STUDIES ON THE PERFORMANCE OF THE "HYDROLYTICALLY ASSISTED" EXTENDED AERATION PROCESS AS A MEANS OF TREATING SOLUBLE ORGANIC WASTE MATERIALS

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DEDICATION

My appreciation to Gwendolyn, my lovely and devoted wife, and to David, Rhonda, and Michael, our children, all of whom have sacrificed so much yet have given much love, understanding, patience, and encouragement. To them this manuscript is dedicated.

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CHAPTER I

INTRODUCTION

The theologian tells us that God walked out into space and with the power of his outstretched arms, commanded it to evolve into an earth, a heaven, the seas, and all other things that were designed to become the great scheme of creation. He, in His all-wise power, knew that someone was needed to have dominion over all of these things--someone to whom He would give sufficient powers and understanding to be able to snatch from the elements the rapid streaks of lightning and so direct its power that it could be used to light and heat up the world, and from its power mountains could be moved. He would have dominion over the fowls of the air, the beasts of the forest, and the powerful waters that make up the rivers, the oceans, and the seas. He would be able to take from the consistency of the earth and from it bring forth food and shelter. He would have a mind conscious of the background of creation, eyes to behold its beauty and wonders, and a soul dedicated to the protection of this wonderful God-given environment. Not that the bioenvironmental engineer is God's gift to mankind, but certainly the responsibility of protecting the environment falls upon his shoulders. For the bioenvironmental engineer, it is a matter of conscience and a professional goal to devise through research and development, chemical and biological processes which will protect and prevent further degradation of his environment.

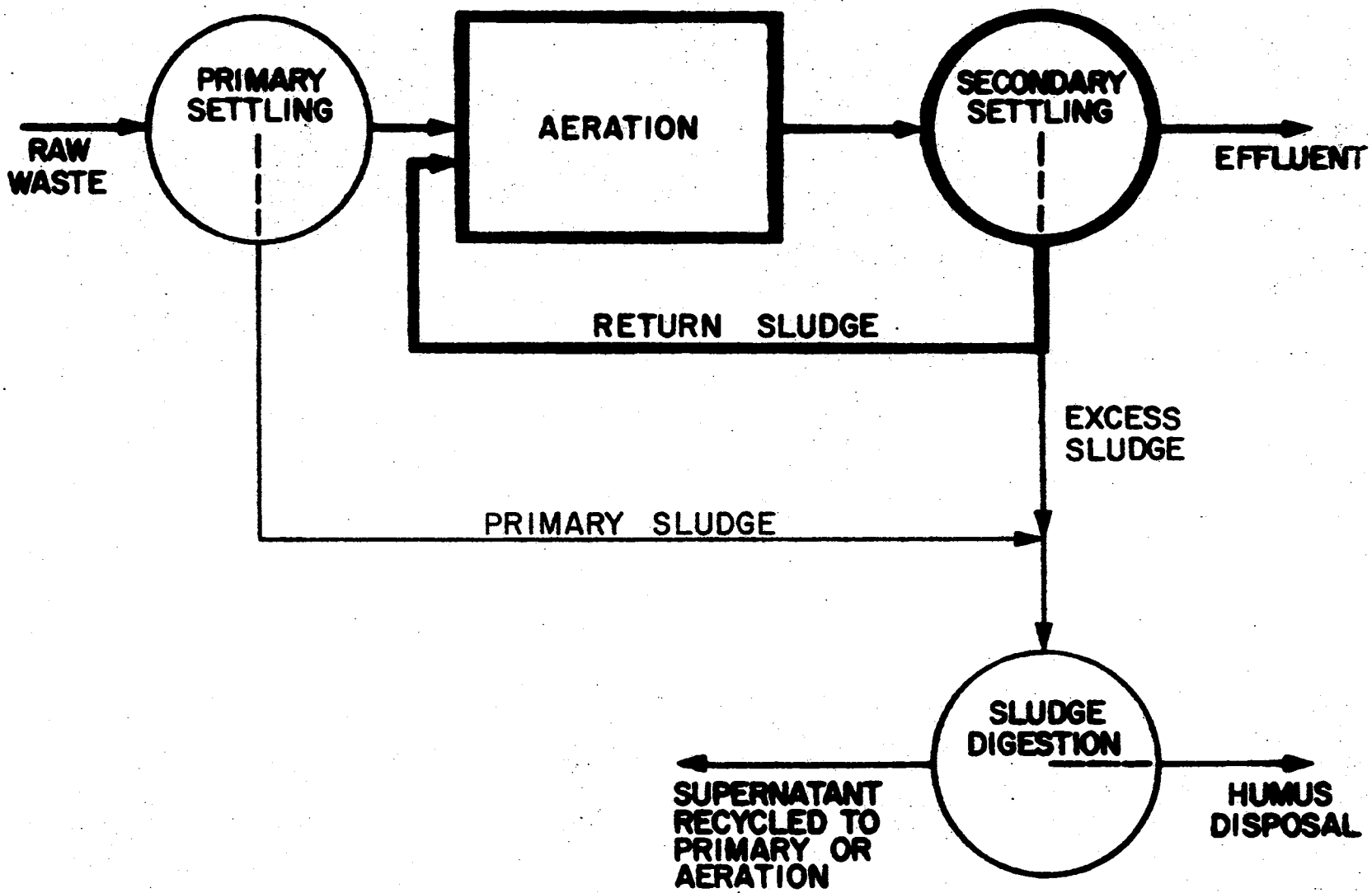
The present awareness of environmental pollution has stimulated researchers to seek better methods of wastewater treatment to assure a good quality effluent prior to discharge to watersheds, and also to seek more effective ways to handle sludge disposal problems. As the use of biological treatment units has increased, the fraction of waste impurities converted into sludge has increased greatly in recent years, and large quantities of waste biological sludges that must be disposed of have been generated. Sludge disposal difficulties have been further amplified by the fact that biological sludges produced during secondary treatment are more voluminous, less concentrated, and more difficult to treat. Data compiled by McCarty (1) show that the volume of secondary sludge produced is many times greater than is primary sludge production. He estimated that the volume of sludge produced from secondary treatment of domestic waste alone would approach 120 mgd by the early 70s, and predicted that it will substantially surpass that figure in future years.

Not only are large quantities of waste solids accumulated every day, but the day-to-day cost of sludge disposal frequently exceeds the cost of any other single process in the treatment plant. Although the sludge volume is usually less than one percent of the total influent, recent studies (2)(3) indicate that, for activated sludge plants, sludge handling cost accounts for from 21 to 50 percent of the total plant operating and maintenance cost. Other investigators have estimated that sludge handling may account for as much as 65 percent of the total capital and operating cost, depending on the method of disposal used. The environmental engineer must keep foremost in his mind the fact that continued growth of urban areas, industrial expansions, and public recognition of the need to control pollution, along with the

increasing demands for clean water for all purposes, make it necessary to improve our wastewater treatment technology. Water quality standards, now a fact, provide the guidelines, and pollution control facilities, in order to meet these standards, may have to take on many forms. Pollution comes from many sources and in varying amounts and concentrations. It is derived from municipal wastes as well as from industrial wastes. One phase of this study deals with a soluble synthetic organic waste in which glucose is the carbon source. Another portion deals with the treatment of an industrial waste from the wood pulping industry.

The activated sludge process has become one of the most frequently used secondary treatments for waste effluents. The development of the activated sludge process marked an important advance in secondary treatment of organic material. In the past fifty years, many modifications of the process have been developed and placed into field operation. A more recent modification is the extended aeration process, versions of which have been placed into operation within the last 20 years. The extended aeration process differs from other modifications in that it combines sludge disposal and wastewater purification. Figure 1 shows a schematic flow diagram of a conventional activated sludge process and the extended aeration modification. The major elements of the modification are shown in heavy lines. It can be seen that in the extended aeration process, all sludge is returned to the aerobic reactor. In theory there is no excess sludge; therefore, sludge handling and ultimate sludge disposal are not required. If such a situation did occur, it could be said that the incoming organic matter in the waste was totally oxidized to CO_2 and water.

Figure 1. Comparison of the Extended Aeration and Conventional Activated Sludge Processes


PRIMARY SETTLING
AERATION
SECONDARY SETTLING
RAW WASTE
EFFLUENT
RETURN SLUDGE
EXCESS SLUDGE
PRIMARY SLUDGE
SLUDGE DIGESTION
SUPERNATANT RECYCLED TO PRIMARY OR AERATION
HUMUS DISPOSAL

It is obvious that a treatment plant which could dispose of all organic solids and not produce any sludge residue would be the ideal design, and perhaps the sanitary engineer's ultimate dream. However, this type of process has not been fully developed. Many researchers argue the feasibility of such a design. The design itself seems almost inconceivable in biological systems, where sludge handling is thought to be a necessary evil associated with biological treatment processes.

The first treatment plant to be used as an extended aeration unit was the underloaded conventional activated sludge plant at East Palestine, Ohio (4). In 1947, this plant was operated with 100 percent return of final settlings to the aeration tanks with no sludge wasted, and an excellent effluent was obtained. In 1950, as a result of the East Palestine operations, three extended aeration plants were installed in Ohio to treat milk wastes. Industrial wastewater was first treated by this process in 1951. In 1952, two plants were used to treat a combined industrial and domestic waste.

Following this early use in Ohio, the number of extended aeration plants increased to more than 2600 in 1962 (5), and their popularity is still increasing because of their applicability to the waste treatment problems encountered in rapidly developing suburban areas.

Model studies of the process have been numerous. Many of the studies have employed synthetic wastes in an attempt to examine the conceptual principle of the process. The theory of total oxidation of the biological sludge produced in this treatment process aroused much interest in the pollution control field, and a great deal of research has been conducted to investigate this concept. The prime research question was: could secondary treatment be combined with autodigestion

of sludge to bring about, effectively, total wet oxidation of the organic material?

Within the past five years, an extensive investigative effort regarding this process has been conducted in the bioengineering laboratories of the Oklahoma State University. The more pertinent questions that had to be answered concerning this process were: (1) Could such a plant be operated without wasting sludge? When the process was proposed, it was thought that endogenous respiration of the organic matter produced during removal or metabolism of the organic substrates in the waste would balance new growth of biological cells, and that an equilibrium solids concentration would be eventually established. If this did occur, no solids wastage would be necessary and theoretically, total oxidation and a steady state with respect to biological solids concentration would be attained. (2) Would there be an accumulation of inert material which could not remove substrate and could not be used as substrate, and if so, how long would it take for such inert material to cause the plant to fail? It was generally thought by early researchers that the process was biologically unsound; that it was theoretically impossible to oxidize totally the organic matter of the cell to CO_2 and water, and that there would be a biologically inert fraction remaining that would continually build up and take over the system.

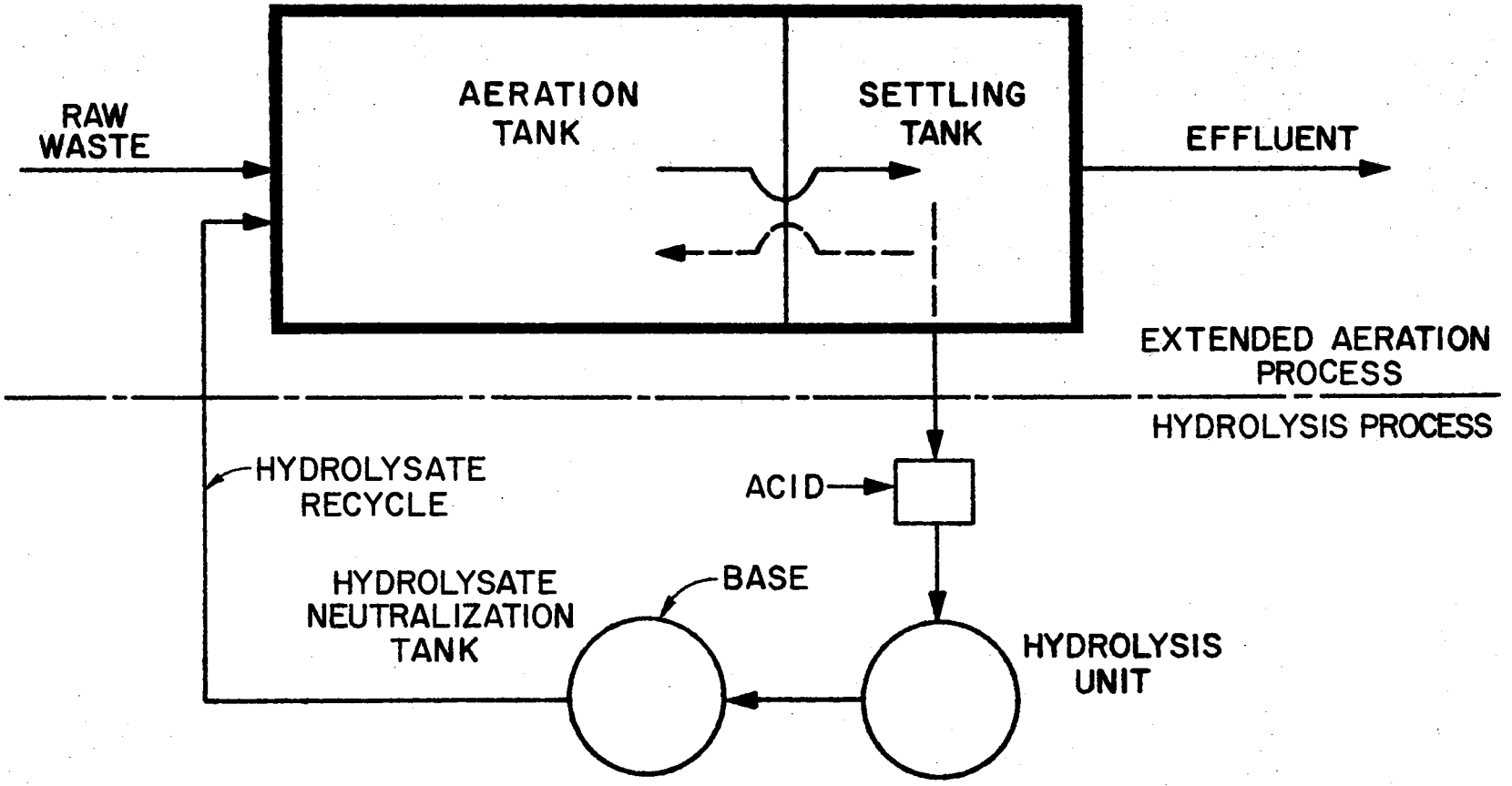
In order to prove or disprove the ability of the extended aeration process to achieve total oxidation of organic material, four lines of investigations were conducted at Oklahoma State University by Gaudy and co-workers.

The major experimental study envisioned was the operation of an

extended aeration laboratory pilot plant over a long period of time with positive retention of biological solids, in order to determine if such a system would lose its substrate removal capabilities because of so-called inert material. Secondly, the operational stability of such a system under shock loading was studied. Results from these investigations provided definite indication that the so-called inert biological fraction did not continually build up in the system, and that the system could not be expected to undergo metabolic failure. It was also found that an equilibrium solids concentration was never attained, and that solids concentrations went though cycles of increase and decrease. It was reasoned that during the periods of decreasing solids concentration, the solids which had previously been accumulating were serving as a carbon source for other members of the population. Basic metabolic studies on the metabolism of various fractions of microbial cells were made and reported. Although the concept of total oxidation was proven to be sound and it was found that such a system could be operated for a long period of time under various environmental changes, such a system could cause some major engineering problems. It was realized that solids could accumulate to high levels and settling problems could be encountered before a natural cycle of accelerated autodigestion might occur. The fourth line of investigation then involved various ways and means to enhance the initiation of the autodigestive cycle to avoid solids buildup. This led to the development of a new design model for the treatment of soluble organic material via the extended aeration activated sludge process incorporating the chemical hydrolysis modification (Figure 2).

In a previous study, the process was operated with a regular

Figure 2. Proposed Extended Aeration Activated Sludge Process Incorporating Chemical Hydrolysis for Control of Sludge Concentration


RAW
WASTE
AERATION
TANK
SETTLING
TANK
EFFLUENT
EXTENDED AERATION
PROCESS
HYDROLYSIS PROCESS
HYDROLYSATE
RECYCLE
ACID
HYDROLYSATE
NEUTRALIZATION
TANK
BASE
HYDROLYSIS
UNIT

withdrawal, hydrolysis, and refeeding schedule at a normal waste organic loading for the extended aeration process. In the present study, it was desirable to determine if this process could be operated at higher organic loadings. Although there were many alternative modes of operation of the process, the mode of choice was the same weekly hydrolysis and refeeding schedule as used formerly. Thus the results at the higher loadings could be more readily compared to those of the previous study. It is the continuation of these studies with which the present investigation is concerned.

The hydrolytic assist method presently under investigation utilizes the extended aeration modification of the activated sludge process for biological treament of organic material and incorporation of acid hydrolysis to enhance autodigestion and eliminate excess solids buildup. The "hydrolytic assist" method utilizes acidification to pH 1 with concentrated sulfuric acid. This is followed by five hours of autoclaving at a pressure of 15 psi and temperature of 121^{o}C. After neutralization to pH 7, the hydrolyzed sludge is fed back to a growing system as substrate.

The overall aims of this research can be generally stated as follows:

(1) To obtain operational data for various loadings and predetermined withdrawal schedules for hydrolysis, the purpose being to gain insight into engineering design factors.

(2) To operate such a plant using a whole waste as well as a synthetic waste.

(3) To further delineate the growth constants μ_{max} and K_s for hydrolysate as substrate.

(4) To provide as much information as possible for design and operation procedures pertinent to the extended aeration process incorporating the "hydrolytic assist."

CHAPTER II

LITERATURE REVIEW

The activated sludge process has been recognized for a long time as a very efficient means of treating organic material. The process itself dates back to the early 1900s. Many modifications to this process have come about since its early inception. One such modification is the extended aeration process which was developed in the early 50s.

Hoover, et al., and Porges, et al. (6)(7)(8)(9)(10) were the first investigators to test the concept and theory of the extended aeration total oxidation systems. It was reasoned from their investigations using dairy waste as a substrate that the digestion of organisms by their own respiration has a definite practical importance. They hypothesized that if endogenous respiration proceeds at a great enough rate, microorganisms oxidize their own tissue rapidly enough to keep the system in balance. Under such conditions, sludge does not accumulate. However, it was pointed out that if autooxidation was not sufficient, sludge would accumulate, making sludge disposal necessary. Early studies by Porges and co-workers indicated that the average endogenous respiration rate for cells fed skim milk solids was 10 µl O_2/hr/mg cells.

Using the equation for the endogenous oxidation of the sludge, for which a chemical formula had been previously established, they calculated that the cell tissue was oxidized endogenously at the rate of one

percent per hour. Hence, a system containing 2500 mg/l sludge when fed 1000 mg/l skim milk solids (which would produce 500 mg/l sludge) would not result in the accumulation of solids if the detention time was 20 hours.

Although Porges, et al. were the first to propose the concept of total oxidation, the theory was stated in more detail by D. E. Drier (11) in this way:

> "If there is an unlimited food supply with the proper nutritional balance, the microorganisms are in the log growth stages and bacterial growth is limited only by the microorganisms' ability to reproduce. The oxygen uptake rate is increased due to adsorption of the organic load, and the synthesis of new cells. As the oxidation of the organic load proceeds, a declining growth phase is reached due to limitations on available food, and the oxygen uptake rate also declines. When there is just enough food to keep the microorganisms alive, the so-called endogenous metabolism exists. When the substrate is unable to supply sufficient organic matter for synthesis and energy, the rate of destruction exceeds the rate of growth. The microorganisms then obtain energy by autodigestion of the cell protoplasm, and the biologically degradable organic matter in the cells is oxidized to carbon dioxide, water, and ammonia."

Based on the findings of Porges and co-workers, Thayer (12)(13) developed a waste disposal plant applicable to small dairies. Plants were constructed at dairies located in Germantown, Dayton, and Toledo, Ohio. These plants represented the first actual application of laboratory studies in the extended aeration process. These plants were operated with detention times varying from 36 to 41 hours in the aeration tank, and two to four hours in the settling tank. The influent BODs varied from 567 to 926 mg/l, and the final effluent BODs ranged from 11 to 31 mg/l. Purification efficiency for these systems was approximately 96 percent. All sludge from the settling tank was returned to the head end of the aeration tank.

In 1956, Eckenfelder (14) reported on results of his studies on the oxidation kinetics of biological sludges. He stated that sludges accumulated in a biooxidation system will undergo oxidation at varying rates depending upon factors of temperature, waste characteristics, microbial content, and sludge age, and that the microbial content of the sludge will vary widely depending upon the nature of the waste being treated. He also concluded that endogenous degradation of sludge proceeds with first order decreasing rate kinetics. The rate decreases and approaches a limit of about 40-60 percent volatile solids reduction. He concluded that the remaining constituents were resistant to further oxidation and would provide a residue for sludge disposal.

In 1958, Tapleshay (15) reported on the total oxidation process marketed by the Chicago Pump Company. The process was primarily designed for schools, small subdivisions, factories, shopping centers, and trailer parks. Tapleshay believed the concept of total oxidation to be feasible and recommended the design of activated sludge plants with long aeration time (24 hours) and four hours settling. He recommended completely eliminating the digester and primary clarifier.

Regarding the concept of total oxidation, Forney and Kountz (16) performed a study using skim milk waste in a continuous flow system, and concluded that the concept of total oxidation was feasible.

Symons and McKinney (17) concluded that total sludge recycle was not possible on a long-term basis, and that sludge wastage is essential for successful operation of an activated sludge system. Using a daily batch-fed system grown on sodium acetate as substrate and operated for a period of 35 days with 100 percent sludge recycle, they found that volatile biological solids increased throughout the test period for

each experiment. They concluded that the accumulated material, which was observed to be mostly extracellular polysaccharides, was resistant to biological degradation. On this basis, they refuted the concept of total oxidation.

After Symons and McKinney published their paper, Kountz and Forney (18) reevaluated their stand on the total oxidation concept. From the results of their studies on metabolic energy balances in a multi-unit, total oxidation system operated for six months, they concluded that a residual material (polysaccharide) remained, equivalent to 20-25 percent of the new sludge produced. They estimated the actual endogenous loss of solids per day to be two percent of the total weight of activated sludge, and the accumulation of non-oxidizable sludge per day was estimated at 0.6 percent of the total weight of activated sludge. From these conclusions they, too, rejected the concept of total oxidation on the basis that it is not possible within a reasonable time and reasonable size treatment system.

Busch and Myrick (19) performed a series of experiments in 1959 to determine the limitation of the total oxidation process. They did this by means of bench-scale digestion units. They used both batch-fed and continuously-fed, completely-mixed systesm with glucose as the substrate. The feeding rate was increased from one to six grams per day in a 5.5-liter digester. This represents solids concentrations of 200 to 1000 mg/l. No wasting of biological solids was practiced, although some solids were lost in the plant effluent. They found that soluble BOD in the supernatant and plant effluent were consistently below 10 mg/l at BOD loadings ranging from 0.05 to 1.7 lb BOD/lb volatile suspended solids. They also observed that no equilibrium solids level was

attained even after 103 days of operation at BOD loadings of 0.05 lb/lb volatile suspended solids. From these studies, they concluded that total oxidation is neither theoretically nor practically attainable. They stated that some buildup of solids is inevitable unless effluent carryover of solids is sufficient for balance.

Washington and Symons (20) conducted experiments on extended aeration treatment units in 1960. The purpose of their experiments was to confirm under controlled conditions the accumulation of volatile solids over an extended period of time, and to determine the general composition of the sludge under prolonged aeration. The study was made in batch and continuously fed systems using glycine, sodium acetate, and glucose as substrates to represent the effect of amino acids, fatty acids, and carbohydrates.

The accumulation of volatile solids amounted to about 10-15 percent of the ultimate BOD of the substrate removed under equilibrium operations for wastes which were carbohydrates or fatty acid in nature. They also conducted studies on the extent of degradation of various cellular components of the sludge from the three systems under endogenous conditions for 27 days. The protein and fat fractions were found to be readily degradable during the endogenous respiration phase. The carbohydrate content of the sludge increased with time of autolysis, indicating an inertness in the carbohydrate fraction of cells. They theorized that the biologically inert volatile solids which would be expected to accumulate in the activated sludge systems would average 47-56 percent polysaccharide, 39 to 47 percent protein, and 3 to 8 percent fats.

McCarty and Broderson (21) concluded that in the extended aeration

system, if no facilities for disposal of excess sludge are provided, the system will accumulate solids and discharge the excess solids in the effluent. The sludge which would accumulate in the unit would include the synthesized biological solids and some biologically inert materials which were present in the influent waste, i.e., grit particles and certain biologically resistant organics such as cellulose. This suggested a very interesting point; that is, that industrial waste and municipal waste should receive separate consideration when designing extended aeration processes. Municipal wastes will always contain a certain fraction of relatively inert material. They also pointed out that the efficiency of operation of the extended aeration process was closely related to the effectiveness of the settling tank in retaining suspended solids. They suggested that in order to maintain 85 percent BOD_5 removal efficiency, the organic loading should be less than 40 lbs BOD_5/day/1000 cu ft. They found that although fairly high average efficiencies could be maintained at higher loadings, fluctuation of effluent quality would be greater. They also cautioned that nitrification in the aeration tank would cause false values for BOD removal efficiency as well as enhance possibilities for a rising sludge in the settling tank.

In 1965, Washington, Hetling, and Rao (22) reported a long-term adaptation of microorganisms to an acclimated sludge mass. In their study, batch-fed reactors with glucose as the substrate were operated for one year with total retention of solids. Their results showed that biological solids did not accumulate at a constant rate. The systems did not reach a steady state condition, but demonstrated periods of increasing biological solids as well as periods of decreasing biological

solids. They surmised that the period of decreasing solids concentration was caused by adaptation of an organism to the accumulated sludge mass. Although there was no measurement of effluent solids, they observed that there was essentially no loss of volatile solids in the effluent throughout the 12-month study, and therefore the decline in solids could not be attributed to loss in the effluent.

During the 1960s, several studies of the extended aeration process were conducted. Ludzack (23), using a feed of weak sewage with fish meal operated an extended aeration process at low loadings, long aeration periods, and high mixed liquor suspended solids. He concluded that incomplete aerobic digestion of solids during extended aeration treatment produces high solids carryover in the effluents. He also stated that operation of the process with high solids increases the variability in effluent quality and chances for gross solids discharges, and that periodic withdrawals of unit solids for ultimate disposal reduce effluent solids carryover.

In 1965, Sawyer (24) presented some guidelines for the operation of the extended aeration process. These general guidelines included an aeration time of 24 hours, a BOD loading of approximately 15 lbs BOD/day /1000 cu ft, and 5000 to 8000 mg/l biological solids concentrations.

Upon recognizing the possibility of achieving total wet oxidation through operation of the extended aeration process, and noting the controversy that appeared to exist regarding the feasibility of such a process, Gaudy and co-workers undertook a long range systematic experimental approach to attempt to show conclusively whether such a system could work. They attempted to show whether the total oxidation concept was consistent with sound microbiological theory and, also, to recommend

engineering practices for design and operational control. Their first line of investigation was to study the operational stability of this process. Ramanathan, Gaudy, and Ragthaidee (25) conducted experiments to determine the response of the extended aeration process to shock loading. It was shown in their study that an extended aeration system could withstand as much as a five-fold increase in concentration (500 to 2500 mg/l glucose) of inflowing COD without significant loss of removal efficiency. The shock load experiments with extended aeration sludge were conducted at both high and low biological solids concentration and in both batch and continuous-flow studies. The results of these studies gave insight into the operational stability of this process when subjected to an environmental change such as shock loading.

In another series of experiments, Gaudy, Ramanathan, Yang, and DeGeare (26) operated a bench scale extended aeration pilot plant for nearly two years, and concluded that such a system can be operated with good biochemical efficiency without continual solids accumulation and without sludge wasting. They also found that there was no buildup of carbohydrate or protein in the sludge composition. During the entire experiment, all of the biological solids were retained in the system. The only solids removed were those taken for sampling and for small auxiliary experiments (no more than 0.2 percent). They concluded that there is a fluctuation in the concentration of biological solids due to natural biological (ecological) regulation, which caused the accumulation of biological solids to be periodically reduced. Since no solids were wasted, either purposely or inadvertently, this reduction of the biological solids that had accumulated must be due to their now being utilized as a carbon source by other members of the population.

Investigation of the substrate-consuming capabilities of the biological solids and their O_2 uptake capacity showed that as the biological solids accumulate, the specific endogenous O_2 uptake of the sludge drops significantly. However, any possible loss in purification efficiency due to decreased metabolic activity per unit of solids can be amply made up by the large number of organisms present to feed on the waste. It was also observed at times that the cell concentration became so great that it caused settling problems in the clarification chamber and an excessive concentration of biological solids in the effluent. Solids would have been lost were it not for the fact that in these experiments, all effluent was centrifuged and solids returned to the aeration chamber.

Gaudy, Yang, and Obayashi (27) proposed a solution to this problem and called it the "hydrolytic assist." Their proposal, the extended aeration process with "hydrolytic assist," consisted of hydrolyzing chemically a part of the return sludge and returning it to the aeration tank, along with the regular stream of influent substrate. A pilot plant, in which the hydrolytic process was utilized, was operated for one year and it was found that this process is operationally feasible and provides a means to control the concentration of sludge in the total oxidation system.

Other pertinent investigations conducted by Obayashi and Gaudy (28) were undertaken for the express purpose of determining whether extracellular polysaccharides of microorganisms can serve as a carbon source for the growth of other microorganisms. Short-term batch experiments were conducted using microbial polysaccharides obtained from a variety of microorganisms. The results obtained provided direct evidence that extracellular polysaccharide serves as an excellent carbon source for

growth of microorganisms, i.e., it was shown not to be inert organic matter.

In his work with activated sludge, during prolonged endogenous aeration, Goldstein (29) observed the total oxidation of solids accumulated during the substrate removal phase in many of his batch activated sludge extended aeration systems. Further investigation revealed that there was no buildup in carbohydrate content of sludge during endogenous metabolism, thus providing additional strong evidence that carbohydrate material is not biologically inert. Studies by Godlove (30) on the effects of effluent discharge from a hydrolytically-assisted extended aeration plant on the oxygen sag of a simulated stream further demonstrated the effectiveness of this process as a means of treating soluble organic waste material.

Certainly, the research conducted at the Oklahoma State University by Gaudy and co-workers has contributed much to answering some of the questions concerning the use of the extended aeration process as a biological oxidation system. The work accomplished thus far had provided indications that the total cell recycle with the "hydrolytic assist" offered considerable promise, and that further laboratory pilot plant work on the process was warranted. In the present study, the major thrust was to determine the operational behavior of this system at organic loadings higher than those previously used, in order to gain insight into possible design criteria. It was also important in assessing the engineering adaptability of the system to perform studies using an industrial waste as well as the synthetic waste usually employed in fundamental research studies.

CHAPTER III

MATERIALS AND METHODS

Experimental Protocol

A. Batch Experiments

1. Heterogeneous Microbial Populations and Substrates. An initial seed of heterogeneous microorganisms was obtained from the primary clarifier of the pollution control plant at Stillwater, Oklahoma. The composition of the synthetic waste used as the growth medium in these studies is given in Tables I and II. The composition of the growth medium was so chosen that the carbon and energy source limited growth under conditions of otherwise adequate nutrition. The organisms were fed 1000 mg/l substrate in a batch reactor of 9.4-liter capacity and aerated for 24 hours. After 24 hours, approximately one-third of the mixed liquor was wasted and the unit was again fed 1000 mg/l of glucose and aerated for 24 hours. The sludge wasting procedure was discontinued after three weeks in order to build up the biological solids concentrations. When the mixed liquor suspended solids level reached approximately 4500 mg/l (day 35), 1000 ml of the mixed liquor suspended solids was removed from this unit and subjected to acid hydrolysis. Portions of this neutralized hydrolysate were used to conduct growth studies, long-term batch studies, and oxygen uptake experiments.

TABLE I

COMPOSITION OF FEED FOR 500 mg/l GLUCOSE AS SUBSTRATE

Glucose	500 mg/l
$(NH_4)_2SO_4$	250 mg/l
$MgSO_4 \cdot 7H_2O$	50 mg/l
$FeCl_3 \cdot 6H_2O$	0.25 mg/l
$CaCl_2$	3.75 mg/l
$MnSO_4 \cdot H_2O$	5 mg/l
Phosphate buffer, 1.0 M, pH, 7.0	5 ml/l
Tap water	50 ml/l
Distilled water	to volume

TABLE II

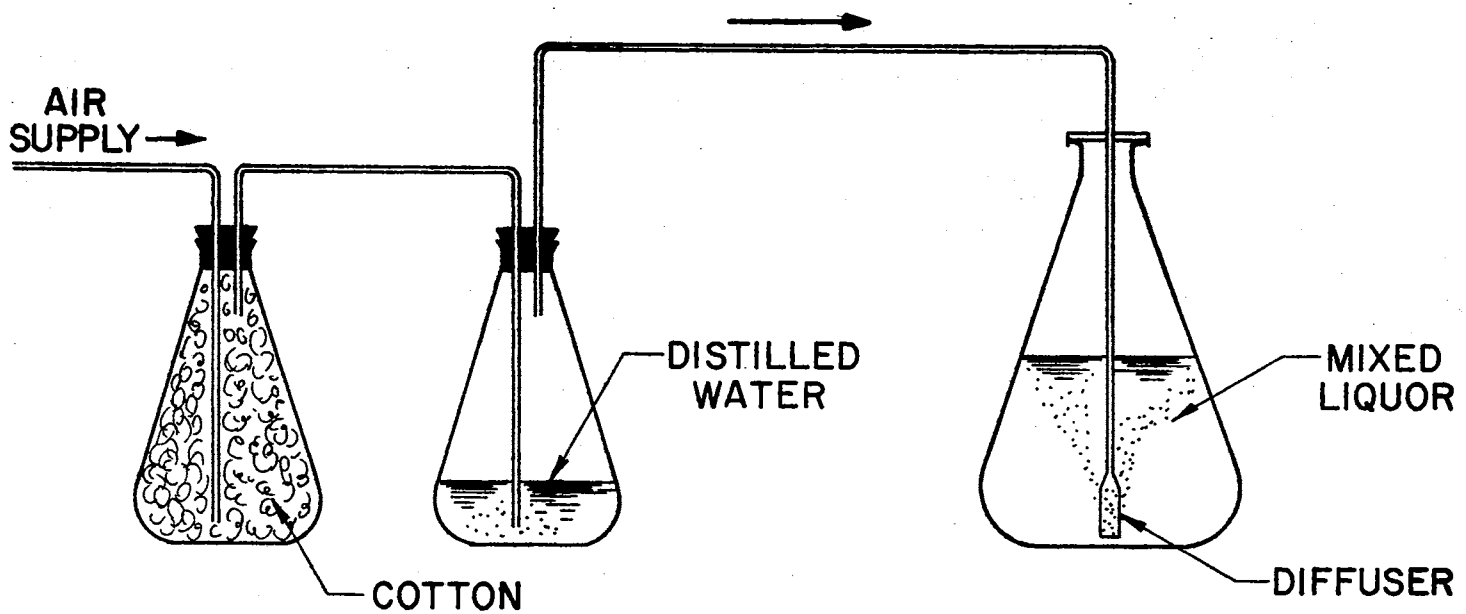
COMPOSITION OF FEED FOR 1000 mg/l GLUCOSE AS SUBSTRATE

Glucose	1000 mg/l
$(NH_4)_2SO_4$	500 mg/l
$MgSO_4 \cdot 7H_2O$	100 mg/l
$FeCl_3 \cdot 6H_2O$	0.50 mg/l
$CaCl_2$	7.50 mg/l
$MnSO_4 \cdot H_2O$	10 mg/l
Phosphate buffer, 1.0 M, pH, 7.0	10 mg/l
Tap water	100 ml/l
Distilled water	to volume

2. Growth Rate Studies. In growth rate experiments, cells which had been previously acclimated to cell hydrolysate, were inoculated into 250 ml-Erlenmeyer flasks containing fresh medium, essential salts added in accordance with Table I and in concentrations proportional to varying concentrations of hydrolysate employed as the sole source of carbon and growth-limiting nutrient. The total volume of sample per flask used in these experiments was 50 ml. This usually consisted of 47-48 mls of growth medium feed, and essential nutrients, plus 2-3 mls of acclimated seed. Concentrations of hydrolysate ranging from 50-1000 mg/l were aerated on an Eberbach shaker at a rate of 100-110 oscillations per minute. Samples were taken periodically and checked for optical density, measured with a Bausch and Lomb Spectronic 20. Change in optical density was used as an index for measuring growth.

3. Long-Term Batch Experiments. Figure 3 shows a schematic drawing of the apparatus used to run long-term batch experiments. Total volume used was two liters. An acclimated cell suspension was used to inoculate the hydrolysate medium. Compressed air, filtered through cotton and saturated with water by bubbling through distilled water, was supplied through sintered glass diffusers. At the time of inoculation, a sample was withdrawn for measurement of chemical oxygen demand and biological solids. Also, the initial optical density was recorded. During each experiment, frequent measurement of optical density permitted construction of a growth curve which was used as a guide in selecting sampling times. Samples were withdrawn for determination of COD and biological solids. The volume of the mixed liquor suspension was measured daily, and any loss due to evaporation was compensated for by the addition of distilled water.

Figure 3. Batch Experimental Reactor for Determining Substrate Utilization and Yield


AIR
SUPPLY
DISTILLED
WATER
MIXED
LIQUOR
COTTON
DIFFUSER

4. Oxygen Uptake. Oxygen uptake studies were conducted on the hydrolysate, using a Warburg respirometer. A reaction volume of 40 ml was employed, using 1.5 ml of 20 percent KOH in the center well. The apparatus was operated at 25°C and 100 oscillations per minute.

B. Batch Experiments on a Whole Waste

The long-term batch experiments were performed in a 5-liter reactor with four sintered glass diffusers used as a source of oxygen and to supply adequate mixing. Compressed air was saturated with water by bubbling it through distilled water prior to its entry to the reactor. The chemical characteristics of the whole waste and composition of growth medium are given in Tables III and IV. The whole waste was diluted 1/50 to give a substrate concentration of 2500 mg/l COD. In characterizing the waste, it was found that of the 2500 mg/l total COD, only about 800 mg/l was biodegradable; that is to say, only 800 mg/l was available as substrate. Nutrients were therefore added on the basis of 1000 mg/l COD to ensure that the carbon and energy source was the growth-limiting factor.

In order to make the waste more receptive to aerobic biological treatment and to make it roughly comparable in concentration to an industrial Kraft mill waste, it was first diluted (1/50) and the pH of the diluted sample adjusted to 7.0. pH adjustment was necessary because the concentrated Kraft waste carried a pH of 12+, and the dilution decreased the pH to only approximately 10.5, which was subsequently adjusted to pH 7.0 with sulfuric acid. Sewage seed from the Stillwater pollution control plant was again chosen as the inoculum seed. Acclimated organisms were then fed the neutralized industrial waste and

aerated for 24 hours. After 24 hours, 1/5th of the mixed liquor suspended solids (one liter) was wasted. The aerators were then removed from the reactor and the mixed liquor was allowed to settle. After settling, most of the supernatant from the mixed liquor was removed to avoid possible buildup of toxic material in the reactor; the unit was then fed and volume brought back to the 5-liter mark. Samples of the feed and of the reactor content before and after feeding were taken daily. COD and solids determinations were performed to gain knowledge of the treatability characteristics of the industrial waste under investigation. Seed from the unit was also taken and transferred to 1500-ml batch units for running short-term batch studies in order to gain further insight into the metabolism of this waste and its use as growth substrate.

TABLE III

PHYSICAL-CHEMICAL CHARACTERISTICS OF INDUSTRIAL WASTE

Source:	Paper pulp industry
Nature:	Concentrated Kraft blowdown liquor
Color:	Amber
Chemical Oxygen Demand	125,000 mg/l
Biological Oxygen Demand (raw) BOD_5	30,000 mg/l
Biological Oxygen Demand (dil) BOD_5	500 mg/l
pH	12.0
Total solids	3000 mg/l

TABLE IV

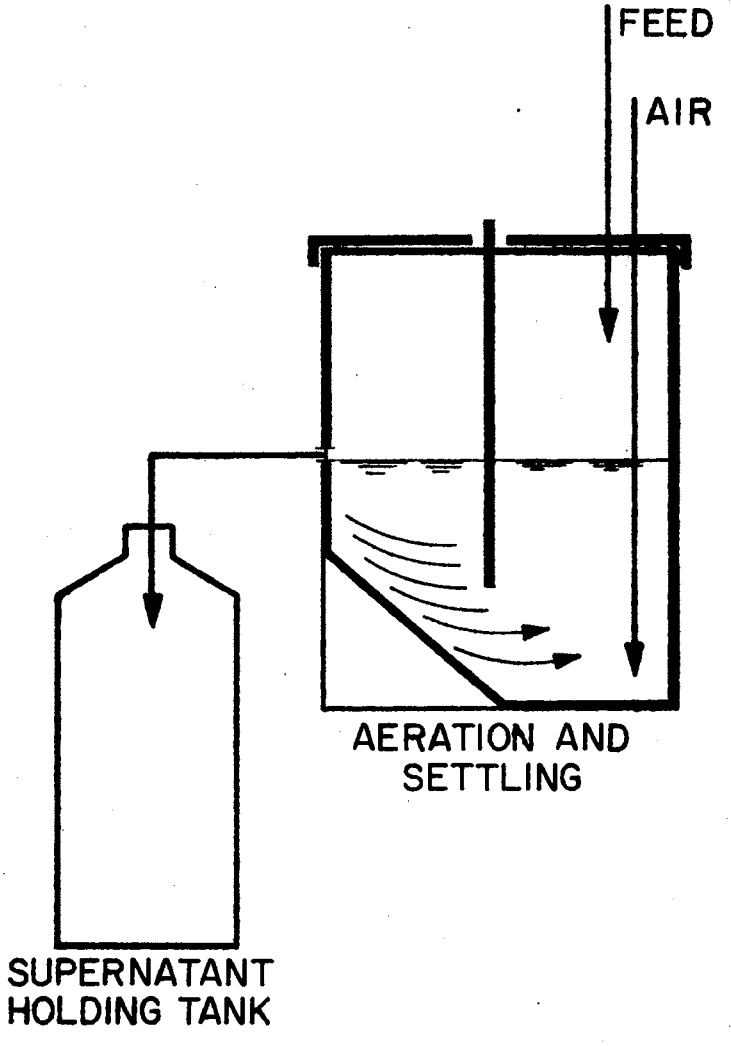
COMPOSITION OF GROWTH MEDIUM FOR INDUSTRIAL WASTE

Substrate COD	2500 mg/l
$(NH_4)_2SO_4$	500 mg/l
$MgSO_4 \cdot 7H_2O$	100 mg/l
$MnSO_4 \cdot H_2O$	10 mg/l
$CaCl_2$	7.5 mg/l
$FeCl_3 \cdot 6H_2O$	0.5 mg/l
Tap water	100 ml/l
1.0 M phosphate buffer, pH 7.0	10 ml/l
Distilled water	to volume

C. Continuous-Flow Reactors

The experimental extended aeration pilot plant used in this study was essentially the same as that used by Yang (31) in his studies on the extended aeration activated sludge process with and without the "hydrolytic assist." A schematic drawing of the extended aeration pilot plant is shown in Figure 4. It should be pointed out that the unit used for the synthetic waste studies and the industrial waste studies were identical. The total volume of the system was 9.4 liters; 6.2 liters of aeration capacity and 3.2 liters in the settling compartment. An adjustable baffle was used to separate the aeration and settling chambers. Compressed air provided not only mixing and oxygen supply to the biological solids, but also "suction" to recycle solids from

Figure 4. Continuous-Flow Extended Aeration Pilot Plant


FEED
AIR
AERATION AND
SETTLING
SUPERNATANT
HOLDING TANK

the settling compartment. Airflow rate was maintained at 2000 cc/min/l. Temperature of the reactor was room temperature. During operation under continuous flow, the feed rate was set to provide an overall detention time of 24 hours, approximately 16 hours of aeration, and 8 hours of settling. The feed solution was channelled to the aeration tank through a dual positive displacement pump (Mini-pump, Milton-Roy Model MM2-B-96R). Alternately, each of the feed lines was cleaned by pumping through a one-percent solution of Clorox in distilled water. Thus, one of the lines was being disinfected while the other was being used. This provided positive control for the retardation of growth in the feed line. Composition of the synthetic waste during continuous-flow operation has already been given (Tables I and II). Daily samples were taken for measurement of biological solids and substrate removal efficiency.

