THE EFFECT OF VARYING SEVERAL OPERATIONAL PARAMETERS ON THE DEWATERING CHARACTERISTICS OF ACTIVATED SLUDGE

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(ABSTRACT)

The purpose of this study was to investigate selective operational parameters and their effect on activated sludge settling and dewatering rates. Several laboratory scale reactors were used in this study and fed with various synthetic substrates. The sludges produced from these reactors were used to examine sludge settling and dewatering characteristics as the selected operational parameters were varied. This study intended to determine if: (1) qualitative shock loadings affect sludge dewatering and settling and will biological systems recover quickly under various conditions; (2) aeration basin dissolved oxygen concentration affects sludge settling and dewatering characteristics; (3) biopolymer content can be correlated with sludge dewatering rates such that biopolymer content can be used as a parameter to monitor sludge dewatering characteristics.

Results from this study indicated that the shock loadings considered here significantly alter the sludge settling and dewatering characteristics of an activated sludge population. Shock loadings may cause shifts in the bacterial population, allowing undesirable

microorganisms to predominate but activated sludge systems can recover from shock loadings caused by the introduction of a different substrate. Also, it was seen that activated sludge dewatering is directly affected by the dissolved oxygen level in the aeration basin and the minimum level required is 2.0 mg/L in a completely-mixed system. A definite relationship was noted between biopolymer production and sludge dewatering with high biopolymer content correlating with poor sludge dewatering and low biopolymer content correlating with good sludge dewatering.

To my parents: the people who shaped my life, made my education possible, and constantly supported me with their guidance and love.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Significant amounts of research effort have focused on evaluating the effect of varying operational parameters on the dewatering characteristics of waste activated sludges. These studies have often followed the review of full-scale treatment plant data which has shown sludges of widely varying dewatering characteristics even though operational parameters are similar in magnitude. Factors such as dissolved oxygen content, substrate loading, particle size, sludge age, and waste nitrogen content have been evaluated for the impact on sludge dewatering rates. Experimental results have varied between research studies, with most conclusions being specific to the waste and/or biological culture utilized.

The identification of an operational parameter which has a predictive capability with respect to sludge dewatering characteristics is desirable since it would provide a convenient monitoring tool for plant operators. Potential problems could be detected or avoided completely by proper monitoring, alleviating long-term dewatering problems and the associated costs well before the development of the problem. However, to date, the picture is still not clear with respect to which of the parameters has a significant role in defining sludge dewatering properties. Also, no new parameters have been presented that monitor sludge dewatering characteristics.

Included in the review of operational parameters for consideration in this study was the type of organic substrate supplied

to the biological system. The ability of microorganisms to utilize specific substrates is a function of the particular organism as well as the time of acclimation provided. Sudden changes in the type of substrate provided may lead to population shifts; more importantly, during the transition to a new equilibrium, drastic changes in dewatering characteristics may be encountered, leading to process upset and unnecessary expense for dewatering operations.

This study proposes to further investigate selective operational parameters and their effect on activated sludge thickening and dewatering rates. Specific objectives were as follows:

(1) determine what effects shock loadings have on sludge dewatering and settling and monitor recovery period;
(2) determine how aeration basin dissolved oxygen concentration affects sludge settling and dewatering characteristics;
(3) attempt to correlate biopolymer content with sludge dewatering rates to determine if it can be used as a parameter to monitor dewatering characteristics; and
(4) determine if activated sludge will recover from shock loadings while being fed the original substrate and new substrate at various proportions.

II. LITERATURE REVIEW

In the past, researchers have attempted to study the activated sludge process by examining each variable separately. These efforts have produced very valuable results but there seems to be a need to tie the whole process together. Since many factors interact in the activated sludge process, an understanding and examination of each of these factors is required to understand the complete process. There were several parameters varied during the course of this study. The dissolved oxygen concentration was increased and decreased. The feed substrate was changed from one source to another and also was studied under shock loading conditions. During each of these separate conditions, the dewatering and thickening characteristics of the sludge were examined. During certain portions of the study, the biopolymer content of the sludge was studied also.

As the reader can see, a significant understanding and overview of the activated sludge process is needed as a background for this study. The purpose of this literature review is to present an overview of the activated sludge process and a more detailed examination of each of the parameters that were varied and each of the operational characteristics that were examined.

Principles of the Activated Sludge Process

In the activated sludge process, a wastewater is introduced to a mixture of microorganisms in a reactor under aerobic conditions. The organic portion of the wastewater is then biologically degraded by the

microorganisms. This organic portion is used by the microorganisms for cell maintenance and production of new cells. The microorganisms are allowed to settle in a clarifier to separate the settled bacteria (sludge) from the treated effluent. The settled sludge is returned to the reactor to maintain the design mixed liquor suspended solids concentration. The excess sludge produced must be discharged (wasted) from the system.

There are now several variations of the activated sludge process. The first variation designed was that of a plug-flow versus a complete-mix system. The complete-mix system is now the most commonly used design. Variations of the complete-mix process include conventional, high rate, contact stabilization, two-stage aeration and extended aeration (1). This review will only examine the conventional complete-mix system as this was the process used in this study. The conventional activated sludge process includes 25 to 50% solids recycle, 1500 to 3000 mg/l mixed liquor suspended solids, 5 to 15 day mean cell residence time, 4 to 8 hours hydraulic retention and 85 to 95% BOD removals (1).

A biological basis was not developed for complete-mix systems until McKinney's (2) and Eckenfelder's (3) work in the 1950's. In McKinney's (2) paper, he described the complete-mix activated sludge process as a process where the untreated wastes are instantly mixed throughout the entire aeration tank. He stated that one-third of the organic material is completely oxidized to carbon dioxide and water while two-thirds of the organic portion is used for synthesis.

Dissolved Oxygen in the Activated Sludge Process

In the activated sludge process, the D.O. concentration must be sufficient for the bacteria to utilize in their biological degradation of organic matter. There have been literally volumes of research studies reporting what D.O. concentration is sufficient. A 2.0 mg/l minimum was proposed in the 1940's by the American Public Health Association Committee on Sewage Disposal and was widely accepted until fairly recent times (4). This minimum value is still generally used as a rule-of-thumb by most treatment plant operators. There is much interest in being able to design an activated sludge process at a lower D.O. level as this would significantly decrease a treatment plant's operating costs. The power cost for aeration of the mixed liquor accounts for 60 to 80 percent of the daily operating cost of a treatment plant (5).

Aeration can be accomplished by several different methods including diffused aeration, mechanical surface aeration, and a combination of diffused aeration and mechanical turbine aerators. There are advantages and disadvantages to any system chosen. The source for the oxygen can be air or a pure oxygen process could be employed. This will be discussed in more detail later in this section. Regardless of the type of aeration used, the fundamental concepts of oxygen transfer are the same.

Two Film Theory: The two film theory of oxygen transfer is probably the most widely accepted concept for explaining the aeration process. It is dependent on one film at the gaseous interface and the

second film at the liquid interface. Both films act as barriers to oxygen transfer into the water. Oxygen transfer can be described at a molecular level as being a mass transfer from one point in space to another point in space. In air there is a mixture of approximately 78% nitrogen and 21% oxygen. The driving force for the oxygen molecules is their concentration in the gas phase and their ability to move through both films into the water phase. The concentration of oxygen molecules can be measured by the partial pressure of the oxygen in the gas phase. The oxygen molecules are in constant motion in the gaseous phase and push against the liquid phase. Oxygen is only slightly soluble in water, approximately 9.2 mg/l at 20°C and one atmosphere pressure (6). The oxygen molecules in the water try to escape and new molecules attempt to enter the water from the gas phase. The gas film and the liquid film offer the resistance to the passage of oxygen into and out of the water. The area of contact between the gas phase and the water is also important since all of the oxygen must pass through the air-water interface.

Mixing and Oxygen Transfer: Over the years, two primary methods have been developed for mixing and oxygen transfer. Both methods have been used about the same length of time and both methods have their positive and their negative characteristics.

The first method, diffused aeration, consists of compressing air and releasing it under pressure at some depth in the aeration tank. The rising air bubbles form the source of oxygen with the bubble surface acting as the contact area between the oxygen and the water.

The degree of turbulence of the air/water mixture determines how rapidly oxygen is transferred into the water (7).

The second method is mechanical surface aeration where a machine pumps water into the air. As the water moves through the air, the oxygen is transferred at the liquid surfaces. Mechanical aerators can be vertical, horizontal, fixed, floating, or combined with diffused aeration to produce a wide variety of different aeration systems.

One of the most important basic factors often overlooked by designers is that oxygen transfer equipment must also keep the mixed liquor in suspension as well as mix the influent wastes in with the microorganisms. Usually, most efficient aeration devices are also efficient mixing devices but there are exceptions (8). The mixing provided must also be sufficient to bring the oxygen bubbles into contact with the microorganisms. The core of the bacterial floc must have a D.O. concentration of 0.1 mg/l or greater which means that the concentration must be at least 2 mg/l in the bulk solution to insure this (9).

The D.O. concentration and its effect on the activated sludge process will be discussed further in the following sections as to how it relates to filamentous microorganisms and sludge handling and dewatering.

Filamentous Microorganisms and Sludge Bulking

Activated sludge that does not settle well is commonly known as bulking sludge. This is one of the most common and serious operational problems that occurs in activated sludge plants, usually caused

by the occurrence of filamentous microorganisms in the mixed liquor. When measured by the sludge volume index (SVI) test, a sludge with an SVI of greater than 150 is often classified as a bulking sludge. The ideal sludge with an SVI less than 100 settles rapidly, leaving a clear supernatant. Bulking has been attributed to several reasons, including low aeration basin D.O., high carbon to nitrogen ratios in the waste, temperature, and certain types of wastes (10).

Sezgin et. al. (11) stated that the relative numbers of filamentous and zoogleal microorganisms in the activated sludge floc was one of the most important factors in determining the physical characteristics of the floc related to settling properties. It seemed to the authors that the outgrowth of the filamentous organisms from the floc into the bulk solution resulted in sludge bulking. This would indicate that, for whatever operational reasons, when the filamentous microorganisms increased in numbers relative to the zoogleal microorganisms, a poor settling floc resulted.

Palm et. al. (12) showed that low mixed liquor D.O. caused bulking sludge that was composed of the filamentous microorganisms Spaerotilus natans. This bulking could be cured in three mean cell residence times by increasing the aeration basin D.O. concentration. This would indicate that the D.O. was not sufficient to penetrate to the floc core of the zoogleal microorganisms, allowing the filamentous microorganisms to increase. This was also postulated by Parker and Merrill (13) who theorized that the difference between the pure oxygen and air systems could be attributed to the formation of an anoxic floc

core at lower D.O. concentrations. Kalinski (14) argued that a minimum D.O. of 2 mg/l was sufficient to insure oxygen at the floc core for air systems and this would provide for good sludge settling characteristics and would provide the same results as a pure oxygen system.

Tomlinson (15) pointed out that a glucose substrate caused filamentous microorganisms to predominate. He also noted that by switching from continuous feeding to discontinuous (batch) feeding, the sludge bulking lessened. Houtmeyers (16) also conducted a study where continuous feeding of glucose caused heavy filamentous growth while batch feeding did not. He theorized that the filamentous microorganisms were suppressed in a batch culture because their substrate removal rate and ability to store substrate was not as great as that of the zoogleal microorganisms. His evidence was that only directly absorbable substrates, i.e., glucose, showed differences from continuous to batch feeding. The interrelated effects of filaments on sludge dewatering and thickening are discussed in the next section which focuses on various aspects of dewatering and thickening.

Sludge Dewatering and Thickening

The feed solids concentration is the single most important variable that affects dewatering. As the feed solids increases there is a decrease in chemical dosage required and an increased throughput of solids (17). This was a prevailing attitude towards sludge dewatering until recently. Some of the more recent findings will be discussed in this section. The primary purpose of sludge dewatering is to remove as much of the liquid portion as possible, allowing the sludge to

handle as a solid and decreasing the total volume that must be disposed of. The vacuum dewatering technique was the method used for this study and will be the only method discussed in this text. There are several other techniques for dewatering sludges that will not be discussed. The specific vacuum technique used was the Buchner funnel test. The other vacuum test that was not used in this study is the filter leaf test. A full discussion of the Buchner funnel test has been developed by Vesilind (18).

The time of filtration is theoretically dependent on the filtration area, volume of filtrate, net filtration pressure, viscosity of filtrate, feed solids concentration, and the specific resistance (r*) to filtration at the particular filtration pressure (19). A reduction in the solids particle size increases r* according to the square of the diameter for the flow of liquid through a bed of solid particles (20). An increase in the fines in the bed increases r* because the specific surface is increased; sludge void areas are also reduced in some instances. This is further shown as the polyelectrolyte requirement for conditioning of activated sludges of low solids content is determined by the colloidal particles present, independent of the solids content for a given sludge (21). There is probably a cross-linking of the polyelectrolyte with the colloidal materials present that generates a gel-like aggregate that encloses the suspended particles, making the sludge more readily dewatered.

The overall efficiency of the activated sludge system depends on the settling and thickening of the sludge in the clarification

portion of the treatment plant. The aeration basin and clarifier must be treated as one integral unit and not as two separate components as the overall performance of each depends on the other. Sedimentation can be defined as the separation from water, by gravitational settling, of suspended particles that are heavier than water (1). In this study, the Sludge Volume Index (SVI) was used to determine the settling efficiency of the sludge. The SVI is defined as the volume in milliliters occupied by 1 gram of a suspension after 30 minutes of settling (22). While the SVI is not a scientific parameter, it is the operational parameter that is the most useful characteristic of sludge settling available to the ordinary treatment plant operator (23). The correlation between studies using the SVI may not be valid because settling efficiency is not a one-parameter property; rather, it is a function of variables such as floc size, mean cell residence time, temperature, microorganism concentration and composition, etc. (24). Also, the SVI determination is not standardized and sedimentation as it occurs in full-scale systems differs from that occurring in small, unstirred cylinders (25). Still, the SVI is useful in comparing the relative settling rates of a given sludge.

It would seem that it would be simple to design a system to optimize the settling of activated sludge. However, this is not the case as the requirements for optimum substrate utilization may be incompatible with the requirements for optimum bioflocculation (26). Optimal substrate utilization occurs while the microorganisms are in

the log growth phase. Conversely, the conditions for bioflocculation improve in the declining growth phase and are optimal in the endogenous phase (26). Therefore, a compromise is made when designing an activated sludge system to encourage good sedimentation. One proposed mechanism for bioflocculation is the presence of naturally occurring extracellular polymers (biopolymers) bridging with the floc structure. This is discussed in the following section.

Biopolymer

It has been postulated that extracellular polymers (biopolymers) produced by microorganisms play a key role in determining activated sludge characteristics. McKinney (27) was one of the first researchers to observe this phenomena. It has been observed that as the mean cell residence time of the cells in the system increases, the settling characteristics of the biological floc are enhanced (28). It has been reasoned that this occurs because the surface charge is reduced as the mean age of the cells is increased. Also, the microorganisms begin to produce biopolymers and eventually become enveloped in a slime layer (29).

There have been four major groups identified as the main components of biopolymer: polysaccharides, proteins, RNA, and DNA (29). These components are present in different ratios with various organic substrates and operating conditions but the components are still the same. There have been several factors examined that affect biopolymer concentration and production in activated sludge. Among these are the carbon:nitrogen, carbon:phosphorus and carbon:sulfur ratios;

oxidation of biopolymers; dissolved oxygen concentrations; biomass loading rates; and biochemical oxygen demand (30). At longer mean cell residence times, settling and bioflocculation is often accompanied by an accumulation of polysaccharide material (29). Also, it has been theorized that biopolymer is the direct cause of bioflocculation during endogenous growth (29). In contrast to this, Gulas et. al. (31) found that endogenous growth was not required for biopolymer production as the presence of sizeable amounts of biopolymer were observed at high specific growth rates.

Bioflocculation can be viewed as the result of the interaction of naturally produced high molecular-weight, long chain polyelectrolytes that bridge with others into an aggregate (29). Other researchers observed that this aggregation could be affected by both charge neutralization and bridging between the bacterial colloids (31,32). Novak (32,33) observed that sludge conditioning agents appear to act in this fashion. It was also reasoned that the polyelectrolyte requirements for activated sludge conditioning is determined by colloidal particles present and is independent of solids content for a given sludge (34). Novak viewed activated sludge as a slurry containing an excess of natural anionic polymers and colloidal materials that interfere with sludge filtration (32). These anionic polymers could be indirectly measured by the optional cationic polymer dose that was required for the optimal dewatering rate. Novak (32) also observed that as a sludge's filtration rate improved, the amount of extractable biopolymer decreased. Conversely, as the biopolymer

concentration increased in the sludge, the filtration rate declined. This was also stated by Gulas (31) as the conditioning requirements for a given sludge were directly related and the specific resistance inversely related to biopolymer concentration present. Novak (32) also noted that an improvement in dewatering corresponded with an improvement in thickening characteristics. Therefore, biopolymer content was also felt to strongly influence sludge-thickening and settling rates. This was explained in one study by reasoning that as the bound water in the sludge increases, the SVI also increases (28). This non-filamentous bulking was accompanied by an accumulation of extracellular material. It was hypothesized that this biopolymer possessed a high degree of hydration which allowed the sludge to contain excessive amounts of bound water. This could also partially explain the poor dewatering associated with high biopolymer content.

Palm et. al. (12) noted a significant quantity of material that was external to the bacterial cells and suggested that this biopolymer acts as the "glue" that binds individual bacteria in an activated sludge floc. Novak noted that the most important fraction of biopolymer is in solution and not associated with the bioflocs (32). This contrasts with the feelings of earlier researchers who thought that the most important floc binding material was within the floc structure.

The understanding of the complex role that biopolymer plays in sludge thickening and dewatering is still incomplete. This understanding has been hindered because of the difficulty of measuring

and various methods utilized in the analysis of biopolymer (33). It is certain that biopolymer does affect sludge properties and a better understanding will enhance the operation of activated sludge treatment plants.

