THE EFFECT OF MEAN CELL RESIDENCE TIME ON THE DEWATERING CHARACTERISTICS OF A BIOLOGICAL SLUDGE

by

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I. INTRODUCTION

Numerous research studies have concluded that sludge dewatering characteristics are significantly affected by the particle size of a sludge. Likewise, past research has also shown that dewatering characteristics tend to vary at different stages of biological activity within an activated sludge system. Claims such as filamentous growth or deflocculated sludges at longer sludge ages, and dispersed, pinpoint sludges at the shorter sludge ages were commonly reported. Results and conclusions of most studies indicated that sludges exhibiting a well flocculated structure normally occuring at sludge ages between five and fifteen days were typically the best sludges for solids-liquids separation.

In operating a wastewater treatment facility it is important to know the above mentioned results, because sludge handling can attribute up to fifty percent of the entire operational costs of a treatment facility. It would therefore seem logical that every plant operator desire to minimize operational costs due to conditioning and subsequential dewatering. Thus it is important to learn how biological activity affects the conditioning requirements and dewatering characteristics of a biological sludge. Likewise, it would be beneficial to investigate how biological activity affects particle size and particle size distribution.

In an attempt to provide data relevant to the description of the interaction between biological activity and sludge dewatering characteristics, the following objectives were formulated:

(1) determine the effect of mean cell residence time (MCRT) on the dewatering characteristics of the resultant biological waste sludges;

(2) determine the size distribution of biological flocs produced at each MCRT;

(3) establish whether or not a relationship exists between biological floc size distribution and sludge dewatering characteristics; and

(4) attempt to define an optimal value or range of MCRT values with respect to the economics of sludge conditioning and dewatering.

II. LITERATURE REVIEW

In reviewing the literature available it became evident that many factors contribute to the dewatering characteristics of a biological sludge. Although some factors influence dewatering characteristics more than others it also became apparent that many of these factors interact to create either a desirable or undesirable sludge with respect to dewatering. The purpose of this literature review is to present some of the factors that affect dewatering, and then summarize how they interact. Likewise, since thickening is usually a prerequisite to dewatering and it is also influenced by many of these same factors, a brief review of thickening concerns will also be incorporated into this literature summary.

Dewatering

The purpose of dewatering is to remove enough of the liquid portion of the sludge such that the sludge will handle as a solid (1). There exists many different techniques for dewatering a sludge, but the scope of this text will investigate vacuum dewatering only since this was the technique used in the experimental portion of this study.

In general, there are two basic techniques for measuring the dewaterability of a sludge under an applied vacuum: 1) the leaf filter test; and 2) the Buchner funnel test. In the Buchner funnel test sludge resistance determinations are made by applying a known vacuum to a predetermined volume of sludge and then recording the volume of filtrate removed per unit of time. This volume-time relationship is then plotted as time over volume (T/V) versus volume (V) to determine the slope of this plot. The slope of this plot represents the "b" term in the specific resistance equation. For a detailed discussion of the Buchner funnel resistance determination theory see Vesilind (1).

Karr and Keinath (2) described the major limitations of the Buchner funnel test as twofold: 1) the specific resistance of a sludge was independent of initial solids concentration only as long as blinding did not occur; and 2) the Buchner funnel does not account for physical applications such as pick-up, release, and scrolling which would limit the ability to scale-up Buchner funnel results to a full scale plant. Actually the only limitation that has any bearing on this study is the blinding problem, since the goal of this study is to compare dewaterability parameters per se and not to design a facility.

Conditioning

Tenney et al (3) reported that attempts to dewater an unconditioned biological sludge would be ineffectual because the sludge is highly compressible. Likewise, Karr and Keinath (2) reported that structural rigidity is changed by conditioning. Tenney et al (3) also reported that all biological sludges, including well bioflocculated ones, need to be conditioned to allow for efficient dewatering. They claimed such conditioning was necessary since an unconditioned sludge results in a layering of the microbes upon dewatering whereas conditioners create a rigid and porous structure.

Cheremisinoff and Maglio (4) reported that conditioning is necessary for all biological sludges to reduce surface charges and hydration at the microbe surface. They also felt that compressibility among other factors affected dewaterability, but that surface charge and hydration were the most important factors in dewatering a sludge. Cheremisinoff and Maglio felt that polyelectrolytes flocculate the sludge by neutralizing the surface charges on the microbe, allowing for desorption of bound water and simultanoeus attachment of solid particles. However, they also claimed that even though a floc has been neutralized it can still adsorb water.

Studies by Roberts and Olsson (5), and Novak et al (6) have shown that optimal polymer dosages for dewatering corresponded to a zero electrophoretic mobility amongst the colloidal fraction of a sludge slurry. Both Roberts and Olsson, and Novak et al concluded that optimal polymer dosage was independent of the solids content of a sludge, but was dependent only upon the colloidal material in the supernatant. These results indicate that the above mentioned neutralization theory is valid suggesting that colloidal particles play a significant role in the actual conditioning of a sludge. Roberts and Olsson (5) also concluded that polyelectrolyte dosages could be reduced by elutriation of the colloidal particles from the sludge.

Particle Size Effects

In the preceding discussion on conditioning it became apparent that colloidal particles within a sludge slurry play a significant role in conditioning and subsequent dewatering. Later studies by Karr and Keinath (2), Knocke *et al* (7), Boepple (8), and others have indicated that particle size is the most important parameter in dewatering. Karr and Keinath made extensive investigations of particle size effects and have shown that: 1) particle size distribution can account for differences in specific resistances; 2) different sludges with similar particle size distributions have similar dewatering rates; and 3) conditioning tremendously affects particle size distribution and thereby improves sludge dewatering characteristics. The authors defined a supracolloidal size range (1-100 microns) which was felt to be the most important contributor to sludge resistance. The reason they claimed is that this size range is responsible for filter and cake blinding which ultimately blocks egression pores and traps the water within the sludge.

Cheremisinoff and Maglio (4) claimed that specific resistance is dominated by particles less than five microns in diameter. They reported that decreased particle size increases the surface to volume ratio exponentially, and this increased surface area corresponds to greater hydration, increased conditioner demand, and increased resistance to dewatering.

Sludge Age Effects

From data gathered from a pilot plant study Pitman (9) concluded that: 1) specific resistance values changed very little between solids retention times of 11 to 25 days 2) specific resistance was highest at 7.5 days, and 3) at a solids retention time of 5 to 6 days the specific resistance values were similar to those of the 11 to 25 day retention times (see Figure 1). Pitman claimed the following factors affected dewatering characteristics: 1) environmental conditions; 2) aeration process; 3) good flocculation-low loading, extensive nitrifying conditions; 4) endogenous growth phase (good dewatering); and 5) anaerobic conditions (decrease in flocculation of microbes and resistance to shear). He concluded that: 1) degree of flocculation is degraded by lack of oxygen; 2) at lower solids retention times anaerobic conditions occured much

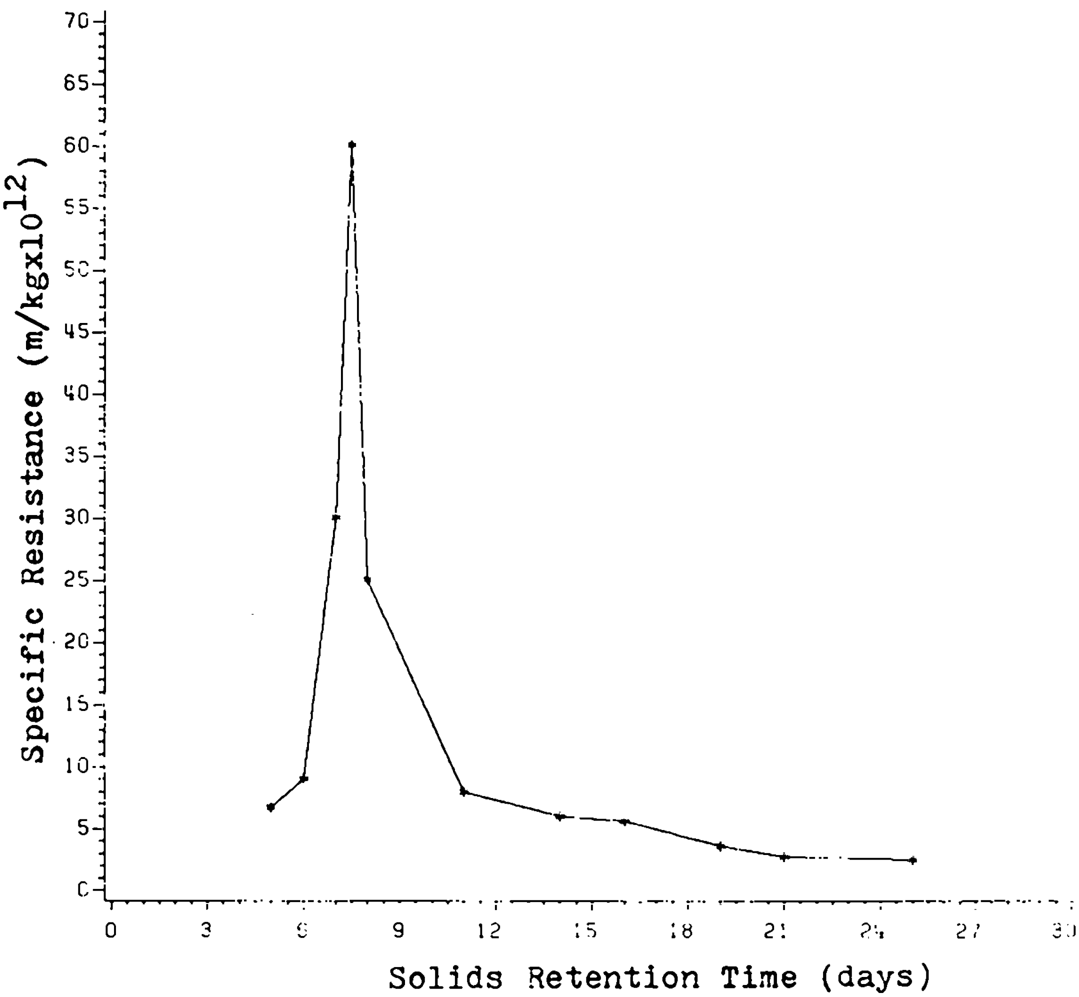

Figure 1. Effect of Solids Retention Time on Specific Resistance - from Pitman (9)

faster; and 3) in general, solids retention times beyond thirty days promoted floc disintegration.

Bisogni and Lawrence (10) reported that the best sludge settling velocities occured between 6 to 30 day solids retention times, and that this sludge was pinpoint and deflocculated. Pipes (11) reported that pinpoint floc occured only at low food to microorganism (F:M) ratios; and that at F:M ratios greater than 0.4/day deflocculation would occur. In contrast both Tenney et al (3) and Pitman (9) agreed that bioflocculation is best under endogenous conditions, and that this would promote a better dewatering sludge.

In another effort to emphasize important plant operating parameters Pitman (12) reported that: 1) bioflocculation efficiency improves with sludge age until an optimum beyond which deflocculation will occur; 2) floc density increases with sludge age; and 3) sludge production decreases with sludge age. Pitman also emphasized the fact that dissolved oxygen (D.O.) is an important design parameter claiming that at a ten day solids retention time one milligram per liter (mg/l) of D.O. is needed for nitrification, whereas at a twenty day solids retention time only 0.5 to 1.0 mg/l of D.O. is needed.

Dissolved Oxygen Effects

In recent years the dissolved oxygen (D.O.) content of activated sludge units has been an element of discussion and argument amongst two opposing theories. On one side there are the supporters of pure oxygen maintained plants, and on the other hand are the proponents that claim pure oxygen plants are no more effective than efficiently run mechanically aerated plants. Both sides agree that insufficient D.O. is deleterious to thickening and dewatering, but it is argued that the pure oxygen aerated systems will produce a superior handling sludge.

Kalinske (13), reviewing microbial studies related to dissolved oxygen effects on activated sludge systems, claimed that 0.1 to 0.3 mg/l of D.O. is sufficient to maintain a dispersed growth of microbes. In other words this is the minimum D.O. content in the sludge slurry that is necessary to support an individual microbe. However, as microbes flocculate and form sludge flocs the microbes at the center of the floc receive that oxygen which is not utilized by surrounding microbes. Thus a D.O. concentration greater than 0.1 to 0.3 mg/l is necessary to maintain all microbes within the sludge floc. Kalinske stated that 2 mg/l of D.O. is sufficient to maintain the aerobic activity at the center of normal activated sludge flocs. In his conclusion Kalinske stated that D.O. concentrations above 2 mg/l add no benefit to sludge handling.

In response to Kalinske's work Chapman _et al_ (14) claimed that pilot plant and laboratory scale studies typically produced smaller flocs requiring less D.O.. This was attributed to the mixing intensity in the smaller scale studies being more turbulent. Chapman _et al_ claimed that the most significant variable affecting D.O. diffusion into the floc was the mean floc size, and floc size distribution, because larger flocs increased diffusion resistance . Chapman, using a model developed by the Union Carbide Corporation, predicted for a 20 micron floc that 1.0 mg/l of D.O. was needed for full penetration; for a 50 micron floc 2.0 to 3.5 mg/l of D.O. was needed; and, for a 75 to 100 micron floc, which Chapman claimed as representative of a typical full scale plant, 3.0 to 5.0 mg/l of D.O. would be needed. The model Chapman used assumed 0.1 mg/l minimum of D.O. at the floc center the same as Kalinske; however, as Parker _et al_ (15) later noted, Chapman gave no indication of F:M ratio, reactor configuration, substrate levels, or theory behind the Union Carbide model. Other claims by Chapman in defense of the pure oxygen system are: 1) pure oxygen plants produce less sludge at the same F:M ratios; 2) higher F:M ratios require higher D.O. levels to maintain sufficient floc penetration; and 3) polymer dosages could be cut by as much as one-third for pure oxygen systems.

Parker *et al* (15) noted that pilot plant and laboratory scale reactors can achieve equivalent or lower power mixing intensities depending upon the type of system used. He also noted that mean floc size was a poor parameter to determine D.O. diffusivity requirements, since the major volume of sludge floc is represented by flocs greater than the mean. Parker, in agreement with Mueller *et al* (16), claimed that typical mean floc sizes in a treatment plant would be 30 to 40 microns and not 75 to 100 microns as reported by Chapman *et al* (14). Parker concluded by agreeing with Kalinske (13) that 2.0 mg/l of D.O. is sufficient to maintain the average activated sludge floc, and that when there is no D.O. deficiency the aerated system can be operated just as efficiently as the pure oxygen systems.

Karr and Keinath (2) noted that mixing intensity does affect floc shear and ultimate floc size. They noted significant increases in floc shear at higher pH's and this corresponded to increases in the supracolloidal (1-100 micron) fraction of the sludge. Parker *et al* (17) in reporting work done by Barker claimed that a plant aerating with three turbines in series could achieve better secondary clarification if the last turbine was shut off. Likewise, Parker proposed a flocculating unit prior to secondary clarification to promote better settling and subsequent sludge handling.

pH Effects

Karr and Keinath (2) showed that pH had some effect on particle size and, subsequently on sludge dewatering rates. They noted the most significant changes at a pH of 11 (see Figure 2) where a significant increase in the supracolloidal (1-100 micron) and colloidal (0.001-1 micron) fractions corresponded to a large increase in specific resistance. Another effect that pH had on the sludge they claimed is that at a low pH the sludge became more resistant to shear, whereas at the higher pH's the sludge became more susceptible to shear. Karr and Keinath claimed that the lower pH's afford better dewatering, because the primary charge in the colloidal particles is reduced and aggregation is promoted. Likewise, Novak et al (6) also noted increased filterability at lower pH's. They claimed that anionic materials that interfere with filtration can be coagulated by acidification of the sludge slurry. They added that this technique is theoretically feasible since literature references indicated that the isoelectric point of biopolymer materials was near pH 3.0 which would allow for optimal filtration due to biopolymer charge neutralization and subsequent coagulation.

Summary

Although only a small portion of this literature review dealt with the effect of mean cell residence time

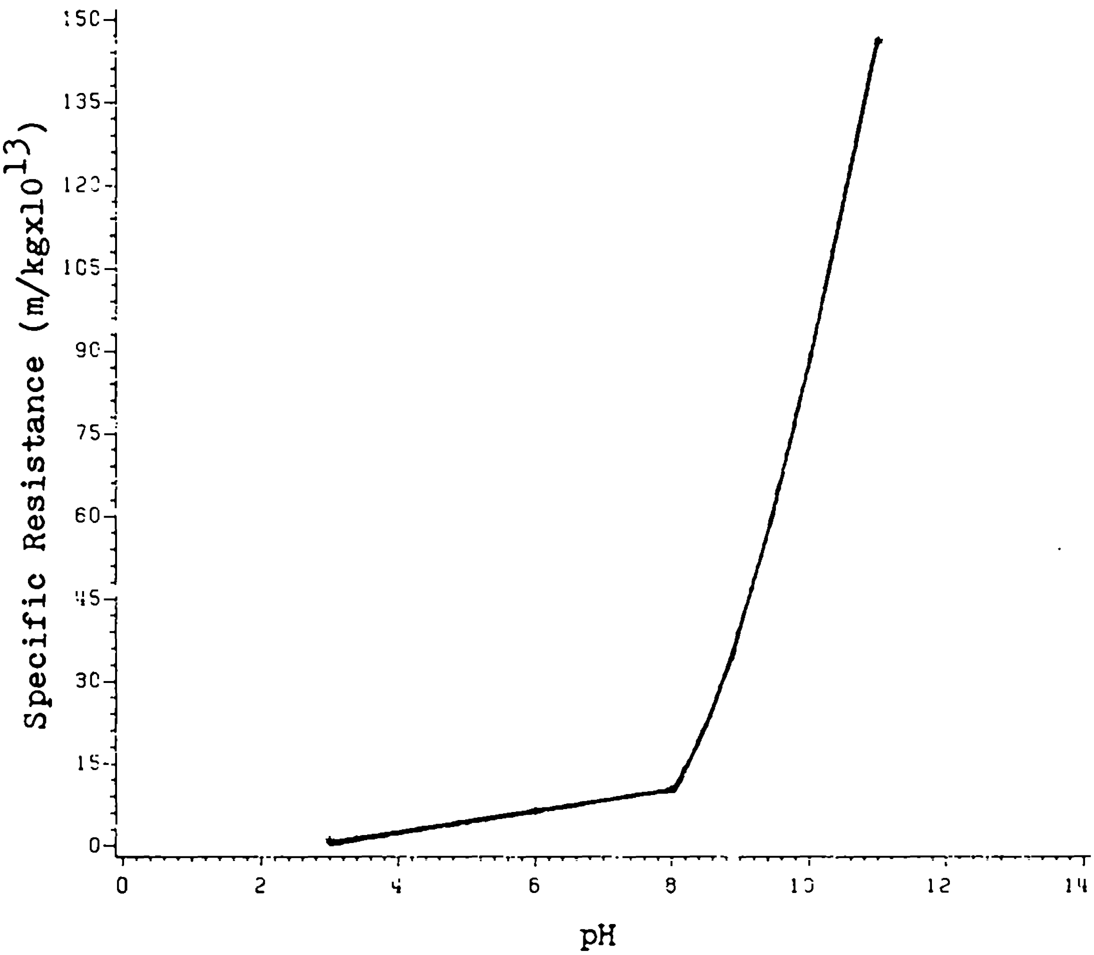

Figure 2. Effect of pH on Specific Resistance - from Karr and Keinath (2)

on dewatering, the overall picture of the many different factors affecting dewatering was presented. As mentioned before some of these factors are more important than others and some affect others to produce a compounding effect. Nonetheless they are all important and must be dealt with wisely by plant operators to reduce sludge handling costs. A flow diagram of the factors that affect dewatering is presented in Figure 3. In the Summary and Conclusions chapter of this text a second flow diagram will be presented incorporating the results of this research study.

