EFFECT OF MEAN CELL RESIDENCE TIME
ON THE
ACID HYDROLYTIC ASSIST ACTIVATED SLUDGE PROCESS

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

Disposal of residual solids is one of the major problems in wastewater treatment. Increasingly strict environmental regulations have resulted in the development of improved treatment methods. Paradoxically, an increase in sludge production results from improved wastewater treatment. Sludge production is expected to reach approximately ten million metric tons per year by 1990(1). Decreasing quantities of available land and strict environmental regulations are limiting the alternatives available for ultimate disposal of sludges.

Quantities and characteristics of wastewater sludges are functions of treatment methods and operating procedures utilized. Types of sludge resulting from sewage treatment can be categorized according to source. Volume reduction through thickening and dewatering is an important aspect of sludge handling and disposal. Biological sludges are usually the most difficult to thicken and dewater; consequently, they represent the most significant problems encountered in sludge management.

Activated sludge treatment of wastewater is probably the most common method of biological treatment utilized. There are many modifications of the activated sludge process and waste sludge production is related to the type of activated sludge system used. In general, the quantity of excess sludge produced is a function of the biological solids residence time in the system, or the mean cell residence time. Mean cell residence time can be used as the primary control parameter in the operation of an activated sludge treatment process.

An inverse relationship exists between mean cell residence time and the specific growth rate of biological organisms. Accordingly, operation of an activated sludge process at higher mean cell residence times takes advantage of lower specific growth rates. Minimization of the specific growth rate also limits sludge production. Therefore, operation of an activated sludge process at higher mean cell residence times results in an overall decrease in the quantity of sludge produced relative to that which would be produced at a lower mean cell residence time.

The extended aeration activated sludge process is a modification of the activated sludge process which incorporates high mean cell residence times to limit excess sludge production. Conceptually, an extended aeration system might be operated without intentional sludge wasting so mean cell residence time would be determined by natural biological attrition and inadvertent loss of biomass from the system due to carry over as suspended solids from the clarification process. Internal control of biomass concentrations would be provided by the process of cellular autodigestion. Steady-state biomass concentrations would occur when the biological growth rate was balanced by the rate of autodigestion and loss of biomass as suspended solids. In practice, a gradual deterioration in sludge settleability occurs if sludge is not wasted periodically for control purposes.

An engineering solution to the problem of solids control in the extended aeration process was proposed by Gaudy, *et al.* (2). After extensive studies of extended aeration, these researchers attempted to provide operational control through chemical hydrolysis of waste sludge so that biological solids could be removed for control purposes, but returned to the process as a soluble substrate. This type of biological treatment is referred to as the hydrolytic assist activated sludge process. Hydrolysis of excess sludge allows the process to approach a level of total oxidation. Under conditions of total oxidation, no net biomass production would occur and the substrate would be converted totally to simple by-products such as carbon dioxide, ammonia and nitrate-nitrogen, and water.

Hydrolysis may be achieved under acid or base conditions. The process of acid hydrolysis would involve pH adjustment to 1.0 or less followed by heat treatment to solubilize cellular material. After neutralization to pH 7.0, the hydrolyzed sludge could be recycled through the treatment process. Base hydrolysis would be a similar process except the pH would be adjusted to 13.0 or higher. Ideally, there would be no residual biological solids to dispose of.

The purpose of this research was to analyze the acid hydrolytic assist activated sludge process and obtain information on biomass production, kinetic characteristics, and nitrification at various mean cell residence times. The objectives of this study were to:

1. Evaluate the effect of mean cell residence time on the hydrolytic assist activated sludge process.
2. Quantitatively compare biomass production for the conventional and hydrolytic assist activated sludge processes over a range of mean cell residence times.
3. Determine kinetic constants for the conventional and hydrolytic assist activated sludge processes.
4. Observe the relative effect of hydrolysis on nitrification.

Mathematical and stoichiometric models of the hydrolytic assist activated sludge process at various mean cell residence times were utilized in this study. Laboratory investigations were conducted to obtain operational data for comparison to the modeling results. A bench-scale treatment process was operated as both a conventional and a hydrolytic assist activated sludge process through a range of mean cell residence times to allow determination and comparison of kinetic parameters.

CHAPTER 2. LITERATURE REVIEW

To accomplish the study objectives, as listed in the Introduction, a thorough literature review was conducted to avoid duplication with other studies and to enhance the experimental design of this study. An attempt was made to relate the kinetics of biological treatment to the hydrolytic assist process. No information was found in the literature pertaining to the effect of mean cell residence time on the chemically assisted activated sludge process.

BIOLOGICAL KINETICS AND TOTAL OXIDATION

Mean cell residence time, θ_c, was utilized by Lawrence and McCarty (3) in developing kinetic equations for design and operation of biological wastewater treatment systems. The following mathematical relationship describes θ_c (4):

$$\theta_c = \frac{(X)_T}{(dX/dt)_T} \qquad (1)$$

Where $(X)_T$ = Total mass of viable microorganisms in the system, and

$(dX/dt)_T$ = Total mass of viable microorganisms removed from the system per unit time.

The important relationship between mean cell residence time and specific growth rate, u, can be recognized by examining the mathematical definition of specific growth rate, as shown below:

$$\mu = \frac{(dX/dt)_g}{X} \qquad (2)$$

Where $(dX/dt)_g$ is the total mass of viable microorganisms appearing in the system per unit time as a result of biological growth.

Equation (2) shows that specific growth rate is the rate of growth of biomass per unit quantity of biomass in the system whereas mean cell residence time is the ratio of a unit quantity of biomass to the unit rate of disappearance of biomass from the system.

The inversely proportional relationship between mean cell residence time and specific growth rate is important in the design and operation of biological treatment systems to minimize excess sludge production. Benefield and Randall (4) presented the following equation expressing the rate of biological growth at steady-state:

$$\frac{1}{\theta_c} = \frac{Y_T\ (ds/dt)_u}{X} - k_d \qquad (3)$$

Where Y_T = Yield coefficient representing the quantity of biomass produced per unit quantity of substrate removed,

$\frac{(ds/dt)_u}{X}$ = Rate of substrate removal per unit quantity of biomass, and

k_d = Biological decay coefficient in dimensions of inverse time.

In Equation (3), sludge production is related to the yield term. In order to minimize sludge production, the system must be designed to minimize the specific growth rate so biomass production can be nearly balanced by biomass decay. This is the basis for the extended aeration activated sludge process where very high mean cell residence times are utilized. Theoretically, as the mean cell residence time approaches infinity, the specific growth rate approaches zero and there would be no excess sludge production. Therefore, from a conceptual point of view, the extended aeration process could be operated without sludge wasting.

Highly efficient internal solids control would be required in an extended aeration activated sludge process to prevent ever increasing accumulations of biomass. Gaudy and Gaudy reported on studies of the extended aeration process and the concept of total oxidation (5). Previous studies had reached three general conclusions. Symmons and McKinney (6); according to Gaudy and Gaudy (5), concluded in 1958 that some components synthesized by cells were not biodegradable and a biological treatment system based on total oxidation would ultimately fail due to an accumulation of metabolically inactive components. Busch and Myrick (7) concluded in 1960; according to a discussion in Gaudy and Gaudy (5), that an extended aeration process could never attain steady-state conditions. Busch and Myrick did not believe that biological growth could be balanced by microbial decay and, therefore, biomass would accumulate until it began leaving the system as suspended solids. Other research discussed by Gaudy and Gaudy (5) included the investigations of Kountz and Fourney (8) who concluded in 1959 that periodic sludge wasting from an extended aeration process would be required since a residual inert fraction would build up in the system.

Kountz and Fourney (8) concluded that a large inert fraction would adversely affect process performance.

An extensive study of the extended aeration process by Gaudy, _et al_. (9) tested the validity of the total oxidation concept. The primary goal of this study was to determine how long a biological treatment system could be operated with the return of all biological solids to the aeration tank before biochemical failure would occur as a result of accumulation of biologically inert material. This experiment was designed for positive retention of solids. The effluent from a laboratory scale reactor was centrifuged to capture any solids inadvertently passing through the clarification process. The investigators estimated that no more than 0.2 percent of the total solids in the system were removed as a result of analytical procedures. The bench scale reactor used in this study was fed a synthetic substrate with glucose as a carbon source. Data obtained during approximately two years of operation by Gaudy _et al_. (9) and continued studies by Gaudy _et al_. (2) indicated that there was no significant accumulation of inert material which could cause biochemical failure.

Results of these studies by Gaudy and co-workers (2,9) contradicted previous theoretical conclusions about extended aeration as were presented by Gaudy and Gaudy (5). Sludge in the system did not increase continuously but followed a cyclic pattern of periodic increases in biomass followed by periods of decreasing biological solids concentration. Throughout the studies organic removal efficiencies (as COD) remained at or above ninety percent. Gaudy et al. (9) felt that solids accumulation was controled internally by mechanisms associated with natural biological processes.

According to Gaudy, et al. (9), internal control of biological solids build-up in the extended aeration process is a complex process consisting of the following mechanisms:

a.) Autolysis by individual species,

b.) Lysis of individual cells by enzymes of other cells,

c.) Bacteriophage infection resulting in cell lysis, and

d.) Natural predation of individual species by higher organisms.

Thus, control of accumulation of biological solids would be a result of the behavior of heterogeneous microbial populations existing in a complex ecosystem.

The conclusions presented by Gaudy et al. (9) indicate that the concept of steady-state biomass concentrations for extended aeration activated sludge systems must be considered from a different perspective. The concept of steady-state for the extended aeration process cannot be defined as a static level of biomass concentration. Instead, there are many factors involved which result in a dynamic biological system where species predominance is continually shifting as a result of changing environmental stresses. This shifting predominance would exhibit a dynamic steady-state situation as reflected by the cyclic patterns in biological solids accumulation reported by Gaudy and co-workers (2,9).

In addition to continued operation of the bench scale unit with positive solids retention, Gaudy _et al_. (2) performed experiments to evaluate the possibility of inert material from one microorganism serving as a source of food for another microorganism. The three major cellular fractions considered in the investigation were the slime layer of encapsulated cells, the nonsoluble shell or sac, and the internal cellular organic material. The results of this study indicated that total oxidation of an individual microorganism would require a series of preparatory metabolic steps allowing the cell to serve as a food source for other microorganisms. The researchers theorized that these metabolic steps represented the critical mechanisms in the process of total oxidation and felt that operational control of the extended aeration process could be improved if these critical steps could be induced artificially.

THE HYDROLYTIC ASSIST EXTENDED AERATION PROCESS

Gaudy _et al_. (2) theorized that the key to operational control of the extended aeration activated sludge process involved control of periods of solids accumulation which preceded the deterioration of sludge settleability. As an engineering solution to this problem, the researchers proposed the use of chemical hydrolysis of waste sludge withdrawn for control purposes. They developed a modification of the extended aeration process which could minimize sludge disposal problems through a process of chemically enhanced biological treatment. Figure 1 is a schematic representation of the hydrolytic assist acti-

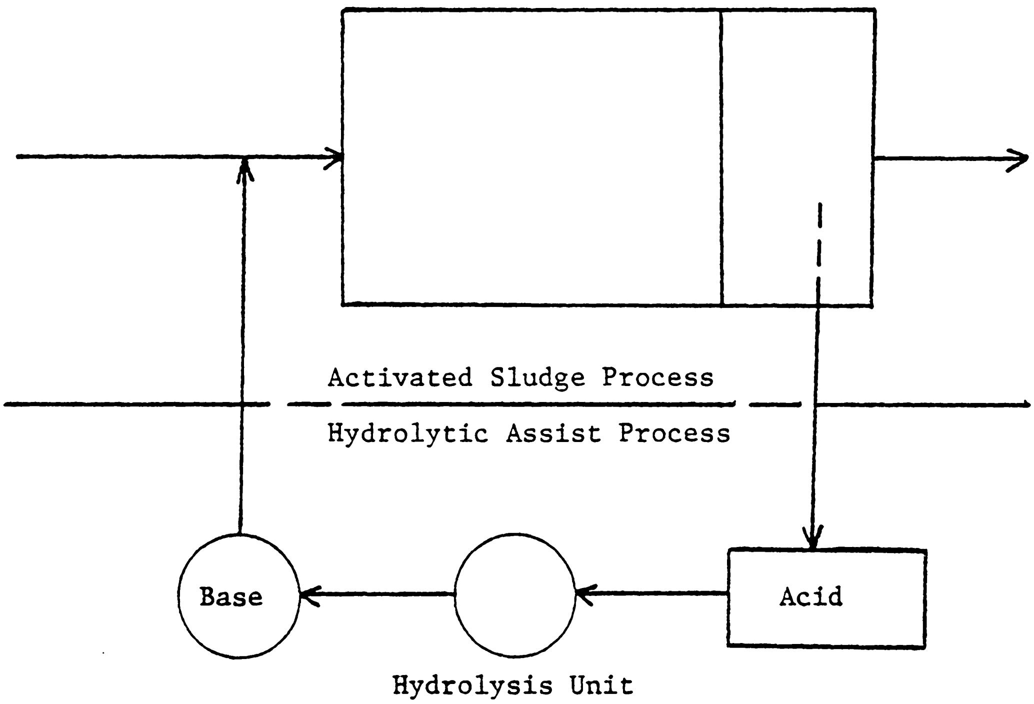

Figure 1. Schematic representation of the Hydrolytic Assist Activated Sludge Process, after Gaudy, *et al*. (2).

vated sludge process which was proposed by Gaudy et al. (2). Two possible modes of operation are periodic withdrawal and hydrolysis of sludge for control purposes or continuous hydrolysis and recirculation of solubilized sludge. Treatment of nutrient deficient wastes could be enhanced through hydrolysate recycle reducing the need for nitrogen or phosphorus addition.