D. "Hydrolytic Assist"

The flow scheme for the hydrolysis process was shown in Figure 2. The hydrolysate was prepared by taking 900 ml per week of settled sludge from the settling compartment of the extended aeration pilot plant and lowering the pH to 1.0 with concentrated sulfuric acid. The sludge was then placed in a laboratory autoclave for five hours at 15 psi and 121^{o}C. The hydrolyzed sludge was then neutralized to pH 7.0 with sodium hydroxide (NaOH) and fed with glucose minimal medium to the system. The hydrolysate was fed at a rate of 150 ml/day. This normally increased the organic loading by approximately 150-200 mg/l.

E. Special Studies on Chemical Flocculation

Cell suspensions were taken from the effluent of the continuous-flow unit during periods of poor settling and subjected to jar testing. Various coagulants were tested to determine which would provide the best treatment efficiency. The efficiency was assessed by measuring the turbidity (OD). The tests were performed by adding several dosages of different coagulants to effluent samples, flash mixing for 15 seconds at 96 rpm, and plotting the change in optical density. The optical density was measured by using the Bausch and Lomb Spectronic 20. The jar test apparatus was manufactured by Phipps & Bird, Inc., Richmond, Va.

F. Studies to Determine the Effect of Effluent on a Simulated Stream Model Using the Oxygen Sag

The method used was the same method used by Peil (32) and Godlove (30) in their studies on the effects of effluents from industrial sources and from extended aeration plants on the assimilative capacity of receiving streams.

The reactor used was a flat-bottomed cylindrical Pyrex vessel having a diameter of 8.125 inches and a depth of 18 inches. Oxygen transfer from the atmosphere was facilitated by use of mechanical stirrers. Since the solubility of oxygen in water varies with slight changes in temperature, control of temperature was brought about by use of a constant temperature bath. A Precision Scientific Lo-Temptrol recirculating bath was used. The concentration of dissolved oxygen in the reactor jars was measured electrometrically (Weston-Stack oxygen

analyzer). To ensure consistent results, measurements were taken at the same depth. The probe was standardized for each subsequent test period. The probe was checked for accuracy by comparing probe readings with dissolved oxygen (DO) as measured by the Alsterburg azide modification of the Winkler Method (33). If significant variations occurred, the probe was adjusted to the actual DO as measured by the Winkler Method.

G. Analytical Procedures

Analytical methods and analytical techniques employed were the same for the batch and the continuous-flow reactors. All tests described herein and all calculations made therefrom were in accordance with procedures as listed in "Standard Methods for the Examination of Water and Wastewater" (33). Any variance in the above mentioned procedures will be discussed in detail.

1. Biological Solids

The concentration of biological solids was determined gravimetrically by filtration through membrane filters (0.45 μ pore size, manufactured by the Millipore Filter Corp., Bedford, Mass.). The following procedure was employed for measuring the suspended biological solids. Fresh filter pads were placed in pans made from aluminum foil weighing approximately 1.0-2.0 grams. The pans were placed in a drying oven for one hour at a temperature of 103°C, and then placed in a $CaCO_3$ desiccator for cooling, after which the pans were tared to obtain initial weights. Known volumes of samples were then filtered with the aid of a vacuum pump. Prior to filtration, samples were routinely centrifuged

with a Sorvall Superspeed centrifuge Type SS-1A (Ivan Sorvall, Inc.) at a rate of 10,000 rpm for several minutes. The supernatant from the centrifuge sample was poured off first, and then the pellet of solids which was formed was removed with the aid of a metal spatula and placed on the filter. Filtrate samples were taken at this point for COD determination. The centrifuge tubes were then carefully washed in distilled water to remove any solids particles that might have adhered to the side of the tubes. After complete filtration, the filter pads were returned to the pans in which they had been tared, placed in the drying oven at a temperature of 103^{o}C for one hour, cooled in a desiccator and weighed to determine the biological solids concentration.

2. Chemical Oxygen Demand

The chemical oxygen demand was determined in accordance with "Standard Methods"(33). Mercuric sulfate and silver sulfate were used for all COD determinations.

3. Tests for Stabilization and Oxidation

a. Biochemical Oxygen Demand (BOD). The BOD test provides a quantitative measure of the amount of oxygen (DO) utilized by microorganisms in metabolizing substrates. The azide modification of the Winkler method as outlined in "Standard Methods" (33) was used for this determination.

b. Dissolved Oxygen. Aside from being an integral part of the test for biochemical oxygen demand, the determination of dissolved oxygen is required for detecting and measuring the effect of effluent

discharge on the oxygen resources of a receiving body of water. Dissolved oxygen concentration was monitored electrometrically by the use of a Weston-Stack oxygen analyzer. The probe was standardized periodically against the Winkler Method for dissolved oxygen determination as outlined in "Standard Methods" (33).

4. Microscopic Examination

Wet mount slides of random samples from the continuous flow unit were observed under the microscope to gain some information on the dominant microbial species present, and to note any changes in predominant forms.

5. pH

The pH was determined by use of a Beckman zeromatic pH meter. The meter was standardized periodically at pH 7.0 and pH 4.0.

CHAPTER IV

RESULTS

A pilot plant operation was begun on September 23, 1971, to evaluate the performance of the extended aeration process incorporating chemical hydrolysis for control of solids concentration. The results obtained from this investigation are presented in the following manner. First, information was obtained from batch experiments relative to growth rate kinetics during metabolism of sludge hydrolysate taken from an extended aeration plant growing on glucose as substrate. Also included in this phase are batch experimental data pertinent to the metabolism of an actual industrial waste. Second, the operational performance of the extended aeration process incorporating periodic "chemical assists" while growing on 500 mg/l of glucose as its carbon source is presented. Included in this phase are the effects of various concentrations of several coagulants in the flocculation of biological solids retained in the effluent of the extended aeration pilot plant. The third general topic is the performance of the extended aeration process incorporating "hydrolytic assists" while growing with 1000 mg/l glucose as its carbon source. The fourth phase presents information showing the utilization of the "hydrolytic assist" process as a means of controlling predominance changes brought about in the activated sludge process. The fifth phase outlines the performance of the hydrolytically assisted extended aeration process while growing on concentrated Kraft

waste as its carbon source. The sixth phase of this study shows the effect of various effluents from the extended aeration process on the oxygen sag of a simulated stream.

A. Batch Experiments

1. Studies on the Growth Rate Kinetics and Metabolism of Cellular Hydrolysate Obtained From an Extended Aeration Process Growing on Glucose as the Carbon Source.

To measure the logarithmic growth rate constant, μ, an indirect method for determining biological solids concentration was employed. Percent transmission of cell suspensions were read at 540 nm and converted to optical density units. In this method, assumption is made that optical density is proportional to biological solids concentration. Yu (34) in his studies with mixed cultures metabolizing various carbohydrates found that a linear relationship generally holds true for a given microbial population up to 400-500 mg/l. The logarithmic growth rate constant, μ, was calculated according to the following relationships. Any change in biological solids concentration (or change in optical density), dX/dt, is equal to μ multiplied by X, where μ is the logarithmic growth rate constant and X is the biological solids concentration at time t. Integration of this first order relationship between the limits X_t and X_o yields the following relationship:

$$\mu = \frac{\ln X_t/X_o}{t} \qquad (1)$$

To determine μ, a plot of optical density versus time is made on semi-logarithmic paper. From equation (1) it can be seen that the period of logarithmic growth is the straight line portion of the growth curve when plotted on semi-logarithmic paper. To make calculations

easier, t_d was determined for the straight line portion of the curve; t_d is the time required for the cell mass or optical density to double. Under these conditions, $X_t = 2X_o$, and $\mu = \ln 2t_d$, which yields the following: $\mu = 0.693/t_d$.

Figure 5 shows the effect of initial substrate (hydrolysate) concentration (S_o) on the rate of growth and the total amount of microbial growth as measured by an increase in optical density. The Monod plot (Figure 6) was constructed to determine whether these data fit the hyperbolic relationship of specific growth rate (μ) vs. substrate concentration (S_o). The values for the physiological growth constants, maximum specific growth rate, μ_{max}, and saturation constant, K_s, were determined from the Lineweaver-Burk plot (Figure 7); μ_{max} was found to be 0.680 hr^{-1}, and K_s was 38 mg/l. These values compare favorably with other values obtained with glucose and sewage as substrates.

Figures 8 and 9 show the metabolic response of an acclimated microbial culture growing on a hydrolysate taken from a glucose-fed extended aeration process. The substrate utilization patterns for the two experiments are very similar. COD removal and biological solids accumulation appeared to follow patterns typical of most growth studies. The biochemical efficiency, that is, the percent substrate removal, during the purification phase was 89 and 86 percent, respectively, for the two experiments. The duration of the purification phase was between 8 and 20 hours. Not enough samples were taken during this period to pinpoint the time more precisely. Maximum solids accumulation occurred at the time of maximum removal of exogenous substrate. The percentage of carbon source (COD) that was channelled into cellular synthesis, i.e., the cell yield for two experiments, was 64.7 percent and 57.1 percent.

Figure 5. Growth at Various Initial Substrate Concentrations

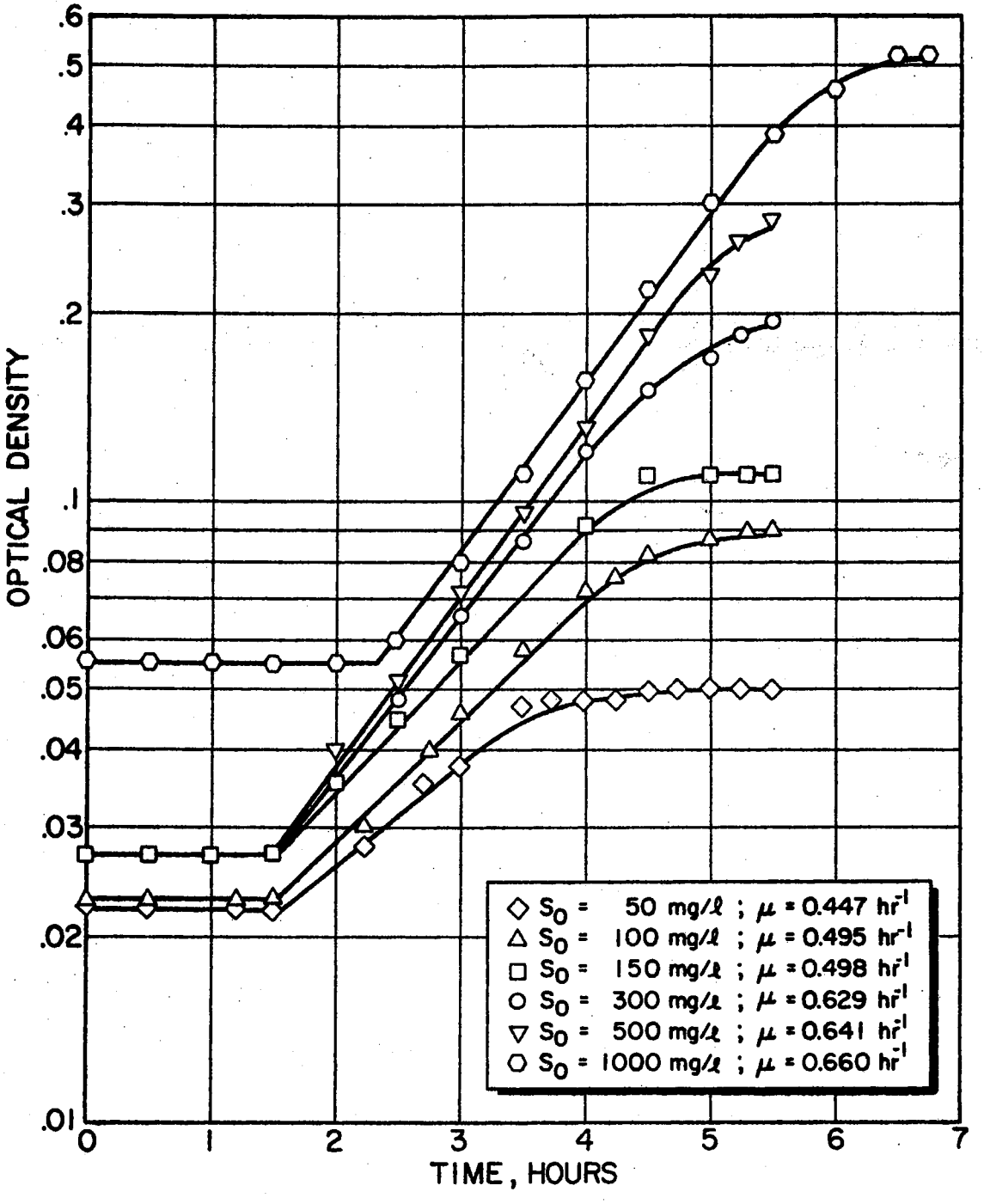

OPTICAL DENSITY
.6
.5
.4
.3
.2
.1
.08
.06
.05
.04
.03
.02
.01
0
1
2
3
4
5
6
7
TIME, HOURS
◇ S0 = 50 mg/ℓ ; μ = 0.447 hr-1
△ S0 = 100 mg/ℓ ; μ = 0.495 hr-1
□ S0 = 150 mg/ℓ ; μ = 0.498 hr-1
○ S0 = 300 mg/ℓ ; μ = 0.629 hr-1
▽ S0 = 500 mg/ℓ ; μ = 0.641 hr-1
⬡ S0 = 1000 mg/ℓ ; μ = 0.660 hr-1

Figure 6. Relationship Between Specific Growth Rate, μ, and Initial Substrate Concentration, S_o

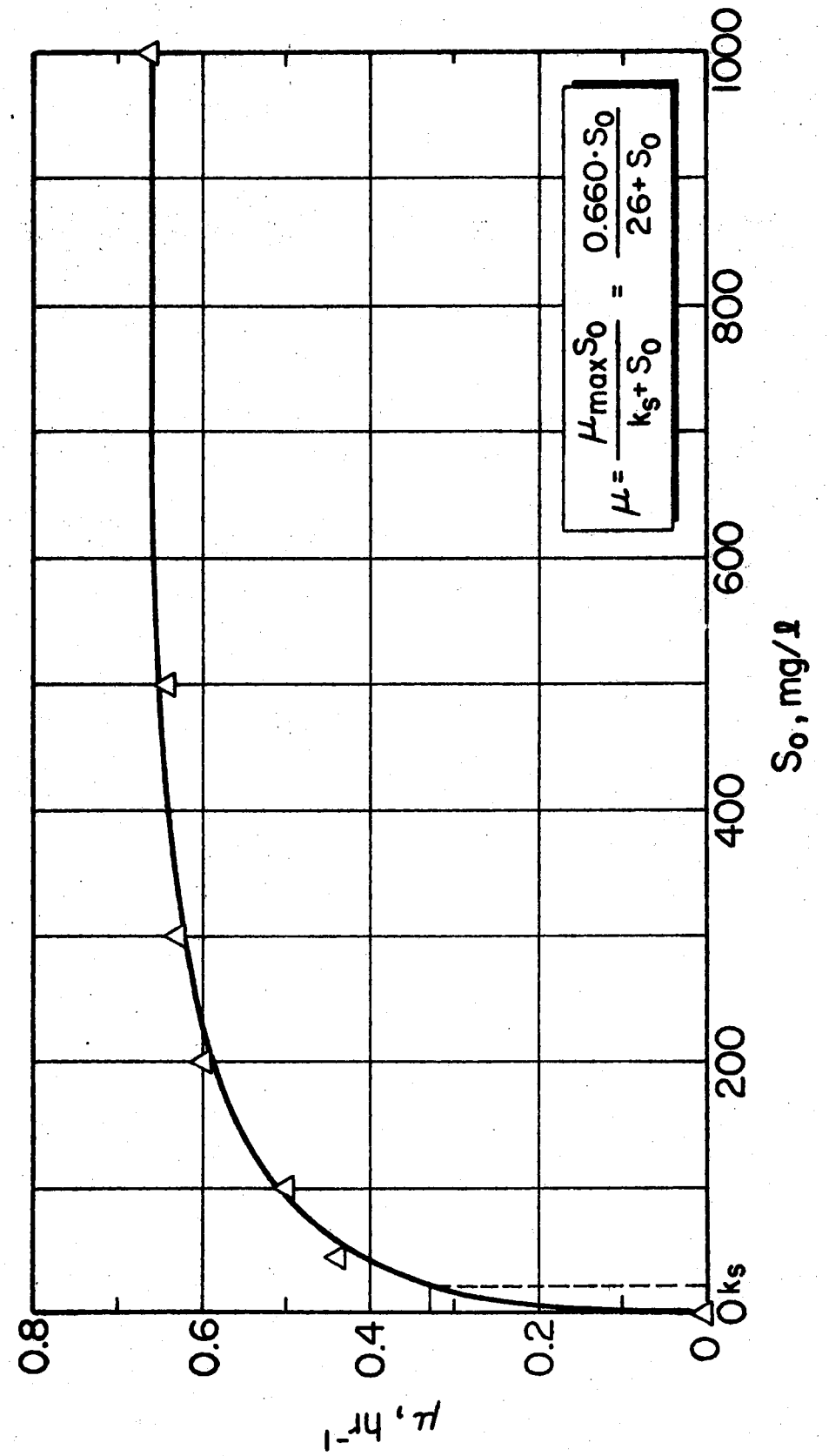

$\mu = \frac{\mu_{max} S_o}{k_s + S_o} = \frac{0.660 \cdot S_o}{26 + S_o}$
0.8
0.6
0.4
0.2
0
Ks
200
400
600
800
1000
S_o, mg/ℓ
μ, hr^{-1}

Figure 7. Reciprocal Plot of μ versus S_o

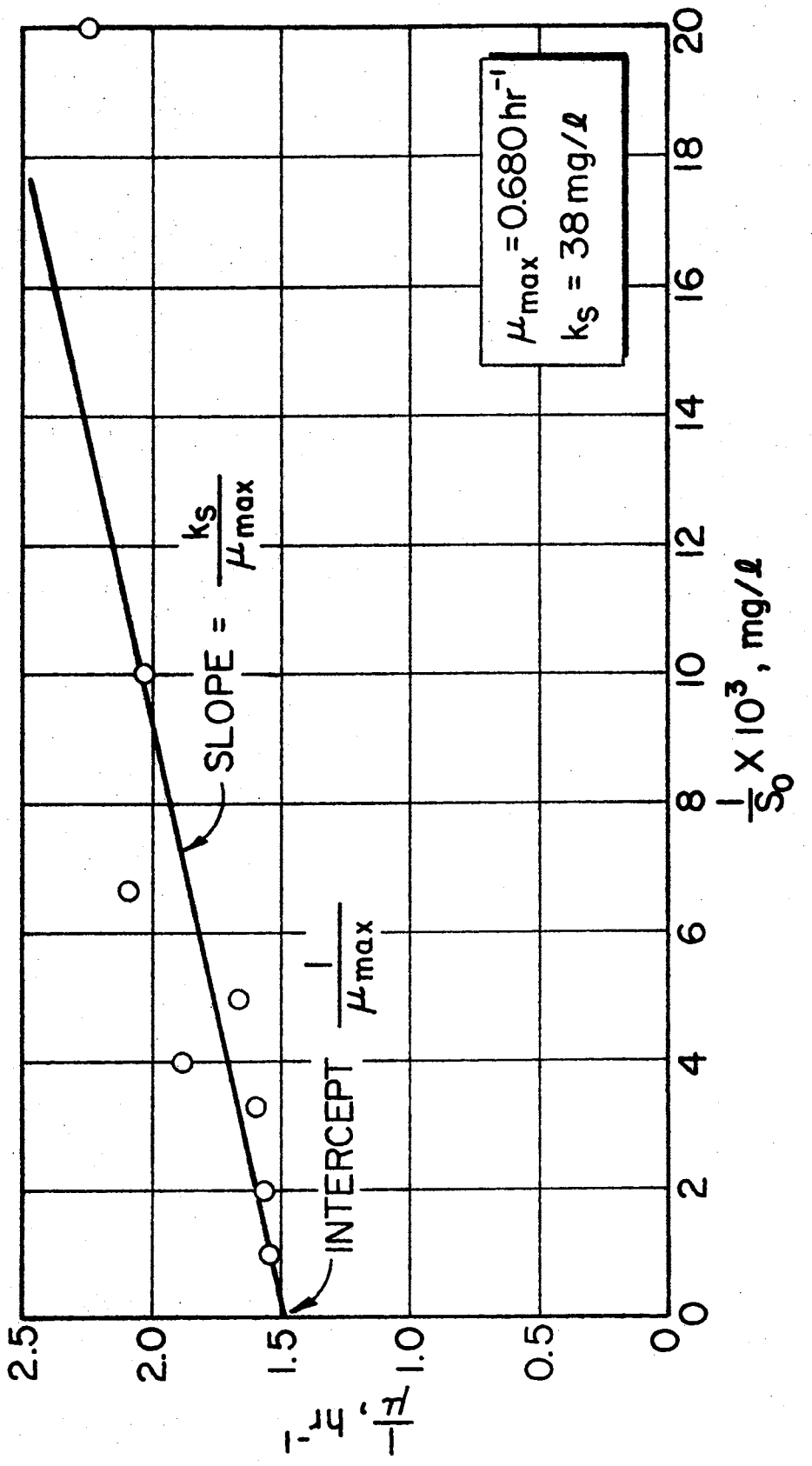

μ_{max}=0.680 hr^{-1}
k_s = 38 mg/ℓ
SLOPE = $\frac{k_s}{\mu_{max}}$
INTERCEPT $\frac{1}{\mu_{max}}$
$\frac{1}{\mu}$, hr^{-1}
$\frac{1}{S_0} \times 10^3$, mg/ℓ
0
0.5
1.0
1.5
2.0
2.5
2
4
6
8
10
12
14
16
18
20

Figure 8. Metabolic Response of an Acclimated Microbial Population Growing on Bacterial Hydrolysate Obtained From a Pilot Plant Operating on Glucose as its Sole Source of Carbon. Seed Taken From Pilot Plant Nov. 19, 1971

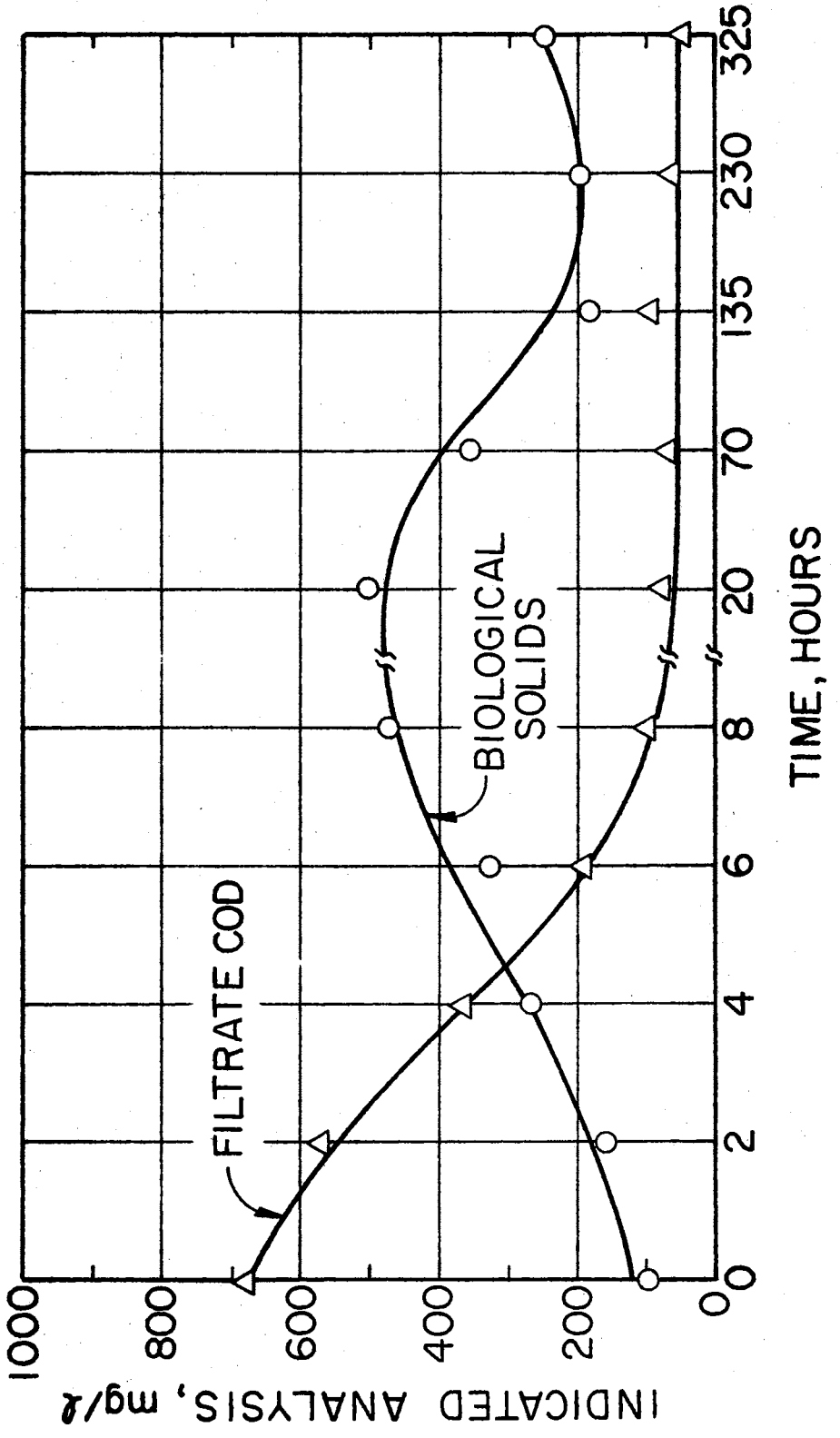
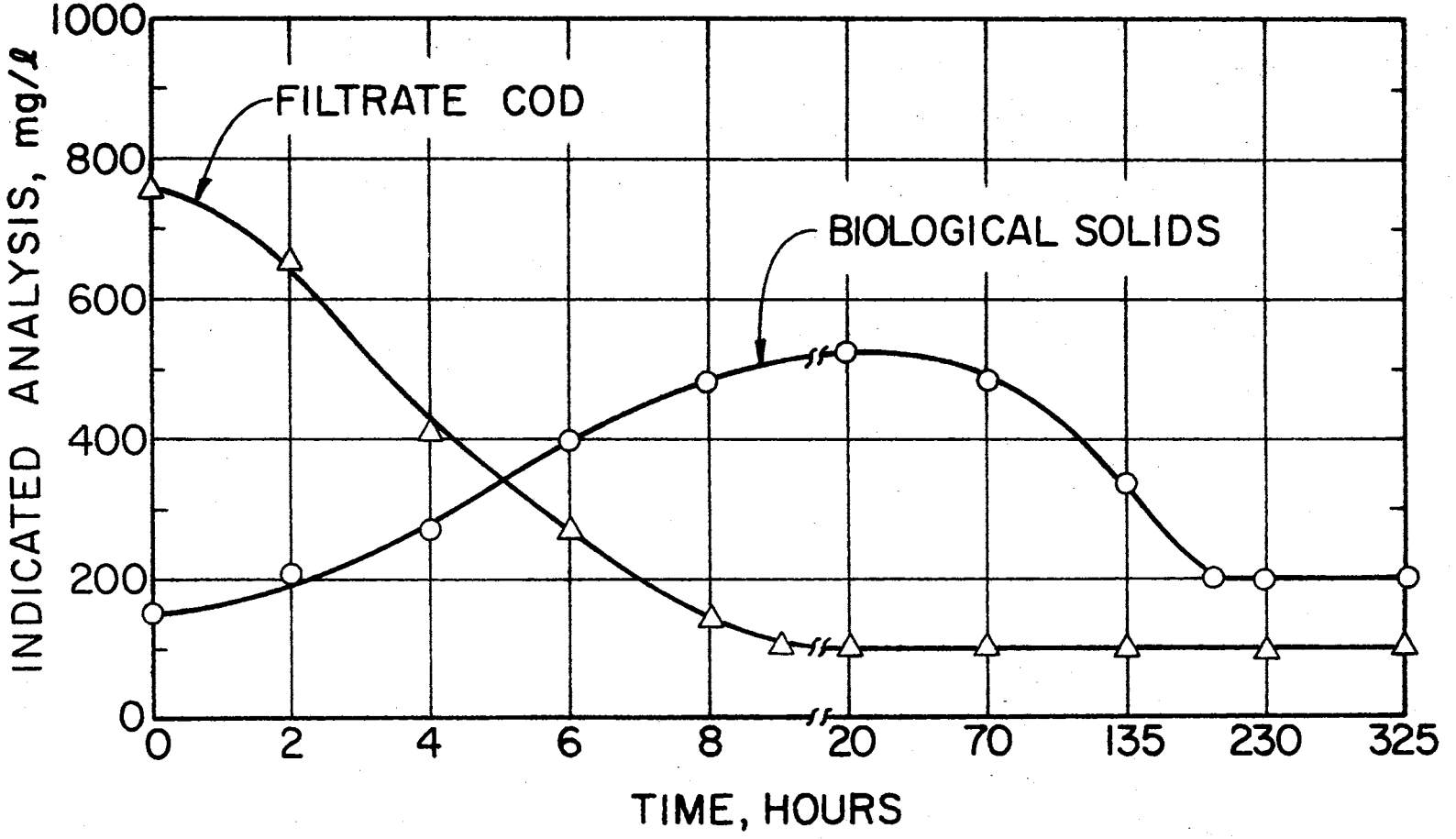

INDICATED ANALYSIS, mg/ℓ
1000
800
600
400
200
0
0
2
4
6
8
20
70
135
230
325
TIME, HOURS
FILTRATE COD
BIOLOGICAL SOLIDS

Figure 9. Metabolic Response of an Acclimated Microbial Population Growing on Bacterial Hydrolysate Obtained From a Pilot Plant Operating on Glucose as its Sole Source of Carbon. Seed Taken From Pilot Plant on Nov. 29, 1971


INDICATED ANALYSIS, mg/ℓ
1000
800
600
400
200
0
FILTRATE COD
BIOLOGICAL SOLIDS
0
2
4
6
8
20
70
135
230
325
TIME, HOURS

Endogenous respiration patterns of the biological solids in both experiments were similar. The rate of endogenous respiration was rather rapid, but total oxidation was not approached in either experiment. It should be pointed out that the two experiments reported herein were run separately but from the same stock hydrolysate. The COD of the stock hydrolysate used was 7616 mg/l. The filtrate COD of the stock hydrolysate was 5902 mg/l. Both experiments were run on filtered hydrolysate.

Figure 10 shows the O_2 uptake pattern for cells utilizing the cell hydrolysate. The Warburg apparatus was used to determine the rate of O_2 uptake. The Warburg apparatus was advantageous for several reasons: (a) temperature could be set and controlled to $\pm$ 0.5°C; (b) oxygen uptake could be measured continually. The oxygen uptake curves show the energy utilized during synthesis and endogenous respiration. Figure 10 shows the results of this experiment plotted on semi-logarithmic paper. It is seen that the slope of the lines increase with substrate concentration, indicating a relationship between exponential O_2 uptake rate and substrate concentration. It can be observed in Figure 10 that at high substrate concentrations (500 mg/l and 1000 mg/l) as well as at some low substrate concentration (100 mg/l) there appeared to be two logarithmic phases. The first log phase, however, appears to be more related to the substrate removal or growth phase. The value from the first log phase was used to construct the plot shown in Figure 11. This figure shows that the relationship between exponential O_2 uptake rate and S_o is of the hyperbolic type similar to the Monod relation between specific growth rate μ and S_o.

Figure 10. Oxygen Uptake at Various Initial Substrate Concentrations

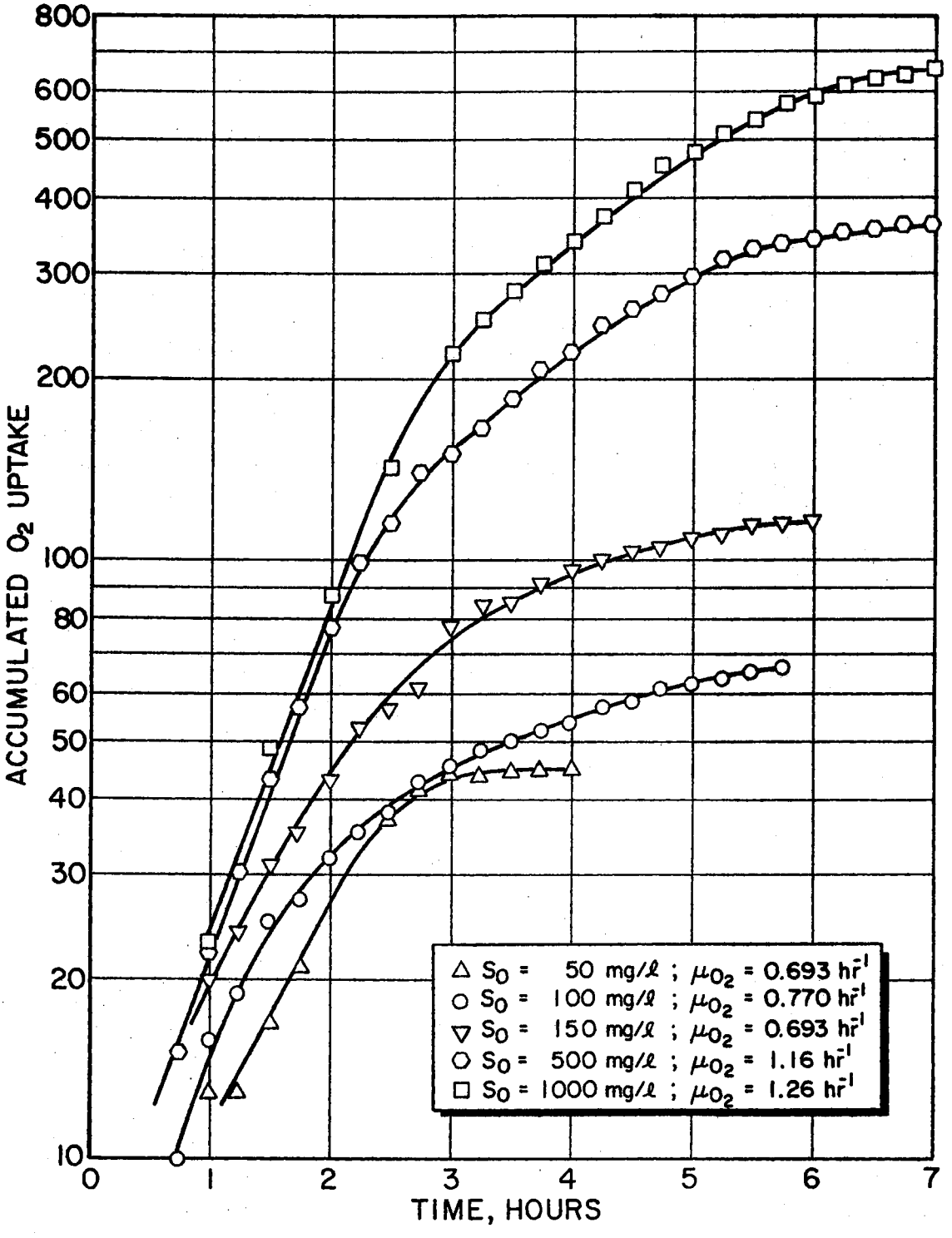
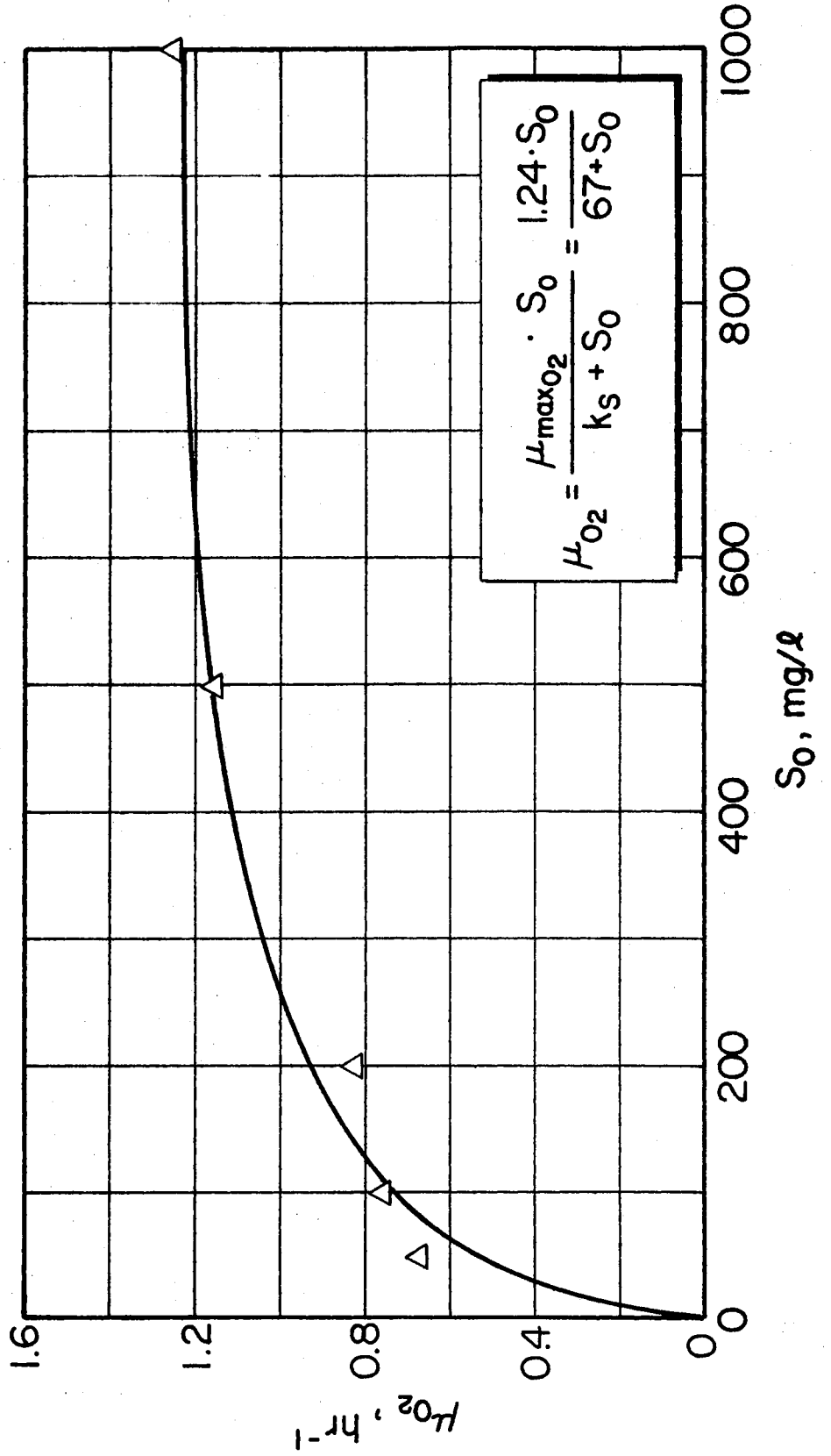

800
600
500
400
300
200
100
80
60
50
40
30
20
10
0
1
2
3
4
5
6
7
ACCUMULATED O_2 UPTAKE
TIME, HOURS
△ S_0 = 50 mg/ℓ ; μ_{O_2} = 0.693 hr^{-1}
○ S_0 = 100 mg/ℓ ; μ_{O_2} = 0.770 hr^{-1}
▽ S_0 = 150 mg/ℓ ; μ_{O_2} = 0.693 hr^{-1}
⬡ S_0 = 500 mg/ℓ ; μ_{O_2} = 1.16 hr^{-1}
□ S_0 = 1000 mg/ℓ ; μ_{O_2} = 1.26 hr^{-1}

Figure 11. Relationship Between Specific O_2 Uptake Rate, μ_{O_2}, and Initial Substrate Concentration, S_o


$\mu_{O_2} = \frac{\mu_{max_{O_2}} \cdot S_o}{k_s + S_o} = \frac{1.24 \cdot S_o}{67 + S_o}$
μ_{O_2}, hr^{-1}
1.6
1.2
0.8
0.4
0
0
200
400
600
800
1000
S_o, mg/ℓ

B. Studies on the Metabolic Characteristics of Kraft Process Pulping Liquor

It should be pointed out here that the substrate used in these experiments was not plant effluent, but a 1/50 dilution of digester blowdown liquor.