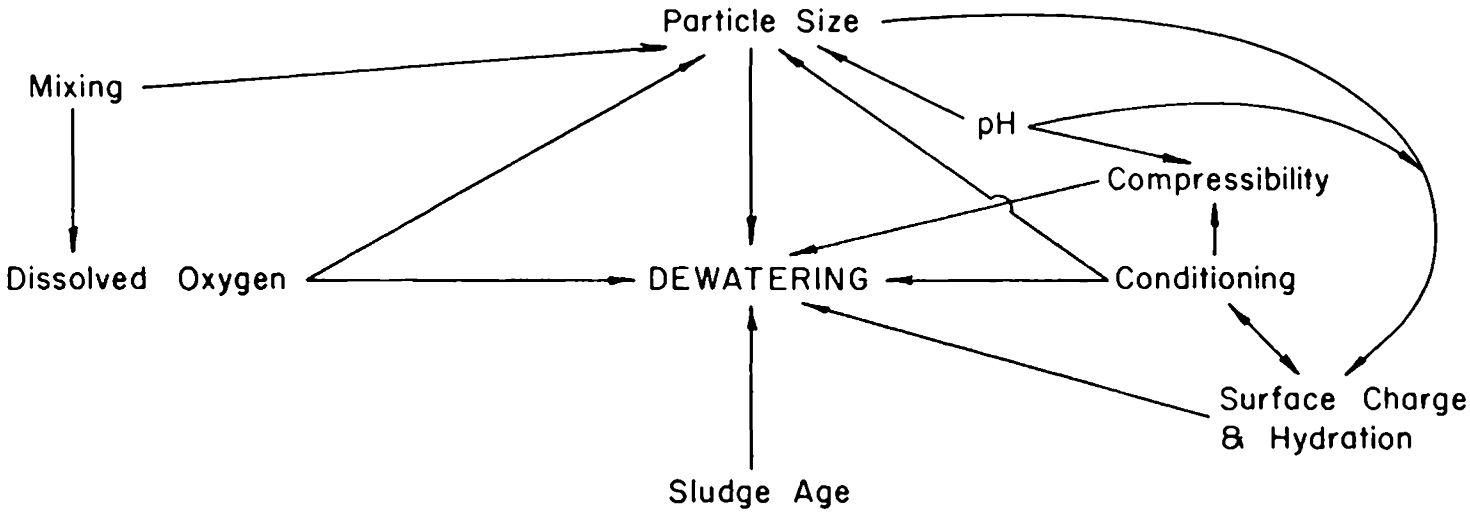

Figure 3. Some Factors and Interrelationships Affecting Dewatering as Reported in the Literature

III. METHODS AND MATERIALS

Laboratory Scale Reactors

Two 45-liter Plexiglas reactors were employed during the laboratory experimental phase of this research study. The reactors simulated an activated sludge aeration basin with internal secondary clarification. By studying these reactors along with parallel monitoring at a full-scale treatment plant, an attempt was made to evaluate the capability of laboratory-scale reactors for predicting full-scale performance with respect to sludge thickening and dewatering characteristics. A schematic diagram of the reactors used is presented in Figure 4. One lab reactor was maintained on a primary effluent substrate obtained from an underloaded activated sludge plant treating a typical domestic sewage waste. The second lab reactor was maintained on a high protein synthetic substrate and inorganic nutrients (see feed solution section for details).

The reactor study cultures were initiated using a seed source from the Blacksburg-V.P.I. Sanitation Authority Plant at Stroubles Creek. Both reactors were filled with aeration basin sludge from the plant, and maintained on a batch feed for approximately two weeks to allow for acclimation to the new substrate and environment (20°C constant

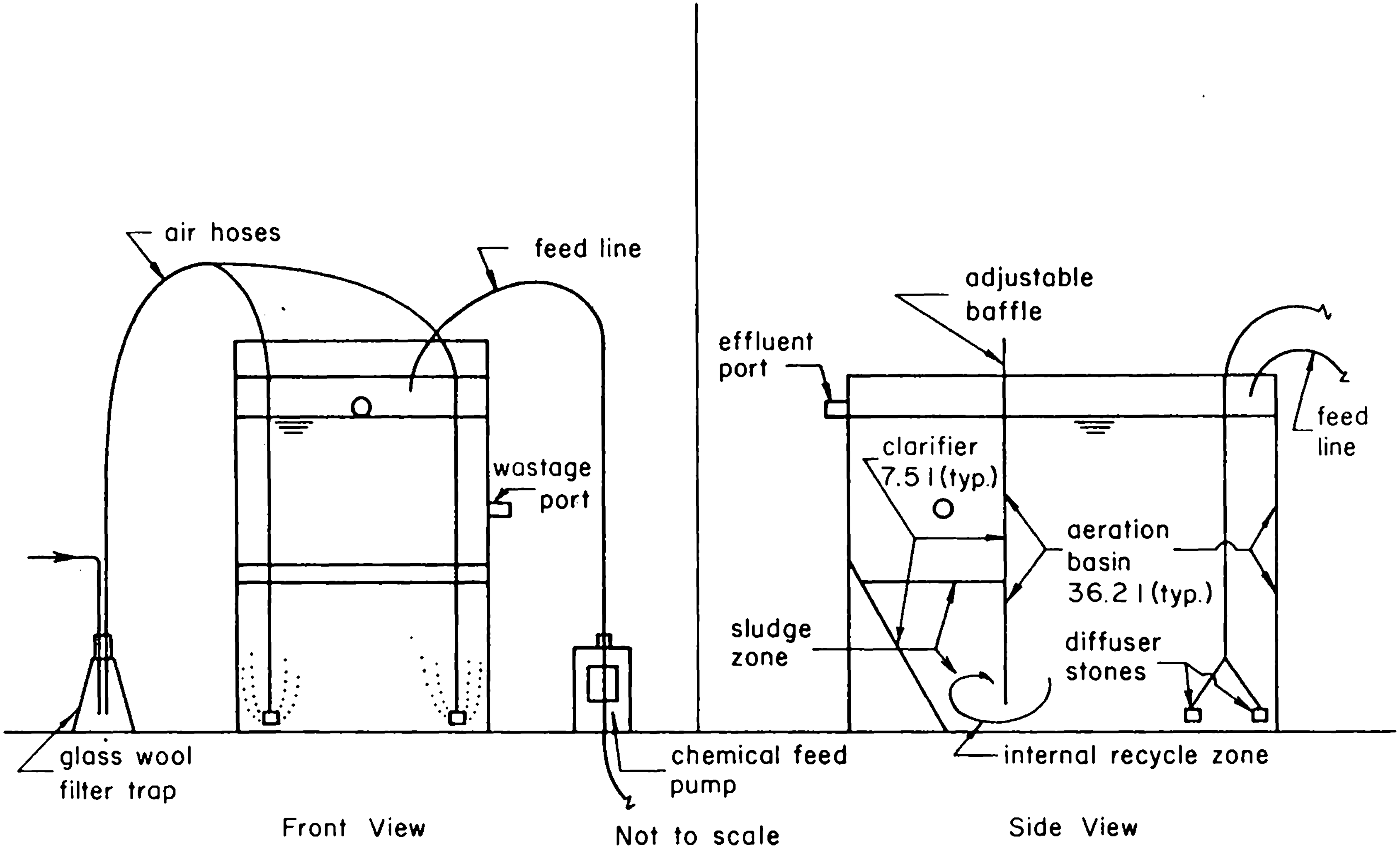

Figure 4. Typical Laboratory Scale Reactor

temperature room), and also to allow for a build-up of solids. After the two week batch feed period the reactors were then started on a continous feed which was used throughout the study.

The substrate was fed to the reactors using a Cole-Parmer (model C-1560 LP, Chicago, Ill.) chemical feed pump, and was applied at a rate to maintain a hydraulic detention time of eight hours in both reactors. Aeration to the reactors was provided via two dual air stone diffusers in each reactor. The air supply was received from the university compressed air supply system and was filtered through a glass wool fiber trap to prevent impurities from entering the reactors. The compressed air was supplied to the reactors at a rate such that the D.O. content of the reactors was always at or near saturation; however, as discussed later, problems with the air supply system did not always allow for saturation to be maintained.

Activated sludge was wasted from the reactors at the same time each day during the course of this study. The procedure for wasting was as follows: 1) effluent hose-line was clamped off; 2) the baffle between the two sections of the reactor was removed; 3) sludge clinging to the sides of the reactor was scraped down; 4) a predetermined volume of activated sludge was removed by opening the wastage port and capturing the waste sludge for suspended solids determinations, dewatering tests, and particle size analysis; and finally 5) the wastage port was closed and the clarification baffle returned to its operational position.

Reactor Feed Solutions

The primary effluent feed reactor was initially planned to be maintained on strictly primary effluent from the Blacksburg waste treatment plant; however, due to the underloaded nature of the facility which yielded a waste extremely low in influent chemical oxygen demand (COD), it was found advantageous to augment the reactor feed with additional COD to maintain a realistic mixed liquor solids concentration. The plant operators were able to counteract the above mentioned problem by operating at a pseudo extended aeration mode, wasting only periodically to maintain a workable mixed liquor concentration. However, in order to maintain steady-state in this study daily wastage was required; therefore some other method besides periodic wasting was needed to maintain a realistic mixed liquor solids level. To do this the influent feed COD was augmented by adding a dog food mixture. Normal primary effluent COD's from the plant typically ranged between 50-150 milligrams per liter (mg/l); the dog food was added at concentrations of 50-100 mg/l of additional COD, yielding a influent feed COD averaging 167 mg/l. After several weeks of operating the reactor with the dog food augmented feed the mixed liquor began to turn filamentous. This problem was corrected by adding certain inorganic nutrients to the feed (see Table I).

The dog food was prepared by blending 150 grams of Moist & Chunky dog chow (Ralston Purina, St. Louis, MO.) with two liters of distilled water in a two-speed Waring blender (New Hartford, CT.) until a creamy texture was formed. This mixture was then poured into a container and allowed to settle for approximately one hour. After settling only the supernatant was poured into the feed solution barrel with 125 liters of primary effluent and the inorganic nutrients. The above feed solution was agitated in the barrel by compressed air to prevent excessive settling out of solids contained in the primary effluent. Preliminary studies showed minimal degradation of substrate within the barrel.

The synthetic feed reactor was maintained on a bacto-peptone (Difco Laboratories, Detroit, MI.) and inorganic nutrients (Fisher-Scientific, Fairlawn, N.J.) feed solution. The bacto-peptone served as a COD source which provided a nominal COD of approximately 250 mg/l. The inorganic nutrients were added to create a substrate that was not limiting in any essential metabolites that the microbial mass might need. All feed concentrations were prepared according to the work of DiSalvo (18) except the potassium dibasic phosphate (K_2HPO_4) which was cut in half

Table I. Composition of Primary Effluent Feed

Constituent	Final Concentration (mg/l)	Remarks
Primary Effluent *	-	provided 50-150 mg/l of COD without the addition of the dog food
Dog Food *	-	added an additional 50-100 mg/l of COD
$(NH_4)_2SO_4$	172.8	10.0 mg/l as N
KH_2PO_4	225.7	28.1 mg/l as P
K_2HPO_4	231.1	22.5 mg/l as P

* - Combined the primary effluent and the dog food provided an average COD of 167 mg/l.

Table II. Composition of Synthetic Wastewater Feed

Constituent	Final Concentration (mg/l)	Remarks
Bacto-peptone	220.5	provided a nominal COD of 250 mg/l
$MgSO_4.7H_2O$	31.3	
$MnSO_4.H_2O$	3.1	
$FeCl_3.6H_2O$	0.4	0.05 mg/l as Fe^{+3}
$CaCl_2$	2.3	
$(NH_4)_2SO_4$	167.4	9.7 mg/l as N
KH_2PO_4	218.7	27.2 mg/l as P
K_2HPO_4	224.0	21.8 mg/l as P

due to economic considerations. All feed chemicals were prepared in two liter stock concentrations by dissolving the appropriate amount of chemical in distilled water. The final feed solution was prepared by mixing the appropriate volumes of nutrients with 129 liters of tap water, in a 55 gallon drum lined with a 40 gallon plastic trash bag.

Substrate and Sludge Samples: Source and Description

The substrate for the lab reactor which was maintained on primary effluent was obtained daily from the weir overflow of the primary clarifier at the Blacksburg plant. This effluent was collected and transported to the lab in five twenty-five liter Nalgene carboys. Likewise mixed liquor samples were taken from the number two aeration basin of the same plant on a daily basis. Effluent samples from the overflow weir of the number two secondary clarifier were also taken on a daily basis to allow for suspended solids analysis. Both mixed liquor and secondary effluent samples were collected and transported in 500 milliliter (ml) plastic bottles with lids. Sludge samples for dewatering tests were collected in twenty liter Nalgene carboys either directly from the aeration basin overflow weir for activated sludge, or from a sampling spigot in the pump house for the waste activated sludge. In collecting the waste activated sludge, the valve was opened and the sludge was then allowed to flow freely for several seconds to allow for mixing to obtain a representative sample. All other data including daily flows, waste activated mixed liquor volatile suspended solids (MLVSS) data, and D.O. concentrations were obtained from daily records compiled by the plant technician.

Steady-State Determinations

Since all lab-scale reactor data were to be compared when the reactors were at a steady-state condition, it was necessary to determine a way of designating steady-state. In this study steady-state was declared when both the reactor mixed liquor suspended solids (MLSS) and the COD removal efficiency reached a constant level for a minimum of one week without any major fluctuations. Also, to allow for culture shifts between the different mean cell residence times (MCRT) a time period of at least three times the new MCRT was provided before steady-state was declared.

Suspended Solids Determinations

In order that steady-state determinations and calculation of MCRT values could be made, it was necessary to determine MLSS and MLVSS on a daily basis, for both of the laboratory-scale reactors. Likewise suspended solids determinations were also performed on the laboratory-scale reactor effluents, and the secondary effluent from the plant. The procedure outlined in Standard Methods for the Examination of Water and Wastewater (19) was used to perform these tests. For the mixed liquor samples 10 milliliters (ml) of sample was filtered through a Whatman Glass Micro Fibre Filter (5.5 cm GF/C). For the effluent samples 100 ml of sample was filtered in similar fashion to the mixed liquor samples. All samples were filtered on a Millipore filtering apparatus (Bedford, Mass.) under 25 inches of mercury (vacuum differential) supplied by a Doerr vacuum pump (Doerr Electric Corp. Cedarburg, Wis.).

Chemical Oxygen Demand (COD)

COD samples were collected once every other day during non-steady state periods and daily during steady-state periods to determine first of all if steady-state existed, and also to check to insure consistent influent COD concentrations to the reactors. COD samples were collected from both reactor influent feeds, and also from their effluents. Samples were collected, preserved, and stored according to Standard Methods. All test procedures were performed in accordance with Standard Methods, except the silver sulfate (Ag_2SO_4) catalyst concentration was reduced by fifty percent. This alteration was determined by experimental COD's to be equivalent to the normal procedure for the wastes used in this study. All COD analyses were performed on a sample size of 20 ml.

Dissolved Oxygen and pH Determinations

Dissolved oxygen (D.O.) and pH were measured periodically to ensure consistency of reactor variables. Hydrogen ion concentration was measured using a Fisher brand Accumet Model 120 pH meter. Normal procedure was first to calibrate the meter using Fisher-Scientific brand pH buffer solutions, and then to measure the sample pH by placing the pH probe in a 500 ml beaker of the sample.

Dissolved oxygen determinations were made using a YSI Model 54A oxygen meter. The D.O. meter was first calibrated, and then the probe was placed into the center of the aeration basin portion of the lab reactor, making sure the D.O. probe was properly submerged to ensure accurate readings.

Sludge Dewatering

Sludge dewatering determinations were made using the standard Buchner funnel apparatus as described by Vesilind (1). The filtering apparatus used is shown in Figure 5.

Sludge was prepared for the dewatering test by first settling the sludge for approximately thirty minutes to concentrate the sludge to approximately one percent solids. The supernatant was then poured off and saved, and 100 ml of the concentrated sludge was measured for the resistance test.

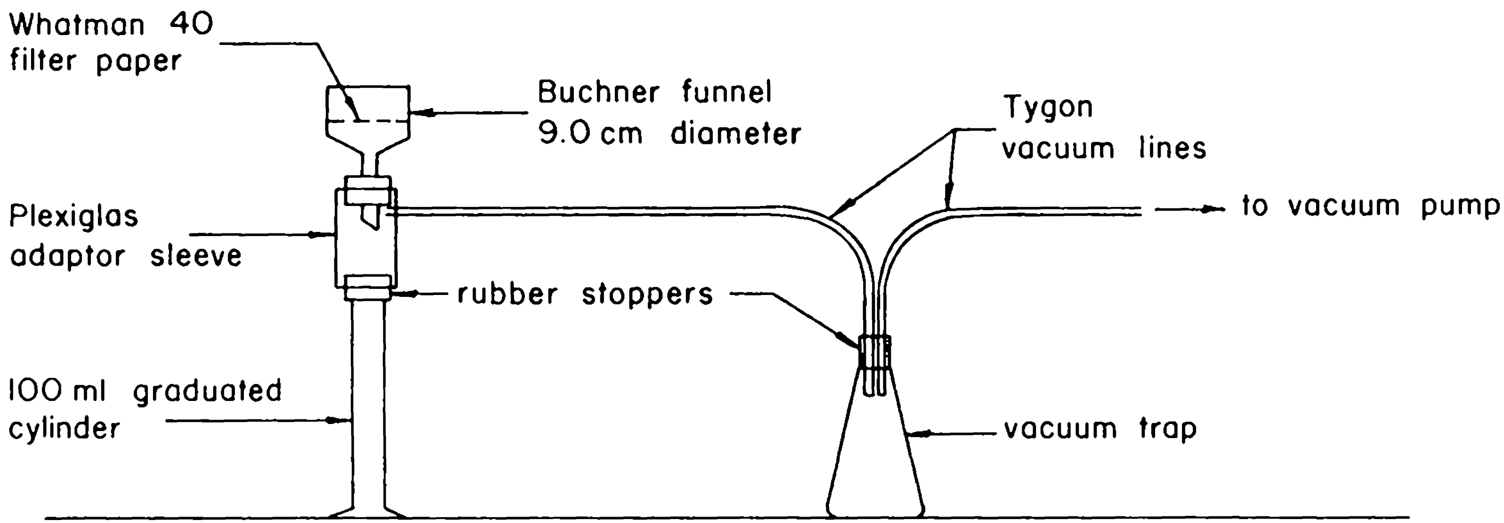

Figure 5. Buchner Funnel Filtration Apparatus

Typical procedure for a Buchner funnel determination was first to place a nine centimeter diameter Whatman 40 filter paper in the Buchner funnel. This filter was then sealed to the Buchner funnel by applying a vacuum (Doerr vacuum pump) and rinsing the filter with distilled water. Once the filter had been sealed the vacuum was stopped and the 100 ml sample of sludge was slowly poured into the funnel such that the sludge did not penetrate under the edge of the sealed filter. The sludge was allowed to sit for several seconds to allow for the development of a cake structure. This time period normally corresponded to the time it took for several drops to fall through the filter into the 100 ml receiving graduated cylinder. Following cake structure development the vacuum was reapplied (standard 15 inches of mercury) and simultaneously a stopwatch (Fisher-Scientific digital) was started. The remainder of the procedure simply involved recording the volume of filtrate collected as a function of dewatering time. Recordings were made every five seconds for the first sixty seconds and then every twenty seconds thereafter until the volume of filtrate did not change in a twenty second period.

