The Effect of Detention Period on the Clarification Efficiency of Nitrified Activated Sludge

1986

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THE EFFECT OF DETENTION PERIOD ON THE CLARIFICATION EFFICIENCY OF NITRIFIED ACTIVATED SLUDGE

BY

JAMES C. BOYD
B.S.E., University of Florida, 1980

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Graduate Studies Program of the College of Engineering University of Central Florida Orlando, Florida

Fall Term
1986
ABSTRACT

Proper performance of the final clarifier in the activated sludge process is vital to total system efficiency. Inadequate clarification can adversely affect substrate removal efficiency due to the biochemical oxygen demand exerted by solids lost in the clarifier effluent. Detention period is one factor which influences clarification performance and thus is of interest to the design engineer. Also of interest is the relationship between detention period and rising sludge conditions in the clarifier, which can lead to a deterioration in clarification efficiency. Rising sludge conditions are believed to be caused by the denitrification of nitrified activated sludge in the final clarifier.

An experimental program was developed to provide the necessary data to support the research objective of determining the singular significance of detention period to the steady-state effluent suspended solids concentration from the final clarifier for nitrified activated sludge. Side-by-side experimental units with a common feed slurry source were utilized in order to minimize complications associated with time-dependent biological characteristics of activated sludge.

The steady-state effluent suspended solids concentration was determined to be significantly affected by the detention period in accordance with a parabolic model which suggests a reduction in effluent suspended solids with increasing detention period up to a 5-hour optimum, above which the concentration increases. The steady-state model was developed through inclusion of additional terms that could be
statistically proven to improve model accuracy. The analysis of variance technique was utilized to confirm the model. Through visual evidence of rising sludge phenomena beyond the optimum detention period and the indication of increasing denitrification activity with increasing detention period, there is evidence to suggest that the impairment of clarification efficiency was due to denitrification within the experimental clarifier units. However, it appears that increasing the detention period to improve clarification efficiency for nitrified activated sludge can be practiced within reasonable limits without experiencing impairment of performance due to denitrification activity.
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CHAPTER I
INTRODUCTION

The need to protect the nation's water quality resources has been formally legislated through passage of the Water Pollution Control Act of 1972. This legislation provided minimum levels of treatment for municipal wastewater discharges. These minimum levels are commonly referred to as secondary treatment standards and include a 30 milligrams per liter (mg/L) effluent limitation for biochemical oxygen demand (BOD) and suspended solids.

The activated sludge process is an accepted methodology utilized to treat wastewater in compliance with secondary treatment standards. The activated sludge process was developed in England by Arden and Lockett (1914) and derived its name from the production of an activated microbial mass capable of stabilizing wastes. The microbial mass is suspended in a reactor vessel through the dispersion of air and hence is referred to as mixed liquor suspended solids (MLSS). Organic waste is introduced into the reactor vessel, also referred to as the aeration basin, in order to convert the waste into less harmful end-products. The basic end-products of this conversion process are carbon dioxide, water, ammonia and new bacterial cells. After a specified period of time, the microbial mass passes into a final clarifier for the gravitational separation of the activated sludge from the treated effluent. Subsequent to clarification, the effluent is typically chlorinated before discharge to a receiving water body or land application site. A portion of the settled sludge from the clarifier is
recycled to the aeration basin, while the remaining portion, which represents the increased population of bacterial cells, is wasted for the purpose of maintaining a constant microbial population.

The performance of the final clarifier is critical to the activated sludge process. The clarifier must provide two vital functions; adequate separation of the activated sludge from the treatment stream and proper thickening of the sludge in order to maintain the desired MLSS concentration in the reactor vessel. A clarification failure results in violation of the suspended solids limitation as well as the BOD standard due to the BOD exerted by the suspended solids.

Among the factors which affect clarification performance, detention period, which is defined as the average time that a hydraulic element resides within the clarifier, has in recent years undergone increasing scrutiny by researchers. Conventional theory attributes optimum clarification to the maintenance of a proper surface overflow rate, which is commonly defined as the influent flow to the final clarifier (excluding recycle) divided by the clarifier surface area. However, recent research has challenged the primary importance of surface overflow rate and suggests that detention period is the more critical criteria, with clarification performance observed to improve with increasing detention period.

The contemplated use of increased detention periods to improve clarification performance may have a detrimental effect when dealing with nitrified activated sludge. Under favorable environmental and operational conditions in the aeration basin, ammonia can be oxidized to nitrites and nitrates. These oxidized forms of nitrogen can be reduced to nitrogen gas under the anaerobic conditions present in the clarifier.
causing the sludge mass to become buoyant and rise to the surface. This phenomenon is termed rising sludge, and can lead to a significant degradation of clarifier performance as the rising solids are lost in the effluent stream. Concern regarding longer detention periods in the clarifier are associated with the belief that rising sludge conditions are intensified by extended solids residence.

This research program has been developed in consideration of the need for further evaluation of the relationship between clarification performance and detention period for nitrified activated sludge. Background information is presented regarding the activated sludge process, the effect of detention period on clarification efficiency and the rising sludge phenomenon. A description of the experimental program is presented, followed by a discussion of the results obtained from the program. Finally, research conclusions and the engineering significance of these conclusions are addressed.
CHAPTER II
BACKGROUND

Importance of Final Clarification

The performance of the final clarifier in the activated sludge system can significantly affect overall system efficiency. A typical activated sludge system is depicted in Figure 1. Basic system components include the aeration basin, where influent substrate is oxidized through biological processes, and the final clarifier, where the biomass is separated from the effluent. Principal system flows include the influent flow ($Q_I$), the underflow or recycled sludge flow from the final clarifier ($Q_r$), the waste sludge stream ($Q_w$) and the clarified effluent ($Q_e$).

Total system efficiency is defined as the ratio of substrate removed to influent substrate, with the substrate typically measured in terms of milligrams per liter of five day biochemical oxygen demand ($BOD_5$). The significance of final clarification to this efficiency is related to the $BOD_5$ exerted by effluent suspended solids that escape removal in the final clarifier. Dick (1970) estimates that for each mg/L of suspended solids present in the effluent, the $BOD_5$ of the effluent is increased by approximately $0.6$ mg/L.

Factors which influence final clarifier performance have been summarized by Tuntoolavest et al. (1983) and are categorized as those factors affecting bioflocculation in the aeration basin and sludge settling in the final clarifier. A summation of these factors is presented in Table 1. It is noted that those factors affecting aeration
Figure 1. Schematic Of Typical Activated Sludge System
TABLE 1

FACTORS AFFECTING THE PERFORMANCE OF ACTIVATED SLUDGE FINAL CLARIFIERS

<table>
<thead>
<tr>
<th>Factors Affecting Aeration Basin Bioflocculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Solids retention time (SRT)</td>
</tr>
<tr>
<td>• Mixed liquor suspended solids concentration in the aeration basin</td>
</tr>
<tr>
<td>• Turbulence level in the aeration basin</td>
</tr>
<tr>
<td>• Sludge recycle rate</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Factors Affecting Final Clarifier Sludge Settling</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Mixed liquor suspended solids concentration in the aeration basin</td>
</tr>
<tr>
<td>• Sludge recycle rate</td>
</tr>
<tr>
<td>• Surface overflow rate</td>
</tr>
<tr>
<td>• Detention period</td>
</tr>
</tbody>
</table>
basin bioflocculation (sludge retention time, mixed liquor suspended solids, aeration basin turbulence and sludge recycle rate) are all operational variables, i.e., these factors can be varied for a given activated sludge system. In contrast, certain factors which solely affect final clarifier sludge settling (surface overflow rate and detention period) are design parameters that generally cannot be significantly varied subsequent to construction of the final clarifier.