Table V shows the results of a 28-day batch study to characterize this industrial waste and to gain insight regarding its metabolic behavior when subjected to aerobic biological treatment. The batch unit consisted of a 5-liter reactor and operated as outlined in the Materials and Methods section. Samples were taken once daily before and after feeding, and analyzed for substrate utilization as measured by the ΔCOD test (35). Solids determinations were also performed to obtain cell yield values. From the data, ΔCOD and yield values were calculated using the following formulas:

$$\Delta COD = COD_i - COD_e \tag{2}$$

$$Y = \frac{\text{weight of organisms formed}}{\text{weight of substrate used}} = \frac{\Delta \text{biological solids}}{\Delta COD} \tag{3}$$

It can be seen from Table V that the average 24-hour ΔCOD was 673 mg/l. This ranged from a low value of 360 mg/l to a high of 983 mg/l. Values of less than 600 mg/l were observed in less than 15 percent of the samples analyzed; that is, in only four days out of the 28 days examined. The average increase in solids was 320 mg/l. Sludge yields ranged from 0.23 to 0.98; 0.98 was reported in one out of the 28 days analyzed. Values in excess of 0.7 were found in only four of the 28 days studied. Periodically, samples of the feed and effluent were also taken for measurement of BOD_5. The average BOD_5 of the feed was 517 mg/l. The average BOD_5 of the effluent was 67 mg/l. This represents

TABLE V

TREATMENT OF KRAFT PULP MILL WASTE IN A BATCH OPERATED ACTIVATED SLUDGE REACTOR

Date	Initial COD	Final COD	Initial Solids	Final Solids	Δ Solids	Δ COD	Yield	BOD_5 Feed	BOD_5 Eff	Δ BOD_5
12/13/72	4000	3600	3500	3750	250	400	2.62			
14	3600	3000	2780	3165	385	600	0.64			
15	3500	3060	2385	2700	315	440	0.72			
16	3360	3000	2025	2380	355	360	0.98			
17	4095	3400	1980	2290	310	695	0.43			
18	4310	3500	1800	2180	350	810	0.43	560	80	480
19	4250	3550	1744	2058	314	700	0.45			
20	4410	3710	1696	1971	325	700	0.46			
21	3800	2900	1670	1875*	205	900	0.23			
22	3800	3000	1930	2195*	265	800	0.33	520	80	440
23	4300	3600	2130	2410*	280	700	0.40			
24	4700	3900	2435	3090*	655	800	0.81			
25	4300	3600	2815	3135*	320	700	0.46			
26	4600	3100	3010	3355*	345	900	0.38			
27	4200	3400	3155	3425*	270	800	0.34			
28	3600	2872	3480	3645*	165	728	0.23			
29	3724	2979	3530	3815*	285	745	0.38			
30	3179	2766	3560	3830	330	413	0.79			
31	2872	2002	3385	3700	315	872	0.46	545	42	563
1/1/73	3192	2554	2280	2575	295	638	0.46			
2	3405	2448	1850	2100	250	957	0.26			
3	3830	2847	1555	1890	334	983	1.34			
4	3405	2660	1360	1720*	360	745	1.48			
5	3192	2447	1300	1610*	310	745	0.42	520	80	440
9	3190	2445	1795	2240*	495	745	0.66			
10	3850	3210	1715	1930*	215	640	0.33			
11	4100	3400	1540	1890*	300	700	0.43			
7/12/73	3120	2501	1145	1500*	355	619	0.58	440	44	396
Average	3782	3073	2270	2585	320	673	0.48	517	65	452

*Mixed liquor not wasted

Figure 12. Metabolic Response of an Acclimated Microbial Population Growing on a Kraft Mill Waste. Experiment of Nov. 9, 1972

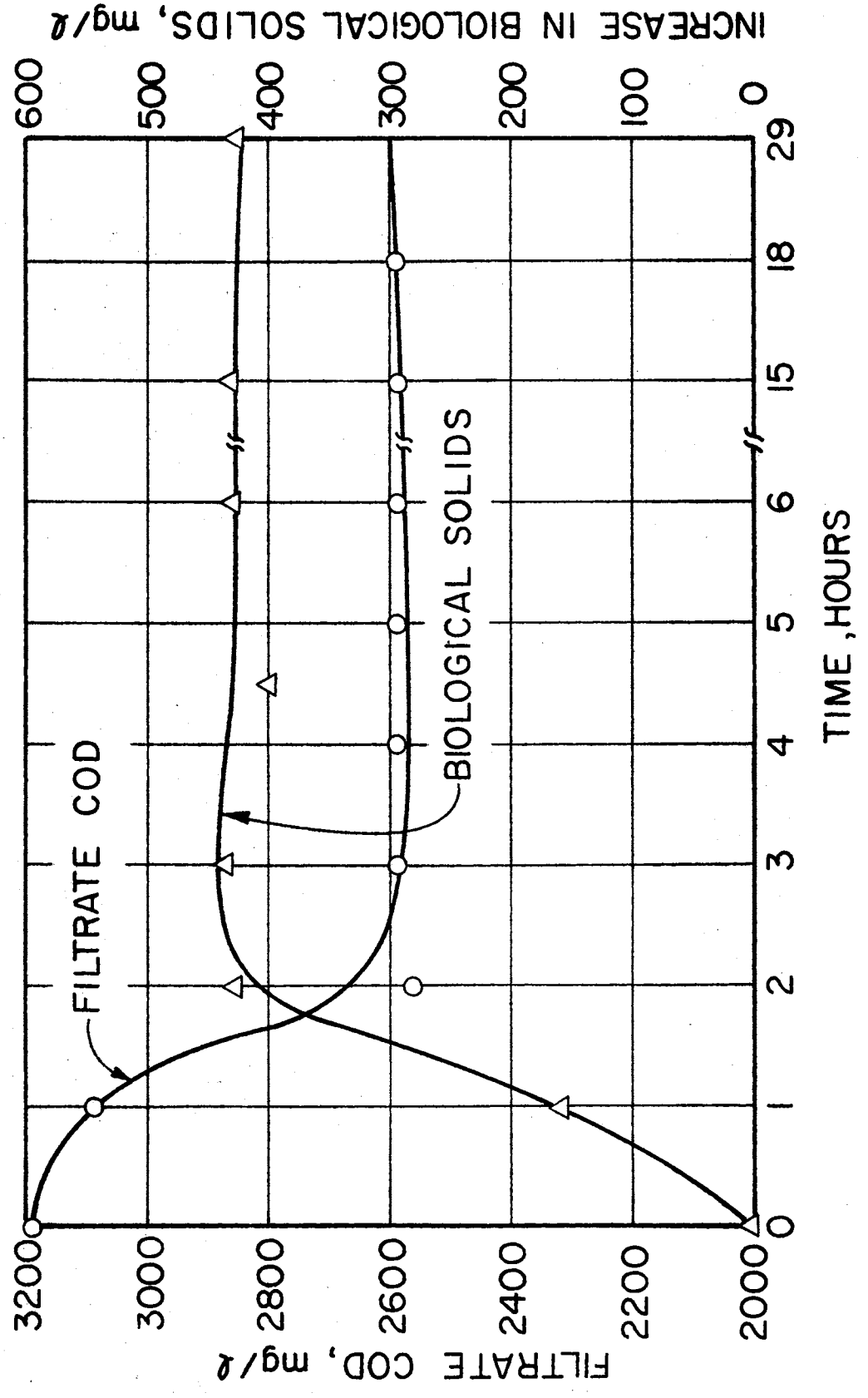

INCREASE IN BIOLOGICAL SOLIDS, mg/ℓ
600
500
400
300
200
100
0
29
18
15
6
5
4
3
2
1
0
TIME, HOURS
FILTRATE COD
BIOLOGICAL SOLIDS
3200
3000
2800
2600
2400
2200
2000
FILTRATE COD, mg/ℓ

Figure 13. Metabolic Response of an Acclimated Microbial Population Growing on a Kraft Mill Waste. Experiment of Dec. 7, 1972

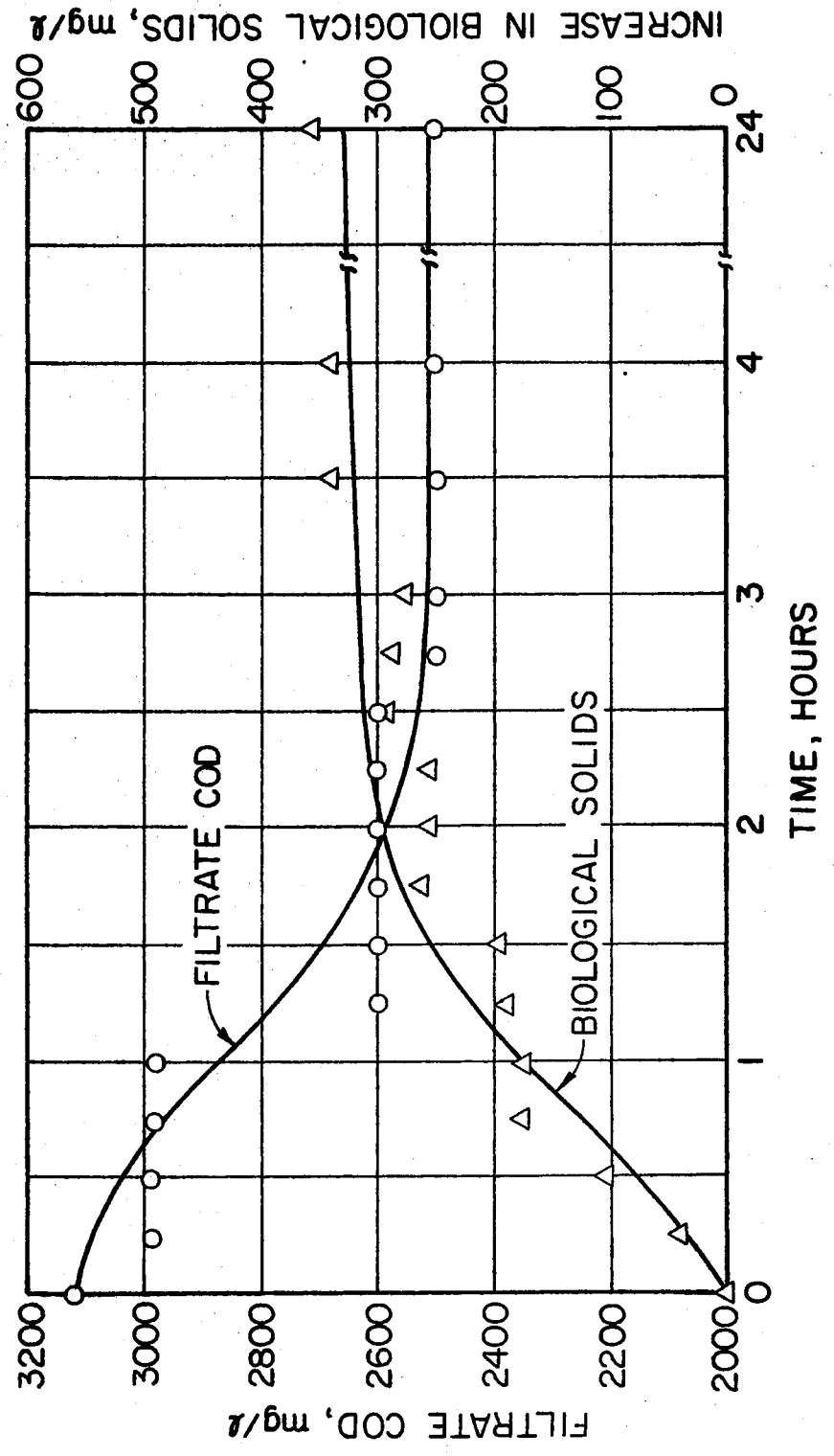

FILTRATE COD, mg/ℓ
INCREASE IN BIOLOGICAL SOLIDS, mg/ℓ
TIME, HOURS
FILTRATE COD
BIOLOGICAL SOLIDS
3200
3000
2800
2600
2400
2200
2000
600
500
400
300
200
100
0
0
1
2
3
4
24

Figure 14. Metabolic Response of an Acclimated Microbial Population Growing on a Kraft Mill Waste. Experiment of Jan. 6, 1973

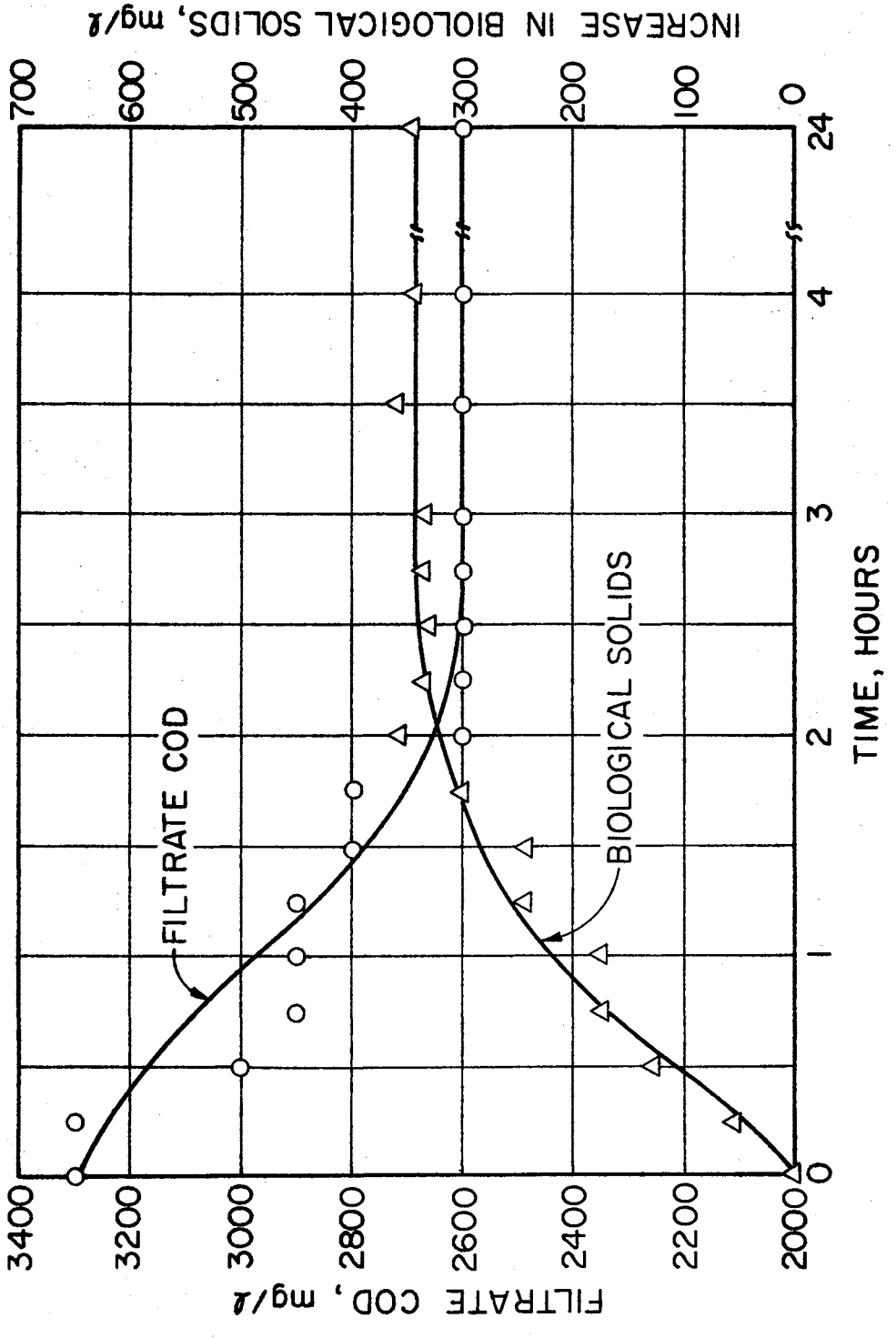
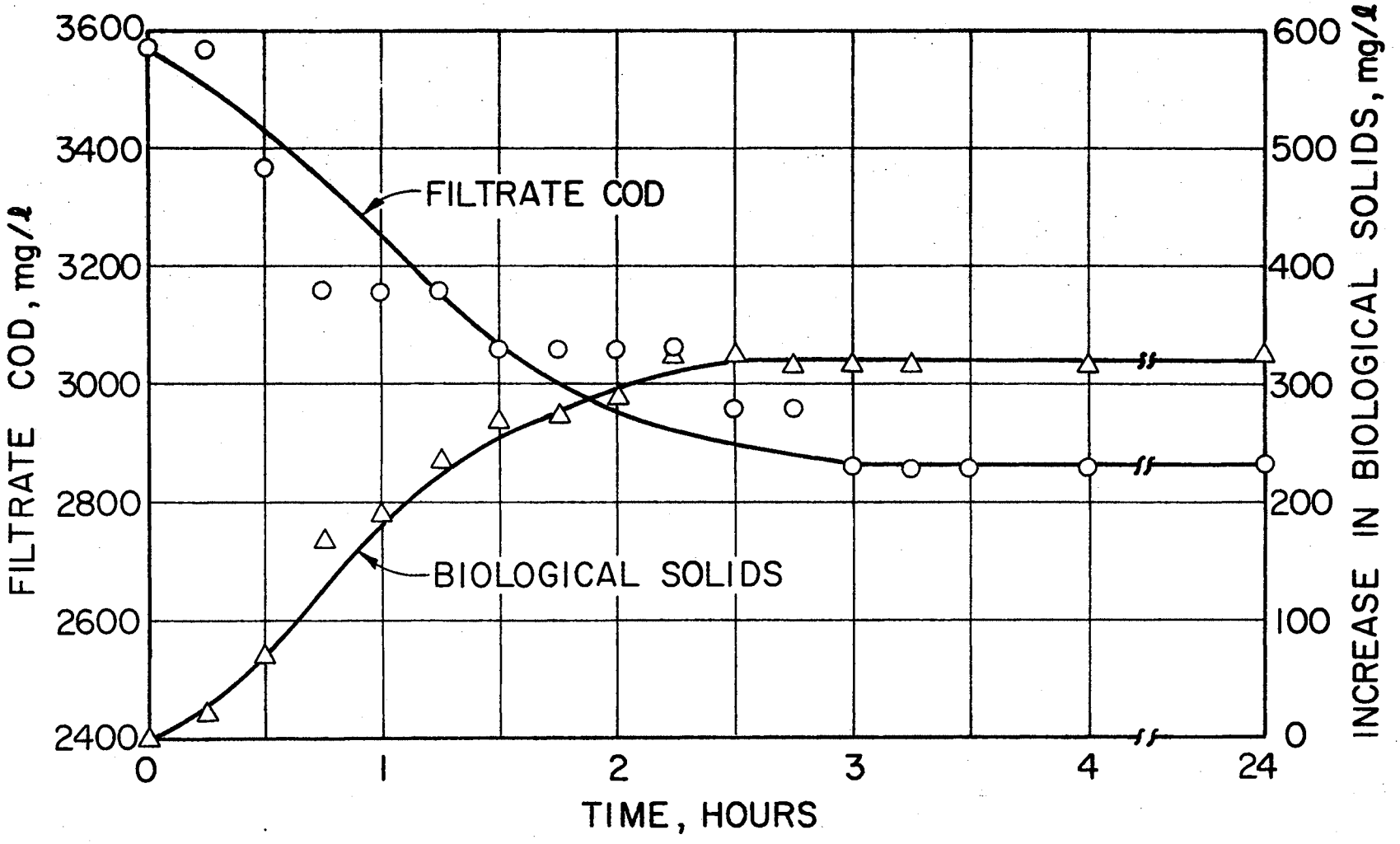

FILTRATE COD, mg/ℓ
3400
3200
3000
2800
2600
2400
2200
2000
INCREASE IN BIOLOGICAL SOLIDS, mg/ℓ
700
600
500
400
300
200
100
0
TIME, HOURS
0
1
2
3
4
24
FILTRATE COD
BIOLOGICAL SOLIDS

Figure 15. Metabolic Response of an Acclimated Microbial Population Growing on a Kraft Mill Waste. Experiment of Jan. 16, 1973


FILTRATE COD
BIOLOGICAL SOLIDS
FILTRATE COD, mg/l
INCREASE IN BIOLOGICAL SOLIDS, mg/l
TIME, HOURS
3600
3400
3200
3000
2800
2600
2400
600
500
400
300
200
100
0
0
1
2
3
4
24

a purification efficiency of 87 percent. Figures 12, 13, 14, and 15 show examples of the daily response of this batch-fed extended aeration plant. Samples were taken every hour for eight hours, and one was taken at the end of 24 hours. The purpose here was to gain insight into the time period required for the utilization of exogenous substrate and the time at which maximum growth was achieved. From these data, yield values were also determined by equation (3). The yield values calculated from the data of Figures 12-15 ranged from 0.46 to 0.72. It can also be noted that substrate utilization was completed and maximum growth achieved within two to four hours. Very little, if any, autodigestion of the solids took place within the 24-hour test period. It should also be pointed out that the substrate utilization and growth patterns for the industrial waste did not follow the smooth kinetic curve commonly observed in experiments of this nature. The waste contained a large non-biodegradable fraction which might have caused the irregularities in growth patterns noted in these experiments, or the "stepped" nature of these data may actually reflect metabolism of different components of the waste.

Figure 16 shows another short-term batch experiment in which the yield value was observed to be 0.5. Figure 17 shows results from the same experiment in which BOD_5 was used as a measure of substrate utilization. It can be noted that a ΔCOD value of 814 mg/l was equivalent to a BOD_5 value of 490 mg/l. It is interesting to note that the BOD_5 removal efficiency was 79.5 percent. It is also interesting to note that the BOD_5:ΔCOD ratio for this experiment was 0.602; it is generally accepted in the pollution control field that the BOD_5 represents about 0.6-0.7 of the ultimate BOD.

A short-term batch experiment was also conducted to study the

Figure 16. Metabolic Response of an Acclimated Microbial Population Growing on a Kraft Mill Waste. Experiment of Jan. 9, 1973

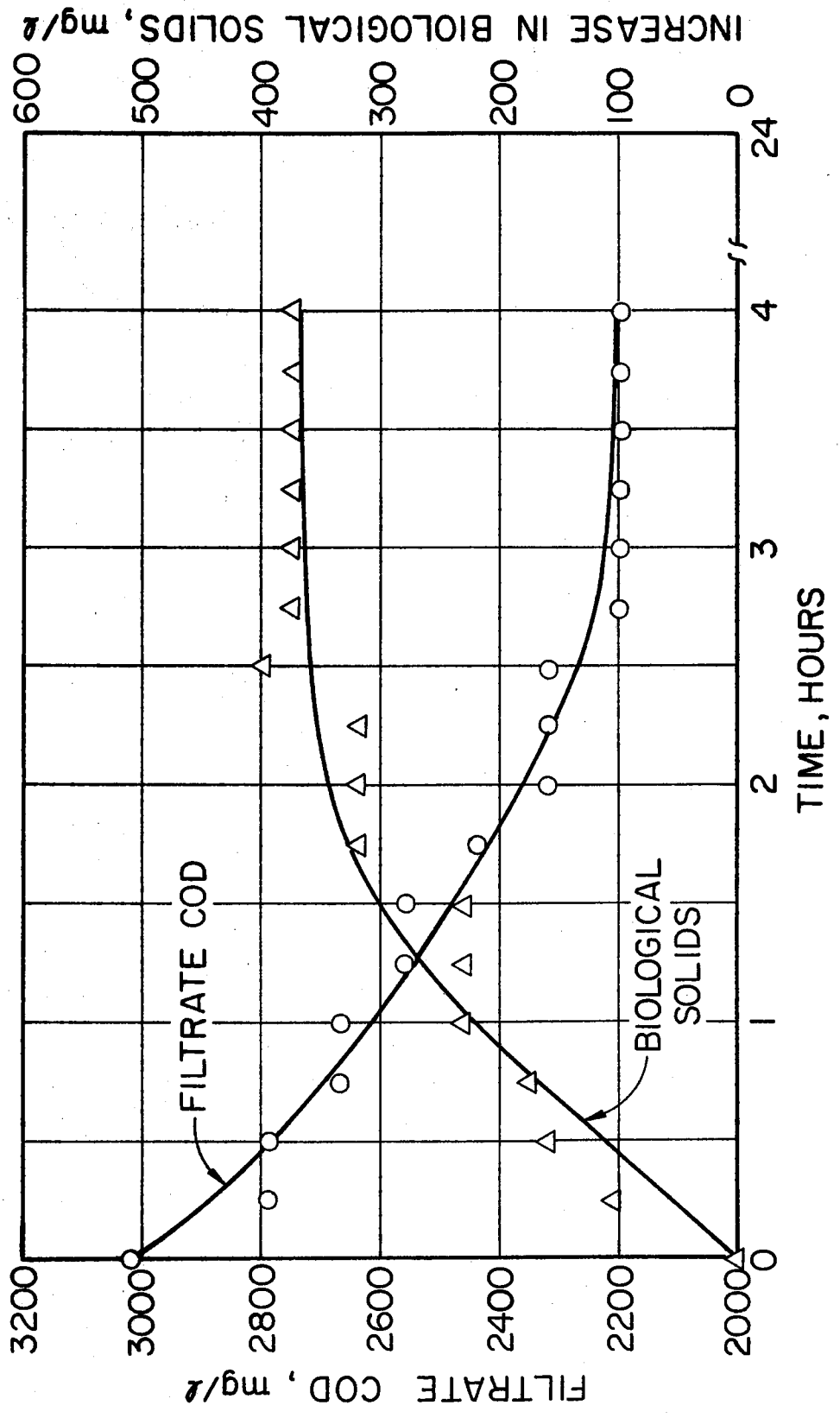
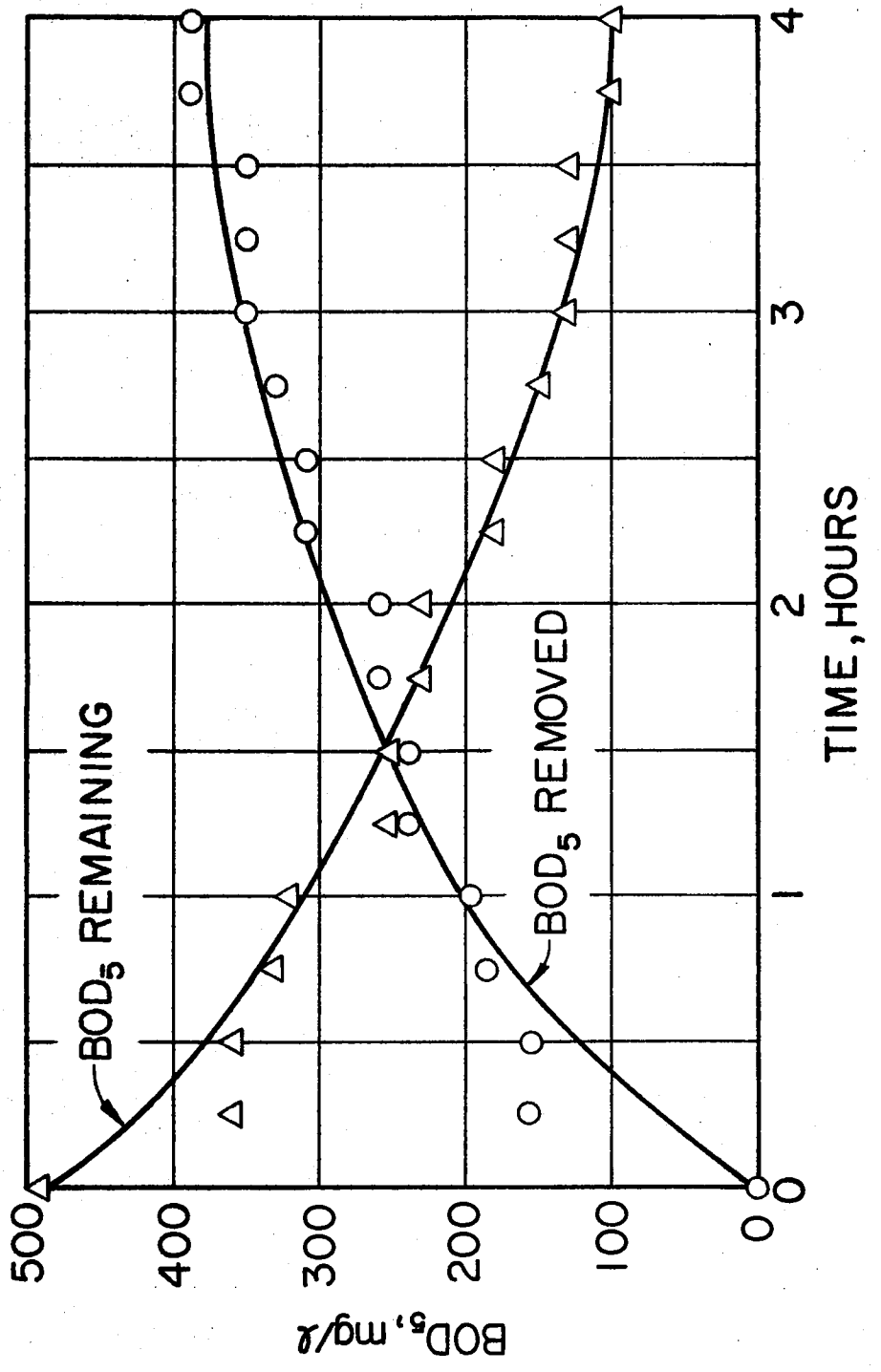

FILTRATE COD, mg/ℓ
INCREASE IN BIOLOGICAL SOLIDS, mg/ℓ
TIME, HOURS
FILTRATE COD
BIOLOGICAL SOLIDS
3200
3000
2800
2600
2400
2200
2000
600
500
400
300
200
100
0
0
1
2
3
4
24
hr

Figure 17. Metabolic Response of an Acclimated Microbial Population Growing on a Kraft Mill Waste. Experiment of Jan. 9, 1973


BOD5, mg/ℓ
500
400
300
200
100
0
0
1
2
3
4
TIME, HOURS
BOD5 REMAINING
BOD5 REMOVED

metabolic characteristics of a hydrolyzed biological sludge taken from an extended aeration process growing on the Kraft waste, the purpose being to evaluate the availability of the hydrolyzed sludge as a carbon source for other aerobic microorganisms. Neutralized hydrolysate was fed to a growing system developed from a mixed seed consisting of cells from the extended aeration pilot plant and a small sewage inoculum. Figure 18 shows the results of this experiment. The initial unfiltered COD of the hydrolyzed solids was 720 mg/l; the COD of the filtrate was 340 mg/l. It can be seen that all of the filtered COD fed to the unit was removed after 24 hours. BOD_5 of the filtered hydrolysate was 200 mg/l; 93 percent of this BOD_5 was removed within eight hours.

Figure 19 shows a similar experiment in which the unfiltered COD was 900 mg/l, the filtered COD was 440 mg/l. The filtrate BOD_5 was 240 mg/l. In this experiment, the sludge was washed prior to hydrolysis. Again, values of nearly 100 percent removal of soluble COD and BOD are shown, indicating that the soluble portion of the hydrolyzed cells taken from a system growing in a Kraft industrial waste can be used as substrate for other heterogeneous populations.

C. Operational Performance of the Extended Aeration Process Incorporating the "Hydrolytic Assist;" S_i = 500 mg/l Glucose

The extended aeration activated sludge pilot plant was put into operation on September 23, 1971. For the first 46 days, the plant was batch-fed 1000 mg/l glucose each day. On day 47, the feed was reduced to 500 mg/l glucose. On day 64, the plant was changed from batch

Figure 18. Metabolic Response to Cell Hydrolysate Obtained From Pilot Plant Operating on Kraft Mill Waste as Carbon Source. Experiment of Feb. 9, 1973

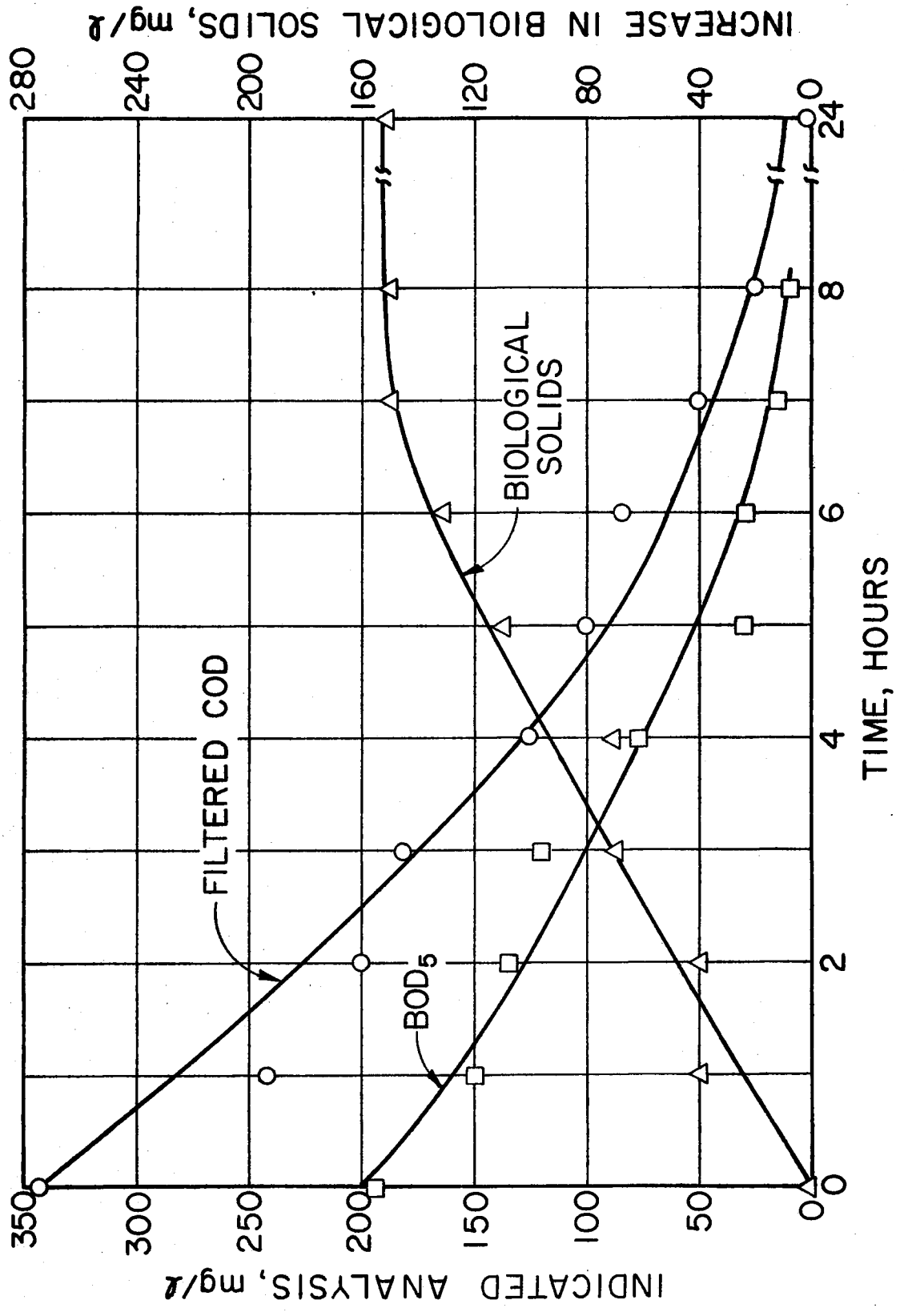
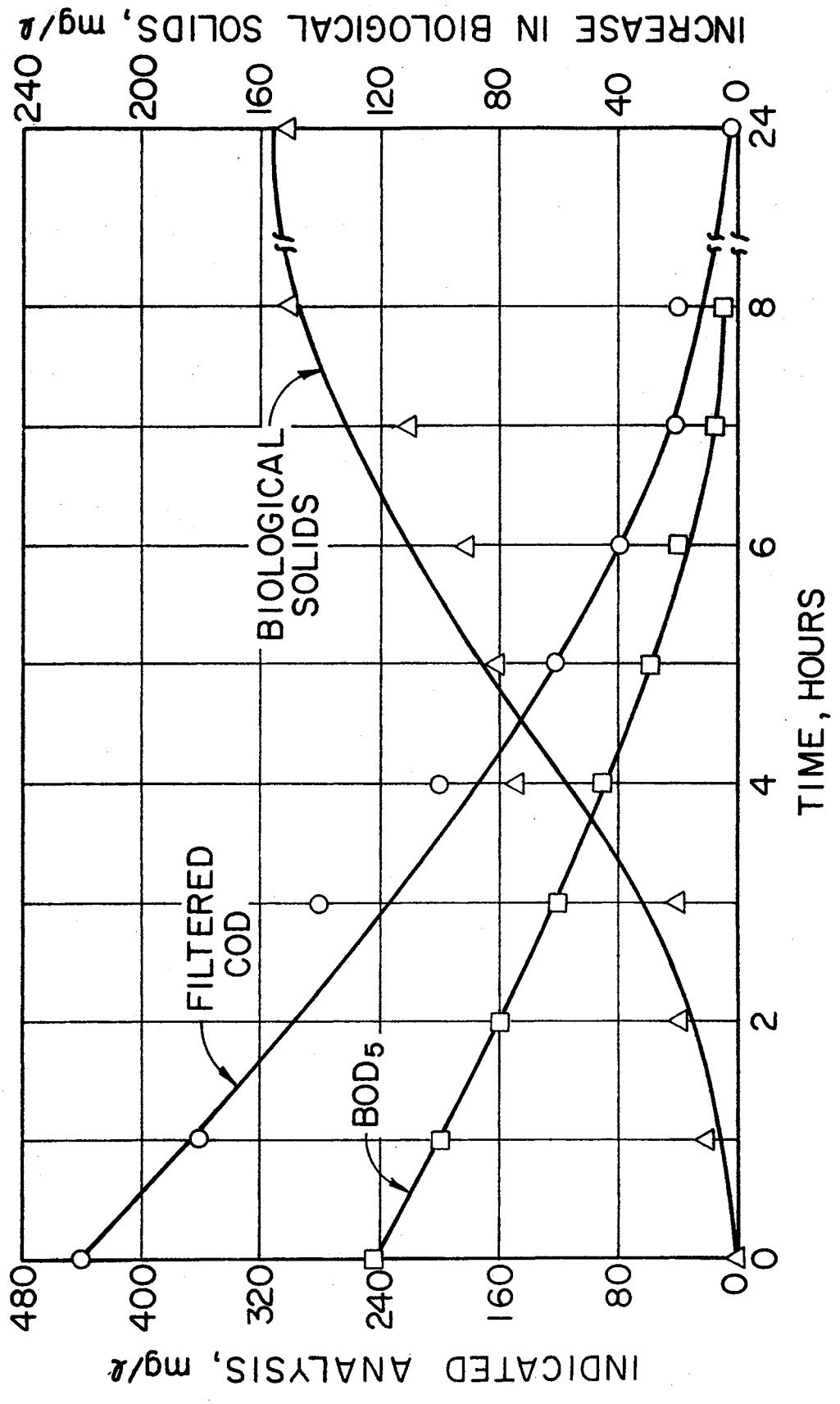

INDICATED ANALYSIS, mg/ℓ
INCREASE IN BIOLOGICAL SOLIDS, mg/ℓ
TIME, HOURS
FILTERED COD
BIOLOGICAL SOLIDS
BOD5
0
50
100
150
200
250
300
350
0
40
80
120
160
200
240
280
0
2
4
6
8
24

Figure 19. Metabolic Response to Cell Hydrolysate of Washed Sludge Obtained From a Pilot Plant Operating on Kraft Mill Waste. Experiment of Feb. 16, 1973


INCREASE IN BIOLOGICAL SOLIDS, mg/ℓ
240
200
160
120
80
40
0
INDICATED ANALYSIS, mg/ℓ
480
400
320
240
160
80
0
BIOLOGICAL SOLIDS
FILTERED COD
BOD_5
0
2
4
6
8
24
TIME, HOURS

feeding to continuous flow. The plant was operated as a continuous-flow unit without using the "hydrolytic assist" from day 64 until day 130. During this period, sludge was withdrawn from the unit and hydrolyzed for separate batch studies to determine the sludge characteristics. Figure 20 shows the performance of the extended aeration plant during the first 130 days. It can be seen in Figure 20 that the biological solids concentration in the system after 130 days of operation was slightly below 6000 mg/l. The biochemical purification efficiency based on filtrate COD was in general about 90 percent. Toward the end of this period (see days 124-130), there were some settling problems with the sludge. Figure 21 shows 10 weeks of performance data of the extended aeration pilot plant incorporating periodic sludge withdrawal, hydrolysis, and refeeding the hydrolysate to the aeration tank. The neutralized hydrolyzed sludge was fed back along with 500 mg/l of glucose over a period of six days. Throughout this phase, the effluent from the pilot plant was characterized by determinations of filtrate COD, unfiltered COD, and biological solids. During the first three weeks of sludge withdrawal and refeeding, the settling problems which had started on about day 124, persisted.

