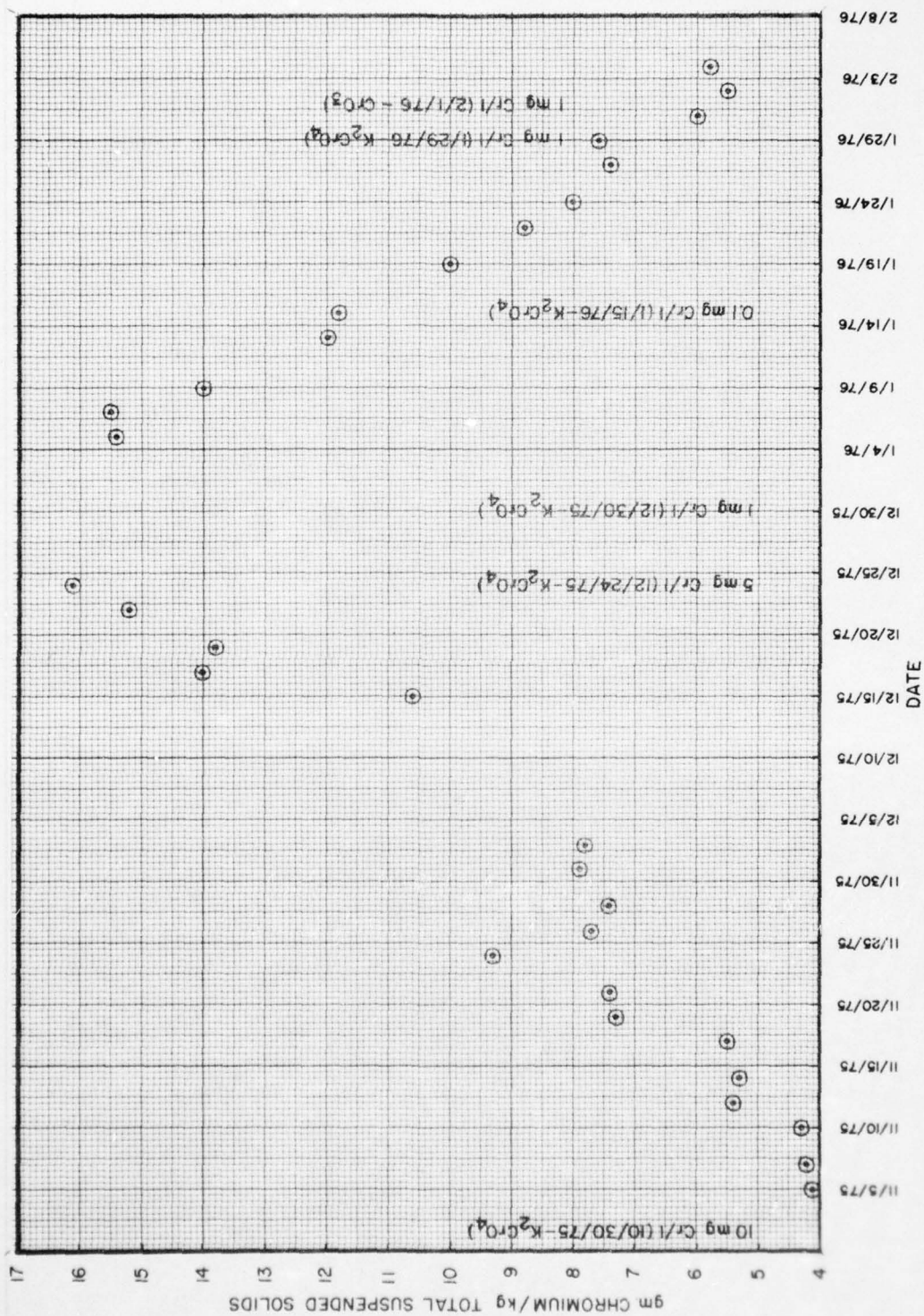
FIGURE 28.--RETURN SLUDGE CHROMIUM-SOLIDS WEIGHT RATIO vs. TIME
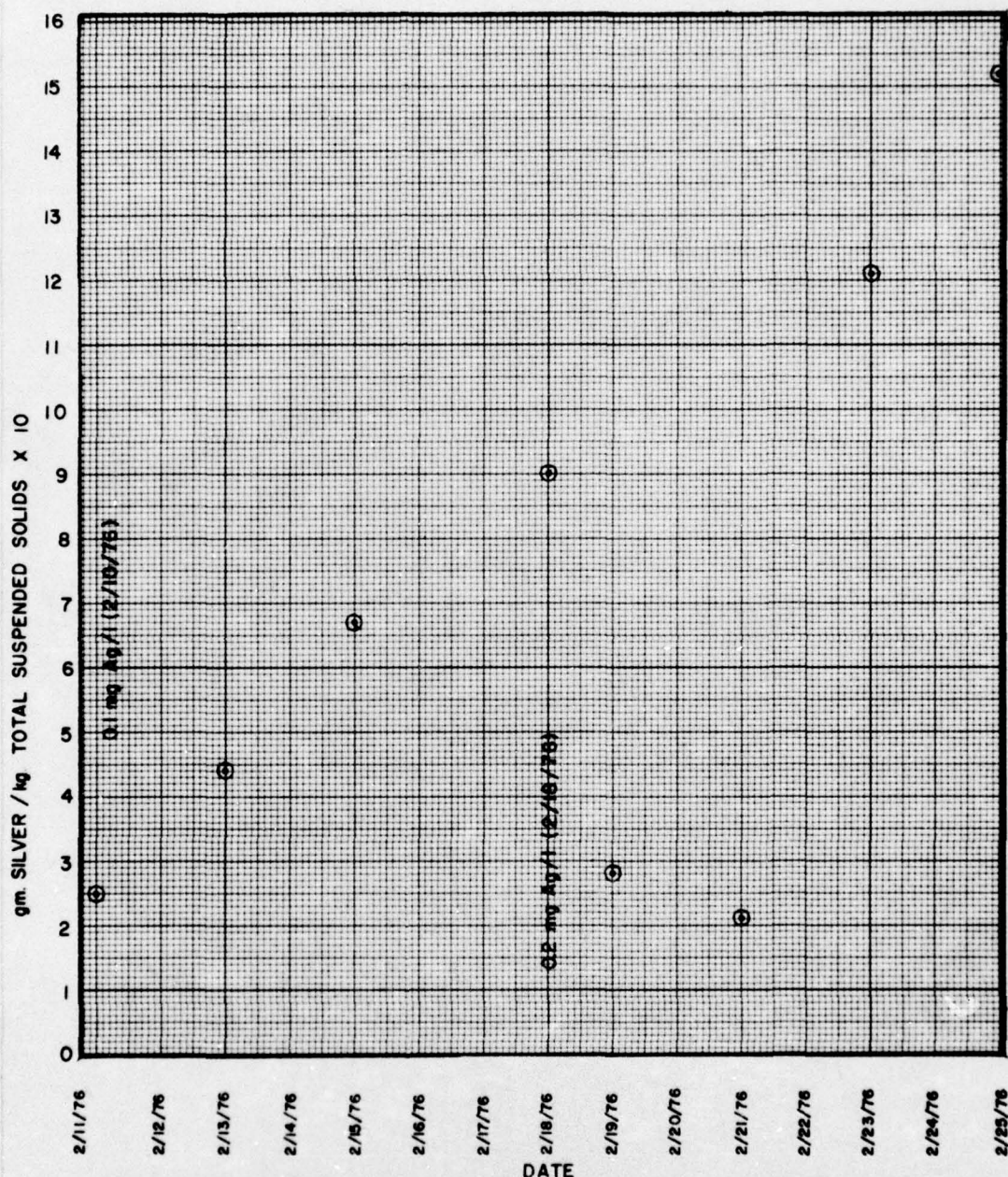
FIGURE 29.--MiXED LIQUOR SILVER-SOLIDS WEIGHT RATIO vs. TIME
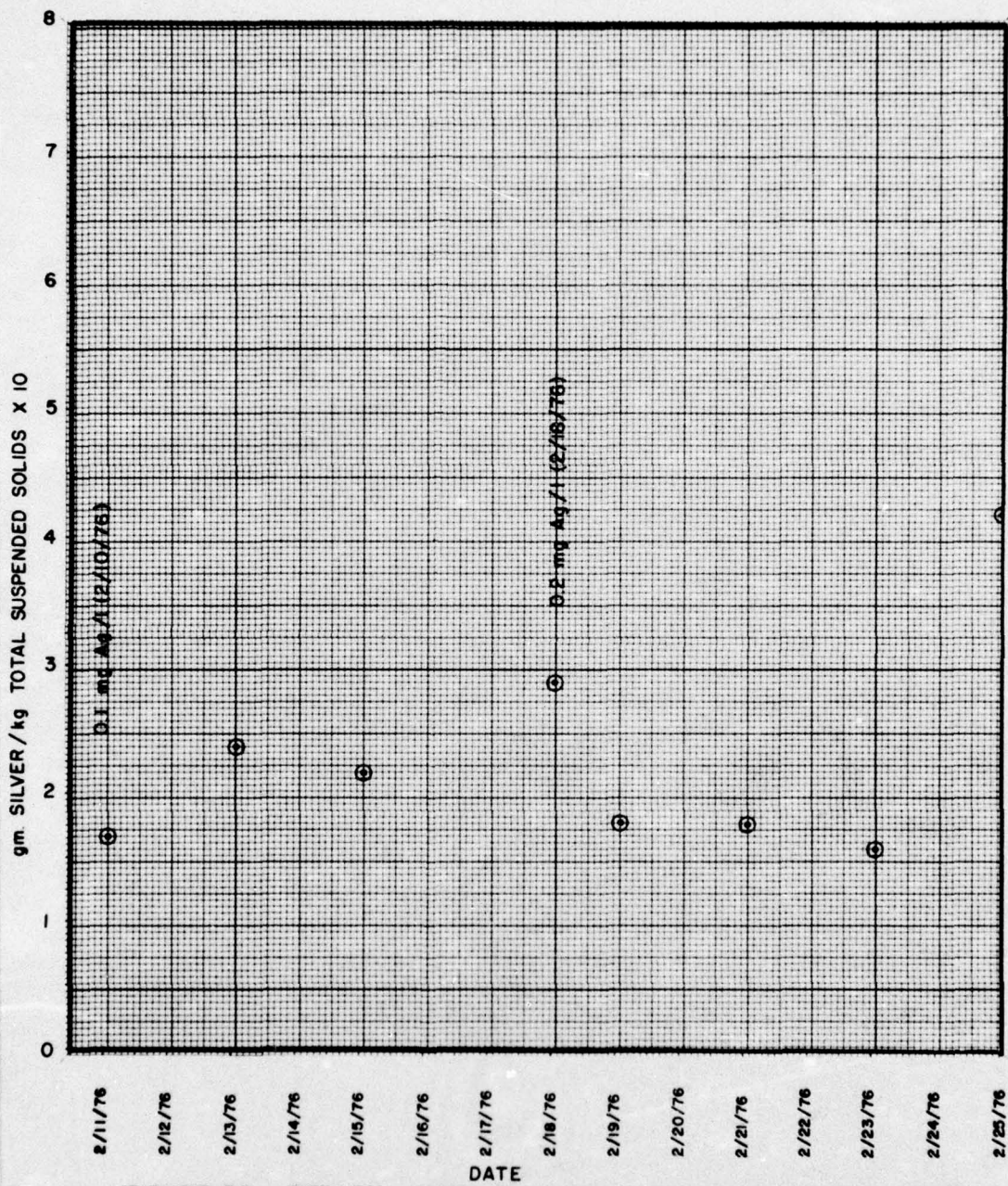
FIGURE 30--RETURN SLUDGE SILVER-SOLIDS WEIGHT RATIO vs. TIME

Accordingly, based on reports in the literature and the results of this research, it is obvious that activated sludge possesses the capability of highly concentrating a heavy metal. Rudolfs and Zuber[75] and Ruchhoft[76] suggested that the adsorption or zeolitic capacity of sludge could be used to remove heavy metals. This capability appears to be the main phenomenon responsible for heavy metal removal by the activated sludge process. Continued heavy metal removal under continuous heavy metal influent conditions is believed to be related to several other factors which in combination are responsible for metal removal from the system. These factors are discussed in a later section of this chapter.