An investigation of the effect of long term operation of the hydrolytic assist activated sludge process on treatment efficiency was conducted and the results were reported by Gaudy (10). In this study, a laboratory scale treatment unit was operated with positive solids retention and tested under shock loading conditions after almost three years of operation. The investigators found that the system's ability to purify waste had not decreased as a result of prolonged operation without intentional solids removal. Studies performed later by Gaudy et al. (11) evaluated the performance of the hydrolytic assist activated sludge process with high substrate concentrations as would be encountered in treating many industrial wastewaters. The results showed that the process was capable of 96% organic removal efficiency at concentrations up to 2000 mg/l as COD.

Although there were concerns that inert material would accumulate and cause biochemical failure of the process, Gaudy (10) reported that this did not happen. Specifically, extracellular polysaccharides were expected to contribute to the increase of the inert fraction. Experimental results indicated, however, that the protein and carbohydrate content of the sludge after prolonged operation was similar to that of a normal healthy microbial population. Further experiments by Gaudy (10) involved the removal of five different extracellular polysaccharides from cells grown in pure cultures in order to test their suitability as substrate material. When these five extra cellular polysaccharides were utilized as the sole carbon source for an activated sludge, all were readily removed after a period of acclimation.

Results of a bench scale study of the hydrolytic assist extended aeration process were reported by Yang and Gaudy (12). This research was aimed at developing hydrolysis procedures and techniques utilizing hydrolysis as an operational control mechanism. Based on previous observations of periodicity and theories regarding the process of autodigestion (5, 9, 10, 11), Yang and Gaudy (12) chose a range within which the mixed liquor suspended solids concentration was to be maintained. The idea was to enhance the autodigestive process by using hydrolysis to induce the difficult metabolic processes whenever the biomass concentration approached the upper limit chosen.

The method of hydrolysis utilized by Yang and Gaudy (12) involved adjustment of the waste sludge pH to 1.0 and the temperature to 121°C. The hydrolysate was then neutralized before return to the treatment system. Experiments were conducted to study the effect of acid concentration on the degree of solubilization. The results indicated that 75 to 80 percent solubilization was attained regardless of the acid concentration. Sulfuric acid was used instead of hydrochloric acid to avoid interference from the chloride ion in the COD test.

The pilot study by Yang and Gaudy (12) showed that the periodicity of solids accumulation and decline could be controlled through the use of chemical hydrolysis. According to the reported data of this pilot plant study, chemical hydrolysis had a dampening affect on the fluctuating solids concentrations allowing the mixed liquor suspended solids concentration to be maintained within a range of 3000 to 5000 mg/l. Similar success in controlling biomass concentrations was reported by Yang and Chen (13) in laboratory studies of biological treatment of a soluble organic industrial waste incorporating chemical hydrolysis of waste sludge.

Experiments by Yang and Gaudy (12) indicated that sludge hydrolysate was readily metabolized by freshly cultured cells following a lag period. Such a lag period would not be evident in an activated sludge system with a highly complex and concentrated microbial population. Yang and Gaudy (12) compared the hydrolysate of older cells to hydrolysate prepared from younger cells and found that a slightly higher residual COD results from biological treatment of a wastewater which included older cell hydrolysate. Throughout this investigation the data indicated a variation in the influent COD of 45 mg/l to 100 mg/l resulting from the hydrolysate recycle. This study involved a synthetic substrate utilizing glucose as a carbon source at a concentration of 300 mg/l as COD.

Most of the research pertaining to the chemically assisted extended aeration process involved highly soluble substrates. To evaluate the effect of an inert fraction on the hydrolytic assist activated sludge process, Gaudy et al. (14) investigated the performance of the process in treating a waste with a high ash content. Secondary sludge from a municipal wastewater treatment plant utilizing trickling filter biological treatment was hydrolyzed and used as a stock solution for preparing wastewater to be treated in a bench scale activated sludge process. The bench scale process was operated with periodic hydrolysis of waste sludge. The substrate prepared in this study had a high organic concentration as well as a high ash content. The process was tested with influent organic concentrations of 500 mg/l and 1000 mg/l as COD. The ash content of the sludge averaged 49 percent at the lower organic concentration and 55 percent at the higher concentration. Results of treatment of both organic concentrations indicated that the ash content did not increase continually but reached limiting values. The ash content did not affect COD removal efficiency and the process produced a highly nitrified effluent.

Increases in total solids concentrations in the effluent were reported by Gaudy et al. (14) in treating a high ash content wastewater with the hydrolytic assist activated sludge process. These increases in total solids were attributed to high concentrations of dissolved inorganic solids corresponding to the release of inorganic solids by the biomass. Since the higher total dissolved solids could result in a need for further treatment, Gaudy et al. (14) performed some tests which indicated ion exchange treatment would work well in reducing the effluent total dissolved solids concentration. The researchers pointed out that some forms of tertiary treatment normally provided for other reasons would successfully reduce dissolved solids at no extra capital cost.

Deterioration in sludge settleability is associated with the extended aeration process. Gaudy *et al*. (14) reported improved settleability following hydrolysis of a high ash content sludge. The researchers did report some problems with rising sludge during the early portions of their studies, but found that overall, higher concentrations of biomass could be sustained in the process without the usual settleability problems.

The only information found in this review of the literature pertaining to the evaluation of kinetic constants for the hydrolytic assist activated sludge process was included in an article by Yang and Chen (13). As mentioned earlier, this research involved the use of the hydrolytic assist process in treating a soluble organic industrial wastewater. Kinetic constants were determined during the first six days of operation (without hydrolysis) and during days 79 through 85 when portions of recycle sludge were hydrolyzed prior to recycle. The method of evaluating the constants was not clear and the data indicate a variation in biomass concentration of 1000 mg/l during both evaluation periods. The effluent COD concentrations, however, were constant during both evaluation intervals.

Since the yield coefficient during hydrolysis was 75 percent lower than it was without hydrolysis, Yang and Chen (13) concluded that a 75 percent reduction in sludge production was achieved by sludge hydrolysis. Similarly, the researchers attribute a 64.5 percent reduction in maximum specific growth rate and a 65.6 percent reduction in decay rate to the use of hydrolysis. These conclusions are misleading since the sludge age had increased greatly between the first and second evaluation periods. The reduction in the specific growth rate coincides with the increased sludge age. Any reduction in sludge production within the system would be due primarily to an increased sludge age rather than a result of partial hydrolysis of recycle sludge. Naturally, the net sludge production from the process would be reduced since the waste sludge was recycled to the system after hydrolysis.

Hydrolysis has been used primarily as a biological solids control mechanism for the extended aeration activated sludge process. Apparently there has been no research involving the effect of mean cell residence time on the hydrolytic assist activated sludge process. The research by Yang and Chen (13) represents the only information found pertaining to treatment kinetics for the hydrolytic assist activated sludge process.

APPLICATIONS OF SLUDGE HYDROLYSIS

A modification of the aerobic digestion process incorporating sludge hydrolysis was studied by Singh and Patterson (15). Waste activated sludge was partially solubilized by chemical hydrolysis prior to aerobic digestion in an effort to improve the digestion rate. In addition to acid hydrolysis incorporating heat treatment, other hydrolysis methods such as sonication and heat treatment alone were tested and found to work successfully. The researchers found that solubilization would not be significantly improved by prolonged heat treatment. Acid hydrolysis and heat treatment were used in this study and solids reductions of 60 to 70 percent were achieved by hydrolysis prior to digestion.

At food to microorganism ratios of 0.30 to 1.05 milligrams of COD per milligram of volatile solids, approximately a 40 percent reduction in volatile suspended solids was achieved by chemically assisted digestion at solids retention times of 2, 3 and 4 days. A conventional digester operated at a 4 day mean cell residence time only obtained a 16 percent reduction in volatile suspended solids. Singh and Patterson (15) reported that the overall reduction achieved in digestion of solubilized sludge was actually less than the solids reduction by hydrolysis alone. The authors did not report the volatile solids content of the hydrolyzed sludge so complete evaluation of the effect on volatile solids reduction is not possible. An increase in volatile solids was reported during digestion in parts of the study. This increase in volatile solids was probably a result of biological substrate utilization since hydrolysis would result in elevated levels of soluble COD. When operated at lower food to microorganism ratios

(0.15 to 0.20) the digestion of hydrolyzed sludge resulted in the same overall reduction in volatile solids obtained by hydrolysis alone with the added benefit of soluble COD reduction.

Although the results of research by Singh and Patterson (15) indicate a reduction in required detention time through the use of hydrolysis, the process would be expensive. Also, the return of hydrolyzed sludge to activated sludge processes operated at higher mean cell residence times would negate the need for sludge digestion. Return of hydrolysate to conventional activated sludge plants operated at lower mean cell residence times would result in high influent organic concentrations which would have to be accounted for in design. Activated sludge processes operated at higher mean cell residence times would be better suited for treating high organic concentrations resulting from hydrolysate recycle. Chemically assisted biological sludge digestion could be a viable method for reducing aerobic digester volume requirements if, as indicated by Singh and Patterson, acceptable volatile solids reduction can be achieved at lower detention times. Chemically assisted aerobic digestion would be used in conventional activated sludge plants and fixed-film media biological treatment plants where hydrolysate return would not be a viable alternative. Singh and Patterson (15) performed a cost analysis in 1974 and found the cost for this process to be very high. However, increasing quantities of sludge and climbing costs of sludge handling and disposal could make this a cost effective alternative some day.

The use of hydrolysis on waste activated sludge from pulp mill wastewater treatment was investigated by Lee et al. (16). Bleached kraft whole mill wastes are acidic and require neutralization prior to biological treatment. For this reason, Lee et al. (16) investigated alkaline hydrolysis since the resulting hydrolysate could be used in the neutralization of the acidic influent. Heated chemical digesters were utilized in this bench scale study. The digestors were operated in excess of pH 12 at various temperatures but optimum performance was obtained at 70°C with 70 to 80 percent solubilization reported. These researchers found that the hydrolysate was stable and pH changes would not result in precipitation.

Lee et al. (16) reported improved settleability when the hydrolytic assist process was used but noted a decrease in compactibility of the sludge towards the end of 36 days of continuous operation. The authors attributed improved settleability to enhancement of the coagulation process by solubilized protein and polysaccharides. A gradual increase in mixed liquor suspended solids was attributed solely to an accumulation of inert indigestible material, but data were not presented to verify that theory. At least part of the increase in mixed liquor suspended solids can be explained by an increase in volatile solids resulting from biological utilization of increased soluble organic material. This could not be verified by the data but seems to be a logical conclusion.

Because of concerns over the effect of hydrolysis on nitrification, Yang and Gaudy (12) conducted analyses to evaluate the nitrifying characteristics of the hydrolytic assist activated sludge process. The authors report that there would be no adverse effects and the process would be capable of producing a highly nitrified effluent. Also, the nitrifying characteristics were found to be independent of organic loading as the process was tested at high and low organic loadings.

Positive retention of biological solids in the hydrolytic assist activated sludge process combined with solubilization of biomass creates conditions of nutrient recycle. Lee *et al*. (16) found that 0.06 to 0.08 milligrams of nitrogen (measured as total Kjeldahl nitrogen) would be released during hydrolysis for each milligram of sludge treated. Similarly, they reported that 0.01 milligrams of phosphate (as phosphorus) would be released for each milligram of sludge hydrolyzed. The condition of nutrient recycle was also emphasized by Gaudy *et al*. (11) as well as Yang and Gaudy (12). Thus, the hydrolytic assist activated sludge process might be very beneficial for treating nutrient deficient wastewaters. The possible savings in chemical costs for nutrient addition would help balance the costs associated with the hydrolytic assist process.

Cost estimates for the hydrolytic assist acitvated sludge process were reported by Lee *et al*. (16) for the treatment of pulp mill wastewater. The authors found that the cost would not be prohibitive when compared to the cost of sludge disposal. None of the other researchers reported specific information on cost estimates. The possible savings in sludge disposal costs along with the reduction in required nutrient addition are important benefits of the hydrolysis process which must be considered in any analysis. In addition to equipment and chemical costs for hydrolysis, additional aeration requirements would increase the cost of hydrolysis as was pointed out by Lee *et al.* (13).

SUMMARY

Previous research indicates that the hydrolytic assist activated sludge process is a technically feasible method of minimizing waste sludge production. Chemical hydrolysis is a method of artificially inducing the difficult metabolic steps leading to cellular autodigestion. Past studies have focused on the use of hydrolyis with the extended aeration activated sludge process. For this reason, the effect of mean cell residence time on the hydrolytic assist activated sludge process has not been evaluated. Although an accumulation of inert material has been associated with the hydrolytic assist process, a review of previous investigations indicates that the process is not susceptible to biochemical failure as a result of a build-up of indigestible material. As may be concluded from the above discussion, there is a need to evaluate the effect of mean cell residence time on the hydrolytic assist process. Also, further information on the kinetics of wastewater treatment with the hydrolytic assist activated sludge process will be needed for future design considerations.

CHAPTER 3. MATERIALS AND METHODS

Evaluation of the effect of mean cell residence time (θ_c) on a hydrolytic assist activated sludge process involved a two phase study. Mathematical relationships were utilized to model the hydrolytic assist acitvated sludge process in an effort to predict actual operational results. Laboratory studies of a bench-scale biological reactor were then conducted to evaluate kinetic constants and compare the actual results to the predicted results.

BIOKINETIC EQUATIONS

Kinetic equations used in this portion of the research were developed by Lawrence and McCarty (3) to express microbial growth and substrate utilization. Procedures presented by Sherrard (17, 18) were utilized to develop stoichiometric equations.

Figure 1 presented in the Literature Review, represents schematically the hypothetical treatment process modeled. To model the process, the following assumptions were made:

a.) Complete mixing would be provided in the aeration basin,

b.) Steady-State conditions would prevail,

c.) Under Steady-State conditions, the influent substrate concentration would be constant,

d.) No microbial solids would be present in the influent,

e.) No microbial activity would take place in the secondary clarifier, f.) There would be no sludge accumulation in the secondary clarifer and it would exhibit a high degree of solids capture efficiency,

g.) The substrate was considered to be completely soluble; casein ($C_8H_{12}N_2O_3$) was used due to the availability of values for kinetic constants as reported by Sherrard (18),

h.) Nitrification would be inhibited,

i.) Wastewater treatment kinetics would be unaffected by hydrolysate recycle, and

j.) Mean cell residence time would remain constant in the transition from the conventional process to the hydrolytic assist activated sludge process.