The biological solids decreased rather steadily during the first three weeks of operation. This was due in most part to loss of solids in the effluent. During the last six withdrawal periods, the biological solids in the reactor remained around 3000 mg/l. The purification efficiency based on filtrate COD remained between 90 and 95 percent throughout the test period. The average purification efficiency between days 154 and 184 was 95.5 percent. Day 154 was chosen because it represents the day on which the settling had become more normal, and

Figure 20. Performance of an Extended Aeration Pilot Plant Operating Without the "Hydrolytic Assist." Days 0-130, Sept. 23, 1971, to Jan. 30, 1972

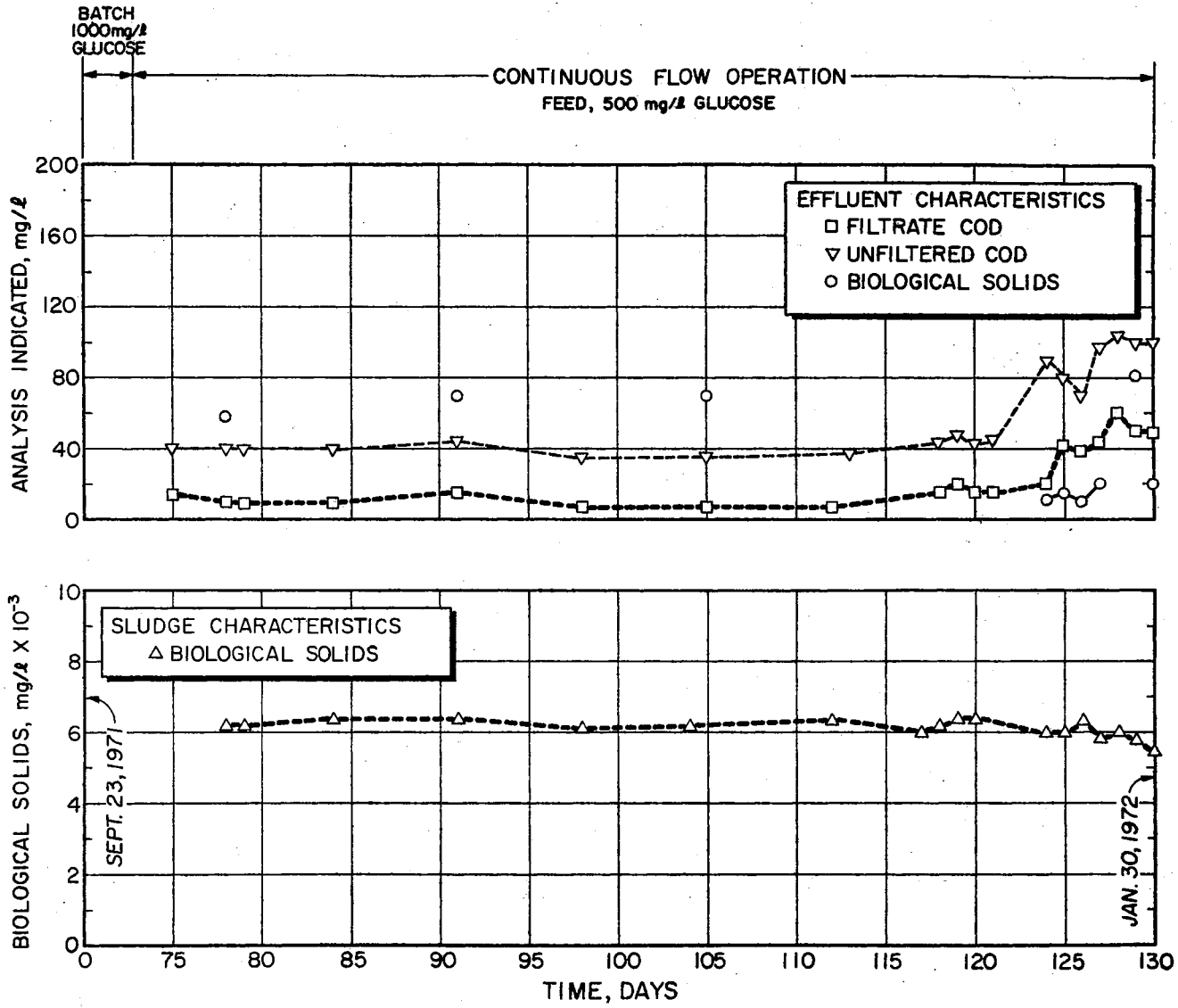
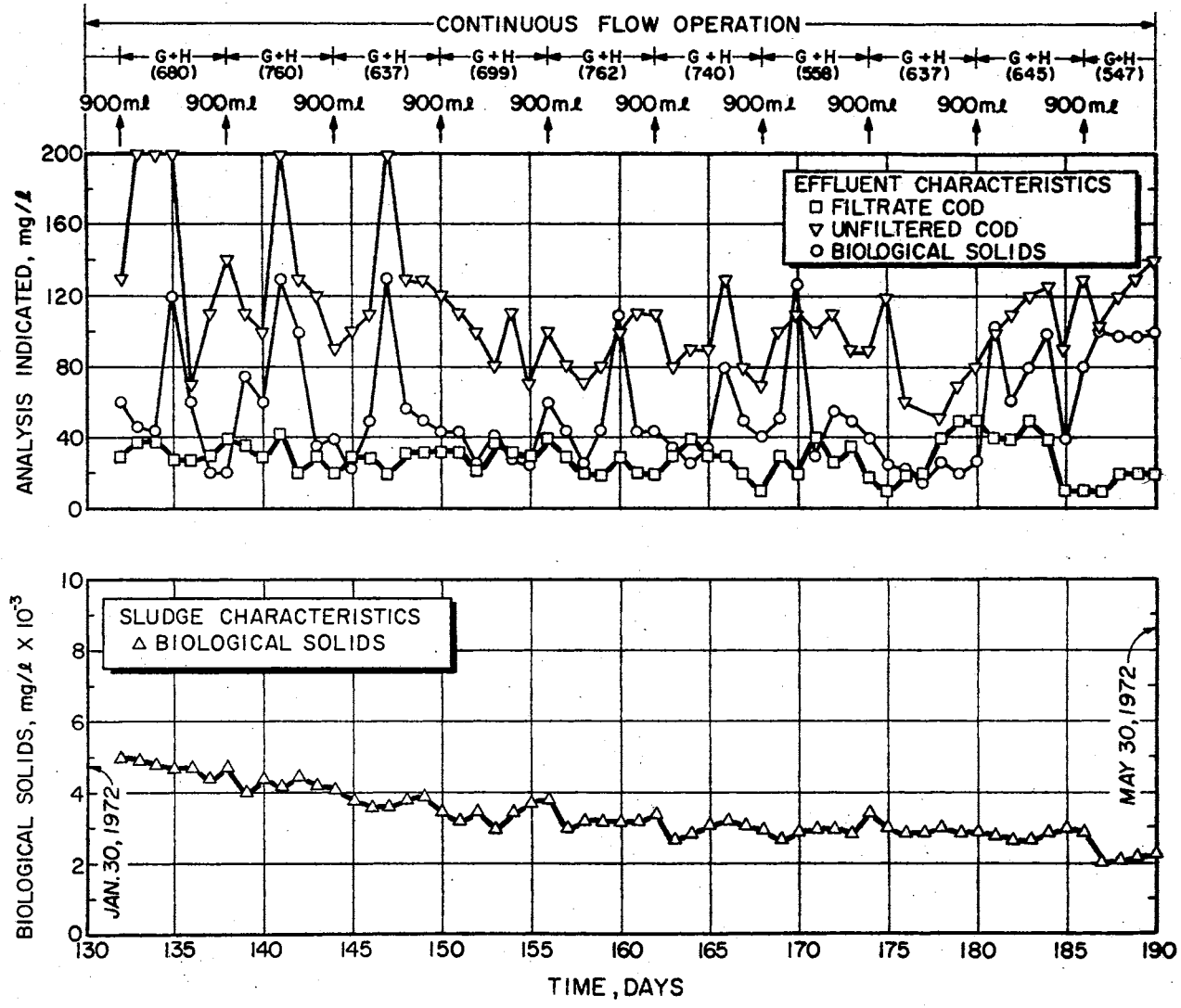

BATCH
1000mg/ℓ
GLUCOSE
CONTINUOUS FLOW OPERATION
FEED, 500 mg/ℓ GLUCOSE
ANALYSIS INDICATED, mg/ℓ
200
160
120
80
40
0
EFFLUENT CHARACTERISTICS
□ FILTRATE COD
▽ UNFILTERED COD
○ BIOLOGICAL SOLIDS
BIOLOGICAL SOLIDS, mg/ℓ X 10⁻³
10
8
6
4
2
0
SLUDGE CHARACTERISTICS
△ BIOLOGICAL SOLIDS
SEPT. 23, 1971
JAN. 30, 1972
0
75
80
85
90
95
100
105
110
115
120
125
130
TIME, DAYS

Figure 21. Ten-week Performance Data of the Extended Aeration Pilot Plant, Incorporating the "Hydrolytic Assist," While Growing on 500 mg/l of Glucose. Days 130-190, Jan. 30, 1972, to May 30, 1972


CONTINUOUS FLOW OPERATION
G+H (680)
G+H (760)
G+H (637)
G+H (699)
G+H (762)
G+H (740)
G+H (558)
G+H (637)
G+H (645)
G+H (547)
900mℓ
ANALYSIS INDICATED, mg/ℓ
EFFLUENT CHARACTERISTICS
□ FILTRATE COD
▽ UNFILTERED COD
○ BIOLOGICAL SOLIDS
SLUDGE CHARACTERISTICS
△ BIOLOGICAL SOLIDS
BIOLOGICAL SOLIDS, mg/ℓ X 10⁻³
JAN. 30, 1972
MAY 30, 1972
TIME, DAYS

day 184 represents the conclusion of a 30-day test period. The average concentration of biological solids in the reactor during this same period was 3064 mg/l. The average filtrate COD was 29 mg/l, and the average biological solids in the effluent was 48 mg/l.

Figures 22-31 are a more detailed presentation of the weekly performance of the pilot plant while undergoing weekly hydrolysis and refeeding. Figure 22 shows the first week's performance. The mixed liquor suspended solids was 5000 mg/l at the beginning of the first week, and at the conclusion of the refeeding period or sixth day, the mixed liquor solids was 4600 mg/l. Biological solids in the effluent averaged less than 50 mg/l; purification efficiency based on filtrate COD was in excess of 90 percent. The COD of the raw hydrolysate was 8771 mg/l; COD of the filtered hydrolysate was 6194 mg/l. The COD of the glucose feed plus hydrolysate was 680 mg/l.

Figure 23 shows the second week's performance. At the time of withdrawing sludge for hydrolysis (day 138, i.e., day zero in Figure 23) the mixed liquor suspended solids was 4600 mg/l; at the end of the refeeding period, the mixed liquor suspended solids was 4100 mg/l. Biological solids in the effluent averaged about 75 mg/l; purification efficiency based on filtrate COD was in excess of 90 percent. The COD of the hydrolysate was 8700 mg/l; COD of the filtrate was 6200 mg/l. The COD of the glucose feed plus hydrolysate was 760 mg/l.

Figure 24 shows the third week's performance. At the beginning of the hydrolysate withdrawal period, the mixed liquor suspended solids was 4100 mg/l. At the end of the refeeding period, the mixed liquor suspended solids was 3500 mg/l. Biological solids in the effluent averaged about 50 mg/l. Purification efficiency based on filtrate COD

Figure 22. First Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 132-139. Glucose Feed, 500 mg/l

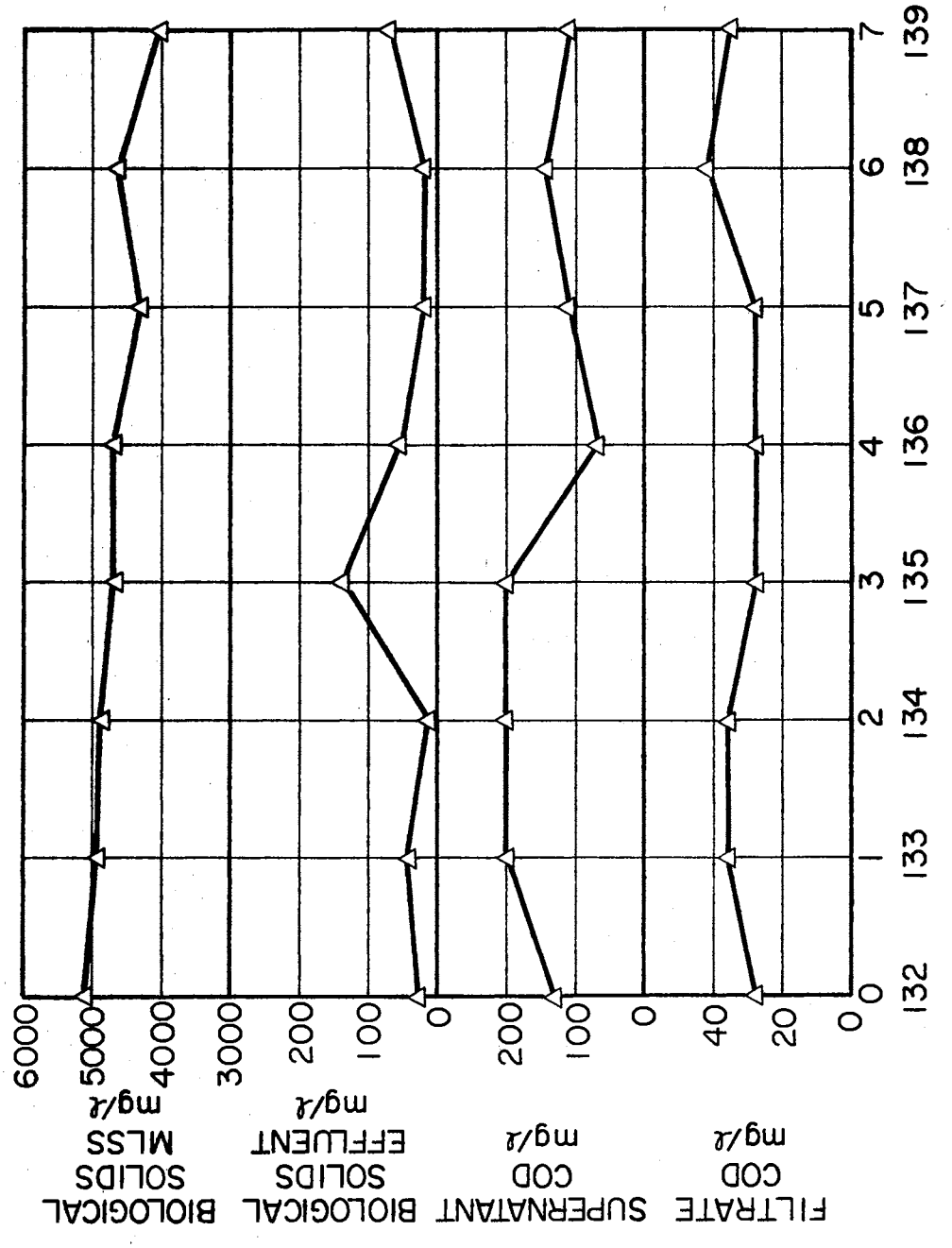

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
0
20
40
0
100
200
0
100
200
0
100
200
0
1000
2000
3000
4000
5000
6000
132
133
134
135
136
137
138
139
0
1
2
3
4
5
6
7
TIME, DAYS

Figure 23. Second Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 138-145. Glucose Feed, 500 mg/l

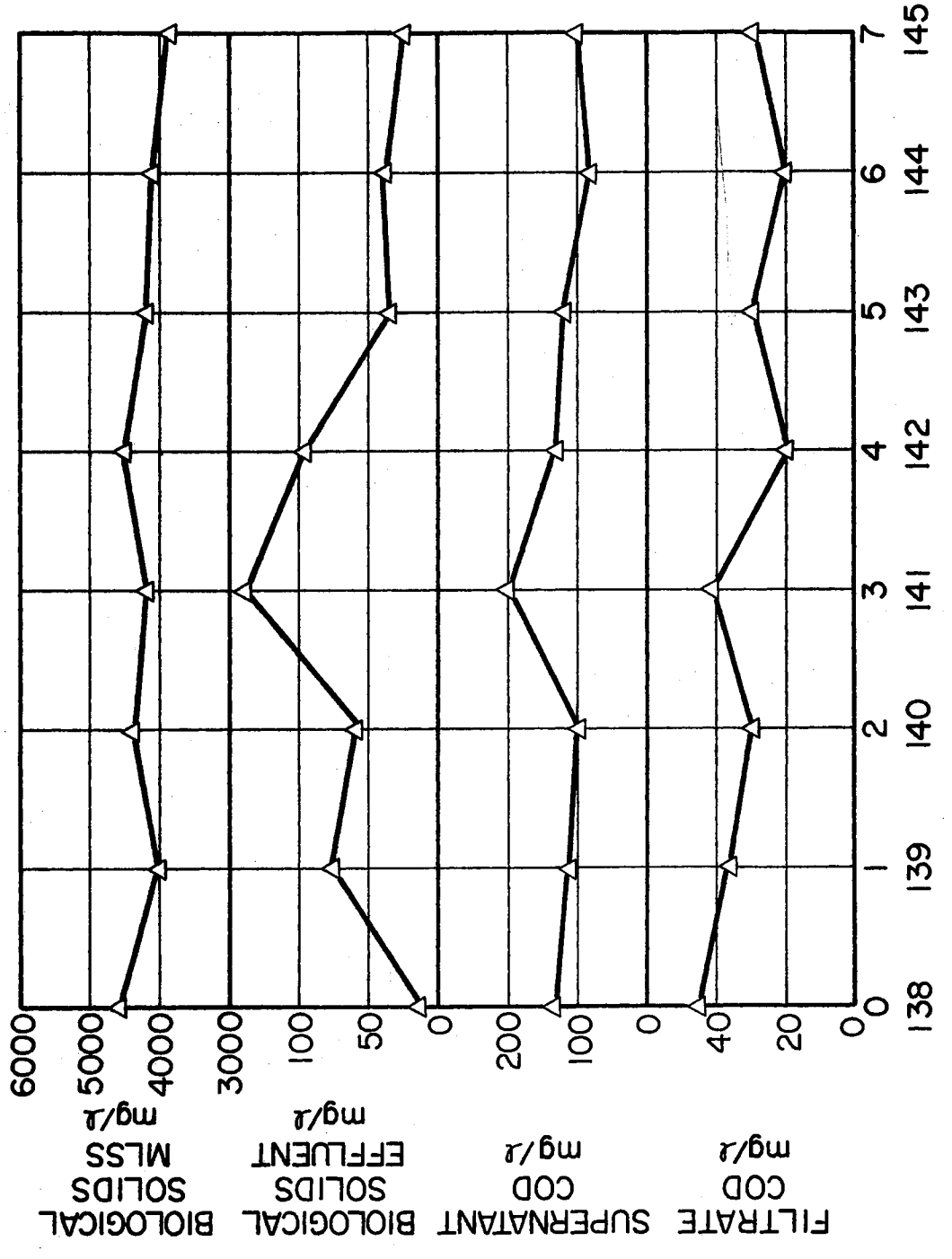
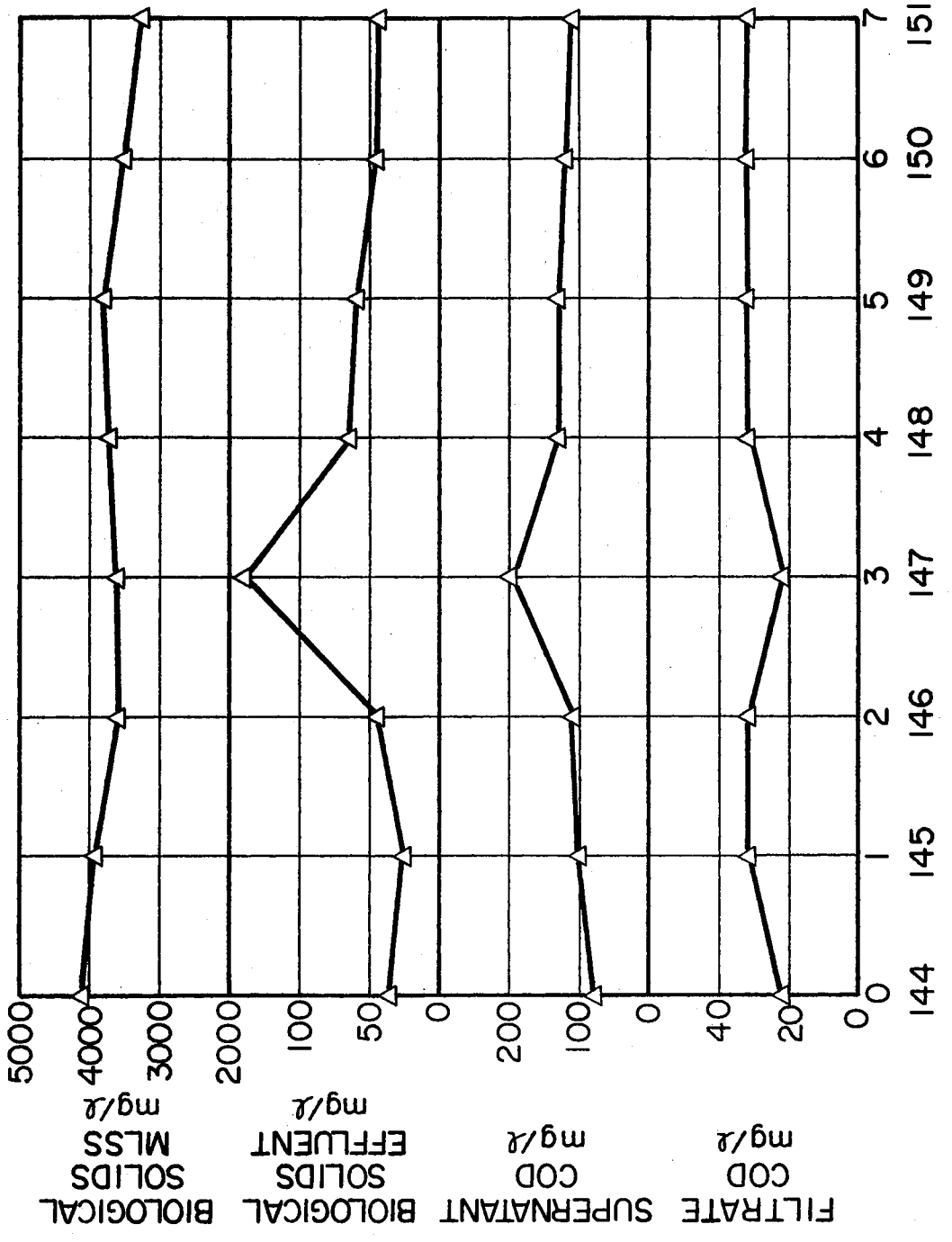

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
0
20
40
0
100
200
0
50
100
3000
4000
5000
6000
138
139
1
2
140
141
3
4
142
143
5
6
144
145
7
TIME, DAYS

Figure 24. Third Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 144-151. Glucose Feed, 500 mg/l


FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
0
20
40
0
100
200
0
50
100
2000
3000
4000
5000
144
145
146
147
148
149
150
151
0
1
2
3
4
5
6
7
TIME, DAYS

averaged above 90 percent. COD of the unfiltered hydrolysate was 8738 mg/l. COD of the filtrate hydrolysate was 6400 mg/l. The COD of the feed glucose plus hydrolysate was 637 mg/l.

Figure 25 shows the fourth week's performance. At the beginning of the hydrolysate withdrawal period, the mixed liquor suspended solids was 3600 mg/l; at the end of the refeeding cycle, the mixed liquor suspended solids was 3800 mg/l. Biological solids in the effluent averaged less than 50 mg/l; purification efficiency based on filtrate COD was 95 percent. COD of the unfiltered hydrolysate was 7500 mg/l; the filtrate COD was 6400 mg/l. The COD of the feed glucose plus hydrolysate was 699 mg/l.

Figures 26 and 27, the fifth and sixth weeks' performance data, showed similar trends. The mixed liquor suspended solids was about 3000 mg/l at the beginning of both weeks, and 3100 mg/l at the end of the week. Biological solids in the effluent averaged about 50 mg/l for both weeks. Purification efficiency based on filtrate COD averaged in excess of 90 percent for both weeks. The COD of the hydrolysate was 7500 mg/l, and the unfiltered COD was 6000 mg/l for both weeks. The COD of the feed glucose plus hydrolysate averaged 750 mg/l for both weeks.

Figures 28-30 (weeks seven, eight, and nine) also displayed similar patterns. The biological solids concentration in the mixed liquor at the beginning of the seventh week was 3000 mg/l; at the end of the refeeding period, the mixed liquor suspended solids concentration was 3500 mg/l. At the beginning of the eighth week, the mixed liquor suspended solids concentration was 3500 mg/l; at the end of the refeeding cycle, the mixed liquor suspended solids concentration was 2900 mg/l.

Figure 25. Fourth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 150-157. Glucose Feed, 500 mg/l

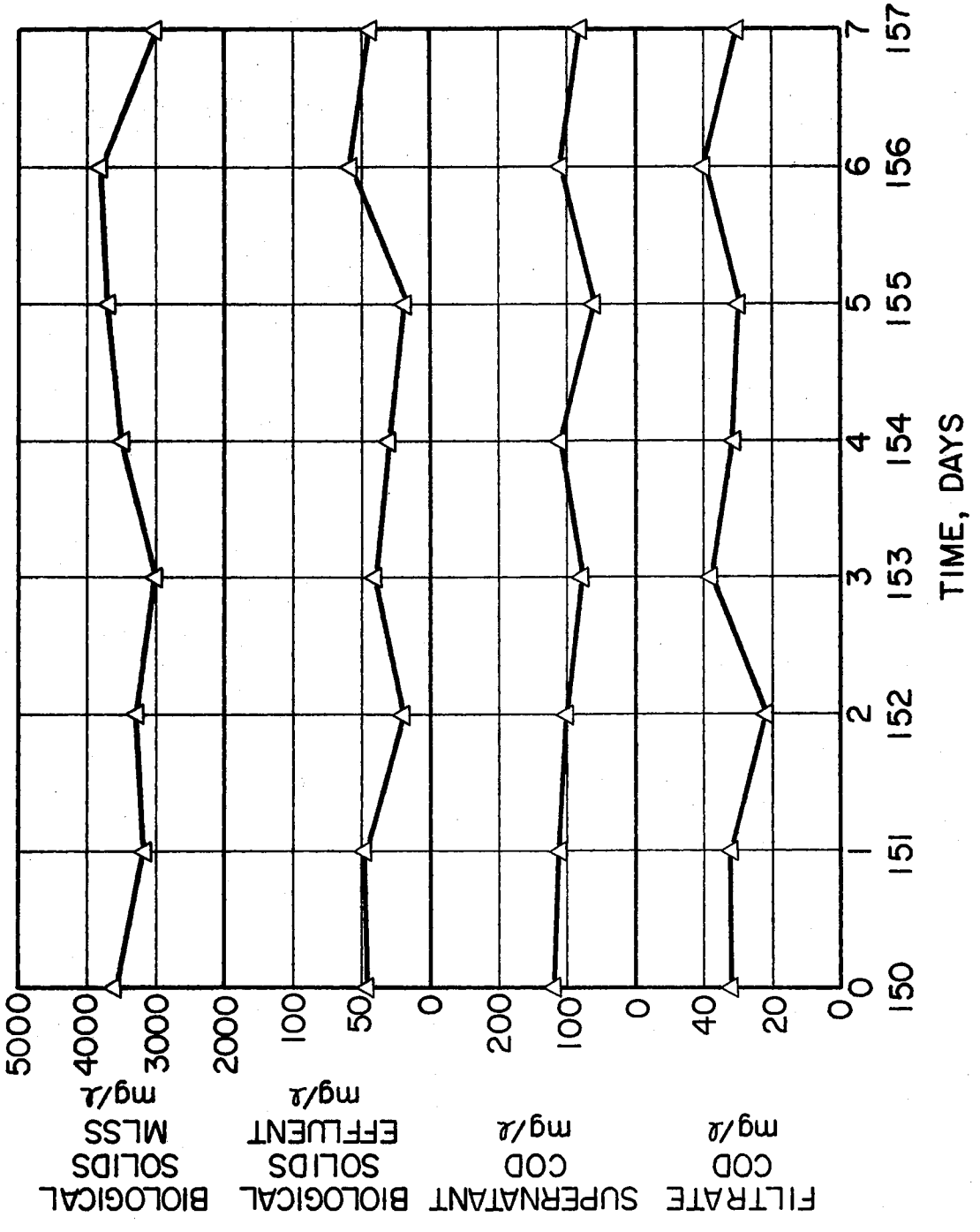

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
TIME, DAYS
0
20
40
0
100
200
0
50
100
2000
3000
4000
5000
150
151
152
153
154
155
156
157
0
1
2
3
4
5
6
7

Figure 26. Fifth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 156-163. Glucose Feed, 500 mg/l

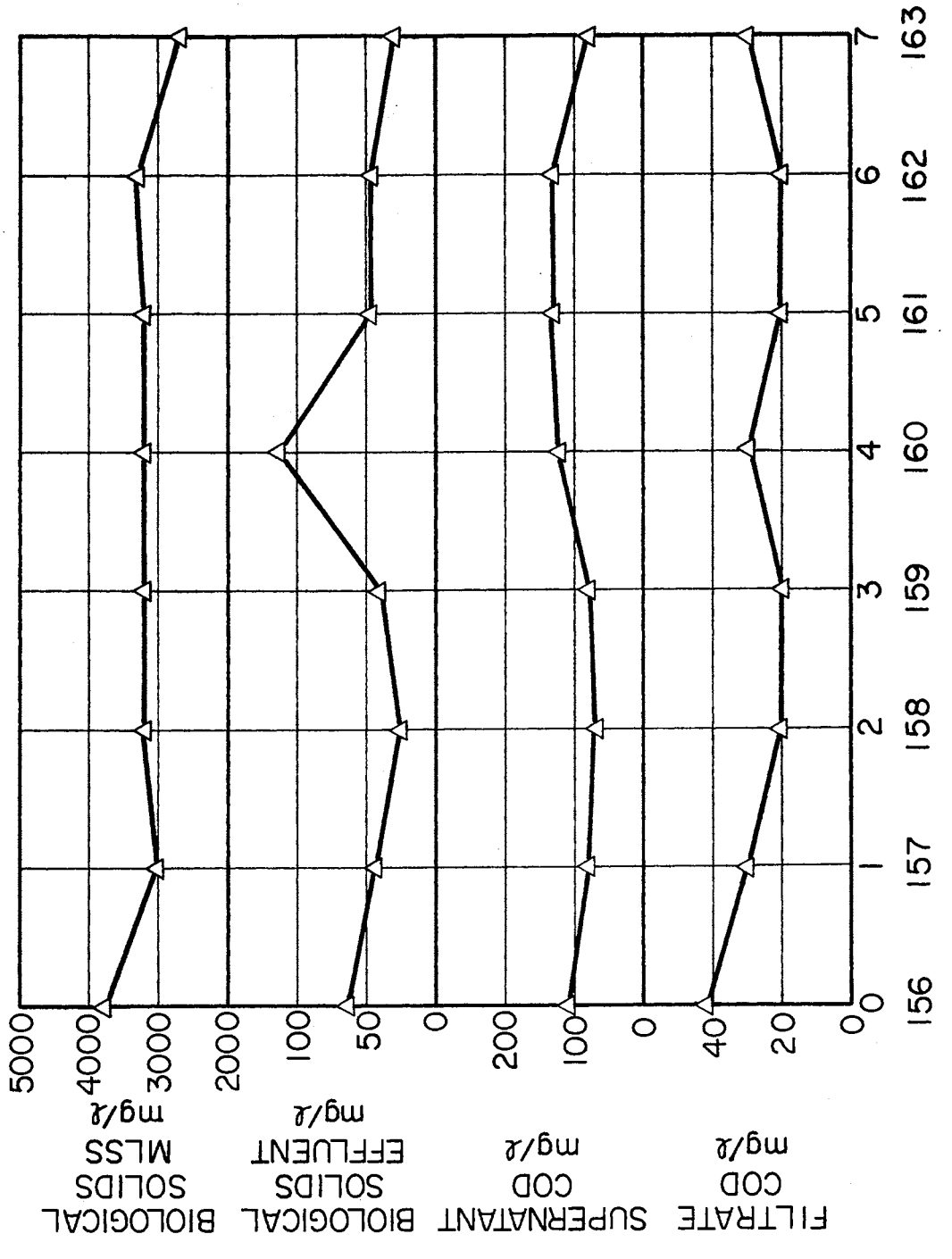

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
0
20
40
0
100
200
0
50
100
2000
3000
4000
5000
156
157
158
159
160
161
162
163
0
1
2
3
4
5
6
7
TIME, DAYS

Figure 27. Sixth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 162-169. Glucose Feed, 500 mg/l

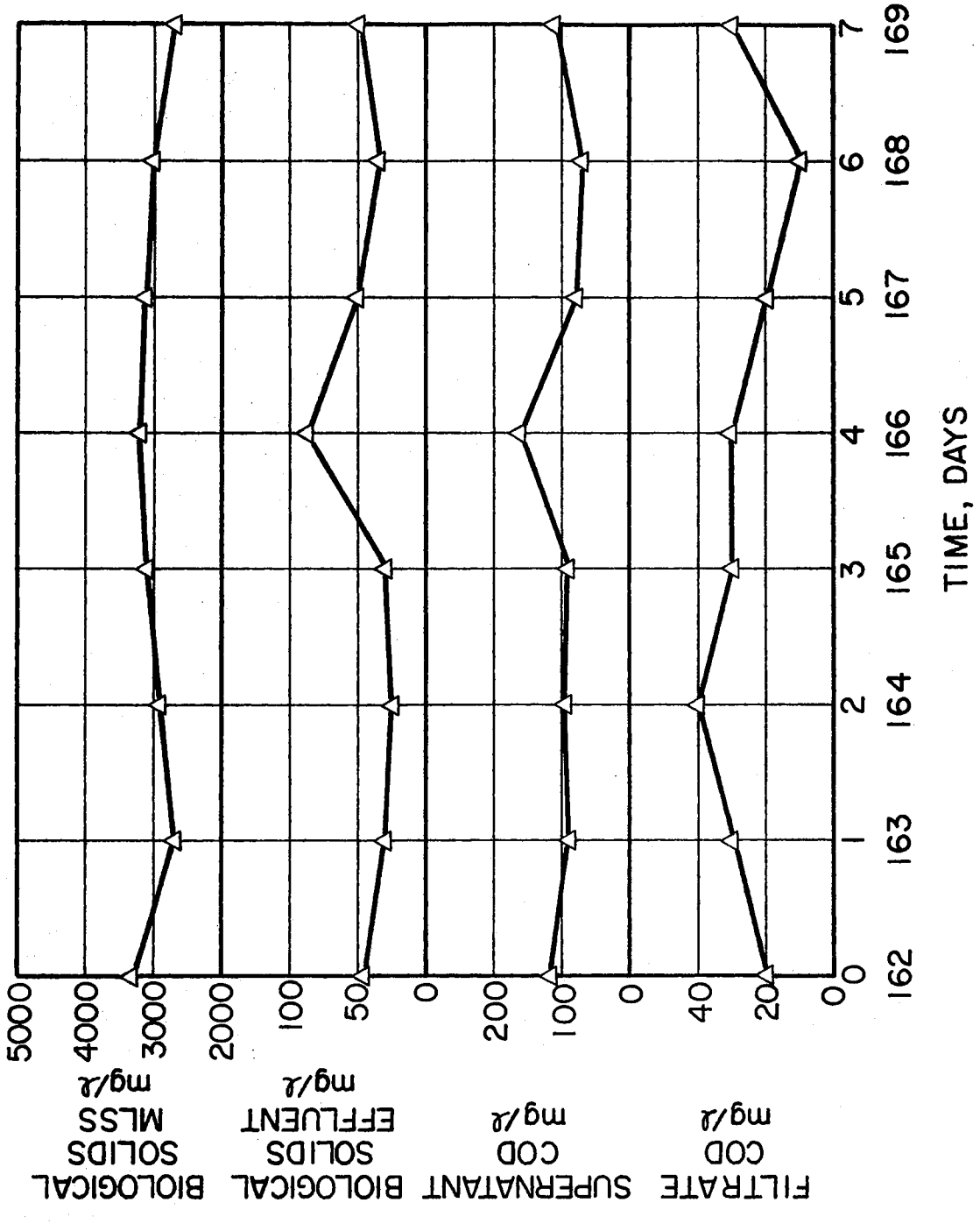

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
TIME, DAYS
0
20
40
0
100
200
0
50
100
2000
3000
4000
5000
162
163
164
165
166
167
168
169
0
1
2
3
4
5
6
7

Figure 28. Seventh Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 168-175. Glucose Feed, 500 mg/l

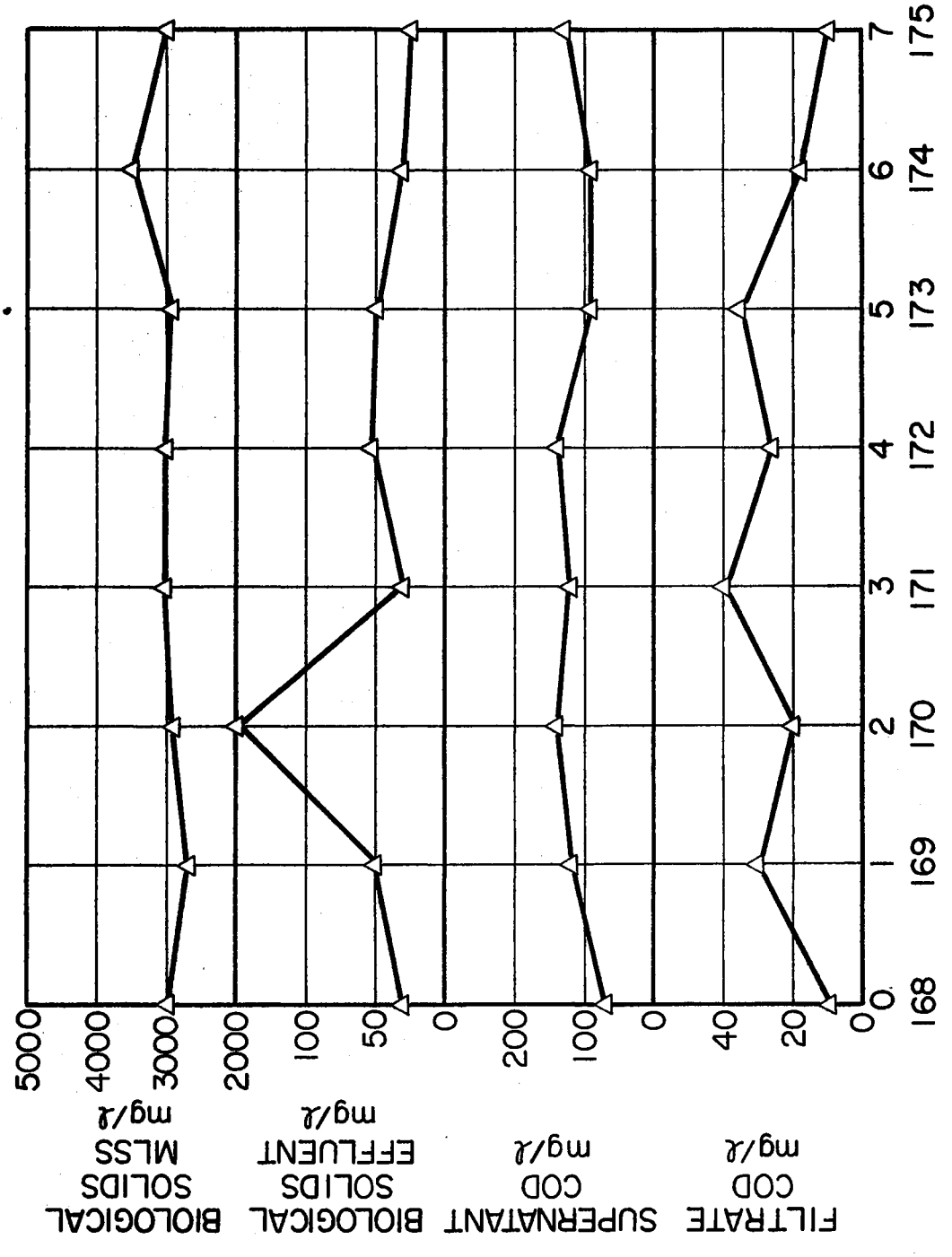

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
TIME, DAYS
0
20
40
0
100
200
0
50
100
2000
3000
4000
5000
168
169
170
171
172
173
174
175
0
1
2
3
4
5
6
7

Figure 29. Eighth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 174-181. Glucose Feed, 500 mg/l