Analysis of Influent Heavy Metal Concentration and Heavy Metal Removal Efficiency Relationship

Significant silver removal was achieved during the silver study at the lower influent concentrations. At the 0.1 mg Ag/l level, 2/11/76 through 2/18/76, total silver removal efficiency was approximately 90%. At the 0.2 mg/l level, 2/19/76 through 2/25/76, total silver removal efficiency was approximately 65%. When the system was spiked to the 0.5 mg/l level, 2/27/76, silver removal efficiency immediately dropped to less than 10%. These observations clearly demonstrate the dramatic effect that influent silver concentration has on silver removal.

Analysis of Heavy Metal Removal by the
Activated Sludge Treatment Process

The original objective of this research and the corresponding experimental design was directed toward a study of nitrification aspects in relation to heavy metal removal. The data thus collected, although not completely supportive, provide sufficiently strong indications to warrant development of the following theory on heavy metal removal by the activated sludge process.

Examination of the basic equation for sludge production (Equation 1, page 10) shows that, in general, as influent COD increases with the other factors remaining stable, the sludge yield increases. Under any given conditions, as sludge yield increases, the sludge wasting rate must be increased to maintain steady state conditions in an activated sludge process which employs sludge recycle. A logical consequence of increased wasting rate of a heavy metal ladened sludge is removal of heavy metal from the main treatment system. Accordingly, the sludge wasting rate would be the main mechanism affecting heavy metal removal efficiency. The degree of effect which sludge wasting has on heavy metal removal efficiency is further dependent on several additional co-related factors.

As fresh sludge is produced because of cell growth, an increased heavy metal concentration capability is developed. As metal is concentrated by existing sludge, the capability of this sludge to further concentrate a heavy metal is reduced. Potentially, a balance of these opposing capabilities is achieved dependent upon the amount of

fresh sludge and older sludge removed from the system by sludge wasting.

Another factor contributing to heavy metal removal efficiency is the rate at which the system is loaded with a heavy metal in comparison to the overall rate at which sludge is capable of concentrating the heavy metal. This factor is obviously related to the influent metal concentration. The effect of influent metal concentration was observed in the silver study.

There are probably other related factors; however, those mentioned are considered the major ones involved. Therefore, heavy metal removal efficiency by an activated sludge process is considered to be a function of:

1. the sludge production rate, as a positive term;

2. the overall metal concentration rate by the sludge, as a positive term;

3. the sludge wasting rate of metal ladened sludge, as a positive term;

4. the system metal loading rate, as a negative term; and

5. the sludge wasting rate of fresh sludge containing little or no metal, as a negative term.

A direct parallel between this theory and the well established principles of activated carbon treatment[101] may be qualitatively supported by pertinent observations made during this research.

The silver loading rate in relation to the silver concentration rate by the sludge and the corresponding silver concentration capacity of the sludge apparently is very similar to the breakthrough curve

concept used in activated carbon treatment. Although the silver loading rate at the 0.1 mg Ag/l level exceeded the silver removal rate via sludge wasting, the sludge was able to concentrate silver at a rate high enough to result in significant silver removal efficiency. The 0.2 mg/l level silver loading rate in combination with the reduced sludge silver-concentration capacity, and very likely a corresponding reduced silver-concentration rate, caused a reduction in silver removal efficiency at this influent Ag level. When the 0.5 mg/l level silver loading rate was imposed on the system, silver break-through evidently occurred with system failure in terms of silver removal efficiency immediately following.

Chromium removal was not detected during the chromium study apparently because of the rapid manner in which the system was loaded with chromium. Chromium breakthrough evidently occurred when the influent Cr level was increased to 1 mg/l during acclimation. After reducing the influent Cr level from 10 mg/l to 1 mg/l and subsequently 0.1 mg/l, the sludge rapidly lost chromium (FIGURES 27 and 28, pages 83 and 84), indicating the system's potential for recovery after breakthrough and saturation of the sludge with chromium. This de-saturation phenomenon seems to support a self-regenerative potential of the sludge which results, at least partially, from fresh sludge production.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Nitrification and Heavy Metal Removal

Varying degrees of nitrification do not appear to have a significant direct effect on heavy metal removal in the activated sludge treatment process. Future similar research in which significant variations in sludge wasting rates are possible may provide sufficient data to comment further on this potential relationship. If, in fact, such a relationship does exist, it is believed that its effect on heavy metal removal will be minimal.

Heavy Metal Concentration Effect on Nitrification and COD Removal

The results of this research clearly demonstrate that adequately acclimated nitrifying microorganisms can perform in highly concentrated heavy metal environments without inhibition of nitrification.

High concentrations of heavy metals appear to reduce the COD removal efficiency of activated sludge. However, with adequate sludge wasting as a means of maintaining relatively low metal concentrations in the sludge, reduction of COD removal efficiency should not occur in a full-scale treatment facility.

Detection of Heavy Metals in Wastewaters

Any surveillance program designed to detect heavy metals in a wastewater should include analyses for heavy metals in the biological mass of any type of biological treatment process.

Heavy Metal Removal Mechanism

Activated sludge possesses a capability for concentrating heavy metals in a manner similar to the principles of activated carbon adsorption. This capability is the main phenomenon leading to heavy metal removal by the activated sludge process. Sludge wasting subsequently is the key mechanism involved in removal of heavy metal from the system.

Activated sludge appears to possess a self-regenerative capability for concentrating heavy metals. Additionally, waste activated sludge which has been enriched with heavy metals is a potential source for economical valuable material recovery. Accordingly, application of the activated sludge process to treatment of domestic and industrial wastewater containing heavy metals appears highly desirable for reasons of versatility and financial profit.

Certainly, more research is required to fully develop the theory of heavy metal removal presented in this dissertation. Several specific recommendations for future research by other workers are warranted.

Any laboratory research undertaken which involves bench-scale treatment studies should employ a continuous flow system with sludge recycle from a separate sedimentation unit. Use of domestic sewage seems highly desirable; however, the sewage may require supplemental additions of a carbon source to increase the COD, thus permitting flexibility in the sludge wasting rate.

Continuous flow treatment studies should be designed to permit analysis of each major contributing factor to heavy metal removal

both singularly and in combination with each other. The parameters
that appear to be pertinent are the metal loading rate, sludge metal-
concentration rate, sludge production rate, and sludge wasting rate.

The sludge metal-concentration rate may vary depending on the
metal or metals in a wastewater and the characteristics of the waste
(domestic or industrial). Therefore, separate studies should be made
for each specific case of interest.

Research directed toward heavy metal recovery should consider
volatile suspended solids. In addition, data should be developed
concerning residual heavy metal concentration in the sludge after
subjection to temperatures normally achieved by current sludge in-
cineration techniques as a means of sludge disposal.

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APPENDIX

TABLES

TABLE I.--System Operation Parameters - Chromium Study

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
10/10/75					
Control System	15.0	154	24,640	--	0.12
Test System 1	15.0	143	22,880	--	0.13
Test System 2	15.0	147	23,520	--	0.12
10/13/75					
Control System	15.0	7,618	22,080	2.9[1]	0.14
Test System 1	14.5	6,081	21,440	3.5[1]	0.14
Test System 2	14.5	5,760	21,120	3.7[1]	0.15
10/14/75					
Control System	15.5	102	16,320	--	--
Test System 1	15.5	107	17,120	--	--
Test System 2	15.0	107	17,120	--	--
10/15/75					
Control System	15.3	1,866	17,120	9.2[1]	0.11
Test System 1	15.0	1,866	16,968	9.1[1]	0.12
Test System 2	15.0	1,866	17,120	9.2[1]	0.12
10/16/75					
Control System	15.5	91	14,560	--	0.13
Test System 1	15.5	96	15,360	--	0.13
Test System 2	15.0	98	15,680	--	0.13

TABLE I.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
10/17/75					
Control System	--	370	16,000	43.2[1]	0.19
Test System 1	--	933	17,120	18.3[1]	0.13
Test System 2	--	1,257	17,760	14.1[1]	0.15
10/18/75					
Control System	15.5	2,079	17,440	8.4[1]	--
Test System 1	15.3	959	16,320	17.0[1]	--
Test System 2	15.3	1,121	16,480	14.7[1]	--
10/19/75					
Control System	16.5/14.2[2]	961	16,320	17.0[1]	--
Test System 1	15.5/14.5	319	15,680	49.2[1]	--
Test System 2	15.5/15.0	96	15,360	--	--
10/20/75					
Control System	15.3	1,389	15,680	11.3[1]	0.22
Test System 1	14.5	1,529	15,840	10.4[1]	0.21
Test System 2	15.0	1,177	15,360	13.1[1]	0.23
10/21/75					
Control System	15.3	88	14,080	--	--
Test System 1	15.0	89	14,240	--	--
Test System 2	15.3	97	15,520	--	--

TABLE I.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
10/22/75					
Control System	--	3,197	21,440	6.7	0.14
Test System 1	--	2,846	20,640	7.3	0.14
Test System 2	--	2,660	20,640	7.8	0.14
10/23/75					
Control System	14.3	210	15,552	74.1[1]	--
Test System 1	14.3	218	16,656	76.4[1]	--
Test System 2	14.3	208	15,440	74.2[1]	--
10/24/75					
Control System	--	2,384	17,600	7.4	0.18
Test System 1	--	739	15,520	21.0	0.19
Test System 2	--	1,599	16,960	10.6	0.18
10/25/75					
Control System	14.5/14.8	41	13,120	--	--
Test System 1	13.5/14.3	46	14,720	--	--
Test System 2	14.0/14.3	44	14,080	--	--
10/26/75					
Control System	--	41	13,120	--	--
Test System 1	--	45	14,440	--	--
Test System 2	--	48	15,360	--	--

TABLE I.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
10/27/75					
Control System	--	787	14,080	17.9	0.26
Test System 1	--	997	18,080	18.1	0.18
Test System 2	--	970	17,120	17.6	0.19
10/28/75[3]					
Control System	--	94	15,040	--	--
Test System 1	--	1,121	21,600[4]	19.3	--
10/29/75					
Control System	--	105	16,860	--	0.16
Test System 1	--	134	21,504	--	0.10
10/31/75					
Control System	--	1,206	18,896	15.7	0.13
Test System 1	--	2,124	22,256	10.5	0.11
11/01/75					
Control System	20.0	--	--	--	--
Test System 1	20.0	--	--	--	--
11/02/75[5]					
Test System 1	19.0/25.0	340	19,408	57.1	0.20
11/03/75	30.0	1,370	19,584	14.3	0.30