Mean cell residence time was used as the main process control variable and was defined as:

$$\theta_c = \frac{VX}{Q_w X_r + Q_{eff} X_{eff}} \tag{4}$$

where

θ_c = mean cell residence time, days,

V = aeration tank volume, liters,

X = aeration tank mixed liquor suspended solids, mg/l,

X_r = return sludge microbial solids concentration, mg/l,

X_{eff} = effluent microbial solids concentration, mg/l,

Q_w = waste sludge flow rate, l/day, and

Q_{eff} = effluent flow rate, l/day.

Effluent substrate concentration was determined from the relationship:

$$S_1 = \frac{K_s(1 + k_d\theta_c)}{\theta_c\ (Y_{max}k - k_d) - 1} \tag{5}$$

where

S_1 = effluent substrate concentration, mg/l COD,

K_s = saturation constant (substrate concentration at 50% maximum utilization rate), mg/l COD,

k_d = biomass decay coefficient, days^{-1},

Y_{max} = maximum biomass yield coefficient, mg VSS/mg COD, and

k = maximum rate of substrate utilization per unit weight of biomass, days^{-1}.

Aeration tank biomass concentration was calculated from:

$$X = \frac{Ymax\ (S_o - S_1)\ \theta_c}{1 + k_d\theta_c\theta} \tag{6}$$

where

S_o = influent substrate concentration, mg/l COD, and

θ = hydraulic detention time, days.

Waste sludge production was determined from:

$$P_x = \frac{8.34\ Y_{max}\ Q(S_o\text{-}S_1)}{1 + k_d\theta_c} \tag{7}$$

where

P_x = waste sludge production per unit time, lb/day), and

Q = influent flow rate, l/day.

Y_{obs}, a variable yield coefficient used in quantifying process reactions was defined by:

$$Y_{obs} = \frac{Y_{max}}{1 + k_d\theta_c} \qquad (8)$$

To use biokinetic equations in modeling the hydrolytic assist activated sludge process, it was necessary to quantify the effect of the hydrolysate return on the process. For this reason, waste sludge was considered to be completely solubilized by hydrolysis. Hydrolysate was expressed in terms of additional influent substrate concentration expressed as chemical oxygen demand.

Theoretical oxidation of sludge was described by the following equation (19):

$$C_5H_7NO_2 + 5O_2 \longrightarrow 5CO_2 + 2H_2O + NH_3 \qquad (9)$$

showing that, theoretically, 5 moles of oxygen would be required for each mole of sludge oxidized, or 1.42 pounds of oxygen per pound of sludge. The theoretical quantity of additional chemical oxygen demand (COD) in the hydrolysate was then determined from the following equation:

$$S_r = \frac{1.42\ P_x}{8.34\ Q} \qquad (10)$$

where S_r represented the organic concentration of the hydrolysate return flow expressed as COD.

The actual substrate concentration applied to the aeration tank during hydrolysis, $\overline{S}_o$, was found by adding the theoretical influent substrate concentration of 184 mg/l casein (S_o = 256 mg/l COD) to the theoretical COD of the hydrolysate return flow.

Mathematical modeling using the previously described biokinetic equations was performed at θ_c values of 3, 10, 15 and 25 days. Additional data used in the modeling process, including values for biokinetic coefficients, are presented in Table I. Iterative calculations using the preceding equations were conducted until steady-state results were obtained. Steady-state was assumed to have been achieved when the net increase in biomass concentration over a previous day had decreased to one percent of the previous value.

STOICHIOMETRIC EQUATIONS

Information obtained from the biokinetic equations was used to develop stoichiometric equations describing the biochemical relationships of the treatment process in each mode. To simplify calculations, the equations were formulated under the assumption that nitrification would be inhibited. While this may not be a realistic assumption, the results would give relative relationships useful in comparing the hydrolytic assist activated sludge process to the conventional activated sludge process. Recycling of cellular nitrogen and the increase in ammonia-nitrogen would indicate favorable conditions for nitrification. This aspect of the hydrolytic assist process was emphasized by Gaudy (10).

The following general stoichiometric equation was used to describe

Table I. Data for Biokinetic and Stoichiometric Equations

Q = 10 MGD

S_o = 256 mg/l COD

V = 2.5 Million Gallons

Y_{max} = 0.50 mg VSS/mg COD

k_d = 0.08 Day^{-1}

k = 6.00 Day^{-1}

the biochemical reaction in the aeration tank for the treatment of casein:

$$x_oC_8H_{12}N_2O_3 + x_1O_2 \longrightarrow y_oC_5H_7O_2N + y_1C_8H_{12}N_2O_3 + y_2NH_3 + y_3CO_2 + y_4H_2O \qquad (11)$$

y_o, the molar coefficient of biomass in the stoichiometric equation was determined from the following relationship, as reported by Sherrard and Schroeder (17):

$$y_o = \frac{Y_{obs}\ (\text{COD utilized})}{\text{molecular weight of the biomass}} \qquad (12)$$

After determining y_o, the balanced stoichiometric equation was determined for each θ_c.

To represent the overall total oxidation of the substrate, it was necessary to assume that excess biomass produced would undergo complete oxidation to carbon dioxide, ammonia, and water as follows:

$$y_oC_5H_7O_2N + x_2O_2 \longrightarrow y_2NH_3 + y_3CO_2 + y_4H_2O \qquad (13)$$

This equation was then combined with the original stoichiometric equation for the conventional mode to obtain a balanced equation representing total oxidation of substrate at each θ_c.

LABORATORY INVESTIGATION

Laboratory studies were initiated to obtain actual operational results for comparison of the hydrolytic assist activated sludge process to the conventional process. In addition to observing variation in biomass production, data were collected over a range of θ_c values to allow calculation of biokinetic constants and to observe the effect of hydrolysis on nitrification.

Biological Reactor

A bench-scale biological reactor was used in the laboratory investigation. The 9.27 liter plexiglass reactor unit had an adjustable baffle which could be removed completely for maintenance purposes. An effluent port consisting of a rubber stopper with a 0.25 inch diameter glass tube approximately 2.0 inches long through its center was connected to a 42 inch length of rubber tubing for gravity discharge of the effluent. Two 18 liter carboys were used for influent and effluent reservoirs. The reactor was operated as a continuous-flow, completely mixed unit. The adjustable baffle provided clarification and internal sludge recirculation. Mixing and aeration was provided by utilizing the laboratory compressed air supply line. The air was fed through a 0.12 inch diameter rubber tube with an air stone attached to the end submerged in the aeration basin. The air flow was not metered and was found to vary greatly from day to day based on visual observations. Air flow was continually adjusted to maintain mixing without creating excess turbulence which would result in loss of mixed liquor over the sides of the reactor. Figure 2 is a schematic representation of the experimental treatment system.

Wastewater Pumping

A Calgon Model 8 chemical feed pump was used to provide a constant

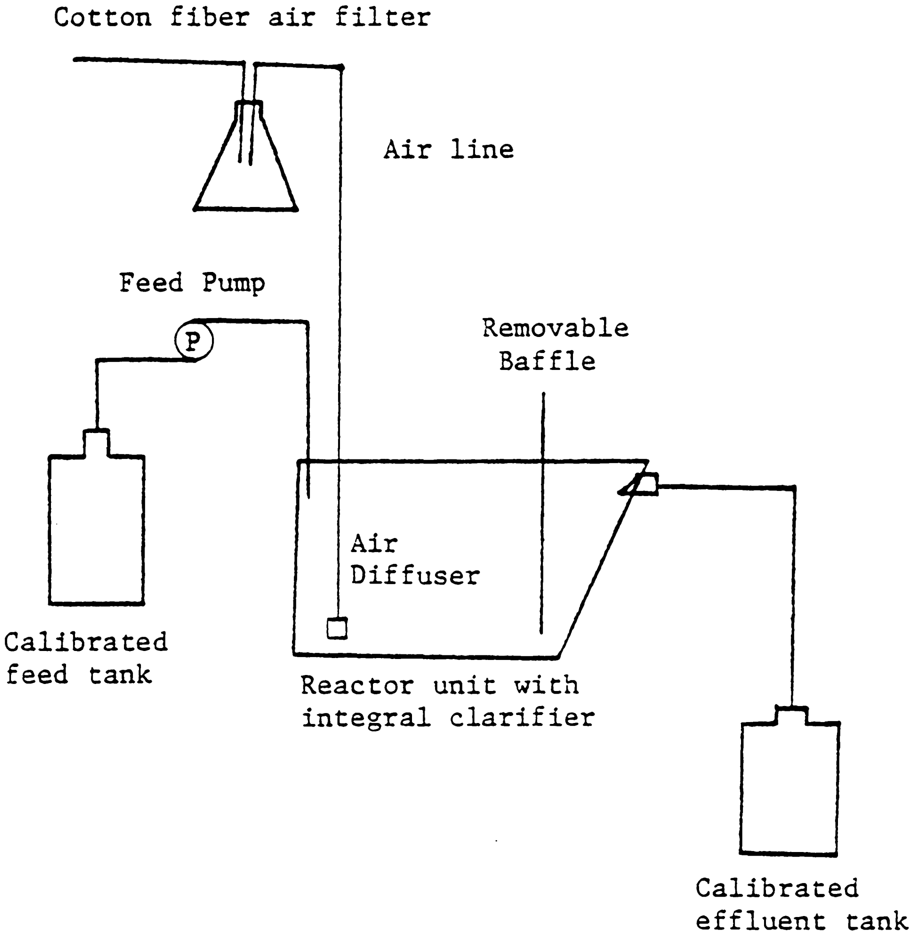

Figure 2. Diagram of bench-scale treatment unit.

influent flow rate to the reactor. The pump was a positive displacement type diaphragm pump which was capable of metering flows of 0.05 gallons per hour to 1.0 gallons per hour at a maximum pressure of 75 pounds per square inch. The flow rate was adjusted to provide a flow of 14 liters per day for the experimental studies. The pump was calibrated and adjusted as needed to maintain a constant flow rate throughout the study.

Wastewater Composition

A soluble, synthetic wastewater consisting of Bactopeptone and the necessary inorganic nutrients was used in the study. A phosphate buffer solution provided buffer capacity and served as a phosphorus source. Ammonium sulfate was utilized as a source of nitrogen. Excess nutrients were provided so carbon would be the limiting nutrient. Table II provides a list of the components used in the wastewater. The daily quantities of the stock solutions were mixed together and diluted to 16 liters with tap water. During hydrolysis, the hydrolysate was added and the mixture was diluted to 16 liters plus an equivalent volume of water to account for the hydrolysate. The influent wastewater had a COD of approximately 400 mg/l and an ammonia concentration of approximately 113 mg/l as nitrogen before the addition of the hydrolysate.

Daily Operating Procedures

The influent reservoir, pump, and influent tubing were chlorinated every 48 hours. On alternate days, the lines were flushed with tap

Table II. Components of Synthetic Wastewater for Laboratory Investigation

Parameter	Concentration, mg/l
Bacto-Peptone*	352.7
M_gSO_4 7 H_2O	50.0
M_nSO_4 H_2O	5.0
F_eCl_3 $6H_2O$	0.6
$CaCl_2$	3.8
NH_4 - N	113.0
KH_2PO_4	698.8
K_2HOP_4	1431.1

*COD = 400 mg/l

water. A solution of tap water and commercial bleach was used for disinfection. The effluent discharge tubing and reservoir were also cleaned periodically. Following chlorination, thorough rinsing was provided to remove all chlorine from the system before putting it back in operation.

While the reactor feed appurtenances were being cleaned each day, the effluent tube was clamped and the baffle was removed. The baffle and the reactor sidewalls were scraped to remove and re-suspend any biomass adhering to the plexiglass. After scraping and mixing, sludge wasting was accomplished using a dipper and a graduated cylinder. The sludge wasting rate was based on the desired θ_c and the average effluent solids concentration. The sludge wasting rate was held constant at each θ_c even though the effluent solids concentration varied.

Sample Collection

Daily samples of the influent and the effluent were collected to be analyzed for COD and nitrate-nitrogen. The samples were preserved with concentrated sulfuric acid and refrigerated at four degrees centigrade in plastic sample bottles. Alkalinity, pH and solids analyses were performed on the day collected and did not require preservation. As a result of equipment limitations, organic and ammonia-nitrogen determinations were not possible. Nitrate-nitrogen production was measured as a relative indicator of nitrification efficiency.

Hydrolysis Procedure

Hydrolysis was accomplished by adjusting the pH of the waste sludge to less than or equal to 1.0 and placing it in an autoclave for 60 minutes at 120° C and a pressure of 15 pounds per square inch. Concentrated sulfuric acid was used to lower the pH. After autoclaving, the sludge was allowed to cool before adjusting the pH to a range of 7.0 to 7.5 using a 50% sodium hydroxide solution.

The hydrolysate was refrigerated each day and added to the influent reservoir with the feed solution on the following day. Care was taken to insure complete mixing of the hydrolysate and the feed solution. Residual solids were very fine and remained in suspension very well, so continuous mixing of the feed reservoir was not needed.

ANALYTICAL PROCEDURES

Solids

Mixed liquor suspended solids and effluent suspended solids were determined on a daily basis according to the procedures outlined in Section 208 D of Standard Methods for the Examination of Water and Wastewater (20). Whatman 934 AH, 5.5 cm, 0.45 micron, glass fiber filters were used for filtration. Various vacuum filtration devices were used throughout the study but generally consisted of a vacuum air pump attached to a 500 ml glass suction flask and Millipore membrane filter funnel. Effluent sample volumes of 100 ml and 10 ml mixed liquor sample volumes were used for solids determination. Volatile solids were not routinely measured due to the highly soluble nature of the substrate. As a result of concerns about the possible accumulation of an inert fraction, check samples were analyzed towards the end of the study.