The resulting volume versus time data recorded during a Buchner funnel run was then plotted as time over volume (T/V) versus volume (V) in order that the slope, the "b" term in the specific resistance equation, might be calculated. For details of the equations and variables used in calculating specific resistance, see Appendix A.

Solids Determinations

All solids determinations were performed using the following procedure: 1) aluminum tare pans were weighed using either a four place vernier readout Sartorius (W. Germany), or a four place digital readout Mettler AC 100 (Hightstown, N. J.); 2) samples of approximately 20 ml for the liquid like samples, or a small portion of cake for the solid-semisolid samples was placed in the pre-weighed tare pans and weighed immediately; 3) samples were then placed in a drying oven at 105 degrees celsius for twenty-four hours; and 4) samples were then removed from the oven, cooled in a dessicator for fifteen minutes, and then weighed.

Solids determinations were made on all feed solids, filtrate solids, and cake solids for the Buchner funnel test in order that the "w" term in the specific resistance could be calculated. See Appendix A for equations used for solids determinations and also for calculating the "w" term.

Compressibilty

Compressibility tests were performed to see if the rigidity of the sludge flocs was changing with respect to

MCRT. This information would afford the plant operator with vital statistics as to which sludge age is the best suited for operating with his equipment.

Compressibility determinations were made using a standard Buchner funnel apparatus and the techniques described in the dewatering section of this chapter. By varying the vacuum pressure (7,10,15, and 20 inches of mercury) on the dewatering test four values of the sludge's resistance were determined. The logarithm of specific resistance was then plotted versus the logarithm of vacuum pressure, and the resulting slope (S_o) of the plot was defined as the sludge's compressibility (1). Vesilind (1) claimed that at an S_o value of zero the sludge was considered incompressible, and the higher the S_o value the more compressible the sludge is.

Conditioning

Conditioning was used in this study not to evaluate which conditioner works best, nor to find the optimal dosage of conditioner, but to evaluate the dosage of conditioner at various MCRT values that would yield an acceptable dewatering sludge as defined by an arbitrary working value. In this study $20x10^{11}$ meters per kilogram (m/kg) was defined as the desired dewatering resistance value. In other words a sludge was conditioned and dewatered with increasing conditioner dosages until a resistance value of $20x10^{11}$ m/kg was obtained.

In this study the conditioner used was a high molecular weight, cationic polymer, Purifloc C31 (Dow Chemical Company, Midland, Mich.). To prepare the polymer, one gram of the polymer was dissolved in one liter of distilled water to yield a stock solution concentration of approximately 1000 mg/l. In conditioning the sludge a predetermined amount of polymer solution was added to the appropriate volume of sludge to yield a final volume of two liters, at the desired conditioner concentration (see Appendix A for sample calculation). This sludge-polymer mixture was then immediately rapid mixed at 100 revolutions per minute (rpm) for thirty seconds, and flocculated at 20 rpm for a minimum of two minutes, or until good flocculation had occured. A Phipps and Bird (Richmond, Va.) six paddle stirrer was used for all conditioning studies. The conditioned sludge was then poured into a two liter column and allowed to settle. Specific resistance determinations were then made on the concentrated sludge in similar fashion to the techniques described in the dewatering section of this chapter.

Particle Size Analysis

All particle size analyses were performed using a HIAC particle size analyzer (Model PC-320 by Pacific Scientific). This instrument was capable of counting the individual sludge particles within specified diameter ranges, and printing the total number at each range out on a digital readout counter. The analyzer worked on an electronic light sensing basis; as a particle of sludge entered the light sensor the light was blocked out. The instrument then registered the corresponding area of light blocked on a photodiode and calculated a diameter of a circle (spherical particles are assumed) corresponding to that area.

Since the particle counter sensor is only able to measure one particle at a time it was necessary to dilute all samples. If the sample was too concentrated with respect to sludge particles, more than one particle would enter the sensor at one time, and a red light indicating either a clogged sensor or too concentrated of a sample would come on. Most samples in which particle counts were performed on were usually diluted by a ratio of 1:1000; however some finer sludges needed to be diluted to as much as 1:20,000. Dilutions were made using a simple pipeting technique.

In preparing a sample for a particle count the corresponding sludge used for a dewatering test was diluted with filtered supernatant that had previously been poured off the settled sludge. The dilution supernatant was always filtered with a 3.0 micron or smaller type SS Millipore filter on a Millipore filtering apparatus (Millipore Corp., Bedford, Mass.). Once mixed the particle count sample was then screened through a 297 micron sieve to prevent excessively large particles from entering the sensor. All samples were then poured into a 125 ml Ehrlenmeyer flask which served as the holding vessel for the particle count. The sample was placed in the HIAC Automatic Bottle Sampler where an applied pressure differential provided the necessary driving force to place the sample through the sensor. The particle counts were then recorded from the digital readout.

It should be noted that this particle counter instrument was capable of counting particles in two major size categories: 1) 1 to 60 microns; and 2) 5 to 300 microns. For this study only the 5 to 300 micron range was employed. Within this 5 to 300 micron range, twelve different channels corresponding to twelve size ranges were possible. Two different size range categories within the 5 to 300 micron range were used throughout this study: 1) for finer, less flocculated sludges the ranges went from 5 to 115 microns in increments of 10 microns leaving the last channel to count from 115 to 300 microns; and 2) for the more flocculant sludges the ranges went from 5 to 225 microns in increments of 20 microns leaving the last channel to count from 225 to 300 microns.

Each sludge type was typically counted using one of the above mentioned range categories; however, if the 10 micron increment category was selected, and a large number of particles existed in the 115 to 300 micron range then it was felt more beneficial to perform a second analysis using the 20 micron increments. Likewise, if in using the 20 micron increments small counts were recorded at the higher size ranges, then it was felt that the 10 micron increments would be more appropriate. All samples were tested in duplicate, and if similar only one count was used for analysis; however, in cases where the counts were significantly different the two were averaged. It should also be noted that the samples were stirred gently during counting procedures to prevent settling out of the larger particles, and at the same time not disrupting the actual flocs by a shearing action. Stirring was provided by a built-in magnetic stirrer in the automatic bottler sampler and a small metal object (normally a paper clip) placed in the sample itself.

MCRT and F:M Ratio Determinations for the Plant Data

Once MCRT values and F:M ratios had been calculated for each day of plant data, these values were then applied to a moving average weighting procedure developed by Berthouex and Hunter (20), and new MCRT values and F:M ratios were calculated. This procedure made use of a weighting factor "phi" which incorporated and weighted previous days MCRT values or F:M ratios, respectively into calculating values for an individual day. A "phi" factor of 0.7 was used in all MCRT and F:M ratio calculations for the plant data. This 0.7 "phi" factor incorporated values for the previous ten days at different proportions in calculating the desired value for a particular day.

IV. RESULTS AND DISCUSSION

Mean Cell Residence Time Effects Upon Dewatering

As noted by Pitman (9) (see Figure 1) MCRT seemed to have a drastic effect upon sludge dewatering resistance values at several lower MCRT values. Pitman reported a significant increase in specific resistance at solids retention times between seven and eight days. At the higher MCRT values Pitman's results indicated no significant change in specific resistance, likewise at the lowest MCRT values Pitman's results indicated no significant difference in specific resistance values when compared to the higher MCRT resistance values. Pitman corresponded the increase in dewatering resistance at the seven to eight day retention times with an increase in mobile ciliates, which remained dispersed and unflocculated. He concluded that the higher MCRT values which produced minimal mobile ciliates and an abundance of attached forms; coupled with a low hydraulic detention time to wash out remaining mobile ciliates, would yield sludges with minimal dewatering resistances. Likewise, Benefield and Randall (21) also emphasized the fact that the higher MCRT values and minimal hydraulic detention times were the most desirable design parameters. Both of the above mentioned sources expounded upon operating a plant in the so-called "endogenous growth phase" for optimal treatment and optimal sludge handling characteristics.

In examining Figure 6, results from the laboratory-scale reactors of this study, dewatering resistance values were lower by an order of magnitude of two when compared to the results recorded by Karr and Keinath (2), and lower by an order of magnitude of one when compared to Pitman's (9) results. The lab reactors also did not yield a sharp increase in specific resistance at the 7-8 day retention times as reported by Pitman, but it is important to note that this study did not investigate all of the same MCRT values that Pitman has reported on. What the lab reactors did show, however, was a large decrease in specific resistance in moving from the four day MCRT to the eight day MCRT value.

At the lower MCRT values for the lab reactors the trends were similar in that both reactors yielded a large decrease in specific resistance in going from the four to eight day MCRT values. At the higher MCRT values, however, the trends were not quite as similar. As noted in Figure 6, the synthetic reactor yielded no significant increase in dewatering resistance between the ten and fifteen day MCRT values, whereas the primary reactor did. A possible explanation for this difference is the corresponding F:M ratios, as shown in Figure 7 and recorded in Tables B-1 & B-2. At the highest MCRT value the pri-

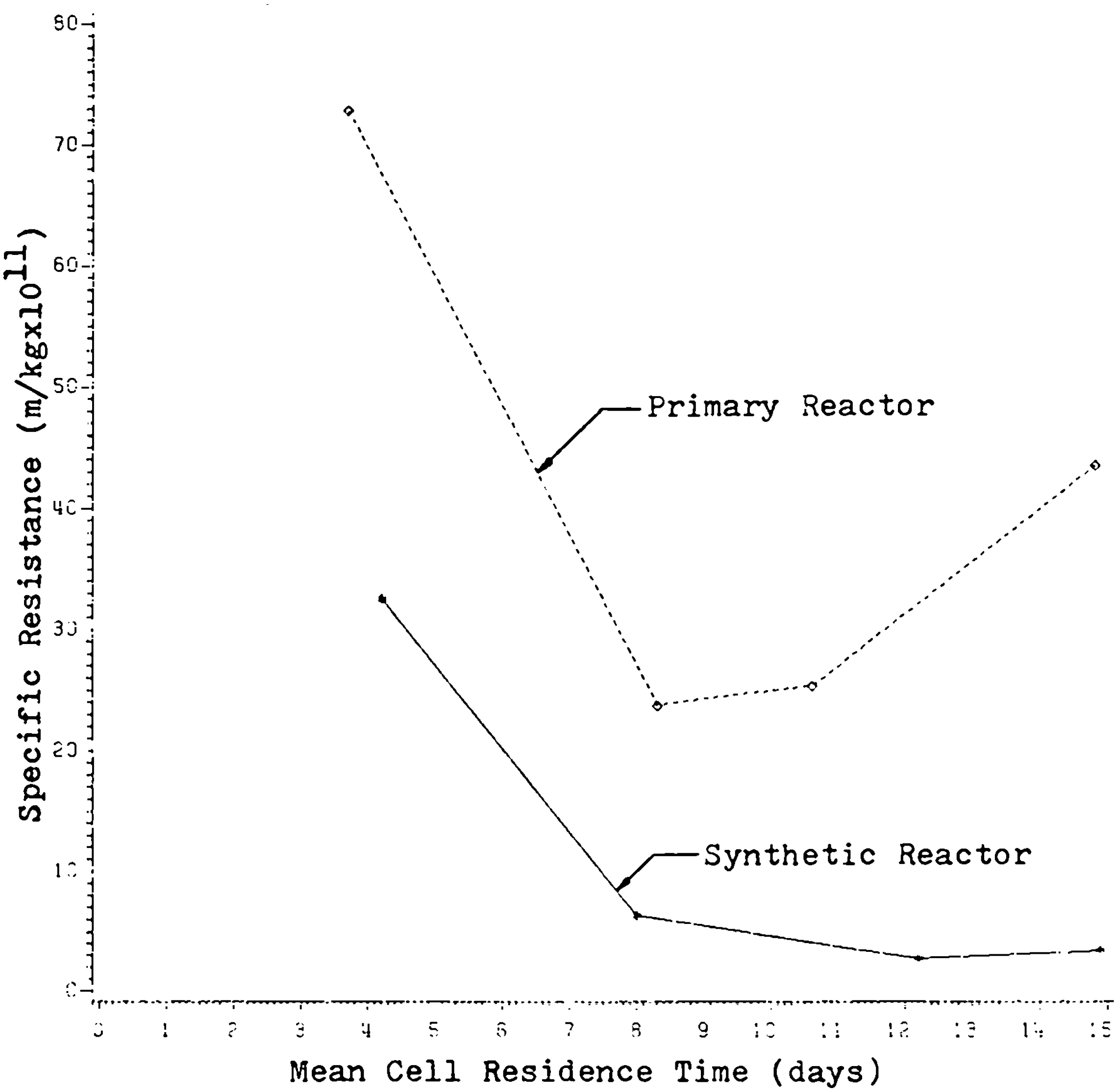

Figure 6. Effect of Mean Cell Residence Time on Specific Resistance for the Laboratory Scale Reactors

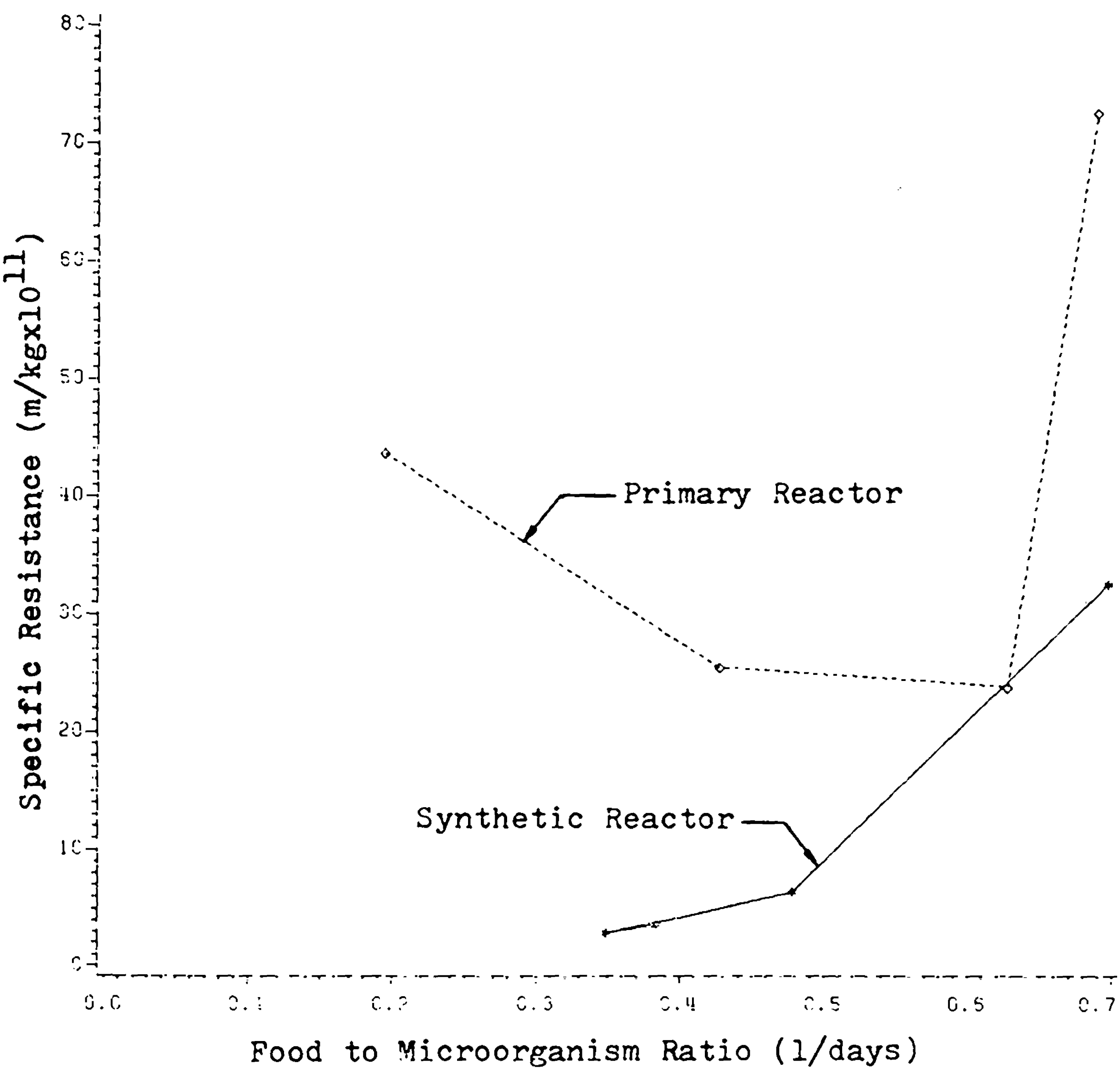

Figure 7. Effect of Food to Microorganism Ratio on Specific Resistance for the Laboratory Scale Reactors

mary reactor had a much lower F:M ratio than did the synthetic reactor. This lower F:M ratio resulted from the extremely low COD of the primary effluent. This data point corresponded to a time period in which COD loading to the plant was minimal, and thus the major source of COD to the primary reactor was the dog food.

Figure 8 presents results of dewatering studies from a full-scale wastewater treatment facility. As can be noted in Table B-3 much of the plant data corresponded to extended aeration treatment in which MCRT values over thirty days were commonly reported. All data points with MCRT values greater than thirty days were considered under the category of extended aeration. However, for the range of MCRT values recorded and the corresponding resistance values there appeared to be no trend or correlation. It is important to note that during periods of extended aeration operation when no sludge wasting was occuring, MCRT values became highly dependent upon secondary clarifier effluent solids, and thus MCRT values were highly variable.