TABLE I.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
11/04/75	30.0	550	18,592	36.8	0.31
11/05/75	29.5	1,608	18,112	11.3	0.24
11/06/75	28.5/30.0	374	18,464	49.4	0.28
11/07/75	27.5/30.0	1,394	19,600	14.1	--
11/08/75	28.5/30.0	770	19,584	25.4	--
11/09/75	--	728[6]	19,728	27.1	--
11/10/75	28.8	1,613	19,968	12.4	0.29
11/11/75	--	425	19,696	46.3	0.25
11/12/75	28.0/30.0	1,010	19,816	19.6	0.23
11/13/75	--	342	20,080	58.7	0.39
11/14/75	29.8	2,207	19,808	9.0	0.30
11/15/75	29.5	988	19,136	19.4	--
11/16/75	--	1,540	18,208	11.8	--

TABLE I.--(Continued)

	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
11/17/75	29.5	1,467	18,248	12.4	0.27
11/18/75	29.5	452	16,992	37.6	0.30
11/19/75	28.5/30.0	1,438	18,448	12.8	0.24
11/20/75	28.5	865	18,464	21.3	--
11/21/75	28.5	1,158	18,208	15.7	0.25
11/22/75	20.0/30.0	1,016	17,456	17.2	--
11/24/75	29.0	835	17,136	20.5	0.34
11/25/75	29.0/30.0	1,702	16,656	9.8	0.38
11/26/75	29.5	1,023	17,056	16.7	0.31
11/27/75	28.5/30.0	--	--	--	--
11/28/75	29.8	1,695	17,296	10.2	0.28
11/29/75	29.0	2,790	16,320	5.8	--
11/30/75	--	3,350	14,704	4.4	--

TABLE I.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
12/01/75	28.0/29.5	1,301	12,560	9.7	0.31
12/02/75	--	940	12,128	12.9	--
12/03/75	29.5	1,558	11,088	7.1	0.40
12/04/75	--	579	9,744	16.8	0.47
12/05/75	--	195	10,416	53.4	0.64
12/06/75	--	422[6]	12,192	28.9	--
12/07/75	--	595	12,320	20.7	--
12/08/75	--	118	11,936	101.2	0.54
12/09/75	--	775	13,424	17.3	--
12/10/75	--	206	12,176	59.1	0.46
12/11/75	29.5	209	12,686	60.7	0.39
12/12/75	28.0/30.0	254	12,960	51.0	0.33
12/13/75	--	777	12,464	16.0	--

TABLE I.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
12/14/75	30.0	--	--	--	--
12/15/75	30.0	3,280	11,960	3.6	0.42
12/16/75	--	802	13,040	16.3	0.42
12/17/75	29.5	1,459	11,968	8.2	0.43
12/18/75	29.0/30.0	4497[7]	11,840	26.4	0.40
12/19/75	30.0	1,111	11,392	10.3	0.42
12/20/75	29.0	108	10,416	96.4	--
12/21/75	29.0/29.8	242	11,072	45.8	--
12/22/75	28.8/30.0	1,322	12,704	9.6	0.40
12/24/75	29.5	1,047	12,544	12.0	0.37
12/30/75	--	102	16,368	--	--
01/05/76	29.0	2,291	17,936	7.8	0.25
01/06/76	--	1,645	14,080	8.6	0.39

TABLE I.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
01/07/76	29.0	2,053	15,168	7.4	0.31
01/08/76	--	599	12,926	21.6	--
01/09/76	29.5	2,085	14,256	6.8	0.46
01/12/76	30.0	610	14,656	24.0	0.40
01/13/76	29.0	1,910	13,648	7.1	0.40
01/14/76	--	378	12,944	34.2	0.40
01/15/76	29.0	2,471	14,720	6.0	0.30
01/16/76	--	1,030	12,800	12.4	0.35
01/18/76	28.0/30.0	--	--	--	--
01/19/76	28.5/30.0	2,133	13,808	6.5	0.38
01/20/76	--	680	11,952	17.6	0.46
01/22/76	28.5/30.0	2,155	11,920	5.5	0.41

TABLE I.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
01/23/76	--	1,112	12,048	10.8	0.36
01/24/76	27.5/30.0	2,591	10,416	4.0	0.59
01/25/76	29.8	--	--	--	--
01/27/76	25.5/30.0	2,708	16,080	5.9	0.27
01/28/75	28.5/30.5	1,730	14,144	8.2	0.30
01/29/76	30.0	1,849	12,528	6.8	0.36
01/30/76	28.5/30.0	1,090	15,392	14.1	0.34
01/31/76	28.0/30.0	1,968	13,280	6.7	0.32
02/01/76[a]	--	2,137	17,120	8.0	0.25
02/02/76	29.0	2,841	16,192	5.7	0.39

TABLE I.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
02/03/76	--	1,425	13,744	9.6	0.47
02/04/76	29.0	2,284	14,704	6.4	0.39

1Effluent solids concentration not available for inclusion in sludge age calculation.
2For all double entries, the first value is the flow rate prior to adjustment and the second value is the flow rate after adjustment.
3Test System 2 taken out of service.
4MLSS increased by addition of mixed liquor from Test System 1.
5Control System taken out of service on 11/01/75; all remaining entries apply to Test System 1.
6Effluent suspended solids estimated by averaging the values for the preceding and following days.
7Return sludge solids concentration estimated by averaging the values for the preceding and following days.
8Chromium source changed from K_2CrO_4 to CrO_3.

TABLE II.--System Operation Parameters - Silver Study

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
02/06/76	30.0	86	13,808	--	--
02/07/76 10:00 AM	30.0	102	16,176	--	--
9:50 PM	--	2,423	18,464	6.9[1,2]	--
02/08/76	--	100	15,968	--	--
02/09/76	--	2,229	17,840	8.0	0.34
02/10/76	--	1,969	14,896	7.6	0.34
02/11/76	28.0/29.5[3]	1,288	15,488	12.0	0.30
02/12/76	27.5/30.0	795	16,672	21.0	0.28
02/13/76	28.5/30.0	1,847	15,712	8.5	0.31
02/14/76	--	971	17,168	17.7	0.25
02/15/76	28.0/30.0	1,357	15,360	11.3	0.30
02/16/76	28.0/30.0	654	14,704	22.5	0.46
02/17/76	27.5/30.0	494	16,752	33.9	0.32

TABLE II.--(Continued)

Date	Influent Flow Rate (ml/min)	Waste Activated Sludge (mg)	Total Suspended Solids in Aeration (mg)	Sludge Age (days)	Food to Micro-organism Ratio (mg COD/mg MLSS-day)
02/18/76	29.0/30.0	1,524	15,648	10.3	0.32
02/19/76	30.5	1,718	15,952	9.3	0.31
02/20/76	30.5	365	17,024	46.6	0.29
02/21/76	30.0	1,388	17,456	12.6	0.27
02/22/76	25.8/30.0	--	--	--	--
02/23/76	31.0/30.5	1,509	16,224	10.8	0.34
02/24/76	30.8	1,059	17,488	16.5	0.31
02/25/76	30.0	1,594	18,496	11.6	0.26
02/26/76	30.0	668	16,992	25.4	0.28
02/27/76	27.5/30.0	840	16,960	20.2	0.27

[1]Effluent suspended solids not available for inclusion in sludge age calculation.
[2]Sludge age computed using total wasted sludge and the average of total solids in aeration for the day.
[3]For all double entries, the first value is the flow rate prior to adjustment and the second value is the flow rate after adjustment.

TABLE III.--pH - Chromium Study

Date	pH			
	Influent	Mixed Liquor	Return Sludge	Effluent
10/13/75				
Control System	7.8	7.7	7.7	8.2
Test System 1	7.8	7.7	7.6	7.8
Test System 2	7.8	7.7	7.6	7.8
10/20/75				
Control System	--	7.7	7.5	--
Test System 1	--	7.6	7.5	7.8
Test System 2	--	8.0	7.5	7.9
10/22/75				
Control System	7.3	7.6	7.8	7.7
Test System 1	7.4	7.7	7.6	7.8
Test System 2	7.4	7.8	7.5	7.8
10/24/75				
Control System	7.7	8.0	7.7	7.9
Test System 1	7.6	8.0	7.6	7.9
Test System 2	7.6	7.8	7.8	8.2
10/27/75				
Control System	7.6	7.7	7.4	7.7
Test System 1	7.4	7.8	7.4	7.7
Test System 2	7.4	7.8	7.4	7.6
10/29/75[1]				
Control System	7.4	--	--	7.7
Test System 1	7.4	--	--	7.7
10/31/75				
Control System	7.2	7.5	7.3	7.6
Test System 1	7.3	7.5	7.4	7.7
11/01/75				
Control System	7.3	--	--	7.6
Test System 1	7.4	--	--	7.6
11/02/75[2]				
Test System 1	7.3	--	--	7.9
11/03/75	7.8	7.5	7.4	7.6
11/04/75	7.4	--	--	7.6

TABLE III.--(Continued)

Date	pH			
	Influent	Mixed Liquor	Return Sludge	Effluent
11/05/76	7.3	7.4	7.4	7.6
11/06/75	7.3	--	--	7.5
11/07/75	7.4	7.4	7.4	7.6
11/08/75	7.6	--	--	8.1
11/10/75	7.6	7.6	7.7	7.8
11/11/75	7.3	--	--	7.4
11/12/75	7.5	7.5	7.4	7.6
11/13/75	7.4	--	--	7.5
11/14/75	7.5	7.4	7.4	7.5
11/15/76	7.6	--	--	7.5
11/17/75	7.6	7.6	7.3	7.5
11/18/75	7.7	--	--	8.3
11/19/75	7.5	7.7	7.5	7.7
11/20/75	7.5	--	--	7.9
11/21/75	7.6	7.7	7.5	7.9
11/24/75	7.4	7.6	7.4	7.8
11/25/75	7.5	--	--	7.6
11/26/75	7.6	7.7	7.5	7.9
11/27/75	7.6	--	--	7.8
11/28/75	7.7	7.8	7.6	7.9
11/29/75	7.4	--	--	7.8
12/01/75	7.6	7.5	7.5	7.7

TABLE III.--(Continued)

| Date | pH | | | |
	Influent	Mixed Liquor	Return Sludge	Effluent
12/02/75	7.5	--	--	7.6
12/03/75	7.7	7.7	7.6	7.7
12/04/75	7.6	--	--	7.6
12/08/75	7.2	--	--	7.6
12/09/75	7.4	--	--	7.4
12/10/75	7.5	--	--	7.9
12/11/75	7.5	--	--	7.5
12/12/75	7.5	--	--	7.5
12/15/75	7.6	7.6	7.5	7.6
12/16/75	7.5	--	--	7.5
12/17/75	7.5	7.5	7.4	7.6
12/18/75	7.6	7.4	--	7.5
12/19/75	7.6	7.6	7.5	7.7
12/21/75	7.5	--	--	7.6
12/22/75	7.7	7.6	7.5	7.8
12/23/75	7.6	--	--	7.7
12/24/75	8.1	7.7	7.6	8.2
12/31/75	7.6	--	--	7.9
01/05/76	7.6	7.6	7.8	8.0
01/06/76	7.5	--	--	7.8
01/07/76	7.7	7.7	7.5	7.9
01/08/76	7.6	--	--	7.7

TABLE III.--(Continued)

Date	pH			
	Influent	Mixed Liquor	Return Sludge	Effluent
01/09/76	7.5	7.7	7.5	7.8
01/12/76	7.5	--	--	8.0
01/13/76	7.6	7.8	7.6	7.9
01/14/76	7.5	--	--	8.0
01/15/76	7.7	7.7	7.6	7.9
01/16/76	7.5	--	--	7.8
01/19/76	7.6	7.7	7.6	7.8
01/20/76	7.5	--	--	7.8
01/22/76	7.6	7.6	7.4	7.8
01/23/76	7.5	--	--	7.8
01/24/76	7.7	7.8	7.6	8.1
01/27/76	7.8	7.6	7.5	7.9
01/28/76	7.6	--	--	7.8
01/29/76	7.7	7.6	7.4	7.9
01/30/76	7.5	--	--	7.7
01/31/76	7.6	7.7	7.5	8.0
02/01/76[3]	7.6	--	--	7.8
02/02/76	7.5	7.6	7.4	7.9
02/03/76	7.4	--	--	7.7
02/04/76	7.6	7.6	7.4	8.0

[1]Test System 2 taken out of service on 10/28/75.
[2]Control System taken out of service on 11/01/75; all remaining entries apply to Test System 1.
[3]Chromium source changed from K_2CrO_4 to CrO_3.