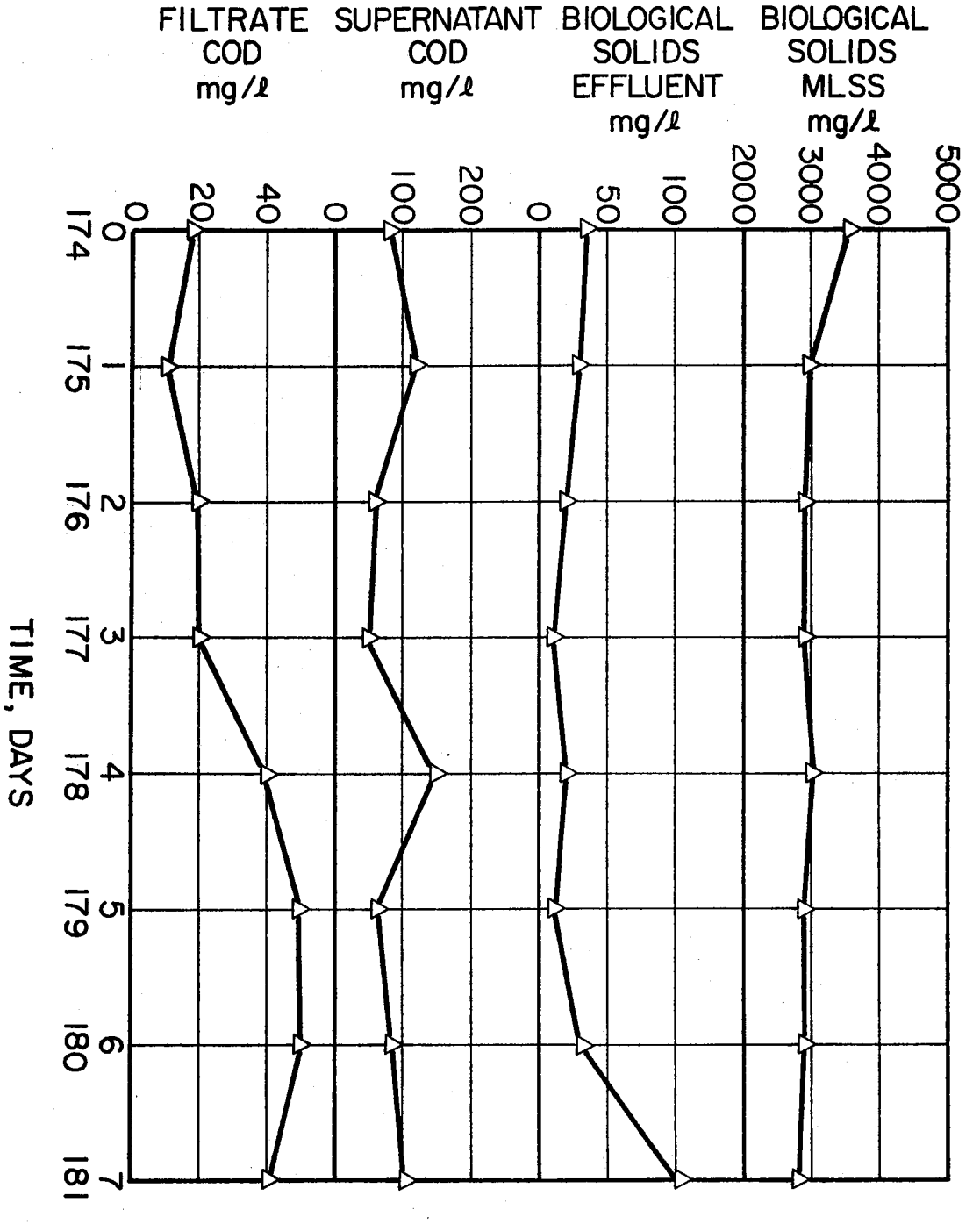
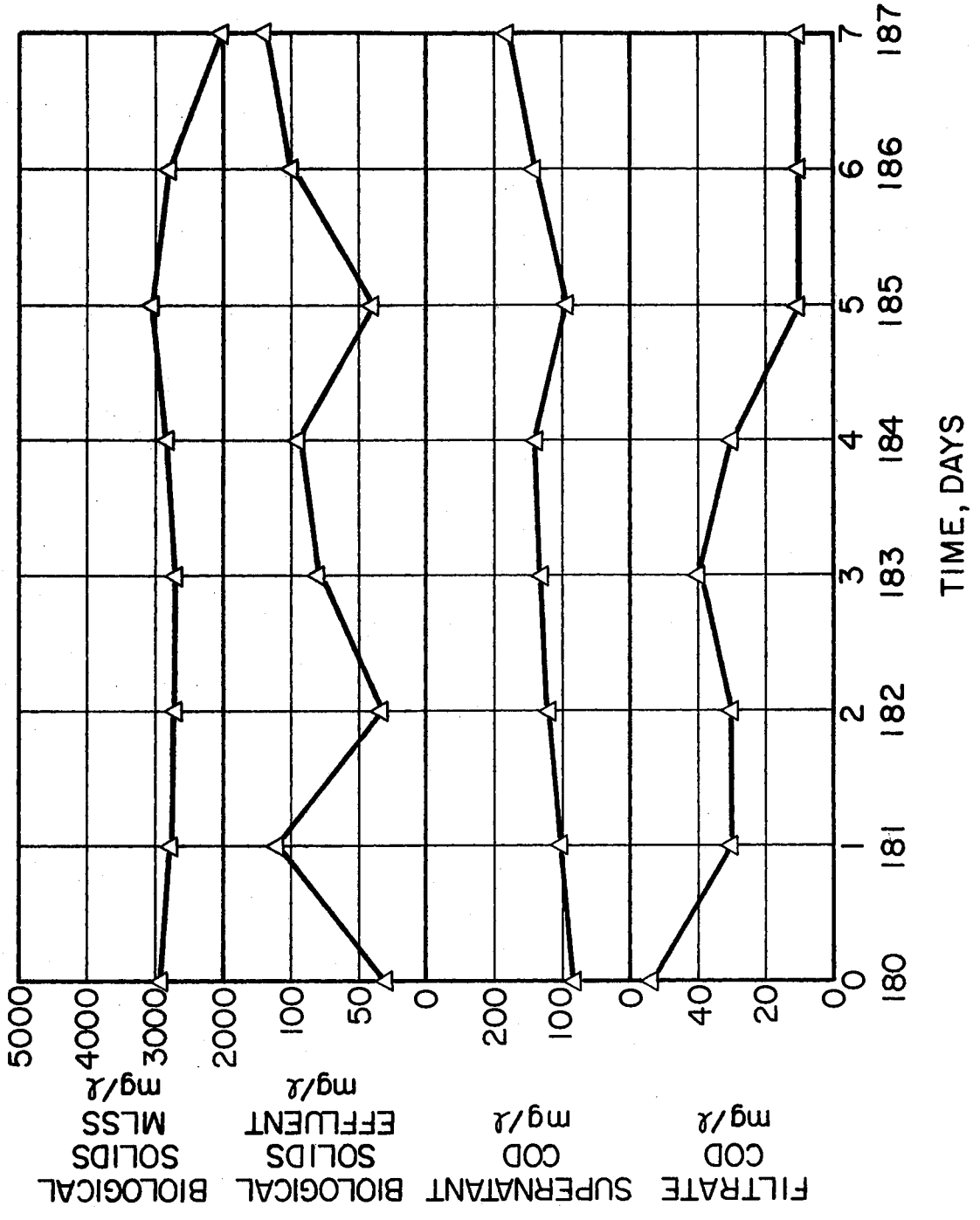

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
0
20
40
0
100
200
0
50
100
2000
3000
4000
5000
174
175
176
177
178
179
180
181
0
1
2
3
4
5
6
7
TIME, DAYS

Figure 30. Ninth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 180-187. Glucose Feed, 500 mg/l


FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
TIME, DAYS
0
20
40
0
100
200
0
50
100
2000
3000
4000
5000
180
181
182
183
184
185
186
187
0
1
2
3
4
5
6
7

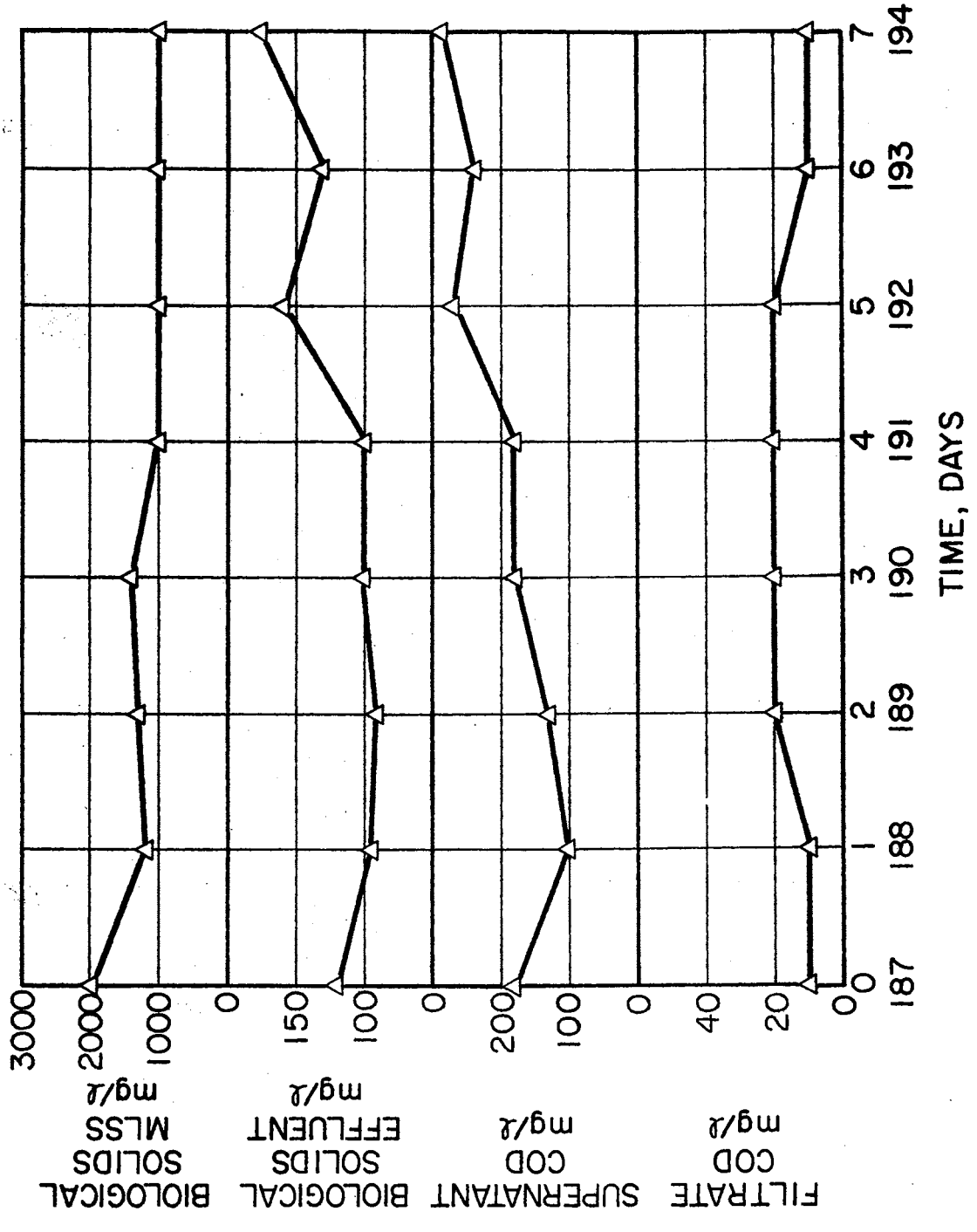
At the beginning of the ninth week, the biological solids concentration was 2900 mg/l; at the end of the refeeding period, the mixed liquor solids concentration was 2900 mg/l. Purification efficiency based on filtrate COD was in excess of 90 percent for all three weeks.

Figure 31 shows the performance during the tenth week of operation. The mixed liquor biological solids concentration at the beginning of this period was 2900 mg/l, and at the end of the test period, 2000 mg/l. Biological solids concentration in the effluent averaged 125 mg/l; however, purification efficiency based on filtrate COD remained in excess of 90 percent. The COD of the unfiltered hydrolysate of the withdrawn cells was 2800 mg/l. COD of the filtrate was 2000 mg/l. During this period, the pilot plant began to experience some settling problems. There were no pH changes noted in the mixed liquor; pH remained between 6.8 and 7.0. Although microscopic examinations were not performed at this time, there was no filamentous growth noticed in the clarifier nor was bulking a problem.

D. Chemical Flocculation of Suspended Biological Solids in the Effluent of the Extended Aeration Activated Sludge Pilot Plant

The extended aeration process could be considered one that should enhance development of flocculating microbial populations, since it is operated under starvation conditions which are generally thought to be needed for development of a flocced microbial population. However, from time to time, settling problems are encountered due, perhaps, to changes in predominance of species caused, for example, by pH changes.

Figure 31. Tenth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 187-194. Glucose Feed, 500 mg/l

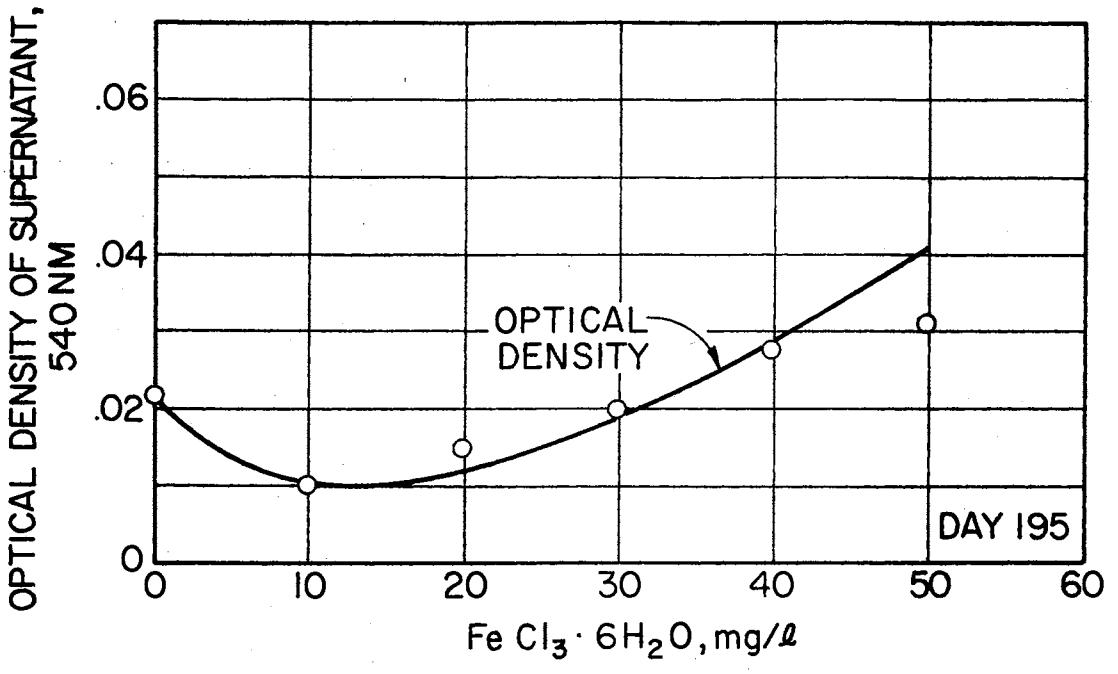

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
TIME, DAYS
187
188
1
189
2
190
3
191
4
192
5
193
6
194
7
0
20
40
0
100
200
0
100
150
0
1000
2000
3000

One method for control of non-settling sludge is through the addition of chemical flocculants. Since the pilot plant was experiencing settling problems which, based on experimental evidence and observation, was not due to a pH change or any apparent change in predominance, experiments were conducted to determine a suitable coagulant that might be used as a remedial step in correcting the existing sludge settling problem. Experiments were designed to gain some insight into the optimum concentrations and kinds of flocculating agents that might enhance settling. Some of the results of these studies are shown in Figures 32 through 34. From these results, it appeared that ferric sulfate, $Fe_2(SO_4)_3$, would be the best reagent to flocculate biological solids in the effluent of the extended aeration activated sludge process.

E. Operational Performance of the Extended Aeration Process Incorporating the "Hydrolytic Assist;" S_1 = 1000 mg/l Glucose

Figure 35 shows the performance of the pilot plant prior to changing the feed from 500 mg/l glucose to 1000 mg/l glucose. It also shows the acclimation period prior to resuming periodic sludge withdrawal and subsequent hydrolysis and refeeding. It should be noted that during this period, purification efficiency based on filtrate COD remained above 90 percent. There was also a short period in which settling problems were encountered, and the problem was corrected with the addition of ferric sulfate as a flocculant. On day 215, the feed was switched from 500 mg/l glucose to 1000 mg/l glucose. The biological solids in the reactor increased from 1100 mg/l on day 215 to 6000 mg/l by day 232. Weekly withdrawals of 900 ml of settled sludge for hydrolysis and

Figure 32. Effects of Concentration of Indicated Coagulants on Flocculation and Settling of Biological Solids Retained in the Effluent of the Extended Aeration Pilot Plant. Day 195 - April 4, 1972


OPTICAL DENSITY OF SUPERNATANT, 540 NM
.06
.04
.02
0
OPTICAL DENSITY
DAY 195
0
10
20
30
40
50
60
Fe Cl3 · 6H2O, mg/ℓ

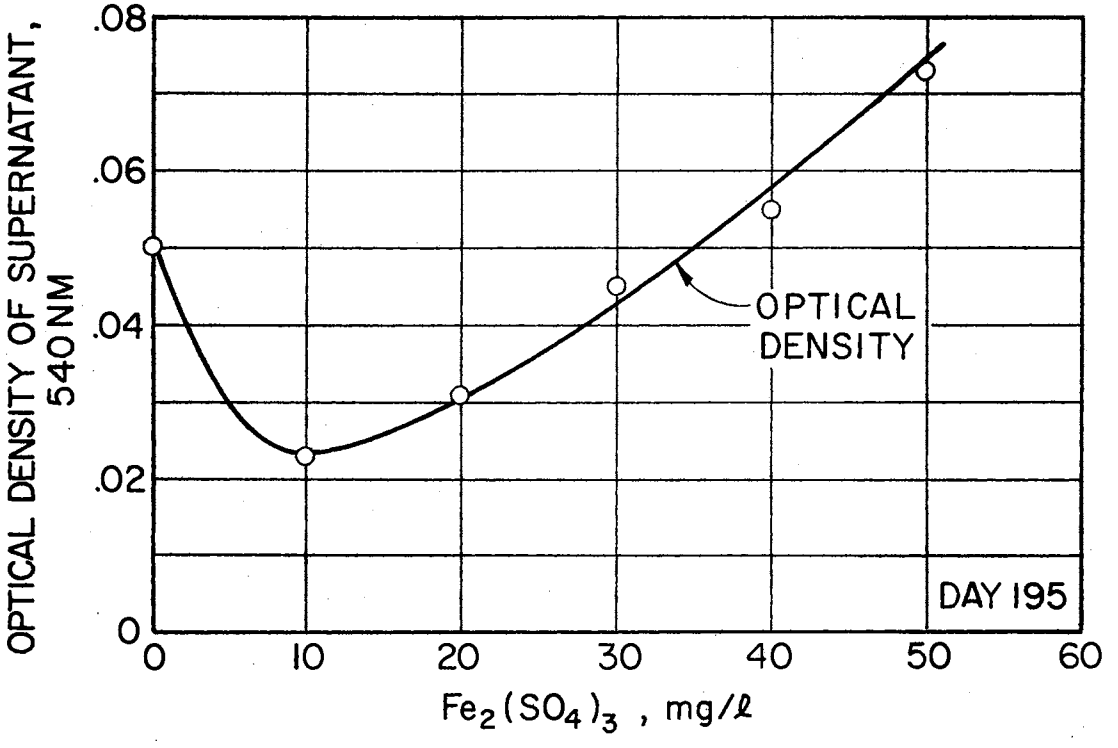
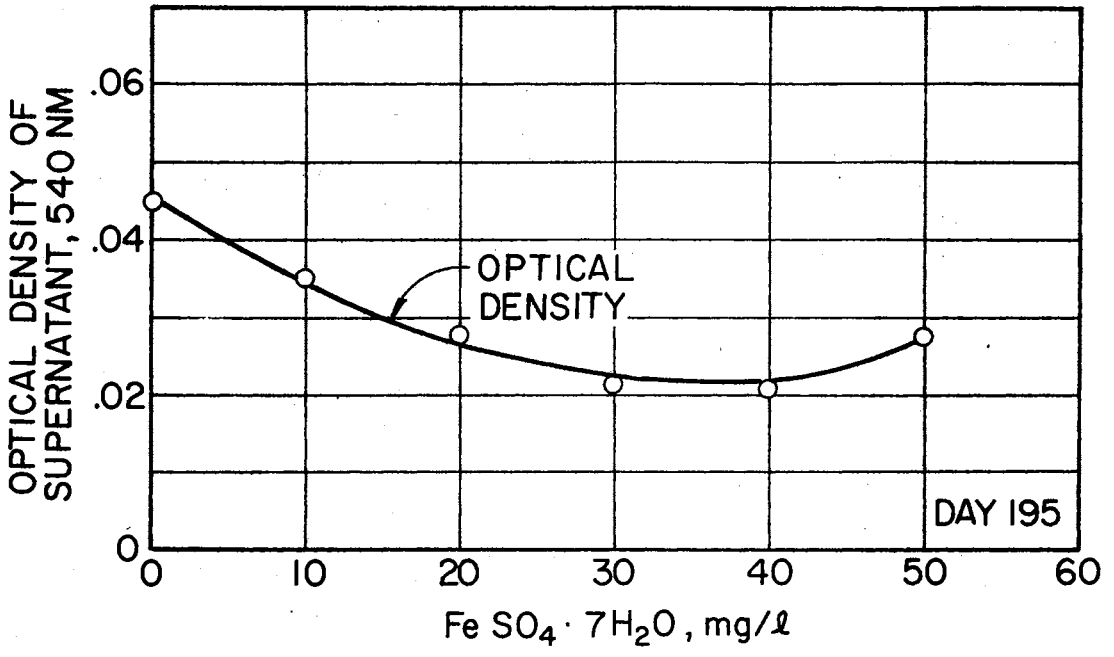

OPTICAL DENSITY OF SUPERNATANT, 540 NM
.08
.06
.04
.02
0
OPTICAL DENSITY
DAY 195
0
10
20
30
40
50
60
Fe2(SO4)3 , mg/ℓ

Figure 33. Effects of Concentration of Indicated Coagulants on Flocculation and Settling of Biological Solids Retained in the Effluent of the Extended Aeration Pilot Plant. Day 195 - April 4, 1972


OPTICAL DENSITY OF SUPERNATANT, 540 NM
.06
.04
.02
0
OPTICAL DENSITY
DAY 195
0
10
20
30
40
50
60
Fe SO4 · 7H2O, mg/ℓ

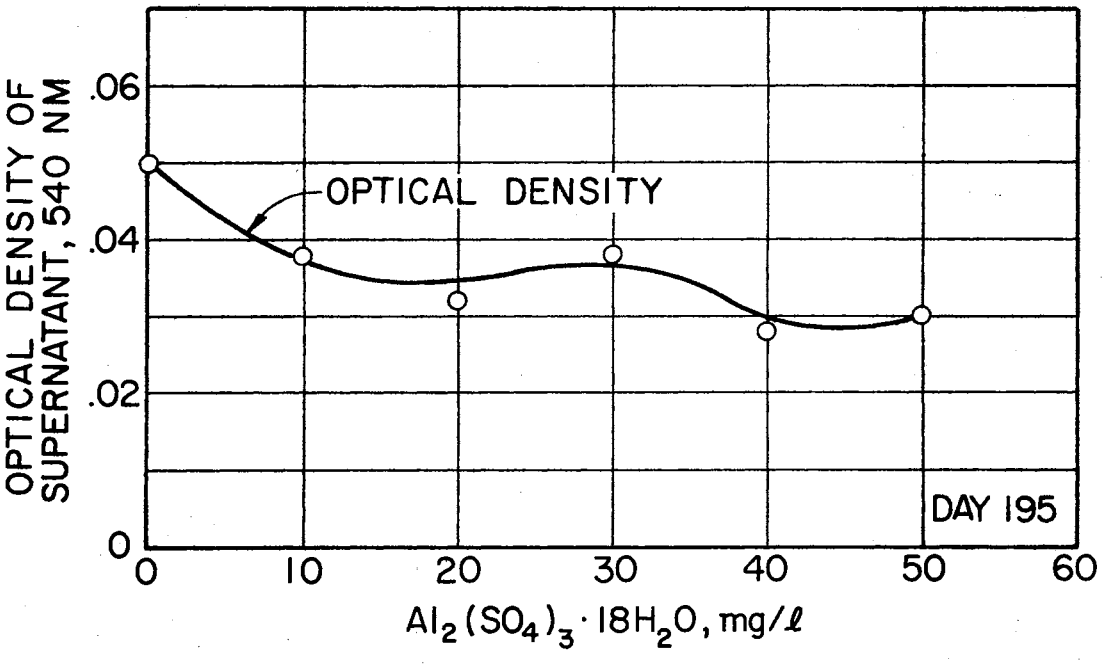
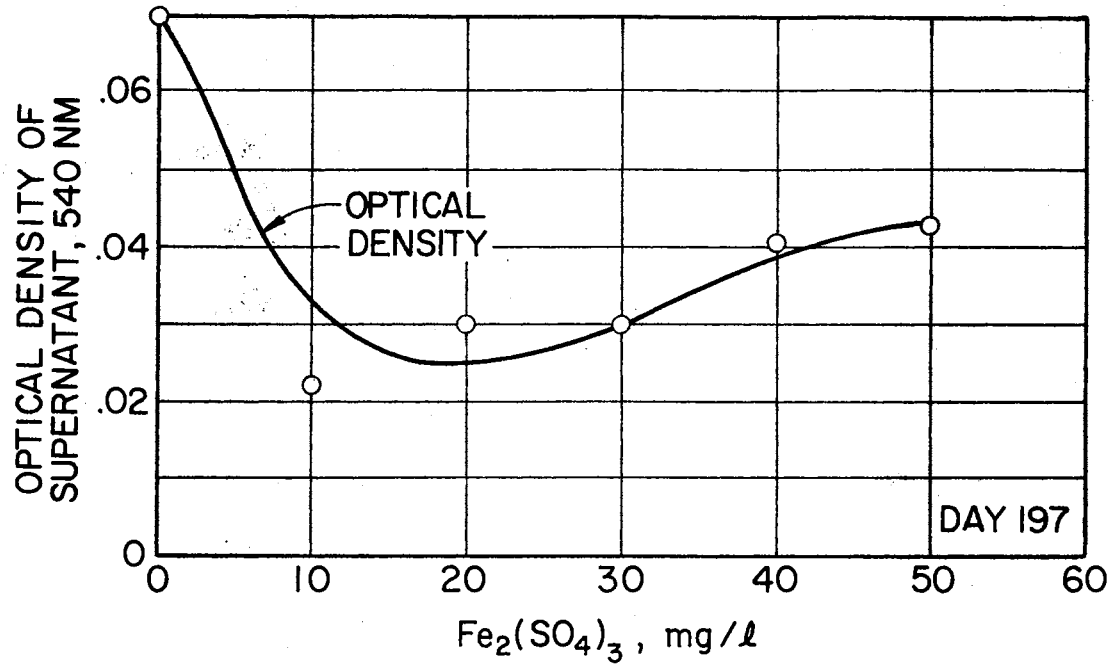

OPTICAL DENSITY OF SUPERNATANT, 540 NM
.06
.04
.02
0
OPTICAL DENSITY
DAY 195
0
10
20
30
40
50
60
Al2(SO4)3 · 18H2O, mg/ℓ

Figure 34. Effects of Concentration of Indicated Coagulants on Flocculation and Settling of Biological Solids Retained in the Effluent of the Extended Aeration Pilot Plant. Day 197 - April 6, 1972


OPTICAL DENSITY OF SUPERNATANT, 540 NM
.06
.04
.02
0
OPTICAL DENSITY
DAY 197
0
10
20
30
40
50
60
$Fe_2(SO_4)_3$, mg/ℓ

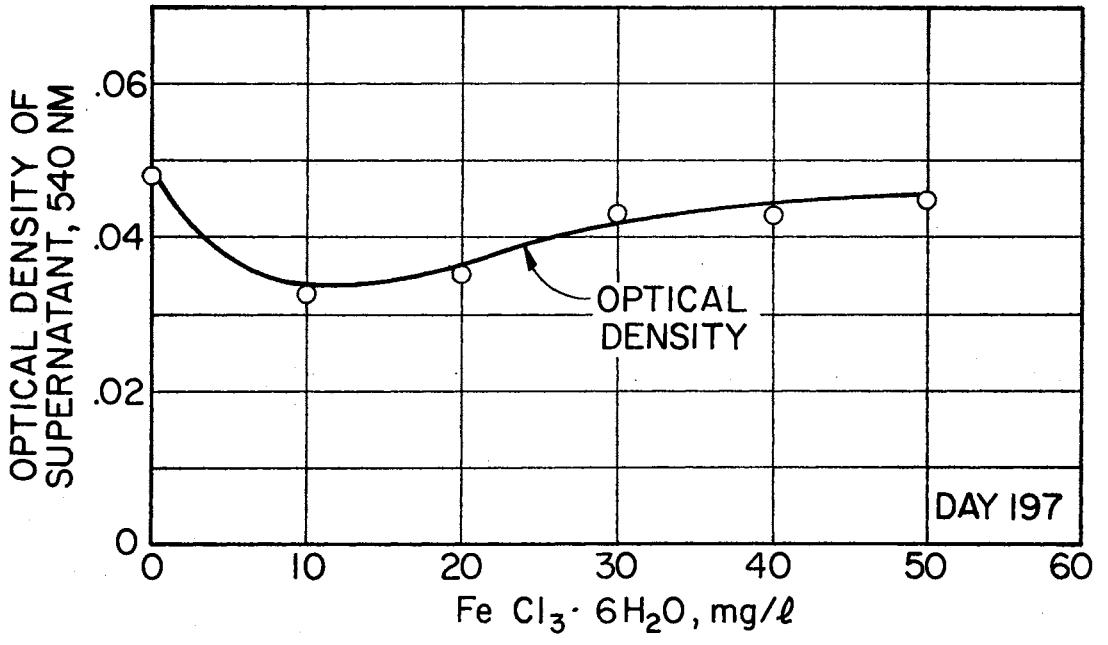
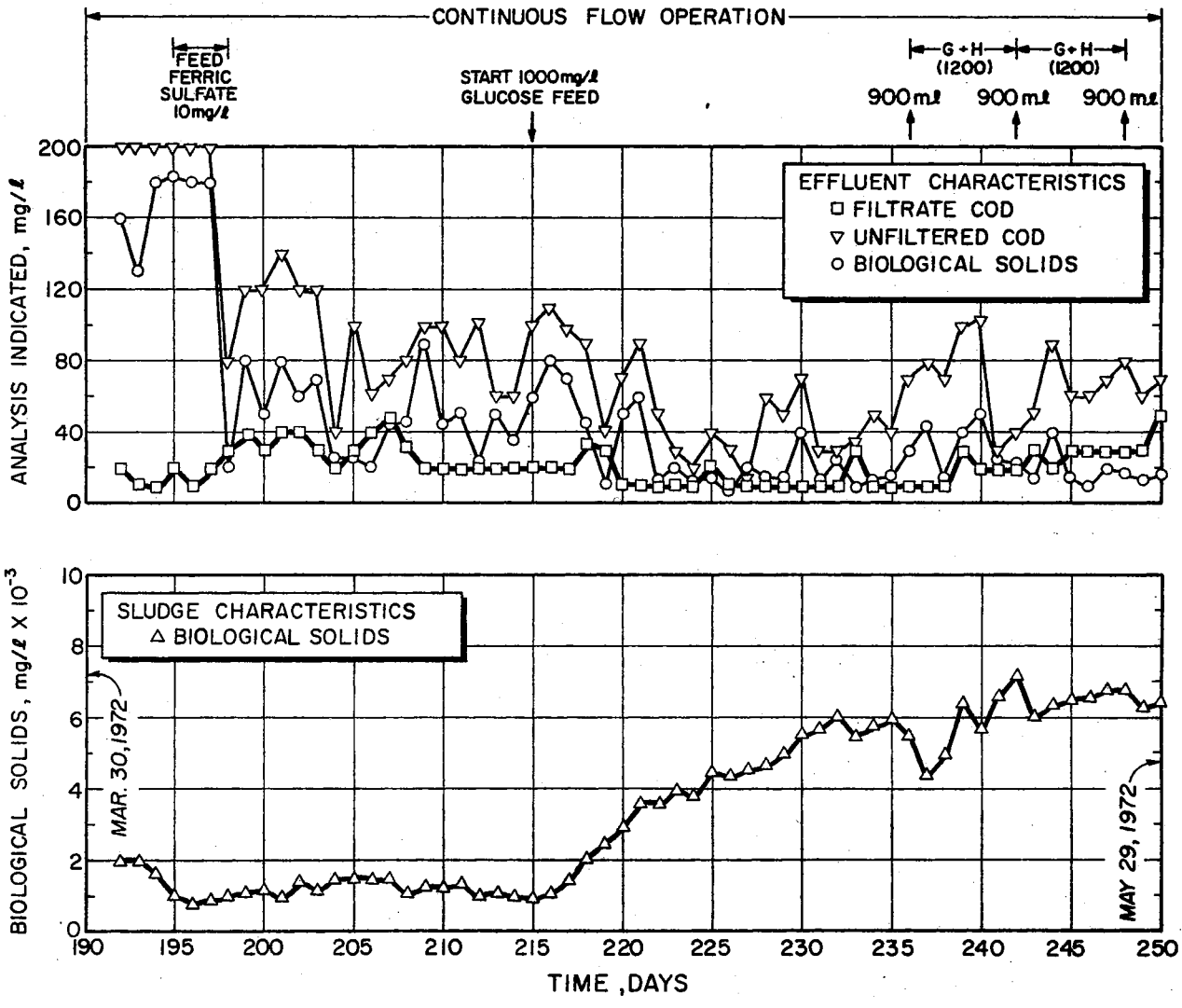

OPTICAL DENSITY OF SUPERNATANT, 540 NM
.06
.04
.02
0
OPTICAL DENSITY
DAY 197
0
10
20
30
40
50
60
$Fe\ Cl_3 \cdot 6H_2O$, mg/ℓ

Figure 35. Performance Data for the Continuous-Flow Pilot Plant - Days 190-250 - March 30, 1972, to May 29, 1972


CONTINUOUS FLOW OPERATION
FEED FERRIC SULFATE 10mg/ℓ
START 1000mg/ℓ GLUCOSE FEED
G+H (1200)
G+H (1200)
900mℓ
900mℓ
900mℓ
EFFLUENT CHARACTERISTICS
□ FILTRATE COD
▽ UNFILTERED COD
○ BIOLOGICAL SOLIDS
ANALYSIS INDICATED, mg/ℓ
SLUDGE CHARACTERISTICS
△ BIOLOGICAL SOLIDS
BIOLOGICAL SOLIDS, mg/ℓ X 10⁻³
MAR. 30, 1972
MAY 29, 1972
TIME, DAYS

refeeding began on day 236.

Figure 36 shows 10 weeks of performance data for the extended aeration pilot plant while operating with the "hydrolytic assist." The neutralized hydrolysate was fed to the unit along with 1000 mg/l glucose over each six-day period. At the beginning of this test period, the biological solids concentration in the reactor was 5500 mg/l. At the close of the test period, the biological solids concentration was 6600 mg/l. The average biological solids concentration in the effluent during this time was 34 mg/l. The average filtrate COD in the effluent was 34 mg/l, and the average unfiltered COD in the effluent was 64 mg/l. The average biological solids concentration in the reactor was 6123 mg/l; the average purification efficiency based on filtrate COD was 97.5 percent.

Figures 37-46 show weekly performances. The sludge characteristics and effluent characteristics were similar for each of the 10 weekly test periods. The COD of the hydrolysate for the 10-week period was as follows:

First week, unfiltered COD, 8000; filtered COD, 6032 mg/l.

Second week, unfiltered COD, 8640; filtered COD, 5616 mg/l.

Third week, unfiltered COD, 7676; filtered COD, 4848 mg/l.

Fourth week, unfiltered COD, 8660; filtered COD, 5360 mg/l.

Fifth week, unfiltered COD, 7835; filtered COD, 4536 mg/l.

Sixth week, unfiltered COD, 6161; filtered COD 5454 mg/l.

Seventh week, unfiltered COD, 10,000; filtered COD, 7200 mg/l.

Eighth week, unfiltered COD, 8200; filtered COD, 5400 mg/l.

Ninth week, unfiltered COD, 7800; filtered COD, 6400 mg/l.

Tenth week, unfiltered COD, 8400; filtered COD, 6400 mg/l.

Figure 36. Ten-Week Performance Data of the Extended Aeration Pilot Plant Incorporating the "Hydrolytic Assist" While Growing on 1000 mg/l Glucose. Days 235-295 - May 14, 1972, to July 13, 1972

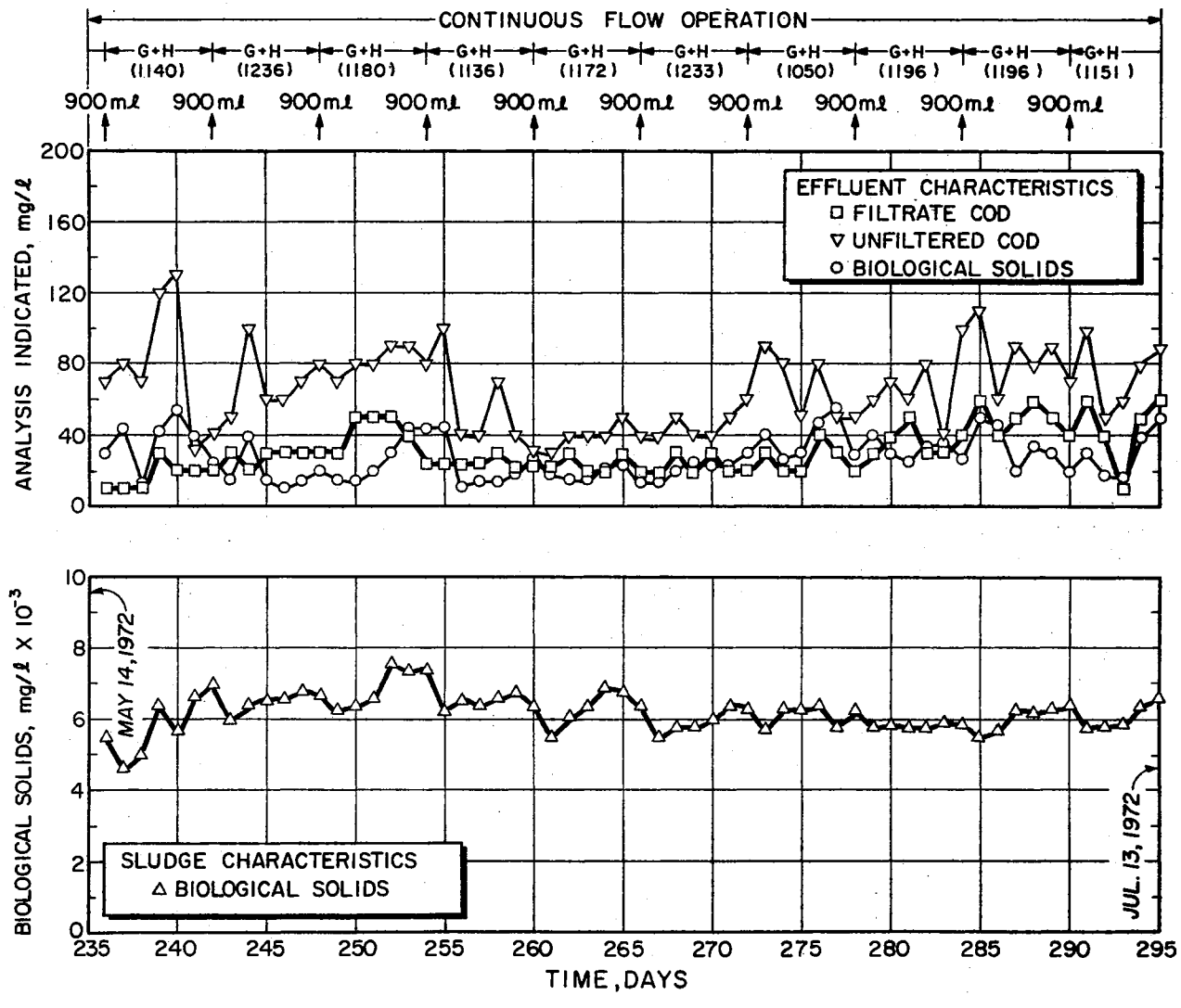

CONTINUOUS FLOW OPERATION
G+H (1140)
G+H (1236)
G+H (1180)
G+H (1136)
G+H (1172)
G+H (1233)
G+H (1050)
G+H (1196)
G+H (1196)
G+H (1151)
900 ml
ANALYSIS INDICATED, mg/l
EFFLUENT CHARACTERISTICS
FILTRATE COD
UNFILTERED COD
BIOLOGICAL SOLIDS
BIOLOGICAL SOLIDS, mg/l X 10⁻³
MAY 14, 1972
JUL. 13, 1972
SLUDGE CHARACTERISTICS
BIOLOGICAL SOLIDS
TIME, DAYS

Figure 37. First Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 236-243. Glucose Feed, 1000 mg/l

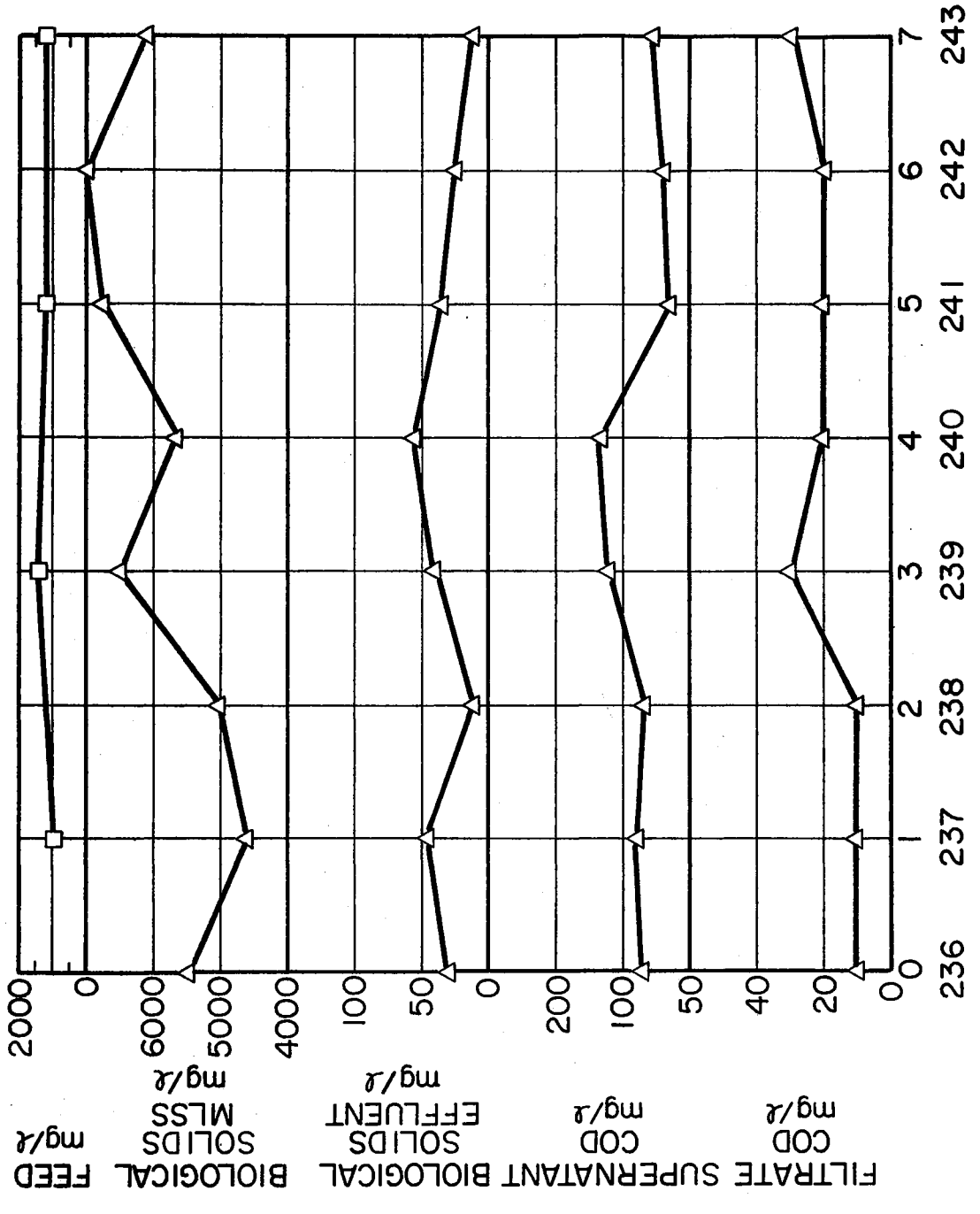

FILTRATE SUPERNATANT BIOLOGICAL
COD mg/ℓ
COD mg/ℓ
SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
FEED mg/ℓ
0
20
40
50
100
200
0
50
100
4000
5000
6000
0
2000
236
237
238
239
240
241
242
243
0
1
2
3
4
5
6
7
TIME, DAYS