As a factor which influences final clarifier sludge settling, detention period is of obvious interest to the design engineer. In order to further investigate the significance of detention period, a literature search was conducted to review research findings in this area.

**Importance of Detention Period**

The detention period is the average time that a hydraulic element resides within the clarifier and can be determined by either of the following equations:

\[
\begin{align*}
\theta_t &= \frac{V}{Q_i + Q_r} \\
\theta_d &= \frac{V}{Q_i}
\end{align*}
\]

where \( V \) is the total clarifier volume and \( Q_i \) and \( Q_r \) are respectively defined as the influent and sludge recycle flows. \( \theta_t \), as represented by Equation (1), is the total detention period within the final clarifier and is based on the total combined input flow (\( Q_i + Q_r \)). \( \theta_d \), as defined by Equation (2), is the design detention period within the final clarifier, and is based on the influent flow (\( Q_i \)), neglecting the sludge recycle flow. The detention period represented by Equation
(2) is termed the design detention period in accordance with the observation made by Dick (1976) that the recycle flow is normally excluded in the calculation of recommended detention periods. However, Chapman (1983) advocates the consideration of total input flow to the clarifier for hydraulic design criteria, since the total input flow influences removal efficiency. Results of studies conducted by Chapman (1983) and Margio (1985) demonstrate that increased total input flow results in poorer effluent quality. Dick (1976) observed that use of the entire clarifier volume in the calculation of detention period, as is the standard design practice, ignores the fact that a portion of the clarifier depth is occupied by sludge and is thus unavailable for clarification.

Final clarifiers provide two principal functions, thickening and clarification. As noted by Dick (1976), the capacity of an activated sludge process for a given aeration volume is dependent on the MLSS concentration that can be maintained. Correspondingly, the MLSS concentration in the aeration basin is a function of the suspended solids concentration of the recycle sludge; hence, the importance of the thickening function of the final clarifier. Thickening performance can be evaluated through the theory of solids flux as described by Dick (1970). Relating solids flux to clarifier performance, Dick (1976) notes that the provision of adequate thickening area and solids storage depth is necessary to prevent propagation of solids into the clarification (or clear) zone, which could result in high suspended solids loss as the sludge blanket is lost over the effluent weir.
Assuming that adequate thickening area and solids storage depth are provided to prevent thickening failure, Chapman (1983) notes that consideration must also be given to the clarification function of the final clarifier. The significance of detention period to clarification efficiency has been researched by Dietz and Keinath (1984), Tuntoolavest et al. (1983), Dick (1976), Fitch (1957) and Chapman (1983). Dietz and Keinath (1984) found that clarification efficiency is strongly related to the clear zone detention period for a calcium carbonate slurry, with the clear zone for their experimental system being defined as the region above the feed well. For most full scale clarifiers wherein the feed enters as a submerged waterfall, they noted that the clear zone is defined as the region above the thickened sludge blanket. Dietz and Keinath further suggested that the dependence of clarification efficiency on detention period is associated with the flocculation of suspended solids in the clear zone, since the concentration of suspended solids remaining after flocculation is theoretically decreased by an increase in detention period. This observation is supported by Gregory (1979), who points out that the removal of suspended solids in the clarifier is a result of flocculation and entrapment of particles as well as sedimentation. Dick (1976) concluded that due to the flocculent nature of activated sludge solids, the specification of detention period is apparently an appropriate design standard for clarification. However, Dick further noted that activated sludge clarification is inhibited by floc deterioration in the aeration zone, and suggested that better floc conditioning may be warranted than that which is realized by increased detention period. Parker (1983) advocates the use of a mildly
stirred flocculation step between the aeration zone and the final clarifier in order to incorporate finely divided solids into the floc.

An evaluation of the effect of a matrix of factors on activated sludge clarification efficiency, including detention period, was conducted by Tuntoolavest et al. (1983) and Chapman (1983). Tuntoolavest et al. found that the effluent suspended solids concentration was inversely proportional to detention period in the final clarifier. A similar conclusion was reached by Chapman, wherein he found that removal efficiency increases significantly as tank depth increases.

An independent evaluation of detention period was conducted by Fitch (1957). Through use of a calcium carbonate slurry, Fitch demonstrated that detention period was a major variable governing clarification efficiency.

Detention period in the final clarifier can be increased by either increasing the tank area or tank depth. An increase in tank area would also have an affect on the surface overflow rate, which is commonly defined as the plant influent flow divided by the clarifier surface area. The apparent importance of surface overflow rate is evidenced by the specification of typical design ranges in most design manuals. This importance was theoretically established by Hazen (1904), and has been experimentally confirmed in numerous studies, including the study conducted by Tuntoolavest et al. (1983), wherein they concluded that the effluent suspended solids concentration from a pilot-scale activated sludge plant was directly proportional to the surface overflow rate. However, recent research has challenged the primary importance of surface overflow rate. In their study of clarifier efficiency utilizing
a calcium carbonate slurry, Dietz and Keinath (1984) concluded that clarifier performance was only marginally affected by surface overflow rate within the range of values examined experimentally. Further, this effect was not determined to be statistically significant. Dietz and Keinath noted that since surface overflow rate and detention period are inversely related, i.e., a decrease in detention period for a clarifier of constant dimensions results in an increase in surface overflow rate, the perceived correlation between surface overflow rate and clarifier efficiency may be actually attributable to detention period. A similar observation was made in research conducted by Cashion and Keinath (1983), wherein they concluded that surface overflow rate had little effect on the effluent suspended solids concentration from a pilot-scale activated sludge plant for surface overflow rates less than 980 gallons per day per square foot (gpd/ft²). Fitch (1957) in his research also found that detention period can be of considerably greater significance than surface overflow rate for flocculent suspensions.

Provided that adequate area is available to ensure proper thickening, several researchers have advocated an increase in tank depth as opposed to an increase in surface area. An economic analysis performed by Dietz and Keinath (1984) suggests that a deep clarifier with a small diameter is less expensive than a shallow clarifier with a large diameter, primarily due to the greater cost of the clarifier mechanism for the larger diameter unit. Based on simulation results from computer optimization modeling, Huguenard (1986) determined that the most economical method of providing an increase in detention period is to increase the clarifier depth. Chapman (1983) concluded that the deterioration in effluent quality resulting from increased flow to the
clarifier is greater for a shallow depth than for a deep depth. Chapman also noted that increased depth provides storage for solids displaced from the aeration basin during peak flow periods. In their study of wastewater flocculator - clarifiers, Parker and Stenquist (1986) concluded that deeper clarifiers with flocculation features (e.g., enlarged feed well) can handle significantly greater surface overflow rates than shallow conventional clarifiers. Performance data reviewed by Parker and Stenquist indicate that deep flocculator - clarifiers can produce average suspended solids concentrations of \(10\) mg/L or less at surface overflow rates up to \(1200\) gpd/ft\(^2\). They further noted that the performance data for deep flocculator - clarifiers was generally unresponsive to changes in surface overflow rate less than \(1200\) gpd/ft\(^2\), while in comparison, the performance of shallow clarifiers degrades rapidly with increasing overflow rates. Parker and Stenquist attribute this response to the propagation of the sludge blanket towards the effluent weirs.