Shock Loadings

When an activated sludge plant is operating, there can be times when it may be subjected to changing environmental conditions which disrupt its steady-state condition (35). Any environmental conditions tending to do this can be termed a shock load. If these conditions are not controlled by the plant's design, the biological response of the microorganisms must handle these changes. A shock load may be quantitative (concentration of influent substrate), qualitative (change in type of substrate), hydraulic, or a combination of two or more. Also, changes in chemical composition of the waste, pH, and temperature can cause shock loading conditions. This study examined qualitative shock loads only as an examination of all of these factors would be a complete study in itself.

It was theorized in the past, with a diverse microbial population and a substrate with several components, that all components were metabolized concurrently (36). However, studies employing mixed microbial populations in which two compounds comprised the organic substrate indicated that the presence of one substrate could prevent or hinder the uptake of the other compound even though the population had previously been acclimated to it (35). This would not have been expected to occur with mixed populations in accord with previous

beliefs. It was known from basic research studies that certain enzymes required to metabolize specific substrates are not present in the cell at all times but are produced only when needed (i.e., inducible enzymes) (36,37). The required inducible enzymes are produced by the cell in response to the presence of the particular substrate for which they are needed. The time required to stimulate this response represents the acclimation period. If the organism is not genetically coded to make this switch, it cannot make the required enzymes and, therefore, cannot use the substrate (37). This is one way in which changes in predominance of species are brought about in natural populations when changes in the available substrate occur. In response to a qualitative change in substrates, the cells can acclimate, or there may be an adaptation of the population, or a combination of both. Both mechanisms of response may overlap or go on concurrently, with or without a disruption in system efficiency. Ghosh et. al. (38) noted that the uptake of two substrates could be assimilated concurrently because of continual population shifts and the presence of new dominant cultures.

In practical applications, waste streams do not completely "turn over" during shocks; some of the former substrates are present with the new. It would seem that the former substrate would continue to be removed while the system attempted to accommodate the new substrate. This is one possibility but the reverse may also be true. That is, the new substrate may prevent continued synthesis of the enzymes required for metabolism of the former substrate. The control

mechanism by which the synthesis of one group of enzymes is blocked and another triggered is known as metabolite repression (39). One important point is why the first enzymes which have already been synthesized cannot continue to function. It would seem that with a large amount of acclimated sludge that the organisms would continue functioning on the original substrate even though the new substrates may have prevented production of new enzymes. It was concluded that in addition to metabolite repression, another more immediately acting mechanism by which the functioning of the already existing enzyme system may be inhibited partially or completely by the presence of new substrate (39).

Due to the wide range of qualitative changes in influent substrate that can occur, it is impossible to predict the effects of these changes on removal efficiency and other parameters. There are some factors, however, that seem to minimize loss of system efficiency due to qualitative shock loadings. In some cases, the age of the sludge seems to provide a moderating effect on the degree of interference which one substrate may exert on the removal of another (35). The use of completely-mixed reactors also helps to minimize qualitative shocks since the influent substrate is diluted into the system, allowing the system more time to generate a metabolic or ecological response. An equilization basin, usually recommended for smoothing out peaks in flow rate and substrate concentration, is also useful in preventing abrupt changes in the waste composition.

III. METHODS AND MATERIALS

In this chapter, the experimental methods used to achieve the objectives of this study will be discussed. These methods included setting up bench-scale reactors and analyzing various aspects of their operation. Also, the equipment and chemicals used in each test will be presented.

Laboratory-Scale Reactor Studies

Two 45-liter Plexiglas reactors were used during the first half of this study. During the second half of this study, three 9-liter and one 18-liter reactors were used. A schematic diagram of the reactors is shown in Figure 1. The aeration basin of the 45-liter reactor was 37.5 liters; the clarifier was 8.5 liters. The 18-liter reactor had an aeration basin of 13.6 liters and a 4.4 liter clarifier. Each of the 9-liter reactors had 7.8 liter aeration basins with 1.2 liter clarifiers.

The reactors were labeled to differentiate between each portion of the study. A time table of the study is shown in Table I to simplify the task of relating to the reader which reactor was used for each part of the study. During the first half of the study, the reactor used for the shock loading portion was designated Reactor 1; the D.O. effects study was conducted using Reactor 2. For the second half of the study (the recovery period using two substrates) the four reactors were designated 1A, 2A, 3A, and 4A, respectively. Reactor 1A was the 18-liter reactor while the

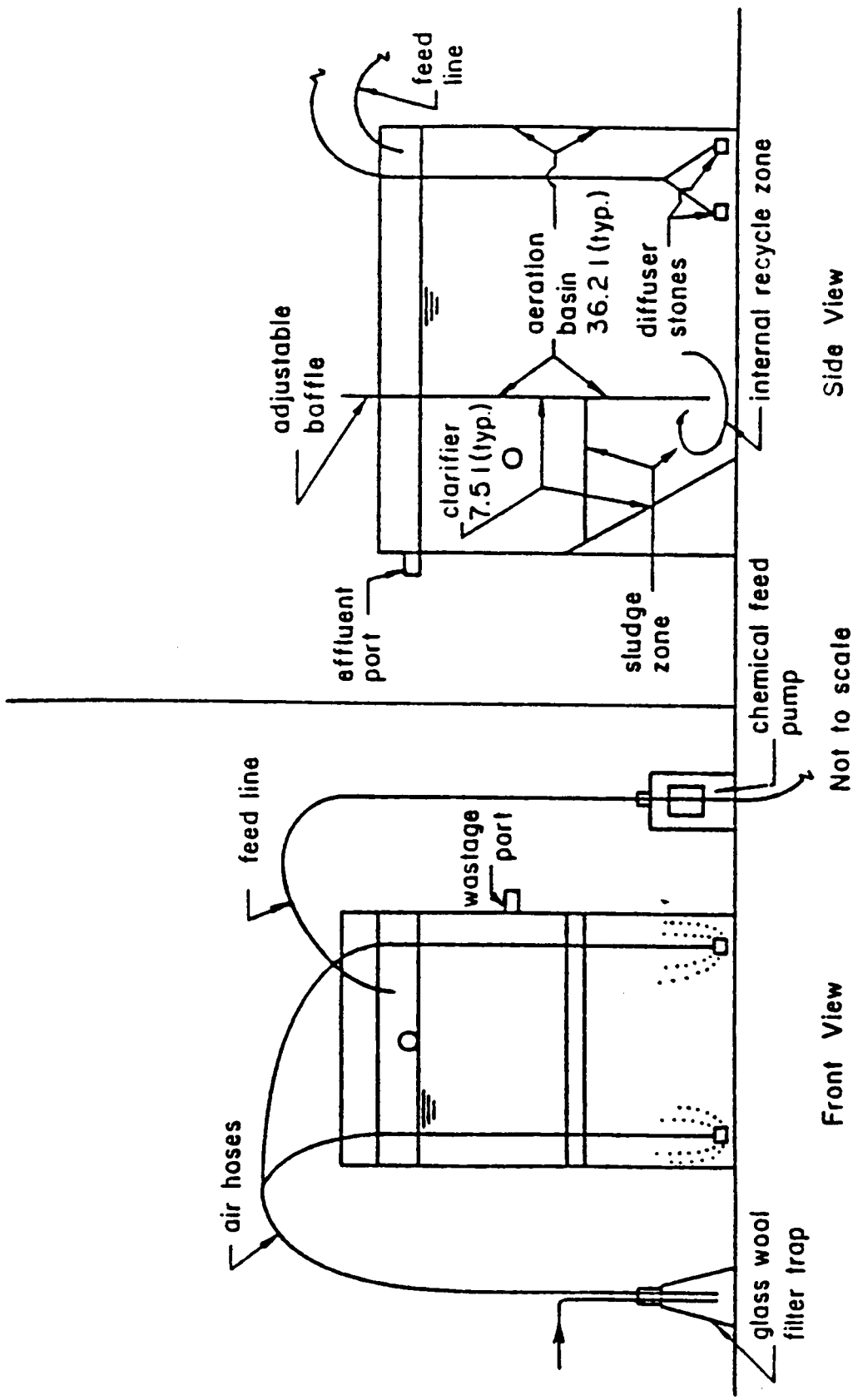

Figure 1. Typical Laboratory Scale Reactor

TABLE I. TIME TABLE OF STUDY

Days	Substrate
Reactor 1	
1-81	Bacto Peptone
81-114	Egg Albumin
115-156	Bacto-Peptone
157-174	Glucose
175-218	Bacto-Peptone
219-284	Glucose/Bacto-Peptone (in varying ratios)
Reactor 2	
1-216	Bacto-Peptone

other three were the 9-liter reactors. Each reactor functioned as a completely mixed activated sludge aeration basin followed by a secondary clarifier.

The reactor cultures were initiated using seed from the Blacksburg-VPI Sanitation Authority Plant at Stroubles Creek. The reactors were filled with aeration basin sludge from the plant and kept on a batch feed for ten days to provide time for acclimation to the synthetic feed and laboratory conditions. For the second half of the study, the four reactors were started using Reactor 1 sludge as the initial seed. Throughout the study the reactors were kept in a room with a constant temperature of 20 degrees Celsius.

After this period of batch operation, the reactors were fed on a continuous basis for the rest of the study. A Cole-Palmer (model C-1560, LP, Chicago, Ill.) chemical feed pump was used to supply the feed at a rate necessary to maintain a twelve hour hydraulic detention time.

Two dual air stone diffusers were used in each reactor to aerate the biological solids. The air supply came from the university compressed air supply system and was filtered through glass wool to minimize contamination. The dissolved oxygen (D.O.) concentration of the reactors was kept near the saturation level except when the effect of D.O. concentration on sludge dewatering characteristics was being examined. Then, along with the diffusers, a mixer (Arthur H. Thomas Co., Type

NSE-11R, Philadelphia, Pa.) was used to insure complete mixing at low D.O. levels. Also, a plexiglas top was used during the D.O. study to minimize atmospheric reaeration.

During the study, activated sludge was wasted from the reactors on a daily basis at the same time each day. The procedure for wasting was: 1) the feed pump was unplugged; 2) the effluent hose was clamped shut; 3) the baffle between aeration basin and clarifier was removed; 4) the sludge was scraped off the reactor wall; 5) the sludge was mixed to insure homogeneity; 6) the waste hose was unclamped to allow a certain amount of sludge to be withdrawn and kept for further testing; 7) the waste hose was clamped shut and the effluent hose was unclamped; 8) the baffle was returned to its original position and the feed pump restarted. Wasting of sludge allowed for the maintenance of a 10-day mean cell residence time (MCRT) for all studies.

Steady-State Determinations

As in all continuous-flow reactor studies, steady-state conditions are desirable for the collection of meaningful operating data. At the beginning of this study thirty days or three times the required MCRT elapsed before using other methods of determining steady-state. In this study, steady-state was assumed when the mixed liquor suspended solids (MLSS), effluent suspended solids, and effluent chemical oxygen demand (COD) were at constant levels without major (+/-5%) fluctuations.

Feed Solutions

Throughout the course of this study, an influent chemical oxygen demand (COD) of 400 milligrams per liter (mg/l) was maintained for each reactor. However, several different organic substrates were used to supply this influent COD. During the first half of this study bacto-peptone (Difco Laboratories, Detroit, Mi.) was used in Reactors 1 and 2 except when egg albumin (Sigma Chemical Company, St. Louis, Mo.) and glucose (Fisher-Scientific, Fairlawn, N.J.) were introduced as shock loadings. Various ratios of glucose and bacto-peptone were used as substrates during the second half of the study. Reactor 1A had a 20% glucose and 80% bacto-peptone feed composition. The feed composition of Reactor 2A was 40% glucose and 60% bacto-peptone. Reactor 3A was fed 60% glucose and 40% bacto-peptone and the substrate for Reactor 4A was 100% glucose.

In addition to a COD source, inorganic nutrients were added to insure that no other chemical would limit the growth of the bacterial mass. The chemicals used in each part of this study and their respective concentrations are presented in Table II. The final feed solution was prepared by adding the calculated volume of chemicals to a calculated volume of tap water. For the large reactors, 55 gallon drums lined with plastic liners were used. Five gallon Nalgene carboys were used as feed containers for the 9-liter and 18-liter reactors.

TABLE II. COMPOSITION OF SYNTHETIC WASTEWATER FEED

Chemical	Final Concentration (mg/L)
Bacto-Peptone or Egg Albumin or Glucose	400 as COD
$MgSO_4H_2O$	50.0
$MnSO_4H_2O$	5.0
$FeCL_36H_2O$	0.6
$CaCl_2$	3.75
KH_2PO_4	38.83 (4.83 as P)
K_2HPO_4	79.10 (7.70 as P)

Solids Determinations

It was important to measure MLSS and effluent suspended solids daily since these values were used to determine if steady-state conditions existed. These tests were performed using methods described in Standard Methods for the Examination of Water and Wastewater (22). The sample was filtered through a Whatman Glass Micro Fibre Filter. Twenty milliliters was the sample volume used for MLSS and 100 mL for effluent suspended solids. The samples were filtered through a Millipore filtering apparatus (Bedford, Mass.) using a 25 inch Hg vacuum differential supplied by a Duerr vacuum pump (Duerr Electric Corp., Cedarburgh, Wis.).

The procedure that follows was used for all percent solids determinations: 1) aluminum tare pans were weighed empty using a four-place digital readout Mettler AC100 (Hightstown, N.J.); 2) ten mL of a liquid sample or a portion of the cake for the semi-solid samples was placed in the pre-weighed pans and weighed; 3) samples were placed in an oven at 105°C for twenty-four hours; and 4) samples were taken out of oven, placed in dessicator for fifteen minutes to cool, and then weighed.

Percent solids determinations were calculated for initial solids and cake solids to determine the "w" term in the specific resistance equation. Also, the percent solids was measured for solids flux determinations.

Dissolved Oxygen and pH Determinations

Dissolved oxygen (D.O.) concentrations and pH were measured daily so that the reactor conditions could be kept as constant as possible. The pH was determined using a Fisher Accumet Model 120 pH meter. The meter was standardized with buffer solutions at pH 7 and 10 (Fisher-Scientific) each day before a reading was taken. The pH probe was then placed in a 300 mL beaker containing a sample of aeration basin sludge and the pH measured.

A YSI Model 54A oxygen meter was used to measure the D.O. concentration. The probe was calibrated daily to insure accurate readings. After the probe was positioned in the center of the reactor's aeration basin, the probe mixer was turned on and the D.O. meter allowed to equilibrate before data collection.

Chemical Oxygen Demand

COD data was collected for two important reasons. The effluent COD data were used to aid in the determination of steady-state conditions. Also, COD data were used to insure that the influent COD of the synthetic feed did not vary. Samples of 20 mL were collected every other day from the reactors' influent and effluent flow and stored according to Standard Methods (22). The COD analysis was performed after 20 samples had been collected, usually within one week after collection.

Sludge Dewatering

Dewatering testing was performed using a Buchner funnel filtration device similar to the one shown in Figure 2. The sludge was prepared for dewatering by settling for thirty minutes to concentrate the solids. Then, the supernatant was decanted and 100 mL of the concentrated sludge was used in the dewatering test.

The typical procedure for dewatering was as follows. First, a nine centimeter diameter Whatman 40 Ashless filter paper was rinsed with distilled water and sealed to the Buchner funnel by applying a vacuum (General Electric Model 5KH30KN90 pump, Fort Wayne, Indiana). After sealing the filter, the pump was turned off and a 100 mL sludge sample poured into the funnel. The sludge was then allowed to sit in the funnel for a few seconds until two to three drops of filtrate passed into the graduated cylinder. Then, the vacuum was reapplied (15 inches of mercury) and a stop-watch (Fisher-Scientific digital) started. The volume of filtrate was then measured as a function of filtration time. Measurements were made every five seconds for one minute; testing continued to a maximum of five minutes filtration time.

The data were plotted graphically to aid in the calculation of sludge specific resistance. The specified equation used and all associated variables are listed and explained in greater detail in Appendix A.

$$r^* = \frac{2PA^2b}{vw}$$

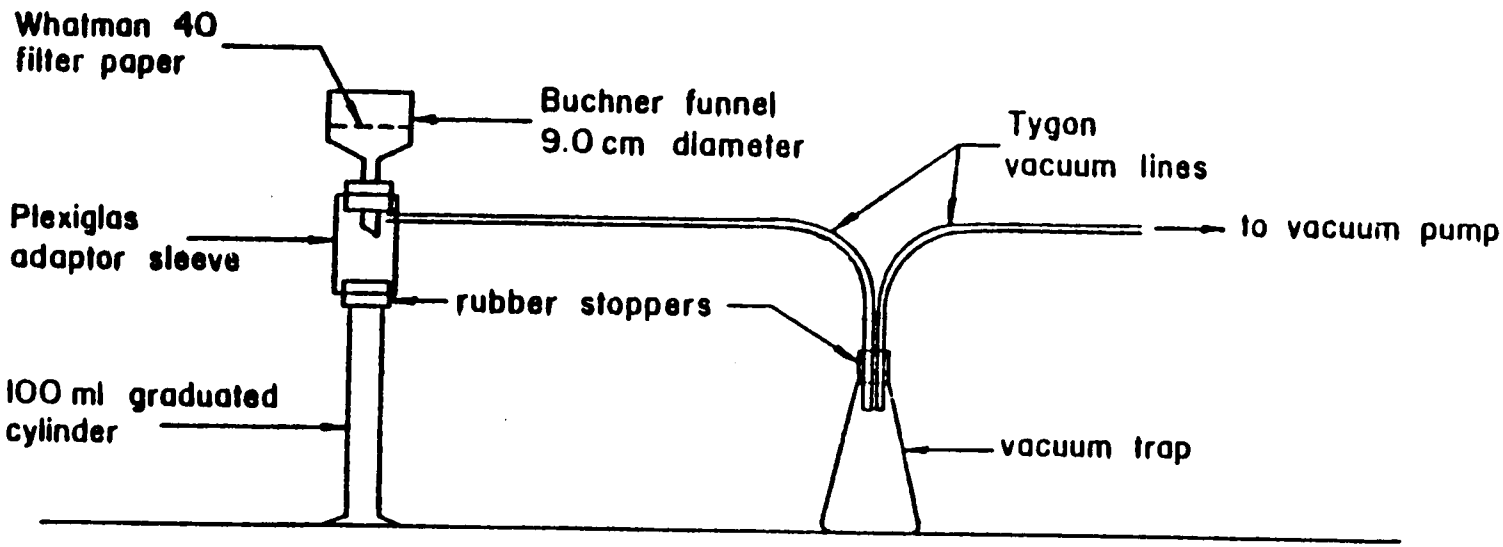

Figure 2. **Buchner Funnel Filtration Apparatus**

Sludge Settling

In this study, sludge settling was measured by two methods. One method was the sludge volume index (SVI) as described by Vesilind (18). Solids flux was the second method used as described by Metcalf and Eddy (1). For SVI, the sludge was settled in a plastic two liter graduated cylinder with a diameter of 7.8 cm. The two liter cylinder was used for solids flux along with 4.5 liter plexiglas columns with a diameter of 11.4 cm. The height of the sludge was the same for both columns at the start of each test.