TABLE IV.--Dissolved Oxygen/Temperature - Chromium Study

| | Dissolved Oxygen (mg/l) | | Temperature (°C) |
	Mixed Liquor	Return Sludge	Mixed Liquor
Date			
10/20/75			
Control System	8.1	--	20.0
Test System 1	8.2	--	19.6
Test System 2	8.1	--	19.4
10/22/75			
Control System	8.0	--	20.0
Test System 1	8.0	--	19.8
Test System 2	8.0	--	19.5
10/24/75			
Control System	8.0	--	20.6
Test System 1	7.9	--	20.4
Test System 2	8.0	--	20.1
10/29/75[1]			
Control System	7.9	--	20.8
Test System 1	7.8	--	20.6
10/31/75			
Control System	8.0	--	20.5
Test System 1	7.8	--	20.5
11/02/75[2]			
Test System 1	7.5	--	21.0
11/03/75	8.1	2.4	20.4
11/05/75	8.3	1.8	18.5
11/07/75	7.8	1.8	20.6
11/10/75	8.2	1.8	19.2
11/12/75	7.4	0.9	17.5
11/14/75	6.5	1.7	17.7
11/17/75	7.2	1.0	18.4
11/19/75	8.0	0.8	19.8

TABLE IV.--(Continued)

| Date | Dissolved Oxygen (mg/l) | | Temperature (°C) |
	Mixed Liquor	Return Sludge	Mixed Liquor
11/21/75	8.3	0.8	17.3
11/24/75	7.7	0.8	18.3
11/26/75	7.8	0.8	17.0
11/28/75	7.8	0.8	20.4
12/01/75	8.0	--	19.4
12/03/75	7.9	1.3	20.0
12/07/75	6.3	1.2	--
12/09/75	6.6/5.8[3]	1.0	18.0
12/10/75	5.4	0.5	19.2
12/11/75	5.1	0.4	18.5
12/12/75	5.3	0.5	19.0
12/13/75	4.7	0.4	18.5
12/14/75	3.1	0.3	20.5
12/15/75	4.6	0.4	18.5
12/16/75	4.7	0.5	16.5
12/17/75	5.8	0.9	17.1
12/18/75	5.6	--	16.6
12/19/75	5.5	0.8	16.4
12/22/75	6.0	0.7	18.7
12/24/75	5.8	0.7	20.0
12/27/75	5.7	0.6	19.0
01/05/76	5.7	0.2	20.5

TABLE IV.--(Continued)

| Date | Dissolved Oxygen (mg/l) | | Temperature (°C) |
	Mixed Liquor	Return Sludge	Mixed Liquor
01/07/76	5.7	0.5	16.5
01/09/76	5.1	0.5	17.1
01/12/76	5.0	--	20.0
01/13/76	4.9	0.4	19.4
01/15/76	5.1	0.4	20.0
01/19/76	5.5	0.4	18.4
01/22/76	4.5	0.4	20.5
01/24/76	5.3	0.4	19.2
01/27/76	6.2	0.4	22.5
01/29/76	5.3	0.4	20.1
01/31/76	5.3	0.3	20.4
02/02/76[4]	4.7	0.4	18.4
02/04/76	5.5	0.4	20.0

[1]Test System 2 taken out of service on 10/28/75.
[2]Control System taken out of service on 11/01/75.
[3]Porous stone bar aeration device replaced by plexiglas tube aeration device. First value given was determined prior to exchange and second value was determined one hour after exchange.
[4]Chromium source changed from K_2CrO_4 to CrO_3 on 02/01/76.

TABLE V.--Suspended Solids - Chromium Study

Date	Influent (mg/l)		Mixed Liquor (mg/l)		Return Sludge (mg/l)		Effluent (mg/l)	
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS
10/10/75								
Control System	--	--	3,080	--	--	--	--	--
Test System 1	--	--	2,860	--	--	--	--	--
Test System 2	--	--	3,000	--	--	--	--	--
10/13/75								
Control System	--	--	2,760	--	--	--	--	--
Test System 1	--	--	2,680	--	--	--	--	--
Test System 2	--	--	2,600	--	--	--	--	--
10/14/75								
Control System	--	--	2,040	--	--	--	--	--
Test System 1	--	--	2,140	--	--	--	--	--
Test System 2	--	--	2,120	--	--	--	--	--
10/15/75								
Control System	--	--	2,140	--	--	--	--	--
Test System 1	--	--	2,120	--	--	--	--	--
Test System 2	--	--	2,140	--	--	--	--	--
10/16/75								
Control System	--	--	1,820	--	--	--	--	--
Test System 1	--	--	1,920	--	--	--	--	--
Test System 2	--	--	1,960	--	--	--	--	--

TABLE V.--(Continued)

Date	Influent (mg/1)		Mixed Liquor (mg/1)		Return Sludge (mg/1)		Effluent (mg/1)	
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS
10/17/75								
Control System	--	--	2,000	--	--	--	--	--
Test System 1	--	--	2,140	--	--	--	--	--
Test System 2	--	--	2,220	--	--	--	--	--
10/18/75								
Control System	--	--	2,180	--	--	--	--	--
Test System 1	--	--	2,040	--	--	--	--	--
Test System 2	--	--	2,060	--	--	--	--	--
10/20/75								
Control System	--	--	1,960	--	10,700	--	--	--
Test System 1	--	--	1,980	--	10,500	--	--	--
Test System 2	--	--	1,920	--	9,850	--	--	--
10/21/75								
Control System	--	--	1,760	--	--	--	--	--
Test System 1	--	--	1,780	--	--	--	--	--
Test System 2	--	--	1,940	--	--	--	--	--
10/22/75								
Control System	30	--	2,680[1]	--	7,250	--	40	--
Test System 1	30	--	2,580[1]	--	6,500	--	30	--
Test System 2	10	--	2,580[1]	--	6,800	--	20	--

TABLE V.--(Continued)

Date	Influent (mg/l) TSS	VSS	Mixed Liquor (mg/l) TSS	VSS	Return Sludge (mg/l) TSS	VSS	Effluent (mg/l) TSS	VSS
10/23/75								
Control System	--	--	1,944	--	--	--	--	--
Test System 1	--	--	2,082	--	--	--	--	--
Test System 2	--	--	1,930	--	--	--	--	--
10/24/75								
Control System	10	--	2,200	--	6,200	--	0	--
Test System 1	0	--	1,940	--	5,450	--	0	--
Test System 2	0	--	2,120	--	5,750	--	0	--
10/25/75								
Control System	--	--	1,640	--	--	--	--	--
Test System 1	--	--	1,840	--	--	--	--	--
Test System 2	--	--	1,760	--	--	--	--	--
10/26/75								
Control System	--	--	1,640	--	--	--	--	--
Test System 1	--	--	1,800	--	--	--	--	--
Test System 2	--	--	1,920	--	--	--	--	--
10/27/75								
Control System	20	--	1,760	--	3,950	--	10	--
Test System 1	25	--	2,260	--	5,550	--	10	--
Test System 2	20	--	2,140	--	5,400	--	10	--

TABLE V.--(Continued)

Date	Influent (mg/l) TSS	VSS	Mixed Liquor (mg/l) TSS	VSS	Return Sludge (mg/l) TSS	VSS	Effluent (mg/l) TSS	VSS
10/28/75[2]								
Control System	--	--	1,880	--	--	--	--	--
Test System 1	--	--	2,700[3]	--	--	--	--	--
10/29/75								
Control System	--	--	2,108	--	--	--	--	--
Test System 1	--	--	2,688	--	--	--	--	--
10/31/75								
Control System	22	--	2,362	--	8,185	--	7	--
Test System 1	17	--	2,782	--	9,095	--	16	--
11/1/75[4]								
Test System 1	--	--	2,426	--	--	--	8	--
11/03/75	17	--	2,448	--	9,905	--	12	--
11/04/75	--	--	2,324	--	--	--	9	--
11/05/75	4	--	2,264	--	11,975	--	13	--
11/06/75	--	--	2,308	--	--	--	6	--
11/07/75	9	--	2,450	--	11,475	--	8	--
11/08/75	--	--	2,448	--	--	--	15	--

TABLE V.--(Continued)

Date	Influent (mg/l) TSS	Influent (mg/l) VSS	Mixed Liquor (mg/l) TSS	Mixed Liquor (mg/l) VSS	Return Sludge (mg/l) TSS	Return Sludge (mg/l) VSS	Effluent (mg/l) TSS	Effluent (mg/l) VSS
11/09/75	--	--	2,466	--	--	--	--	--
11/10/75	21	--	2,496	--	12,065	--	12	--
11/11/75	--	--	2,462	--	--	--	7	--
11/12/75	12	--	2,477	--	11,000	--	0	--
11/13/75	--	--	2,510	--	--	--	5	--
11/14/75	9	--	2,476	--	11,430	--	0	--
11/15/75	--	--	2,392	--	--	--	11	--
11/16/75	--	--	2,276	--	--	--	33[5]	--
11/17/75	10	--	2,281	--	12,280	--	9	--
11/18/75	--	--	2,124	--	--	--	8	--
11/19/75	3	--	2,306	--	11,070	--	10	--
11/20/75	--	--	2,308	--	--	--	0	--
11/21/75	8	--	2,276	--	10,200	--	5	--
11/22/75	--	--	2,182	--	--	--	21[6]	--

TABLE V.--(Continued)

Date	Influent (mg/l)		Mixed Liquor (mg/l)		Return Sludge (mg/l)		Effluent (mg/l)	
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS
11/24/75	5	--	2,142	--	8,870	--	0	--
11/25/75	--	--	2,082	--	--	--	37	--
11/26/75	5	--	2,132	--	10,955	--	1	--
11/28/75	18	--	2,162	--	13,735	--	12	--
11/29/75	--	--	2,040	--	--	--	15	--
11/30/75	--	--	1,838	--	--	--	15	--
12/01/75	6	--	1,570	--	7,700	--	14	--
12/02/75	--	--	1,516	--	--	--	20	--
12/03/75	2	--	1,386	--	13,485	--	11	--
12/04/75	--	--	1,218	--	--	--	12	--
12/05/75	--	--	1,302	--	--	--	3	--
12/06/75	--	--	1,524	--	--	--	--	--
12/07/75	--	--	1,540	--	--	--	12	--
12/08/75	--	--	1,492	--	--	--	1	--

TABLE V.--(Continued)