In Figure 9, a plot of specific resistance versus F:M ratio for the full-scale wastewater treatment plant, no well defined trend was realized. It did appear, however, that the highest resistance values occured at the lower F:M ratio values. The plant never attained the higher F:M ratio values, therefore no real trend comparison

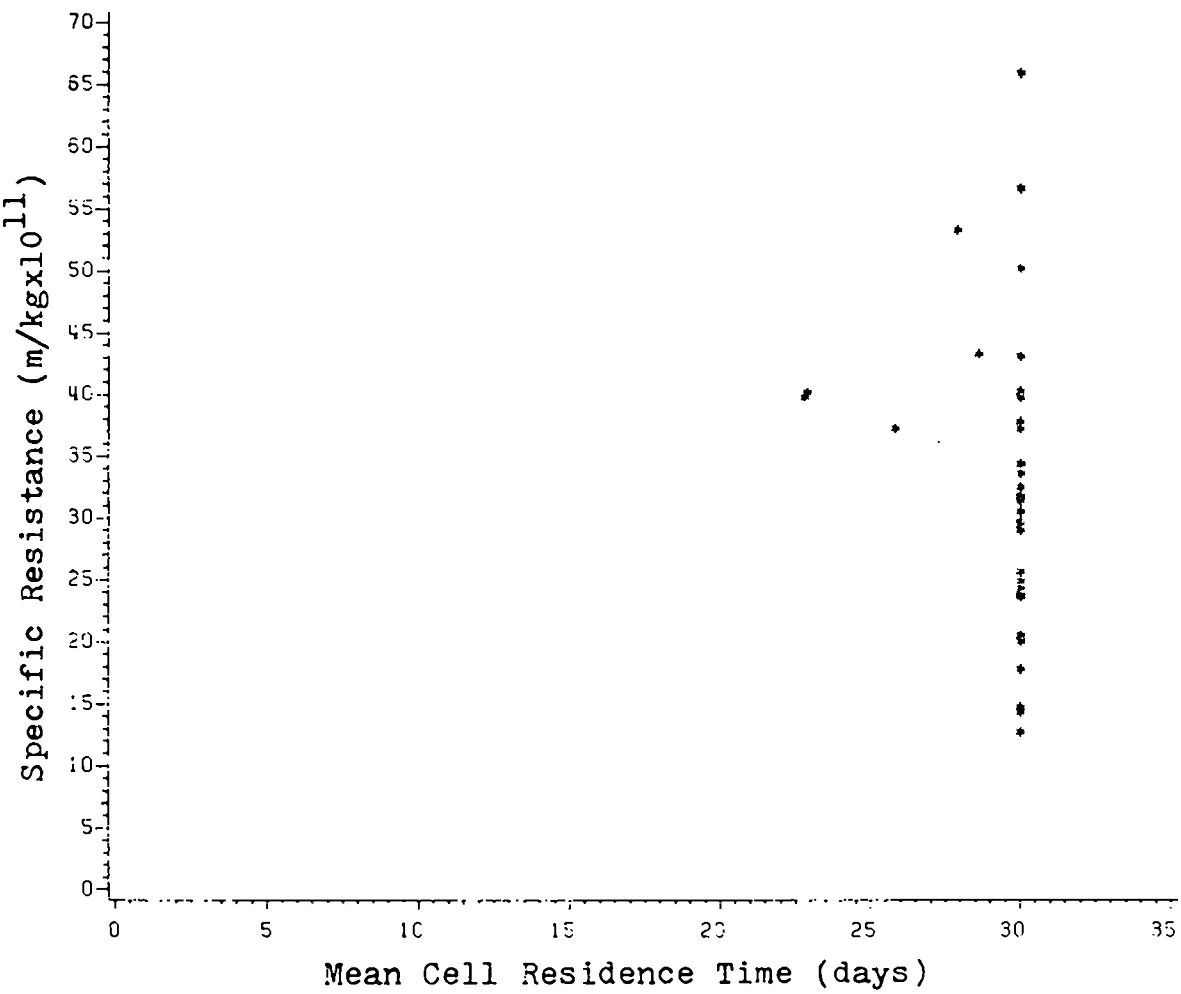

Figure 8. Effect of Mean Cell Residence Time on Specific Resistance for Aeration Basin Sludge

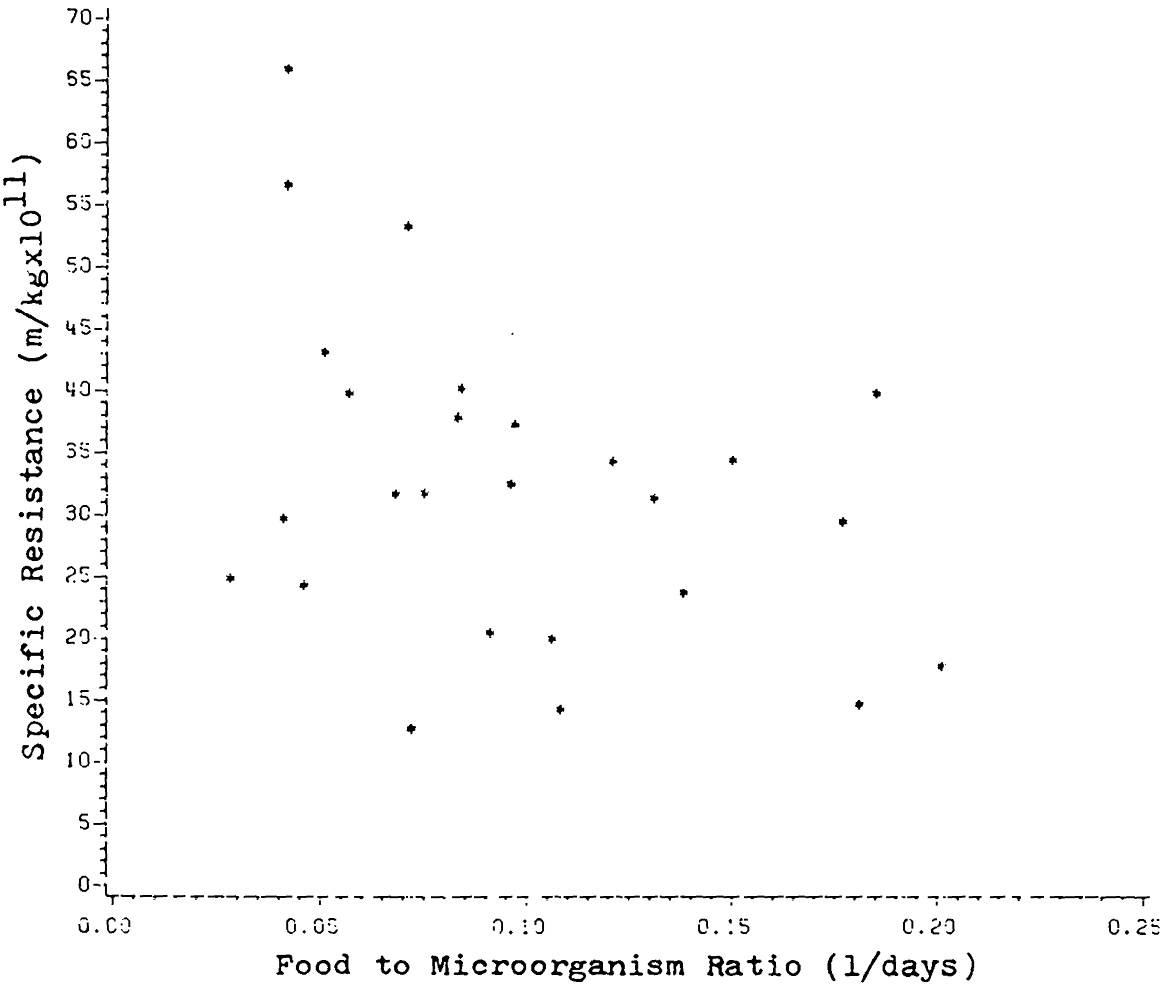

Figure 9. Effect of Food to Microorganism Ratio on Specific Resistance of Aeration Basin Sludge

could be made between the full-scale plant and the lab reactors.

In literature studies it has been reported that MCRT and F:M ratio are inversely related and will yield a curve similar to the one described by Sherrard (22). For a constant influent substrate concentration, and by varying only MCRT this curve can be generated. Likewise, many different MCRT versus F:M ratio curves can be generated by using different constant influent substrate concentrations and varying the MCRT for each different influent concentration used. An example of two such curves is presented in Figure 10. One curve is data presented by Bisogni and Lawrence (10) which resulted from a lab reactor fed with a glucose substrate at a COD concentration of 375 mg/l, applied at a rate to maintain a hydraulic detention time of six hours. The second curve resulted from the synthetic feed reactor of this study which was maintained on an influent substrate of bacto-peptone, with a COD concentration of 250 mg/l, applied at a rate to maintain an eight hour hydraulic detention time. For Pitman's results and the primary effluent reactor (see Figure 11), however, the curves were not similar to the ones described by Sherrard. It appeared that the results in Figure 11 actually consisted of points on several MCRT curves.

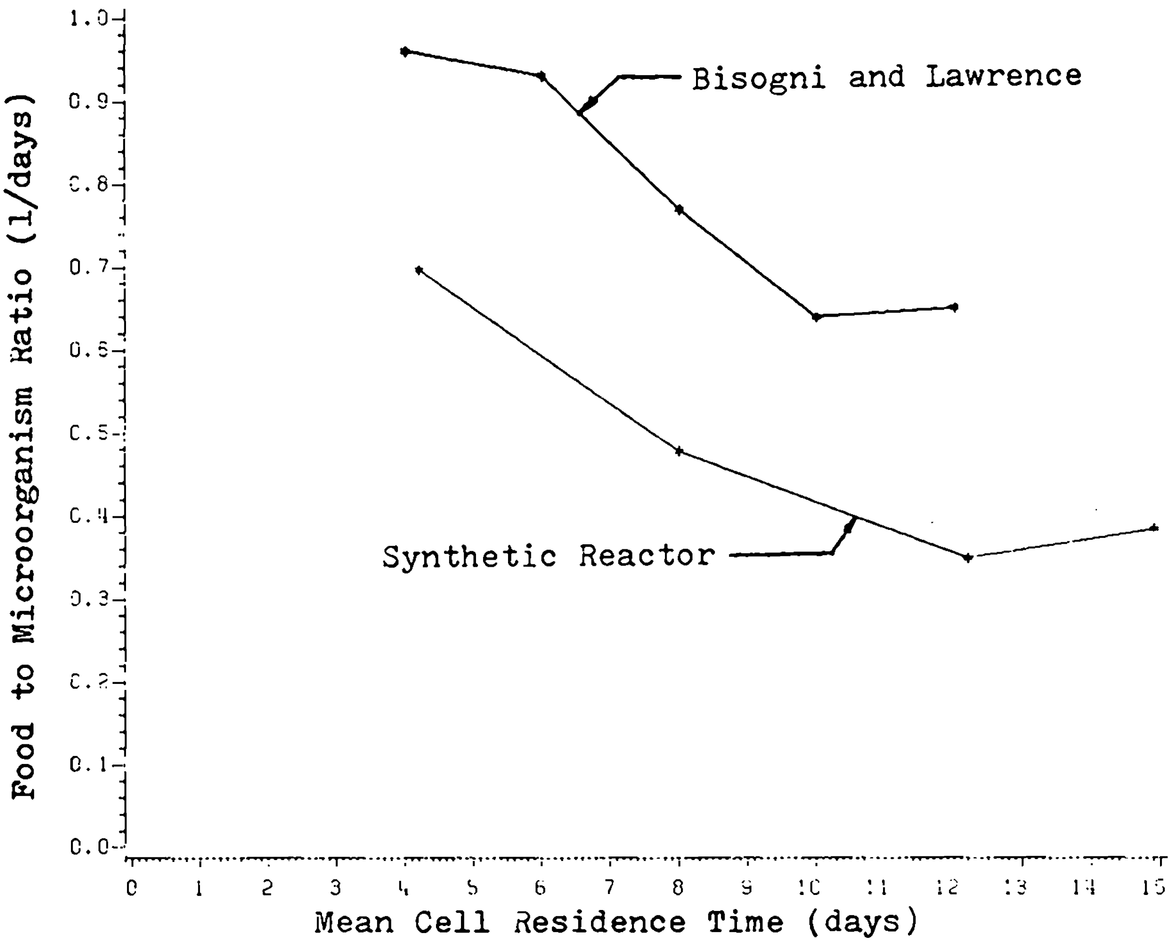

Figure 10. Relationship between Mean Cell Residence Time and Food to Microorganism Ratio for the Synthetic Reactor and Bisogni and Lawrence's (10) Data

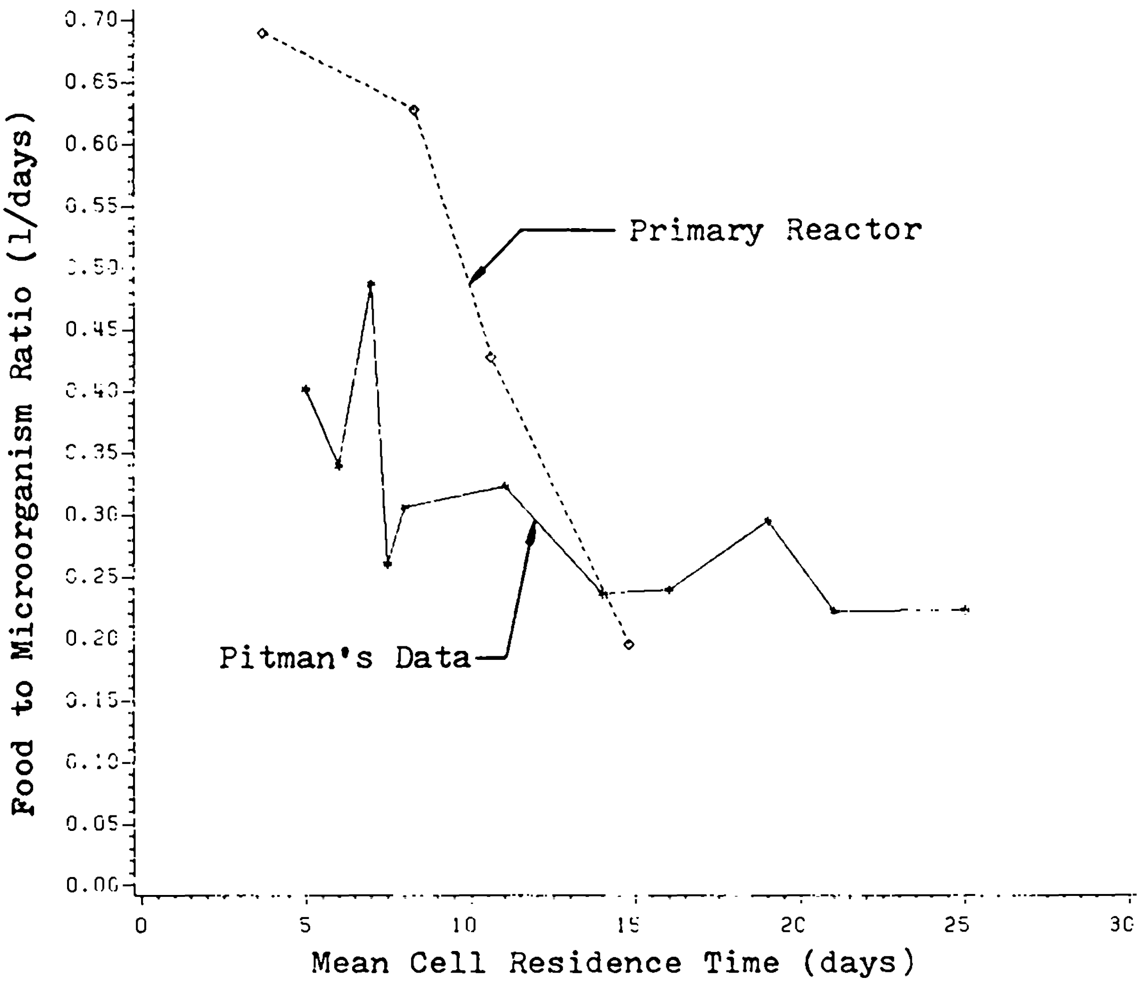

Figure 11. Relationship between Mean Cell Residence Time and Food to Microorganism Ratio for the Primary Reactor and Pitman's (9) Data

Although the trends as described by Sherrard (22) existed for the data presented in Figure 11 it can be seen that at identical MCRT values two or more corresponding F:M ratios might exist. Likewise, in Figure 10 one can observe that at identical MCRT values two different F:M ratios can exist with the converse being true, also.

Since two identical MCRT values can occur at two very different F:M ratios, and vice-versa, it would appear that other factors, in addition to sludge age, control the dynamics of an activated sludge system. Some factors that may cause these differences are: 1) assimilability of substrate - different culture growth rates; 2) presence of proper nutrients; 3) presence of toxic materials; and 4) efficiency of solids-liquids separation - namely secondary clarification.

Since, in examining Pitman's data, the full-scale plant data, and the lab reactor data there was no obvious trend correlation for specific resistance versus MCRT, it appears that MCRT, in general, is not an effective means to predict optimal dewatering rates. In examining the lab reactor data, however, trends did tend to correlate between the two reactors, especially when incorporating the specific specific resistance versus F:M ratio data into the overall picture. Thus, some relationship between MCRT, F:M ratio and specific resistance might exist for an individual activated sludge system, or systems that are strikingly similar such as the lab reactors. In other words a plant operator might be able to ascertain an MCRT value or F:M ratio that will yield the most efficient dewatering sludge for his particular plant. However, to say that since one plant operates efficiently at a certain sludge age would suggest that others would do so also, could be very erroneous. A prime example of this can be realized by examining the full-scale plant data. This plant operated at MCRT values from 20-500 days, obviously most of these days were during an extended aeration operation, however, under very diverse and fluctuating conditions this plant did not yield any striking changes in specific resistance. In Pitman's work, however, it was claimed that MCRT values beyond thirty days would promote deflocculation of the sludge. Likewise, many of todays text books also indicate that activated sludge plants operating in the extended aeration mode normally produce poor settling sludges resulting from deflocculation.

It appears from the literature study and the results of this study that each plant, pilot plant and laboratory reactor defines a unique microbial system which will respond to operational procedures in a unique way. To say that there was an optimum MCRT value or F:M ratio for dewatering cound not be founded. Even to define a range of MCRT values could be highly erroneous with respect to sludge conditioning and dewatering. The principles behind sludge age, however, are well founded and can be generalized upon when the topics are sludge production and oxygen requirements. However, when sludge conditioning and dewatering are the topics of study, other parameters must also be considered. Parameters such as the ones mentioned in the Literature Review chapter and parameters that are discussed in this chapter are also essential to control to obtain an optimal dewatering sludge. Other parameters that could effect dewatering that have not been mentioned and will not be discussed in any detail are: 1) toxicity effects; 2) population effects - dispersed growth and overcrowding; 3) biopolymer production and type; and 4) the effect that particle size of primary effluent has on the dewaterability of the activated sludge.

Dissolved Oxygen Effects Upon Dewatering

In examining Figure 12 there appeared to be no correlation between dissolved oxygen (D.O.) concentrations and sludge dewatering resistance. Also, it can be seen by examining Table B-3 in Appendix B that there were actually very few days in which the D.O. concentration was below 2.0 mg/l, a level regarded by many as the minimum D.O. concentration which prevents significant deterioration of bacterial sludge flocs (13,15,16).