**Detention Period and Rising Sludge**

Influent to the activated sludge process typically contains a significant concentration of ammonia. Under the proper environmental and operational conditions in the aeration basin, such as high pH, high temperature and extended sludge retention times, the propagation of nitrifying bacteria is favored. These bacteria oxidize ammonia to nitrites and nitrates. These oxidized nitrogen compounds can be reduced to nitrogen gas under the anaerobic conditions present in the final clarifier.
Increasing the clarifier volume in order to achieve a longer detention period and hence improve clarification efficiency causes concern in relation to the rising sludge phenomenon. In their presentation of clarifier design improvements, Stukenberg et al. (1983) point out the serious problem associated with floating sludge solids, which was concluded to result from denitrification in the clarifier. The authors note that in addition to the generation of obnoxious odors, significant deterioration of the clarifier effluent quality can occur. Design references presented by Tchobanoglous (1979) and the U.S. Environmental Protection Agency (1975) also discuss rising sludge problems caused by denitrification of nitrites and nitrates in the clarifier. The principal mechanism in the rising sludge phenomenon is the entrainment of nitrogen gas in the sludge layer. If sufficient gas is formed, the sludge becomes buoyant and rises to the surface, even after a relatively short detention period. In a case study, Eves (1981) documented problems associated with extended sludge residence in secondary clarifiers. Undesirable solids overflow was attributed to floc buoyancy caused by denitrification. In a test program at a wastewater treatment plant in Tolleson, Arizona, Parker and Stenquist (1986) observed significant rising sludge problems which adversely affected clarification removal efficiency. They attributed the problem to denitrification in the clarifier feed well, and noted that a decrease in clarifier detention period helped reduced denitrification.

An extensive review of the rising sludge phenomenon was conducted by Sawyer and Bradney (1945), wherein they studied rising sludge problems occurring at a wastewater treatment plant in Sioux Falls, South Dakota. Sawyer and Bradney studied several aspects of the problem,
including nutritional influences, critical oxidized nitrogen concentrations and nitrification inhibition. The authors concluded that the biological denitrification of nitrates to nitrites and then to nitrogen gas caused sludge buoyancy in the clarifier. The concentration of oxidized nitrogen below which floating did not occur ranged from 5 to 10 mg/L among the experiments. This observation led the authors to conclude that one possible control measure would be to prevent the production of oxidized nitrogen in excess of these critical concentrations. Sawyer and Bradney also observed that low temperatures and high organic loading limited nitrification, while a low BOD to nitrogen ratio in the influent sewage tended to form nitrifying sludges. Chemical substances which inhibited nitrifying and denitrifying bacteria, including copper sulfate and chlorine, had adverse effects on the BOD removal efficiency of the Sioux Falls plant.

The time required for sludge from the Sioux Falls plant to rise in batch settling tests as noted by Sawyer and Bradney is of importance in relation to the specification of detention period for clarifiers which must settle nitrified sludge. After samples of the activated sludge were placed in batch cylinders, the authors noted rising times ranging from 60 to greater than 150 minutes based on environmental conditions and the concentration of oxidized nitrogen. The duration required for manifestation of rising sludge problems is of concern in relation to recommended detention periods utilized by engineers for clarifier design. The Great Lakes - Upper Mississippi River Board of State Sanitary Engineers (1973), commonly abbreviated as the GLUMRB, has published design criteria for wastewater treatment plants, with the value of certain criteria dependent on the particular activated sludge
process modification. Nitrification is generally achieved with the extended aeration process. The GLUMRB recommended detention period for clarifiers following this process ranges from 3 to 4 hours depending on plant influent flow, exceeding the times noted by Sawyer and Bradney for rising sludge to occur. However, a direct comparison cannot be made, since conventional clarifiers do not operate in the batch mode but rather utilize continuous sludge withdrawal. Nonetheless, rising sludge problems are manifested at conventional facilities in response to excessive detention periods, as noted by Parker and Stenquist (1986). Due to the rising sludge phenomenon, increasing detention period to improve clarification efficiency may have an adverse effect when dealing with nitrified activated sludge. Clarifier sidewater depths greater than 16 feet have been advocated by Parker (1983). For a clarifier with a fixed surface area, this increased depth would correspond with increased detention period. The GLUMRB (1973) recommended surface overflow rate for the extended aeration process ranges from 300 to 600 gpd/ft². For a clarifier sidewater depth of 16 feet, the corresponding detention periods based on plant influent flow range from 4.8 to 9.6 hours. Assuming a 50 percent recycle rate, the corresponding detention periods based on total flow (influent plus recycle) range from 3.2 to 6.4 hours. These detention periods greatly exceed the batch settling times associated with the occurrence of rising sludge.

Need for Further Evaluation of Detention Period

Detention period within the clarifier has been identified as a factor affecting clarifier performance, although its importance is masked by its inverse relationship with another performance factor.
surface overflow rate. Researchers have noted a deterioration in effluent quality with an increase in flow to the final clarifier. The question arises whether this deterioration is due to decreased detention period or increased surface overflow rate. Studies cited herein have either failed to address the singular significance of detention period for activated sludge (i.e., detention period was evaluated within a matrix of other factors), or have used calcium carbonate slurries to address the singular significance. Therefore, there is a need to further evaluate the singular significance of detention period for activated sludge independent of variation in the surface overflow rate.

In regard to the clarification of nitrified activated sludge, several researchers cited herein have noted the occurrence of rising sludge and associated deterioration of clarification efficiency. Of particular concern are the sludge rising times determined from batch settling tests conducted by Sawyer and Bradney (1945) which ranged from 60 to more than 150 minutes. These durations required for manifestation of the rising sludge phenomenon are significantly less than detention periods recommended for design, although a direct comparison cannot be made since conventional clarifiers utilize continuous sludge withdrawal. However, the use of longer detention periods in response to apparent improvement in clarification efficiency may intensify the rising sludge phenomenon. Therefore, a trend towards longer detention periods in order to improve clarification efficiency should be further evaluated in relation to the potential manifestation of rising sludge problems when dealing with nitrified activated sludge.
CHAPTER III
RESEARCH OBJECTIVE

The final clarification process is critical to the overall efficiency of activated sludge treatment systems, as evidenced by the observation made by Dick (1970) that for each mg/L of suspended solids present in the effluent, the BOD$_5$ of the effluent is increased by approximately 0.6 mg/L. Researchers including Dietz and Keinath (1984), Tuntoolavest et al. (1983), Fitch (1957) and Chapman (1983) have established that detention period significantly affects final clarifier performance, with the consensus observation that clarification efficiency improves with increasing detention period. However, the significance of detention period for activated sludge has been masked by its inverse relationship with surface overflow rate. The studies conducted by Tuntoolavest et al. (1983) and Chapman (1983) on activated sludge clarification efficiency evaluated detention period within a matrix of other factors. Research conducted by Dietz and Keinath (1984) did evaluate the singular significance of detention period in relation to surface overflow rate. However, a calcium carbonate slurry was utilized in order to ensure constant slurry characteristics. Fitch (1957) also attempted to evaluate detention period in relation to surface overflow rate, but again, a calcium carbonate slurry was utilized. These studies which utilized calcium carbonate slurry identified the significance of detention period, with the Dietz and Keinath study clearly distinguishing between the effect of detention period and surface overflow rate. However, verification that activated
sludge behaves in a similar manner with respect to detention period, independent of variation in the surface overflow rate, is needed.