Alkalinity and pH

Influent and effluent alkalinity and pH measurements were made in accordance with the procedures outlined in Section 402 and Section 403 of "Standard Methods" (20). A pH endpoint of 4.5 was used in measuring total alkalinity. Various commercial pH meters were used for pH determination throughout the study depending on equipment availability.

Chemical Oxygen Demand (COD)

The influent and effluent COD concentrations were measured in accordance with Section 508 of "Standard Methods" (20). Sample volumes of 20 ml were analyzed for both influent and effluent samples. As a result of a procedural error, filtered COD determinations were not made during the first four steady-state intervals. During the last two periods of steady-state analysis, both filtered and unfiltered samples were analyzed in order to obtain information useful in correcting for soluble COD concentrations in samples from the first four sampling periods.

Based on comparisons of total and soluble COD in samples from the last two steady-state periods along with volatile effluent suspended solids determinations, the following relationship was used to calculate soluble COD for the first four steady-state periods:

$$(S_1)_{sol} = (S_1)_{total} - 1.42(0.94)X_e \qquad (14)$$

where

S_e = effluent COD concentration, mg/l,

1.42 = mg COD exerted per mg biomass,

0.94 = volatile fraction of suspended solids, and

X_e = effluent suspended solids concentration, mg/l.

Nitrogen

Due to limited equipment availability, organic and ammonia-nitrogen concentrations were not checked regularly. Limited analysis of the influent verified the theoretical ammonia nitrogen concentration in the synthetic wastewater. Nitrate-nitrogen (NO_3^--N) production was used as a relative measure of nitrification efficiency. The nitrate-nitrogen concentration was measured in the influent as well as in the effluent during hydrolysis to observe the effect of hydrolysate return flow. Nitrate-nitrogen was measured by the Brucine Method presented in Section 419 D of "Standard Methods" (20). A suitable stirred boiling water bath, as required in the test procedures was not available, so a standard 4-quart cooking pot and hot plate were used. Vigorous boiling was achieved and an aluminum foil cover was placed over the test tube rack to prevent sample contamination during color development. To obtain reasonable results, the standard curve had to be developed with each set of samples tested. Duplicate standards of six known concentrations were used each time to check for testing errors. Volumetric glassware was used to obtain suitable dilutions of the samples since the test sensitivity requires the sample tested to be in the concentration range of 0.2 to 0.8 mg/l of nitrate-nitrogen. Many samples had to be repeated due to analytical errors.

ANALYSIS OF LABORATORY DATA

The results of the laboratory investigation were used to compare biomass production, nitrification characteristics, and kinetic parameters of the conventional and hydrolytic assist activated sludge processes. Determination of mixed liquor suspended solids, nitrate production, and COD were discussed in the previous section. The purpose of this section is to discuss the evaluation of kinetic values.

Mean Cell Residence Time

Mean cell residence time, θ_c (days), was calculated according to the following equation, as discussed by Sherrard (17):

$$\theta_c = \frac{VX}{Q_w X_w + (Q-Q_w)X_e} \tag{15}$$

where

V = volume of aeration basin, liters,

X = biomass concentration in aeration basin, mg/l,

Q_w = volumetric flow rate of waste sludge, l/day,

X_w = biomass concentration of waste sludge, mg/l,

Q = influent volumetric flow rate, l/day, and

X_e = secondary effluent biomass concentration, mg/l.

Specific Substrate Utilization Rate

The specific substrate utiliztion rate, U, expressed as $days^{-1}$ was calculated from the relationship:

$$U = \frac{S_o - S_1}{\theta X} \qquad (16)$$

where

S_o = influent substrate concentration, mg/1,

S_1 = effluent substrate concentration, mg/1, and

θ = hydraulic detention time, days.

Observed Yield Coefficient

The observed yield coefficient, Y_{obs}, expressed as milligrams of biomass per milligram of substrate removed, was calculated as follows:

$$Y_{obs} = \frac{\theta X}{\theta_c (S_o - S_e)} \qquad (17)$$

Food to Microorganism Ratio

The food to microorganism, F/M, was calculated from the following relationship:

$$F/M = \frac{S_o}{\theta X} \qquad (18)$$

Kinetic Equation

The following equation was used to describe biological growth and substrate utilization:

$$\frac{1}{\theta_c} = YU - k_d \tag{19}$$

where

Y = yield coefficient, mass of microorganisms produced per unit mass of substrate removed, and

k_d = biological decay coefficient, days^{-1}.

Utilizing the linear form of this kinetic equation, the laboratory results were used to develop a plot of $1/\theta_c$, on the ordinate, against U on the abscissa. The slope of the resulting line would be equivalent to the yield coefficient, and the decay coefficient would be the value of the ordinate intercept.

CHAPTER 4. RESULTS

Results of theoretical predictions and laboratory investigations of the acid hydrolytic assist activated sludge process are presented in this section. Biokinetic calculations are presented first since these results were used in deriving stoichiometric expressions and prediction of on-line performance characteristics. The balanced stoichiometric equations are presented next, followed by the results of an actual bench-scale study of the acid hydrolytic assist activated sludge process.

BIOKINETIC EQUATIONS

Results of iterative calculations utilizing equations 4 through 10 are presented in Appendix Table A-1. Two values are reported for each parameter at each of the mean cell residence times used. The first value represents the steady-state result before the initiation of hydrolysate return flow. The second value reported in Table A-1 represents the new steady-state result under hydrolysis conditions. These two values can be used to compare, on a theoretical basis, the conventional activated sludge process to the hydrolytic assist activated sludge process at different mean cell residence times.

The variation of combined influent-hydrolysate substrate concentration as a function of mean cell residence time is illustrated in Figure 3. The influent organic concentration was held constant at 256 mg/l (as COD) while the combined influent-hydrolysate organic strength

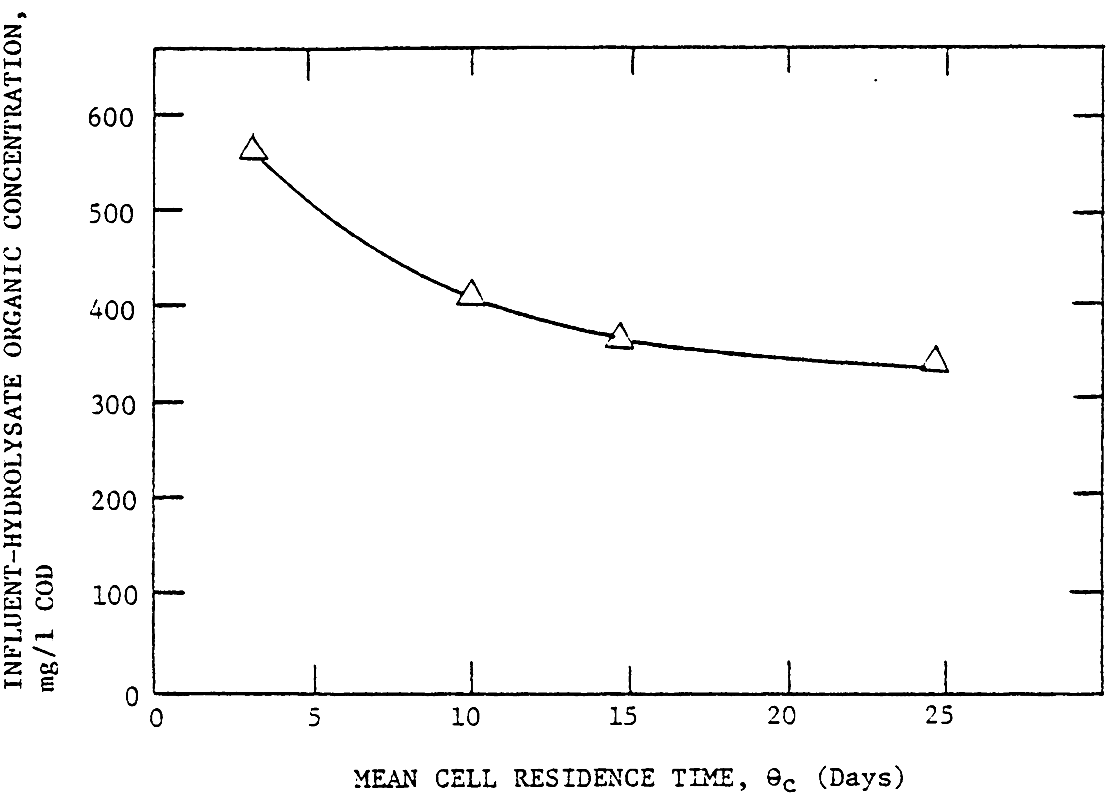

Figure 3. Variation of combined influent-hydrolysate organic concentration for biokinetic model as a function of mean cell residence time.

varied from 567 mg/l at a 3 day mean cell residence time to 333 mg/l at a 25 day mean cell residence time.

Steady-state biomass concentrations under conditions of hydrolysis ranged from 2.3 to 1.3 times the initial concentration as the mean cell residence time was increased from 3 days to 25 days. Figure 4 demonstrates the difference in steady-state biomass concentrations for the conventional and hydrolytic assist activated sludge processes. The time period required to return to steady-state conditions after initiation of hydrolysis ranged from 8 days to 4 days as the mean cell residence time increased from 3 days to 25 days.

Sludge production characteristics of the hydrolytic assist activated sludge process are important because the quantity of waste sludge requiring hydrolysis affects process design considerations. Sludge production for the conventional and hydrolytic assist activated sludge processes is shown in Figure 5. The sludge production for the conventional process decreased from 7964 pounds per day to 3489 pounds per day while the sludge production for the hydrolytic assist activated sludge process decreased from 18418 pounds per day to 4556 pounds per day as the mean cell residence time was increased from 3 to 25 days.

STOICHIOMETRIC EQUATIONS

Using the procedures outlined in Chapter 3, balanced stoichiometric equations were developed to describe the biochemical aspects of the activated sludge process. Three basic biochemical expressions were

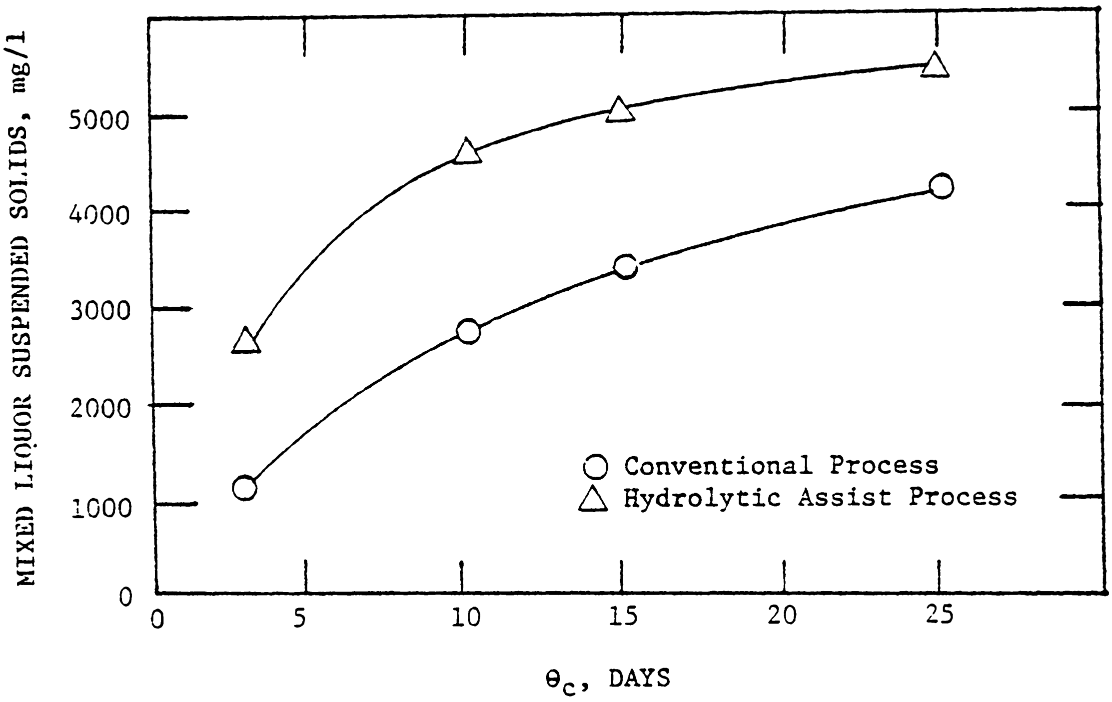

Figure 4. Mixed liquor suspended solids as a function of mean cell residence time for the biokinetic model.