The sludge sample used for the SVI was a fraction of what was wasted daily. For this method the cylinder was filled to the two liter mark with sludge and settled for thirty minutes.

The solids flux method was more difficult. The first trial was conducted using the concentration of sludge in the reator. Next, the sludge was allowed to settle for various lengths of time after being withdrawn from the reactor, and then the supernatant was poured back into the reactor. Different concentrations were achieved by pouring off different amounts of supernatant before mixing. The solids-liquid interface was measured every 30 seconds for 15 minutes and every minute for the last 45 minutes of each trial. After completion of each trial, a solids sample was taken and the sludge was poured back into the reactor. It took a great deal of time for this method and care had to be taken to insure that the sludge's properties were not changed during the testing. For this reason, only three to four trials were conducted each time this method was used.

Biopolymer

During the first half of the study, the biopolymer content of the sludge was measured. A gel chromatograph method was used as described by Kunjur (40). Samples were collected from the reactor effluent and analyzed the same day. Sephadex G-50 was the gel chosen to use in this study because of its fractionation range. Its fractionation range was 1500 to 30,000 as molecular weight for peptides and globular proteins and 500 to 10,000 as molecular weight for dextrans.

The collected effluent samples were allowed to settle for thirty minutes and 5 mL of the sample supernatent were added at the top of the gel column and eluted with 100 mL of distilled water. The organics concentration in the eluant was monitored by a Buchler Fracto Scan ultra-violet light source set at a wave length of 280 nm. From the calibration plot of the column, the high molecular weight fractions could be measured in terms of peak heights. These peak heights are the numbers reported in the Results and Discussion section.

IV. RESULTS AND DISCUSSION

The results of this study are presented in this chapter and discussed. Appendix B contains the data which were used to construct the figures in this chapter. These data include values for specific resistance, solids flux, SVI, D.O., pH, MLSS, effluent suspended solids, % COD removal and system biopolymer content. The equations used in this study and a listing and description of the variables contained in each equation are presented in Appendix A.

The main emphasis of this study was to evaluate the effect of varying selected operational parameters on sludge thickening and dewatering rates. Therefore, most of the figures in this chapter present specific resistance or solids settling/thickening data as a function of time. Biopolymer data and visual observations are also included here. The results are presented and discussed in subsections.

Substrate Shock Loading

Baseline Development. Background sludge characteristics were necessary to fully evaluate the effects of varying operational parameters. Therefore, Reactor 1 was allowed to maintain steady-state conditions for approximately one month before the first shock loading was applied. Figure 3 shows specific resistance values over this time period. A specific resistance value of 22×10^{11} m/kg was determined as an average for this period of operation. This value was used for Reactor 1 to compare good reactor conditions to subsequent changes in

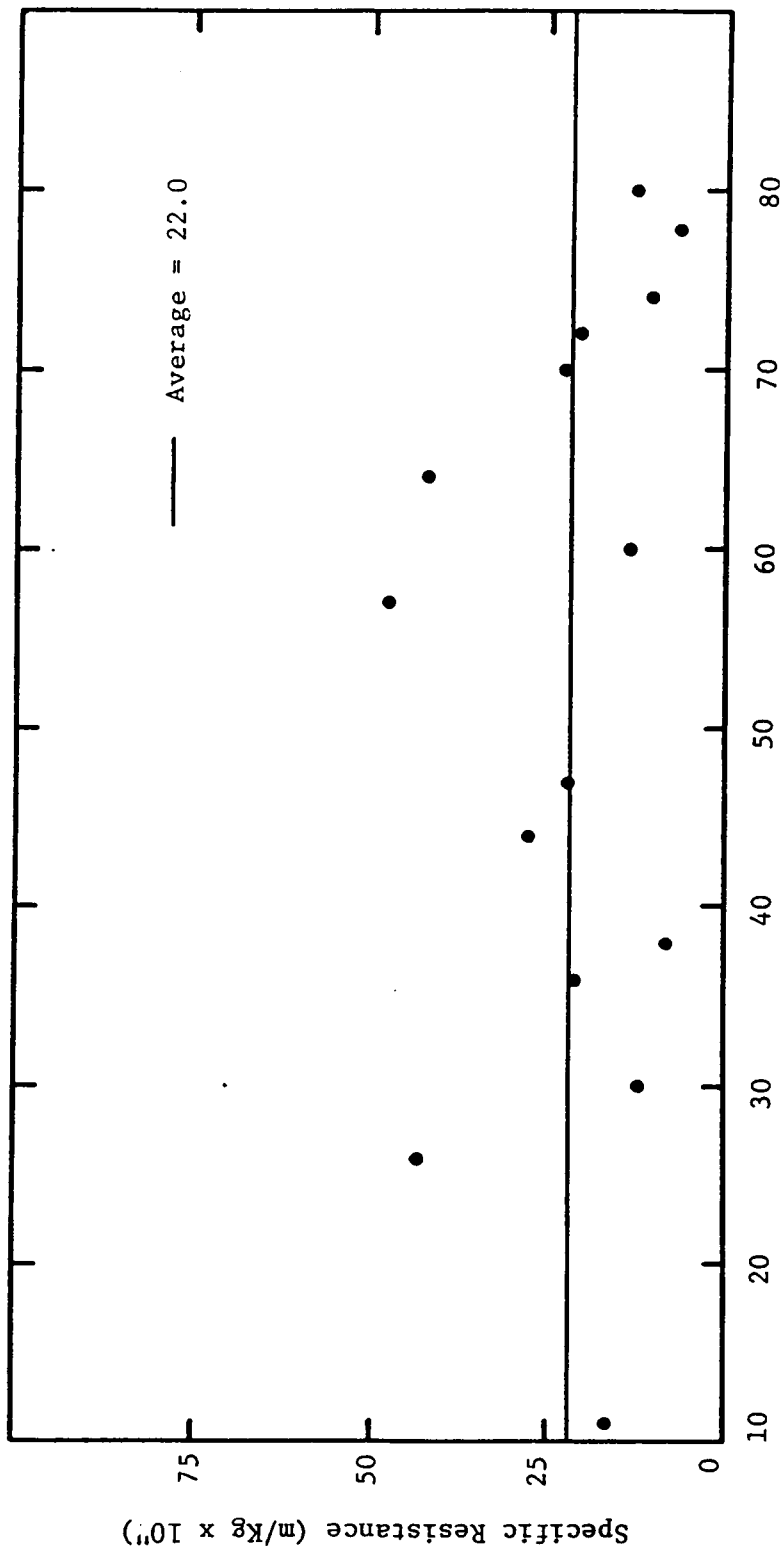

Figure 3. Specific Resistance of Reactor 1: Day 1 to Day 80

reactor operation. This value compares well with typical values found in the literature for activated sludge (18).

Egg Albumin Feed. Data presented in Figure 4 show the effect that changing the organic feed source to egg albumin had on sludge dewatering rates. After the feed was switched from bacto-peptone to egg albumin, there was an immediate increase in the observed sludge specific resistance. It decreased to the average level for one day but then increased and remained above the average level noted for the bacto-peptone feed. After the feed was returned to using bacto-peptone, the specific resistance increased sharply to over 400 m/Kg before decreasing again to the background level.

Solids flux data were highly erratic during the bacto-peptone and egg albumin feeding phases. Due to the low number of samples tested in each flux analysis, it was difficult to ascertain feed effects on thickening rates. However, the effluent suspended solids concentration was consistently higher when egg albumin was used as the organic substrate (data shown in Figure 5). Also, the reactor MLSS concentration decreased during this time which prompted the end of this particular part of the study. The effluent had a whitish color; the clarifier did not have a good, clear solid-liquid interface.

In examining Figures 3 thru 5, it seems evident that the introduction of egg albumin as a substrate had a definite effect on the sludge. It also seems likely that the introduction of egg albumin, a protein, caused the bacterial population to shift. The

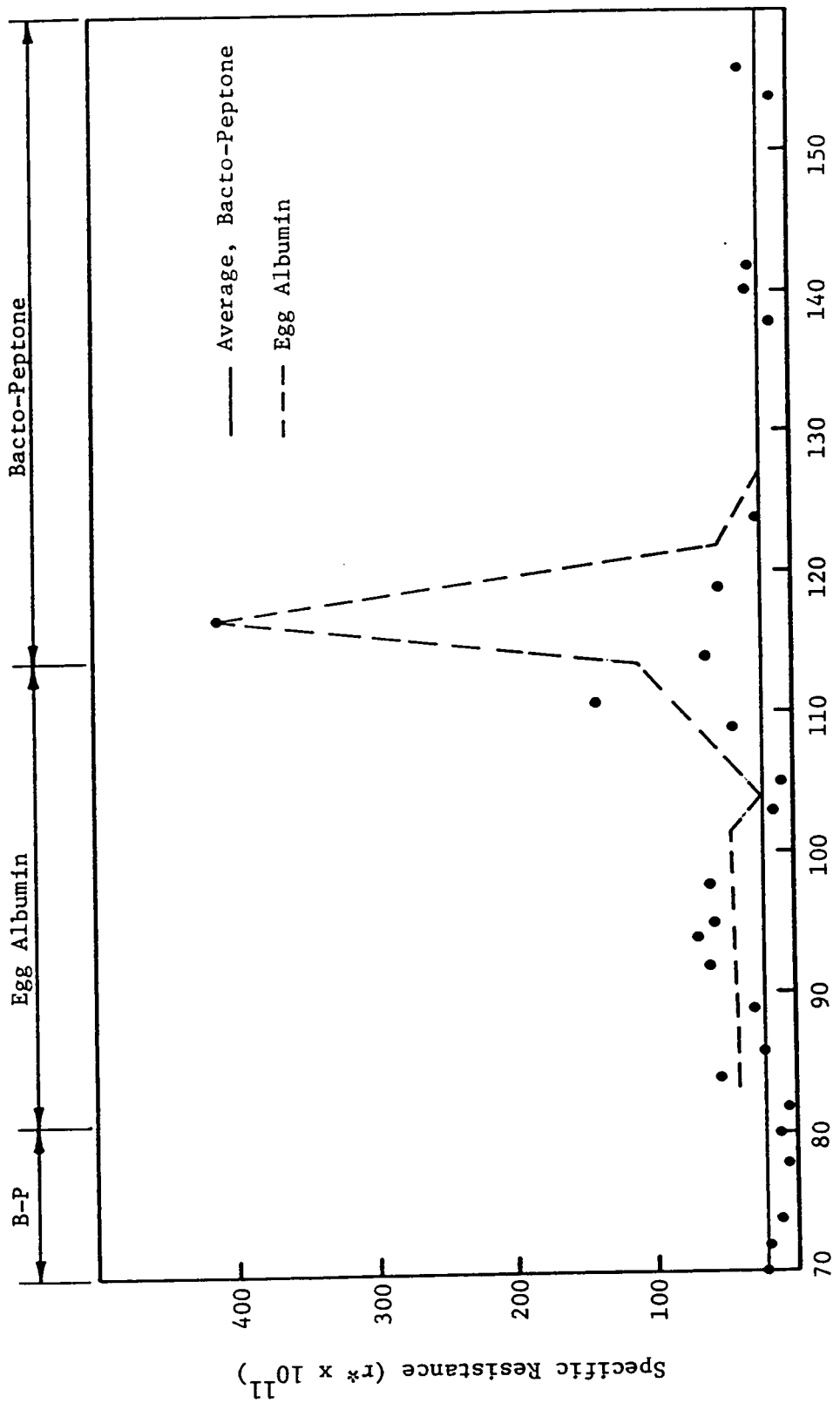

Figure 4. Specific Resistance of Reactor 1 - Egg Albumin: Day 70 to Day 156

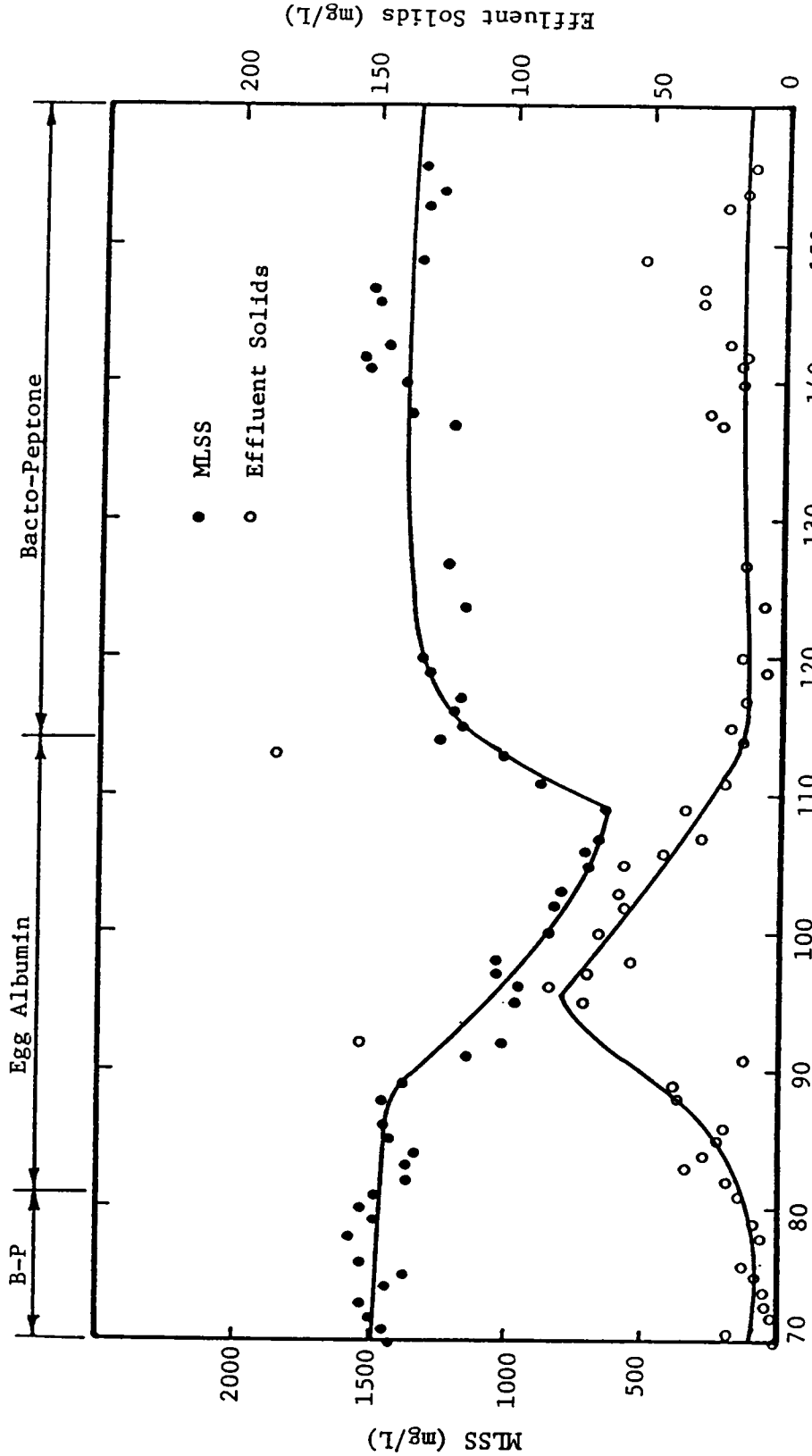

Figure 5. MLSS and Effluent Solids of Reactor 1 - Egg Albumin: Day 70 to Day 156

organisms that responded well to bacto-peptone may not have responded to egg albumin as well. Another explanation could be that in acclimating to a new substrate, organisms were forced to use alternate enzymes or metabolic pathways and, hence, after the cells' characteristics and their settling and dewatering properties. By visual observation, the sludge changed from a dark brown to a light yellow-white color after the introduction of egg albumin. It appeared that Gaudy's (39) description of a population shift due to a qualitative change in substrates applied in this case. The sludge was seen to change visually along with a corresponding increase in specific resistance.

As noted previously, the specific resistance values returned to the background value almost immediately after the bacto-peptone feed was resumed. This seems to indicate that the bacto-peptone preferring organisms became the predominant species again very quickly. An alternative explanation would again be related to the cells' individual metabolism and possible change to becoming one small part of a sludge floc which settles and dewaters well. An interesting part of this is how quickly the sludge returned to its original dewatering rate. This showed that biological systems do have the capability of recovery after system upsets. Time may be all that is needed to correct the situation.

Glucose Feed. After allowing Reactor 1 six weeks of recovery and renewed operation using a bacto-peptone feed, glucose was utilized as the only organic source in a new loading condition. Immediately the

specific resistance began to increase until it reached a maximum value of 300 x 10^{11} m/Kg as shown in Figure 6. The specific resistance then declined but was still much higher than the background condition. No settling or thickening tests were performed on this culture because as soon as the glucose feed was initiated, settling deteriorated which ended in solids wash-out as shown in Figure 7. The MLSS concentration did increase over a ten day period only to wash out again. This particular feed study was ended at this point. There was a second attempt with glucose feed, utilizing an initial ten day acclimation period using a batch mode of operation. However, as soon as the reactor was switched to continuous operation, there was solids wash-out associated with very poor settling.