A possible detrimental effect associated with an increase in detention period in order to improve clarification efficiency is related to the rising sludge phenomenon. This phenomenon is of concern for nitrified activated sludge. As established by Sawyer and Bradney (1945), the biological denitrification of nitrates to nitrites and then to nitrogen gas in the clarifier results in sludge buoyancy. Solids overflow resulting from sludge buoyancy can lead to significant deterioration in clarification efficiency. In batch settling tests, Sawyer and Bradney noted occurrence of the rising sludge phenomenon for sludges with oxidized nitrogen concentrations ranging from 5 to 10 mg/L, which they termed the critical concentration. The researchers also noted rising sludge problems for those batch tests with durations ranging from 60 to greater than 150 minutes. These observations made by Sawyer and Bradney are of interest in the specification of detention period for nitrified activated sludge in that they have identified oxidized nitrogen concentrations that may trigger the rising sludge phenomenon, and have noted durations required for the sludge to rise which are well below detention periods commonly used in practice. The specification of detention periods beyond those commonly cited for design in response to evidence which supports the contention that clarification efficiency is improved with increasing detention period could intensify the rising sludge potential of nitrified sludges. A direct comparison between the rising times noted by Sawyer and Bradney and detention period cannot be made since their experiments were based
on batch settling tests which are incompatible with the continuous recycling of sludge practiced in conventional activated sludge facilities. Therefore, an evaluation of any detrimental effect in relation to increased detention period which could be attributed to the rising sludge phenomenon for nitrified activated sludge is necessary. The activated sludge should exhibit oxidized nitrogen concentrations in excess of the critical values noted by Sawyer and Bradney.

In consideration of the need for further evaluation of the relationship between detention period and clarification efficiency, the objective of this research program is to determine the singular significance of detention period to the steady-state effluent suspended solids concentration from the final clarifier for nitrified activated sludge. An experimental program was developed to provide the necessary data to support this objective.
CHAPTER IV
EXPERIMENTAL PROGRAM

Description of Experimental Program

An experimental program was developed to provide the necessary data to support the research objective of determining the singular significance of detention period to the steady-state effluent suspended solids concentration from the final clarifier for nitrified activated sludge. Side-by-side experimental units with a common feed slurry source were utilized in order to minimize complications associated with time-dependent biological characteristics of activated sludge. The evaluation of clarifier performance in response to detention period is based on steady-state conditions. Similar research conducted by Dietz (1982) and Margio (1985) indicated that an experimental period of 8 hours was sufficient to achieve steady-state.

The activated sludge feed slurry source was obtained from the aeration basin at the University of Central Florida (UCF) Wastewater Treatment Facility, which is located adjacent to the experiment area. The UCF facility is operated in the extended aeration mode at a long solids retention time (26 days) and thus the activated sludge was expected to be fully nitrified. For verification, the feed slurry was sampled for nitrate concentration at the end of the 8-hour period. The feed slurry MLSS concentration was approximately 2700 mg/L for each experiment, although some variation was noted due to the operational dynamics of the UCF facility. Mixed liquor at the UCF facility
generally exhibits a pH ranging from 6.9 to 7.0 and a temperature ranging from 20 to 22°C. The dissolved oxygen concentration ranges between 1 to 3 mg/L, with 1.5 mg/L being the operational set point.

Further description of the experimental program requires a discussion of flow units. Flow to or from the clarifier can be expressed in absolute terms, i.e., cubic meters per day, or in terms specific to the clarifier surface area. For example, the surface overflow rate, which is commonly defined as the plant influent flow divided by the clarifier surface area, is expressed in absolute metric terms as cubic meters per square meters per day. However, in specific terms, the absolute units simplify to meters per day (m/day), and can be further converted to meters per hour (m/hr). It is often convenient to express clarifier flow in this manner. For example, in order to determine the total clarifier detention period in hours, the clarifier water depth in meters is divided by the sum of the total flow to the clarifier expressed in meters per hour.

As a matter of convenience, the terms recycle flow and underflow are used interchangeably in the description of this experimental program. It is noted that for most activated sludge plants, the underflow from the final clarifier is comprised of recycle flow and waste sludge flow as illustrated in Figure 1. However, the waste sludge flow is only a small percentage of the underflow, and thus no distinction is made herein between recycle flow and underflow.

In order to address the singular significance of detention period, the surface overflow rate was held constant throughout the experimental program. The relationship between surface overflow rate and the minimum
clarifier underflow rate required to prevent a thickening overload was determined through a settling flux analysis of the activated sludge from the UCF facility as described by Margio (1985). Assuming a surface overflow rate of 8.15 m/day (200 gpd/ft²), the minimum required underflow rate to prevent a thickening overload was determined to be 3.7 m/day, which is equivalent to approximately 50 percent of the assumed surface overflow rate.

The assumed 8.15 m/day surface overflow rate is low in terms of standard design practice. However, a low rate was selected in order to promote clarification efficiency and thus eliminate any potential masking effect that a detrimental surface overflow rate may have on the relationship between clarifier performance and detention period. Additionally, a low surface overflow rate was desired in order to achieve high detention periods with reasonable experimental unit depths.

The sum of the surface overflow rate and the underflow rate is equivalent to the total flow, or feed rate, to the final clarifier. Detention periods studied in this research program were defined based on total flow and total clarifier sidewater depth. In order to maintain a constant surface overflow rate, the detention period was varied through use of different clarifier sidewater depths and variable recycle rates while maintaining a constant clarifier surface area.

A summary of the experimental program is presented in Table 2. As noted, the experimental units were labeled Column A and Column B and a total of five experiments were conducted. Recycle flow rates were varied between 50 to 150 percent to effect a variation in detention period for 2 m and 3 m experimental column sidewater depths. However,
<table>
<thead>
<tr>
<th>EXP.</th>
<th>COLUMN</th>
<th>SURFACE OVERFLOW RATE (m/hr)</th>
<th>PERCENT RECYCLE</th>
<th>UNDERFLOW RATE (m/hr)</th>
<th>FEED RATE (m/hr)</th>
<th>COLUMN WATER DEPTH (m)</th>
<th>DETENTION PERIOD (hr)</th>
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<tr>
<td>1*</td>
<td>A</td>
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<td>3.92</td>
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<tr>
<td></td>
<td>B</td>
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<td>0.17</td>
<td>0.51</td>
<td>3</td>
<td>5.88</td>
</tr>
</tbody>
</table>

*Experiment 1 is a replicate of Experiment 4 conducted by Margio (1985). These two replicate experiments were utilized for experimental error analysis.
the recycle rate was held constant for both columns during each individual experiment in order to eliminate the effect of recycle rate on clarification efficiency. The 50 percent recycle rate is equivalent to the minimum underflow rate required to prevent a thickening overload as determined by Margio (1985) for the UCF activated sludge slurry, while the 150 percent recycle rate represents the upper end of the recycle range recommended by the GLUMRB (1973) for extended aeration facilities. Resulting detention periods range between 2.36 to 5.88 hours, and are considered to be inclusive of detention periods commonly cited for design as well as detention periods which may be attained through use of deeper clarifiers as advocated by Parker (1983). Surface overflow, underflow and feed rates are expressed in terms of meters per hour for convenience in calculating the detention period. For the purpose of experimental error analysis, the experimental program includes two replicate experiments held constant at a detention period of 4.42 hours in columns A and B. These replicate experiments include Experiment 1 conducted by this researcher and Experiment 4 conducted by Margio (1985).

Description of Experimental Units

The side-by-side experimental units, as depicted in Figure 2, consisted of cast acrylic settling columns 20.3 centimeters (cm) in diameter. Column sidewater depths of 2 or 3 meters were obtainable through removal of a 1 m column section. The center feedwell and effluent weir box were also constructed of cast acrylic. The feedwell was 6.35 cm in diameter and extended 1 m below the free water surface. The weir box enclosed a series of 90° v-notch weirs which were milled
Figure 2. Side-By-Side Experimental Settling Units
into the top of the column. A stirring rake was installed to prevent potential coning problems at the base of the column and was operated at a speed of one revolution per minute.