Date	Influent (mg/l)		Mixed Liquor (mg/l)		Return Sludge (mg/l)		Effluent (mg/l)	
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS
12/09/75	--	--	1,678	--	--	--	16	--
12/10/75	--	--	1,522	--	--	--	3	--
12/11/75	--	--	1,586	--	--	--	3	--
12/12/75	--	--	1,620	--	--	--	4	--
12/13/75	4	2	1,558	1,156	18,520	14,870	11	7
12/15/75	23	21	1,495	1,216	24,627	17,630	27	21
12/16/75	--	--	1,630	--	16,920	--	1	--
12/17/75	1	--	1,496	--	15,000	--	6	--
12/18/75	0	0	1,480	1,000	--	--	0	0
12/19/75	6	--	1,424	--	11,980	--	3	--
12/20/75	--	--	1,302	--	--	--	1	--
12/21/75	--	--	1,384	--	--	--	4	--
12/22/75	17	--	1,558	--	11,710	--	8	--
12/24/75	10	--	1,568	--	11,485	--	2	--

TABLE V.--(Continued)

Date	Influent (mg/l)		Mixed Liquor (mg/l)		Return Sludge (mg/l)		Effluent (mg/l)	
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS
12/30/75	--	--	2,046	--	--	--	--	--
12/31/75	--	--	1,556	--	--	--	--	--
01/05/76	27	--	2,242	--	17,190	--	20	--
01/06/76	--	--	1,760	1,360	--	--	33	22
01/07/76	26	--	1,896	--	16,745	--	16	--
01/08/76	--	--	1,616	--	--	--	12	--
01/09/76	30	--	1,782	--	19,210	--	13	--
01/12/76	--	--	1,832	--	--	--	12	--
01/13/76	28	--	1,706	--	21,145	--	6	--
01/14/76	--	--	1,618	1,274	--	--	7	7
01/15/76	21	--	1,840	--	20,325	--	20	--
01/16/76	--	--	1,600	1,266	--	--	22	22
01/19/76	16	--	1,726	--	18,740	--	15	--

TABLE V.--(Continued)

Date	Influent (mg/1)		Mixed Liquor (mg/1)		Return Sludge (mg/1)		Effluent (mg/1)	
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS
01/20/76	--	--	1,494	1,200	--	--	14	9
01/22/76	20	--	1,490	--	18,175	--	17	--
01/23/76	--	--	1,506	1,200	--	--	24	12
01/24/76	44	--	1,302	--	14,165	--	34	--
01/27/76	27	--	2,010	--	15,445	--	33	--
01/28/76	--	--	1,768	1,382	--	--	38	25
01/29/76	21	--	1,566	--	13,680	--	17	--
01/30/76	--	--	1,924	1,474	--	--	23	17
01/31/76	16	--	1,660	--	15,250	--	17	--
02/01/76[7]	--	--	2,140	1,506	--	--	47	22
02/02/76	23	--	2,024	--	18,570	--	31	--

TABLE V.--(Continued)

Date	Influent (mg/l)		Mixed Liquor (mg/l)		Return Sludge (mg/l)		Effluent (mg/l)	
	TSS	VSS	TSS	VSS	RSS	VSS	TSS	VSS
02/03/76	--	--	1,718	1,342	--	--	31	12
02/04/76	3	--	1,838	--	17,660	--	20	--

[1]Samples taken from aeration unit effluent line rather than in-situ.
[2]Test System 2 taken out of service.
[3]MLSS increased by addition of mixed liquor from Test System 1.
[4]Control System taken out of service; ramining entries apply to Test System 1.
[5]Sample taken shortly after clarifier side wall was rodded to dislodge sludge.
[6]Withdrawal of sludge from clarifier was impeded by a piece of glass rod accidentally dropped into the clarifier.
[7]Chromium source changed from K_2CrO_4 to CrO_3.

TABLE VI.--Chemical Oxygen Demand - Chromium Study

Date	Influent (mg COD/1)		Effluent (mg COD/1)		COD Removal Efficiency (%)	
	Total	Soluble	Total	Soluble	Total	Soluble
10/10/75						
Control System	140	--	--	--	--	--
Test System 1	139	--	--	--	--	--
Test System 2	135	--	--	--	--	--
10/13/75						
Control System	143	55	38	21	73.4	61.8
Test System 1	148	55	42	21	71.6	61.8
Test System 2	148	63	38	17	74.3	73.0
10/15/75						
Control System	84	--	25	--	70.2	--
Test System 1	92	--	25	--	72.8	--
Test System 2	97	--	42	--	56.7	--
10/16/75						
Control System	88	--	75	--	14.8	--
Test System 1	105	--	71	--	32.4	--
Test System 2	105	--	25	--	76.2	--
10/17/75						
Control System	139	--	29	--	79.1	--
Test System 1	98	--	29	--	70.4	--
Test System 2	122	--	24	--	80.3	--

TABLE VI.--(Continued)

Date	Influent (mg COD/l)		Effluent (mg COD/l)		COD Removal Efficiency (%)	
	Total	Soluble	Total	Soluble	Total	Soluble
10/20/75						
Control System	156	60	36	--	76.9	--
Test System 1	156	60	36	20	76.9	66.7
Test System 2	164	36	36	20	78.0	44.4
10/22/75						
Control System	142	83	--	--	--	--
Test System 1	134	59	--	--	--	--
Test System 2	134	87	--	--	--	--
10/24/75						
Control System	156	105	31	23	80.1	78.1
Test System 1	148	109	27	27	81.8	75.2
Test System 2	152	105	35	23	77.0	78.1
10/27/75						
Control System	172	--	51	--	70.3	--
Test System 1	160	--	55	--	65.6	--
Test System 2	160	--	51	--	68.1	--
10/29/75[1]						
Control System	132	--	35	--	73.5	--
Test System 1	109	--	43	--	60.6	--
10/31/75						
Control System	117	98	35	--	70.1	--
Test System 1	121	102	31	31	74.4	69.6

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TABLE VI.--(Continued)

Date	Influent (mg COD/l)		Effluent (mg COD/l)		COD Removal Efficiency (%)	
	Total	Soluble	Total	Soluble	Total	Soluble
11/01/75						
Control System	133	--	27	--	79.7	--
Test System 1	102	--	27	--	73.5	--
11/02/75[2]						
Test System 1	142	--	34	--	76.1	--
11/03/75	137	100	52	--	62.0	--
11/04/75	135	--	68	--	49.6	--
11/05/75	102	73	49	37	52.0	49.3
11/06/75	127	--	53	--	58.3	--
11/10/75	139	106	69	45	50.4	57.5
11/11/75	122	--	49	--	59.8	--
11/12/75	114	82	37	29	67.5	64.6
11/13/75	182	--	41	--	77.5	--
11/14/75	137	104	35	33	74.5	68.3
11/17/75	115	81	48	37	58.3	54.3

TABLE VI.--(Continued)

Date	Influent (mg COD/1)		Effluent (mg COD/1)		COD Removal Efficiency (%)	
	Total	Soluble	Total	Soluble	Total	Soluble
11/18/75	119	--	49	--	58.8	--
11/19/75	109	77	61	36	44.0	53.2
11/21/75	110	90	57	29	48.2	67.8
11/24/75	138	101	75	49	45.7	51.5
11/25/75	150	--	61	--	59.3	--
11/26/75	125	93	53	32	57.6	65.6
11/28/75	111	82	35	25	68.5	69.5
12/01/75	98	57	45	12	54.1	78.9
12/02/75	116	--	65	--	44.0	--
12/03/75	101	77	56	28	44.6	63.6
12/04/75	108	--	70	--	35.2	--
12/05/75	156	--	58	--	62.8	--
12/08/75	153	--	68	--	55.6	--

TABLE VI.--(Continued)

Date	Influent (mg COD/l)		Effluent (mg COD/l)		COD Removal Efficiency (%)	
	Total	Soluble	Total	Soluble	Total	Soluble
12/10/75	131	--	81	--	38.2	--
12/11/75	113	--	52	--	54.0	--
12/12/75	107	--	51	--	52.3	--
12/15/75	117	57	49	4	58.1	93.0
12/16/75	126	--	71	--	43.7	--
12/17/75	121	93	77	36	36.4	61.3
12/18/75	113	--	62	--	45.1	--
12/19/75	112	79	50	39	55.4	50.6
12/22/75	122	85	65	45	46.7	47.1
12/24/75	110	--	41	35	62.7	--
01/05/76	107	71	40	24	62.6	66.2
01/06/76	130	--	56	--	56.9	--
01/07/76	111	86	51	33	54.1	61.6

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TABLE VI.--(Continued)

Date	Influent (mg COD/1)		Effluent (mg COD/1)		COD Removal Efficiency (%)	
	Total	Soluble	Total	Soluble	Total	Soluble
01/09/76	153	104	59	39	61.4	62.5
01/12/76	137	--	46	--	66.4	--
01/13/76	132	67	40	24	69.7	64.2
01/14/76	125	--	37	--	70.4	--
01/15/76	107	85	37	29	65.4	65.9
01/16/76	107	--	64	--	40.2	--
01/19/75	129	97	58	32	55.0	67.0
01/20/76	127	--	77	--	39.4	--
01/22/76	118	95	75	30	36.4	68.4
01/23/76	106	--	33	--	68.9	--
01/24/76	155	103	71	34	54.2	67.0
01/27/76	118	81	61	18	48.3	77.8
01/28/76	105	--	47	--	55.2	--

TABLE VI.--(Continued)

Date	Influent (mg COD/l)		Effluent (mg COD/l)		COD Removal Efficiency (%)	
	Total	Soluble	Total	Soluble	Total	Soluble
01/29/76	103	75	38	26	63.1	65.3
01/30/76	128	--	68	--	46.9	--
01/31/76	105	70	34	8	67.6	88.6
02/01/76[3]	101	--	60	--	40.6	--
02/02/76	150	97	75	26	50.0	73.2
02/03/76	155	--	54	--	65.2	--
02/04/76	138	98	59	24	57.2	75.5

[1]Test System 2 taken out of service on 10/28/75.
[2]Control System taken out of service on 11/01/75; remaining entries apply to Test System 1.
[3]Chromium source changed from K_2CrO_4 to CrO_3.