After this second wash-out, reactor 1 was again operated in the batch mode until its sludge was used to seed four smaller reactors for the "Recovery of Sludge Handling Characteristics" section of this chapter. This portion of the study is explained in the following subsection.

It seemed that the activated sludge reacted similarly to the second shock loading (pure glucose feed) as it did to the first. However, the change in the bacterial population was more evident by visual observation during the glucose loading. Before the glucose feed was applied, the sludge was a yellowish-brown in color and the effluent was clear. Afterwards, the color of the sludge became lighter yellow each day until it appeared greenish-yellow. The effluent also became less clear as more solids washed out of the

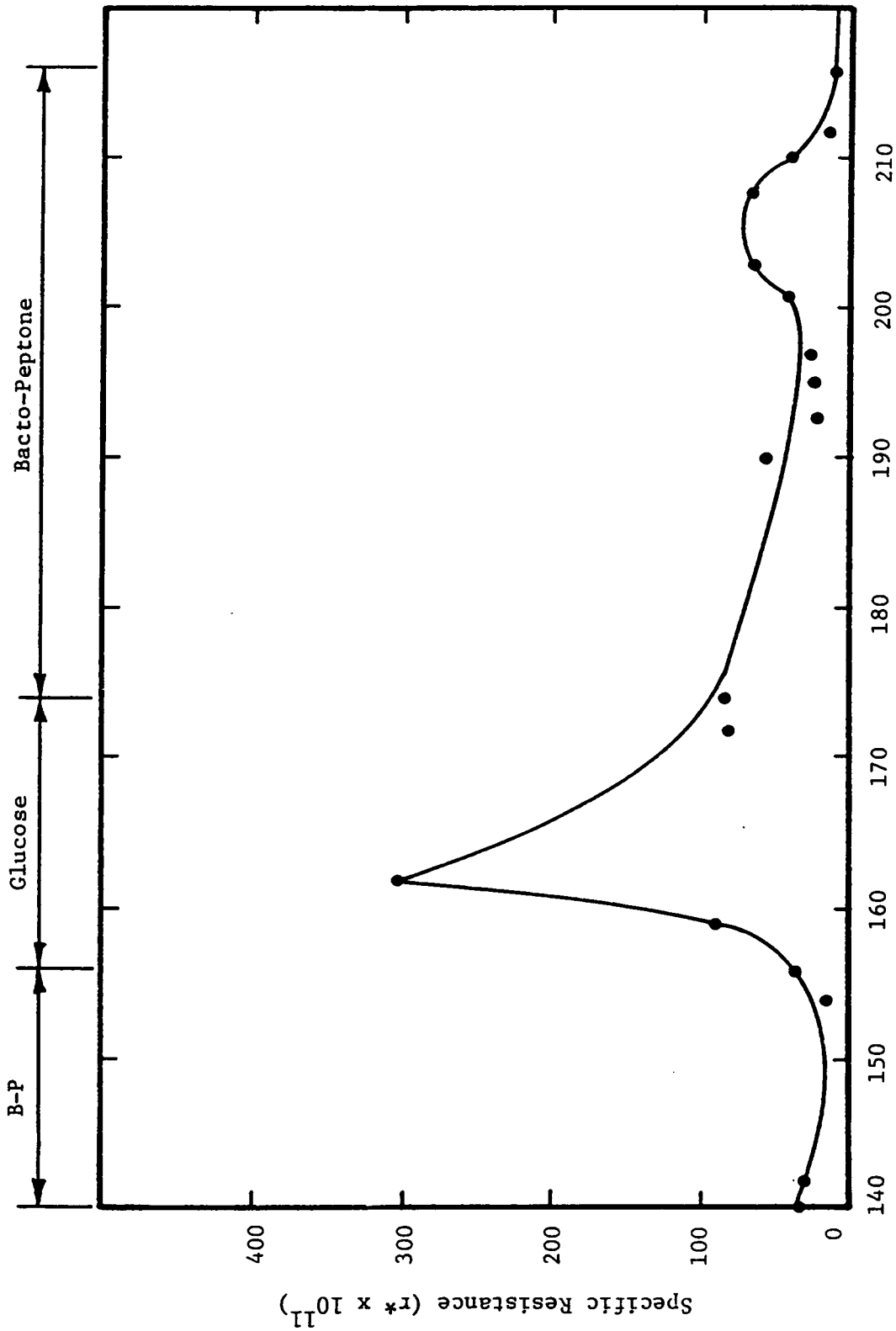

Figure 6. Specific Resistance of Reactor 1 - Glucose: Day 140 to Day 216

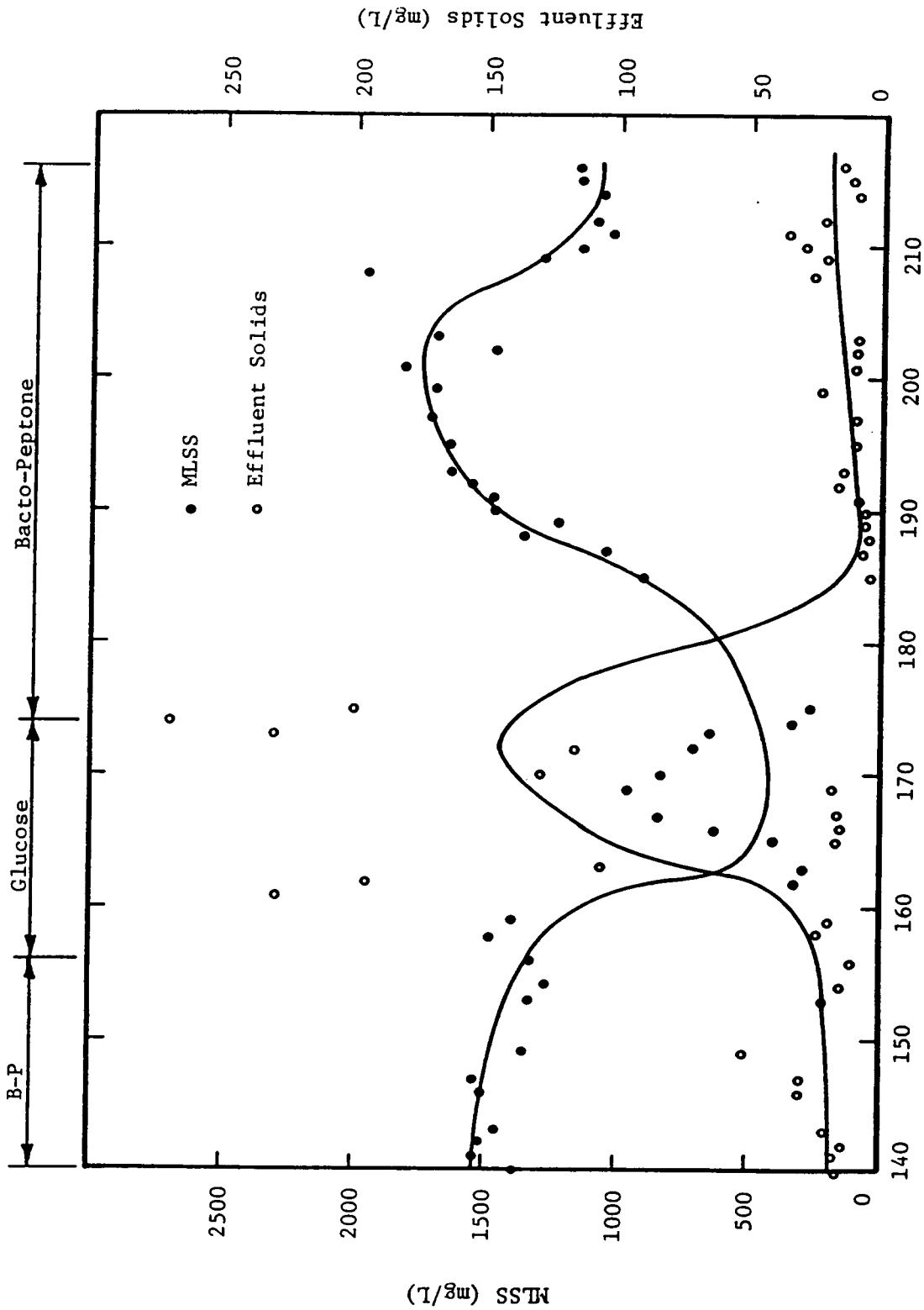

Figure 7. MLSS and Effluent Solids of Reactor 1 - Glucose: Day 140 to Day 216

system. Immediately before the glucose feed was ended, the color of the sludge was completely grey. A microscope was used to examine the sludge several times and it was found to be extremely filamentous which would account for the poor settling. It appeared obvious that a certain segment of the bacterial population dominated in Reactor 1 when fed glucose. Also, it seemed that this segment was composed of filamentous organisms that caused the sludge dewatering and settling properties to deteriorate. It is not certain why such a rapid change was seen in the activated sludge after switching substrates. Perhaps it was because the organisms that preferred bacto-peptone as a substrate did not or could not physically acclimate readily to the glucose, allowing the filamentous organisms to dominate the sludge handling properties. Again, Gaudy's (39) description of population shifts due to a qualitative change in substrates applied here also. Tomlinson (15) and Houtmeyers (16) conducted studies where glucose feeding caused filamentous microorganisms to predominate. These filamentous microorganisms were termed "bulking sludge" as the sludge showed poor settling characteristics. Sezgin et. al. (11) noted that the relative numbers of filamentous and zoogleal microorganisms in the floc was one of the most important factors with respect to poor settling. This was obvious in this case as the filamentous microorganisms were very predominant, ultimately leading to extreme solids wash-out.

As in the case of the first substrate shift to egg albumin, after the bacto-peptone feed was reapplied, the average background

dewatering rate was reached in a relatively short period of time. The sludge also returned to its original yellowish-brown color. This again showed the capability of a biological system to recover quickly after the system had been dramatically affected.

Glucose/Bacto-Peptone Feed: Sludge Handling Characteristics

As mentioned previously, Reactors 1A through 4A were started using the activated sludge from Reactor 1 after it had been fed a 100% glucose batch feed for three weeks. The first reactor to be discussed is Reactor 1A which was maintained on a twenty percent glucose and eighty percent bacto-peptone feed combination.

1. Results of the 20% Glucose/80% Bacto-Peptone Feed Reactor Study. Data presented in Figure 8 show that even after three weeks of acclimation in Reactor 1, poor settling rates were still a problem when Reactor 1A began operation. However, the specific resistance was very good as it remained below the aforementioned background level. During the first twenty-one days of operation, while Reactor 1A was kept in the batch mode, the settling characteristics were much improved as measured by the SVI test. The SVI decreased from 160 to 54; the sludge also dewatered well as evidenced by low specific resistance values (data shown in Figure 8). After beginning continuous operation on the twenty-first day, the specific resistance increased five-fold immediately while the SVI showed a slower increase over a period of ten days. The specific resistance then showed a dramatic decrease and, except for a couple of exceptions, proceeded to decrease to a minimum of approximately 6×10^{11} m/Kg. After the

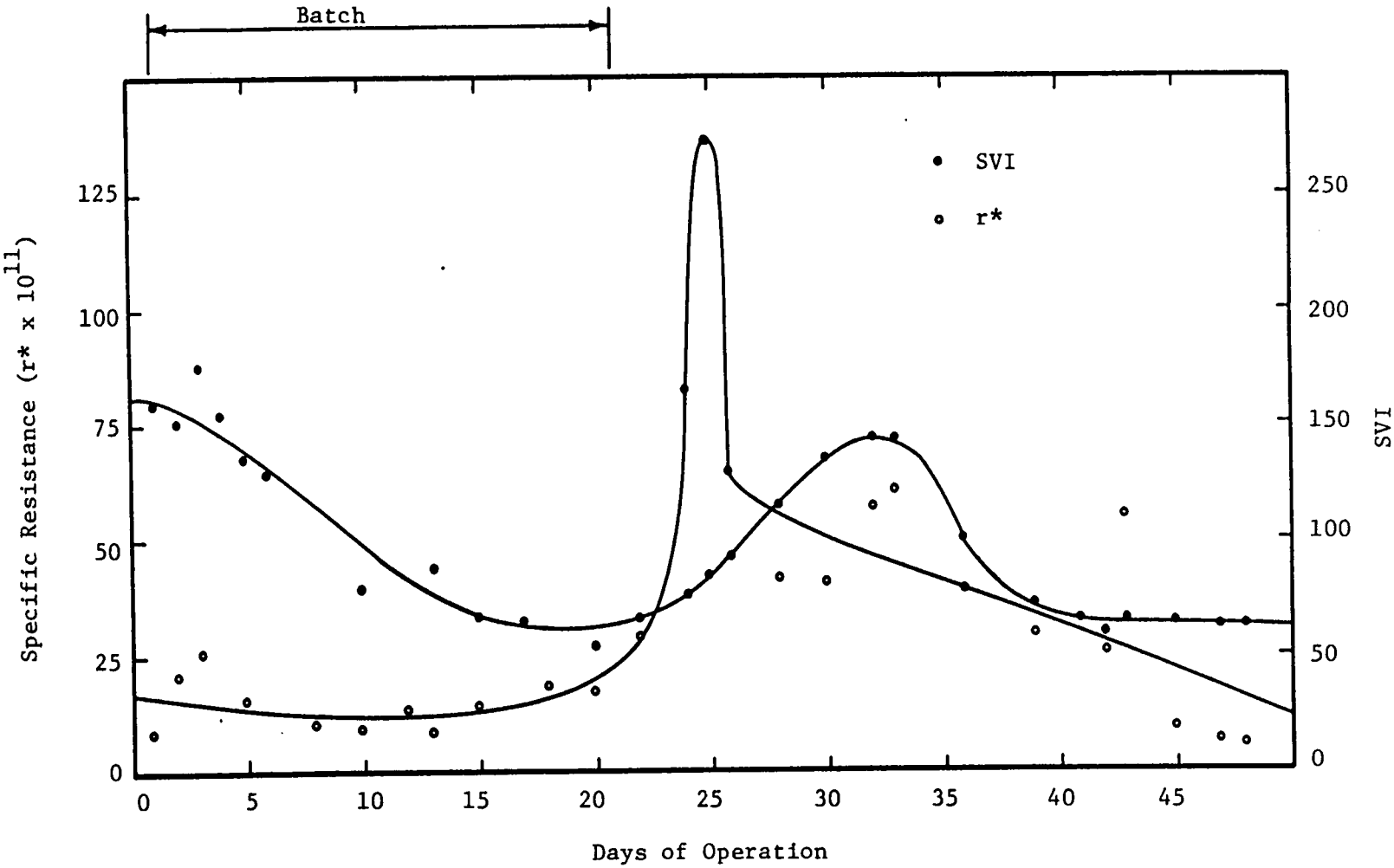

Figure 8. Specific Resistance and SVI of Reactor 1A - 20% Glucose: Day 0 to Day 50

SVI reached a maximum of 140, it also decreased down to an acceptable level in the low 60's before the study was ended.

In examining these results, it is evident that the 20% glucose/ 80% bacto-peptone combination had a direct effect on the sludge properties. Both SVI and specific resistance values showed that the sludge did well after starting this organic feed combination. Two factors could have been responsible. First, the time provided in the batch mode allowed the microorganisms time for acclimation without chance of solids wash-out. The second factor could have been that the organisms responded favorably to the bacto-peptone portion of the feed and this affected the sludge properties positively. Of course, it could have also been a combination of both factors. These factors will be discussed more later in this section after the other three combination feed results have been examined.

It was mentioned earlier that the switch from batch to continuous operation affected the activated sludge. The only parameter that was changed in effect was the hydraulic detention time if one considers the batch period as a system with an exceedingly long detention time. When switched to continuous flow, the hydraulic detention time was maintained at eight hours as in the rest of the study. It is not clear to the author if this did indeed have an effect on the system. More discussion will come later on this topic after the other results have been examined.

2. Results of the 40% Glucose/60% Bacto-Peptone Feed Reactor Study. As was the case with Reactor 1A, sludge settling rates were

very poor and specific resistance values low at the beginning of operation of Reactor 2A. Figure 9 shows that specific resistance stayed very low and SVI decreased slowly through the twenty-three days of batch operation. The SVI decreased from 247 on day 1 to 50 on day 23 of batch operation; the specific resistance values were found to range from 4 to 15 x 10^{11} m/Kg. However, after continuous operation began the reactor was only able to operate for one week before solids wash-out. The MLSS decreased very rapidly as shown in Figure 10. The specific resistance increased twenty-fold and only showed a decrease at the last because the initial solids in the dewatering test was only 0.17%. The SVI also increased very quickly and the last reading was 956 when there was no minimal settling of the sludge in a thirty minute period.

The trends were the same here as in Reactor 1A. The major difference was that 1A did not wash out and resumed normal operation while 2A did wash out. It would seem that the feed combination with 40% glucose had an effect which did not allow the system to recover after continuous operation began. This will be discussed more after examining the other feed combinations.