Variable speed Masterflex positive displacement pumps were utilized to control the feed and underflow rates. A Model 7018 was used to deliver the feed slurry while a Model 7015 was utilized for underflow pumping. As previously discussed, the feed rate was equivalent to the sum of the specified surface overflow and underflow rates. The overflow and underflow were directly wasted to facilitate precise control of the feed and underflow streams. This procedure facilitated precise control in that the overflow and underflow streams could be individually monitored through use of a graduated cylinder and stopwatch to ensure that the flow rates were consistent with the experimental design. Each column was individually operated with dedicated feed and underflow pumps equipped with tachometers.

A 450 liter plastic cylindrical reservoir was used to contain the feed slurry during the 8-hour experimental period. The activated sludge was kept aerobic through utilization of an aeration system consisting of an air compressor and a PVC diffuser ring. Suction tubes from the feed pumps were suspended in the reservoir at the same location to ensure that the settling columns were receiving common feed slurry.

Description of Experimental Procedure

The step-by-step procedure consistently utilized for each experiment is summarized as follows:

1. Completely fill the settling columns with tap water.
2. Transfer the activated sludge from the UCF aeration basin to the feed slurry reservoir through use of a screw centrifugal pump and garden hoses. Fill reservoir, allowing three to four inches of freeboard.

3. Turn on feed slurry reservoir aeration system for the duration of the experiment.

4. Turn on stirring rake in each settling column.

5. Set each feed pump to the desired initial speed and deliver feed slurry to the feedwell of each settling column.

6. Set each underflow pump to the desired initial speed and withdrawal underflow from each settling column.

7. Continue operation for the duration of the 8-hour period to reach steady-state.

8. Collect replicate feed, overflow and underflow samples for characterization of steady-state conditions.

A curve relating pump speed to flow rate was developed for each pump to facilitate the setting of the initial pump speeds. As previously noted, overflow and underflow streams were continually monitored throughout the duration of the experiment through use of a graduated cylinder and stopwatch to verify that the flow rates were consistent with the experimental design. Any variation was promptly corrected through adjustment of the appropriate pump speed. Setting the desired underflow rate and then maintaining the proper overflow rate through adjustment of the feed rate was found to be the most expedient method for ensuring flow control.
Overflow and underflow samples were taken at intervals of one hour. Overflow effluent samples were withdrawn by placing the suction line of a variable speed positive displacement pump just below the free water surface of the weir crest. The underflow was sampled directly from the underflow waste line. Feed slurry samples taken at the 8-hour period were taken from the feed pump discharge line. Single samples of the effluent and underflow were taken at hours 1 through 7 for each column. At the 8-hour steady-state period, replicate effluent, underflow and feed slurry samples were collected for the characterization of steady-state conditions for each column. Single effluent and feed slurry samples were also collected for the determination of nitrate concentrations. The number of replicate samples and sample size are presented in Table 3. Samples for suspended solids analysis were preserved by refrigeration at 4°C, while samples collected for nitrate analysis were preserved through the addition of sulfuric acid to lower the pH to below 2 and refrigeration at 4°C. Suspended solids analyses were analyzed within 24 hours of collection, while nitrate analyses were conducted within 48 to 72 hours of collection.

Suspension solids analysis followed the procedure for total nonfilterable residue presented in Standard Methods (1975). Generally, each sample undergoing suspended solids analysis was vacuum-filtered through a pre-weighed and pre-washed Whatman GF/C glass fiber filter pad, after which it was dried overnight in an oven set at 103 to 105°C. The following day, the filter pads containing the dried solids were removed from the oven and placed in a desiccator for cooling prior
TABLE 3

SAMPLING SCHEDULE FOR EACH COLUMN

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>1-7 HOUR SUSP. SOLIDS</th>
<th>8 HOUR NITRATE</th>
<th>8 HOUR SUSP. SOLIDS</th>
<th>COLLECTED SAMPLE SIZE* (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FREQUENCY</td>
<td>NUMBER</td>
<td>NUMBER</td>
<td>NUMBER</td>
</tr>
<tr>
<td>Effluent</td>
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<td>10</td>
</tr>
<tr>
<td>Underflow</td>
<td>hourly</td>
<td>1</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Feed</td>
<td>none</td>
<td>-</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

*For samples with high solids content, only a portion of the collected sample was analyzed.
to determining the dry solids weight. Nitrate analysis was conducted in conformance with the Brucine colorimetric method as detailed in Standard Methods (1975).
CHAPTER V
RESULTS AND DISCUSSION

General Observations

Subsequent to introduction of mixed liquor into the settling column, three distinct zones began to form: thickened sludge blanket, dispersed sludge blanket and clear zone. The thickened sludge blanket generally stabilized after 3 to 4 hours and extended approximately 18 to 20 cm above the bottom of the column. An exception to this depth was noted in Experiment 5, where the thickened blanket grew steadily throughout the day to a thickness of approximately 50 cm at the conclusion of the experiment. The depth of the thickened sludge blankets were generally the same in both columns during each experiment, with variations of no more than 1 to 2 cm between columns.

The dispersed sludge blanket extended from the top of the thickened sludge blanket to the bottom of the feed well, while the clear zone extended from the interface with the dispersed sludge blanket to the effluent weir. During all of the experiments, dispersed sludge particles were observed rising in the clear zone towards the effluent discharge. The number of dispersed particles in the clear zone generally appeared to decrease after approximately 6 hours. The clear zone also appeared to become more colored throughout the experiment; this condition was especially noticeable after approximately 7 hours.

The variation of Experiment 5 from the earlier experiments, as noted in regard to the thickened sludge blanket depth, was also manifested in the appearance of the clear zone. The number of dispersed
particles in the clear zone was visually greater than in previous experiments, and bubbles were noted in the effluent samples. Additionally, a light scum formed along the weir edges. The detention periods for Experiment 5 were 3.92 hours in Column A and 5.88 hours in Column B, which were at the high end of the experimental range. The observations noted during Experiment 5 suggest that sludge rising was occurring.

The maintenance of constant feed and underflow rates required continual attention and was accomplished through minor speed adjustments of the feed and recycle pumps. Adjustments were based on constant monitoring of the overflow and underflow rates through use of a graduated cylinder and stopwatch.

Another operating condition that required careful attention involved the underflow suction line. Generally once during each experiment, the suction line of one or both columns became plugged with a solids particle. Prompt removal of the particle resulted in recycle flow stoppages of less than 30 seconds.

**Experimental Results**

Column A and B experimental results for the 8-hour average steady-state condition, including the effluent, underflow and feed suspended solids concentrations, are presented in Table 4 for experiments 1 through 5. The Appendix contains a complete listing of the 8-hour steady-state experimental data.