Figure 38. Second Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 242-249. Glucose Feed, 1000 mg/l

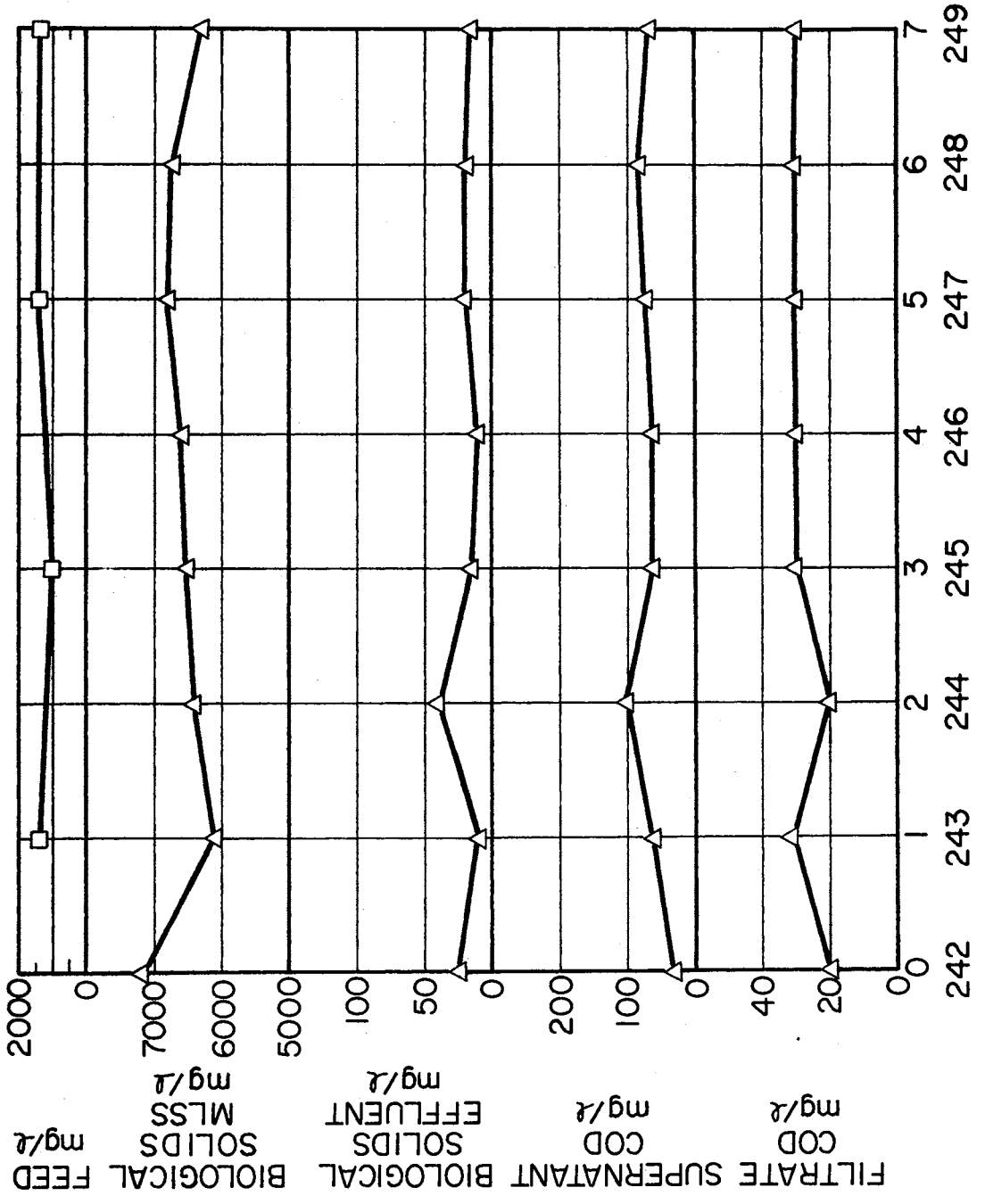

FILTRATE SUPERNATANT BIOLOGICAL BIOLOGICAL FEED
COD COD SOLIDS SOLIDS MLSS mg/ℓ
mg/ℓ mg/ℓ EFFLUENT mg/ℓ mg/ℓ
0 40 200 50 7000 2000
20 100 100 6000
0 0 0 5000
242 243 244 245 246 247 248 249
0 1 2 3 4 5 6 7
TIME, DAYS

Figure 39. Third Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 248-255. Glucose Feed, 1000 mg/l

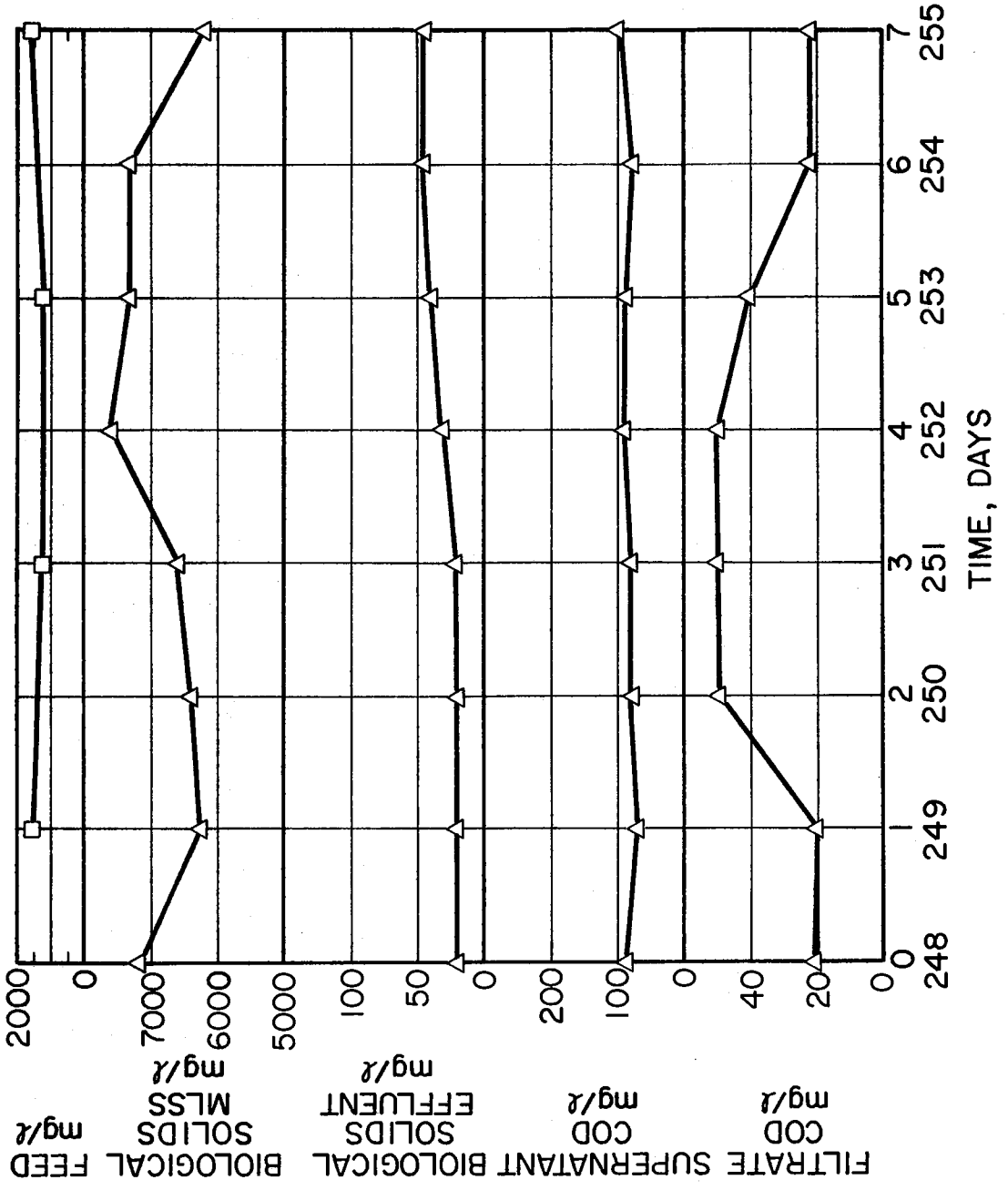

FILTRATE SUPERNATANT BIOLOGICAL BIOLOGICAL FEED
COD COD SOLIDS SOLIDS
mg/ℓ mg/ℓ EFFLUENT MLSS
mg/ℓ mg/ℓ
TIME, DAYS
0 1 2 3 4 5 6 7
248 249 250 251 252 253 254 255
0 20 40
0 100 200
0 50 100
0 5000 6000 7000
0 2000

Figure 40. Fourth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 254-261. Glucose Feed, 1000 mg/l

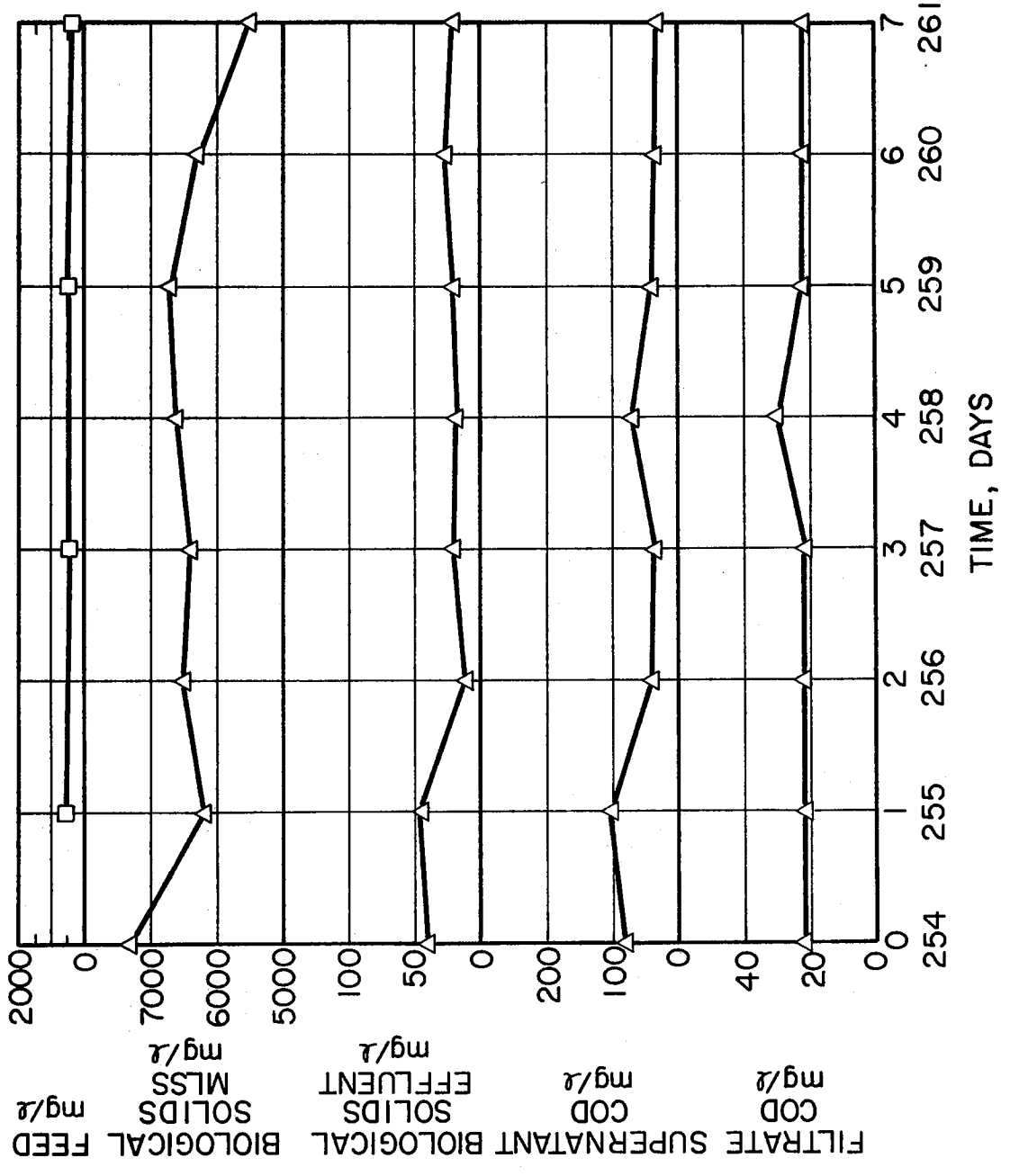

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
FEED mg/ℓ
0
20
40
0
100
200
0
50
100
5000
6000
7000
0
2000
254
255
256
257
258
259
260
261
0
1
2
3
4
5
6
7
TIME, DAYS

Figure 41. Fifth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 260-267. Glucose Feed, 1000 mg/l

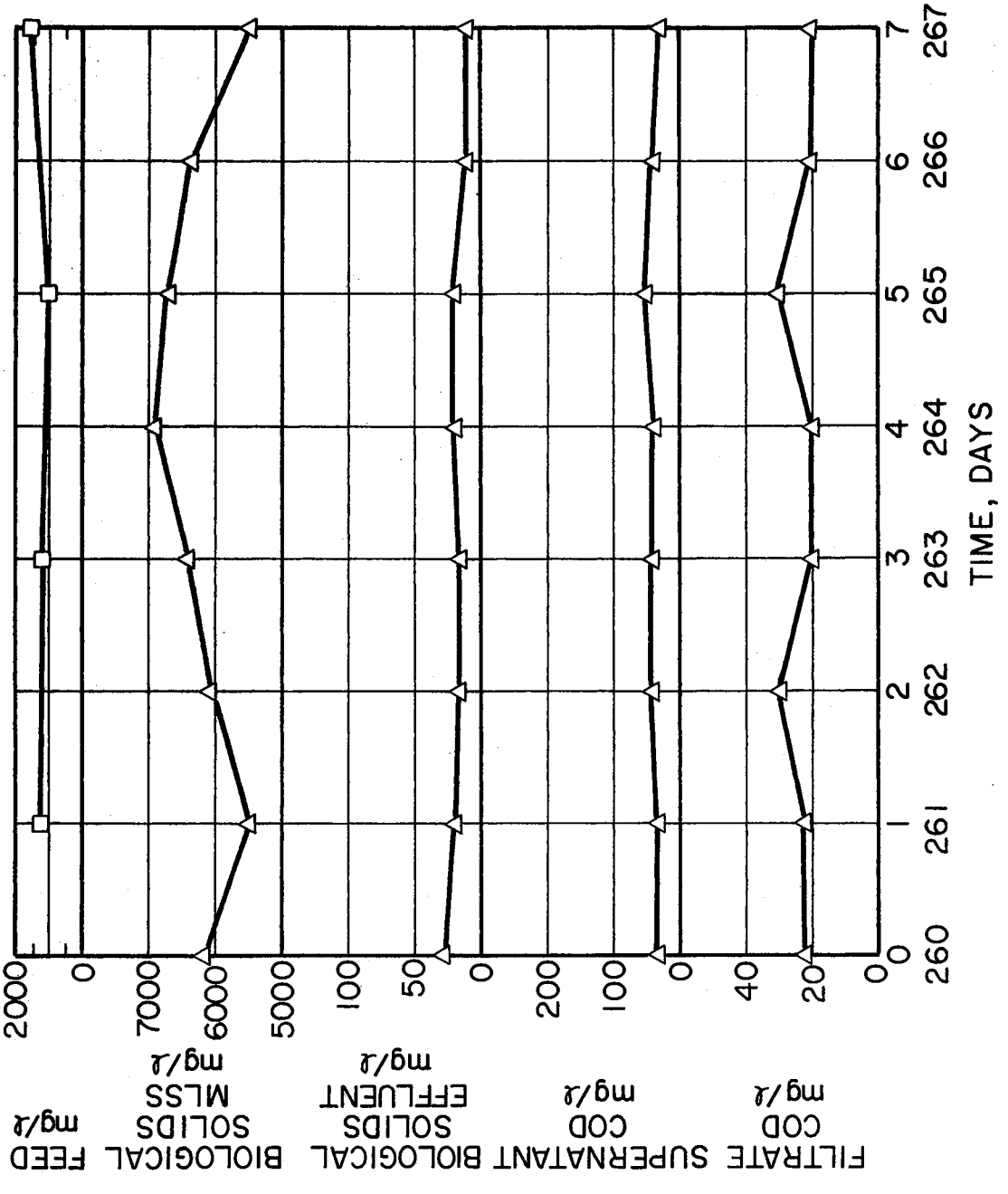

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
FEED mg/ℓ
TIME, DAYS
260
261
262
263
264
265
266
267

Figure 42. Sixth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 266-273. Glucose Feed, 1000 mg/l

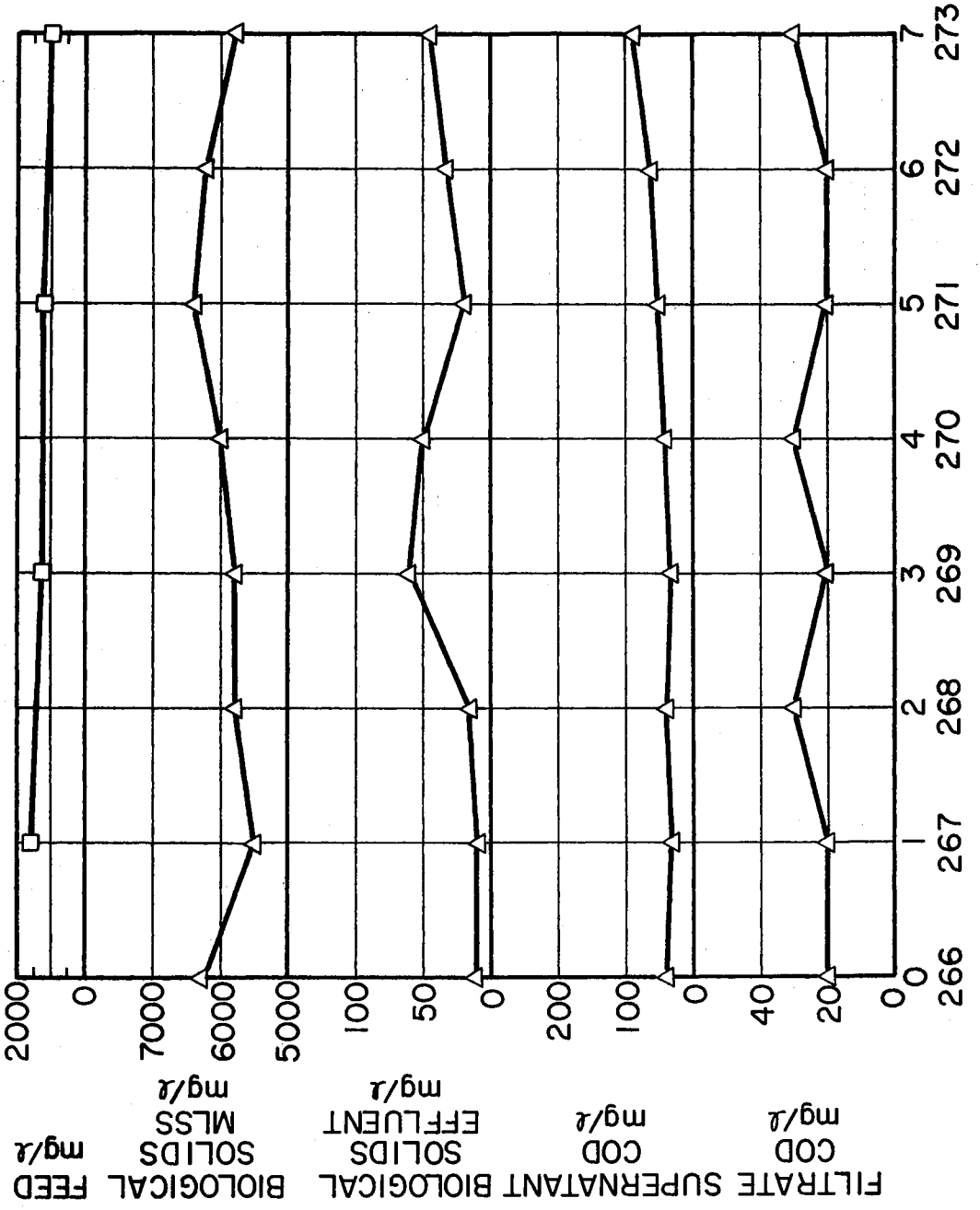

FILTRATE SUPERNATANT BIOLOGICAL BIOLOGICAL FEED
COD COD SOLIDS SOLIDS
mg/ℓ mg/ℓ EFFLUENT MLSS mg/ℓ
mg/ℓ
TIME, DAYS
0 266
1 267
2 268
3 269
4 270
5 271
6 272
7 273
20 40 0 100 200 0 50 100 5000 6000 7000 0 2000

Figure 43. Seventh Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 272-279. Glucose Feed, 1000 mg/l

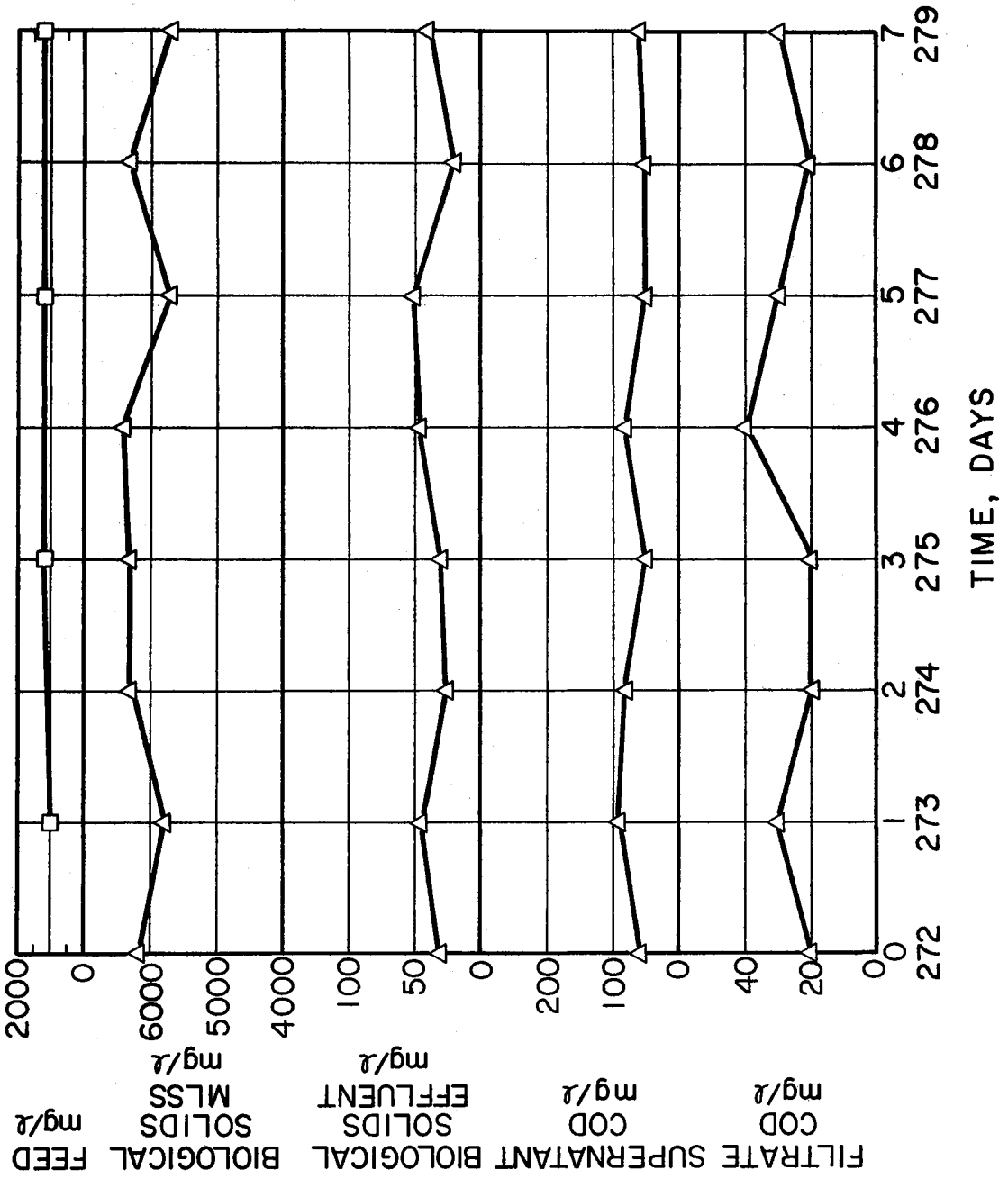

FILTRATE SUPERNATANT BIOLOGICAL BIOLOGICAL FEED
COD COD SOLIDS SOLIDS
mg/ℓ mg/ℓ EFFLUENT MLSS
mg/ℓ mg/ℓ
TIME, DAYS
272 273 274 275 276 277 278 279
0 1 2 3 4 5 6 7
0 20 40
0 100 200
0 50 100
0 4000 5000 6000
0 2000

Figure 44. Eighth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 278-285. Glucose Feed, 1000 mg/l

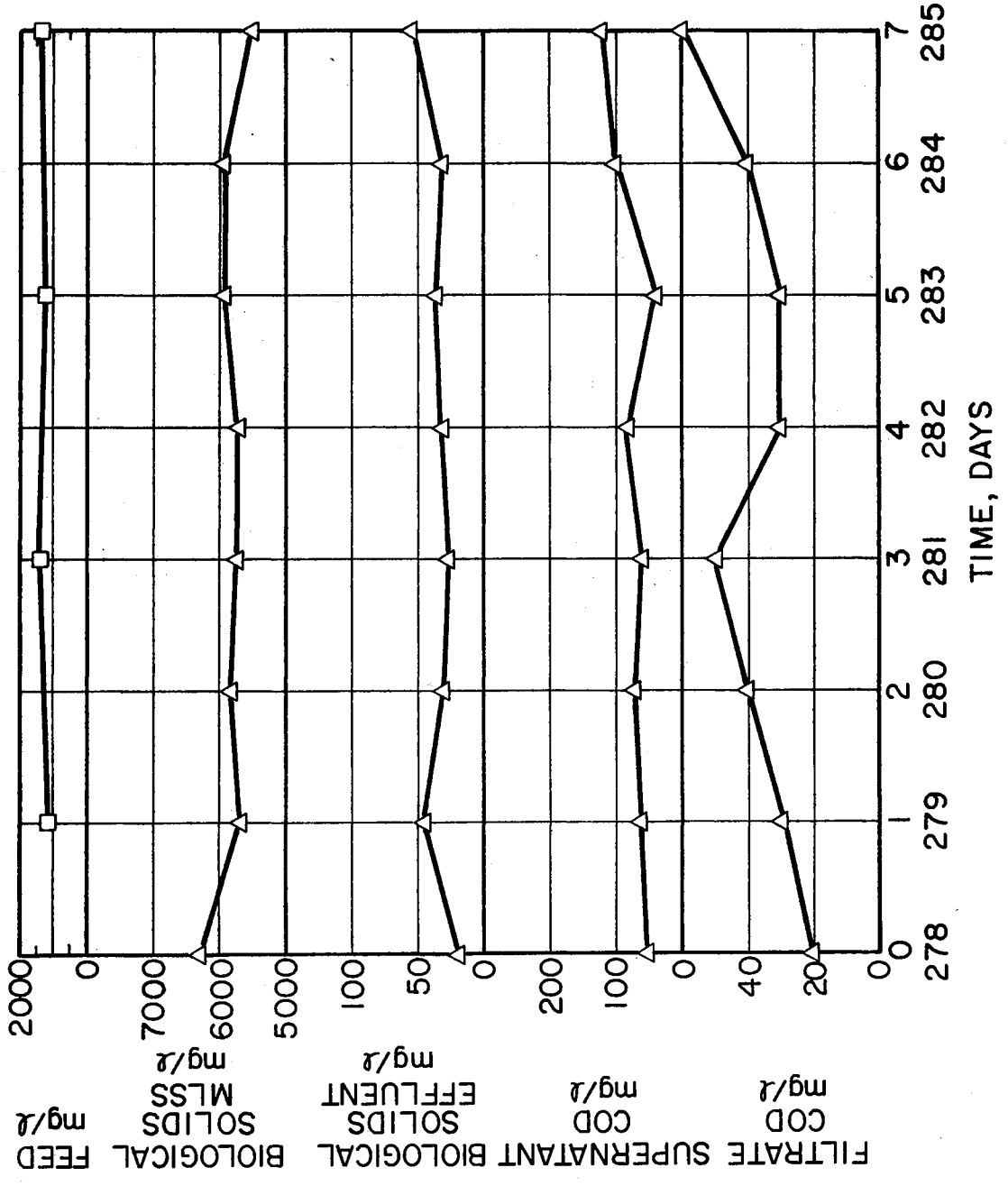

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
FEED mg/ℓ
TIME, DAYS
278
279
280
281
282
283
284
285
0
1
2
3
4
5
6
7
20
40
0
100
200
0
50
100
5000
6000
7000
0
2000

Figure 45. Ninth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 284-291. Glucose Feed, 1000 mg/l

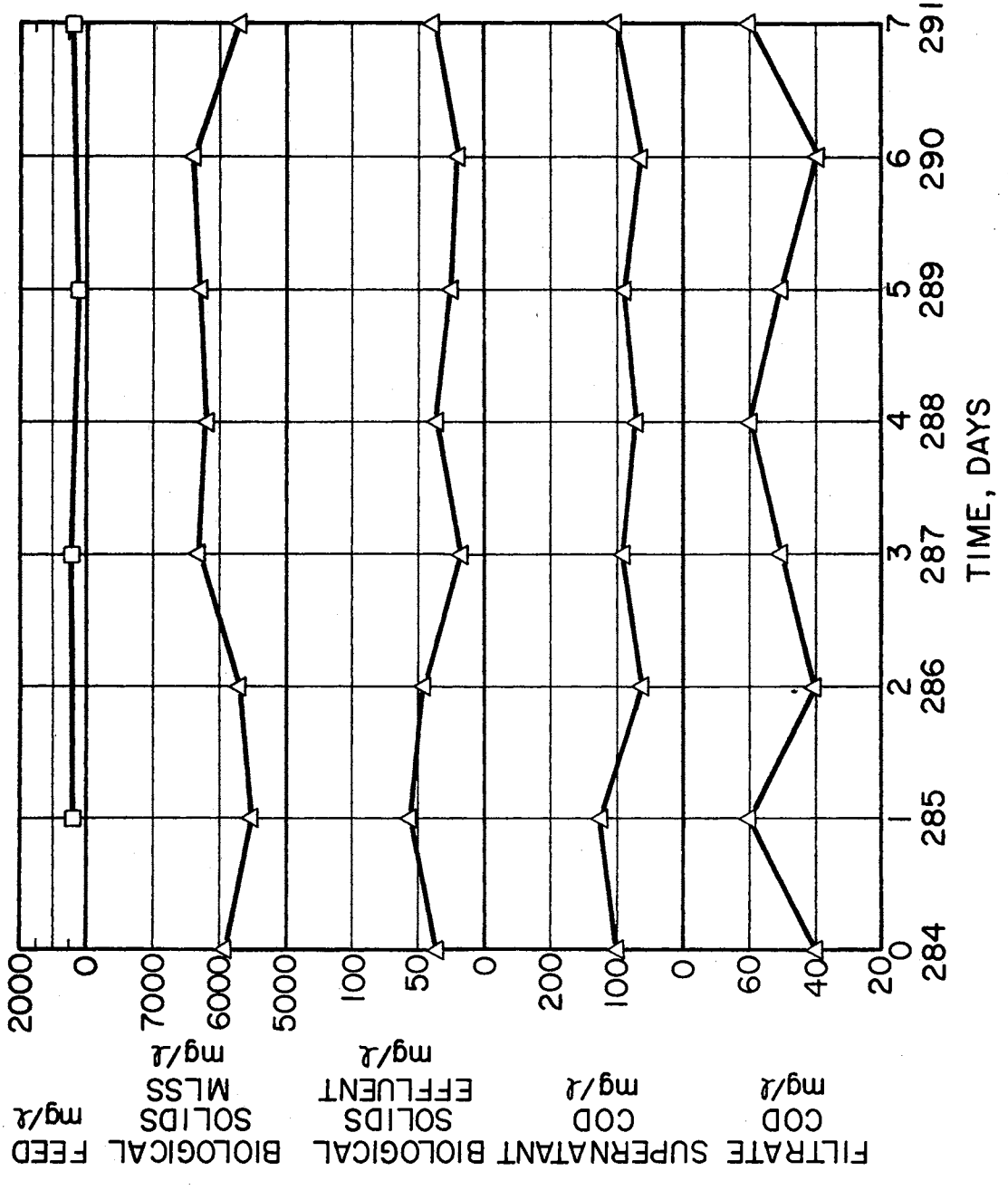
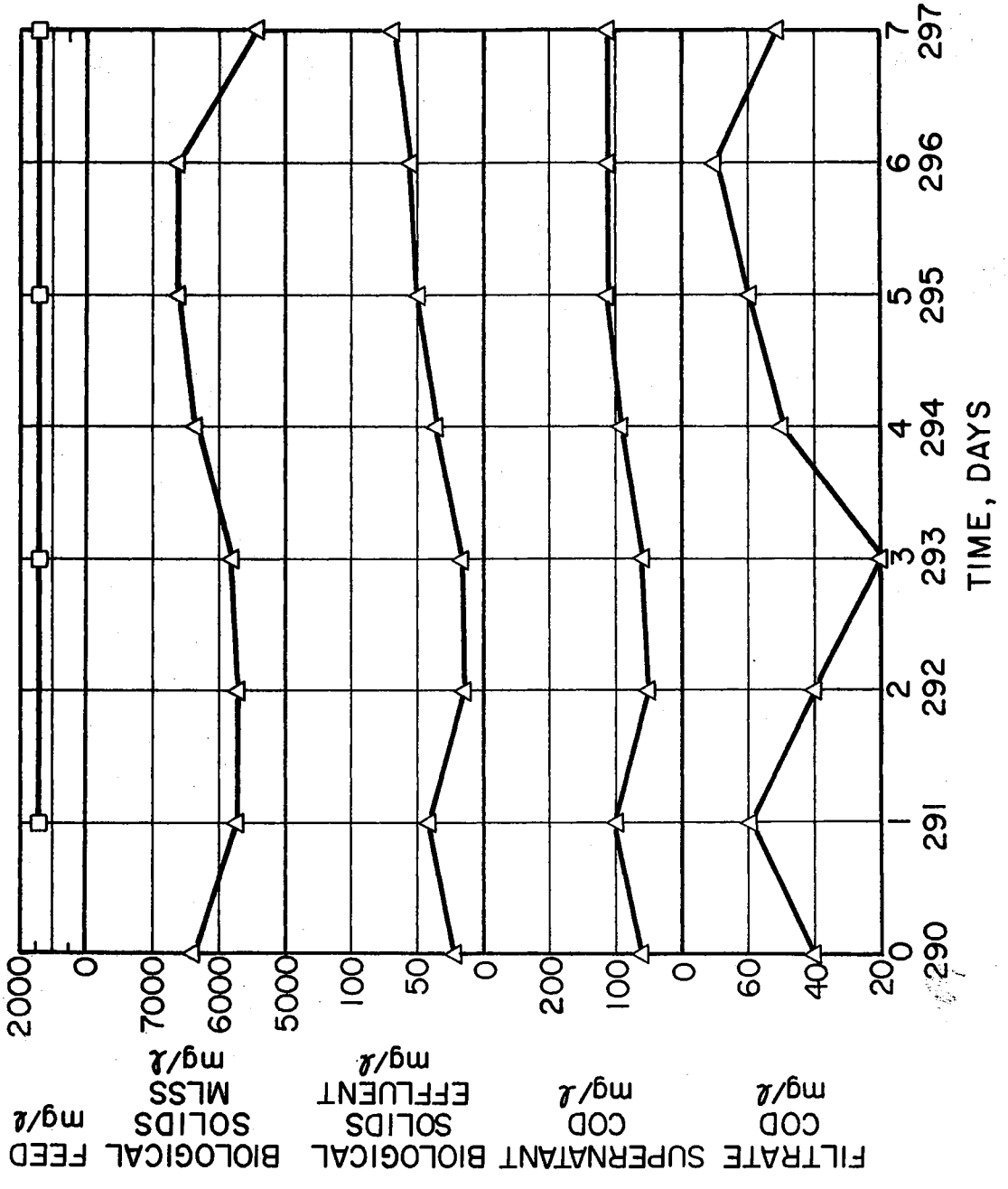

FILTRATE COD mg/ℓ
SUPERNATANT BIOLOGICAL COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
FEED mg/ℓ
TIME, DAYS
284
285
286
287
288
289
290
291
0
1
2
3
4
5
6
7
20
40
60
0
100
200
0
50
100
5000
6000
7000
2000
0

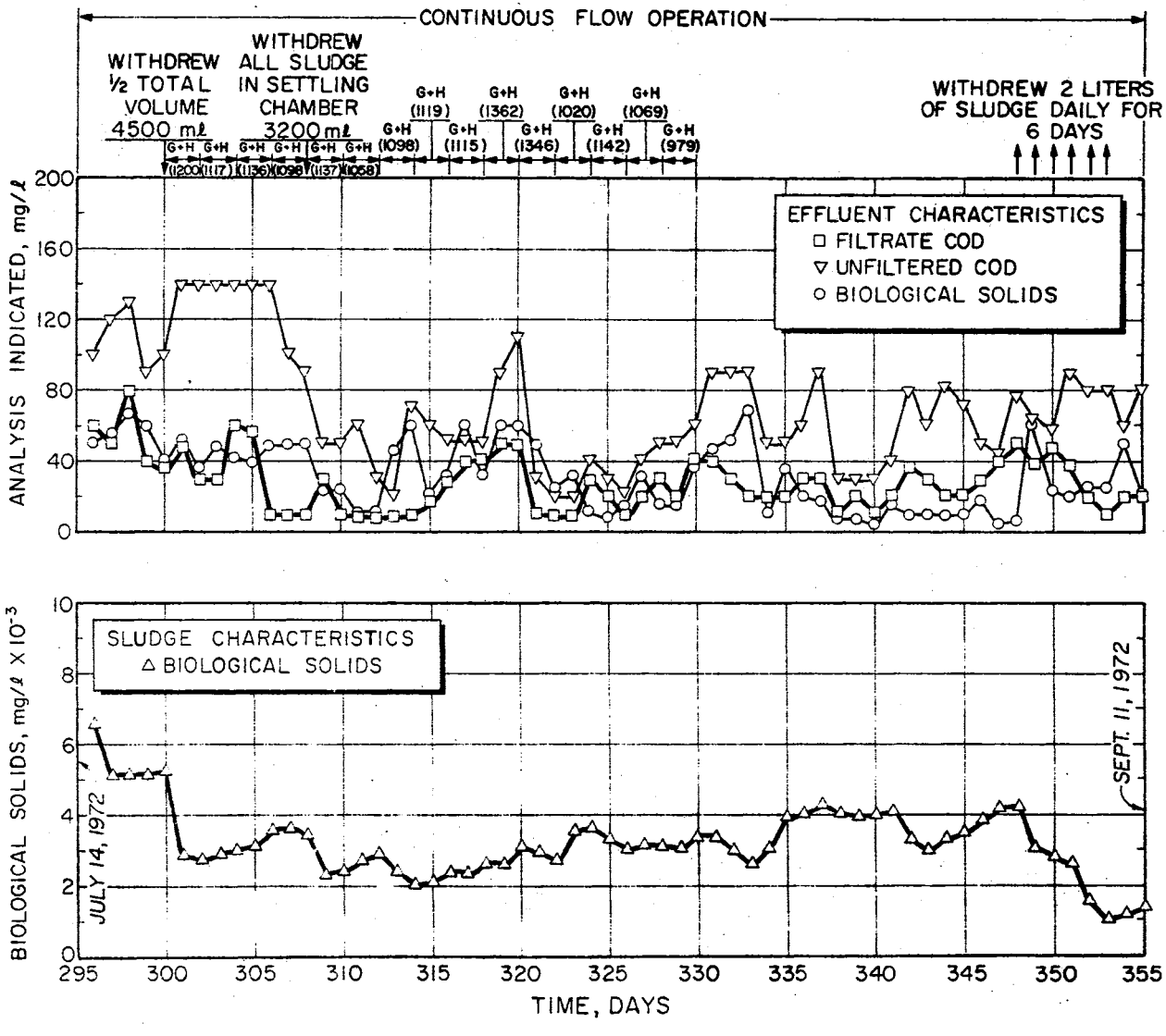
Figure 46. Tenth Week's Performance Data of the Extended Aeration Pilot Plant With Weekly Withdrawal, Hydrolysis, and Refeeding. Days 290-297. Glucose Feed, 1000 mg/l


FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
FEED mg/ℓ
TIME, DAYS
290
291
292
293
294
295
296
297
0
1
2
3
4
5
6
7
40
60
0
100
200
0
50
100
5000
6000
7000
0
2000

F. Studies to Test the Effectiveness of the "Hydrolytic Assist" Process as a Means of Controlling Predominance Changes Developed in the Extended Aeration Activated Sludge Pilot Plant

During the ninth and tenth weeks of operation at 1000 mg/l glucose feed, there was some indication that the sludge might be beginning to bulk. However, it can be noted from Figures 45 and 46 that there was no marked change in purification efficiency. The pH in the aeration tank was 6.7. Microscopic examination of wet mounts from the settling tank revealed the presence of filamentous microorganisms. The usual treatment plant methods of coping with bulking sludges (36-42) are to kill the responsible organisms by chlorinating the returned sludge, or to discharge the entire sludge mass and start over again. It has been pointed out by Heukelekian (38) and Ruchhoft and Kachmar (42) that some filamentous organisms are very efficient degraders of wastes high in carbohydrates. This indicates that the main problem arising from bulking sludge is not impairment of the purification mechanism, but solid liquid separation in the secondary clarifier, the lack of which allows the solids to escape. Such a situation developed in this pilot study in which settling was hampered because of bulking sludge. It was thought that perhaps the "hydrolytic assist" could be used to decrease the population of filamentous microorganisms, thereby allowing some other species present in the heterogeneous mixture to become predominant. Using the "hydrolytic assist" as a control procedure, one-half of the total volume of the system was withdrawn and subjected to acid hydrolysis (day 300, Figure 47). The pH of the aeration tank at the

Figure 47. Performance Data for the Hydrolytically-Assisted Extended Aeration Process While Utilizing the Hydrolysis Procedure as a Method of Enhancing a Change in Species Predominance. Days 295-355 - July 14, 1972, to Sept. 11, 1972


CONTINUOUS FLOW OPERATION
WITHDREW ½ TOTAL VOLUME 4500 mℓ
WITHDREW ALL SLUDGE IN SETTLING CHAMBER 3200 mℓ
WITHDREW 2 LITERS OF SLUDGE DAILY FOR 6 DAYS
G+H (1098)
G+H (1119)
G+H (1115)
G+H (1362)
G+H (1346)
G+H (1020)
G+H (1142)
G+H (1069)
G+H (979)
EFFLUENT CHARACTERISTICS
□ FILTRATE COD
▽ UNFILTERED COD
○ BIOLOGICAL SOLIDS
ANALYSIS INDICATED, mg/ℓ
SLUDGE CHARACTERISTICS
△ BIOLOGICAL SOLIDS
BIOLOGICAL SOLIDS, mg/ℓ X 10⁻³
JULY 14, 1972
SEPT. 11, 1972
TIME, DAYS

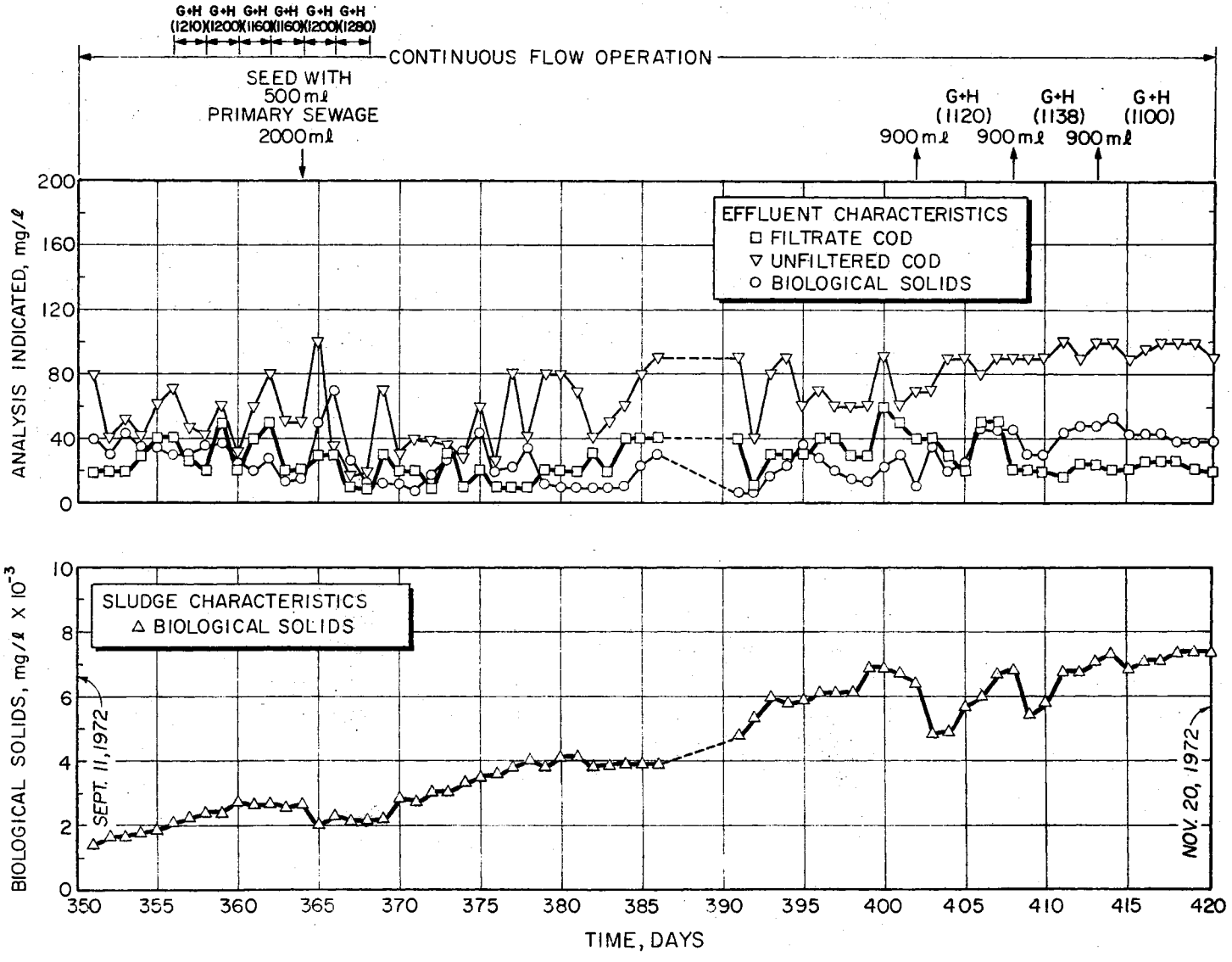
time of withdrawal was 6.70; the COD of the unfiltered raw hydrolysate was 5600 mg/l; the COD of the filtrate hydrolysate was 3800 mg/l. On day 308 (Figure 47), all of the solids in the final clarifier were removed (approximately 3400 ml) and subjected to acid hydrolysis. The pH in the aeration tank at this withdrawal was 6.7. The COD of the unfiltered hydrolysate was 4312 mg/l; the filtrate COD was 3332 mg/l. It should be noted that the general solubility of the hydrolysate for the filamentous sludge was similar to that from the non-filamentous sludge. No filamentous materials were observed in the hydrolysate.