It is important to note however, that extended periods of anaerobic conditions did cause notable deterioration of sludge floc. This problem occured at least four times throughout the extent of this study in which the air supply to the lab reactors was completely off for at times as long as six hours. Prior to each occurence the activated sludge, especially the synthetic feed sludge, consisted of well defined flocs. However, after each period without the air, apparent problems were noted. The sludge no longer appeared flocculant nor did its dewatering resistance remain at normal low values. It was hypothesized in accordance with material presented by Kalinske (13), Chapman _et al_ (14), Parker and Merrill (15), and

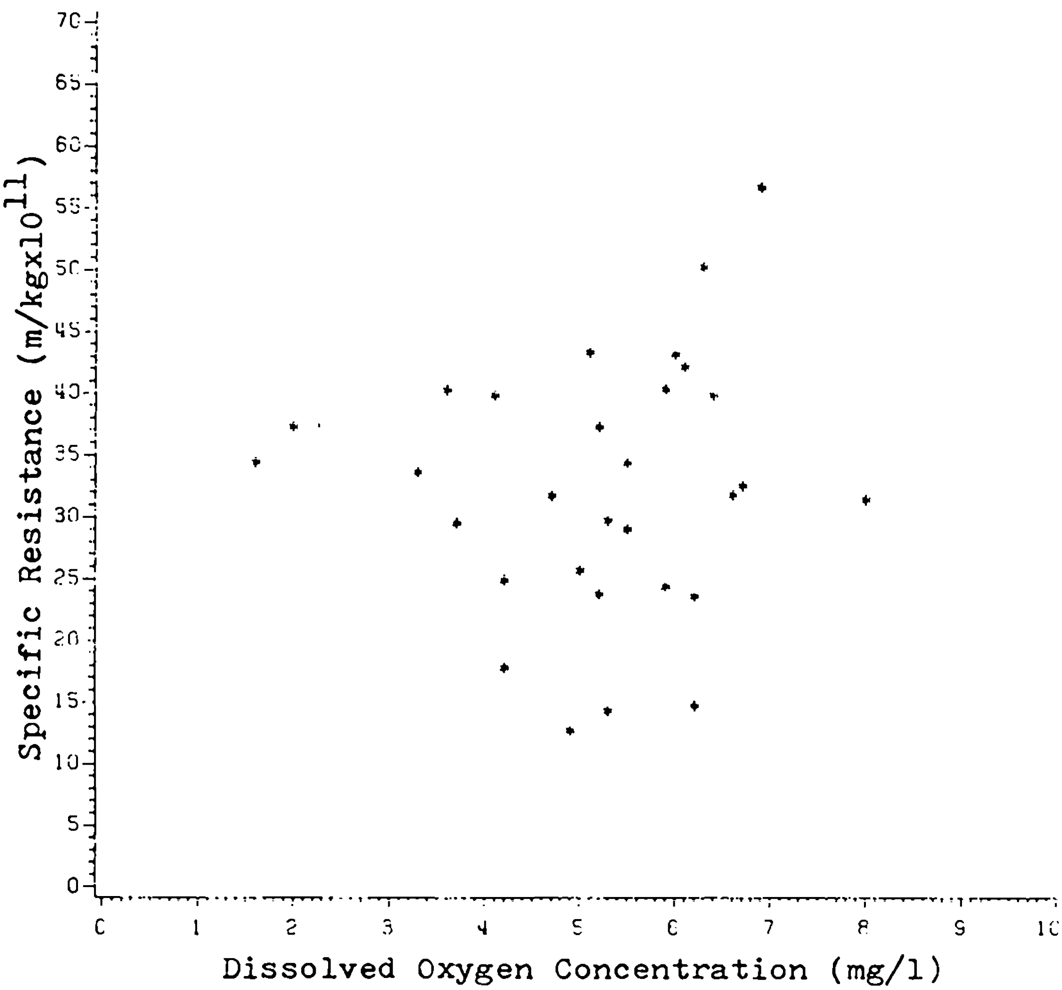

Figure 12. Effect of Dissolved Oxygen Concentration on Specific Resistance of Aeration Basin Sludge

Mueller *et al* (16) that the microbes in the large flocs were sufficated by surrounding microbes, and deflocculation resulted. Also the settling out of the activated sludge into a mat-like layer when the air was off would also impose oxygen deficiencies to those microbes on the bottom.

Another aspect of dissolved oxygen that was inherently built into this study was the effect that solids-liquids separation, namely secondary clarification, had on subsequent dewatering. Since secondary clarifiers are not aerated it is logical that anaerobiosis can occur. Low recycle ratios and/or slow settling rates can cause D.O. depletion in activated sludges within secondary clarifiers. A typical example of sludge deterioration from the aeration basin through the secondary clarifier is shown in Figure 13. In Figure 13 a noticed shift in surface area in favor of smaller diameter particles was realized in the sludge as it moved from the aeration basin through the secondary clarifier and out the wastage ports in the return mixed liquor lines. This increase in surface area in favor of smaller diameter particles for the waste activated sludge corresponded to increased dewatering resistance.

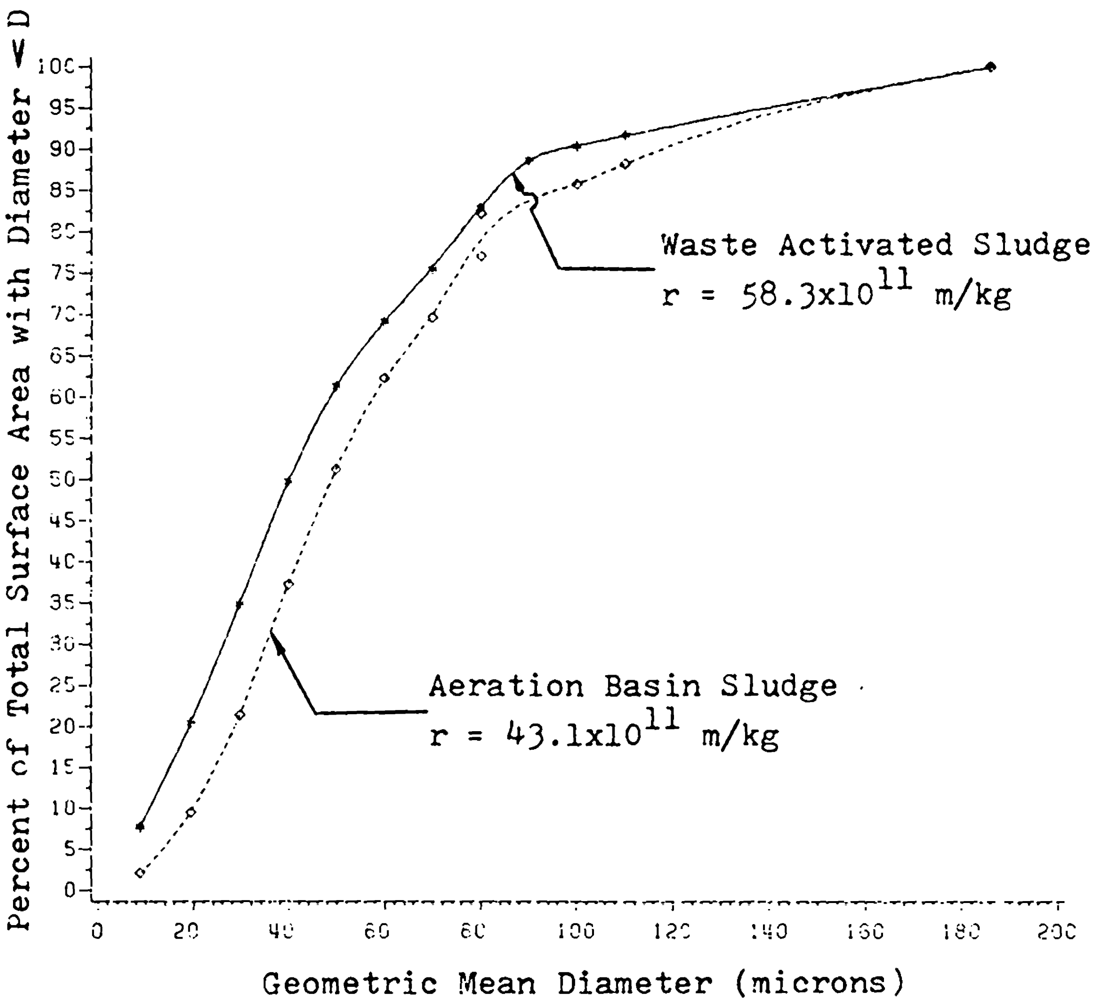

Figure 13. Change in the Particle Size Distribution of Activated Sludge from the Aeration Basin through the Secondary Clarifier

Particle Size Effects Upon Dewatering

As noted by Karr and Keinath (2) in their extensive study of particle size effects on dewatering resistance of biological sludges, and Knocke et al (7) in their study on metal hydroxide sludges, particle size was the major factor in dewatering resistances of the respective sludges examined. Figures 14 & 15 present plots of surface area distributions for each MCRT of both laboratory reactors. First of all it can be seen by examining Figure 14 that although the curves are very similar for all MCRT values, the specific resistance of the 4.2 day MCRT was significantly higher than the other resistance values. The only difference was that this sludge sample had a significant fraction more surface area associated with the smaller diameter ranges. This difference was noted mainly between the 10-130 micron ranges. In Figure 15 the curves were not quite as similar, but it was apparent that the curve with the highest associated surface area in the lower diameter size range had the highest specific resistance. In comparing the 14.8 day MCRT curve with the 3.7 day MCRT curve the major difference was noted between the 10-55 micron diameter ranges.

Karr and Keinath mentioned that sludge dewatering

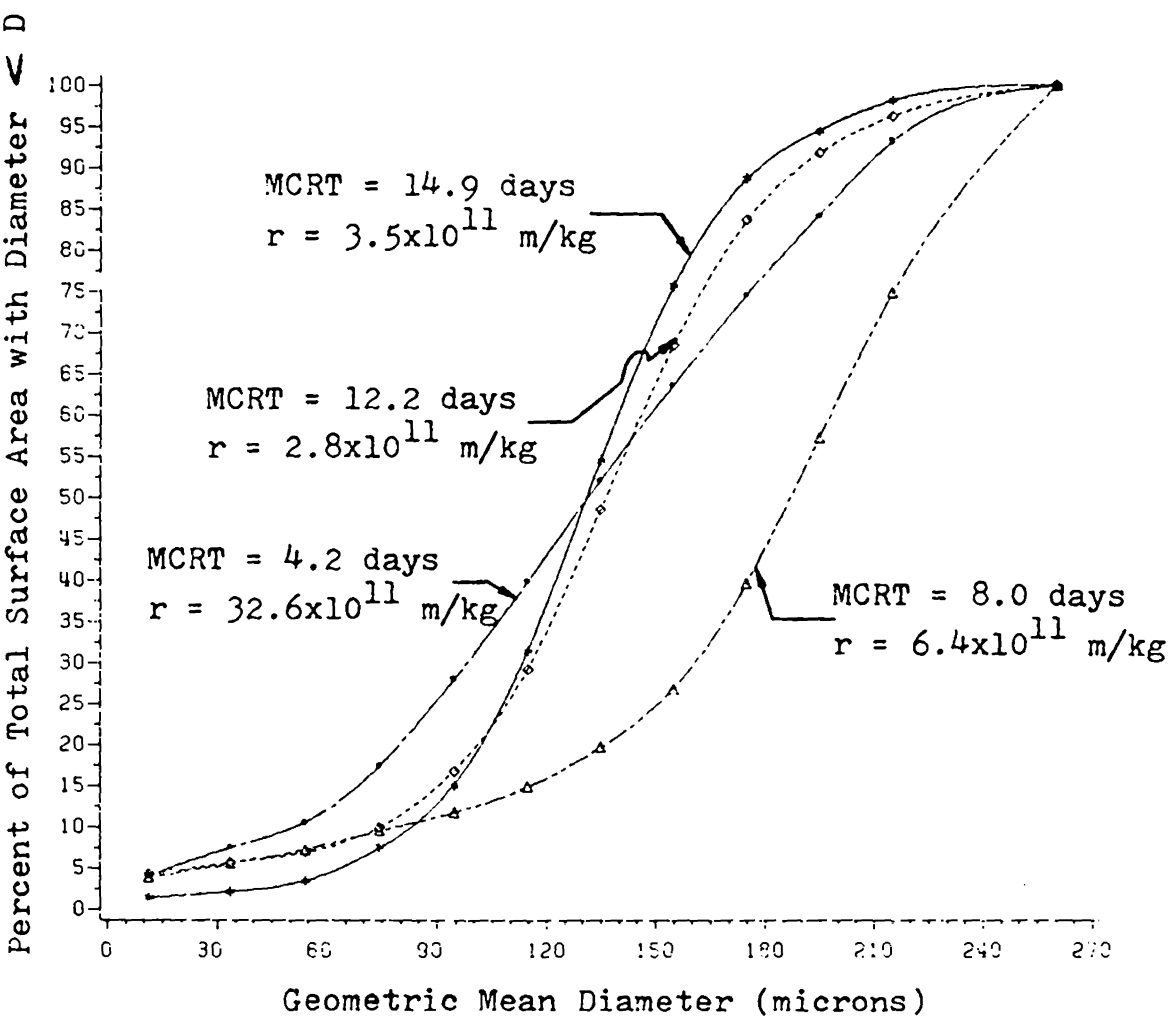

Figure 14. Relationship between Mean Cell Residence Time and Particle Size Distribution for the Synthetic Reactor

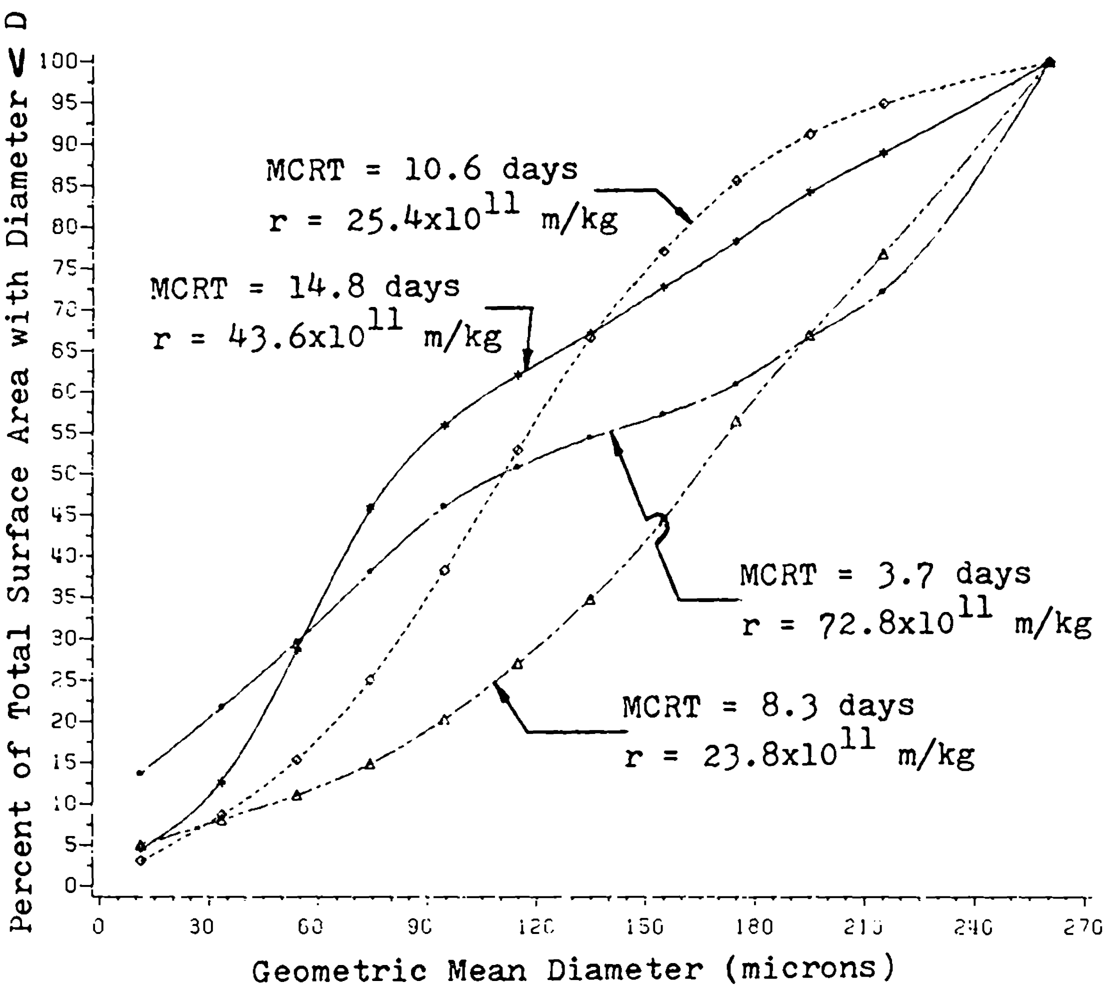

Figure 15. Relationship between Mean Cell Residence Time and Particle Size Distribution for the Synthetic Reactor

resistances resulted mainly from the presence of a supra-colloidal fraction (1-100 microns) within the sludge. In the above examples it was apparent that there was a larger fraction of associated surface area in this range for the samples with higher specific resistances. Probably the best example of which particle size range was contributing most to dewatering resistance is shown in Figure 14. At a MCRT of 8.0 days this sludge appeared to have the majority of its surface area in the larger particle size ranges as compared to the curves of the other MCRT values. However, this MCRT curve had the second highest associated specific resistance. The obvious answer lies in the smaller particle size fraction from approximately 10-75 microns where this sludge had equivalent or higher associated surface area than other sludges with similar resistances.

It was evident that the smaller diameter particles affected dewatering the most; yet it remained difficult to pinpoint the actual size range in which particle size was no longer a factor. Karr and Keinath's (2) 1-100 micron range could not be refined any further, because of the limitation defined in using their sequential particle filtration technique. Knocke, et al (7) using a similar particle counter to the one used in this study, reported that particle mean diameters from 8-20 microns were the major contributors to dewatering resistance in metal hydroxide sludges. In this study the best estimate of the range affecting dewatering the most was from 10-75 microns, because in examining Figures 14 & 15 as well as Tables B-4 & B-5 in Appendix B there was no clear cut evidence that a smaller particle diameter range was responsible.

Effect of Mean Cell Residence Time on Conditioning

Before any conclusions are made it is important to reiterate the fact that optimal polymer dosage determinations were not the purpose of this portion of the study. The real purpose of this portion of the study was in fact to see if there existed an optimal MCRT with respect to dewatering in order that economic considerations could be made in choosing between, polymer dosage costs, sludge handling costs, and other costs affected by varying MCRT. To do this, as mentioned previously, sludges were conditioned at various polymer concentrations until a defined arbitrary specific resistance was reached. For this study $20x10^{11}$ m/kg was chosen as a reasonable level of dewatering resistance.