Feed slurry and column A and B effluent nitrate concentrations for experiments 1 through 5 are presented in Table 5. The concentrations reported in Table 5 were determined from single grab samples taken at
<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>COLUMN</th>
<th>DETENTION PERIOD (hr)</th>
<th>EFFLUENT SUSPENDED SOLIDS CONCENTRATION (mg/L)</th>
<th>UNDERFLOW SUSPENDED SOLIDS CONCENTRATION (mg/L)</th>
<th>FEED SUSPENDED SOLIDS CONCENTRATION (mg/L)</th>
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</thead>
<tbody>
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<tr>
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<td>1.95</td>
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<td>3024</td>
</tr>
<tr>
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**Table 5**

8-HOUR FEED SLURRY AND EFFLUENT NITRATE CONCENTRATIONS

<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>COLUMN</th>
<th>DETENTION PERIOD (HR)</th>
<th>FEED SLURRY NITRATE CONCENTRATION (mg/L)*</th>
<th>EFFLUENT NITRATE CONCENTRATION (mg/L)*</th>
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</thead>
<tbody>
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<td>1</td>
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<td>6.8**</td>
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<td>A</td>
<td>2.94</td>
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<tr>
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<td>5.88</td>
<td></td>
<td>15.8</td>
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</table>

*Nitrate Nitrogen as N, mg/L

**Sampled from UCF aeration basin. The remaining samples were obtained from the feed slurry reservoir.
the 8-hour period in order to verify that the activated sludge slurry was in a nitrified condition. Examination of the nitrate concentrations presented in Table 5 indicates that a nitrified activated sludge slurry was utilized in all five experiments. Feed slurry nitrate samples for experiments 1 and 2 were sampled from the UCF plant aeration tank rather than the feed slurry reservoir. As discussed in the experimental procedure, feed slurry from the UCF aeration basin was transferred to the reservoir at the beginning of each experiment. Due to the variation in aeration basin mixed liquor characteristics resulting from biological activity and changes in raw wastewater composition during the experiment, the feed slurry in the reservoir and the mixed liquor in the aeration basin were not identical throughout the 8-hour experimental period. The discrepancy in sampling location accounts for the feed slurry nitrate concentrations being less than the effluent nitrate concentrations for experiments 1 and 2. Feed slurry nitrate samples for experiments 3 through 5 were properly taken from the feed slurry reservoir.

The nitrate concentrations presented in Table 5 are suggestive of denitrification activity. For experiments 3 through 5 (proper feed slurry sampling point), the effluent nitrate concentrations are consistently less than the feed slurry nitrate concentration. Further, the longer the detention period, the greater the difference between the feed slurry nitrate concentration and the effluent nitrate concentration. These observations suggest denitrification activity increases with increasing detention period, and will be considered when...
discussing the relationship between detention period and the effluent steady-state suspended solids concentration.

A plot of steady-state effluent suspended solids concentration versus detention period is presented in Figure 3. The plot indicates a decrease in effluent suspended solids concentration with increasing detention period. A statistical analysis is necessary in order to address the significance of this apparent relationship.

Selection of Steady-State Model

Models are employed to describe the relationship between variables. The objective of this analysis is to determine the relationship between detention period (the independent variable) and effluent suspended solids concentration (the dependent variable). The effluent suspended solids concentration is considered the dependent variable since the independent manipulation of detention period is theorized to produce a dependent effect on the effluent suspended solids concentration. Statistical techniques were employed to define models that represent the experimental relationship between steady-state effluent suspended solids concentration and detention period.

Statistical Background

The statistical analysis was limited to utilization of linear models. A general two-parameter linear model can be expressed as follows (Mendenhall 1968):

\[ y = B_0 + B_1x + e \]  

(3)
Figure 3. Steady-State Effluent Suspended Solids Concentration Versus Detention Period
where \( y \) is the dependent or response variable, \( B_0 \) and \( B_1 \) are model parameters, \( x \) is the independent variable, and \( e \) is a random variable which represents the variability of \( y \) for a given value of \( x \).

The linear model expressed by Equation (3) represents a straight-line relationship between the response and independent variables. However, the models developed for consideration herein will not be restricted to straight-line forms, since the inclusion of a second-order term can be used to describe a curvilinear relationship between the dependent and independent variables.

A curvilinear response linear model is represented by Equation (4):

\[
y = B_0 + B_1 x + B_2 x^2 + e
\]  

Equation (4) is the mathematical relationship for a parabola. The significance of this model will be evaluated, since it is postulated that effluent suspended solids concentrations at high detention periods may increase due to denitrification activity.

The random error term as expressed in equations (3) and (4) is assumed to have a mean equal to zero and a constant variance equal to the variance of the observed values of \( y \) (Neter and Wasserman 1974). Hence, the predicted value of \( y \) is a probability distribution whose mean is expressed by the following equation (Mendenhall 1968):

\[
\hat{y}_i = B_0 + B_1 x_i
\]  

where \( \hat{y}_i \) is the predicted value of the dependent variable, \( B_0 \) and \( B_1 \) are parameter estimates and \( x_i \) is the independent variable. Model parameters will be estimated through utilization of the least squares
technique, which seeks to minimize the sum of squares of deviations between observed and predicted values of $y$.

The accuracy of the linear model in defining the relationship between the response and independent variables can be improved through inclusion of additional terms, such as addition of the $B_{2x^2}$ term to Equation (3) to produce the curvilinear Equation (4). This accuracy is quantified through the residual sum of squares technique, which represents the deviation between observed and predicted values for the dependent variable. The residual sum of squares is expressed as follows (Neter and Wasserman 1974):

$$RSS = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$  \hspace{1cm} (6)

where $RSS$ is the residual sum of squares and $y_i$ is the observed value of the dependent variable. Model accuracy is increased through inclusion of additional terms, since the model would more closely approximate the observed response, thereby minimizing the difference between observed and predicted values.

Although the inclusion of additional terms can increase the accuracy of the model, the inclusion of too many terms may compromise the usefulness of the model. A determination of the significance of including additional terms in the model may be accomplished through use of the analysis of variance technique, wherein terms are sequentially added to the model as long as it can be proven that a statistically significant reduction in the residual sum of squares is accomplished through term addition.
The deviation between the observed and predicted values of $y$, as represented by the residual sum of squares, is attributable to two factors; lack of fit and experimental error. Lack of fit represents the error associated with model specification, i.e., lack of fit attributable to the mathematical limitations of the model. For this particular experimental program, lack of fit is also attributable to the time-dependent biological characteristics of activated sludge. Although the use of side-by-side experimental units eliminates time-dependent variations for a particular experiment, these variations cannot be eliminated when comparing a range of experiments conducted at different times.

Experimental error results from such independent variables as sampling and analytical error which occur during determination of the observed values. A useful method for estimation of experimental error is the use of replicate experiments.

The hypothesis associated with the analysis of variance technique requires that the parameter (e.g., $B_2$) associated with the additional term (e.g., $x^2$) be equal to zero, which is equivalent to stating that inclusion of the term does not improve the model. The analysis of variance requires a comparison between the hypothesis mean square and the error mean square.

The hypothesis mean square ($HMS$) is calculated as follows:

$$HMS = \frac{HSS}{HDF}$$

where $HSS$ is the hypothesis sum of squares and $HDF$ is the hypothesis degrees of freedom. The hypothesis sum of squares is determined by
calculating the difference between the residual sum of squares for the two models under comparison:

\[ HSS = RSS_1 - RSS_2 \]  \hspace{1cm} (8)

where \( RSS_1 \) and \( RSS_2 \) are the residual sum of squares for models 1 and 2 respectively. The hypothesis degrees of freedom (HDF) is equal to the number of independent constraints associated with the hypothesis. For this analysis, the hypothesis degrees of freedom is equal to one, since the only constraint established by the hypothesis is represented by setting the additional term parameter equal to zero.

Replicate experiment pairs, held constant at a detention period of 4.42 hours in columns A and B, were analyzed to provide an estimate of experimental error. Two replicate experiment pairs were conducted, one by this researcher (Experiment 1) and one by Margio (1985). The steady-state effluent suspended solids concentrations determined by Margio were \( 0.91 \text{ mg/L} \) and \( 0.84 \text{ mg/L} \) for columns A and B respectively. For the experimental error estimation, Experiment 1 conducted by this researcher is termed Replicate Experiment Pair Y, while the experiment conducted by Margio is termed Replicate Experiment Pair Z.