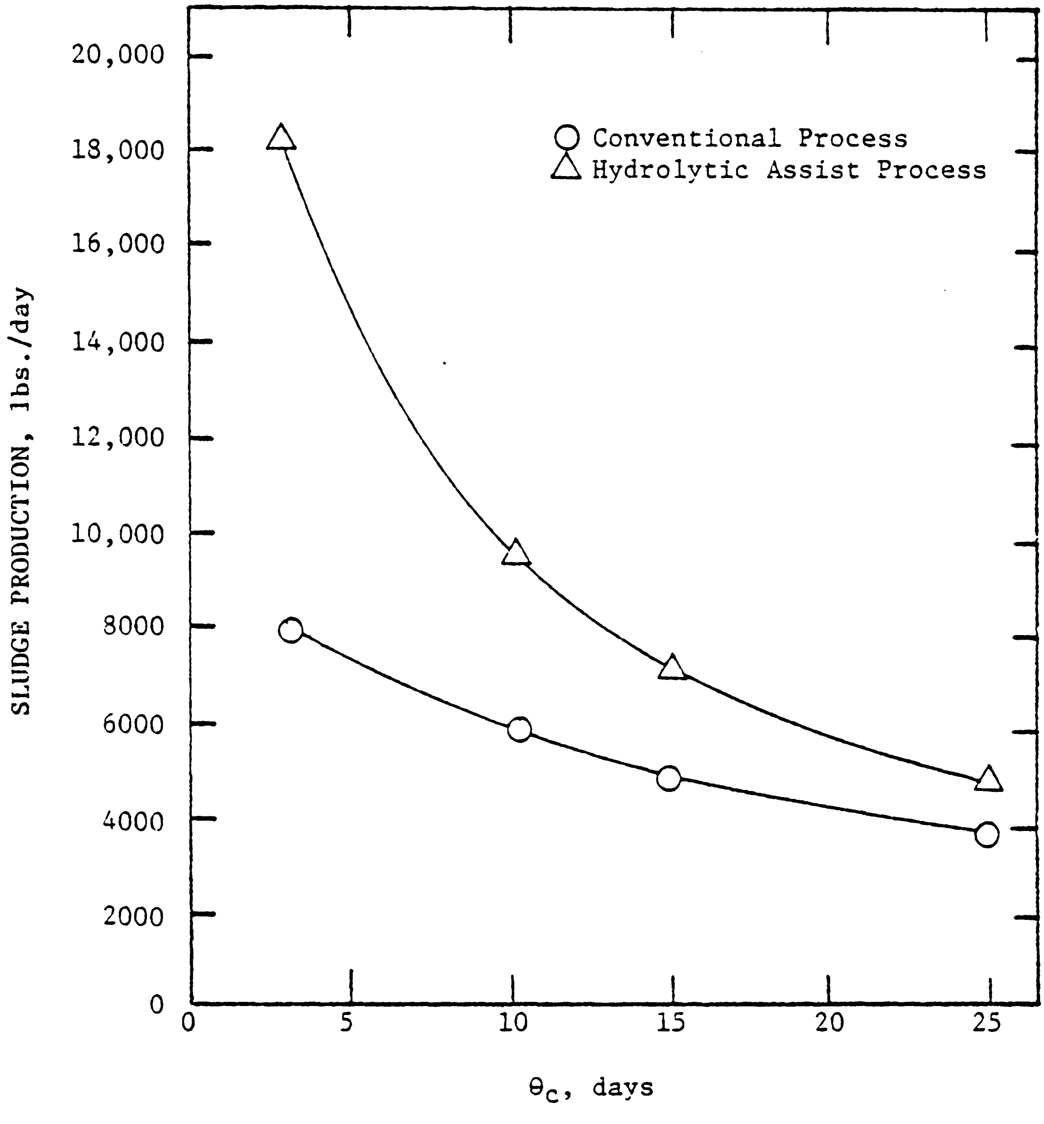

Figure 5. Excess sludge production as a function of mean cell residence time for the biokinetic modeling results of the conventional and hydrolytic assist activated sludge processes.

developed for each mean cell residence time. First, a balanced stoichiometric equation for the conventional activated sludge process was developed for each mean cell residence time. Then, an intermediate equation was developed for each mean cell residence time to represent the biochemical activity within the biological reactor under conditions of combined influent-hydrolysate substrate loading. Finally, a balanced stoichiometric equation was developed to represent the overall total oxidation of the substrate removed at each mean cell residence time.

All three of the stoichiometric equations developed at each mean cell residence time are contained in Appendix B. The overall balanced stoichiometric equations for the conventional activated sludge process are presented in Table III. For comparison, the stoichiometric equations representing total oxidation of the substrate removed at each mean cell residence time for the hydrolytic assist activated sludge process are presented in Table IV.

LABORATORY RESULTS

The bench-scale study of the hydrolytic assist activated sludge process was conducted over a four month period. Results presented in this section for the conventional and hydrolytic assist activated sludge processes were obtained from a single bench-scale reactor and represent treatment by a common microbial population throughout the study. The results of operation in the conventional treatment mode may be considered as baseline or control data. The steady-state results for

Table III. Balanced Stoichiometric Equations for the Conventional Activated Sludge Process as a Function of θ_c

θ_c (Days)	Balanced Stoichiometric Equation
3	$C_8H_{12}N_2O_3 + 4.825\ O_2 \longrightarrow 0.515\ C_5H_7O_2N + 0.075\ C_8H_{12}N_2O_3 + 1.135\ NH_3 + 4.825\ CO_2 + 1.745\ H_2O$
10	$C_8H_{12}N_2O_3 + 5.885\ O_2 \longrightarrow 0.375\ C_5H_7O_2N + 0.030\ C_8H_{12}N_2O_3 + 1.565\ NH_3 + 5.885\ CO_2 + 2.16\ H_2O$
15	$C_8H_{12}N_2O_3 + 6.286\ O_2 \longrightarrow 0.308\ C_5H_7O_2N + 0.024\ C_8H_{12}N_2O_3 + 1.644\ NH_3 + 6.268\ CO_2 + 2.312\ H_2O$
25	$C_8H_{12}N_2O_3 + 6.700\ O_2 \longrightarrow 0.228\ C_5H_7O_2N + 0.020\ C_8H_{12}N_2O_3 + 1.732\ NH_3 + 6.700\ CO_2 + 2.484\ H_2O$

Table IV. Balanced Stoichiometric Equations for the Hydrolytic Assist Activated Sludge Process as a Function of θ_c

θ_c (Days)	Balanced Stoichiometric Equation
3	$C_8H_{12}N_2O_3 + 7.4\ O_2 \longrightarrow 0.075\ C_8H_{12}N_2O_3 + 1.85\ NH_3 + 7.40\ CO_2 + 2.775\ H_2O$
10	$C_8H_{12}N_2O_3 + 7.76\ O_2 \longrightarrow 0.03\ C_8H_{12}N_2O_3 + 1.94\ NH_3 + 7.76\ CO_2 + 5.714\ H_2O$
15	$C_8H_{12}N_2O_3 + 7.808\ O_2 \longrightarrow 0.024\ C_8H_{12}N_2O_3 + 1.952\ NH_3 + 7.808\ CO_2 + 2.928\ H_2O$
25	$C_8H_{12}N_2O_3 + 7.840\ O_2 \longrightarrow 0.020\ C_8H_{12}N_2O_3 + 1.960\ NH_3 + 7.840\ CO_2 + 2.94\ H_2O$

operation of the conventional and hydrolytic assist modification to the activated sludge process are presented in Appendix C. Kinetic data for the laboratory study are summarized in Table V for both methods of treatment. Nitrate-nitrogen production is summarized in Table VI for both treatment methods.

Conventional Activated Sludge Process

Initially, a constant sludge wasting rate of 350 ml/day was used. During the steady-state period at this wasting rate, an average θ_c of 23.6 days resulted. An average influent substrate concentration of 399 mg/l as COD was maintained throughout this interval. An average biomass concentration of 3358 mg/l was recorded during this first steady-state period yielding a food to microorganism ratio of 0.18 $days^{-1}$. Average effluent suspended solids concentration was 11 mg/l. Corrected soluble effluent COD concentration was 22 mg/l, while the measured unfiltered COD during the same interval was 46 mg/l. Nitrate-nitrogen production, measured as an effluent concentration, averaged 62 mg/l at this θ_c while an average effluent pH of 6.3 was recorded. Specific substrate utilization rate was calculated to be 0.17 $days^{-1}$ and the variable yield coefficient was 0.25 mg VSS/mg COD.

During the second period of investigation, a sludge wasting rate of 600 ml/day resulted in a steady-state average θ_c of 13.0 days. Average influent substrate concentration at steady-state was 400 mg/l while the average unfiltered effluent COD was 47 mg/l and the corrected

Table V. Summary of Kinetic Data from Laboratory Study

Conventional Activated Sludge Process

Parameter	Units	Results		
θ_c	Days	23.6	13.0	5.9
u	Days^{-1}	0.04	0.08	0.17
X_a	mg/l	3358	1916	1020
X_e	mg/l	11	16	15
S_o	mg/l	399	400	391
S_e	mg/l	22	25	26
S_o-S_e	mg/l	377	374	365
U	Days^{-1}	0.17	0.30	0.54
Y_{obs}	mg/mg	0.25	0.26	0.31
F/M	Days^{-1}	0.18	0.32	0.58

Hydrolytic Assist Activated Sludge Process

Parameter	Units	Results		
θ_c	Days	22.3	12.4	4.4
u	Days^{-1}	0.04	0.08	0.23
X_a	mg/l	3545	2220	901
X_e	mg/l	17	25	49
S_o	mg/l	454	444	444
S_e	mg/l	15	14	29
S_o-S_e	mg/l	439	427	415
U	Days^{-1}	0.19	0.29	0.70
Y_{obs}	mg/mg	0.24	0.28	0.33
F/M	Days^{-1}	0.19	0.30	0.74

Table VI. Summary of Nitrate-Nitrogen Production from Laboratory Study

Conventional		Hydrolytic Assist	
θ_c (Days)	NO_3^--N (mg/l)	θ_c (Days)	NO_3^--N (mg/l)
23.6	62	22.3	84
13.0	85	12.4	91
5.9	6	4.4	0

soluble effluent COD was 25 mg/l. Average steady-state biomass concentration was 1916 mg/l resulting in a food to microorganism ratio of 0.32 days^{-1}. Average effluent suspended solids for this interval was 16 mg/l. Effluent nitrate-nitrogen concentration averaged 85 mg/l at this θ_c while an average effluent pH of 5.6 was recorded. A specific substrate utilization rate of 0.30 days^{-1} was calculated and the observed yield coefficient was 0.32 mg/mg.

During the third study interval, a sludge wasting rate of 1.4 l/day resulted in an average θ_c of 5.9 days at steady-state. The average influent substrate concentration was 391 mg/l while the filtered effluent COD was 26 mg/l. During this interval, the average steady-state biomass concentration was 1020 mg/l while the average effluent suspended solids concentration was 15 mg/l. The food to microorganism ratio at this θ_c was 0.58 days^{-1}. An average effluent nitrate-nitrogen concentration of 67 mg/l was measured and an average effluent pH of 7.3 was recorded. A specific substrate utilization rate 0.54 days^{-1} was calculated and the observed yield coefficient was 0.31 mg VSS/mg COD.

Acid Hydrolytic Assist Activated Sludge Process

At the initial sludge wasting rate of 350 ml/day, an average θ_c of 22.31 days resulted during steady-state operation of the acid hydrolytic assist activated sludge process. An average influent COD of 454 mg/l resulted when the hydrolysate recycle was combined with the synthetic wastewater. The average unfiltered effluent COD was 38 mg/l while the corrected soluble effluent COD was 15 mg/l. At steady-state, the average biomass concentration was 3545 mg/l and the average effluent suspended solids concentration was 17 mg/l. An average food to microorganism ratio of 0.19 days^{-1} resulted for this interval. Average effluent nitrate-nitrogen concentration was 84 mg/l and an average pH of 5.2 was recorded. Specific substrate utilization rate at this θ_c was 0.19 days^{-1} and the observed yield coefficient was 0.24 mg/mg.

During the second experimental period for the hydrolytic assist process, an average θ_c of 12.4 days resulted when sludge was wasted at a rate of 600 ml/day. An average influent-hydrolysate concentration of 444 mg/l as COD was measured at steady-state while the average unfiltered effluent COD was 48 mg/l. Corrected soluble effluent COD was 14 mg/l at this θ_c. An average steady-state biomass concentration of 2220 mg/l resulted and the food to microorganism ratio was 0.30 days^{-1}. Average effluent suspended solids concentration was 25 mg/l. An average effluent nitrate-nitrogen concentration of 96 mg/l was measured at this θ_c and an average effluent pH of 5.9 was recorded. For this θ_c, the calculated value of the specific substrate utilization rate was 0.29 days^{-1} and the variable yield coefficient was 0.28 mg VSS/mg COD.

For the third test period of the hydrolytic assist process, an average θ_c of 4.4 days resulted when sludge was wasted at a rate of 1.4 l/day. Average influent-hydrolysate organic concentration was 441 mg/l as COD while the average filtered effluent COD was 29 mg/l. Average unfiltered effluent COD during this interval was 102 mg/l. At this θ_c, the average steady-state biomass concentration was 901 mg/l yielding a food to microorganism ratio of 0.74 days^{-1}. Average effluent suspended solids concentration was 49 mg/l. An average effluent pH of 7.4 was recorded for this steady-state period and no nitrate-nitrogen was detected in the effluent. Specific substrate utilization rate was 0.70 days^{-1} and the variable yield coefficient was 0.33 mg VSS/mg COD.

CHAPTER 5. DISCUSSION

In this chapter, the mathematical predictions and laboratory results are analyzed. Where possible, the results are related to information discussed in the literature. The laboratory results are compared to theoretical results and the information is evaluated in accordance with the objectives of this research project.

BIOKINETIC EQUATIONS

Continual recycle of hydrolysate might be expected to create conditions of ever increasing biomass concentrations. The increased organic loading from the hydrolysate would promote further biological growth leading to increased waste sludge production and, subsequently, further increases in the organic loading. However, some limiting concentration would be expected due to physical or biological constraints on the system. Prior to utilization of the biokinetic model, the steady-state biomass concentration associated with the extended aeration process was expected to approximate the steady-state biomass concentration for the hydrolytic assist process at any mean cell residence time. In other words, the steady-state biomass concentration would be constant and independent of mean cell residence time for the hydrolytic assist activated sludge process.

As indicated in Figure 3 in the previous chapter, the influent-hydrolysate substrate loading reached a new steady-state value for each mean cell residence time. This value reflects the new equilibrium established between microbial growth and hydrolysate recycle. Therefore, the quantity and organic strength of the hydrolysate have specific steady-state values for a given mean cell residence time in a manner similar to biomass and waste sludge production. In fact, the quantity and strength of hydrolysate are directly dependent on biomass and waste sludge production.