Table III presents polymer dosages on a percent by weight basis that were needed to condition aeration basin

Table III. Polymer Dosages Required to Condition Aeration Basin and Waste Activated Sludge to a Specific Resistance Value of 20×10^{11} m/kg

Aeration Basin			Waste Activated		
MCRT (days)	F:M ratio (1/days)	Polymer Dosage (% by weight)	MCRT (days)	F:M ratio (1/days)	Polymer Dosage (% by weight)
>30	0.052	<0.041	>30	0.033	<0.045
>30	0.047	>0.043<0.086	>30	0.014	>0.041<0.082
>30	0.035	<0.051	>30	0.035	<0.041
>30	0.145	<0.045	>30	0.138	<0.039
>30	0.104	<0.045	>30	0.140	<0.067
>30	0.108	<0.045	>30	0.061	<0.075
>30	0.079	<0.062	>30	0.114	<0.048
>30	0.046	<0.048	>30	0.173	>0.066<0.132
>30	0.178	<0.071	>30	0.113	>0.260<0.347
>30	0.122	>0.095<0.189	>30	0.084	>0.304<0.507
>30	0.093	>0.102<0.164			
>30	0.082	>0.161<0.217			

sludge and waste activated sludge to the above defined working resistance value. Associated F:M ratios and MCRT values are also given in Table III. As can be seen there appeared to be no trend or correlation between either MCRT or F:M ratio with polymer dosage. It is important to note, however, that conditioner dosages for the sludges examined in this study were well below typical polymer dosages as reported in the literature. For this study the range of polymer required was from 0.0-0.5 % by weight with a typical dosage being less than 0.1 % by weight. Normal polymer requirements as reported by Vesilind (1) and Eckenfelder (23) were between 0.5 % and 1.0 % by weight.

For the synthetic reactor sludge only one MCRT value yielded a specific resistance above the working value. This occured at the 4.2 day MCRT value, and required a polymer dosage between 0.072 % and 0.145 % by weight to obtain the working resistance value. The primary reactor on the other hand was conditioned with polymer dosages between approximately 0.05 % and 0.40 % by weight with no resulting flocculation. Investigations into the possibility of the dog food creating an increase in the supernatant colloidal fraction and thereby increasing the conditioner demand were examined, but the particle counts revealed no significant increase in the number of particles present in the lower size ranges. It is possible, however, that particles less than five microns in diameter, which was the lower limit of the particle counter, could have accounted for this increase in polymer demand over what would normally be expected by examining typical dosages required for the aeration basin sludge from the full-scale plant.

Figures 16 & 17 present particle size distribution data for sludges requiring different conditioner dosages. As can be noted the sludges with the higher initial resistances and larger associated surface area in the smaller diameter particle ranges required the larger quantities of conditioner. As reported by Cheremisinoff and Maglio (4), surface area is an important parameter in determining polymer dosages. Thus, larger surface areas associated with smaller diameter particles would then account for the increased polymer dosages as reported by Cheremisinoff and Maglio and depicted in Figures 16 & 17.

Figure 18 presents particle size data showing the typically observed result of conditioning a sludge. As shown by Knocke, et al (7), increased polymer dosages shifted particle size distributions toward the larger particle size ranges and likewise decreased resistance values. No effect of overdosing was investigated in this study.

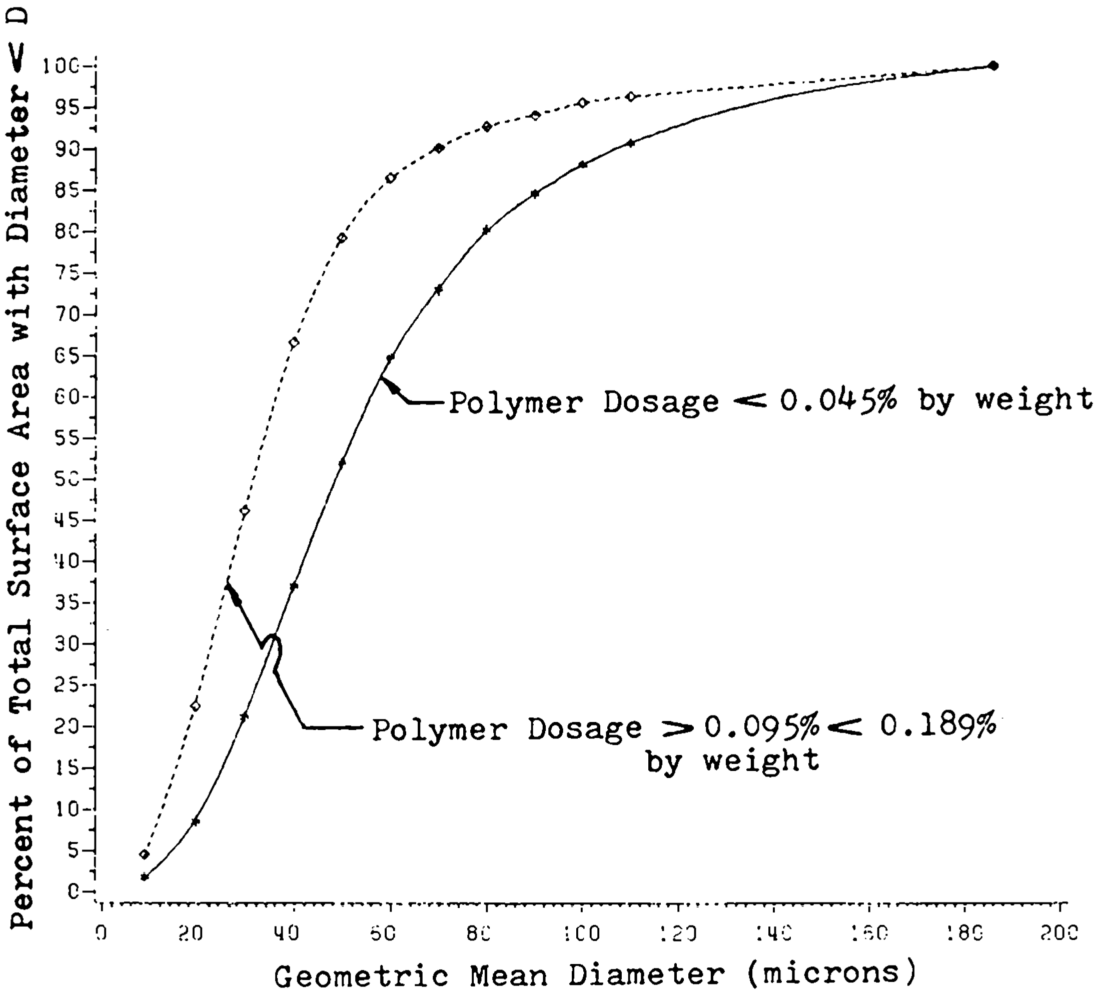

Figure 16. Effect of Particle Size Distribution on Required Polymer Dosage for Aeration Basin Sludge

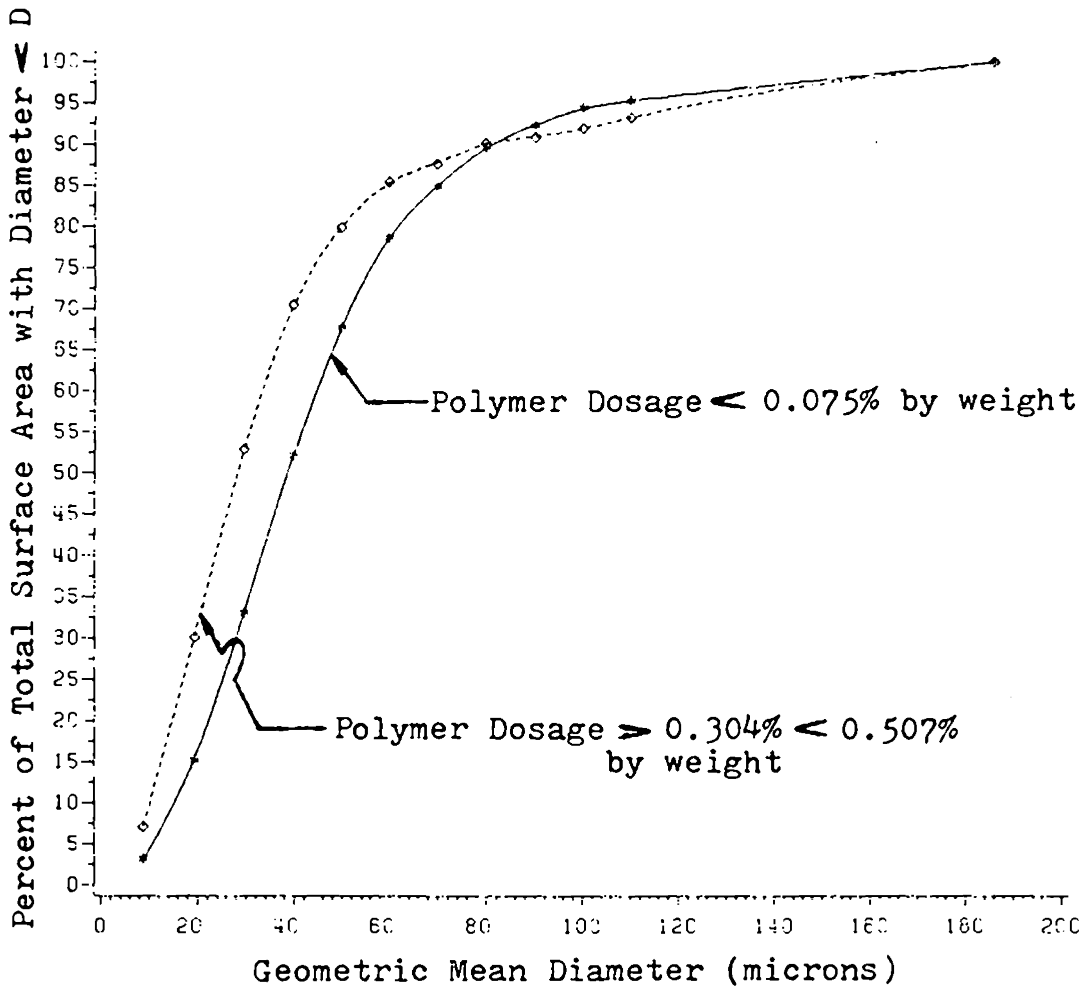

Figure 17. Effect of Particle Size Distribution on Required Polymer Dosage for Waste Activated Sludge

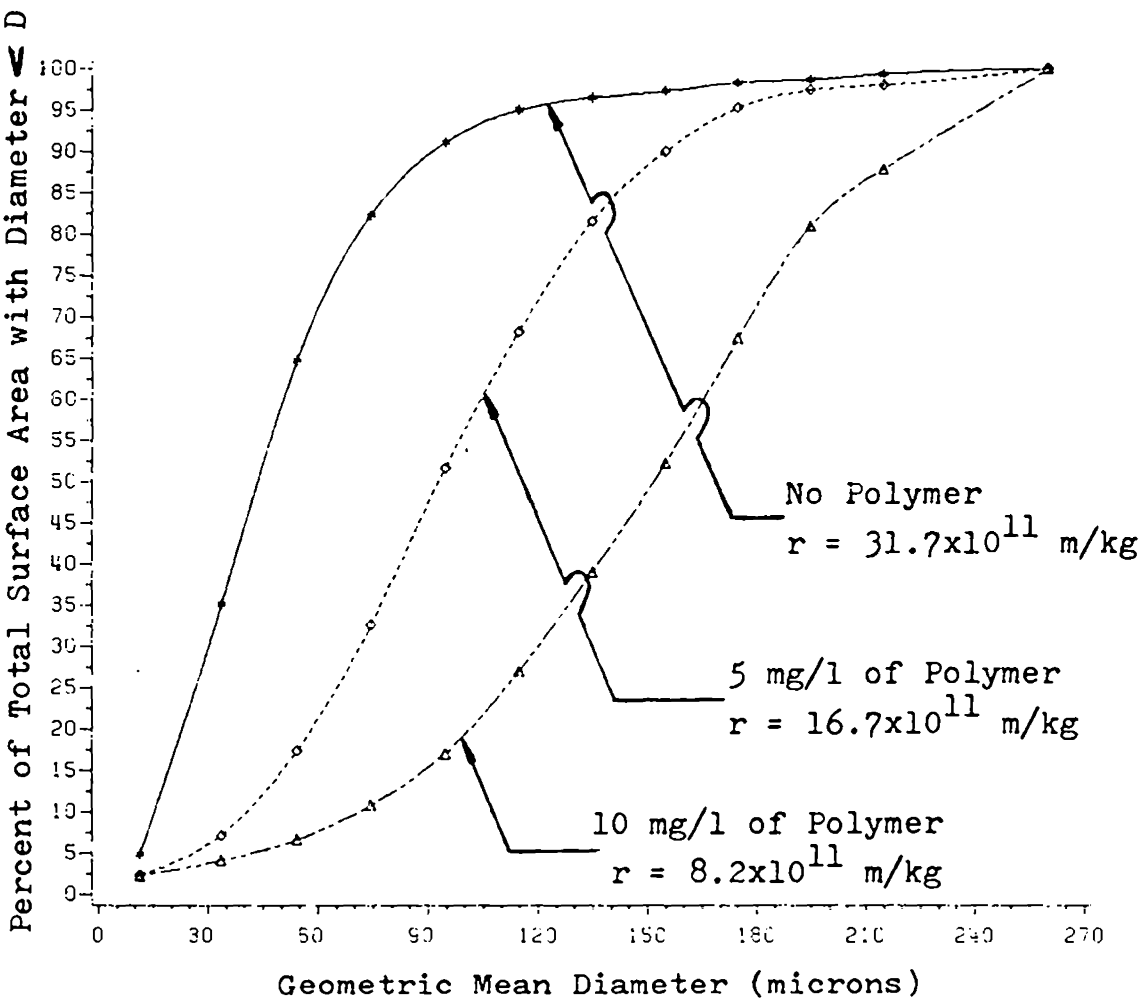

Figure 18. Typical Effect of Polymer on Particle Size Distribution

Effect of Mean Cell Residence Time on Compressibility

In examining Figure 19, which is a plot of compressibility versus MCRT, it can be seen that the synthetic reactor displayed a much more variable coefficient of compressibility. It is important to note, however, that resistance determinations for the synthetic reactor were subject to a much greater variability since the water was removed very rapidly from this sludge. It is not known whether this variability inherent in the dewatering determinations for the synthetic sludge could account for the variability in compressibility shown in Figure 19. In plotting the points on the log-log plot of vacuum pressure versus specific resistance for the primary reactor sludge and the aeration basin sludge a straight line resulted. For the synthetic reactor sludge, however, the log-log plot did not form a straight line and a residual line was extremely difficult to determine.

In examining both the results from the lab reactors and the full scale plant it appeared that MCRT had no significant effect on sludge compressibility. These sludges exhibited a relatively high compressibility, greater than one, while normal domestic sludge compressibilities range from 0.4 to 0.85 (1).

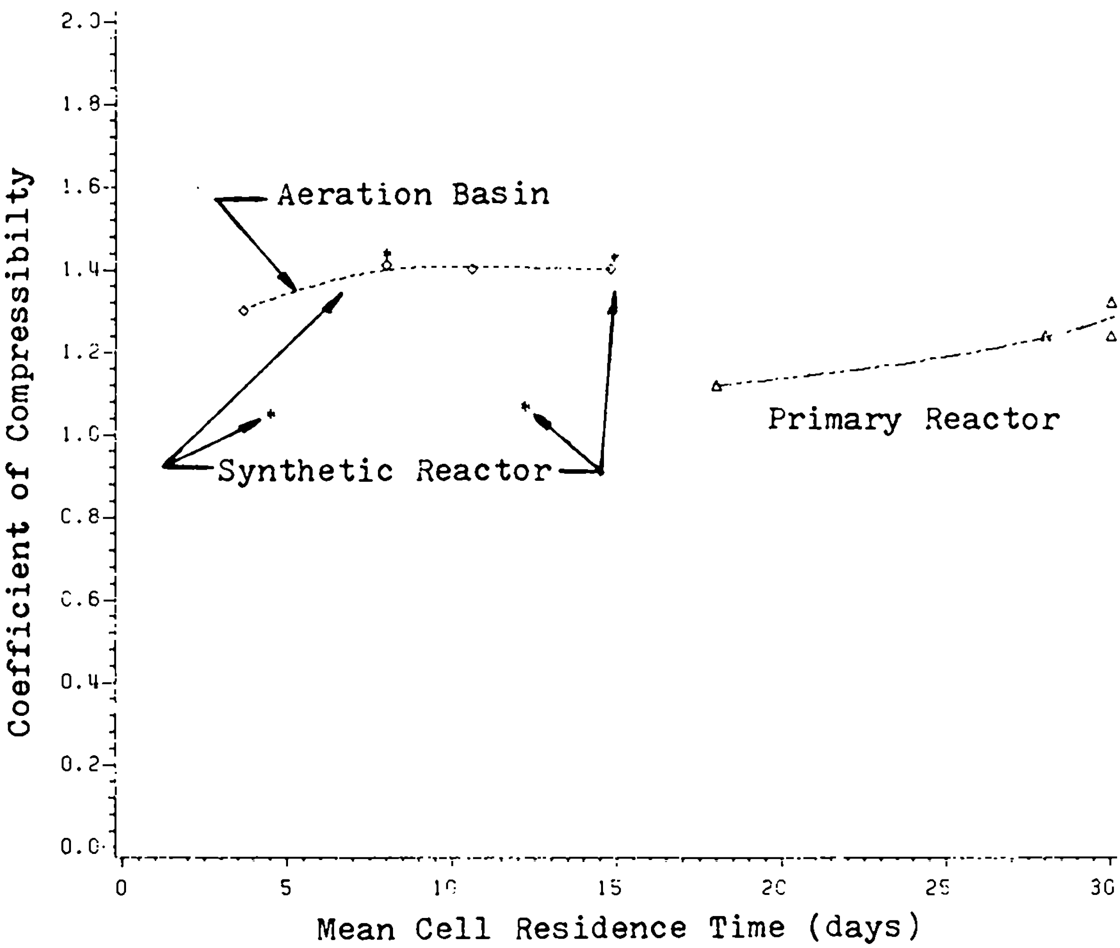

Figure 19. Effect of Mean Cell Residence Time on Aeration Basin, Synthetic Reactor and Primary Reactor Sludges

V. SUMMARY

Figure 20 presents a final flow diagram of factors that effect dewatering. As can be noted particle size was indeed a very important factor in dewatering. From this figure one can observe that many other of the once felt factors that effect dewatering do so only by first affecting particle size. However, to say that dewatering is now a simplified problem for the plant operator could be a gross overstatement, because the plant operator must deal with all these factors accordingly.

Particle size, however, does give the plant operator a valuable tool if he chooses to use it. For example, if there are problems with dewatering within a plant the operator could monitor particle size and likewise alter operational procedures that might effect particle size, until the desired results occur. As for MCRT controlling the dewatering process no evidence could be found to indicate that there is an optimum MCRT value with respect to dewatering. However, it was shown in the laboratory reactors that particle size distribution shifts did result by changing the MCRT value of the reactor. Thus, like all the other factors that effect particle size the plant operator can also vary MCRT or F:M ratio to attempt to obtain a particle size distribution that will yield optimal dewatering rates.