The neutralized hydrolysate was fed back to the system along with 1000 mg/l glucose at the rate of 300 ml/day. This was twice as much hydrolysate per day as had been previously used in refeeding procedures. During this time, daily microscopic examination was conducted on the mixed liquor suspended solids. Although the filamentous population was decreased considerably by the hydrolysis procedure, filaments still dominated and bulking persisted. It should be pointed out that the total mixed liquor suspended solids concentrations in the aeration tank was reduced from 6600 mg/l to 2400 mg/l under this severe withdrawal schedule. The total mixed liquor suspended solids concentration after completion of the refeeding cycle was 4000 mg/l. It took 28 days to complete the refeeding cycle. It was noted after the refeeding period that although filamentous microorganisms were still prominent, there was the presence of increasing amounts of other microorganisms within the culture medium. This was taken as an indication that the "hydrolytic assist" process could serve as a means for controlling predominance changes in activated sludge processes. To gain further information, another experiment was conducted. This time, all of the sludge

in the final clarifier was removed daily for as long as there was some indication of the presence of bulking filamentous microorganisms. For six days (see Figure 47), 2000 ml sludge was withdrawn from the final clarifier. At the end of this withdrawal period, the mixed liquor suspended solids in the unit was reduced from 4000 to 1000 mg/l. The withdrawn sludge was hydrolyzed, neutralized, and fed back at 1000 ml/day along with 1000 mg/l glucose. At the end of the 12-day refeeding cycle, filamentous microorganisms were reduced considerably and other microorganisms were beginning to predominate. Over the period shown in Figure 47, the biochemical removal efficiency remained well above 90 percent. The biological solids concentration in the effluent fluctuated somewhat between 20 mg/l to 140 mg/l. However, the average solids concentration in the effluent was about 50 mg/l. In Figure 48 it can be seen that during the refeeding phase, the treatment efficiency was very high.

In order to speed up the predominance change brought about through the aid of the "hydrolytic assist" process, the pilot plant was seeded with 500 ml of primary sewage. This was done on day 369 (Figure 48). By day 379, settling had returned to normal; there was a change in color of the sludge. Microscopic examination showed that there were very few strands of filamentous microorganisms present. Microscopic examination also revealed the presence of protozoa in the mixed liquor. It should be noted that after reseeding, the pilot plant was placed on 1000 mg/l glucose feed only. All previously withdrawn hydrolysate had been re-fed to the unit. As seen in Figure 48, the mixed liquor suspended solids in the aeration tank at the time of reseeding was 2000 mg/l. After 40 days, the solids concentration had risen to 6800 mg/l.

Figure 48.. Performance of the Extended Aeration Process After Reseeding to Bring About a Predominance Change. Days 350-420 - Sept. 11, 1972, to Nov. 20, 1972


G+H G+H G+H G+H G+H G+H
(1210)(1200)(1160)(1160)(1200)(1280)
CONTINUOUS FLOW OPERATION
SEED WITH
500 mℓ
PRIMARY SEWAGE
2000 mℓ
G+H
(1120)
900 mℓ
G+H
(1138)
900 mℓ
G+H
(1100)
900 mℓ
EFFLUENT CHARACTERISTICS
□ FILTRATE COD
▽ UNFILTERED COD
○ BIOLOGICAL SOLIDS
ANALYSIS INDICATED, mg/ℓ
200
160
120
80
40
0
SLUDGE CHARACTERISTICS
△ BIOLOGICAL SOLIDS
BIOLOGICAL SOLIDS, mg/ℓ X 10⁻³
10
8
6
4
2
0
SEPT. 11, 1972
NOV. 20, 1972
350
355
360
365
370
375
380
385
390
395
400
405
410
415
420
TIME, DAYS

Biochemical purification during this period was excellent, and remained above 95 percent. Biological solids in the effluent averaged less than 40 mg/l. On days 401, 407, and 413, 900 ml of sludge were withdrawn from the clarifier and hydrolyzed, neutralized, and re-fed to the system. Figures 49-51 show the weekly performance of the unit under these conditions. The COD of the hydrolysate of sludge withdrawn on day 401 was 9,780 mg/l, unfiltered COD was 7000 mg/l. The COD of the hydrolysate withdrawn on day 407 was 10,067 mg/l; unfiltered COD was 6195 mg/l. The COD of the hydrolysate withdrawn on day 413 was 9880 mg/l for the unfiltered sample, and the filtrate COD was 6700 mg/l. The biochemical purification based on filtrate COD remained above 90 percent for each week. Biological solids in the effluent averaged less than 50 mg/l for each week.

G. Performance of the Hydrolytically Assisted Extended Aeration Process Growing on Dilute Kraft Mill Digester Blowdown Liquor as Carbon Source

The sludge employed in initiating this study was 1200 ml of acclimated cells taken from the batch unit used for the ΔCOD study, along with 1500 ml of settled sewage taken from the pollution control plant at Stillwater, Oklahoma. This initial seeding was diluted to nine liters, and continuous-flow operations begun. The substrate consisted of a 1/50 dilution of Kraft pulp mill digester blowdown liquor. The mixed liquor solids concentration in the reactor at the beginning of the continuous flow operation was 2570 mg/l. The pilot plant was placed into operation on Jan. 17, 1973, and continuous monitoring of

Figure 49. First Week's Performance Data, After Reinitiating Operation With the "Hydrolytic Assist" to the Extended Aeration Pilot Plant. Days 401-408. Glucose Feed, 1000 mg/l

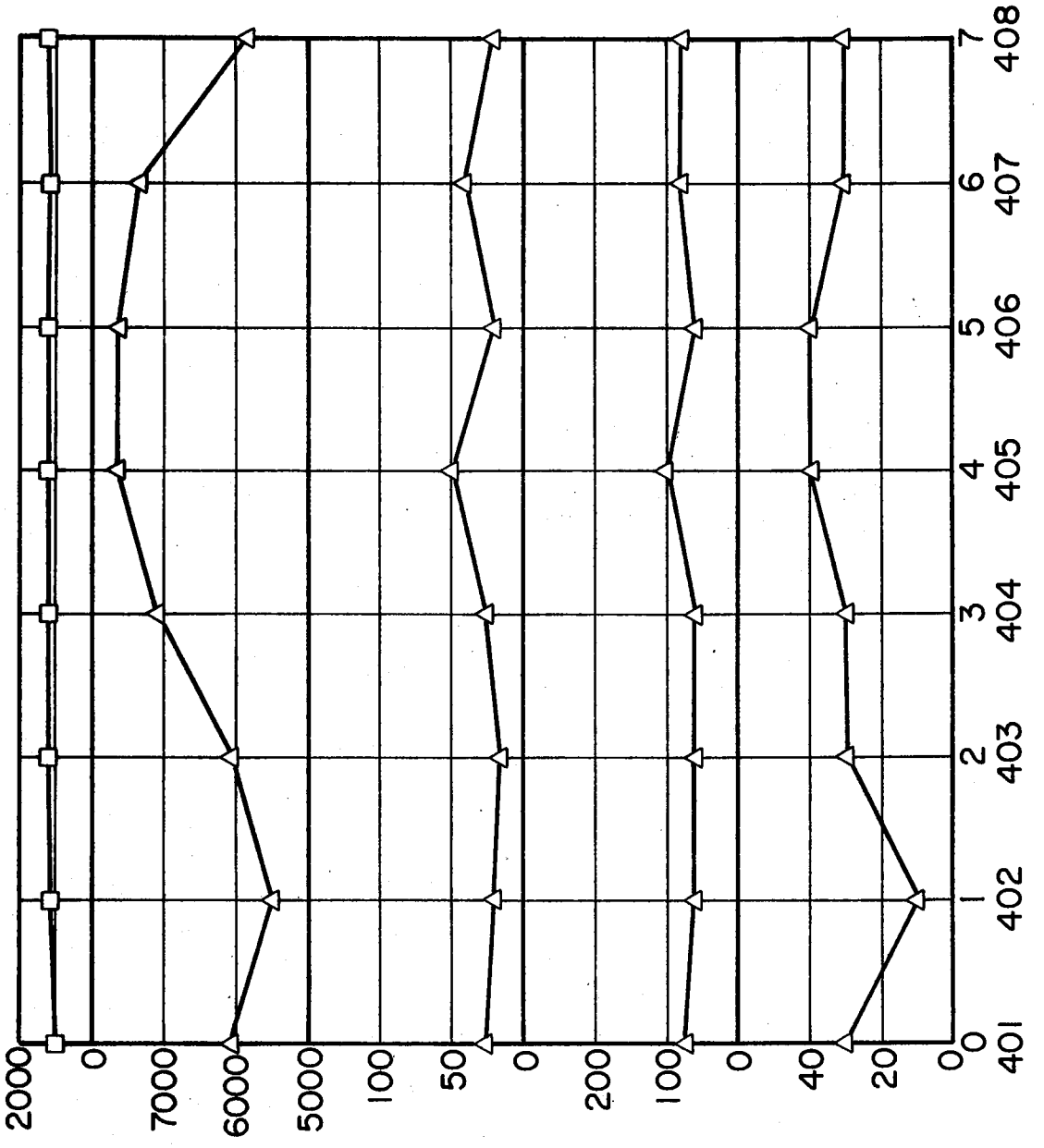
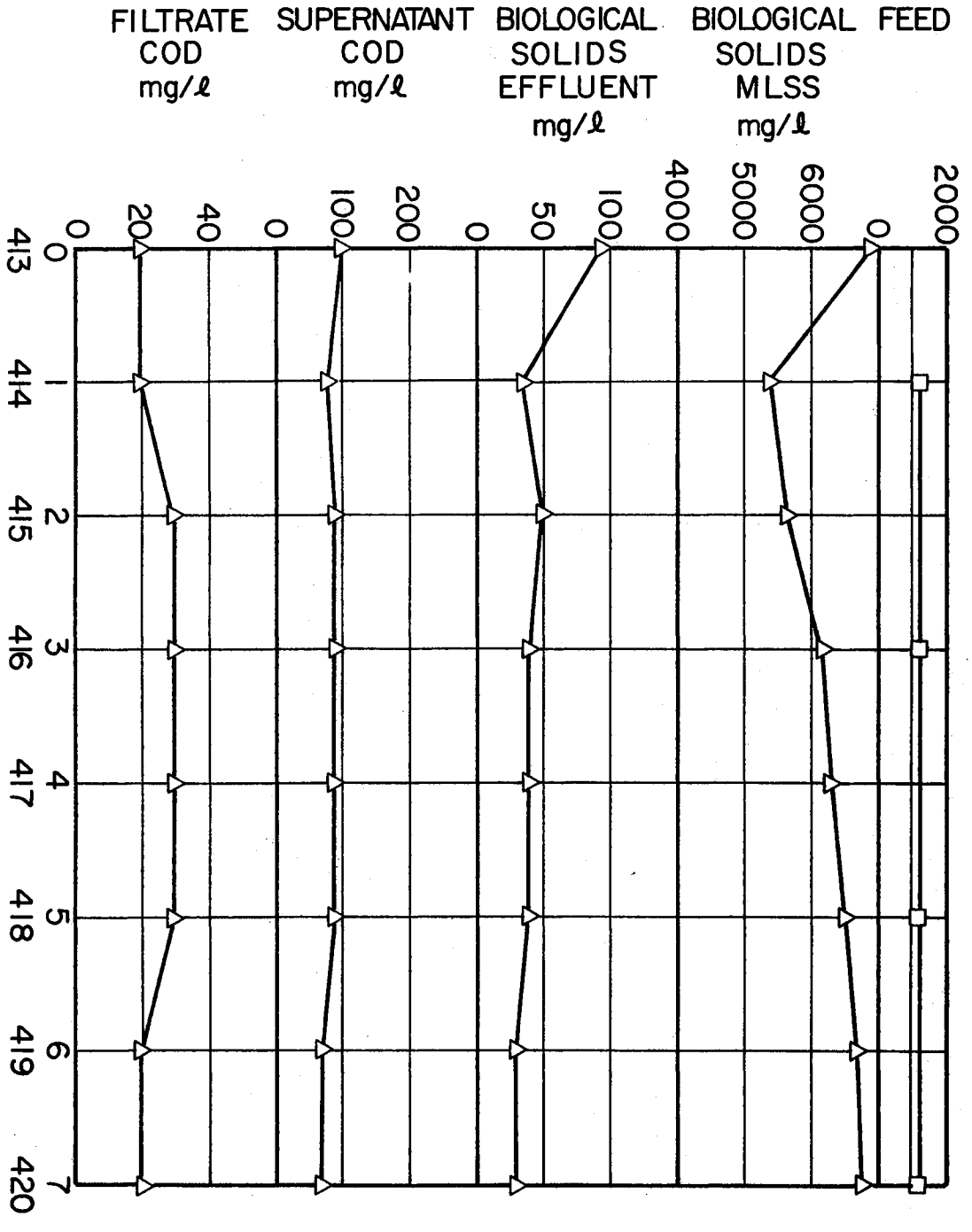

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
FEED
0
20
40
0
100
200
0
50
100
5000
6000
7000
2000
401
402
1
403
2
404
3
405
4
406
5
407
6
408
7

Figure 50. Second Week's Performance Data, After Reinitiating Operation With the "Hydrolytic Assist" to the Extended Aeration Pilot Plant. Days 407-414. Glucose Feed, 1000 mg/l

FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
FEED
20
40
60
0
100
200
0
50
100
4000
5000
6000
0
2000
407
408
1
409
2
410
3
411
4
412
5
413
6
414
7

Figure 51. Third Week's Performance Data, After Reinitiating Operation With the "Hydrolytic Assist" to the Extended Aeration Pilot Plant. Days 413-420. Glucose Feed, 1000 mg/l


FILTRATE COD mg/ℓ
SUPERNATANT COD mg/ℓ
BIOLOGICAL SOLIDS EFFLUENT mg/ℓ
BIOLOGICAL SOLIDS MLSS mg/ℓ
FEED
0
20
40
0
100
200
0
50
100
4000
5000
6000
0
2000
413
414
415
416
417
418
419
420
0
1
2
3
4
5
6
7

biological solids concentration and effluent characteristics begun on Jan. 26, 1973. The pilot plant used in this investigation was of the same type as used in the study of the synthetic glucose waste.

Figure 52 shows 60 days of performance data for the extended aeration pilot plant. The average filtrate COD of the effluent (COD_e) was 1480 mg/l. The average ΔCOD, that is, COD_i-COD_e, was 1200 mg/l. The results were similar to those for the experiments with synthetic waste. Purification efficiency was not hindered by the addition of hydrolysate along with the regular feed. Batch studies performed (Figures 18, 19) on the soluble fraction of the hydrolyzed cells show this material to be an available carbon source for other heterogeneous microorganisms.

It can be noted from Figure 52 that the biological solids concentration in the effluent varied from 30-200 mg/l. At times the systems developed situations in which there was a large amount of solids carryover with the effluent. It was surmised that the problem was not necessarily due to a poor settling sludge, but due to some amount of turbulence which was periodically caused by air bubbles being swept into the settling compartment. This had a tendency to disperse the settled solids in the clarifier, causing solids to be lost in the effluent carryover. To support the surmise that poor settling was probably due to the design of the clarifier and not the nature of the biological mass produced, samples were taken and subjected to routine settling tests each week. Samples of the results from these tests are shown in Figure 53. As can be seen in this figure, the settling characteristics of the mixed liquor in the reactor were excellent, and settling proceeded very rapidly. In only 15 minutes, the sludge had concentrated four-fold.

Figure 52. Performance of an Extended Aeration Pilot Plant Operating With the "Hydrolytic Assist" and Kraft Mill Waste as Carbon Source

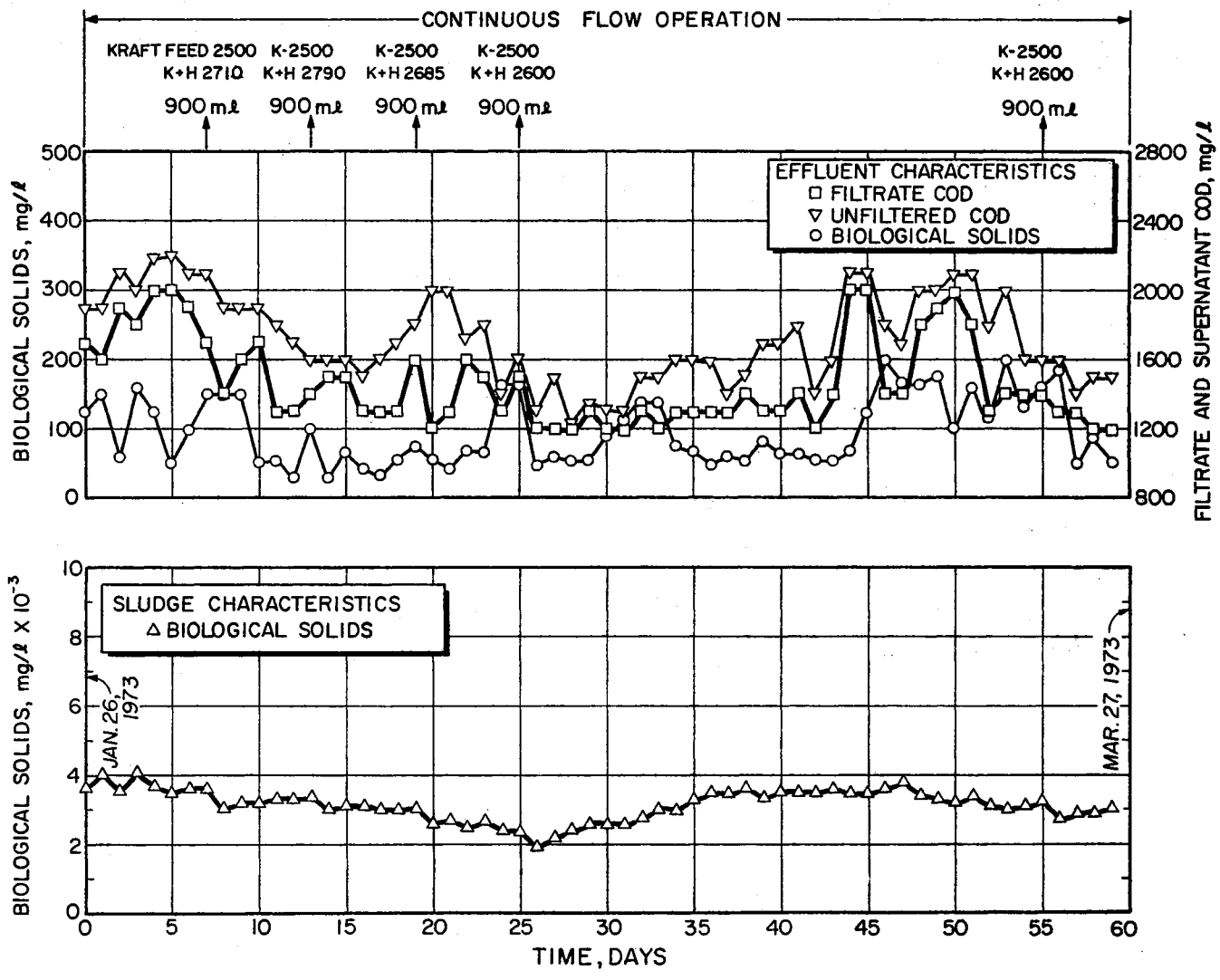
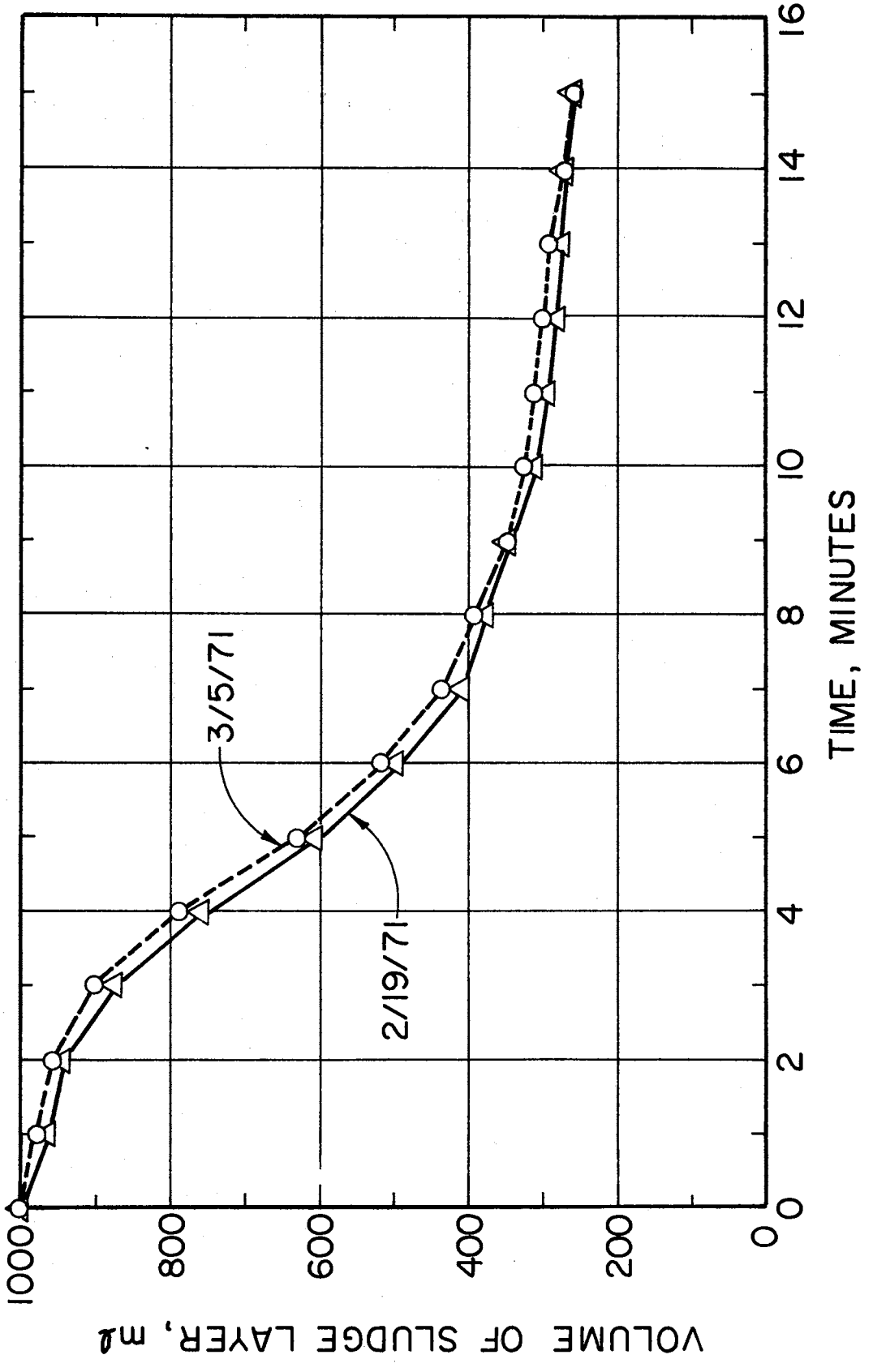

CONTINUOUS FLOW OPERATION
KRAFT FEED 2500 K+H 2710
K-2500 K+H 2790
K-2500 K+H 2685
K-2500 K+H 2600
K-2500 K+H 2600
900 mℓ
900 mℓ
900 mℓ
900 mℓ
900 mℓ
EFFLUENT CHARACTERISTICS
□ FILTRATE COD
▽ UNFILTERED COD
○ BIOLOGICAL SOLIDS
BIOLOGICAL SOLIDS, mg/ℓ
FILTRATE AND SUPERNATANT COD, mg/ℓ
SLUDGE CHARACTERISTICS
△ BIOLOGICAL SOLIDS
BIOLOGICAL SOLIDS, mg/ℓ X 10⁻³
JAN. 26, 1973
MAR. 27, 1973
TIME, DAYS

Figure 53. Settling Characteristics of a Hydrolytically-Assisted Extended Aeration Activated Sludge


VOLUME OF SLUDGE LAYER, ml
1000
800
600
400
200
0
0
2
4
6
8
10
12
14
16
TIME, MINUTES
3/5/71
2/19/71

H. O_2 Uptake Characteristics of Various Effluents From the Extended Aeration Pilot Plant

To further evaluate the extended aeration process incorporating the "hydrolytic assist" and to give support to its effectiveness in treating soluble organic waste material, effluent samples from the pilot plant were tested periodically to determine their effect on O_2 resources in receiving streams. One such test using the open stirred jar technique is shown in Figure 54. During the first 24 hours, replenishment of the dissolved oxygen previously removed chemically by the addition of sodium sulfite and cobalt was measured to determine the rate of atmospheric reaeration (K_2) in the jar reactor. In this particular run, a K_2 value of 0.099 hr^{-1} was calculated from the DO data. After the reaeration period, effluent substrate was added to the reactor in a 50/50 ratio with tap water, and the DO measured during both the deoxygenation and recovery periods. During this experiment (days 239-240), the pilot plant was fed 1000 mg/l glucose plus sludge hydrolysate. The total feed concentration was 1200 mg/l. The filtrate COD of the plant effluent was 43 mg/l. The biological solids concentration was 58 mg/l, and the total organic content (COD) was 130 mg/l. Examination of Figure 54 shows a slow decrease in DO with an accompanying slow recovery period. The corresponding O_2 uptake curve indicates that a total of 22.5 mg/l of oxygen was required by the microorganisms after five days. An experiment was run using raw cell hydrolysate obtained from the cells in the pilot plant on day 369 of continuous flow operation (Figure 55). An acclimated seed was obtained from the settling

Figure 54. DO Profile and O_2 Uptake in an Open Stirred Reactor due to Addition of Treated Effluent From the Extended Aeration Pilot Plant Operated With 500 mg/l Glucose Feed. Days 239-240

Substrate Characteristics:

Extended Aeration Effluent
Days of Operation, 239-240 (May 18-19, 1972)
Total Supernatant COD (Se) = 130 mg/l
Biological Solids (Xe) = 58 mg/l
Filtrate COD (S_f) = 43 mg/l

Dilution Ratio = 50/50

K_2 = 0.099 hr^{-1} Temp. = 22°C

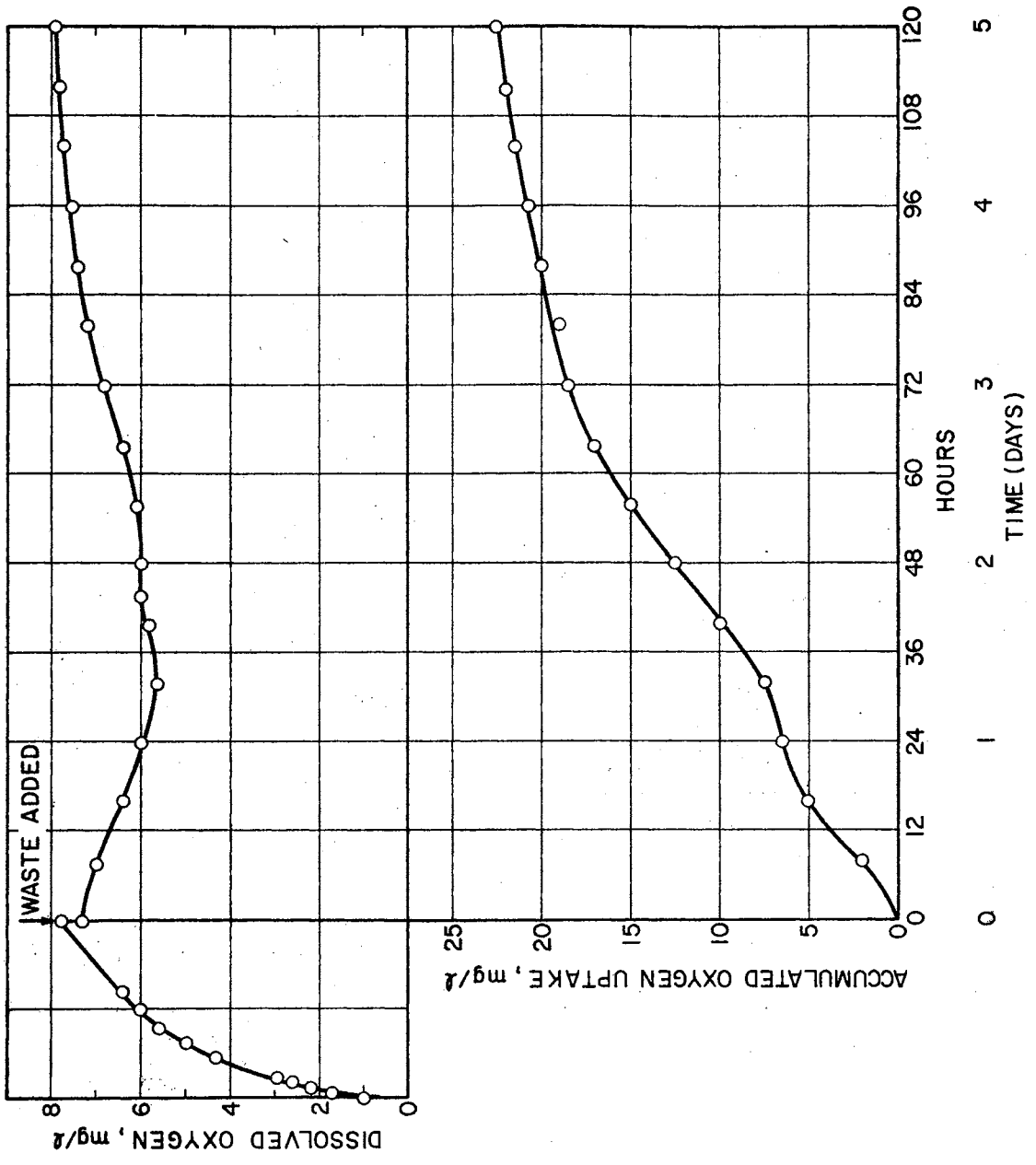

DISSOLVED OXYGEN, mg/ℓ
WASTE ADDED
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
HOURS
TIME (DAYS)

Figure 55. DO Profile and O_2 Uptake in an Open Stirred Reactor due to Addition of Treated Effluent From the Extended Aeration Pilot Plant Operated with 50 mg/l Sludge Hydrolysate. Day 369

Substrate Characteristics:

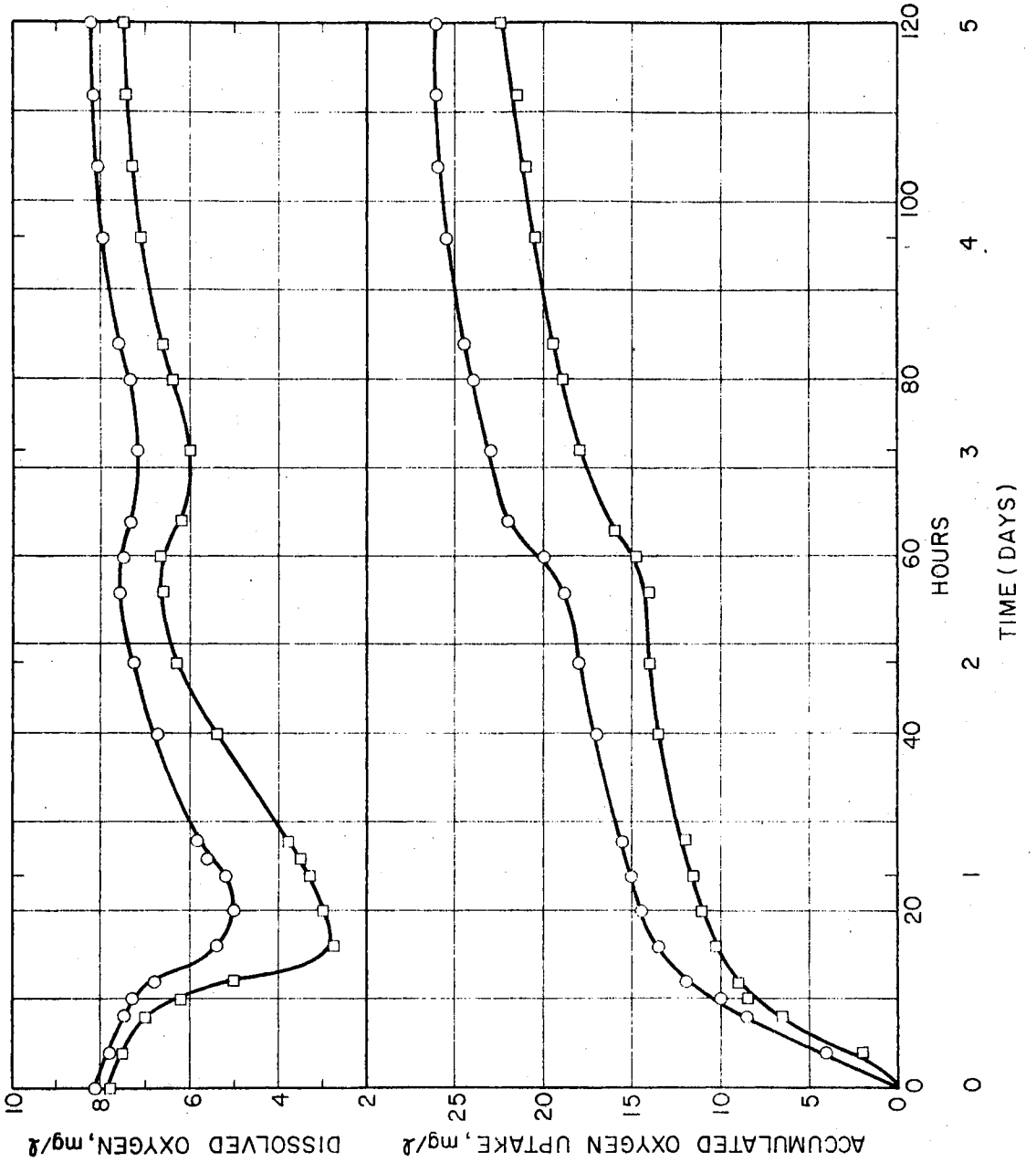
Hydrolysate From Extended Aeration Unit
Day of Operation, 369 (Sept. 25, 1972)
Total COD = 6400 mg/l
Seed = Extended Aeration Effluent

Conditions in Open Reactors

Total COD = 50 mg/l
Seeding Volume = 50 mg/l

○ = Jar 1, K_2 = 0.120 hr^{-1}

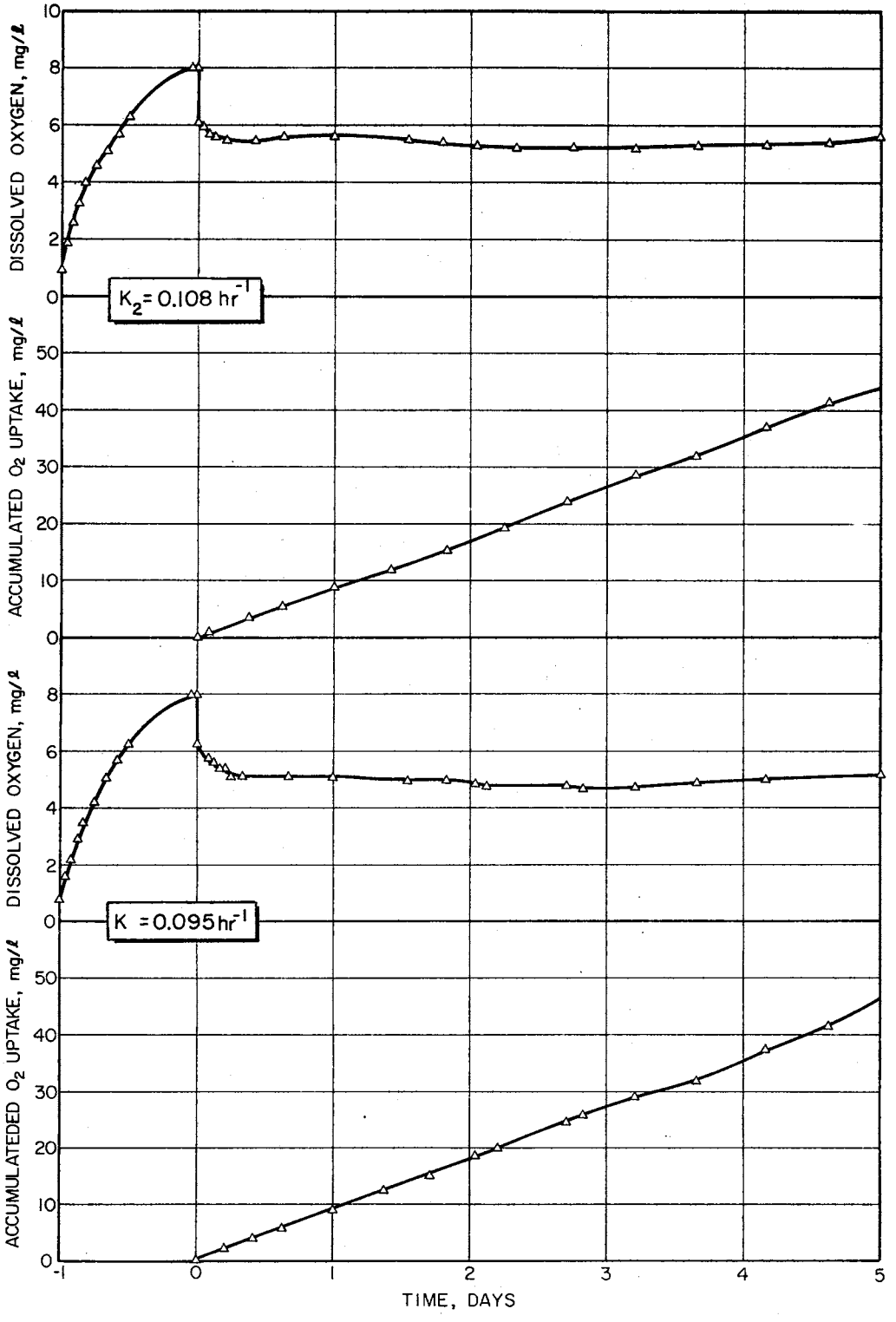
□ = Jar 2, K_2 = 0.088 hr^{-1}


DISSOLVED OXYGEN, mg/ℓ
ACCUMULATED OXYGEN UPTAKE, mg/ℓ
HOURS
TIME (DAYS)

tank, and adequate phosphate buffer was added to maintain the pH at or near 7.0. The unfiltered COD of the cell hydrolysate was 6400 mg/l; the concentration of hydrolysate added to the reactor was 50 mg/l. The seed concentration added was 0.5 percent by volume. As seen in Figure 55, there were two separate phases of deoxygenation and oxygen recovery. The accumulated O_2 uptakes after five days were 26.2 mg/l and 21.4 mg/l, respectively.