3. Results of the 60% Glucose/40% Bacto-Peptone Feed Reactor Study. Reactor 3A reacted similarly to the first two. However, the SVI decreased slower than in Reactor 1A or 2A after starting at a higher initial value as shown in Figure 11. The specific resistance was again low and stayed at approximately 10 x 10^{11} m/Kg until continuous operation began after 31 days of batch operation. Continuous

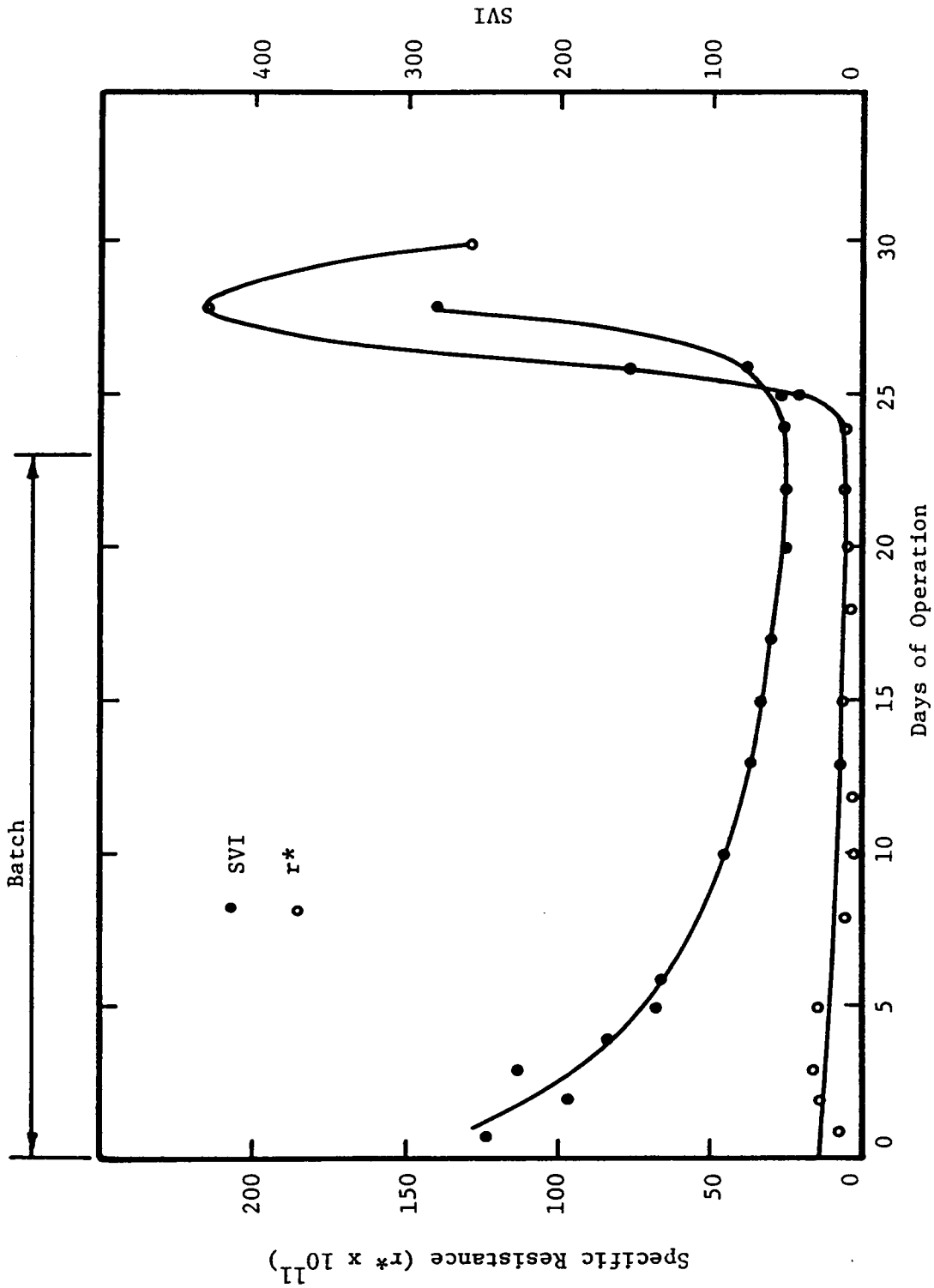

Figure 9. Specific Resistance and SVI of Reactor 2A - 40% Glucose: Day 0 to Day 30

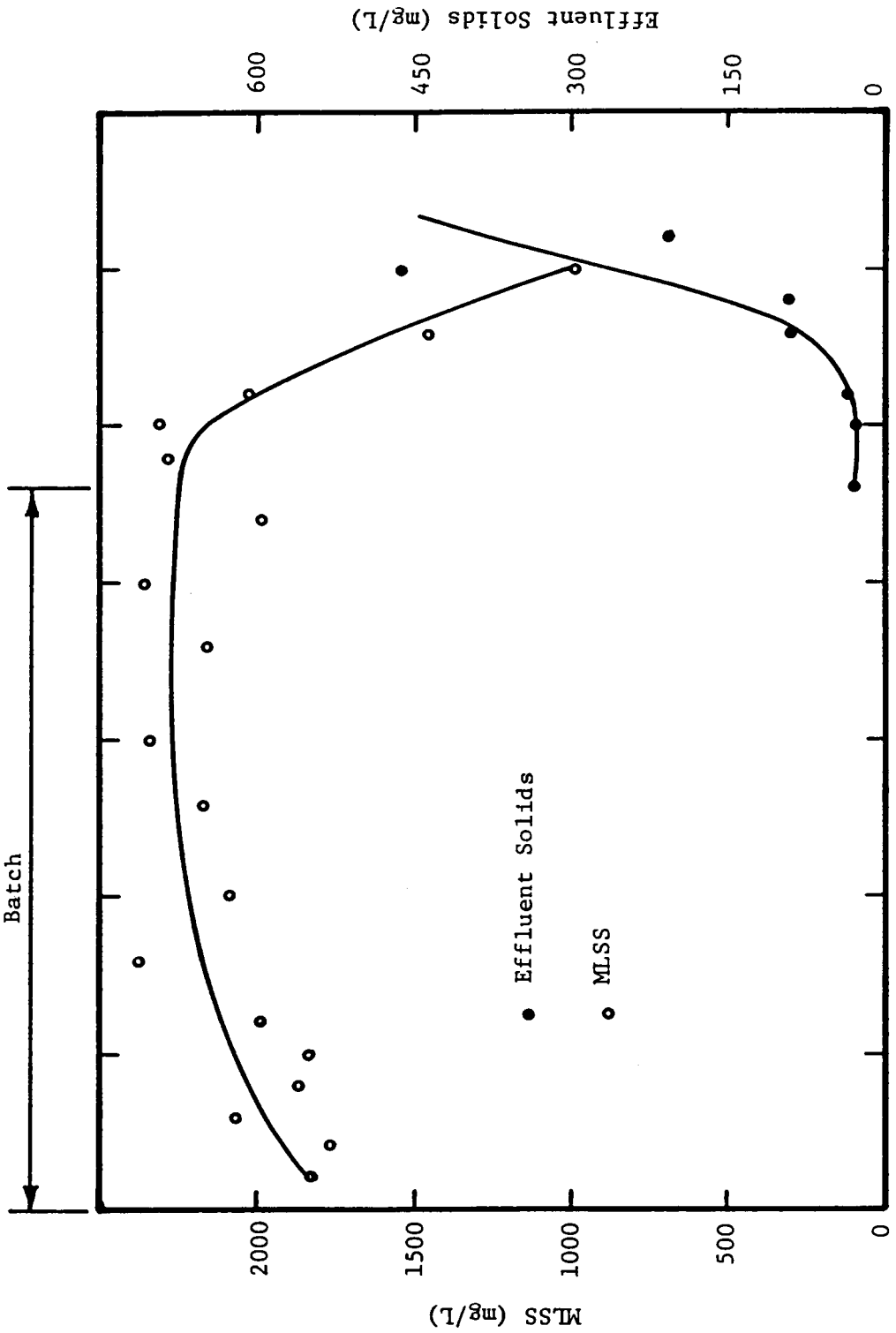

Figure 10. MLSS and Effluent Solids of Reactor 2A - 40% Glucose: Day 0 to Day 30

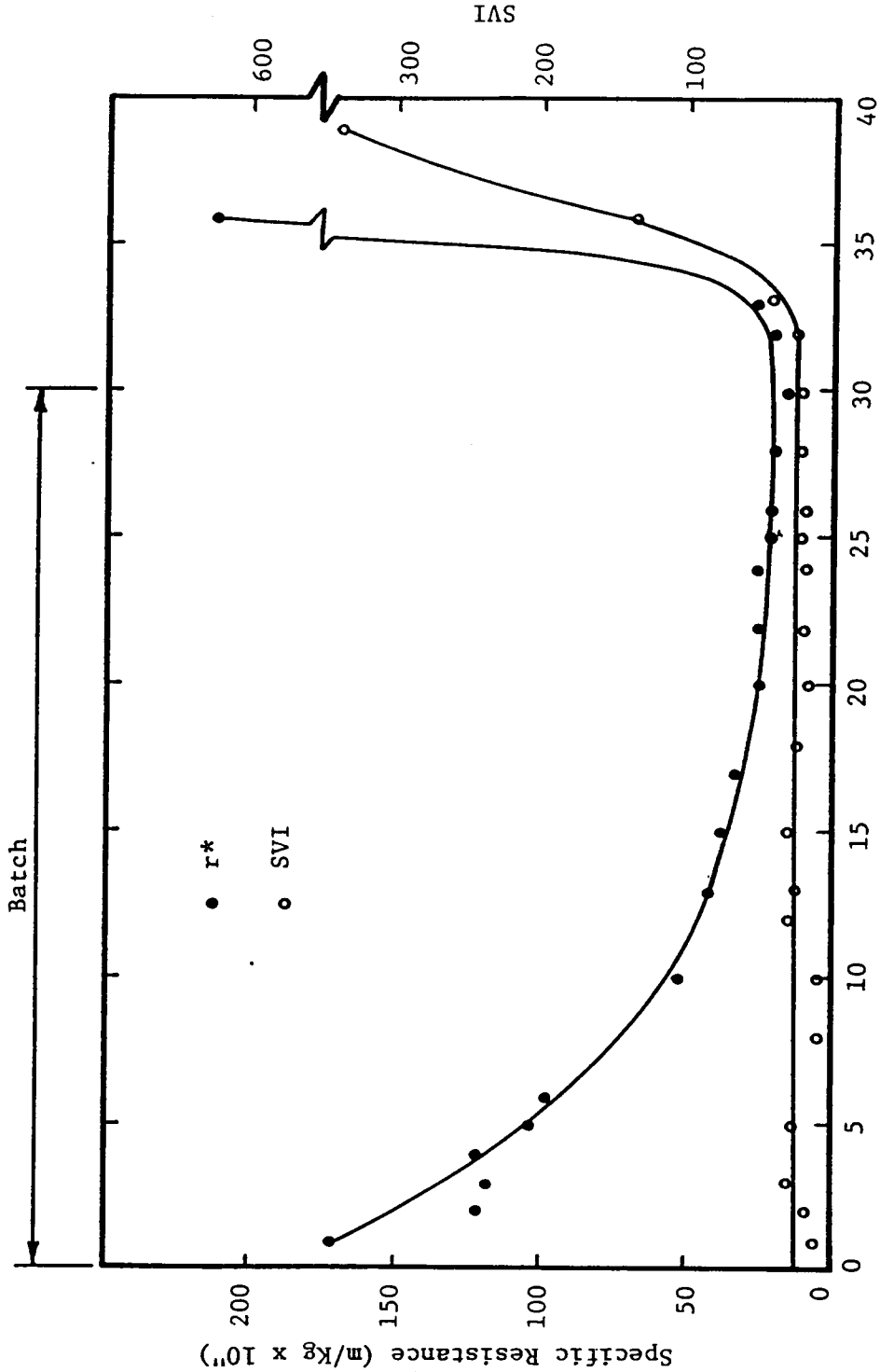

Figure 11. Specific Resistance and SVI of Reactor 3A - 60% Glucose: Day 0 to Day 39

operation lasted for a week until the MLSS was down to 260 mg/1, as seen in Figure 12, and the reactor operation was halted. During this time, the specific resistance increased to 170 x 10^{11} m/Kg and the SVI increased to values above 600 before solids wash-out occurred. The same trend was seen in Reactor 2A when wash-out occurred after continuous operation began.

4. Results of the 100% Glucose Feed Reactor Study. Reactor 4A was the same culture throughout since Reactor 1 had been fed 100% glucose before being divided. Figure 13 shows that it also had the same trends of specific resistance being relatively low and SVI decreasing during the batch acclimation period. The SVI for this feed reactor started out the highest and decreased the slowest of all four reactors. Continuous operation began after thirty-two days in the batch mode. The SVI increased slowly for about ten days and then increased quickly to 185 and 586, respectively, the next two sampling days. One thing that differed in this reactor was that the specific resistance maintained a value below 10 x 10^{11} m/Kg and did not increase when continuous operation began. The end of this phase of the study came when the SVI increased and wash-out of the reactor's solids had begun.

Comparison of Reactor's Sludge Properties

The same general trends for SVI and specific resistance were present in all four reactors during the batch mode. The SVI decreased over time and specific resistance remained relatively low. However, the SVI began at a higher level and declined more slowly as the

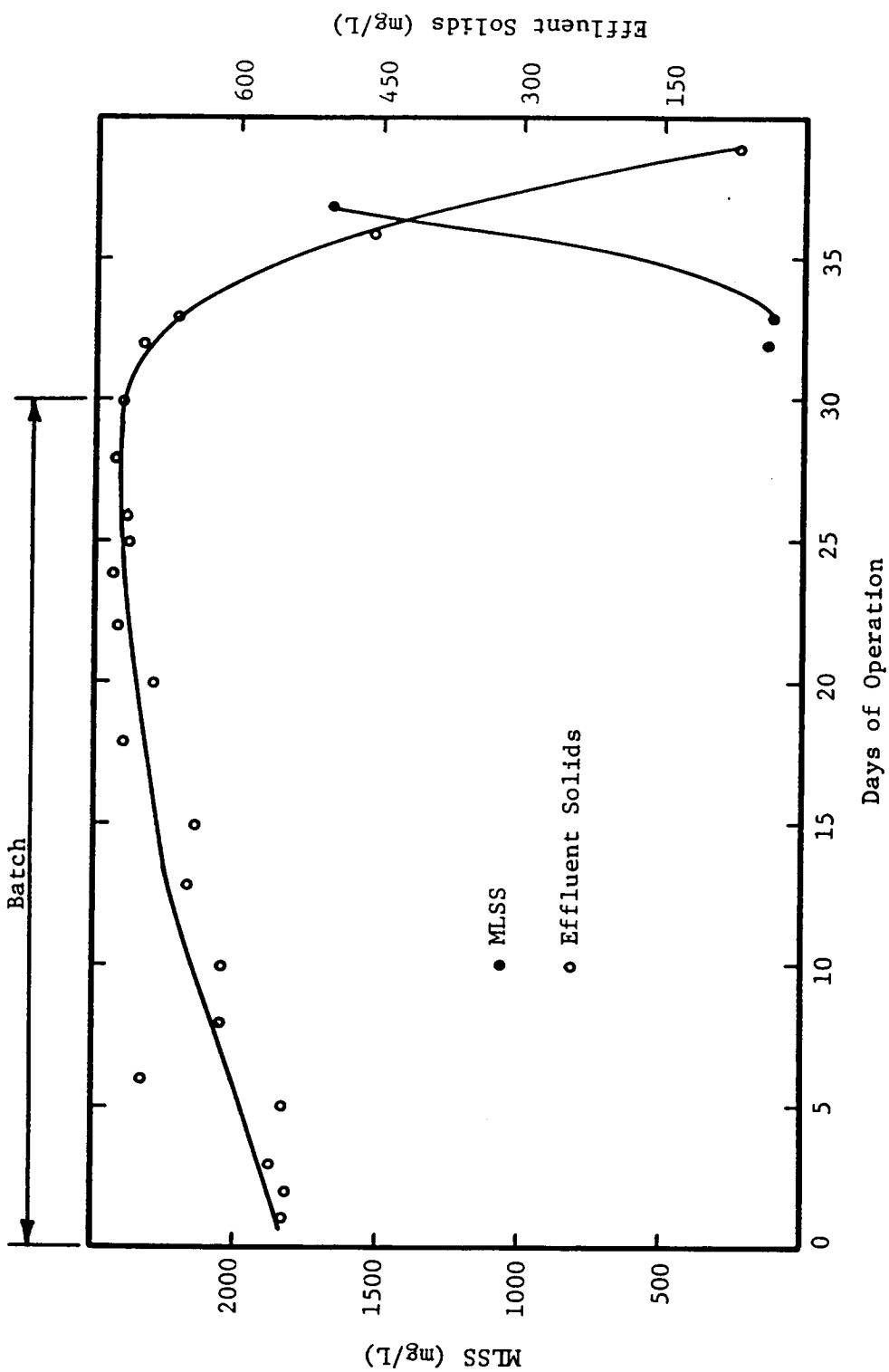

Figure 12. MLSS and Effluent Solids of Reactor 3A - 60% Glucose: Day 0 to Day 39

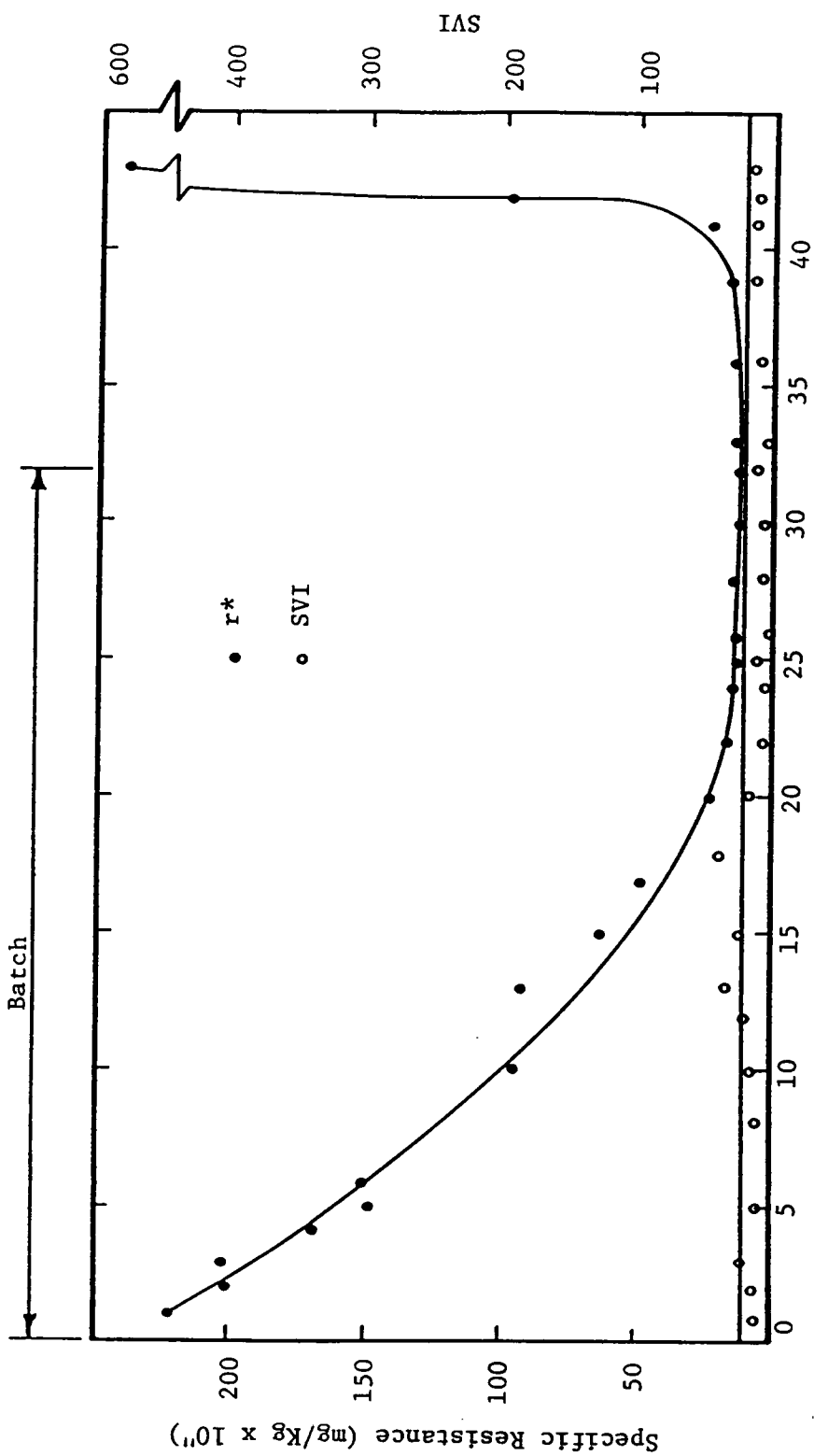

Figure 13. Specific Resistance and SVI of Reactor 4A - 100% Glucose: Day 0 to Day 43

percentage of glucose in the feed combination increased (Table III). This would suggest that glucose did have a direct effect on the organisms and their settling and dewatering characteristics. As the percentage of glucose decreased and bacto-peptone increased, the organisms responded favorably as indicated by their sludge characteristics. This would indicate that both factors discussed previously did have an effect on the sludge properties examined. These factors were: 1) the organisms that responded well to the original substrate did not respond as well to the new substrate and; 2) a shift in population was caused by the new substrate, causing organisms to predominate which did not have good handling characteristics. This was shown by Reactor 1A since it was the only reactor to maintain continuous operation and also had the best sludge handling characteristics as shown in Table III. This table shows that the time it took to reach an SVI of 100 and 200 was directly affected by the organic feed combination.