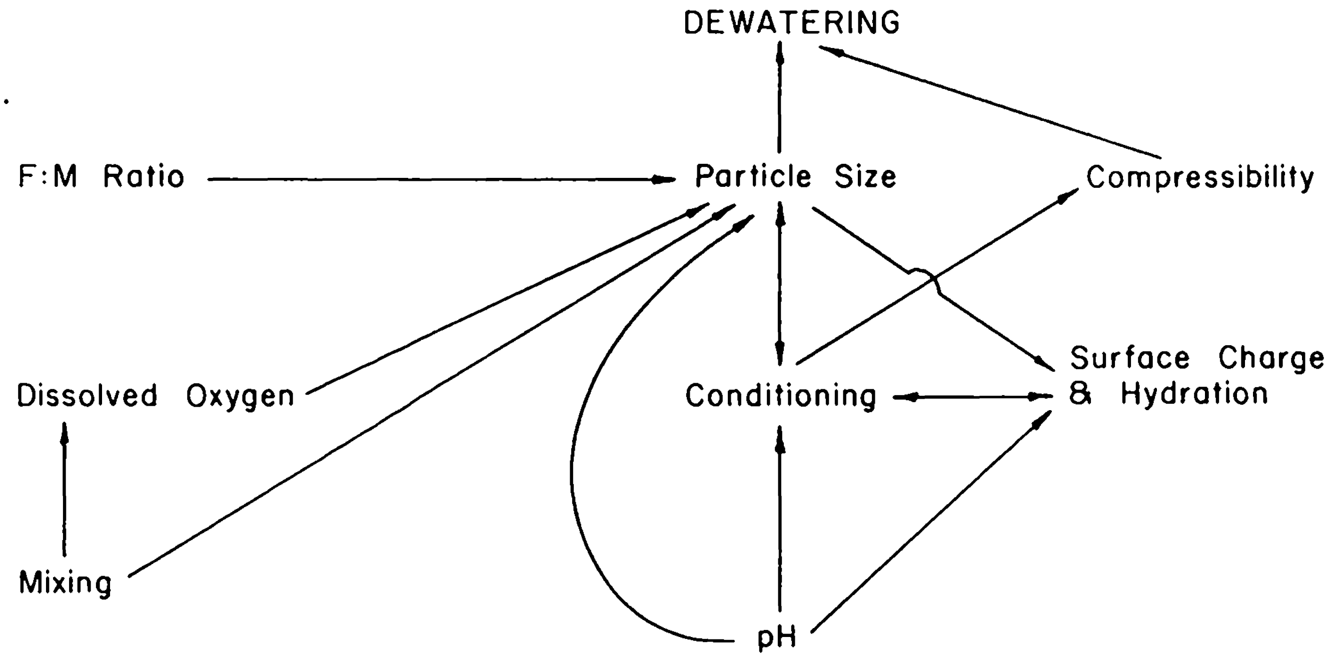

Figure 20. Some Factors and Interrelationships Affecting Dewatering

VI. CONCLUSIONS

In examining the data presented in the previous chapters and in Appendix B it became apparent that dewatering was affected in many ways. During experimental procedure and as a result of several malfunctions the importance of these effects upon dewatering were revealed. From these data the following conclusions were made:

1. Relationships between specific resistance and MCRT for the full-scale plant could not be effectively evaluated, since most of this data corresponded to extended aeration treatment in which MCRT values were exceptionally high and variable. Likewise, trend comparisons between the full-scale plant and laboratory reactors could not be effectively evaluated.
2. Laboratory reactors yielded a significant decrease in dewatering resistance in moving from a four day MCRT to an eight day MCRT value.
3. Particle size was the most important factor in dewatering biological sludges, and it was affected by conditioner dosages and extended periods of anaerobiosis. Varying MCRT or F:M ratio also affected particle size in the laboratory reactors
4. Extended periods of low dissolved oxygen and discontinous mixing had adverse effects upon dewatering.
5. Conditioner requirements were shown to be dependent

upon sludge particle size.

6. Sludge compressibility was not significantly affected by MCRT.

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APPENDIX A: Useful Equations

Table A-1: Useful Equations

1. $$\text{MCRT (days)} = \frac{XV}{XV_w + X_e(Q - V_w)}$$

2. $$\text{F:M (mg COD/mg MLVSS-day)} = \frac{QS_i}{XV}$$

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

4. $$w\ (\text{kg/m}^3) = \frac{C_k(C_f - C_i)}{C_i - C_k}(10)$$

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

6. Polymer addition example: to obtain a polymer concentration of approximately 5 mg/l in a final volume of two liters of sludge-polymer mixture, using a stock polymer concentration of approximately 1000 mg/l.

   i. VC = VC (V = Volume, C = Concentration)
   2000 ml (5 mg/1000 ml) = "x" (1000 mg/1000 ml)
   "x" = 10 ml of stock polymer needed

   ii. Therefore, 10 ml of stock polymer solution was added to 1990 ml of sludge to yield a final volume of two liters with a polymer concentration of 5 mg/l.

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_f = solids concentration (% by weight) of filtrate resulting from vacuum filtration test

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

F:M = food to microorganism mass ratio

MCRT = mean cell residence time

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 or plant (liters/day, or MGD)

r = specific resistance of a sludge

S_i = influent COD concentration (mg/l)

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 the reactor, or of the plant aeration basin (liters, or MG)

V_w = volume of activated sludge wasted daily from the system (liters, or MG)

Table A-2: Summary of Variables Used (cont.)

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

X = MLVSS of the reactor, or of the plant aeration basin (mg/l)

X_e = MLVSS of the reactor effluent, and of the secondary clarifier effluent (mg/l)

Table A-3: Moving Average Computer Program

```
DIMENSION DO(176),DOA(176)
REAL DO, DOA
READ, N, PHI
READ, (DO(I),I=1,N)
DO 2 I=1,N
DOA(I)=(1.-PHI)*DO(I)
DO 3 J=1,100
K=I-J
IF(K.LT.1) GO TO 2
FACTOR=PHI**J
IF(FACTOR.LT.0.001) GO TO 2
DOA(I)=DOA(I)+DO(I-J)*FACTOR*(1.-PHI)
3 CONTINUE
2 PRINT,I,DO(I),DOA(I)
PRINT,PHI
STOP
END
```

Note: This program was adapted to the WATFIV fortran language by Dr. W. R. Knocke from the work presented by Berthouex and Hunter (20).

APPENDIX B: Recorded and Calculated Data

Table B-1: Synthetic Reactor Data

Steady-State #	Influent COD (mg/l)	Effluent COD (mg/l)	Percent COD Removal	MLVSS (mg/l)	MCRT (days)	F:M (days^{-1})	Resistance (m/kgx10^{11})
Steady-State #1	226	28	88	1610	14.3	0.421	5.91
	246	28	89	1880	14.7	0.393	2.74
	230	20	91	1880	15.0	0.367	2.76
	230	24	90	1860	15.3	0.371	3.60
	234	20	91	1910	15.3	0.368	2.28
average			89.8		14.9	0.384	3.46
Steady-State #2	202	24	88	1880	12.2	0.322	2.56
	254	32	87	2100	13.7	0.363	3.07
	230	32	86	2080	12.8	0.332	3.46
	242	28	88	2220	12.2	0.327	-
	246	32	87	1950	12.9	0.378	1.90
	238	32	87	1760	10.7	0.406	3.50
	238	32	87	1990	12.9	0.359	2.49
	266	32	88	-	-	-	3.13
	258	24	91	2290	12.8	0.338	2.76
	238	24	90	2180	12.1	0.328	1.85
average			87.9		12.2	0.349	2.75
Steady-State #3	234	24	90	-	-	-	-
	238	24	90	1540	8.5	0.464	3.83
	238	31	87	1660	8.5	0.430	10.10
	247	27	89	1480	8.2	0.501	4.80
	239	43	82	1610	8.0	0.445	5.91
	239	47	80	1530	8.2	0.469	5.62
	223	26	88	1500	7.8	0.446	5.64
	235	18	92	1460	7.1	0.483	5.26

Table B-1: Synthetic Reactor Data (cont.)

Steady-State #	Influent COD (mg/l)	Effluent COD (mg/l)	Percent COD Removal	MLVSS (mg/l)	MCRT (days)	F:M ($days^{-1}$)	Resistance ($m/kg x 10^{11}$)
	263	30	89	1400	7.6	0.564	9.89
	242	30	88	1460	8.0	0.497	6.73
average			87.5		8.0	0.478	6.42
Steady-State #4	-	-	-	830	4.5	-	27.4
	161	20	88	810	4.0	0.596	33.5
	-	-	-	770	4.1	-	40.1
	188	20	89	890	4.4	0.634	27.8
	-	-	-	860	4.1	-	34.0
	227	35	85	790	4.3	0.862	32.9
average			87.3		4.2	0.697	32.6

Note: F:M ratio was measured as mg/l of influent COD per mg/l of MLVSS-day.

Table B-2: Primary Reactor Data

Steady-State #	Influent COD (mg/l)	Effluent COD (mg/l)	Percent COD Removal	MLVSS (mg/l)	MCRT (days)	F:M ($days^{-1}$)	Resistance ($m/kg \times 10^{11}$)
Steady-State #1	120	28	77	1780	14.7	0.202	53.8
	144	24	83	1800	14.8	0.240	53.8
	104	20	81	1680	14.5	0.186	41.5
	128	32	75	1730	14.5	0.222	-
	171	28	84	1690	14.5	0.304	28.4
	111	24	78	1950	14.1	0.171	34.7
average			79.7		14.5	0.221	42.4
Steady-State #2	142	34	76	1240	10.6	0.344	24.0
	202	34	83	1290	11.2	0.470	25.3
	186	34	82	1280	9.6	0.436	21.5
	218	36	83	1280	11.2	0.511	25.1
	151	24	84	1330	11.3	0.341	*
	214	32	85	1220	8.3	0.526	*
	170	32	82	1310	11.0	0.389	*
	139	24	83	1300	12.8	0.320	26.8
	218	36	83	1300	-	0.508	29.9
average			82.3		10.6	0.427	25.4
Steady-State #3	-	-	-	1110	7.9	-	15.8
	178	32	82	1050	8.5	0.509	27.7
	-	-	-	1120	8.1	-	-
	230	32	86	1000	8.4	0.690	32.9
	-	-	-	-	-	-	22.7
	253	32	87	970	7.2	0.782	28.1
	-	-	-	1000	8.9	-	21.5
	253	50	80	1180	7.7	0.643	20.9

Table B-2: Primary Reactor Data (cont.)

Steady-State #	Influent COD (mg/l)	Effluent COD (mg/l)	Percent COD Removal	MLVSS (mg/l)	MCRT (days)	F:M ($days^{-1}$)	Resistance ($m/kg \times 10^{11}$)
	-	-	-	1180	8.4	-	20.4
	202	65	68	1190	9.3	0.509	24.4
average			80.6		8.3	0.627	23.8
Steady-	-	-	-	610	3.5	-	64.6
State #4	184	47	74	820	3.9	0.673	106.1
	-	-	-	710	3.5	-	84.7
	133	47	65	690	3.7	0.655	79.7
	-	-	-	590	4.2	-	-
	212	67	68	730	3.7	0.871	45.7
	-	-	-	580	3.7	-	78.8
	145	51	67	780	3.5	0.558	49.7
average			68.5		3.7	0.689	72.8

Note: F:M ratio was measured as mg/l of influent COD per mg/l of MLVSS-day.

*- indicates days when purple photosynthetic bacteria appeared to interfere with the dewatering results. This problem was corrected by eliminating the culture by covering the reactor with an opaque cover for several days.

Table B-3: Full Scale Plant Data

MLVSS (mg/l)	Waste MLVSS (mg/l)	Effluent Suspended Solids (mg/l)	Specific Resistance: Aeration Basin Sludge (m/kgx10^11)	Specific Resistance: Waste Activated Sludge (m/kgx10^11)	Dissolved Oxygen (mg/l)	MCRT* (days)	F:M* Ratio (1/days)
1000	3000	13	-	-	-	15.1	0.142
940	3590	35	-	-	-	8.6	0.120
1190	3140	25	-	-	-	19.7	0.107
1280	2510	14	-	-	-	20.2	0.110
1475	2800	13	-	-	-	27.1	0.086
1280	3100	18	-	-	-	22.9	0.061
1245	3650	17	-	-	-	34.8	0.032
970	3190	4	53.3	-	-	37.7	0.070
840	1790	17	-	-	-	29.2	0.097
970	2590	14	-	-	-	35.2	0.038
900	1700	4	-	-	-	51.1	0.073
875	2610	17	-	-	-	49.0	-
845	2310	19	24.3	-	-	25.7	0.046
790	1040	10	-	-	-	96.3	0.074
790	1820	8	-	-	-	105.1	0.164
750	1060	9	37.8	-	-	87.9	0.083
745	1620	10	-	-	-	80.3	0.062
825	1780	10	-	-	-	85.7	0.030
905	2760	6	30.5	-	-	149.9	-
910	2210	6	-	-	-	154.8	0.075
975	2590	11	25.0	-	-	93.5	0.091
1085	2340	8	-	-	-	135.4	0.050
1160	3290	7	-	-	-	163.4	0.068
1165	2360	5	20.0	-	-	229.3	0.106
1175	3210	3	-	-	-	375.1	0.054

Table B-3: Full Scale Plant Data (cont.)

MLVSS (mg/l)	Waste MLVSS (mg/l)	Effluent Suspended Solids (mg/l)	Specific Resistance: Aeration Basin Sludge (m/kgx10[11])	Specific Resistance: Waste Activated Sludge (m/kgx10[11])	Dissolved Oxygen (mg/l)	MCRT* (days)	F:M* Ratio (1/days)
1190	3180	15	-	38.9	-	75.1	0.068
1360	2570	3	-	-	-	471.7	0.067
1345	2750	23	-	-	-	67.8	0.039
1330	3250	14	65.9	-	-	115.4	0.042
1360	2850	11	-	-	-	144.5	-
1390	2690	14	-	60.9	5.9	96.2	0.048
1355	3200	11	-	-	5.9	133.7	0.002
1385	4410	11	-	-	5.7	143.7	0.012
1430	4160	12	43.1	58.3	6.2	151.8	0.051
1490	2730	12	-	-	5.9	128.3	0.044
1495	3450	11	56.6	-	5.9	146.5	0.042
1420	3070	15	-	-	5.6	101.6	0.052
1415	-	7	-	74.2	6.0	179.5	0.033
1555	-	5	42.1	-	5.9	354.1	0.041
1335	-	5	-	-	6.9	58.2	0.037
1385	-	6	-	-	6.1	99.0	0.031
1350	-	6	-	-	6.1	73.2	0.026
1330	3170	6	29.7	29.5	5.5	121.9	0.041
1260	3720	8	-	-	5.4	88.9	0.047
1185	4160	6	-	-	5.9	86.3	0.014
1370	3750	11	24.9	-	5.3	56.5	0.028
1295	3780	17	-	30.7	6.1	56.4	0.031
1275	2680	3	-	-	5.5	173.6	-
1280	2960	6	-	-	4.2	105.7	0.079
1280	3550	8	-	-	4.9	119.3	-

Table B-3: Full Scale Plant Data (cont.)

MLVSS (mg/l)	Waste MLVSS (mg/l)	Effluent Suspended Solids (mg/l)	Specific Resistance: Aeration Basin Sludge ($m/kg \times 10^{11}$)	Specific Resistance: Waste Activated Sludge ($m/kg \times 10^{11}$)	Dissolved Oxygen (mg/l)	MCRT* (days)	F:M* Ratio (1/days)
1425	2450	8	-	-	4.9	218.3	0.035
1630	4740	5	-	-	5.6	387.1	0.046
1735	5280	11	29.0	-	7.9	263.4	-
1700	3490	9	-	40.8	6.1	257.1	0.032
1720	2920	6	-	-	5.5	400.9	0.035
1670	2940	14	-	-	6.2	177.4	0.036
1620	3880	22	-	-	4.5	65.8	0.041
1690	3430	8	-	-	5.1	23.1	0.077
1745	3740	3	39.8	-	6.2	61.5	0.057
1520	3380	12	-	-	-	36.9	0.102
1520	3130	6	-	-	-	36.1	0.101
1365	3940	7	-	33.2	6.5	70.3	0.107
1465	2250	9	-	-	7.2	46.2	0.138
1345	4370	9	15.7	23.8	2.1	44.8	0.145
1220	2330	5	-	-	5.2	63.5	0.155
1025	2620	11	-	-	4.3	60.1	0.197
960	2490	9	-	-	6.1	38.3	0.297
1025	1290	7	24.4	-	5.4	58.8	0.398
1250	2280	6	-	-	5.9	213.7	0.104
1345	2570	5	-	-	6.0	324.3	0.078
1265	2900	1	-	-	5.5	1152.1	0.137
1315	3700	8	-	31.7	5.7	155.1	0.140
1305	2610	6	14.7	-	5.0	215.5	0.181
1275	2010	8	-	-	6.2	158.6	0.142
1595	3090	10	-	-	5.8	160.1	0.097

Table B-3: Full Scale Plant Data (cont.)

MLVSS (mg/l)	Waste MLVSS (mg/l)	Effluent Suspended Solids (mg/l)	Specific Resistance: Aeration Basin Sludge (m/kgx10^{11})	Specific Resistance: Waste Activated Sludge (m/kgx10^{11})	Dissolved Oxygen (mg/l)	MCRT* (days)	F:M* Ratio (1/days)
1565	3160	10	-	-	5.9	174.2	0.075
1630	2730	10	-	-	6.0	194.5	0.065
1565	4140	6	14.3	-	5.2	253.9	0.108
1535	3250	8	-	-	5.3	188.0	0.101
1550	2860	7	34.3	-	5.9	221.6	0.121
1445	3360	7	-	21.5	5.5	267.2	0.079
1505	4350	3	-	-	5.2	725.6	0.061
1550	2390	6	-	-	5.9	388.1	0.064
1600	3140	9	-	-	5.1	265.5	0.069
1630	3800	10	25.7	-	5.0	245.3	0.061
1555	3000	5	-	27.4	5.0	540.1	0.054
1580	3280	6	12.7	-	5.5	385.7	0.072
1705	3610	3	-	-	4.9	871.7	0.066
1740	3550	9	-	-	5.5	271.4	0.068
1845	3010	7	23.6	-	6.1	397.6	0.067
1855	2930	6	-	21.5	6.2	447.5	0.066
1855	4650	7	-	-	5.4	367.5	0.036
1840	3960	20	-	-	5.4	69.7	0.109
1800	4600	9	-	-	5.4	162.6	0.093
1660	2870	5	-	-	5.5	275.1	0.122
1640	2600	9	-	-	5.7	114.2	0.098
1750	2750	4	-	-	5.9	490.8	0.086
1890	2820	14	31.8	-	6.4	156.7	0.075
1900	3060	9	-	-	6.6	229.4	0.058
1880	3430	3	-	40.8	6.2	639.4	0.047

Table B-3: Full Scale Plant Data (cont.)