The error mean square (EMS) is computed by Equation (9):

\[ EMS = \frac{ESS}{EDF} \]  \hspace{1cm} (9)

where \( ESS \) is the error sum of squares and \( EDF \) is the error degrees of freedom. To calculate the error sum of squares, the residual sum of squares is determined for each replicate experiment pair by calculating the mean of the observed values for columns A and B and squaring the
The difference between the observed values and calculated mean value. The error sum of squares is then found by totaling the residual sum of squares determined for both replicate experiment pairs. This procedure is summarized by Equation (10):

$$\text{ESS} = \sum_{k=1}^{2} \sum_{j=1}^{2} (y_{kj} - \bar{y}_k)^2$$

(10)

where $k_1$ and $k_2$ represent replicate experiment pairs $Y$ and $Z$ respectively, $\bar{y}_k$ is the mean of the observed steady-state effluent concentrations for replicate experiment pair $k$, $j_1$ and $j_2$ represent columns A and B respectively and $y_{kj}$ is the observed steady-state effluent concentration from column $j$ for the replicate experiment pair $k$. The error degrees of freedom equals the number of observed values associated with the replicate experiments minus one degree of freedom lost for each estimated parameter. Since four observed values are associated with the two replicate experiment pairs, and the mean of each experiment pair was calculated for a total of two estimated parameters, the degrees of freedom associated with the error mean square is equal to two.

The F-test is employed to determine whether the hypothesis mean square is significantly greater than the error mean square for a specified confidence interval. The F-statistic is the ratio of hypothesis mean square to error mean square (Neter and Wasserman 1974).

$$F = \frac{\text{HMS}}{\text{EMS}}$$

(11)

The F-test assumes independent, normally distributed populations and always utilizes a one-tailed rejection region (Mendenhall 1968). The
calculated F-statistic is compared to the tabulated F-statistic for the particular confidence interval. If the calculated F-statistic exceeds the tabulated value, then there is sufficient evidence to reject the hypothesis that the parameter is equal to zero. Conversely, if the calculated F-statistic is less than the tabulated value, then there is insufficient evidence to reject the hypothesis, i.e., the provision of the additional term does not significantly increase the accuracy of the model.

Model Selection

Review of the experimental data plotted in Figure 3 suggests the following equations that may possibly describe the modeled relationship between effluent suspended solids and detention period:

Model I: \[ \hat{Y}_i = B_0 \]  \hspace{1cm} (12)

Model II: \[ \hat{Y}_i = B_1 + B_2x_i \]  \hspace{1cm} (13)

Model III: \[ \hat{Y}_i = B_3 + B_4x_i + B_5x_i^2 \]  \hspace{1cm} (14)

As evidenced by the candidate models, the sequential addition of terms was used as a technique for model building and improvement of model accuracy. Model I represents a simple straight-line relationship wherein the predicted value for the response variable (\( \hat{Y}_i \)) is equal to a constant (\( B_0 \)), which is set equal to the mean of the observed values. Model II attempts to improve model accuracy by including the effect of the independent variable (detention period) in a straight-line relationship. As previously discussed the plotted data indicates a decrease in effluent suspended solids concentration with increasing
detention time. Model III is a curvilinear response linear model representing a parabolic relationship between the dependent and independent variables through inclusion of the square of the detention period term \( (x_1^2) \). This model may more accurately reflect the relationship between effluent suspended solids and detention period due to the postulated detrimental effects of denitrification at higher detention periods.

Parameter estimates and residual sum of squares for each model are presented in Table 6. Model parameters for models I, II and III were estimated through utilization of least squares methodology, while Equation (6) was used to determine the residual sum of squares for each model. Given the parameter estimates, the candidate models are plotted in Figure 4.

The sequential addition of terms does lead to an apparent improvement in model accuracy as evidenced by a decrease in the residual sum of squares from Model I to Model II to Model III. The significance of this apparent improvement must be tested through utilization of the analysis of variance technique.

Determination of the error mean square is summarized in Table 7. As previously discussed, two replicate experiment pairs, conducted at a constant detention period of 4.42 hours, were utilized for experimental error estimation.

The analysis of variance to determine the significance of detention period (comparison of Model I to Model II) is presented in Table 8. The hypothesis associated with this comparison is obtained by setting the parameter estimate \( B_2 \) of the additional term \( (x_1) \) in Model II equal to
TABLE 6
PARAMETER ESTIMATES AND RESIDUAL SUM OF SQUARES
FOR THE CANDIDATE MODELS

<table>
<thead>
<tr>
<th>MODEL NUMBER</th>
<th>PARAMETER ESTIMATES*</th>
<th>RESIDUAL SUM OF SQUARES</th>
</tr>
</thead>
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<td>$B_0$</td>
<td>$B_1$</td>
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<tr>
<td>I</td>
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<td></td>
</tr>
<tr>
<td>II</td>
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</tr>
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<td>III</td>
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</table>

*Unit Basis: Suspended solids - mg/L
Detention period - hr
Figure 4. Plot Of Candidate Models
### TABLE 7
DETERMINATION OF ERROR MEAN SQUARE

<table>
<thead>
<tr>
<th>REPLICATE EXPERIMENT PAIR*</th>
<th>EFFLUENT CONC. (mg/L)</th>
<th>MEAN CONC. (mg/L)</th>
<th>RESIDUAL SUM OF SQUARES</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>COLUMN A</td>
<td>COLUMN B</td>
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</tr>
<tr>
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<td>1.83</td>
<td>1.95</td>
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<td>Z</td>
<td>0.91</td>
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<td>0.875</td>
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</table>

Error Sum of Squares = 0.0072 + 0.0024 = 0.0096

Error Degrees of Freedom = 4 - 2 = 2

Error Mean Square = 0.0096/2 = 0.0048

*Y - Experiment 1 (See Table 4).

Z - Experiment 4 conducted by Margio (1985).
TABLE 8
ANALYSIS OF VARIANCE TO DETERMINE
THE SIGNIFICANCE OF DETENTION PERIOD
(COMPARISON OF MODELS I AND II)

Hypothesis: $B_2 = 0$

Hypothesis Sum of Squares = 9.23 - 8.88 = 0.35
Hypothesis Degrees of Freedom = 1
Hypothesis Mean Square = 0.35

Error Mean Square = 0.0048
Error Degrees of Freedom = 2

$F$ (Calculated) = $0.35/0.0048 = 72.9$
$F (0.05, 1, 2) = 18.5$

Conclusion: There is sufficient evidence to reject the hypothesis that $B_2 = 0$. Therefore, conclude that the steady-state effluent suspended solids concentration is significantly affected by detention period.
zero. As detailed in Table 8, the calculated F-statistic (72.9) is greater than the tabulated F-statistic (18.5) at the 95 percent confidence interval. Therefore, the hypothesis is rejected, and it is concluded that the effluent suspended solids concentration is significantly affected by detention period. Further, since the parameter estimate $B_2$ is negative, the effluent suspended solids concentration decreases with increasing detention period.