One question still unanswered is why Reactor 1A did not wash out and the others did after switching to continuous operation. The sludge settling and dewatering characteristics in Reactor 1A did deteriorate following a switch from a batch to continuous flow mode of operation. However, this culture recovered while the others did not. This again points to the fact that the feed was only twenty percent glucose for Reactor 1A and this seems to have enabled it to recover. The reactor was still dominated by bacto-peptone preferring organisms. The glucose preferring organisms tended to be filamentous

TABLE III. RECOVERY IN SLUDGE SETTLING CHARACTERISTICS

Reactor	Initial SVl	Time for SVl to Decrease to 200 (days)	Time for SVl to Decrease to 100 (days)
1A	160	--	8
2A	247	3.5	9
3A	345	5.5	10.5
4A	445	9.5	17

and this appeared to be the reason for poor dewatering and settling. Also, the reactors showed different characteristics while feeding continuously and in the batch mode. Tomlinson's (15) and Houtmeyer's (16) studies showed the same trend in switching from continuous to batch feeding. Sludge bulking caused by filamentous microorganisms was lessened by switching from continuous to batch feeding. Houtmeyer's study stated that only directly absorbable substrates, i.e., glucose, showed differences from continuous to batch feeding.

One trend that was different in Reactors 2A through 4A was with respect to the specific resistance values observed after switching to a continuous flow mode of operation. While the specific resistance values increased in Reactors 2A and 3A (as did their SVI values) the specific resistance of the sludge in Reactor 4A remained in the 10 to 20 x 10^{11} m/Kg range. The solids level in the reactor remained relatively constant. Also, as may be seen in Figure 13, the sludge settling characteristics deteriorated more slowly than did the sludge in the other reactors. No explanation for the variation in Reactor 4A could be developed.

Dissolved Oxygen Effect on Activated Sludge

This portion of the study attempted to examine the effect of varying aeration basin dissolved oxygen (D.O.) concentrations on activated sludge dewatering rates. As was done in the study which utilized various organic feed solutions, background dewatering characteristics were quantified by allowing Reactor 2 to operate under high oxygen conditions (D.O. > 4 mg/l) for an extended period of time

under steady-state conditions. The average specific resistance was calculated to be 20 x 10^{11} m/Kg as shown in Figure 14. Figure 15 shows the specific resistance values and corresponding D.O. range from Day 97 to Day 172. The D.O. concentration was kept about 4 mg/l until Day 173. It was expected that the specific resistance values would be low during this period. However, this was not the case as is shown in Figure 15. There were a couple of periods where the reactor dewatered very poorly for no apparent reason. The sludge was seen to be different by visual observation but it was not clear why this was the case. At the end of the second apparent cycle, the specific resistance of the sludge had again reached the average background value. The D.O. level was then varied from 0.2 to 6 mg/l beginning Day 173. Figure 16 shows the specific resistance and the D.O. concentration as a function of time. As the D.O. was decreased, the specific resistance increased from below 10 x 10^{11} m/Kg to above 100 and then to almost 900 x 10^{11} m/Kg. The D.O. level was 0.2 mg/l at its lowest level. As the D.O. concentration increased, the specific resistance decreased below 40 x 10^{11} m/Kg before the reactor developed a leak. The sludge that was salvaged was placed in a 18-liter reactor and maintained on a batch basis for two weeks before running to a continuous-flow mode. This showed that the system had recovered with the D.O. above 4 mg/l, as the specific resistance of the sludge remained below 20 x 10^{11} m/Kg. This portion of the study seemed to show what many previous studies have concluded, namely that D.O. concentrations below 2 mg/l often lead to sludge thickening/

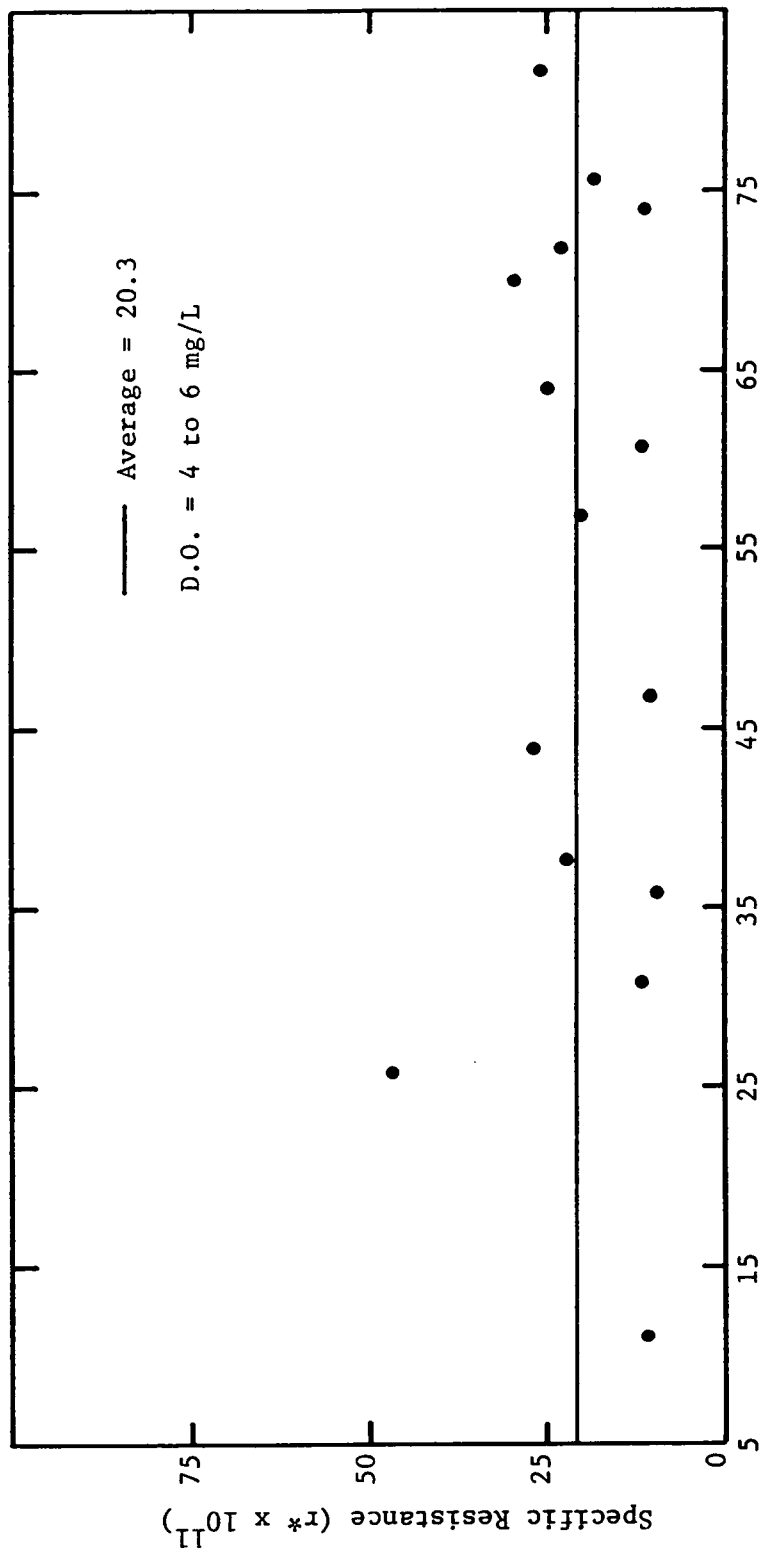

Figure 14. Specific Resistance of Reactor 2: Day 5 to Day 85

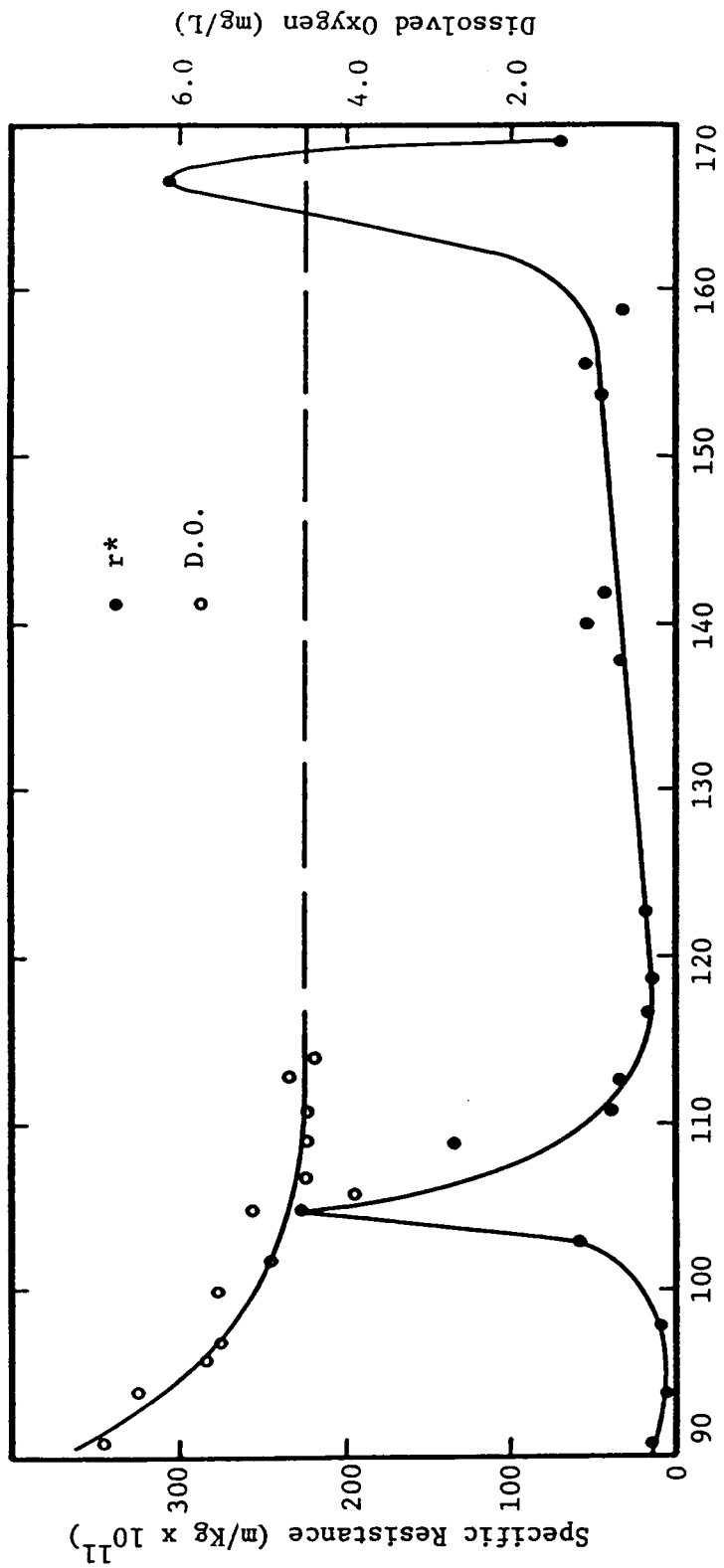

Figure 15. Specific Resistance of Reactor 2 with High D.O. Levels: Day 90 to Day 170

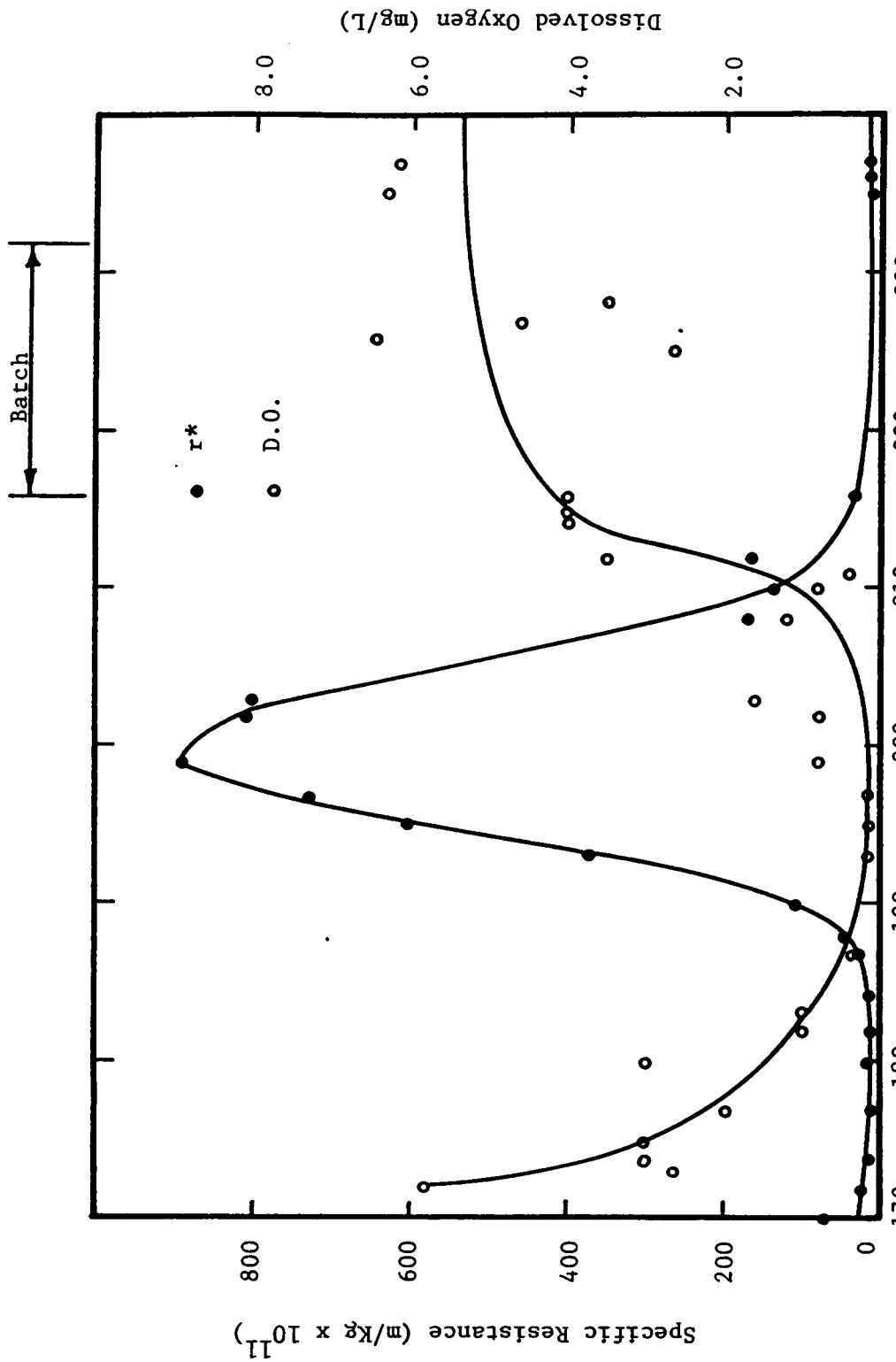

Figure 16. Specific Resistance of Reactor 2 with Low D.O. Levels: Day 170 to Day 237

dewatering problems in biological systems. Palm et. al. (12) and Parker (13) both showed that low D.O. concentrations led to sludge bulking. Palm et. al. theorized that the D.O. was not sufficient to penetrate to the floc core of the zoogleal microorganisms, allowing the filamentous microorganisms to predominate.