MLVSS (mg/l)	Waste MLVSS (mg/l)	Effluent Suspended Solids (mg/l)	Specific Resistance: Aeration Basin Sludge ($m/kg \times 10^{11}$)	Specific Resistance: Waste Activated Sludge ($m/kg \times 10^{11}$)	Dissolved Oxygen (mg/l)	MCRT* (days)	F:M* Ratio (1/days)
1830	2770	8	-	-	6.9	229.2	0.092
1910	3610	16	50.2	-	6.9	58.3	0.111
1890	2620	18	-	33.6	6.3	30.2	-
1910	3260	8	-	-	6.4	55.7	-
1915	2445	10	-	-	6.3	44.8	-
2005	3080	7	-	-	5.7	91.0	-
2125	3080	16	-	-	6.7	49.6	-
1770	3250	9	-	37.5	6.2	50.4	0.131
1900	3000	4	32.5	-	6.7	66.5	0.096
1890	3120	2	-	-	6.7	78.2	0.114
1870	2930	2	31.4	-	8.0	91.7	0.131
1945	3050	23	-	-	8.0	29.0	0.131
1860	3370	34	-	-	7.1	21.0	0.130
1985	3510	17	-	-	6.0	30.0	0.154
1960	3780	11	-	-	4.7	26.0	0.178
1955	3160	9	-	-	2.5	35.0	0.178
1970	3750	4	29.5	-	4.4	73.3	0.177
2165	3200	9	-	-	3.7	26.5	0.188
2230	4790	14	-	27.9	4.4	35.8	0.199
2110	3180	8	-	-	3.0	38.5	0.172
2095	4090	14	-	-	2.5	27.8	0.143
2195	4750	15	-	-	2.6	46.6	0.173
2140	4100	30	-	-	3.6	17.7	0.173
2060	5050	2	17.8	28.8	1.2	44.6	0.201
2320	4130	4	-	-	4.2	47.5	0.177

Table B-3: Full Scale Plant Data (cont.)

MLVSS (mg/l)	Waste MLVSS (mg/l)	Effluent Suspended Solids (mg/l)	Specific Resistance: Aeration Basin Sludge (m/kgx10^11)	Specific Resistance: Waste Activated Sludge (m/kgx10^11)	Dissolved Oxygen (mg/l)	MCRT* (days)	F:M* Ratio (1/days)
2320	4510	8	-	-	5.0	81.4	0.152
2150	5160	22	-	-	0.6	18.0	0.151
2005	5700	14	34.4	-	2.4	33.5	0.150
2120	5530	16	-	-	1.6	27.9	0.122
2155	4660	4	-	42.0	2.6	39.6	0.094
2220	4590	5	-	-	5.6	27.2	-
2430	4100	8	-	-	4.0	34.4	-
2315	4100	2	-	-	6.3	35.5	0.144
2125	4770	4	33.6	-	4.1	37.1	-
2125	4530	22	-	-	3.3	20.1	0.117
2100	5320	9	-	35.6	5.4	19.0	-
2045	4700	3	31.7	-	4.4	32.3	0.068
2070	5630	5	-	-	4.7	36.9	-
2370	4200	3	-	-	3.9	26.7	0.220
2350	4420	4	-	-	5.2	58.0	-
2210	6800	16	-	-	5.2	22.5	-
2065	5060	8	-	47.3	5.7	25.9	0.105
2105	5690	7	-	-	4.0	18.1	0.094
2150	4840	3	40.2	-	3.6	25.2	0.084
2095	4160	20	39.8	-	3.6	14.3	0.185
2175	4910	10	-	-	4.1	22.5	-
2255	-	30	-	-	-	17.4	-
1995	5960	18	-	-	4.7	14.5	0.272
1765	6650	4	-	63.6	3.3	14.1	-
2105	5210	4	40.7	-	2.2	14.6	0.142

Table B-3: Full Scale Plant Data (cont.)

MLVSS (mg/l)	Waste MLVSS (mg/l)	Effluent Suspended Solids (mg/l)	Specific Resistance (m/kgx10^{11}): Aeration Basin Sludge	Specific Resistance (m/kgx10^{11}): Waste Activated Sludge	Dissolved Oxygen (mg/l)	MCRT* (days)	F:M* Ratio (1/days)
1935	5440	4	-	-	4.9	32.3	-
1885	5790	5	-	-	6.2	34.6	0.126
2250	6150	27	-	-	7.0	16.4	-
2935	5530	10	-	-	6.3	133.6	0.103
2725	4030	6	-	-	4.0	26.5	-
2250	5820	1	40.3	-	5.9	41.6	-
2640	4230	2	-	-	3.3	37.3	0.129
2575	4560	1	-	43.1	2.0	40.6	-
2555	4980	2	37.3	-	2.0	35.7	0.097
2945	4180	5	-	-	5.6	38.6	-
2815	4690	5	-	-	7.1	40.1	-
2855	6000	3	-	-	5.6	32.3	0.046
2850	5740	6	-	-	4.5	26.5	-
2780	3870	8	-	-	4.9	26.3	0.118
2685	4860	6	37.3	-	5.2	26.1	-
2860	4460	5	-	52.6	3.5	36.6	0.093
2750	4780	8	-	-	2.5	37.3	-
2860	4170	8	-	-	6.0	35.8	0.076
2820	3920	10	-	-	1.9	27.6	-
2755	3000	6	-	-	0.2	33.4	0.102
2910	4900	7	43.3	58.9	5.1	21.0	-

* - Note: These MCRT values and F:M ratios are before any "phi" factor was applied.

Table B-4: Particle Count Data (Synthetic Reactor)
Percent of Total Surface Area

Channel											
1	2	3	4	5	6	7	8	9	10	11	12
Steady-State #1											
1. Specific Resistance = 5.91×10^{11} m/kg; SGM											
0.68	0.53	0.33	0.80	1.75	3.04	4.27	8.09	8.78	10.46	10.44	50.83
2. Specific Resistance = 2.74×10^{11} m/kg; SGM											
1.47	0.99	0.58	0.62	0.88	1.42	2.32	4.93	5.11	8.01	9.01	64.67
3. Specific Resistance = 2.76×10^{11} m/kg; SGM											
1.33	0.59	0.37	0.59	0.65	1.87	1.83	4.24	5.10	7.91	10.52	64.99

Note: Each channel corresponded to a specified size range category (see the particle size section of the Methods and Materials chapter for details). The plots in the Results and Discussion chapter were made using the geometric mean diameter for each channel. For this study two ranges of geometric means were employed: 1) for the 10 micron incremented counts; and 2) for the 20 micron incremented counts. The smaller size range was designated as "SGM" and the larger as "LGM". The following are the respective geometric means for the above mentioned ranges.

SGM:	8.7	19.4	29.6	39.7	49.8	59.8	69.8	79.8	89.9	99.9	109.9	185.7
LGM:	11.2	33.5	54.1	74.3	94.6	114.6	134.6	154.7	174.7	194.7	214.8	259.8

It is important to note that particle counts with different geometric means cannot be compared.

Table B-4: Particle Count Data (Synthetic Reactor)
Percent of Total Surface Area (cont.)

Channel											
1	2	3	4	5	6	7	8	9	10	11	12
4. Specific Resistance = 3.60×10^{11} m/kg; SGM											
0.47	0.42	0.38	0.62	0.69	1.32	2.52	4.48	5.30	8.94	9.21	65.64
5. Specific Resistance = 2.28×10^{11} m/kg; SGM											
0.74	0.48	0.30	0.53	0.74	1.91	1.95	5.09	6.46	7.98	9.25	64.57
Steady-State #2											
6. Specific Resistance = 2.56×10^{11} m/kg; SGM											
0.82	0.82	0.41	0.53	0.81	0.77	0.98	1.50	2.08	3.33	4.28	83.67
7. Specific Resistance = 3.07×10^{11} m/kg; SGM											
0.87	0.80	0.34	0.37	0.68	0.66	1.23	1.18	2.82	3.85	7.80	79.37
8. Specific Resistance = 3.46×10^{11} m/kg; SGM											
0.73	0.89	0.62	0.59	0.68	0.68	0.90	1.70	2.70	4.91	6.50	79.11
9. Specific Resistance = 1.90×10^{11} m/kg; LGM											
2.83	3.35	2.78	2.66	2.69	3.01	5.67	8.65	8.82	10.50	10.00	39.02
10. Specific Resistance = 3.50×10^{11} m/kg; LGM											
8.23	2.50	1.91	3.39	7.89	11.96	17.23	16.95	14.62	6.39	5.29	3.64

Table B-4: Particle Count Data (Synthetic Reactor)
Percent of Total Surface Area (cont.)

Channel 1	2	3	4	5	6	7	8	9	10	11	12
11. Specific Resistance = 2.49×10^{11} m/kg; LGM											
4.78	1.72	1.07	2.51	7.15	12.37	19.85	19.78	14.47	7.53	4.43	4.32
12. Specific Resistance = 3.13×10^{11} m/kg; LGM											
4.01	2.06	1.46	3.40	8.29	12.88	21.80	22.75	13.15	7.32	1.37	1.50
13. Specific Resistance = 2.76×10^{11} m/kg; LGM											
0.83	0.29	0.45	1.24	3.28	7.98	14.68	19.66	19.91	13.51	7.79	10.38
14. Specific Resistance = 1.85×10^{11} m/kg; LGM											
1.43	0.83	1.23	4.14	7.49	16.41	23.03	21.24	13.04	6.02	3.29	1.85
Steady-State #3											
15. Specific Resistance = 3.83×10^{11} m/kg; LGM											
2.36	0.80	0.39	0.73	1.27	3.12	5.32	7.75	12.98	21.50	19.16	24.61
16. Specific Resistance = 10.10×10^{11} m/kg; LGM											
7.42	2.63	1.29	1.98	2.07	3.04	5.93	8.03	14.38	19.07	15.84	18.33
17. Specific Resistance = 4.80×10^{11} m/kg; LGM											
4.94	1.47	0.87	1.38	1.80	2.43	5.51	8.06	10.28	17.51	16.05	29.71

Table B-4: Particle Count Data (Synthetic Reactor)
Percent of Total Surface Area (cont.)

Channel 1	2	3	4	5	6	7	8	9	10	11	12
18. Specific Resistance = 5.91×10^{11} m/kg; LGM											
4.05	2.02	1.63	2.44	2.45	2.90	4.58	7.06	12.86	19.96	19.44	20.61
19. Specific Resistance = 5.62×10^{11} m/kg; LGM											
4.25	1.50	2.25	3.27	2.58	4.26	4.34	9.11	17.00	1.60	19.84	29.98
20. Specific Resistance = 5.64×10^{11} m/kg; LGM											
2.50	1.17	2.26	2.67	2.47	3.87	5.50	6.39	13.21	15.18	18.05	26.72
21. Specific Resistance = 9.89×10^{11} m/kg; LGM											
3.44	1.31	1.33	1.61	2.17	1.60	4.11	4.65	10.38	11.97	17.56	39.89
22. Specific Resistance = 6.73×10^{11} m/kg; LGM											
1.71	1.18	2.32	2.90	3.72	3.13	4.76	6.17	11.20	12.60	16.48	33.82
Steady-State #4											
23. Specific Resistance = 27.4×10^{11} m/kg; LGM											
4.24	2.87	6.71	9.14	8.92	8.50	9.65	10.25	9.87	10.46	3.95	15.42
24. Specific Resistance = 33.5×10^{11} m/kg; LGM											
5.68	3.24	6.96	10.94	11.59	10.79	12.54	9.32	8.45	6.89	7.18	6.42

Table B-4: Particle Count Data (Synthetic Reactor)
Percent of Total Surface Area (cont.)

Channel											
1	2	3	4	5	6	7	8	9	10	11	12
25. Specific Resistance = 40.1×10^{11} m/kg; LGM											
4.99	2.72	6.54	11.45	13.76	12.21	11.54	8.71	8.53	7.14	5.40	7.02
26. Specific Resistance = 27.8×10^{11} m/kg; LGM											
4.93	5.20	7.40	14.85	15.54	13.46	9.67	7.92	6.52	5.26	4.93	4.32
27. Specific Resistance = 34.0×10^{11} m/kg; LGM											
2.61	3.58	5.78	9.64	14.78	13.96	12.38	9.99	8.80	5.75	4.55	8.20
28. Specific Resistance = 32.9×10^{11} m/kg; LGM											
2.33	2.98	8.09	10.80	15.03	14.45	11.42	11.25	7.46	5.70	4.77	5.71

Table B-5: Particle Count Data (Primary Reactor)
Percent of Total Surface Area

Channel 1	2	3	4	5	6	7	8	9	10	11	12
Steady-State #1											
1. Specific Resistance = 53.8×10^{11} m/kg; SGM											
23.27	10.66	12.72	12.72	5.95	3.51	2.56	3.06	5.17	3.42	2.76	14.19
2. Specific Resistance = 41.5×10^{11} m/kg; LGM											
2.59	9.70	18.41	18.22	10.08	6.03	4.69	4.96	6.43	6.15	3.66	9.09
3. Specific Resistance = 28.4×10^{11} m/kg; LGM											
2.28	4.21	4.72	6.59	7.55	11.24	8.60	10.32	8.36	5.70	5.40	25.04
4. Specific Resistance = 34.7×10^{11} m/kg; LGM											
4.31	6.22	12.19	15.24	10.69	7.63	6.14	6.96	5.07	6.56	5.43	13.55
Steady-State #2											
5. Specific Resistance = 24.0×10^{11} m/kg; LGM											
2.73	4.94	7.01	11.22	16.22	16.73	14.50	9.00	7.22	4.75	1.93	3.76
6. Specific Resistance = 25.3×10^{11} m/kg; LGM											
4.38	4.77	6.64	10.21	14.42	15.86	15.35	10.31	6.29	4.61	4.32	2.84
7. Specific Resistance = 21.5×10^{11} m/kg; LGM											
2.75	4.12	6.41	10.36	15.46	15.34	14.13	10.90	8.12	4.62	2.91	4.87

Table B-5: Particle Count Data (Primary Reactor)
Percent of Total Surface Area (cont.)

Channel 1	2	3	4	5	6	7	8	9	10	11	12
8. Specific Resistance = 25.1×10^{11} m/kg; LGM											
3.15	3.65	4.65	8.45	13.40	13.78	15.90	11.15	9.88	6.88	3.17	5.96
9. Specific Resistance = 38.1×10^{11} m/kg; LGM *											
2.77	4.58	5.49	9.35	11.95	15.67	15.35	10.01	8.77	5.10	3.36	7.61
10. Specific Resistance = 34.7×10^{11} m/kg; LGM *											
3.25	7.75	8.33	9.91	11.52	13.82	11.37	10.18	10.44	3.83	4.86	4.74
11. Specific Resistance = 26.8×10^{11} m/kg; LGM											
2.87	7.79	8.48	9.80	12.20	12.80	12.57	12.04	7.92	7.03	2.20	4.29
12. Specific Resistance = 29.9×10^{11} m/kg; LGM											
3.08	7.17	6.49	8.48	10.46	12.33	10.82	10.40	9.00	8.53	6.44	6.81
Steady-State #3											
13. Specific Resistance = 15.8×10^{11} m/kg; LGM											
2.95	3.17	3.88	5.35	8.29	9.53	9.35	10.69	12.99	9.26	9.01	15.54
14. Specific Resistance = 27.7×10^{11} m/kg; LGM											
4.60	3.65	3.72	5.06	6.23	8.58	8.79	10.43	12.09	11.82	7.31	17.71

* - indicates particle counts performed when the purple bugs were present

Table B-5: Particle Count Data (Primary Reactor)
Percent of Total Surface Area (cont.)

Channel											
1	2	3	4	5	6	7	8	9	10	11	12
15. Specific Resistance = 32.9×10^{11} m/kg; LGM											
14.18	2.50	1.84	3.04	5.23	7.22	7.34	11.77	9.72	5.48	10.68	21.00
16. Specific Resistance = 22.7×10^{11} m/kg; LGM											
5.37	3.34	3.09	4.72	4.18	7.80	8.07	12.44	12.24	12.11	9.60	17.04
17. Specific Resistance = 28.1×10^{11} m/kg; LGM											
3.13	3.14	3.21	3.64	5.29	5.57	7.35	9.71	12.12	10.99	10.29	25.59
18. Specific Resistance = 21.5×10^{11} m/kg; LGM											
2.59	2.38	1.83	2.66	4.18	5.84	6.58	8.12	11.96	11.96	11.25	30.64
19. Specific Resistance = 20.9×10^{11} m/kg; LGM											
4.42	3.86	2.68	3.39	5.24	4.30	7.42	5.88	14.59	11.39	10.08	26.73
20. Specific Resistance = 20.4×10^{11} m/kg; LGM											
2.63	3.84	2.86	2.82	4.51	5.69	6.45	8.05	10.47	11.53	10.15	31.01
21. Specific Resistance = 24.4×10^{11} m/kg; LGM											
3.94	1.96	2.38	2.52	1.45	2.57	5.90	4.29	4.96	10.49	9.01	50.54

Table B-5: Particle Count Data (Primary Reactor)
Percent of Total Surface Area (cont.)

Channel											
1	2	3	4	5	6	7	8	9	10	11	12
Steady-State #4 *											
22. Specific Resistance = 106.1×10^{11} m/kg; LGM											
5.64	2.98	3.21	5.05	7.89	2.80	3.87	2.19	5.58	10.41	11.26	39.11
23. Specific Resistance = 84.7×10^{11} m/kg; LGM											
10.15	5.04	4.47	4.46	7.22	3.54	1.63	4.30	5.48	10.21	4.14	39.38
24. Specific Resistance = 79.7×10^{11} m/kg; LGM											
6.50	4.55	5.74	3.49	4.45	8.73	8.43	4.77	4.06	5.04	6.13	38.12
25. Specific Resistance = 45.7×10^{11} m/kg; LGM											
17.44	10.27	9.83	12.10	9.57	5.11	7.06	4.66	4.46	1.85	4.49	13.15

* - During steady-state #4 the larger geometric mean diameter range was used in order that these particle counts could be compared to the other steady-state coumts. However, the smaller diameter range would have been more appropriate, because there was very few particles in the larger diameter ranges. As a result a great fluctuation is present in the above percent of total surface area values.

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THE EFFECT OF MEAN CELL RESIDENCE TIME ON THE DEWATERING CHARACTERISTICS OF A BIOLOGICAL SLUDGE

by

Terry L. Zentkovich

(ABSTRACT)

The effect that mean cell residence time (MCRT) had on the dewaterability of biological sludges was examined in this study. Aeration basin sludge and waste activated sludge from a full scale domestic wastewater treatment facility, in addition to sludges produced from two laboratory scale reactors fed with a synthetic substrate and a primary effluent-dog food mixture, respectively, were used to perform dewatering tests. The sludges were evaluated at various MCRT values for optimal dewatering resistances, optimal conditioning requirements, and optimal compressibility conditions. Specific resistance determinations were made using a Buchner funnel apparatus to evaluate all of the above mentioned parameters. Also particle size analyses were performed on all sludges to investigate how particle size affected dewatering resistance and conditioner requirements, and also to investigate how MCRT affected particle size. All particle size determinations were made using a HIAC PC-320, twelve channel particle size analyzer.

Results from the study revealed that plants can operate under extended aeration and still maintain good sludge dewatering characteristics. Likewise, by varying MCRT shifts in particle size distribution and corresponding changes in dewatering resistance were noted in the laboratory reactors. However, no optimum MCRT with respect to dewatering could be founded. Particle size proved to be the most important parameter affecting dewatering, and it was affected by conditioning, periods of anaerobiosis, and MCRT in the laboratory reactors.