As a result of the additional nutrient loading from the hydrolysate, the equations predict that the steady-state biomass production will adjust to a new value at each mean cell residence time. The difference between the steady-state biomass concentration for the hydrolytic assist activated sludge process and the conventional process decreases in magnitude as the mean cell residence time is increased, according to the biokinetic model. For this study, this new biomass concentration ranged from 2.3 times to 1.3 times the original concentration as was shown in Figure 4 in the previous chapter. In practice, the actual increase in biomass concentration would be a function of the kinetics of substrate removal and microbial growth.

Excess sludge production for the hydrolytic assist activated sludge process, as predicted by the biokinetic equations, would increase dramatically at lower mean cell residence times. Sludge production is expected to increase with decreasing mean cell residence times. During hydrolysis, as the mean cell residence time decreases, waste sludge production increases at a faster rate than during conventional operation due to the increased organic loading imposed by hydrolysate recycle. This contradicts the conclusion by Yang and Chen (13) regarding reductions in sludge production. While hydrolysis and recycle of waste sludge would reduce the net quantity of sludge requiring handling and disposal, the actual sludge production of the activated sludge process would be increased. The mathematical predictions indicate that use of the hydrolytic assist process would become a very uneconomical alternative at lower mean cell residence times.

For the theoretical example, the time required to reach steady-state conditions following the initiation of continuous hydrolysis decreased with increasing mean cell residence times. It took half as long to reach steady-state at a mean cell residence time of 25 days as it did for a 3 day residence time. This result might be considered misleading because biological kinetics were assumed to remain constant and the microbial population was assumed to be immediately acclimated to the hydrolysate as a food source.

Mathematical predictions were expected to give only relative indications of the effect of hydrolysis on biomass production. Many simplifying assumptions were made and actual laboratory studies were needed to evaluate the effect of mean cell residence time on the hydrolytic assist activated sludge process in accordance with the objectives of this study.

STOICHIOMETRIC EQUATIONS

Stoichiometric equations presented in Table III and Table IV of the previous chapter are considered to represent the biochemical processes of wastewater treatment. The stoichiometric equations based on the theoretical example indicate a higher molecular oxygen requirement for the hydrolytic assist activated sludge process relative to the conventional process. A more dramatic increase in the molecular oxygen requirement with increasing mean cell residence time is predicted for the conventional activated sludge process. The increase in oxygen requirements with increasing mean cell residence times is not as pronounced for the hydrolytic assist activated sludge process because the oxygen requirements of total oxidation are artifically imposed at lower mean cell residence times.

Stoichiometric equations vary at each mean cell residence time because of changing quantities of substrate removed and subsequent changes in the steady-state conditions. The intermediate stoichiometric equations included in Appendix B demonstrate the significant oxygen demand which would be exerted in the aeration basin during hydrolysis. The increase in ammonia-nitrogen evident in the intermediate equations demonstrate the effect of nutrient recycle as was emphasized by Gaudy *et al*. (11) and also by Yang and Gaudy (12).

LABORATORY RESULTS

Since the sludge wasting rate was held constant for the conventional and hydrolytic assist activated sludge processes, the average mean cell residence time was expected to change very little. Actually, there was a general increase in effluent suspended solids during hydrolysis so the mean cell residence time was observed to decrease from the steady-state value established during operation of the conventional activated sludge process.

The influent synthetic waste solution was carefully prepared each day to obtain the desired 400 mg/l COD concentration. It is very interesting to note that the combined influent-hydrolysate organic strength remained nearly constant throughout the investigation. Although the organic loading of the hydrolysate on a mass basis was larger at the lowest mean cell residence time, the increased volume of waste sludge and subsequent volume of hydrolysate off-set the mass loading so a nearly constant organic concentration resulted when the hydrolysate was combined with the regular influent.

Biomass production characteristics for the laboratory reactor were similar to the predictions of the biokinetic model. The combined effect of increased biomass concentration and decreased mean cell residence time resulted in a new steady-state biomass concentration for the hydrolytic assist activated sludge process which, when plotted as a function of mean cell residence time, produces a parallel curve of larger magnitude than the curve for the conventional process. This is illustrated in Figure 6 which is very similar in appearance to Figure 4 which was based on the biokinetic predictions. During the third test period of the hydrolytic assist activated sludge process, the biomass concentration at steady-state was lower than the steady-state biomass con-

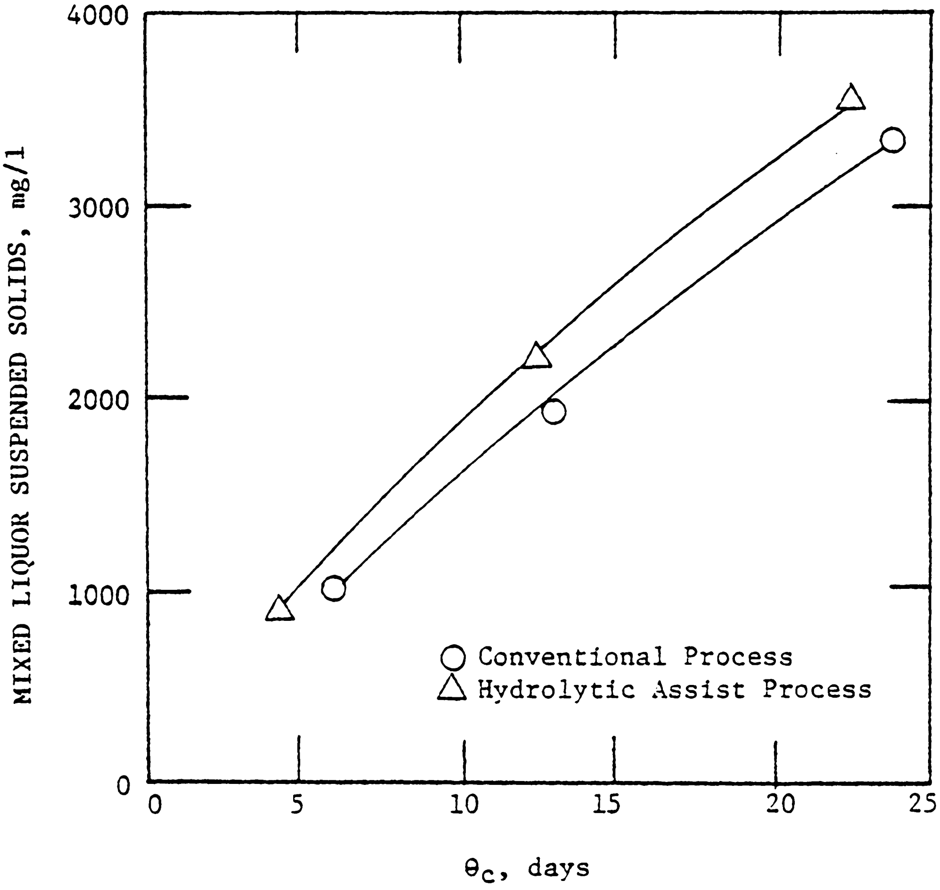

Figure 6. Steady-state biomass concentrations as a function of mean cell residence time based on the results of laboratory studies of the conventional and hydrolytic assist activated sludge processes.

centration for the conventional process. This decrease in biomass concentration was off-set by a corresponding decrease in mean cell residence time so the results during this interval were still in accordance with the predictions.

The effluent suspended solids during steady-state operation of the conventional activated sludge process remained relatively constant for the entire period of investigation. During operation of the hydrolytic assist process, the effluent suspended solids were observed to increase with decreasing mean cell residence time as indicated in Figure 7. During the first and second test intervals, the effluent suspended soids concentrations for the hydrolytic assist process were only slightly higher than the concentrations for the conventional process. During the third test interval,however, the effluent suspended solids concentration was 3.3 times higher during hydrolysis than during conventional operation. However, it is not possible to associate this phenomenon of increased effluent suspended solids directly to the use of the hydrolytic assist process. Significant problems with the air supply were encountered during the third test interval which nearly resulted in a complete failure of the biological treatment system. After this period, the sludge no longer exhibited good flocculating characteristics and, as a result, the solids capture efficiency in the clarifier was reduced.

Periodic intervals of continuous hydrolysis seemed to affect the biomass population distribution but evaluation of this phenomenon was beyond the capabilities of this research project. The color of the

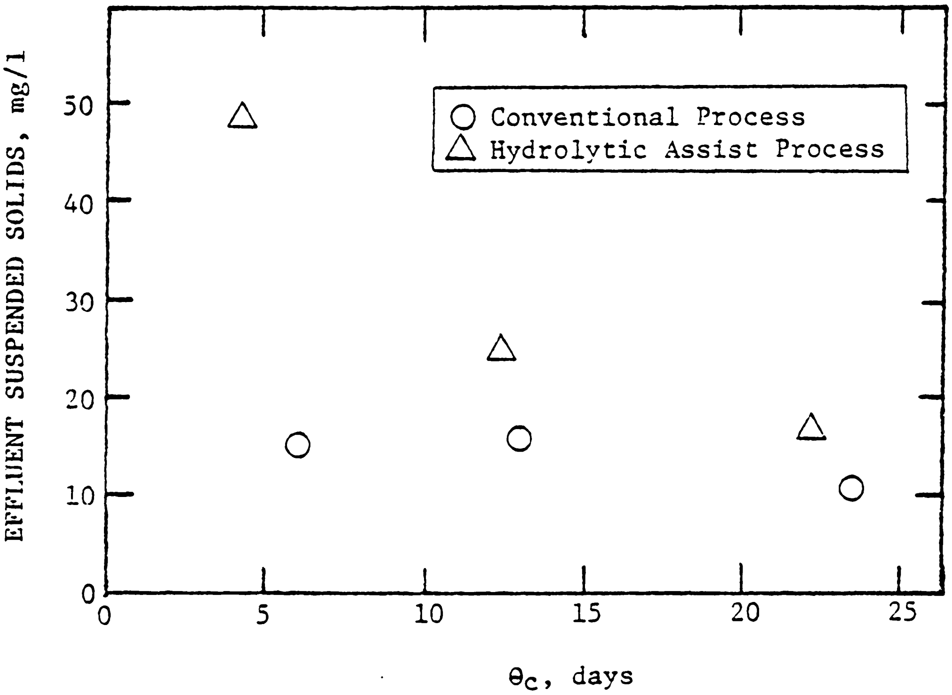

Figure 7. Effluent suspended solids as a function of mean cell residence time based on results of laboratory studies of the conventional and hydrolytic assist activated sludge processes.

activated sludge changed from tan to a rich orange color during the first two test periods and returned to a pale orange during the last period of operation. After periods of oxygen loss due to the previously described failures of the air supply, filamentous growth was observed near the end of the steady-state period for conventional operation during the third test period. Subsequent hydrolysis appeared to prevent the proliferation of filamentous organisms suggesting that this would indeed be a beneficial use of hydrolysis as reported by Gaudy and Gaudy (5).

Hydrolysis might be capable of improving sedimentation at high mean cell residence times because of the release of cellular material such as polysaccharides which may function as polymers due to their long chain molecular structures. At low mean cell residence times, the effect of cellular material on flocculation would be limited since biomass concentration would be lower. It is difficult to conclude from this laboratory investigation if hydrolysis affected sedimentation. Although the effluent suspended solids increased during hydrolysis, this increase was not significant until the last test period as previously discussed.

Substrate removal remained relatively constant during operation of the conventional activated sludge process throughout the period of investigation. The soluble effluent COD during hydrolysis was nearly half the value measured during operation of the conventional process at the two highest θ_c values. For the third interval of study at the lowest θ_c, the soluble effluent COD during hydrolysis was slightly higher than the value measured during conventional operation. The variation in the effluent substrate concentration as a function of θ_c for both treatment methods is illustrated in Figure 8.

Since filtered COD concentrations were not measured during the first two test periods, it is difficult to conclude that hydrolysis was responsible for improved soluble COD removal. However, a review of the actual analytical results indicates that improved soluble COD removal may indeed have occurred during hydrolysis for the first two test periods. By comparing the measured total COD (unfiltered) and effluent suspended solids from the tables in Appendix C for the first two test periods, it is possible to infer that soluble COD removal did improve during hydrolysis. The total effluent COD decreased during the first test period for the hydrolytic assist process even though the effluent suspended solids concentration was higher during hydrolysis than it was during conventional operation. During the second test period, the effluent total COD remained virtually unchanged while the effluent suspended solids concentration increased during operation of the hydrolytic assist process. In addition, the influent organic loading was 47 mg/l higher on the average during all three test periods of the hydrolytic assist process.

Improved substrate removal during hydrolysis could be related to increased enzyme activity resulting from hydrolysate recycle. It is possible that many different cellular enzymes are released during hydrolysis of activated sludge which contains a wide variety of organisms.