TABLE VII.--Influent Nitrogen Species - Chromium Study

Date	TKN (mg/l) Total	TKN (mg/l) Soluble	NH_3-N (mg/l)	ORG-N (mg/l)	NO_2^--N (mg/l)	NO_3^--N (mg/l)	Total-N (mg/l)
10/13/75							
Control System	--	--	25.2	--	--	--	--
Test System 1	--	--	25.1	--	--	--	--
Test System 2	--	--	25.3	--	--	--	--
10/20/75							
Control System	--	--	30.5	--	0	0.2	--
Test System 1	--	--	24.7	--	0	0.1	--
Test System 2	--	--	25.5	--	0	0.1	--
10/22/75							
Control System	35.5	21.8	22.2	13.3	0	--	35.5
Test System 1	40.8	28.5	23.1	17.7	0	0.1	40.9
Test System 2	--	--	22.2	--	0	0.1	--
10/24/75							
Control System	37.9	35.2	23.9	14.0	0.0	--	--
Test System 1	49.2	30.5	23.9	25.3	0.0	0.2	49.4
Test System 2	--	--	23.9	--	0.0	0.2	--
10/27/75							
Control System	37.5	32.1	--	--	--	--	--
10/29/75[1]							
Control System	--	--	16.5	--	--	--	--
Test System 1	--	--	19.8	--	--	--	--
10/31/75							
Control System	--	--	36.3	--	0.0	0.1	--
Test System 1	26.7	24.3	26.3	0.4	0.0	0.1	26.8
11/03/75[2]							
Test System 1	38.5	31.3	30.3	8.2	0.0	0.1	38.6
11/05/75	24.6	23.5	16.2	8.4	0.0	0.1	24.7
11/07/75	40.0	38.7	24.5	15.5	0.0	0.1	40.1
11/10/75	34.4	30.7	20.0	14.4	0.0	0.1	34.5
11/12/75	29.9	27.1	18.0	11.9	0.1	0.1	30.1
11/14/75	38.8	37.2	26.5	12.3	0.0	0.1	38.9

TABLE VII.--(Continued)

Date	TKN (mg/1) Total	TKN (mg/1) Soluble	NH_3-N (mg/1)	ORG-N (mg/1)	NO_2^--N (mg/1)	NO_3^--N (mg/1)	Total-N (mg/1)
11/17/75	30.3	27.4	19.0	11.3	0.1	0.1	30.5
11/19/75	27.4	26.8	19.0	8.4	0.0	0.0	27.4
11/21/75	25.1	23.2	16.2	8.9	0.0	0.1	25.2
11/24/75	36.9	27.7	21.4	15.5	0.0	0.1	37.0
11/26/75	26.0	25.3	18.3	7.7	0.0	0.1	26.1
11/28/75	24.8	24.4	17.0	7.8	0.0	0.1	24.9
12/01/75	--	24.8	16.4	--	0.0	0.1	--
12/03/75	27.6	25.8	17.2	10.4	0.0	0.1	27.7
12/05/75	--	--	19.0	--	--	--	--
12/08/75	--	--	15.2	--	--	--	--
12/10/75	--	--	15.5	--	--	--	--
12/11/75	--	--	19.0	--	--	--	--
12/12/75	--	--	18.7	--	--	--	--
12/15/75	24.3	24.1	24.1	0.2	0.0	0.1	24.4
12/17/75	25.4	24.8	15.0	10.4	0.0	0.1	25.5
12/19/75	27.0	25.4	16.2	10.8	0.0	0.1	27.1
12/22/75	30.1	27.6	17.6	12.5	0.0	0.1	30.2
12/24/75	23.4	20.8	13.6	9.8	0.3	--	--
01/05/76	26.5	24.7	14.5	12.0	0.2	--	--
01/07/76	24.7	22.6	14.8	9.9	0.6	0.1	25.4
01/09/76	29.4	25.5	15.9	13.5	0	0.1	29.5
01/13/76	27.7	24.8	16.1	11.6	0	0.0	27.7

TABLE VII.--(Continued)

| Date | TKN (mg/1) | | NH$_3$-N (mg/1) | ORG-N (mg/1) | NO$_2^-$-N (mg/1) | NO$_3^-$-N (mg/1) | Total-N (mg/1) |
	Total	Soluble					
01/15/76	24.3	22.2	13.8	10.5	0	0.1	24.4
01/19/76	25.9	22.2	14.8	11.1	0	0.1	26.0
01/22/76	53.3	30.0	20.3	33.0	0	0.0	53.3
01/24/76	32.9	28.7	18.8	14.1	0	--	--
01/27/76	31.1	27.2	16.6	14.5	0.3	0.1	31.5
01/29/76	28.2	28.5	16.6	11.6	0.0	0.0	28.2
01/31/76	26.2	24.0	15.6	10.6	0.0	0.0	26.2
02/02/76[3]	31.9	28.3	17.5	14.4	0	0.1	32.0
02/04/76	33.0	27.8	18.0	15.0	0	0.1	33.1

[1]Test System 2 taken out of service on 10/28/75.
[2]Control System taken out of service on 11/01/75; remaining entries apply to Test System 1.
[3]Chromium source changed from K_2CrO_4 to CrO_3 on 02/01/76.

TABLE VIII.--Effluent Nitrogen Species - Chromium Study

Date	TKN (mg/l) Total	Soluble	NH_3-N (mg/l)	ORG-N (mg/l)	NO_2^--N (mg/l)	NO_3^--N (mg/l)	Total-N (mg/l)
10/13/75							
Control System	--	--	0.3	--	--	--	--
Test System 1	--	--	0.1	--	--	--	--
Test System 2	--	--	0.1	--	--	--	--
10/20/75							
Control System	--	--	--	--	--	--	--
Test System 1	--	--	0.2	--	0	18.6	--
Test System 2	--	--	0.1	--	--	--	--
10/22/75							
Control System	1.3	0.5	0.2	1.1	0	18.2	19.5
Test System 1	1.4	0.3	0.1	1.3	0.1	20.0	21.5
Test System 2	--	--	0.2	--	T	15.8	--
10/24/75							
Control System	1.3	0.8	0.2	1.1	T	19.0	20.3
Test System 1	1.1	0.5	0.2	0.9	0.1	25.0	26.2
Test System 2	--	--	--	--	T	24.4	--
10/27/75							
Control System	2.2	0.7	--	--	--	--	--
10/29/75[1]							
Control System	--	--	0.1	--	--	--	--
Test System 1	--	--	0.2	--	--	--	--
10/31/75							
Control System	--	--	0.1	--	T	20.2	--
Test System 1	2.0	0.5	0.1	1.9	T	20.0	22.0
11/03/75[2]							
Test System 1	8.1	7.9	7.3	0.8	0.1	21.5	29.7
11/05/75	4.7	4.3	2.1	2.6	0.1	16.9	21.7
11/07/75	3.0	2.2	0.1	2.9	0.2	22.6	25.8
11/10/75	3.8	2.9	0.2	3.6	0.2	20.6	24.6
11/12/75	2.6	2.0	0.4	2.2	0.1	17.7	20.4
11/14/75	2.7	2.0	0.4	2.3	0.2	27.1	30.0

TABLE VIII.--(Continued)

Date	TKN (mg/l) Total	TKN (mg/l) Soluble	NH_3-N (mg/l)	ORG-N (mg/l)	NO_2^--N (mg/l)	NO_3^--N (mg/l)	Total-N (mg/l)
11/17/75	2.4	2.2	0.4	2.0	0.2	16.3	18.9
11/19/75	3.3	1.3	0.1	3.2	0.1	16.5	19.9
11/21/75	3.0	1.5	0	3.0	0.1	14.5	17.6
11/24/75	4.9	1.9	0.1	4.8	0	19.6	24.5
11/26/75	2.8	1.4	0.1	2.7	0	16.2	19.0
11/28/75	2.4	1.6	0	2.4	0	17.0	19.4
12/01/75	3.7	1.5	0.1	3.6	0.1	16.6	20.4
12/03/75	3.5	1.6	0.1	3.4	0.1	15.8	19.4
12/05/75	--	--	0.3	--	--	--	--
12/08/75	--	--	0.1	--	--	--	--
12/10/75	--	--	0	--	--	--	--
12/11/75	--	--	0	--	--	--	--
12/12/75	--	--	0.1	--	--	--	--
12/15/75	5.4	2.2	0.1	5.3	0.3	21.3	27.0
12/17/75	3.7	1.7	0	3.7	0.3	20.7	24.7
12/19/75	3.3	1.9	0.1	3.2	1.8	19.6	24.7
12/22/75	3.5	2.0	0.1	3.4	0.9	23.3	27.7
12/24/75	3.1	2.1	0.1	3.0	0.3	18.4	21.8
01/05/76	3.9	2.2	0	3.9	0	20.0	23.9
01/07/76	2.6	2.0	0	2.6	0	19.0	21.6
01/09/76	3.0	2.4	0.2	2.8	0	18.6	21.6
01/13/76	2.7	1.6	0.1	2.6	0	19.0	21.7

TABLE VIII.--(Continued)

Date	TKN (mg/l) Total	TKN (mg/l) Soluble	NH_3-N (mg/l)	ORG-N (mg/l)	NO_2^--N (mg/l)	NO_3^--N (mg/l)	Total-N (mg/l)
01/15/76	3.1	1.3	0.1	3.0	0	17.2	20.3
01/19/76	3.3	1.6	0	3.3	0	16.2	19.5
01/22/76	3.2	1.6	0.1	3.1	0	--	--
01/24/76	4.2	1.4	0.1	4.1	0	21.0	25.2
01/27/76	4.1	1.5	0	4.1	0	21.6	25.7
01/29/76	2.8	1.5	0.1	2.7	0	18.8	21.5
01/31/76	3.3	1.5	0	3.3	0	16.0	19.3
02/02/76[3]	4.3	1.1	0	4.3	0	15.4	19.7
02/04/76	3.4	0.9	0	3.4	0	17.0	20.4

[1] Test System 2 taken out of service on 10/28/75.
[2] Control System taken out of service on 11/01/75; remaining entries apply to Test System 1.
[3] Chromium source changed from K_2CrO_4 to CrO_3 on 02/01/76.

TABLE IX.--Alkalinity - Chromium Study

Date	Total Alkalinity (mg CaCO$_3$/l)	
	Influent	Effluent
11/01/75		
Control System	401	258
Test System 1	414	284
11/02/75[1]		
Test System 1	439	267
11/04/75	438	331
11/06/75	439	316
11/08/75	478	348
11/11/75	470	343
11/13/75	473	353
11/15/75	505	344
11/18/75	466	339
11/20/75	465	350
11/25/75	487	327
11/27/75	461	360
11/29/75	460	336
12/02/75	457	324
12/04/75	455	326
12/08/75	449	352
12/09/75	455	347
12/11/75	474	343
12/12/75	468	337
12/16/75	478	356
12/18/75	452	344

TABLE IX.--(Continued)

Date	Total Alkalinity (mg CaCO$_3$/l)	
	Influent	Effluent
12/21/75	462	334
12/23/75	426	341
12/31/75	404	318
01/06/76	425	322
01/08/76	428	323
01/12/76	468	355
01/14/76	470	362
01/16/76	452	357
01/20/76	458	362
01/23/76	468	330
01/28/76	433	310
01/30/76	467	355
02/01/76[2]	466	357
02/03/76	472	356

[1]Control System taken out of service on 11/01/75; remaining entries apply to Test System 1.
[2]Chromium source changed from K_2CrO_4 to CrO_3.