There have been many theories advanced to explain this but the end result remains the same. The sludge floc structure is adversely affected by a lack of oxygen provided and deteriorates to the point where settling and dewatering are severely affected. Also, it appears that at low D.O. conditions, anaerobiosis can occur even in so-called complete-mix systems. This was seen in Reactor 2 at the 0.2 mg/l even though additional mixing was provided to prevent this from happening. A greenish-grey growth appeared on the side of Reactor 2 and there was the distinct odor of hydrogen sulfide being produced. This disappeared a week after the D.O. concentration was increased above 1 mg/l.

The periods of poor dewatering observed sporadically during operation using a high D.O. concentration (D.O. > 4.0 mg/l) cannot be logically explained by the author. The sludge thickening characteristics did not change appreciably and the effluent suspended solids were similar before, during, and after these periods of poor dewatering. It is known that there are many factors which affect biological systems. It appears that, in this case, there was no outside condition which should have affected the system. Researchers have proposed that a bacterial population will shift or go through cycles

of different dominant organisms after being triggered by some unknown mechanism. It is not certain if this happened in this case or not.

Biopolymer Correlation with Specific Resistance

This portion of the study was conducted to determine if biopolymer production could be used to predict good or poor dewatering conditions. A plot of specific resistance as a function of measured supernatant biopolymer content is shown in Figure 17. This figure shows some good general trends. When the sludge dewatering rate was very poor the biopolymer production correspondingly high; if good dewatering rates were observed, the biopolymer production was low. This is also shown in Table IV.

There was mechanical problems encountered with the biopolymer chart recorded and this hindered data collection during several parts of the study. This prevented several samples from being analyzed which may have filled in the middle portion of Figure 17.

Novak (32) observed that as a sludge's filtration rate improved, the amount of extractable biopolymer decreased. As the biopolymer concentration increased in the sludge, the filtration rate declined. Gulas et. al. (31) stated that the conditioning requirements for a given sludge were directly related and the specific resistance inversely related to biopolymer concentration present. This was also the general trend seen in this portion of the study. As the amount of extractable biopolymer increased, the filtration rate declined. When a sufficient D.O. level was maintained, the amount of extractable biopolymer was comparatively low and the filtration rate was very good.

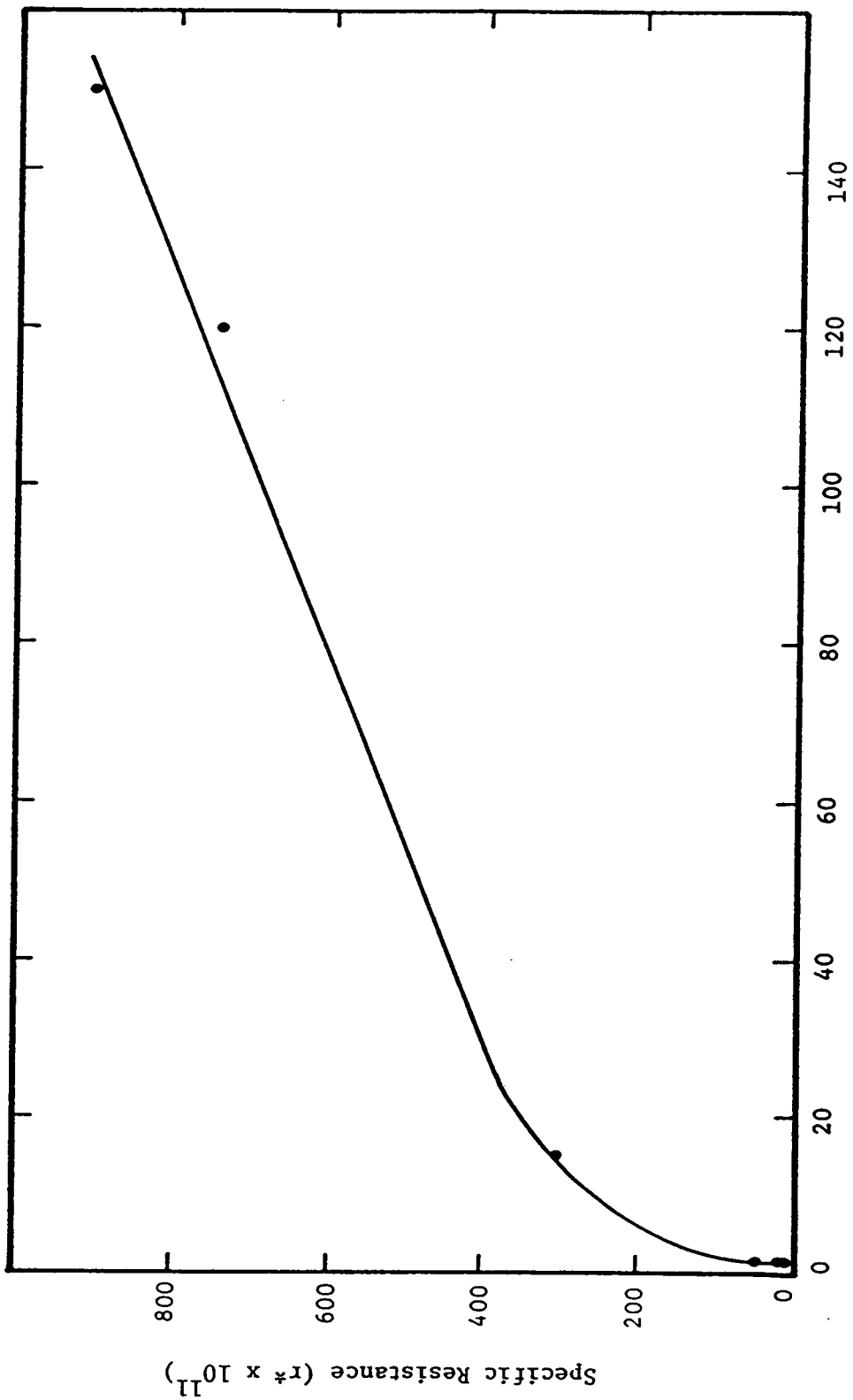

Figure 17. Specific Resistance as a Function of Biopolymer Content

TABLE IV. CORRELATION BETWEEN SPECIFIC RESISTANCE AND BIOPOLYMER

Date	$r^* \times 10^{11}$ (m/Kg)	D.O. (mg/l)	Biopolymer (High Molecular Weight Fraction of Solution)
8/20	17.0	3.0	2.0
8/26	14.0	1.0	2.0
9/9	740.0	0.2	120.0
9/12	910.0	0.2	150.0

V. CONCLUSIONS

This section states the conclusions of this study which were obtained from operating bench scale activated sludge reactors while changing various control parameters. The conclusions that were made based on these results are listed along with ideas for further research in this area.

1. Shock loadings significantly alter the settling and dewatering characteristics of an activated sludge population. The shock loadings may cause shifts in the bacterial population, allowing undesirable microorganisms such as the filamentous types to predominate and cause complete failure of the treatment system.

2. Activated sludge dewatering is directly affected by the dissolved oxygen level in the aeration basin. The minimum level needed for good sludge dewatering is 2.0 mg/L in a completely-mixed system. Values much above 2.0 mg/L do not significantly enhance sludge dewatering.

3. There is a relationship between biopolymer production and sludge dewatering. High biopolymer content correlates with poor sludge dewatering and low biopolymer content correlates with good sludge dewatering.

4. Activated sludge can recover from shock loading caused by the introduction of a different substrate.

Additional research is needed to make these findings useful in daily treatment plant operation. Two types of substrates were examined as shock loads; other common substrates could be examined

to see if they negatively affect activated sludge and its handling properties. Also, it would be beneficial to know the exact types of microorganisms that perdominate when fed these substrates and how to prevent their growth. A simple and standard method for measuring biopolymer is needed to allow this parameter to be used by operators for monitoring their systems. More study is required in the area of activated sludge recovery after upsets and how to enhance the system's stability.

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APPENDIX A

Equations and Variables

Table A-1: Useful Equations

1. $r(m/kg) = \frac{2PA^2b}{vw}$

2. $w(kg/m^3) = \frac{C_k x C_i}{C_k - C_i}$ (10)

3. Percent Solids (% by weight) $= \frac{P_o - P_i}{P_w}$ (100)

4. $SVI = \frac{\text{ml sludge x 1000}}{MLSS}$

Table A-2: Summary of Variables Used

A = filter surface area used in vacuum filtration test (m^2).

b = slope resulting from the plot of "T/V" versus "V" which was obtained from the vacuum filtration test (sec/m^6).

C_i = solids concentration (% by weight) of vacuum filtration test feed sludge.

C_k = solids concentration (% by weight) of sludge cake after vacuum filtration test.

MLSS = mixed liquor suspended solids (mg/L).

p = applied pressure in vacuum filtration test (N/m^2).

p_i = weight of pan (grams, g).

p_o = weight of pan plus contents after drying (g).

p_w = weight of pan plus contents before drying (g).

Q = daily flow through reactor (liters/day).

r = specific resistance of sludge.

v = viscosity of water, at the temperature of the sludge, which was used in the vacuum filtration test ($N\text{-}sec/m^2$).

V = volume of activated sludge wasted daily from the system (liters).

V_w = volume of activated sludge wasted daily from the system (liters).

w = weight of dry solids deposited as cake per volume of filtrate (kg/m^3).

APPENDIX B
Reactor 1, Day 1 - Day 65 (2/24-4/30)

Day	Date	IS %	CS %	r*x10"	pH	D.O. mg/L	MLSS mg/L	Eff. SS mg/L	Biopoly.	COD Removal %	Eff. COD mg/L
1	2-25						--	37			
3	2-27						1330	21			
5	3-1						1250	--			
7	3-3						1260	24			
9	3-5						1170	19			
11	3-7	0.82	7.92	16.2			1355	--			
13	3-9						1140	27			
16	3-12						1170	8			24
26	3-22	0.52	7.99	43.2			1110	49			12
28	3-24						860	--			
29	3-25						915	40			
30	3-26	0.62	7.90	12.3			915	33			
31	3-27						990	38			
32	3-28						1135	17			
33	3-29						1100	--			
34	3-30						1105	36			
35	3-31						1090	17			
36	4-1	0.40	7.39	20.4			1205	6			
37	4-2						1085	11			
38	4-3	0.58	8.99	8.2			1125	3			
39	4-4						1310	28			
40	4-5				5.1		1195	11			
41	4-6				5.0		1300	2			
42	4-7				5.0		1380	23			
43	4-8				6.2		1245	19			
44	4-9	0.37	6.08	28.6	6.4		1235	9			
45	4-10				6.6		1370	26			
46	4-11				6.7		1315	28			
47	4-12	0.40	6.55	22.8	6.7		1170	43			
48	4-13				6.8		1280	18			
49	4-14				6.7		1235	9			
54	4-19				6.1		1560	12			
55	4-20				6.6		1345	11			
56	4-21				6.7		1315	15			
57	4-22	0.39	5.71	48.0	6.8		1495	5			
58	4-23				5.8		1395	11			
59	4-24				5.9		1315	11			
60	4-25	0.52	6.88	13.0	5.0		1380	17			
61	4-26				5.1		1445	16			
62	4-27				6.8		1440	12			
63	4-28				6.8		1350	14			
64	4-29	0.59	6.0	42.0	6.9		1430	38			
65	4-30				6.8		1310	20			
Avg.				25.0							

APPENDIX B
Reactor 1, Day 66 - Day 124 (5/1-6/28)

Day	Date	IS %	CS %	r*x10"	pH	D.O. mg/L	MLSS mg/L	Eff. SS mg/L	Biopoly.	COD Removal %	Eff. COD mg/L
66	5-1				6.8		1360	20			
67	5-2				6.8		1410	--		90	
68	5-3				6.8		1400	22		91	36
69	5-4				6.9		1470	18			
70	5-5	0.24	8.14	23.1	6.8		1410	1			
71	5-6				--		1450	19	0.8	94	24
72	5-7	0.31	8.27	20.3	6.7	5.50	1500	2	0.8	96	16
73	5-8				6.7	5.10	1520	5			
74	5-9	0.21	12.6	11.4	6.7	5.20	1420	6		93	27
75	5-10				6.7		1360	9	0.1		
76	5-11				6.8	4.40	1520	13			
78	5-13	0.54	8.28	7.7	6.2		1580	6			
79	5-14				6.7	4.20	1490	9		86	55
80	5-15	0.58	7.70	13.6	6.3		1530	6			
81	5-16				6.4	3.80	1490	15	0.3	91	35
		Egg Albumin Used as Substrate									
82	5-17	0.45	8.40	6.8	--		1360	19		57	172
83	5-18				6.5	3.50	1370	34	1.8	88	47
84	5-19	0.67	5.90	53.8	6.5	3.00	1330	27		85	59
85	5-20				6.5	4.00	1420	23	0.9	89	43
86	5-21	0.46	6.4	24.6	6.5		1450	20		86	55
88	5-23				6.6	2.50	1450	36			
89	5-24	0.68	6.3	32.1	6.4	4.60	1370	38			
91	5-26				6.4	5.00	1140	12			
92	5-27	0.96	4.6	60.5	6.7	5.10	1010	154	27.0	67	131
94	5-29	0.57	2.4	69.5	6.7	4.75	--	--	12.0		
95	5-30	0.31	8.7	57.2	6.7	4.80	970	72			
96	5-31				7.2	--	960	84	5.1		
97	6-1				6.8	5.30	1030	70		86	55
98	6-2	0.30	7.6	61.7	6.4	--	1030	55			
100	6-4				6.0	5.15	830	67			
102	6-6				6.3	4.95	810	57			
103	6-7	0.17	12.1	16.7	6.3	5.30	790	58		77	91
105	6-9	0.27	13.5	7.4	6.5	5.00	700	57			
106	6-10				6.7	4.70	720	43			
107	6-11				6.8	--	660	29			
109	6-13	0.47	12.1	44.0	6.9	4.40	630	35			
111	6-15	0.96	8.28	145.5	6.8	5.10	880	21	13.2		
113	6-17				6.8	5.00	1020	186		88	48
114	6-18	0.27	9.3	62.3	6.9	4.80	1250	13			
		End of Egg Albumin Use									
115	6-19				6.9		1170	19		88	48
116	6-20				6.7		1200	--			
117	6-21	0.56	6.7	412.8	6.9		1180	14		90	42
119	6-23	0.24	11.1	53.1	7.0		1300	6		88	48
120	6-24				7.0		1320	15			
124	6-28	0.22	9.92	27.1	7.3		1230	7			

APPENDIX B
Reactor 1, Day 127 - Day 203 (7/1-9/15)

Day	Date	IS %	CS %	r*x10"	pH	D.O. mg/L	MLSS mg/L	Eff. SS mg/L	Biopoly.	COD Removal %	Eff. COD mg/L
127	7-1				7.3		1280	14			
137	7-11				--		1260	24		90	
138	7-12	0.34	10.0	17.4	7.3		1360	27		93	28
140	7-14	0.84	7.98	34.6	7.3		1380	16			
141	7-15				7.2		1530	17			
142	7-16	0.42	9.28	31.4	7.3		1505	14			
143	7-17				7.2		1450	21			
146	7-20				7.3		1500	30			
147	7-21				7.3		1525	30			
149	7-23				7.2		1350	51			
153	7-27				7.3		1315	22			
154	7-28	0.90	8.02	17.7	7.3		1260	14			
156	7-30	1.33	8.48	39.9	7.0		1325	12			
		Glucose Used as Substrate									
158	8-1				6.6		1490	34		96	17
159	8-2	0.27	10.16	90.0	6.6		1390	30			
161	8-4				6.5		--	234			
162	8-5	0.18	11.64	303	6.3		315	195			
163	8-6				6.6		290	106			
165	8-8				6.8		405	17			
166	8-9				6.6		630	15			
167	8-10				6.7		845	16		84	66
169	8-12				6.8		710	19			
170	8-13				6.7		630	130			
172	8-15	0.12	9.64	81.4	6.7		335	116		67	131
173	8-16				6.6		--	238			
174	8-17	0.10	17.5	17.5	6.6		970	270		92	33
		End of Glucose									
175	8-18				5.7	7.5	255	200			
		Batch to build up solids 8/18-8/28									
185	8-28				--		955	6			
187	8-30				--		1050	8		88	46
188	8-31				--		1370	6			
189	9-1				--		1230	7			
190	9-2	0.34	9.25	58.1	--		1475	7			
191	9-3				--		1480	9			
192	9-4				--		1555	18			
193	9-5	0.29	10.28	24.4	7.1		1640	16		83	29
195	9-7	0.42	8.28	25.0	7.1		1645	13			
197	9-9	0.52	6.93	26.9	7.1		1730	13			
199	9-11				--		1700	24			
201	9-13	0.49	6.50	46.0	7.2		1805	12			
202	9-14				--	4.90	1475	11			
203	9-15	0.35	9.30	63.3	7.4		1705	11			

APPENDIX B
Reactor 1, Day 208 - Day 237 (9/20-10/19)

Day	Date	IS %	CS %	r*x10"	pH	D.O. mg/L	MLSS mg/L	Eff. SS mg/L	Biopoly.	COD Removal %	Eff. COD mg/L
208	9-20	0.55	6.46	67.8	7.2		1955	27			
209	9-21				6.9		1290	23			
210	9-22	0.62	8.58	40.7	6.7		1140	30			
211	9-23				6.6		1035	36			
212	9-24	0.36	13.43	16.5	6.4	3.40	1080	23			
214	9-26				5.8	6.90	1065	10			
215	9-27				6.6		1150	13			
216	9-28	0.79	8.97	15.9	6.4		1155	16			
		Glucose-Batch Feed 10/1									
221	10-3				7.9		1375	--			
222	10-4				7.7		1350	--			
223	10-5				--		1665	--			
224	10-6				7.5		1720	--			
225	10-7				7.2		1915	--			
226	10-8				7.0		2165	--			
227	10-9				7.0		2130	--			
228	10-10				6.9		2355	--			
		Continuous 10112, Poor Settling, Went Back to Batch									
231	10-13				6.3		1975	--			
232	10-14				6.5		1715	--			
234	10-15				--		1635	--			
235	10-17				5.0	7.30	1450	--			
236	10-18				6.6		1410	--			
237	10-19				6.8	6.30	1485	--			
		Split 45L Reactor into 3-9L and 1-18L									