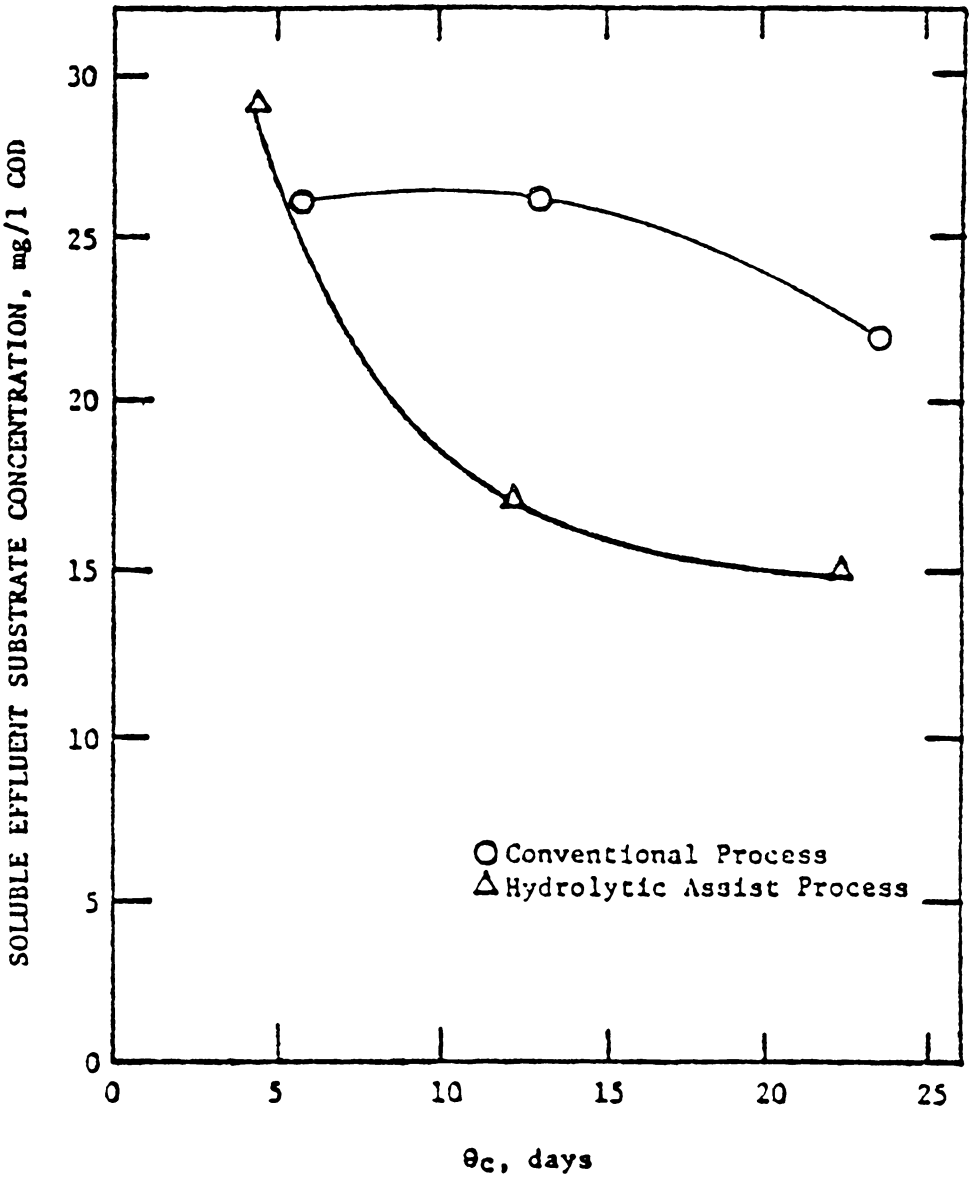

Figure 8. Soluble effluent substrate concentration as a function of mean cell residence time based on results of laboratory studies of the conventional and hydrolytic assist activated sludge processes.

According to Baum (21) an enzyme is a very complicated organic catalyst which can be produced by a living cell. Baum reports that extracellular enzymes are necessary for the utilization of substrate by a living cell. As a minimum, there would be two steps involved in catalytic biochemical reactions. First, an enzyme-substrate complex would be formed when an enzyme molecule collides with a substrate molecule. Then, the second step would involve formation of the products which would be released form the surface of the enzyme.

Hydrolysis and recycle of cellular material could result in an increased concentration of a variety of enzymes, thus improving the probability of collision between substrate molecules and enzymes. The necessary enzyme activators for formation of the enzyme-substrate complex might also be present in larger concentrations. Further studies would be needed to verify this because hydrolysis might also destroy enzymes and enzyme activators. Certain organisms normally faced with enzyme limitations could possibly utilize a larger portion of the substrate during hydrolysis because of the presence of additional enzymes or activators not normally present. Thus, the hydrolytic assist process could result in improved soluble COD removal because of enhanced enzyme activity allowing an increase in substrate removal by the activated sludge organisms.

Although the quantity of substrate removed increased during hydrolysis, the specific substrate utilization rate and the variable yield coefficient did not vary much between the two modes of operation, except during the final study period at the lowest θ_c. The specific substrate utilization rate was much higher for hydrolysis during the final study period than it was during operation of the conventional process. This difference is related to the decreased mean cell residence time and corresponding increase in the specific growth rate as the process was changed from conventional operation to the hydrolytic assist mode of treatment. The change in mean cell residence time was not as significant during the first two study intervals and, consequently, the specific growth rate was nearly constant for conventional and hydrolytic assist operation.

The variable yield coefficient decreased in value as the mean cell residence time increased as is illustrated in Figure 9. The calculated values for the specific substrate utilization rate and the variable yield coefficient indicate that the biomass was in the declining growth phase for the first two trial periods. During the last trial period, the biomass was operating in the exponential growth phase, as indicated by the high specific growth rates for both modes of operation.

When $1/\theta_c$ was plotted as a function of U, the three data points for the conventional process plotted along a straight line with the three data points for the hydrolytic assist activated sludge process. This is illustrated in Figure 10. These results verify that the kinetics of wastewater treatment were the same during hydrolysis as they were during conventional operation of the process. Prior to performing this laboratory study, hydrolysis was expected to affect the kinetic charac-

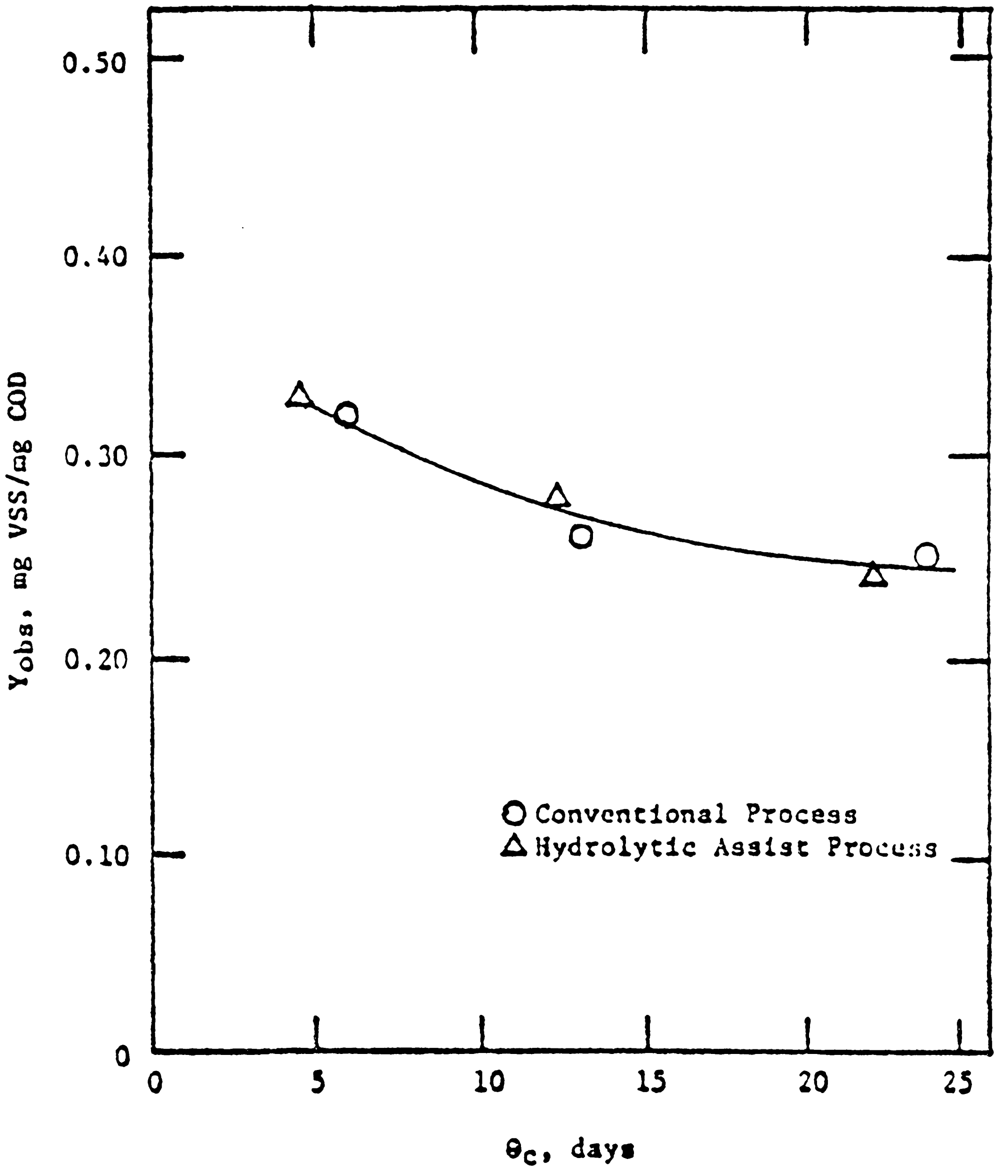

Figure 9. Variable yield coefficient as a function of mean cell residence time based on laboratory investigations of the conventional and hydrolytic assist activated sludge processes.

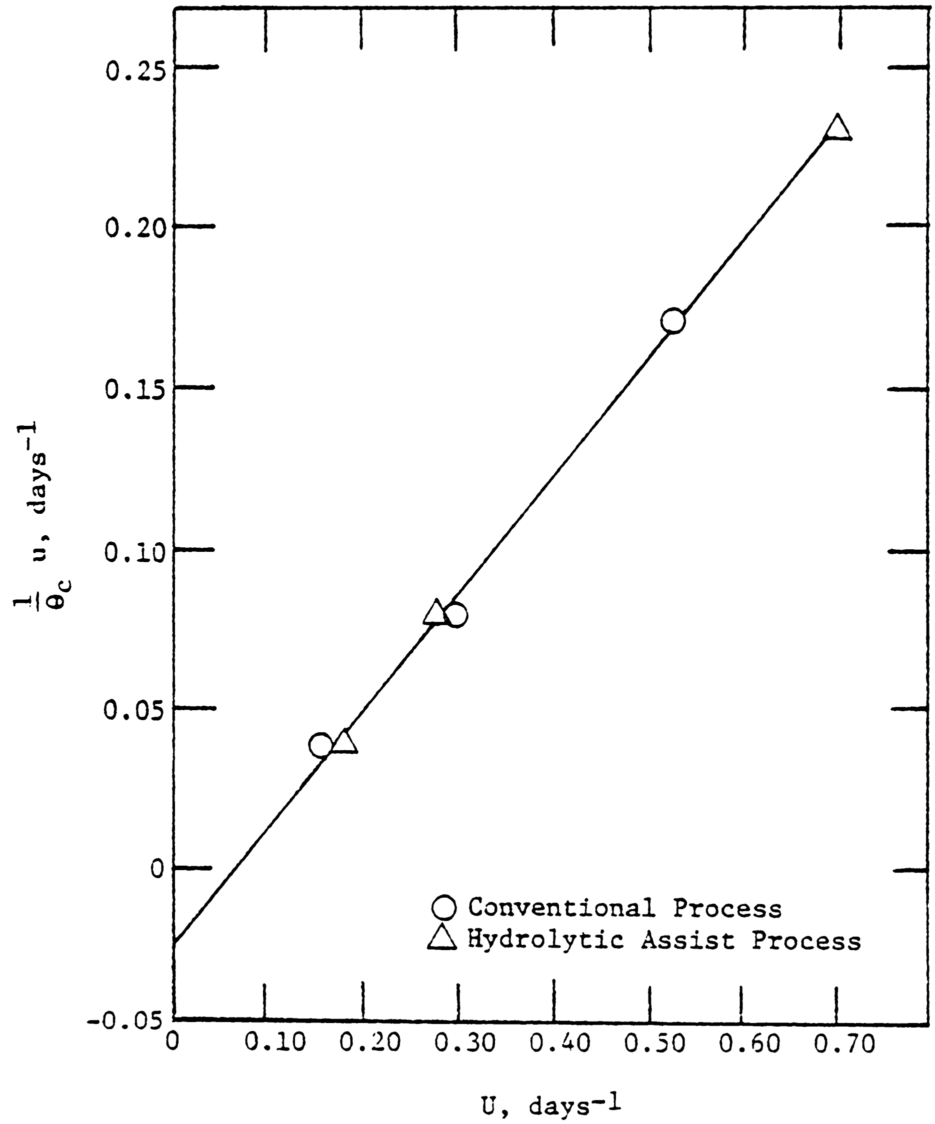

Figure 10. Specific growth rate as a function of specific substrate utilization rate for conventional and hydrolytic assist activated sludge processes based on experimental results.

teristics of the treatment process. Specifically, the decay coefficient was expected to vary since hydrolysis was used to induce cellular autodigestion within the activated sludge system, possibly causing an increase in the value of the decay coefficient. The analytical results indicate that a biological decay coefficient of 0.03 days^{-1} was applicable for both methods of treatment. A yield coefficient of 0.36 mg/mg resulted for both processes. Accordingly, substitution of the laboratory results into equation 19 yields the following equation:

$$\frac{1}{\theta_c} = 0.36\ U - 0.03 \qquad (20)$$

Hydrolysis did not appear to have a significant effect on nitrification in this laboratory study. During the first study interval, there was an observed improvement in nitrification efficiency during hydrolysis. This phenomenon was not observed during the last two study periods. Actually, nitrification did not occur during the last study interval of the hydrolytic assist process at the lowest θ_c and negligible nitrate production was measured during the preceding test of the conventional process. Nitrifiers were probably not well established during the first steady-state interval of the conventional process but became established by the time steady-state was achieved for the hydrolytic assist process. For this reason, the improved nitrification observed during the first study period is not attributed to the use of hydrolysis. Since this waste was not deficient in nitrogen, the benefits of nitrogen recycle were not realized in this study.