Figure 56 shows the results of an open stirred reactor study using effluent obtained from the pilot studies when Kraft processing liquor was fed. The reactor was polluted with 50 percent effluent and 50 percent tap water. The effluent contained 1800 mg/l of supernatant COD and 1400 mg/l of filtrate COD. K_2 values of 0.108 hr^{-1} and 0.095 hr^{-1} were used. The accumulated O_2 uptake after five days was 44 mg/l in each reactor.

Figure 56. DO Profile and O_2 Uptake in an Open Stirred Reactor due to Addition of Effluent From the Extended Aeration Pilot Plant Operated With Kraft Mill Waste as Feed


DISSOLVED OXYGEN, mg/ℓ
ACCUMULATED O2 UPTAKE, mg/ℓ
K2= 0.108 hr-1
DISSOLVED OXYGEN, mg/ℓ
ACCUMULATEDED O2 UPTAKE, mg/ℓ
K = 0.095 hr-1
TIME, DAYS

CHAPTER V

DISCUSSION

It was seen in Figures 5 and 11 that the hyperbolic curve proposed by Monod does adequately represent the data in plots of μ versus S and μ_{O_2} versus S. This relationship between the growth rate and concentration of an essential nutrient was proposed by Monod (43) as a hyperbolic function similar to the equations used to describe the effect of substrate concentration on velocity of enzyme action (44). Although the Monod expression has been successfully used, it must be remembered that it relates the concentration of a single nutrient to the specific growth rate. However, Peil and Gaudy (45) have shown that the hyperbolic relationship applies also to the soluble fraction of a municipal sewage when substrate concentration is measured as total COD. Peil and Gaudy, in investigations using municipal waste, reported an average μ_{max} value for concentrated sewage of 0.45 hr^{-1}. It can be seen in Figure 7 that the maximum growth rate value for a heterogeneous population growing on hydrolysate was 0.680 hr^{-1}. This value was slightly higher than the average μ_{max} values reported by Gaudy and Gaudy (35) for a carbohydrate waste such as glucose. Goldstein (29), in his investigations using acetic acid, reported an average maximum growth rate value of 0.805 hr^{-1} for heterogeneous populations growing on acetic acid. The K_s value obtained from the hydrolysate experiment was 35 mg/l. This can be compared with average values of 75-150 reported by Gaudy and Gaudy (35),

52 reported by Peil and Gaudy (45), and 60 reported by Goldstein (29). In general, the values obtained for μ_{max} and K_s on cell hydrolysate fall within the limit of values obtained in a larger body of kinetic data on cell hydrolysate obtained in the bioengineering laboratories at Oklahoma State University (Goldstein and Gaudy, unpublished data).

The relationship between exponential O_2 uptake and S_o was, in general, of the hyperbolic type similar to that of μ and S_o. The $\mu_{max_{O_2}}$ was 1.24 hr^{-1}, and K_s was 67. Thus, the Monod equation can be written to express the relationship between initial substrate concentration and rate of O_2 uptake.

$$\mu_{O_2} = \frac{\mu_{max_{O_2}} \cdot S_o}{K_s + S_o}$$

This equation provides a fairly good fit to the data obtained in the present study.

The yield values for cells growing on hydrolysate (Figures 8 and 9) were 0.64 and 0.51, respectively. Cell yield, for pure cultures, is considered to be one of the "biological constants." However, it has been amply shown by Gaudy and co-workers (46-48) that yield varies over a considerable range for heterogeneous populations. It has also been proposed by Gaudy and Gaudy (49) that the difference in cell yields for heterogeneous populations metabolizing an exogenous substrate under constant experimental conditions is due mainly to ecological variance of population. The data presented in Figures 8 and 9 were obtained under the same experimental conditions but using a different sewage seed for each experiment. The values found are close to the average yields (0.40-0.60) reported in the literature (35). The cell yield values reported herein were determined at the conclusion of the

substrate removal phase of the growth cycle. It should be pointed out, however, that the yield values determined at the end of the substrate removal phase have been found to apply throughout the growth curve--that is, during exponential and declining phases of growth.

This investigation was concerned with the treatment of soluble organic substrates. It should be pointed out that not all organic matter is soluble nor is it all biodegradable; however, it must be so to exert a BOD. Also, it should be pointed out that entrapped inorganic matter in some waste streams may permit some buildup of an inorganic fraction in the sludge.

The results of this study support the evidence reported by Yang and Gaudy (50) that the hydrolytically assisted extended aeration process can be used effectively in treating a soluble organic waste. It was seen in Figure 21 that the purification efficiency based on filtrate COD averaged 90 percent or better. The purification efficiency, however, was slightly less than that previously reported for a similar system growing on 300 mg/l of glucose and incorporating the same "hydrolytic assist" techniques (31)(50). During this phase of the investigation, some settling problems were encountered. The pH of the system remained between 6.8 and 7.0 during the entire operational period. There were no indications of the presence of filamentous microorganisms or the development of a bulking sludge. It has been surmised that some of the settling problems were inherent in the design of the internal clarifier. The problem seemed to be aggravated by the presence of a low concentration of mixed liquor suspended solids. The problem, however, was successfully controlled through the use of chemical coagulants. The overall results of this phase of investigation compare favorably with

results reported by Yang and Gaudy in the previous pilot study using 300 mg/l glucose (31)(50). They started with a solids level of slightly above 5000 mg/l and, after 15 weeks of operation utilizing periodic weekly withdrawals, had slightly less than 4000 mg/l of solids in the aeration tank. In the present 10-week study using 500 mg/l glucose and the same "hydrolytic assist" techniques, the unit stabilized at 2200 mg/l. The initial solids level at the beginning of the 10-week period was 4500 mg/l. The digestion factor in this study appears to be slightly higher than reported by Yang (31). However, it must be remembered that settling problems were encountered during the course of this study, and this is probably the reason for the lower solids levels at the conclusion of this test period.

The results of this study further support the evidence that the hydrolytically assisted extended aeration process can be used effectively as a means of treating a soluble organic waste even at rather high organic loadings. The organic loading during the phase of the study in which 1000 mg/l glucose was fed to the pilot plant was 100 lb COD/1000 cu ft/day. It can be seen in Figure 36 that with organic loadings of 1000 mg/l of glucose plus hydrolysate refeed, the purification efficiency based on filtrate COD was 97.5 percent. The purification efficiency here was slightly higher than the value presented by Yang and Gaudy (50) in the previous studies using 300 mg/l glucose and even higher than the results reported in this study using 500 mg/l glucose. The solids concentration at the beginning of the test period was 5000 mg/l. At the end of a 10-week test period, the system solids were 5800 mg/l.

The primary development leading to the investigation of the utility

of the "hydrolytic assist" for control of predominance changes was the appearance of a bulking filamentous sludge that would not settle. One of the serious operational problems encountered in the activated sludge process is impairment of sludge settling, resulting in excessive amounts of suspended solids in the effluent. Phenomena resulting in the loss of sludge solids into the effluent include dispersed growth, rising sludge and deflocculation, as well as bulking. When bulking occurs, the sludge is well-formed and the supernatant liquid is clear, but the sludge settles slowly and compacts poorly. Bulking of sludge can occur without an overgrowth of sludge by filamentous microorganisms, but the majority of the bulking cases described in the literature have been cases of filamentous bulking (36-42). Microscopic examination of random wet mounts taken from the aeration tank indicate that the sludge bulking which occurred in this study was due to the presence of filamentous species. Many causes for the predominance of filamentous organisms in activated sludge have been cited (36-42). The reasons for the onset of growth of filamentous organisms in the present study could include a drop in pH due to nitrification. There was a gradual drop in pH from 6.9 to 6.5. This slight decrease in pH may have been enough to foster predominance of the filamentous forms. Although nitrates were not monitored in the present system, there is a possibility that nitrification could have been taking place during the period of the gradual drop in pH. Doubling the amount of buffer in the synthetic feed was not sufficient to hold the pH at 6.9-7.0. Another possibility is the incorporation of neutralized acid hydrolysate as feed to the system. Harrison and Heukelekian (37) have concluded that in the case of Sphaerotilus, luxurious growth is dependent upon a source of organic nitrogen. There

are various ways to attempt to prevent or eliminate the growth of filamentous organisms (38)(40). However, none of the field methods thus far employed have been truly effective.

During the present study, when most of the sludge consisted of filamentous organisms, the "hydrolytic assist" was employed as a control method to rid the system of the undesirable organisms and possibly enhance the growth of more desirable organisms which would settle readily. It should be noted from Figure 47 that at the time of the presence of filamentous growth, the overall purification of the system was not hampered. The main problem was that of settling. On day 300 (Figure 47), one-half of the total sludge was removed from the system and hydrolyzed. On day 308 (Figure 47), all of the sludge in the settling compartment was removed and hydrolyzed. The hydrolyzability of the filamentous organisms was similar to that of the non-filamentous organisms previously developed during this study. That is, acid hydrolysis dissolved the filamentous organisms, and the percent soluble COD of the hydrolysate was approximately the same as that for sludge which did not contain an abundant amount of filamentous organisms. The combined neutralized hydrolysate was then fed back to the system along with 1000 mg/l of glucose at 300 ml/day, which was twice the refeed rate normally used for refeeding. Daily pH determinations and microscopic examinations were made. At the end of the refeeding period, the pH of the aeration tank was 6.8. Settling had improved, and filamentous growth still persisted, but the population had been reduced considerably. Results from this investigation were positive enough to warrant further studies on the possibility of using the "hydrolytic assist" as a means of exerting some control over predominance changes.

On days 348-353, 2000 mls of sludge were withdrawn from the final clarifier and subjected to acid hydrolysis. The combined neutralized hydrolysate was fed back along with 1000 mg/l of glucose at a rate of 1000 ml/day. The pH of the unit at the end of this test period was 6.8. Settling was greatly improved, and microscopic examination revealed the presence of only a small population of filamentous microorganisms. Several non-filamentous species were noticed along with the first indication of the reestablishment of protozoa. The results of this study indicate that the "hydrolytic assist" can be used successfully in bringing about a predominance change in an activated sludge process that has developed a bulking filamentous bio-mass as a dominating form. The present study also shows that the solubilized organic content of filamentous organisms can be used as substrate for other microbial populations.

The pilot plant was reseeded with a small sewage inoculum at the close of the second withdrawal and refeeding period. This was done to ensure the presence of a more desirable heterogeneous population. After this was done, the system came into balance within 10 days. Purification efficiency remained above 90 percent. Settling was restored to normal. Microscopic examination of mixed liquor revealed the presence of only a small number of filamentous organisms.

The industrial waste utilized in this study was obtained from a Kraft pulp mill located in Valliant, Oklahoma. The paper industry is vitally involved with the mounting problems in water pollution control, since water performs a key role in the paper-making process. With an average of over a quarter ton of paper being consumed annually be each person in the United States, the water requirement to meet these demands

places the paper industry among the foremost users of the nation's water resources. The need, therefore, is urgent to improve treatment of wastewater from these industries. The Kraft waste was chosen because of these reasons, and because it afforded the opportunity to evaluate the proposed hydrolytically assisted extended aeration process using an actual industrial waste. The concentrated blowdown liquor was chosen in an effort to reduce the total volume of liquid which had to be shipped to this laboratory, and because it was hoped to complete the pilot plant operation with one sample of organic material.

To begin this fundamental study of wastewater treatment, a chemical and biological analysis of the untreated wastewater was required. Also required were fundamental batch studies to determine what purification efficiencies might be expected from the proposed process. These data provided the basic biological characteristics for the wastewater and information concerning its amenability to aerobic biological treatment. The characteristics usually employed for describing wastewater streams include BOD, COD, suspended solids, and pH. The analyses given in Table III describe the physical and chemical characteristics of the sample of digester blowdown liquor obtained. It was estimated that a dilution of 1/50 would approximate the concentration of waste discharged from the plant. Sulfuric acid was used to adjust the pH of the diluted sample to pH 7.5 ± 0.2. Upon determining the waste characteristics and selecting an organic loading of approximately 2500 mg/l of COD and 500 mg/l BOD_5, batch studies were begun to determine the expected purification efficiency based on the ΔCOD test (35).

The batch unit was developed from a sewage seed and acclimated to the untreated waste for three weeks. Data used to calculate the ΔCOD

for the batch unit were taken from samples collected for 28 continuous days following the acclimation period. Weekly seed samples were taken from the batch unit for separate studies to determine yield values and show metabolic response. The seed used for the continuous flow unit was taken from the batch unit which had been operating for eight weeks. A small inoculum of sewage was added, and the combined seeds acclimated by batch feeding for two additional weeks prior to the beginning of the continuous flow operation. Results from the batch experiments were shown in Figures 13-17. The ΔCOD found in the batch studies was 673 mg/l; however, the ΔCOD determined during the continuous flow study averaged 1200 mg/l (Figure 52). The difference between the ΔCOD found in the batch studies and the ΔCOD found in the continuous flow studies was due possibly to insufficient time for the development of an acclimated microbial population during the batch studies. The obvious thing to have done in a situation like this was to perform a batch study on a more acclimated seed taken from the continous flow unit. However, the difference in the ΔCOD values between the batch and continuous flow units was not realized until late in this investigation when the amount of substrate remaining to complete the continuous flow study was limited. Therefore, a fresh sample of concentrated Kraft liquor was taken from the same source as the original concentrated waste. The sample was analyzed and found to be of similar characteristics and concentration. The COD of the fresh sample was 120,000 mg/l, the BOD_5 was 27,000 mg/l, total solids, 3400 mg/l, and the pH, 12.0. Acclimated seed was taken from the extended aeration pilot plant, and batch studies performed to determine the ΔCOD of the new sample growing in a more acclimated bio-mass. The unit was batch fed at a COD of 2500

mg/l, which was the influent feed concentration of the continuous flow unit.

Fifteen days of performance data provided an average ΔCOD value of 1134 mg/l. This compared favorably with the average of 1200 mg/l ΔCOD value obtained from the continuous flow studies. Figure 57 shows the metabolic response of an acclimated microbial population taken from an extended aeration plant growing on a Kraft waste. From this experiment it can be seen that the ΔCOD was 1000 mg/l; the yield was 0.63, and the purification efficiency based on BOD_5 was 92 percent. These values also compare favorably with the results obtained from continuous flow experiments. The purification based on BOD_5 removal was 91 percent in the continuous flow studies. The relatively low efficiency based on the COD test in both batch and continuous flow is due to the high non-biodegradable fraction present in the untreated waste, i.e., lignin. Figure 58 shows the ΔCOD values for all days tested under batch and continuous flow. Information obtained from the plot shows that the results obtained in batch studies performed with the more acclimated bio-mass approximate more closely the performance of the continuous flow operation. These results tend to indicate the need for caution in using batch experiments to predict the performance in continuous flow operations. Some researchers may argue the validity of using batch studies at all for design pruposes. It was not the purpose of this discussion to argue that particular case, but to offer some explanation as to the difference in ΔCOD values obtained in this investigation. It can be concluded from this phase of investigation that the hydrolytically assisted extended aeration process can be used effectively for the treatment of a diluted Kraft blowdown liquor.

Figure 57. Metabolic Response of an Acclimated Microbial Population Growing on a Kraft Mill Waste

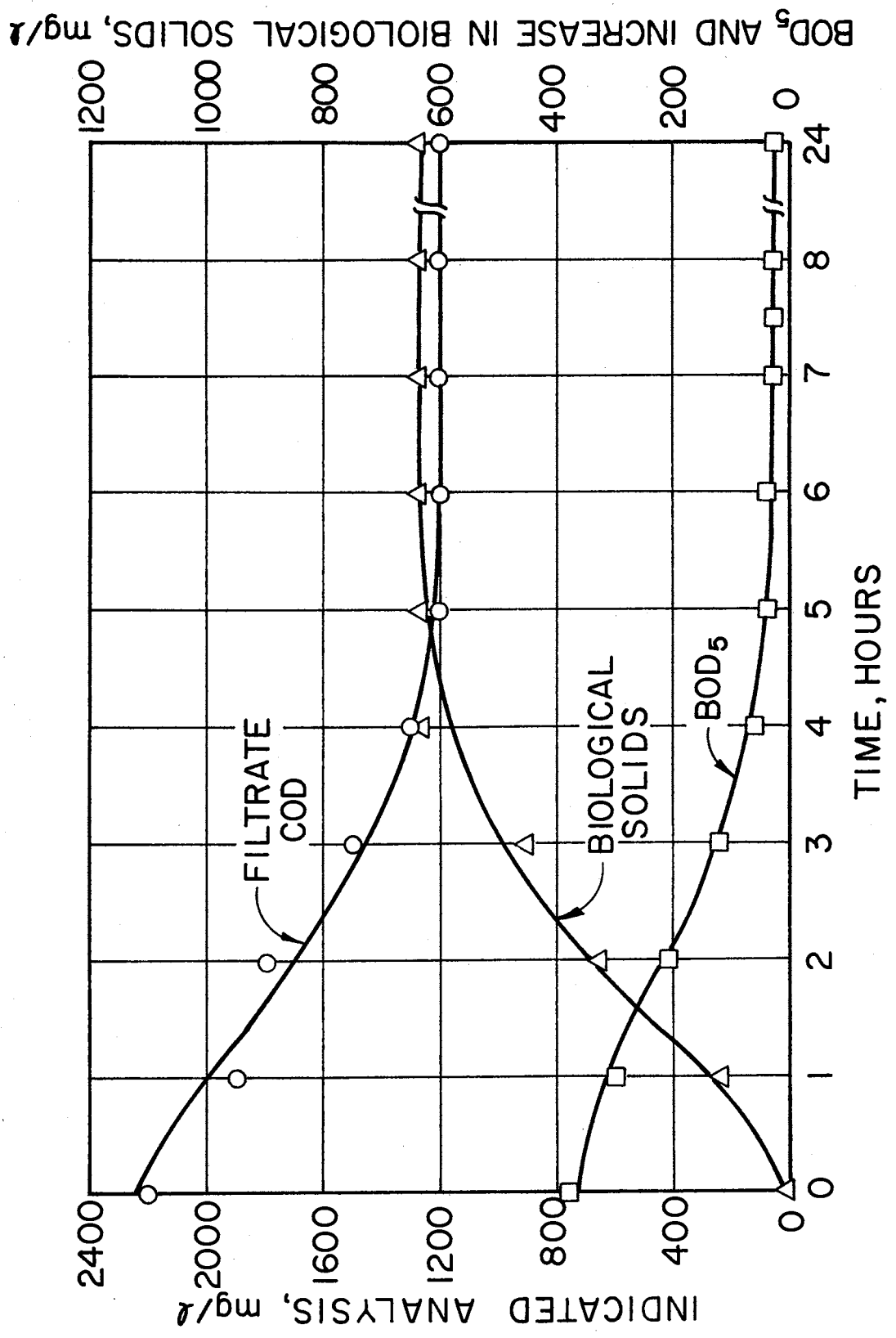
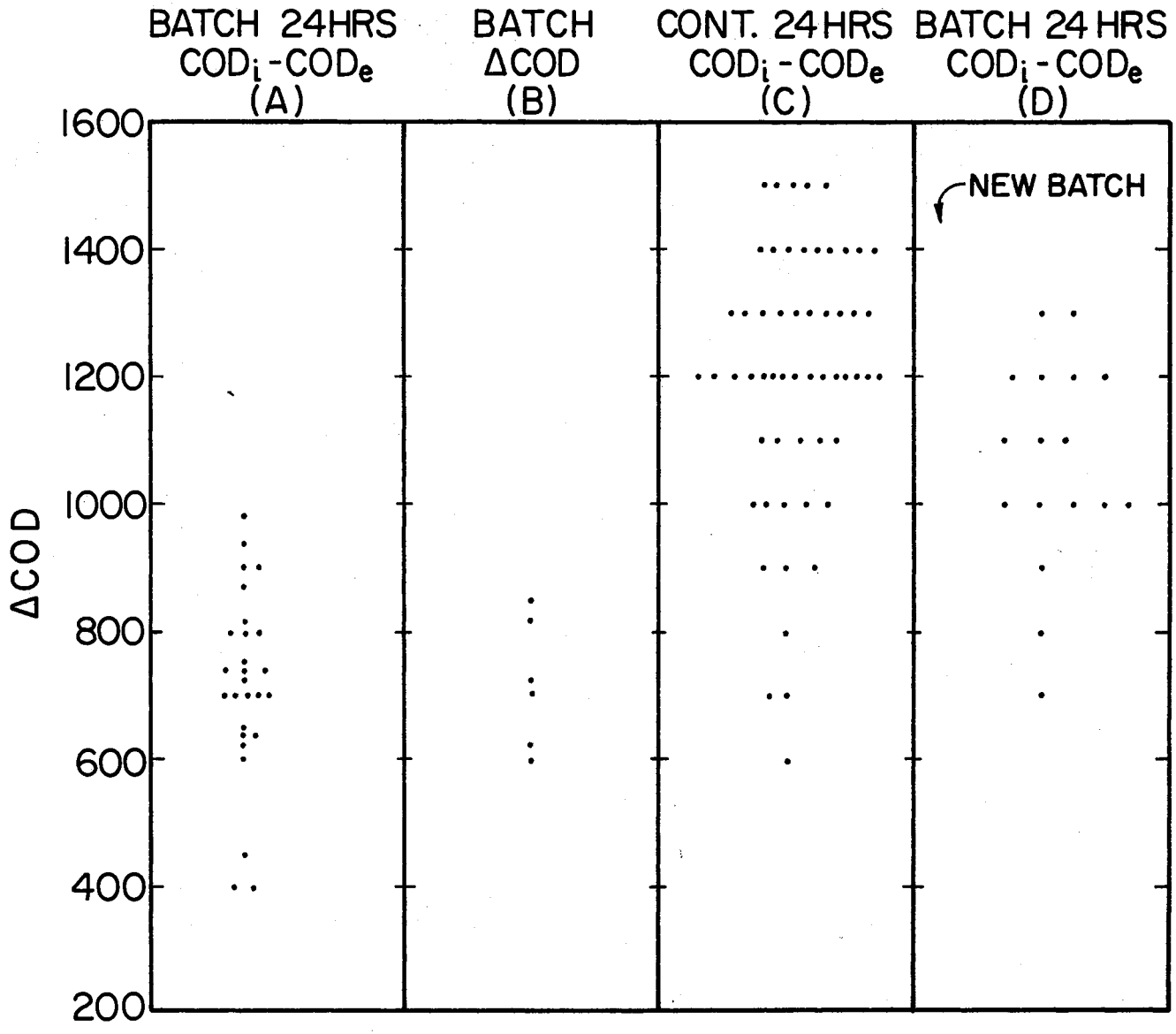

INDICATED ANALYSIS, mg/ℓ
BOD5 AND INCREASE IN BIOLOGICAL SOLIDS, mg/ℓ
TIME, HOURS
FILTRATE COD
BIOLOGICAL SOLIDS
BOD5
0
400
800
1200
1600
2000
2400
0
200
400
600
800
1000
1200
0
1
2
3
4
5
6
7
8
24

Figure 58. Comparison of ΔCOD Results Obtained from Batch and Continuous-Flow Studies


BATCH 24HRS
$COD_i - COD_e$
(A)
BATCH
ΔCOD
(B)
CONT. 24HRS
$COD_i - COD_e$
(C)
BATCH 24 HRS
$COD_i - COD_e$
(D)
NEW BATCH
ΔCOD
1600
1400
1200
1000
800
600
400
200

It can be seen from Figure 52 that after four weeks of operating the pilot plant under continuous flow conditions with periodic sludge withdrawal, hydrolysis, and refeeding, that the mixed liquor suspended solids concentration had reduced from 3660 mg/l to 1900 mg/l. Because of this low level of mixed liquor suspended solids, weekly sludge withdrawals were terminated. The low rate of buildup of solids was probably due to low yields. The yield data collected from batch experiments on the new waste varied from 0.22-0.63. However, 90 percent of the yield values obtained were less than 0.4.

Experiments were performed to test the effect of biologically treated effluents from an extended aeration activated sludge plant on a receiving stream. To accomplish this goal, effluents were taken at different times from the pilot plant while it was being fed a synthetic waste. The effluents were analyzed in an open jar reactor at dilutions that would ensure that the majority of the flow in the simulated stream consisted of treated effluent. One of the values of the procedure used is that the course of O_2 uptake can be determined using dilution factors which will occur in the field. Such is not always the case in using the BOD test. Reaeration rates also can be varied in the reactors to bracket more nearly those values which might be reasonably expected to exist in receiving streams.

In the first experiment (Figure 54), the effects of the pilot plant effluent on the oxygen resource of a receiving stream are shown. The sample was taken during a period of time (day 239-240) when the treatment plant was experiencing settleability problems; both biological solids and substrate concentrations were slightly higher than normal. The pilot plant at the time was being fed 1295 mg/l COD (glucose

plus hydrolysate). Even at such a high organic loading, the pilot plant effluent caused no serious reduction of the DO concentration in the reactor. The purification efficiency of the pilot plant at this time was 90 percent, based on supernatant COD. The total unfiltered effluent COD was 130 mg/l. The effluent in a 50/50 ratio with tap water produced an oxygen deficit of less than 2.0 mg/l in the open reactor which had a K_2 value of 0.099 hr^{-1}. There remained sufficient O_2 reserve in the reactor (5.8 mg/l) to support aquatic life. A DO reserve of 4.0 mg/l is considered adequate in the State of Oklahoma. The results obtained from analyses of various other effluent samples taken from this pilot plant by Godlove (30) concur with the results reported herein.

Another study was conducted to test the effect of a diluted untreated hydrolysate waste on the oxygen resource of a receiving stream. Hydrolyzed activated sludge represents a highly complex substrate material and would be expected to behave very similarly to a raw sewage. The BOD exertion curve in Figure 55 exhibits diphasic O_2 utilization, i.e., two approximately autocatalytic curves connected by an extended "plateau." The hydrolysate produced two distinct phases of DO depression (sags) in the reactor, with the initial depression being the most severe in its oxygen requirements. This type of O_2 uptake curve has been observed in many instances where a raw or synthetic waste is being metabolized by an acclimated population (51)(52). In general, the periods of deoxygenation in the reactor were characterized by an increasing rate of oxygen utilization followed by a period of decreasing rate kinetics during the recovery phase. The final experiment in this phase was conducted on an effluent sample taken from a

pilot plant treating a Kraft pulp waste. The COD of the waste effluent was 1800 mg/l, and a 50/50 dilution of waste and tap water was used. Figure 56 shows the results of this experiment. It can be noted from this figure that there was no appreciable difference between the accumulated O_2 uptake curves for the reactors stirred at different K_2 values. Godlove (30) in similar studies using pilot plant effluent from treatment of a synthetic waste, found that the rate of BOD exertion in the jar with the greater reaeration rate was slightly higher than the jar with a lower K_2 value, causing gradual separation of O_2 uptake curves as the experiment proceeded. A similar effect had been observed by Peil (32) in his studies on several industrial wastes. He had recommended further studies on possible effects of K_2 on O_2 uptake at the relatively low reaeration rates expected in receiving streams. Godlove's work thus tended to substantiate that of Peil in this respect. The results shown in Figure 56, however, indicate that K_2 has little or no effect on O_2 uptake.

CHAPTER VI

SUMMARY AND CONCLUSIONS

A. Batch Studies

1. The growth rate experiments and μ_{O_2} data obtained from the Warburg apparatus showed that Monod's hyperbolic relationship adequately described the relationship between the growth rate and O_2 uptake rate and the substrate concentration for an acclimated heterogeneous microbial population growing on sludge hydrolysate.

2. The cell yield factor obtained from growth studies on an acclimated heterogeneous population using hydrolysate as substrate was within the expectable range of 0.4 to 0.6 which has been found for carbohydrates, acetic acid, and municipal sewage.

3. Hydrolyzed and neutralized cells obtained from a system growing on a synthetic glucose waste and a Kraft mill waste can be used as a carbon source for a heterogeneous microbial population.

B. Continuous-Flow

A pilot plant was operated over a period of time using a modification of the activated sludge extended aeration process incorporating the "hydrolytic assist." The results of this study have led to the following conclusions:

1. Study of the "hydrolytic assist" modification of the extended

aeration process has verified the operational feasibility of periodic withdrawal of sludge, hydrolysis of cells, and refeeding as an effective means of treating soluble organic waste material, and has shown that rather high substrate concentration can be successfully treated.

2. The performance of the unit and the mode of operation during this investigation also show that it is possible to exercise engineering control over the biological solids concentration in the aeration tank without wasting sludge.

3. The capability of the "hydrolytic assist" process as an engineering tool in the secondary (organic substrate removal) treatment of a complex industrial waste has been shown.

4. Repeated withdrawal of filamentous microorganisims (developed during this study), hydrolyzing and refeeding proved a successful engineering expedient to improve settling characteristics by a gradual change in predominance.

5. The study of the effect of effluent discharges on the oxygen resources of a stream, i.e., the open jar tests, showed that the "hydrolytic assist" modification of the extended aeration process produced an effluent which would not be expected to exert severe demands on O_2 resources of a receiving stream.

CHAPTER VII

SUGGESTIONS FOR FUTURE WORK

The experimental results of the present investigation have provided additional support for the practicability and feasibility of utilizing the hydrolytically assisted extended aeration process as a method of purification of soluble organic material and providing engineering control of excess solids buildup. There are, however, various aspects of the work which warrant future investigations.

1. A study of the nitrifying characteristics of the hydrolytically assisted extended aeration process at various organic loadings would be of value, since nitrification of effluent is a major subject of concern in the pollution control field.

2. Further work on the utilization of activated sludge hydrolysate as a sole substrate for the growth of heterogeneous populations would be useful for design purposes.

3. Investigations into the feasibility of employing alkaline hydrolysis as an alternate to acid hydrolysis may be useful, especially in a system that is highly nitrifying, where the hydrolysate might be only partly neutralized. Also, it would be helpful to determine the relative ease or difficulty of hydrolyzing sludge grown on various wastes.

4. The author also suggests that the work on the "hydrolytic assist" as a remedial measure for controlling bulking sludge be

further explored.

5. A study of the hydrolytic assist modification with sludge of sewage origin would be of great value, since it affords a means of minimizing ultimate sludge disposal problems.

6. Although there is much more work which can be usefully accomplished in laboratory-scale study, it would seem that the "hydrolytic assist" modification should now be studied in a large scale pilot plant operation.

BIBLIOGRAPHY

1. McCarty, P. L., "Sludge Concentration - Needs, Accomplishments and Future Goals." Journal Water Pollution Control Federation, 38, 493-507 (1966).

2. Swanson, C. L., "Unit Process Operating and Maintenance Costs for Conventional Waste Treatment Plants." Presented at the 42nd Ohio Water Pollution Control Conference, Dayton, Ohio, June (1968).

3. Bacon, V. W., and Dalton, F. E., "Chicago Metro Sanitary District Makes no Little Plans." Public Works, 97, 66-70 (1966).

4. "A Study of Aerobic Sewage Treatment Plants in Ohio." Ohio Department of Health (1960).

5. Morris, G. L., "Extended Aeration Plants and Intermittent Water Courses." Public Health Service Publication No. 999, WP-8 (1963).

6. Hoover, S. R., Jasewicz, L., Pepinsky, J. B., and Porges, N., "Assimilation of Dairy Wastes by Activated Sludge." Sewage and Industrial Wastes, 23, 167-173 (1951).

7. Hoover, S. R., Jasewicz, L., and Porges, N., "Biochemical Oxidation of Dairy Wastes. IV. Endogenous Respiration and Stability of Aerated Dairy Waste Sludge." Sewage and Industrial Wastes, 24, 1144-1149 (1952).

8. Porges, N., Repinsky, J. B., Headler, N. C., and Hoover, S. R., "Biochemical Oxidation of Dairy Wastes. I. Methods of Study." Sewage and Industrial Wastes, 22, 318-325 (1950).

9. Porges, N., Jasewicz, L., and Hoover, S. R., "Aerobic Treatment of Dairy Wastes." Appl. Microbiol., 1, 262-270 (1953).

10. Porges, N., Jasewicz, L., and Hoover, S. R., "Principles of Biological Oxidation." In Biological Treatment of Sewage and Industrial Wastes, I, 25-48. Reinhold Publ. Corp., New York (1956).

11. Dreier, D. E., "Aerobic Digestion of Solids." Proceedings 18th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 123-139 (1965).

12. Thayer, P. M., "New Design for an Activated Sludge Plant to Treat Milk Wastes." Proceedings, 6th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 171-175 (1951).

13. Thayer, P. M., "Design Features of Activated Sludge Plant to Treat Milk Wastes." Proceedings, 7th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 509-517 (1952).

14. Eckenfelder, W. W. Jr., "Studies on the Oxidation Kinetics of Biological Sludges." Sewage and Industrial Works, 28, 983-990 (1956).

15. Tapleshay, J. A., "Total Oxidation Treatment of Organic Wastes." Sewage and Industrial Wastes, 30, 652-661 (1958).

16. Forney, C., and Kountz, R. R., "Activated Sludge Total Oxidation Mechanism." Proceedings, 13th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 313-320 (1958).

17. Symons, J. M., and McKinney, R. E., "The Biochemistry of Nitrogen in the Synthesis of Activated Sludge." Sewage and Industrial Wastes, 30, 874-890 (1959).

18. Kountz, R. R., and Forney, C., "Metabolic Energy Balances in Total Oxidation Activated Sludge Systems." Sewage and Industrial Wastes, 31, 819-826 (1959).

19. Busch, A. W., and Myrick, N., "Food Population Equilibria in Bench-scale Biooxidation Units." Sewage and Industrial Wastes, 32, 749-759 (1960).

20. Washington, D. R., and Symons, J. M., "Volatile Sludge Accumulation in Activated Sludge Systems." Journal Water Pollution Control Federation, 34, 767-789 (1962).

21. McCarty, P. L., and Broderson, C. F., "Theory of Extended Aeration Activated Sludge." Journal Water Pollution Control Federation, 34, 767-789 (1962).

22. Washington, D. R., Hetling, L. J., and Rao, S. S., "Long Term Adaptation of Activated Sludge Organisms to Accumulated Sludge Mass." Proceedings, 19th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 655-666 (1965).

23. Ludzack, F. J., "Observation on Bench Scale Extended Aeration Sewage Treatment." Journal Water Pollution Control Federation, 37, 1092-1100 (1965).

24. Sawyer, C. N., "Milestones in the Development of the Activated Sludge Process." Journal Water Pollution Control Federation, 37, 151-162 (1965).

25. Ramanathan, M., Gaudy, A. F. Jr., and Ragthaidee, W., "Responses of Extended Aeration Activated Sludge to Quantitative Shock Loads." Proceedings, 19th Oklahoma Industrial Waste and Pollution Control Conference, Stillwater, Oklahoma (1968).

26. Gaudy, A. F. Jr., Ramanathan, M., Yang, P. Y., and DeGeare, T. V., "Studies on the Operational Stability of the Extended Aeration Process." Journal Water Pollution Control Federation, 42, 165-179 (1970).

27. Gaudy, A. F. Jr., Yang, P. Y., and Obayashi, A. W., "Studies on the Total Oxidation of Activated Sludge With and Without Hydrolytic Pretreatment." Journal Water Pollution Control Federation, 43, 40-54 (1971).

28. Obayashi, A. W., and Gaudy, A. F. Jr., "Aerobic Digestion of Extracellular Microbial Polysaccharides." Proceedings, 27th Industrial Waste Conference, Purdue University, Lafayette, Indiana, May (1972)(in press).

29. Goldstein, C. L., "Studies of Acclimated Natural Microbial Populations Grown on Acetic Acid. I. Substrate Removal and Endogenous Phase. II. The Effect of Substrate Concentrations on Exponential Growth Rate Constant." Master's Thesis, Oklahoma State University, Stillwater, Oklahoma, May (1972).

30. Godlove, James W., "Studies on the Effects of Effluent From an Extended Aeration Plant on Assimilation Capacity of Receiving Streams." Master's Thesis, Oklahoma State University, Stillwater, Oklahoma, May (1973).

31. Yang, P. Y., "Studies on Extended Aeration Activated Sludge and a Modification of the Process Employing Chemical Hydrolysis of Portions of the Return Sludge." Doctoral Thesis, Oklahoma State University, Stillwater, Oklahoma, May (1972).

32. Peil, Kelly M., "Studies on the Prediction of the Dissolved Oxygen Profile in Receiving Streams." Doctoral Thesis, Oklahoma State University, Stillwater, Oklahoma, May (1973).

33. Standard Methods for the Examination of Water and Wastewater, 13th Ed., American Public Health Association, New York (1971).

34. Yu, T., "Studies on the Effect of Bacterial Growth on Substrate Removal in Multicomponent Synthetic Waste." Doctoral Thesis, Oklahoma State University, Stillwater, Oklahoma, August (1966).

35. Gaudy, A. F. Jr., and Gaudy, Elizabeth T., "Biological Concepts for Design and Operation of the Activated Sludge Process." Report No. 17090FQJ, Environmental Protection Agency (1971).

36. Hattingh, W. H. J., "Activated Sludge Studies. 3. Influence of Nutrition on Bulking." Water and Waste Treatment, 9, 476-480 (1963).

37. Harrison, M. E., and Heukelekian, H., "Stream Pollution Slime Infestation. Literature Review. I. Sphaerotilus." Sewage and Industrial Wastes, 30, 1278-1302 (1958).

38. Heukelekian, H., and Ingols, R. S., "Studies on Activated Sludge Bulking Induced by Domestic Sewage." Sewage Works Journal, 12, 694-714 (1940).

39. Adamse, A. D., "Bacteriological Studies on Dairy Waste Activated Sludge. 7. Bulking of Activated Sludge." Meded Landbouwhogeschool Wageningen 66-5, 55-67 (1966).

40. Pipes, W. O., "Bulking of Activated Sludge." In Advances in Applied Microbiology, 9, 185-234 (1967).

41. Lackey, J. B., and Wattie, G., "Studies on Sewage Purification. XIII. The Biology of Sphaerotilus natans in Relation to the Bulking Activated Sludge." Sewage Works Journal, 12, 667-684 (1949).

42. Ruchhoft, C. C., and Kachmar, J. F., "Studies on Sewage Purification. XIV. The Role of Sewage Purification in Activated Sludge Bulking." Sewage Works Journal, 13, 3-31 (1941).

43. Monod, J., "The Growth of Bacterial Cultures." Ann. Review Microbiol., 3, Annual Reviews, Inc., Palo Alto, Calif. (1949).

44. Dixon, M., and Webb, E. C., Enzymes. 2nd Ed., Academic Press, Inc., New York (1962).

45. Peil, K. M., and Gaudy, A. F. Jr., "Kinetic Constants for Aerobic Growth of Microbial Populations Selected With Various Single Compounds and With Municipal Wastes as Substrates." Appl. Microbiol., 21, 253-256 (1971).

46. Ramanathan, M., and Gaudy, A. F. Jr., "Studies on Sludge Yield in Aerobic Systems." Journal Water Pollution Control Federation, 44, 441-450 (1972).

47. Gaudy, A. F. Jr., and Ramanathan, M., "Variability in Cell Yield for Heterogeneous Microbial Populations of Sewage Origin Grown on Glucose." Biotechnology and Bioengineering, XIII, 113-123 (1971).

48. Storer, F. F., and Gaudy, A. F. Jr., "Computational Analysis of Transient Response to Quantitative Shock Loadings of Heterogeneous Populations in Continuous Cultures." Environmental Science Technology, 3, 143-149 (1969).

49. Gaudy, A. F. Jr., and Gaudy, Elizabeth T., "Microbiology of Waste Waters." Annual Review of Microbiology, 20, 319-335 (1966).

50. Yang, P. Y., and Gaudy, A. F. Jr., "Control of Biological Solids Concentration in the Extended Aeration Process." Proceedings, 28th Annual Industrial Waste Conference, Purdue University, Lafayette, Indiana, May (1973)(in press).

51. Gaudy, A. F. Jr., Bhatla, M. N., Follett, R. H., and Abu-Niaaj, F., "Factors Affecting the Existence of the Plateau During the Exertion of BOD." Journal Water Pollution Control Federation, 37, 444-458 (1965).

52. Gaudy, A. F. Jr., Bhatla, M. N., and Abu-Niaaj, F., "Studies on the Occurrence of the Plateau in BOD Exertion." Proceedings, 18th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 183-193 (1963).

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