APPENDIX B
Reactor 2, Day 1 - Day 65 (2/25-4/30)

Day	Date	IS %	CS %	r*x10"	pH	D.O. mg/L	MLSS mg/L	Eff. SS mg/L	Biopoly.	COD Removal %	Eff. COD mg/L
1	2-25						1485	27			
3	2-27						1390	21			
5	3-1						1360	--			
7	3-3						1320	19			
9	3-5						1280	8			
11	3-7	0.71	9.22	10.3			1490	--		98	8
13	3-9						1120	3			
16	3-12						1045	12		90	41
26	3-22	0.85	6.13	47.6			1430	17		96	16
28	3-24						1350	15			
29	3-25						1345	6			
30	3-26	0.92	7.43	11.6			1435	6			
31	3-27						1470	8			
32	3-28						1380	26			
33	3-29						1450	--			
34	3-30						1365	3			
35	3-31						1295	27			
36	4-1	0.60	8.45	9.0			1325	16			
37	4-2						1220	19			
38	4-3	0.78	8.55	23.7			1285	7			
39	4-4						1230	30			
40	4-5				5.1		1290	25			
41	4-6				5.0		1400	18			
42	4-7				5.5		1345	36			
43	4-8				6.4		1285	25			
44	4-9	0.80	6.67	27.3	6.5		1220	24			
45	4-10				6.7		1125	31			
46	4-11				6.7		1145	29			
47	4-12	0.80	5.23	10.8	6.7		1060	11			
48	4-13				6.7		1240	14			
49	4-14				6.6		1050	16			
54	4-19				6.3		1335	12			
55	4-20				6.7		1195	15			
56	4-21				6.7		1180	10			
57	4-22	0.87	5.93	20.0	6.8		1235	8			
58	4-23				6.0		1190	14			
59	4-24				6.0		1200	12			
60	4-25	0.52	6.78	12.0	5.2		1215	27			
61	4-26				5.2		1240	15			
62	4-27				6.8		1210	8			
63	4-28				6.9		1160	16			
64	4-29	0.80	5.66	25.0	6.9		1230	44			
65	4-30				6.8		1290	34			
Avg.				20.0							

APPENDIX B
Reactor 2, Day 66 - Day 124 (5/1-6/28)

Day	Date	IS %	CS %	r*x10"	pH	D.O. mg/L	MLSS mg/L	Eff. SS mg/L	Biopoly.	COD Removal %	Eff. COD mg/L
66	5-1				7.0		1180	31			
67	5-2				6.9		1250	64		90	
68	5-3				6.8		1310	40		88	17
69	5-4				6.9		1260	--			
70	5-5	0.27	9.09	29.0	6.9		1230	19			
71	5-6				--		1110	87	0.2	97	12
72	5-7	0.24	10.01	22.7	6.8	4.50	1040	92	0.2	93	28
73	5-8				6.7	3.40	1100	36			
74	5-9	0.21	12.6	11.6	6.8	4.70	1050	6		91	32
75	5-10				6.6		1120	4	0.1		
76	5-11	0.81	9.46	18.4	6.8	4.00	1250	12			
78	5-13				7.0		1210	19			
79	5-14				6.8	5.40	1140	17		73	28
80	5-15				6.5		1150	28	0.1		
81	5-16				6.5	5.10	1100	25			
82	5-17	0.92	8.40	26.1	--		1120	29			
83	5-18				6.7	4.30	1060	41			
84	5-19				6.7	4.70	910	58		84	62
85	5-20				6.7	5.50	940	62		85	59
86	5-21	0.92	9.2	11.6	6.8	5.50	907	46			
88	5-23				7.2		980	28			
89	5-24	1.06	8.1	17.7	7.5	7.50	930	34			
91	5-26	1.02	8.3	13.0	7.8	6.90	740	38	1.5		
92	5-27				7.6	--	700	18	2.1	78	87
94	5-29	1.0	11.4	3.7	7.3	6.50	820	21	1.6		
95	5-30				7.3		830	51			
96	5-31				7.3	5.70	810	13			
97	6-1				7.3	5.50	1030	8		99	2
98	6-2	0.25	12.3	8.0	7.4	--	870	19			
100	6-4				7.3	5.65	960	25			
102	6-6				7.4	4.90	990	15			
103	6-7	0.77	3.7	58.7	7.4	--	970	21		86	56
105	6-9	0.20	8.7	228	7.2	5.10	980	21			
106	6-10				7.3	3.90	950	10			
107	6-11				7.2	4.50	1010	22			
109	6-13	0.29	5.9	135	7.2	4.30	890	29			
111	6-15	0.41	7.42	39.7	7.2	4.35	980	7			
113	6-17				7.2	4.70	1030	11		88	48
114	6-18	0.21	8.81	34.1	7.2	4.40	1240	6			
115	6-19				7.1		1220	14			
116	6-20				7.2		1340	--			
117	6-21	0.40	6.7	15.3	7.2		1430	16	1.4	92	32
119	6-23	0.46	9.8	13.5	7.2		1670	15	0.6		
120	6-24				7.4		1800	18			
124	6-28	0.22	9.92	19.1	7.3		1705	12			

APPENDIX B
Reactor 2, Day 127 - Day 188 (7/1-8/31)

Day	Date	IS %	CS %	r*x10"	pH	D.O. mg/L	MLSS mg/L	Eff. SS mg/L	Biopoly.	COD Removal %	Eff. COD mg/L
127	7-1				7.3		1590	8			
137	7-11				--		1470	3		90	
138	7-12	0.18	6.03	33.0	7.2		1440	14		94	24
140	7-14	0.32	6.09	52.6	7.2		1460	1			
141	7-15				7.1		1550	9			
142	7-16	0.28	6.50	44.9	7.3		1690	10			
143	7-17				7.0		1620	2			
146	7-20				7.0		1725	9	2.0		
147	7-21				7.0		1750	17			
149	7-23				6.6		1615	3			
153	7-27				6.0		1560	33		95	21
154	7-28	0.35	7.16	47.3	6.0		1515	62			
156	7-30	0.84	6.70	53.4	6.3		1525	4			
158	8-1				5.7		1535	10			
159	8-2	0.64	7.40	33.1	5.9		1440	13			
161	8-4				6.4		1310	20			
162	8-5	0.90	7.00		6.8		1355	23			
163	8-6				6.7		1255	21			
165	8-8				7.2		1140	26			
166	8-9				7.3		1080	45			
167	8-10	0.77	4.35	309	7.3		1240	22	15.0	90	42
169	8-12	0.27	6.88	62.3	7.2		1290	69			
170	8-13	0.67	5.56	72.8	7.0		1300	12			
172	8-15	0.33	8.39	24.0	6.9	5.8	1375	12			
173	8-16				6.8	2.6	1430	16			
174	8-17	0.37	9.46	19.0	6.8	3.0	1505	19	2.0	88	46
175	8-18				6.8	3.0	1500	6			
177	8-20	1.57	8.0	6.3	6.7	2.0	1615	8	0.2		
180	8-23	0.48	7.82	16.0	6.7	3.0	1715	6		86	58
181	8-24				6.9		1670	3			
182	8-25	0.50	8.07	13.0	6.8	1.0	1660	1	2.0		
183	8-26				6.8	1.0	1840	14			
184	8-27	0.54	7.34	18.0	--		1685	10			
185	8-28				--		1825	13			
187	8-30	0.54	5.40	34.6	--	0.40	1830	8		90	42
188	8-31	0.73	4.20	46.2	--		1840	12			

APPENDIX B
Reactor 2, Day 189 - Day 237 (9/1-10/19)

Day	Date	IS %	CS %	r*x10"	pH	D.O. mg/L	MLSS mg/L	Eff. SS mg/L	Biopoly.	COD Removal %	Eff. COD mg/L
189	9-1				--		1775	11			
190	9-2	0.58	6.0	107	--	0.20	1915	21			
191	9-3				--		1885	30			
192	9-4				--		1860	26			
193	9-5	0.29	8.0	377	6.8	0.20	1865	48		91	37
195	9-7	0.23	8.0	601	6.8	0.20	1875	36			
197	9-9	0.24	8.0	732	6.8	0.20	1845	36	120		
199	9-11	0.24	8.5	895	--	0.80	1990	50			
201	9-13				7.3		1840	53	150		
202	9-14	0.16	8.1	814	--	0.80	1510	93			
203	9-15	0.33	7.9	802	7.3	1.60	1770	31			
208	9-20	0.22	7.38	164	7.4	1.20	1685	10			
209	9-21				7.3		1620	9			
210	9-22	0.14	12.8	134	7.2	0.80	1240	16		96	17
211	9-23				7.3	0.40	1135	130			
212	9-24	0.16	10.65	170	7.2	3.50	1255	13			
214	9-26				6.9	4.00	1235	12			
215	9-27				7.0	4.00	1350	11			
216	9-28	0.24	13.89	37.3	6.9	4.05	1350	9			
		Reactor Broke, Batch 18-L, 1011 - 10/14									
221	10-3				7.6		1375	--			
222	10-4				7.7		1945	--			
223	10-5				--		2295	--			
224	10-6				7.9		2080	--			
225	10-7				7.8	2.60	1900	--			
226	10-8				7.9	6.50	2715	--			
227	10-9				7.6	4.60	2420	--			
228	10-10				7.5	3.50	2845	--			
231	10-13				7.3		2810	--			
232	10-14				6.8		3015	--			
		Continuous									
234	10-15				--		2420				
235	10-17	1.26	20.4	8.5	5.5	6.30	2320	12		89	44
236	10-18	0.81	18.6	10.0	6.8		2085	18			
237	10-19	0.92	10.6	14.0	6.3	6.20	2055	17			
		END									

APPENDIX B

Reactor 1A, Day 240 - Day 286 (20% Sugar)

Day	Date	Day #	IS	CS	MLSS	pH	r*x10"	SVI
240	10/22	1	0.68	17.32	1620	7.5	8.0	160
241	10/23	2	1.04	15.80	1855	8.0	21.2	151
242	10/24	3	1.07	14.54	1900	7.9	26.5	174
243	10/25	4	--	--	--	7.9		156
244	10/26	5	0.88	14.60	1790	--	15.1	134
245	10/27	6			1800	--		128
247	10/29	8	1.07	15.80	2290	8.1	10.8	
249	10/31	10	1.35	15.10	2240	8.1	9.0	78
251	11/2	12	1.48	13.50	--	8.1	13.0	
252	11/3	13	1.41	14.70	1925	7.9	8.3	88
254	11/5	15	1.62	12.55	2210	8.1	14.6	68
256	11/7	17				8.0		67
257	11/8	18	1.57	13.50	2075	8.0	18.5	
259	11/10	20	1.78	12.36	2035	8.0	17.9	54
260	11/11	21	Go Continuous		2035	8.1		
261	11/12	22	1.68	10.49	2025	7.4	28.9	67
263	11/14	24	1.35	7.29	1940	7.5	83.3	77
264	11/15	25	1.27	10.0	1885	7.1	137.5	87
265	11/16	26	1.34	10.0	1820	7.3	70.9	91
267	11/18	28	0.96	7.92	1760	7.1	41.0	114
269	11/20	30	0.90	7.76	1865	7.1	40.0	134
271	11/22	32	0.88	7.35	1760	6.2	57.0	142
272	11/23	33	0.83	7.60	1620	5.6	61.2	142
275	11/26	36	0.71	11.31	1455	5.7	38.0	100
278	11/29	39	0.70	13.81	1460	5.7	29.5	72
280	12/1	41	0.80	11.09	1285	6.0	32.2	62
281	12/2	42	1.07	10.68	1300	6.0	25.6	58
282	12/3	43	0.87	10.84	1255	6.1	55.8	64
284	12/5	45	0.87	13.91	1275	6.6	8.3	63
285	12/7	47	1.02	14.43	1385	6.4	7.4	61
286	12/8	48	1.25	15.0	1305	6.1	6.0	61

APPENDIX B

Reactor 3A, Day 240 - Day 278 (60% Sugar)

Day	Date	Day #	IS	CS	MLSS	pH	r*x10"	SVI
240	10/22	1	0.60	15.94	1825	7.5	7.9	345
241	10/23	2	0.71	16.28	1810	7.8	10.4	243
242	10/24	3	0.57	17.68	1880	7.8	16.5	239
243	10/25	4				7.9		243
244	10/26	5	0.68	16.50	1820		14.3	209
245	10/27	6			2335			195
247	10/29	8	0.75	17.83	2065	7.8	6.3	
249	10/31	10	0.89	16.03	2065	7.7	6.5	104
251	11/2	12	1.02	12.79		7.7	15.4	
252	11/3	13	1.00	14.00	2190	7.4	13.9	82
254	11/5	15	1.14	13.37	2165	7.7	15.0	78
256	11/7	17						67
257	11/8	18	1.27	15.95	2400	7.7	12.7	
259	11/10	20	1.39	15.27	2300	7.5	9.0	50
261	11/12	22	1.70	15.69	2410	7.7	10.9	52
263	11/14	24	1.50	16.65	2450	7.7	9.1	52
264	11/15	25	1.49	15.90	2375	7.6	11.6	46
265	11/16	26	1.82	14.90	2385	7.7	10.6	46
267	11/18	28	1.44	17.57	2430		11.6	41
269	11/20	30	1.35	17.42	2415	7.8	10.6	37
270	11/21	31	Go Continuous					
271	11/22	32	1.81	15.95	2335	7.3	12.6	43
272	11/23	33	0.91	17.93	2215	7.5	23.7	56
275	11/26	36	0.21	13.13	1535	7.1	69.7	632
278	11/29	39	0.06	10.0	260	6.9	170.0	--

APPENDIX B

Reactor 2A - Day 240 - Day 269 (40% Sugar)

Day	Date	Day #	IS	CS	MLSS	pH	r*x10"	SVI
240	10/22	1	0.73	16.23	1820	7.5	8.0	247
241	10/23	2	0.76	17.21	1760	7.8	14.7	196
242	10/24	3	0.63	17.12	2080	7.6	16.9	224
243	10/25	4			1860	7.7		167
244	10/26	5	0.70	15.49	1835		15.1	136
245	10/27	6			1990			131
247	10/29	8	0.90	17.48	2385	8.0	6.0	
249	10/31	10	1.02	16.88	2090	7.9	3.0	89
251	11/2	12	1.00	15.57		8.0	3.4	
252	11/3	13	0.92	16.40	2180	8.0	8.0	73
254	11/5	15	1.16	14.72	2330	8.1	7.1	64
256	11/7	17						60
257	11/8	18	1.18	17.40	2155	8.0	4.2	
259	11/10	20	1.30	16.58	2375	7.8	6.9	50
261	11/12	22	1.68	17.81	1995	8.1	7.1	50
262	11/13	23	Go Continuous					
263	11/14	24	1.09	14.91	2290	7.6	6.9	52
264	11/15	25	1.09	12.93	2300	7.4	21.9	56
265	11/16	26	1.16	9.97	2020	7.4	77.6	79
267	11/18	28	0.33	13.62	1460	7.4	215.0	281
269	11/20	30	0.17	11.59	995	7.3	129.0	965

APPENDIX B

Reactor 4A - Day 240 - Day 282 (100% Sugar)

Day	Date	Day #	IS	CS	MLSS	pH	r*x10"	SVI
240	10/22	1	0.67	15.68	1685	7.2	6.4	445
241	10/23	2	0.66	16.38	1765	7.0	7.7	402
242	10/24	3	0.64	16.56	1825	6.8	11.7	411
243	10/25	4				7.0		340
244	10/26	5	0.59	17.89	1810		6.0	298
245	10/27	6			1910			312
247	10/29	8	0.62	18.11	2320	7.2	6.4	
249	10/31	10	0.87	16.77	1845	7.1	8.0	190
251	11/2	12	0.84	12.62		7.1	13.5	
252	11/3	13	0.85	15.30	1725	6.7	19.4	185
254	11/5	15	0.90	15.92	1790	6.7	12.8	128
256	11/7	17						99
257	11/8	18	1.33	17.07	1920	6.9	20.9	
259	11/10	20	1.79	16.21	1980	6.4	10.1	45
261	11/12	22	0.94	19.57	1840	6.8	4.1	38
263	11/14	24	1.14	19.95	2035	6.8	3.4	32
264	11/15	25	1.29	19.50	2255	6.5	5.9	31
265	11/16	26	1.40	19.53	2105	6.7	2.4	31
267	11/18	28	1.50	19.72	2150		3.8	28
269	11/20	30	1.50	20.15	2365	6.7	3.0	25
271	11/22	32	0.96	19.48	1995	6.7	6.8	25
			Go Continuous					
272	11/23	33	1.04	13.82	1695	7.0	3.6	30
275	11/26	36	0.59	15.39	1515	7.0	6.7	33
278	11/29	39	0.70	13.81	1350	6.9	9.3	37
280	12/1	41	0.77	14.97	1450	6.8	7.0	48
281	12/2	42	0.60	14.87	1460	6.7	6.6	195
282	12/3	43	0.41	13.29	1545	6.7	9.7	586

APPENDIX B

Day 260 - Day 287

Day	Date	Day #	R 1A SS	R 1 COD	R 2A SS	R 2 COD	R 3A SS	R 3 COD	R 4A SS	R 4 COD
260	11/11	21								
261	11/12	22	38							
262	11/13	23	24		28					
263	11/14	24	--		--					
264	11/15	25	29		28					
265	11/16	26	15		30					
266	11/17	27	--		--					
267	11/18	28	13		90					
268	11/19	29	7		96					
269	11/20	30	11		462					
270	11/21	31	20		214					
271	11/22	32	30		--		44			
272	11/23	33	23				37		57	
273	11/24	34	--							
274	11/25	35	--							
275	11/26	36	27				518		53	
276	11/27	37					--			
277	11/28	38								
278	11/29	39	6						31	
279	11/30	40								
280	12/1	41	1						23	
281	12/2	42	7						17	
282	12/3	43	11						31	
283	12/4	44	11						528	
284	12/5	45	11						322	
285	12/6	46	--							
286	12/7	47	16							
287	12/8	48	15							

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