CHAPTER 6. CONCLUSIONS

Based on the results from predictive mathematical equations, stoichiometric equations, and continuous flow operation of the conventional and hydrolytic assist modification to the activated sludge process, the following conclusions can be made:

a.) Mean cell residence time affects the acid hydrolytic assist activated sludge process the same way it affects the conventional activated sludge process. In design, mean cell residence time would be an important consideration due to large increases in waste sludge to be treated at lower mean cell residence times. The hydrolytic assist activated sludge process would have to be operated at high mean cell residence times to minimize sludge production and allow economical operation.

b.) Biomass production increased during periods of acid hydrolysis because of the higher influent organic concentration resulting from hydrolysate recycle. The difference in biomass production for the conventional and hydrolytic assist activated sludge processes is a function of mean cell residence time. The increase in biomass production for the hydrolytic assist process would be more significant at lower mean cell residence times.

c.) Substrate removal efficiency appeared to improve when the hydrolytic assist activated sludge process was used. Improved substrate removal characteristics may be related to increased enzyme activity resulting from the recycle of cellular enzymes and enzyme activators in the sludge hydrolysate.

d.) Wastewater treatment kinetics were found to be the same for the conventional and hydrolytic assist activated sludge processes. A yield coefficient of 0.36 mg VSS/mg COD and a biological decay coefficient of 0.03 days^{-1} resulted from bench-scale operation of both processes.

e.) Hydrolysis did not appear to affect nitrification in the laboratory investigation. Stoichiometric equations indicate that sludge hydrolysate recycle would create conditions favorable for nitrification and could be especially beneficial in treating nitrogen deficient wastes.

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APPENDIX A - RESULTS OF MATHEMATICAL CALCULATIONS

Table A-1. Results of Biokinetic Modeling

θ_c (Days)	Time (Days)	$\bar{S}_o$ (mg/l)	S_1 (mg/l)	Y_{obs}	X (mg/l)	(lbs./day)
3	1	256.00	19.17	0.400	1146	7964
	8	566.86	19.17	0.400	2650	18418
10	1	256.00	7.66	0.278	2759	5753
	6	416.23	7.66	0.278	4540	9465
15	1	256.00	6.17	0.277	3407	4735
	5	374.87	6.17	0.277	5013	6981
25	1	256.00	5.00	0.167	4183	3489
	4	332.79	5.00	0.167	5463	4556

APPENDIX B - STOICHIOMETRIC EQUATIONS

Table B-1. Balanced Stoichiometric Equations for the Conventional and Hydrolytic Assist Activated Sludge Processes, θ_c = 3 Days

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Equation for Conventional Process

$$C_8H_{12}N_2O_3 + 4.825\ O_2 \longrightarrow 0.515\ C_5H_7O_2N + 0.075\ C_8H_{12}N_2O_3 + 1.135\ NH_3 + 4.825\ CO_2 + 1.745\ H_2O$$

Intermediate Equation

$$2.214\ C_8H_{12}N_2O_3 + 11.157\ O_2 \longrightarrow 1.191\ C_5H_7O_2N + 0.075\ C_8H_{12}N_2O_3 + 3.087\ NH_3 + 11.157\ CO_2 + 4.035\ H_2O$$

Equation for Total Oxidation

$$C_8H_{12}N_2O_3 + 7.4\ O_2 \longrightarrow 0.075\ C_8H_{12}N_2O_3 + 1.85\ NH_3 + 7.40\ CO_2 + 2.775\ H_2O$$

Table B-2. Balanced Stoichiometric Equations for the Conventional and Hydrolytic Assist Activated Sludge Processes, θ_c = 10 Days

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Equation for Conventional Process

$$C_8H_{12}N_2O_3 + 5.885\ O_2 \longrightarrow 0.375\ C_5H_7O_2N + 0.030\ C_8H_{12}N_2O_3 + 1.565\ NH_3 + 5.885\ CO_2 + 2.16\ H_2O$$

Intermediate Equation

$$1.626\ C_8H_{12}N_2O_3 + 6.683\ O_2 \longrightarrow 0.617\ C_5H_7O_2N + 0.030\ C_8H_{12}N_2O_3 + 2.575\ NH_3 + 9.683\ CO_2 + 3.554\ H_2O$$

Equation for Total Oxidation

$$C_8H_{12}N_2O_3 + 7.76\ O_2 \longrightarrow 0.03\ C_8H_{12}N_2O_3 + 1.93\ NH_3 + 7.76\ CO_2 + 5.714\ H_2O$$

Table B-3. Balanced Stoichiometric Equations for the Conventional and Hydrolytic Assist Activated Sludge Processes, θ_c = 15 Days

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Equation for Conventional Process

$$C_8H_{12}N_2O_3 + 6.286\ O_2 \longrightarrow 0.308\ C_5H_7O_2N + 0.024\ C_8H_{12}N_2O_3 + 1.644\ NH_3 + 6.268CO_2 + 2.312\ H_2O$$

Intermediate Equation

$$1.46\ C_8H_{12}N_2O_3 + 9.183\ O_2 \longrightarrow 0.461\ C_5H_7O_2N + 0.024\ C_8H_{12}N_2O_3 + 2.411\ NH_3 + 9.183\ CO_2 + 3.386\ H_2O$$

Equation for Total Oxidation

$$C_8H_{12}N_2O_3 + 7.808\ O_2 \longrightarrow 0.024\ C_8H_{12}N_2O_3 + 1.952\ NH_3 + 7.808\ CO_2 + 2.928\ H_2O$$

Table B-4. Balanced Stoichiometric Equations for the Conventional and Hydrolytic Assist Activated Sludge Processes, θ_c = 25 Days

---

Equation for Conventional Process

$$C_8H_{12}N_2O_3 + 6.700\ O_2 \longrightarrow 0.228\ C_5H_7O_2N + 0.010\ C_8H_{12}N_2O_3 + 1.732\ NH_3 + 6.700\ CO_2 + 2.484\ H_2O$$

Intermediate Equation

$$1.30\ C_8H_{12}N_2O_3 + 8.750\ O_2 \longrightarrow 0.298\ C_5H_7O_2N + 0.020\ C_8H_{12}N_2O_3 + 2.262\ NH_3 + 8.750\ CO_2 + 3.244\ H_2O$$

Equation for Total Oxidation

$$C_8H_{12}N_2O_3 + 7.840\ O_2 \longrightarrow 0.020\ C_8H_{12}N_2O_3 + 1.960\ NH_3 + 7.840\ CO_2 + 2.940\ H_2O$$

APPENDIX C - LABORATORY RESULTS

Table C-1. Steady-state Laboratory Results for First Test Period of the Conventional Activated Sludge Process

Day	pH	Alkalinity (mg/l)	X_a (mg/l)	X_e (mg/l)	S_o (mg/l)	S_e* (mg/l)	NO_3^--N (mg/l)
1	—	—	3120	10	388	36	74
2	—	—	3290	4	420	40	66
3	6.3	—	3630	11	404	36	63
4	6.3	—	3360	9	400	48	73
5	6.3	—	3370	19	400	39	56
6	6.3	—	3480	14	400	35	43
7	6.3	—	3320	8	375	45	60
8	6.3	—	3290	9	404	16	60
Average	6.3	—	3358	11	399	37	61.9

θ_c = 23.61 Days
μ = 0.04 Days^{-1}
F/M = 0.18 Days^{-1}
U = 0.17 Days^{-1}
Y_{obs} = 0.25 $^{\text{mg VSS}}/_{\text{mg COD}}$

Corrected Effluent Soluble COD = 37 - 1.42 (0.94) 11 = 22 mg/l

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* Unfiltered COD

Table C-2. Steady-state Laboratory Results for First Test Period of the Hydrolytic Assist Activated Sludge Process

Day	pH	Alkalinity (mg/l)	X_a (mg/l)	X_e (mg/l)	S_o (mg/l)	S_e* (mg/l)	NO_3^--N (mg/l)
1	5.3	—	3770	18	449.1	39.2	86
2	5.2	—	3450	16	457.8	26.2	88
3	5.2	—	3310	18	462.2	34.9	90
4	5.2	—	3640	17	418.6	30.5	76
5	4.9	—	3510	16	468.0	40.0	86
6	5.2	—	3590	19	468.0	56.0	80
Average	5.17	—	3545	17.33	454	38	84

θ_c = 22.31 Days
μ = 0.04 Days^{-1}
F/M = 0.19 Days^{-1}
U = 0.19 Days^{-1}
Y_{obs} = 0.24 $^{\text{mg VSS}}/_{\text{mg COD}}$

Corrected Soluble Effluent COD = 38 - 1.42 (0.94) 17 = 15 mg/l

* Unfiltered COD

Table C-3. Steady-state Laboratory Results for Second Test Period of the Conventional Activated Sludge Process

Day	pH	Alkalinity (mg/l)	X_a (mg/l)	X_e (mg/l)	S_o (mg/l)	S_e* (mg/l)	NO_3^--N (mg/l)
1	5.85	69.00	1830	17	398.40	37.85	94
2	5.70	56.35	1920	22	398.40	49.80	64
3	5.60	43.70	1930	11	402.38	47.81	82
4	5.60	41.40	1880	15	394.42	61.75	94
5	5.60	39.10	1960	15	402.38	45.82	83
6	5.30	27.60	1980	11	402.38	41.83	87
7	5.60	41.40	1800	20	398.40	49.80	88
8	5.40	25.30	2030	20	402.38	39.84	87
Average	5.58	42.98	1916	16	400	47	85

θ_c = 13.0 Days

μ = 0.08 Days^{-1}

F/M = 0.32 Days^{-1}

U = 0.30 Days^{-1}

Y_{obs} = 0.32 $^{\text{mg VSS}}/_{\text{mg COD}}$

Corrected Soluble Effluent COD = 47 - 1.42 (0.94) 16 = 25 mg/l

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* Unfiltered COD

Table C-4. Steady-state Laboratory Results for Second Test Period of the Hydrolytic Assist Activated Sludge Process

Day	pH	Alkalinity (mg/l)	X_a (mg/l)	X_e (mg/l)	S_o (mg/l)	S_e* (mg/l)	NO_3^--N (mg/l)
1	6.20	118.16	2160	29	431	44	96
2	6.05	128.55	2380	31	445	48	100
3	5.85	82.80	2220	33	461	40	104
4	5.60	69.00	2390	23	449	48	100
5	5.70	63.25	2150	22	427	52	86
6	5.90	158.70	2020	14	451	56	90
Average	5.88	103.41	2220	25	444	48	96

θ_c = 12.4 Days
μ = 0.08 Days^{-1}
F/M = 0.30 Days^{-1}
U = 0.29 Days^{-1}
Y_{obs} = 0.28 $^{\text{mg VSS}}/_{\text{mg COD}}$

Corrected Effluent Soluble COD = 48 - 1.42 (0.94) 25 = 14 mg/l

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* Unfiltered COD

Table C-5. Steady-state Laboratory Results for Third Test Period of the Conventional Activated Sludge Process

Day	pH	Alkalinity (mg/l)	X_a (mg/l)	X_e (mg/l)	S_o (mg/l)	S_e* (mg/l)	NO_3^--N (mg/l)
1	7.20	494.5	1010	11	395.92	14.14	11.8
2	7.20	506.0	1010	6	391.88	20.20	11.0
3	7.35	545.1	1060	11	363.60	26.26	9.4
4	7.35	554.3	1060	16	393.90	22.22	5.2
5	7.35	584.2	1000	24	399.96	32.32	3.8
6	7.35	575.0	980	22	399.96	40.40	4.5
Average	7.30	543.18	1020	15	391	26	6.5

θ_c = 5.9 Days
μ = 0.17 Days^{-1}
F/M = 0.58 Days^{-1}
U = 0.54 Days^{-1}
Y_{obs} = 0.31 $^{\text{mg VSS}}/_{\text{mg COD}}$

* Filtered COD

Table C-6. Steady-state Laboratory Results for Third Test Period of the Hydrolytic Assist Activated Sludge Process

Day	pH	Alkalinity (mg/l)	X_a (mg/l)	X_e (mg/l)	S_o (mg/l)	S_e* (mg/l)	NO_3^--N (mg/l)
1	7.45	648.6	970	44	446.4	30.3	0
2	7.45	632.5	940	42	438.3	30.3	0
3	7.30	———	820	55	454.5	26.3	0
4	7.40	648.6	880	52	442.4	30.3	0
5	7.40	———	930	47	438.3	26.3	0
6	7.40	———	880	52	446.4	28.3	0
7	7.40	650.9	890	54	442.4	30.3	0
Average	7.40	645.15	901	49	441	29	0

θ_c = 4.4 Days

μ = 0.23 Days^{-1}

F/M = 0.74 Days^{-1}

U = 0.70 Days^{-1}

Y_{obs} = 0.33 $^{\text{mg VSS}}/_{\text{mg COD}}$

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* Actual Filtered COD; Average Unfiltered Effluent COD was 102 mg/l.

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EFFECT OF MEAN CELL RESIDENCE TIME
ON THE
ACID HYDROLYTIC ASSIST ACTIVATED SLUDGE PROCESS

by

R. L. Schoenthaler

(ABSTRACT)

Handling and disposal of residual solids from wastewater treatment plants is an expensive and difficult task. The acid hydrolytic assist activated sludge process is one method of minimizing sludge production from a biological wastewater treatment process.

Acid hydrolysis of waste sludge involves pH adjustment to 1.0 or less followed by heat treatment. The hydrolyzed sludge can then be adjusted to a neutral pH and recycled to the treatment process as soluble organic material. In effect, hydrolysis promotes cellular autodigestion by artifically inducing the normally difficult metabolic steps. The use of hydrolysis in the extended aeration process allows periodic sludge wasting for control purposes but avoids the problem of ultimate sludge disposal.

Previous research was limited to the use of hydrolysis in the extended aeration process. The effect of mean cell residence time, θ_c, on an activated sludge process utilizing hydrolysis had not been evaluated. Also, only limited information is currently available regarding the kinetics of wastewater treatment with the hydrolytic assist acti-

vated sludge process. The purpose of this research was to gain additional insight into the hydrolytic assist activated sludge process with regard to mean cell residence time and the kinetics of wastewater treatment. Determination of the relative effect of hydrolysis on nitrification in the activated sludge process was a secondary objective of this study.

Mathematical and stoichiometric equations were used to predict process performance characteristics. A laboratory investigation was then conducted to obtain actual operational results for comparison. A description of the investigative procedures and results is included along with a review of the literature.