TABLE X.--Chromium

Date	Influent (mg Cr/l)		Mixed Liquor (mg Cr/l)		Return Sludge (mg Cr/l)		Effluent (mg Cr/l)	
	Total	Soluble	Total	Soluble	Total	Soluble	Total	Soluble
10/20/75[1]								
Control System 0	0	--	0.5	--	2.9	--	0	--
Test System 1	0	--	0.6	--	3.2	--	--	--
10/22/75[1]								
Control System 0	0	--	0.9	--	1.9	--	0.5	--
Test System 1	0.7	--	2.0	--	3.8	--	0.7	--
10/24/75[1]								
Control System 0	0	--	1.2	--	1.6	--	0	--
Test System 1	1.2	--	--	--	5.9	--	1.4	--
10/31/75[1,2]								
Test System1	13.3	--	19.6	--	33.6	--	9.6	--
11/03/75	10.8	--	17.2	--	41.6	--	10.0	--
11/05/75	10.0	9.3	18.8	9.1	57.2	8.5	10.0	9.1
11/07/75	10.8	9.8	20.0	9.5	57.2	9.5	10.0	9.5
11/10/75	9.2	10.1	21.6	9.8	60.4	8.7	9.2	9.5
11/12/75	9.6	9.8	21.6	9.8	69.2	9.8	10.0	9.8
11/14/75	10.0	10.7	24.4	10.1	70.8	10.1	10.0	10.7

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TABLE X.--(Continued)

Date	Influent (mg Cr/l)		Mixed Liquor (mg Cr/l)		Return Sludge (mg Cr/l)		Effluent (mg Cr/l)	
	Total	Soluble	Total	Soluble	Total	Soluble	Total	Soluble
11/17/75	10.0	10.1	25.2	9.5	>80	12.0	9.2	10.1
11/19/75	9.6	10.1	24.4	10.1	91.2	10.1	9.6	10.1
11/21/75	10.0	9.8	23.8	9.8	84.8	9.8	9.6	9.8
11/24/75	9.6	9.4	23.4	9.6	92.0	9.6	9.4	9.4
11/26/75	9.8	9.6	24.0	9.6	93.6	9.6	9.6	9.6
11/28/75	9.6	9.6	23.0	9.6	111.4	9.8	9.2	9.6
12/01/75	11.0	9.6	22.7	9.4	70.1	9.2	10.6	9.4
12/03/75	10.5	9.8	22.1	9.6	108.5	9.6	--	10.0
12/11/75	--	--	--	--	--	--	--	9.9
12/12/75	--	--	--	--	--	--	--	9.7
12/15/75	10.0	9.7	28.0	8.6	262.4	1.6	9.6	8.6
12/16/75	--	--	--	--	--	6.3	--	--
12/17/75	11.2	11.2	30.7	9.4	216.3	6.4	9.9	9.9
12/19/75	9.9	9.7	30.7	9.4	174.7	8.8	9.9	9.7

TABLE X.--(Continued)

Date	Influent (mg Cr/l)		Mixed Liquor (mg Cr/l)		Return Sludge (mg Cr/l)		Effluent (mg Cr/l)	
	Total	Soluble	Total	Soluble	Total	Soluble	Total	Soluble
12/22/75	9.9	10.0	32.0	9.7	185.0	7.1	9.6	9.7
12/24/75	10.6	9.7	33.3	9.0	190.1	5.7	9.6	9.0
12/25/75	5.4	--	--	--	--	--	5.1	--
12/26/75	5.4	--	--	--	--	--	5.1	--
12/30/75	6.1	--	--	--	--	--	5.7	--
01/05/76	0.9	1.1	34.4	0.9	265.0	0.2	0.9	0.9
01/07/76	0.9	1.1	30.6	0.8	259.2	0.1	0.9	1.0
01/09/76	1.0	1.5	27.5	1.3	269.4	0.4	0.9	1.3
01/13/76	0.9	1.2	24.0	0.9	254.7	0.1	0.8	1.1
01/15/76	1.0	1.5	22.2	1.3	239.4	0.1	1.0	1.2
01/19/76	0.1	0.2	15.6	0.1	186.9	0.1	0.1	0.1
01/22/76	0.1	0.1	13.3	0.1	160.6	0.5	0.1	0.2
01/24/76	0.1	0.1	10.9	0.1	113.9	0.2	0.2	0.0
01/27/76	0.1	0.1	14.0	0.1	113.9	0.0	0.2	0.1

TABLE X.--(Continued)

Date	Influent (mg Cr/l)		Mixed Liquor (mg Cr/l)		Return Sludge (mg Cr/l)		Effluent (mg Cr/l)	
	Total	Soluble	Total	Soluble	Total	Soluble	Total	Soluble
01/29/76	0.1	0.1	10.9	0.1	104.3	0.1	0.1	0.1
01/31/76	1.1	1.5	12.0	1.2	91.2	0.1	0.9	1.2
02/02/76[3]	0.9	1.5	13.7	1.1	103.0	0.1	0.8	1.0
02/04/76	0.8	1.4	14.8	1.0	103.0	0.2	0.6	1.1

[1]Samples were preserved using HCl and values are, therefore, questionable. All remaining samples were preserved with HNO_3.
[2]Control System taken out of service on 11/01/75; all remaining entries apply to Test System 1.
[3]Chromium source changed from K_2CrO_4 to CrO_3 on 02/01/76.

TABLE XI.--pH - Silver Study

| Date | pH | | | |
	Influent	Mixed Liquor	Return Sludge	Effluent
02/09/76	7.5	--	--	7.7
02/11/76	7.5	7.6	7.4	7.9
02/12/76	7.5	--	--	7.7
02/13/76	7.6	7.5	7.4	8.0
02/14/76	7.5	--	--	7.7
02/15/76	7.7	7.6	7.4	8.0
02/16/76	7.4	--	--	7.6
02/17/76	7.4	--	--	7.7
02/18/76	7.6	7.6	7.5	7.8
02/19/76	7.6	7.6	7.4	7.8
02/20/76	7.6	--	--	7.7
02/21/76	7.7	7.6	7.4	8.0
02/23/76	7.7	7.5	7.4	7.8
02/24/76	7.5	--	--	7.7
02/25/76	7.6	7.5	7.3	7.8
02/26/75	7.6	--	--	7.6
02/27/76	7.6	--	--	7.7

TABLE XII.--Dissolved Oxygen/Temperature - Silver Study

	Dissolved Oxygen (mg/1)		Temperature (°C)
Date	Mixed Liquor	Return Sludge	Mixed Liquor
02/06/76	6.9	--	19.5
02/07/76			
10:30 AM	6.6	--	20.5
8:30 PM	5.5	--	19.5
02/08/76	5.2	--	19.2
02/09/76	5.0	--	21.5
02/10/76	5.2	0.5	20.2
02/11/76	5.0	0.4	20.2
02/13/76	4.5	0.3	21.2
02/15/76	5.0	0.4	20.0
02/18/76	4.4	0.4	21.0
02/19/76	4.5	0.3	20.6
02/21/76	4.9	0.4	20.2
02/23/76	4.6	0.3	19.6
02/25/76	4.3	0.4	19.5
02/27/76	4.4	--	21.0

TABLE XIII.--Suspended Solids - Silver Study

Date	Influent (mg/l)		Mixed Liquor (mg/l)		Return Sludge (mg/l)		Effluent (mg/l)	
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS
02/06/76	--	--	1,726	--	--	--	--	--
02/07/76								
10:30 AM	--	--	2,022	--	--	--	--	--
2:25 PM	--	--	2,308	--	--	--	--	--
02/08/76	--	--	1,996	--	--	--	--	--
02/09/76	--	--	2,230	1,604	--	--	--	--
02/10/76	37	--	1,862	--	14,790	--	25	--
02/11/76	18	--	1,936	--	13,150	--	4	--
02/12/76	--	--	2,084	1,525	--	--	16	6
02/13/76	24	--	1,964	--	13,720	--	16	--
02/14/76	--	--	2,146	1,634	--	--	20	17
02/15/76	8	--	1,920	--	14,165	--	4	--
02/16/76	--	--	1,838	1,416	--	--	13	5
02/17/76	--	--	2,094	--	--	--	9	--
02/18/76	16	--	1,956	--	14,025	--	8	--

TABLE XIII.--(Continued)

Date	Influent (mg/l)		Mixed Liquor (mg/l)		Return Sludge (mg/l)		Effluent (mg/l)	
	TSS	VSS	TSS	VSS	TSS	VSS	TSS	VSS
02/19/76	19	--	1,994	--	13,670	--	13	--
02/20/76	--	--	2,128	1,700	--	--	6	6
02/21/76	13	--	2,182	--	13,010	--	6	--
02/23/76	11	--	2,028	--	13,095	--	9	--
02/24/76	--	--	2,186	1,722	--	--	22	11
02/25/76	19	--	2,312	--	12,065	--	12	--
02/26/76	--	--	2,124	--	--	--	13	--
02/27/76	--	--	2,120	--	--	--	17	--

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TABLE XIV.--Chemical Oxygen Demand - Silver Study

Date	Influent (mg COD/l)		Effluent (mg COD/l)		COD Removal Efficiency (%)	
	Total	Soluble	Total	Soluble	Total	Soluble
02/09/76	144	--	65	--	54.9	--
02/10/76	123	--	43	--	65.0	--
02/11/76	114	79	28	18	75.4	77.2
02/12/76	112	--	34	--	69.6	--
02/13/76	116	84	30	20	74.1	76.2
02/14/76	104	--	37	--	64.4	--
02/15/76	113	81	18	20	84.1	75.3
02/16/76	161	--	46	--	71.4	--
02/17/76	128	--	33	--	74.2	--
02/18/76	117	89	36	20	69.2	77.5
02/19/76	113	81	28	12	75.2	85.2
02/20/76	114	--	26	--	77.2	--
02/21/76	110	82	24	18	78.2	78.0

TABLE XIV.--(Continued)

Date	Influent (mg COD/l)		Effluent (mg COD/l)		COD Removal Efficiency (%)	
	Total	Soluble	Total	Soluble	Total	Soluble
02/23/76	124	92	40	22	67.7	76.1
02/24/76	124	--	28	--	77.4	--
02/25/76	110	81	29	17	73.6	79.0
02/26/76	111	--	31	--	72.1	--
02/27/76	111	--	38	--	65.8	--

TABLE XV.--Influent Nitrogen Species - Silver Study

Date	TKN (mg/l) Total	TKN (mg/l) Soluble	NH$_3$-N (mg/l)	ORG-N (mg/l)	NO$_2^-$-N (mg/l)	NO$_3^-$-N (mg/l)	Total-N (mg/l)
02/11/76	34.3	31.0	21.2	13.1	0	0	34.3
02/13/76	37.7	31.2	15.2	22.5	0	0	37.7
C2/15/76	37.2	34.2	19.3	17.9	0	0	37.2
02/18/76	30.6	27.9	16.1	14.5	0	0	30.6
02/19/76	29.9	26.4	15.5	14.4	0	0	29.9
02/21/76	30.6	26.5	15.2	15.4	0	0	30.6
02/23/76	28.3	25.9	14.2	14.1	0	0	28.3
02/25/76	35.3	37.3	17.0	18.3	0.1	0	35.4

TABLE XVI.--Effluent Nitrogen Species - Silver Study

Date	TKN (mg/1) Total	TKN (mg/1) Soluble	NH$_3$-N (mg/1)	ORG-N (mg/1)	NO$_2^-$-N (mg/1)	NO$_3^-$-N (mg/1)	Total-N (mg/1)
02/11/76	1.6	0.9	0	1.6	3.4	16.4	21.4
02/13/76	1.7	0.6	0.1	1.6	1.6	18.0	21.3
02/15/76	1.4	1.0	0	1.4	0.2	20.8	22.4
02/18/76	1.8	1.0	0	1.8	0	16.6	18.4
02/19/76	2.2	0.5	0	2.2	0	15.2	17.4
02/21/76	4.5	2.1	0.1	4.4	0	16.0	20.5
02/23/76	2.2	1.1	0	2.2	0	15.8	18.0
02/25/76	2.4	1.2	0	2.4	0	21.0	23.4

TABLE XVII.--Alkalinity - Silver Study

Date	Total Alkalinity (mg CaCO$_3$/l)	
	Influent	Effluent
02/09/76	461	355
02/12/76	462	323
02/14/76	475	335
02/16/76	465	349
02/17/76	468	350
02/20/76	457	341
02/24/76	451	345
02/26/76	451	308
02/27/76	459	307

TABLE XVIII.--Silver

Date	Influent (mg Ag/1)		Mixed Liquor (mg Ag/1)		Return Sludge (mg Ag/1)		Effluent (mg Ag/1)	
	Total	Soluble	Total	Soluble	Total	Soluble	Total	Soluble
02/10/76	0.01	--	0.04	--	0.32	--	0.05	--
02/11/76	0.13	0.06	0.49	0.01	2.25	0.01	0.02	0.01
02/13/76	0.10	0.08	0.86	0	3.30	0	0.02	0.01
02/15/76	0.10	0.08	1.30	0.01	3.11	0	0.02	0.01
02/18/76	0.10	0.07	1.77	0	4.20	0.01	0.02	0.01
02/19/76	0.16	0.11	0.58	0.03	2.50	0.01	0.04	0.03
02/21/76	0.16	0.12	0.49	0.03	2.30	0.01	0.05	0.02
02/23/76	0.15	0.12	2.50	0.04	2.10	0.03	0.07	0.04
02/25/76	0.16	0.12	3.55	0.03	5.08	0.02	0.06	0.04
02/27/76	0.44	--	--	--	--	--	0.40	--

TABLE XIX.--Relationship of COD Removal and Influent Chromium

Date	Total COD Removal Efficiency (%)	Influent Total Chromium Concentration (mg/l)
10/13/75[1]		
Control System	73.4	0
Test System 1	71.6	0
Test System 2	74.3	0
10/15/76[1]		
Control System	70.2	0
Test System 1	72.8	0
Test System 2	56.7	0
10/16/75[1]		
Control System	14.8	0
Test System 1	32.4	0
Test System 2	76.2	0
10/17/75[1]		
Control System	79.1	0
Test System 1	70.4	0
Test System 2	80.3	0
10/20/75[1]		
Control System	76.9	0
Test System 1	76.9	0.1
Test System 2	78.0	0.1
10/24/75[1]		
Control System	80.1	0
Test System 1	81.8	2.0
Test System 2	77.0	2.0
10/27/75[1]		
Control System	70.3	0
Test System 1	65.6	4.0
Test System 2	68.1	4.0
10/29/75[1,2]		
Control System	73.5	0
Test System 1	60.6	7.0
10/31/75[1]		
Control System	70.1	0
Test System 1	74.4	10.0

TABLE XIX.--(Continued)

Date	Total COD Removal Efficiency (%)	Influent Total Chromium Concentration (mg/l)
11/01/75[1]		
Control System	79.7	0
Test System 1	73.5	10.0
11/02/75[1,3]		
Test System 1	76.1	10.0
11/03/75	62.0	10.8
11/04/75[1]	49.6	10.0
11/05/75	52.0	10.0
11/06/75[1]	58.3	10.0
11/10/75	50.4	9.2
11/11/75[1]	59.8	10.0
11/12/75	67.5	9.6
11/13/75[1]	77.5	10.0
11/14/75	74.5	10.0
11/17/75	58.3	10.0
11/18/75[1]	58.8	10.0
11/19/75	44.0	9.6
11/21/75	48.2	9.6
11/24/75	45.7	9.6
11/25/75[1]	59.3	10.0
11/26/75	57.6	9.8
11/28/75	68.5	9.6
12/01/75	54.1	11.0
12/02/75[1]	44.0	10.0

TABLE XIX.--(Continued)

Date	Total COD Removal Efficiency (%)	Influent Total Chromium Concentration (mg/l)
12/03/75	44.6	10.5
12/04/75[1]	35.2	10.0
12/05/75[1]	62.8	10.0
12/08/75[1]	55.6	10.0
12/10/75[1]	38.2	10.0
12/11/75[1]	54.0	10.0
12/12/75[1]	52.3	10.0
12/15/75	58.1	10.0
12/16/75[1]	43.7	10.0
12/17/75	36.4	11.2
12/18/75[1]	45.1	10.0
12/19/75	55.4	9.9
12/22/75	46.7	9.9
12/24/75	62.7	10.6
01/05/76	62.6	0.9
01/06/76[1]	56.9	1.0
01/07/76	54.1	0.9
01/09/76	61.4	1.0
01/12/76[1]	66.4	1.0
01/13/76	69.7	0.9
01/14/76[1]	70.4	1.0
01/15/76	65.4	1.0
01/16/76[1]	40.2	1.0

TABLE XIX.--(Continued)

Date	Total COD Removal Efficiency (%)	Influent Total Chromium Concentration (mg/l)
01/19/76	55.0	0.1
01/20/76[1]	39.4	0.1
01/22/76	36.4	0.1
01/23/76[1]	68.9	0.1
01/24/76	54.2	0.1
01/27/76	48.3	0.1
01/28/76[1]	55.2	0.1
01/29/76	63.1	0.1
01/30/76[1]	46.9	1.0
01/31/76	67.6	1.1
02/01/76[1]	40.6	1.0
02/02/76	50.0	0.9
02/03/76[1]	65.2	1.0
02/04/76	57.2	0.8

[1]Chromium concentrations on dates corresponding to this footnote are expected values from system spiking. Concentrations on dates not corresponding to this footnote are determined values.
[2]Test System 2 taken out of service on 10/28/75.
[3]Control System taken out of service on 11/01/75; remaining entries apply to Test System 1.

TABLE XX.--Relationship of COD Removal and Influent Silver

Date	Total COD Removal Efficiency (%)	Influent Total Silver Concentration (mg/l)
02/09/76[1]	54.9	0
02/10/76	65.0	0.01[2]
02/11/76	75.4	0.13
02/12/76[1]	69.6	0.10
02/13/76	74.1	0.10
02/14/76[1]	64.4	0.10
02/15/76	84.1	0.10
02/16/76[1]	71.4	0.10
02/17/76[1]	74.2	0.10
02/18/76	69.2	0.10
02/19/76	75.2	0.16
02/20/76[1]	77.2	0.20
02/21/76	78.2	0.16
02/23/76[1]	67.7	0.20
02/24/76	77.4	0.15
02/25/76[1]	73.6	0.20
02/26/76[1]	72.1	0.50
02/27/76	65.8	0.44

[1]Silver concentrations on dates corresponding to this footnote are expected values from system spiking. Concentrations on dates not corresponding in this footnote are determined values.
[2]Determined prior to spiking system.

TABLE XXI.--Relationship of Chromium and Total Suspended Solids

Date	Suspended Chromium Concentration[1] (mg/l)				Suspended Chromium-Solids Weight Ratio (gm Cr/kg TSS)			
	Influent	Mixed Liquor	Return Sludge	Effluent	Influent	Mixed Liquor	Return Sludge	Effluent
11/05/75	0.7	9.7	48.7	0.9	175.0	4.3	4.1	69.2
11/07/75	1.0	10.5	47.7	0.5	111.1	4.3	4.2	62.5
11/10/75	-0.9	11.8	51.7	-0.3	--	4.7	4.3	--
11/12/75	-0.2	11.8	59.4	0.2	--	4.8	5.4	--[2]
11/14/75	-0.7	14.3	60.7	-0.7	--	5.8	5.3	--[2]
11/17/75	-0.1	15.7	>68	-0.9	--	6.9	>5.5	--
11/19/75	-0.5	14.3	81.1	-0.5	--	6.2	7.3	--
11/21/75	-0.2	14.0	75.0	-0.2	--	6.2	7.4	--
11/24/75	0.2	13.8	82.4	0	40.0	6.4	9.3	--[2]
11/26/75	0.2	14.4	84.0	0	40.0	6.8	7.7	0
11/28/75	0	13.4	101.6	-0.4	0	6.2	7.4	--
12/01/75	1.4	13.3	60.9	1.2	233.3	8.5	7.9	85.7
12/03/75	0.7	12.5	98.9	--	350.0	9.0	7.3	--

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TABLE XXI.--(Continued)

Date	Suspended Chromium Concentration[1] (mg/l)				Suspended Chromium-Solids Weight Ratio (gm Cr/kg TSS)			
	Influent	Mixed Liquor	Return Sludge	Effluent	Influent	Mixed Liquor	Return Sludge	Effluent
12/15/75	0.3	19.4	260.8	1.0	13.0	13.0	10.6	37.0
12/17/75	0	21.3	209.9	0	0	14.2	14.0	0
12/19/75	0.2	21.3	165.9	0.2	33.3	15.0	13.8	66.7
12/22/75	-0.1	22.3	177.9	-0.1	--	14.3	15.2	--
12/24/75	0.9	24.3	184.4	0.6	90.0	15.5	16.1	300.0
01/05/76	-0.2	33.5	264.8	0	--	14.9	15.4	0
01/07/76	-0.2	29.8	259.1	-0.1	--	15.7	15.5	--
01/09/76	-0.5	26.2	269.0	-0.4	--	14.7	14.0	--
01/13/76	-0.3	23.1	254.6	-0.3	--	13.5	12.0	--
01/15/76	-0.5	20.9	239.3	-0.2	--	11.4	11.8	--
01/19/76	-0.1	15.5	186.8	0	--	9.0	10.0	0
01/22/76	0	13.2	160.1	-0.1	0	8.9	8.8	--
01/24/76	0	10.8	113.7	0.2	0	8.3	8.0	5.9

TABLE XXI.--(Continued)

Date	Suspended Chromium Concentration[1] (mg/l)				Suspended Chromium-Solids Weight Ratio (gm Cr/kg TSS)			
	Influent	Mixed Liquor	Return Sludge	Effluent	Influent	Mixed Liquor	Return Sludge	Effluent
01/27/76	0	13.9	113.8	0.1	0	6.9	7.4	3.0
01/29/76	0	10.8	104.2	0	0	6.9	7.6	0
01/31/76	-0.4	10.8	91.1	-0.3	--	6.5	6.0	--
02/02/76	-0.6	12.6	102.9	-0.2	--	6.2	5.5	--
02/04.76	-0.6	13.8	102.8	-0.5	--	7.5	5.8	--

[1] Suspended chromium is defined as total chromium minus soluble chromium.
[2] No suspended solids were detected.

TABLE XXII.--Relationship of Silver and Total Suspended Solids

Date	Suspended Silver Concentration[1] (mg/l)				Suspended Silver-Solids Weight Ratio (gm Ag/kg TSS)			
	Influent	Mixed Liquor	Return Sludge	Effluent	Influent	Mixed Liquor	Return Sludge	Effluent
02/11/76	0.07	0.48	2.24	0.01	3.89	0.25	0.17	2.50
02/13/76	0.02	0.86	3.30	0.01	0.83	0.44	0.24	0.63
02/15/76	0.02	1.29	3.11	0.01	2.50	0.67	0.22	2.50
02/18/76	0.03	1.77	4.10	0.01	1.88	0.90	0.29	1.25
02/19/76	0.05	0.55	2.49	0.01	2.63	0.28	0.18	0.77
02/21/76	0.04	0.46	2.29	0.03	3.08	0.21	0.18	5.00
02/23/76	0.03	2.46	2.07	0.03	2.73	1.21	0.16	3.33
02/25/76	0.04	3.52	5.06	0.02	2.11	1.52	0.42	1.67

[1] Suspended silver is defined as total silver minus soluble silver.

VITA

Paul Allen Richards was born October 15, 1940 in Crowley, Louisiana. He is the son of Mr. and Mrs. Paul Richard Puissegur. He was graduated from Crowley High School in 1958. He received the Bachelor of Science degree in Civil Engineering from the University of Southwestern Louisiana in 1963. He entered the United States Air Force and received a commission in September, 1963. He entered Texas A&M University in 1965 under the Air Force Institute of Technology Program and received the Master of Science Degree in Civil Engineering in 1967. He is currently a Major in the United States Air Force and has worked on the Doctor of Philosophy Degree under the Air Force Institute of Technology Program with United States Air Force Academy sponsorship and will return to the Air Force Academy as a faculty member in the Civil Engineering, Engineering Mechanics and Materials Department. Major Richards is a registered Professional Engineer in the State of Louisiana.

Major Richards is married to the former Ann Lyman of Opelousas, Louisiana. He has two children, Paul Jr. and Christine.

The typist for this dissertation was Mrs. Joyce Hyden.