Table 9 presents the analysis of variance to determine the significance of the square of detention period (comparison of Models II and III). The hypothesis associated with this comparison is obtained by setting the parameter estimate ($B_5$) of the additional term ($x_i^2$) equal to zero. The additional term is determined to be significant, since the calculated F-statistic (79.2) is greater than the tabulated F-statistic (18.5) at the 95 percent confidence interval. Rejection of the hypothesis leads to the conclusion that the effluent suspended solids concentration is significantly affected by the square of detention period. Further, the effluent suspended solids concentration decreases with increasing detention period up to a certain optimum period, above which the effluent suspended solids concentration tends to increase.

**Discussion**

Based on a comparison of the candidate models I, II and III by the analysis of variance technique, Model III was selected to describe the response between steady-state effluent suspended solids concentration and detention period for the experimental data. The mathematical relationship for Model III, including values for the associated parameter estimates, is presented as follows:
TABLE 9

ANALYSIS OF VARIANCE TO DETERMINE
THE SIGNIFICANCE OF THE SQUARE OF DETENTION PERIOD
(COMPARISON OF MODELS II AND III)

Hypothesis: $B_5 = 0$

Hypothesis Sum of Squares = $8.88 - 8.50 = 0.38$
Hypothesis Degrees of Freedom = 1
Hypothesis Mean Square = $0.38$

Error Mean Square = $0.0048$
Error Degrees of Freedom = 2

$F \text{ (Calculated)} = \frac{0.38}{0.0048} = 79.2$
$F (0.05, 1, 2) = 18.5$

Conclusion: There is sufficient evidence to reject the hypothesis that $B_5 = 0$. Therefore, conclude that the steady-state effluent suspended solids concentration is significantly affected by the square of detention period.
Model III:  \[ \hat{y}_i = 5.107 - 1.163x_i + 0.115x_i^2 \]  

where \( \hat{y}_i \) is the predicted steady-state effluent suspended solids concentration in mg/L and \( x_i \) is the detention period in hours.

This parabolic relationship represents decreasing values for the response variable up to an optimum value for the independent variable, after which the response variable increases. It is stressed that this relationship is independent of surface overflow rate, since the surface overflow rate was held constant at 8.15 m/day (200 gpd/ft\(^2\)) throughout the experiments. The optimum value for the independent variable (detention period) can be found by differentiating the equation and setting the change in the response variable (\( \text{dy} \)) equal to zero.

\[
\text{dy} = \phi = -1.163 + 0.23x
\]

Solution of Equation (16) for the optimum detention period results in a value of 5 hours. Thus, based on the mathematical approximation of the response as represented by Model III, the minimum effluent suspended solids concentration is expected to occur within a detention period of 5 hours. This relationship is depicted graphically by the plot of Model III as presented in Figure 4.

The relationship between clarification efficiency and detention period can be related to the possible detrimental effects of denitrification activity. As previously noted, nitrate concentrations reported in Table 5 were determined from single grab samples taken at the 8-hour period in order to verify that the activated sludge was in a nitrified condition. However, given the visual evidence of denitrification activity and the quantitative evidence of impaired
clarification efficiency at high detention periods, a discussion of the possible detrimental effects of denitrification is warranted.

The reversal of the trend of decreasing effluent suspended solids concentration with increasing detention period after a 5-hour optimum is suggestive of the possible detrimental effects of denitrification at high detention periods. As evidence of denitrification activity, the feed slurry and effluent nitrate concentrations for experiments 3 through 5 are compared in Table 10. (Results from experiments 1 and 2 are not compared since the feed slurry nitrate concentrations were sampled from the UCF plant aeration tank rather than feed slurry reservoir.) It is noted that the greatest difference between the feed slurry nitrate concentration and the effluent nitrate concentration occurred at the highest detention period (5.88 hours). Furthermore, the greater the detention period, the greater the reduction in nitrate concentration from the feed slurry to the effluent. Given this evidence, it is apparent that denitrification activity was occurring throughout the experiments, and that this activity tended to increase with increasing detention period.

Visual evidence of denitrification activity and associated rising sludge phenomena was noted for Experiment 5, which was conducted at detention periods of 3.92 hours (Column A) and 5.88 hours (Column B). The thickened sludge blanket was approximately two and one-half times the depth of the thickened blanket in previous experiments, and the number of dispersed particles in the clear zone was visually greater than in previous experiments, resulting in a light scum along the weir edges. Bubbles were also observed in the effluent samples.
TABLE 10
COMPARISON OF 8-HOUR FEED SLURRY AND EFFLUENT NITRATE CONCENTRATIONS

<table>
<thead>
<tr>
<th>EXPERIMENT*</th>
<th>DETENTION PERIOD (hr)</th>
<th>FEED SLURRY NITRATE CONCENTRATION (mg/L)**</th>
<th>EFFLUENT NITRATE CONCENTRATION (mg/L)**</th>
<th>DIFFERENCE (mg/L)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>4(A)</td>
<td>2.36</td>
<td>24.7</td>
<td>24.5</td>
<td>0.2</td>
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<tr>
<td>4(B)</td>
<td>3.53</td>
<td>24.7</td>
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<td>1.1</td>
</tr>
<tr>
<td>3(A)</td>
<td>3.92</td>
<td>25.3</td>
<td>24.2</td>
<td>1.1</td>
</tr>
<tr>
<td>5(A)</td>
<td>3.92</td>
<td>20.8</td>
<td>19.4</td>
<td>1.4</td>
</tr>
<tr>
<td>3(B)</td>
<td>5.88</td>
<td>25.3</td>
<td>21.9</td>
<td>3.4</td>
</tr>
<tr>
<td>5(B)</td>
<td>5.88</td>
<td>20.8</td>
<td>15.8</td>
<td>5.0</td>
</tr>
</tbody>
</table>

*Experiment Number (Column Number)

**Nitrate Nitrogen as N, mg/L
The conditions noted by Sawyer and Bradney (1945) considered necessary for the rising sludge phenomenon to occur were present throughout the experimental program. Sawyer and Bradney cited critical oxidized nitrogen concentrations of 5 to 10 mg/L required for significant sludge rising. In comparison, feed slurry nitrate concentrations ranged from 6.8 mg/L to 25.3 mg/L among the experiments conducted for this research program. Sawyer and Bradney further noted durations required for the sludge to rise ranging from 60 to greater than 150 minutes. These durations were obtained from batch settling tests and were not thought to be directly comparable to conventional clarifiers which utilize continuous sludge withdrawal. The experimental results of this research program tend to support this contention, since detention periods ranging from 2.36 to 5.88 hours were analyzed, and no adverse effects from denitrification activity were noted for detention periods less than 5 hours, based on the finding that steady-state effluent suspended solids concentrations decreased with increasing detention period up to this optimum value. It is stressed that the relationship between effluent suspended solids and detention period as determined by this research program is independent of surface overflow rate, since the surface overflow rate was held constant at 8.15 m/day (200 gpd/ft²) throughout the experiments.
CHAPTER VI
CONCLUSIONS AND ENGINEERING SIGNIFICANCE

Conclusions

The singular significance of detention period to the steady-state effluent suspended solids concentration from the final clarifier for nitrified activated sludge was evaluated through utilization of side-by-side experimental units with a common feed slurry source. The steady-state effluent suspended solids concentration was determined to be significantly affected by the detention period in accordance with the following model:

\[ \hat{y}_i = 5.107 - 1.163x_i + 0.115x_i^2 \]  \hspace{1cm} (15)

where \( \hat{y}_i \) is the predicted steady-state effluent suspended solids concentration in mg/L and \( x_i \) is the detention period in hours. The steady-state model was developed through inclusion of additional terms that could be statistically proven to improve model accuracy. The analysis of variance technique was utilized to confirm the model. The modeled relationship is independent of surface overflow rate which was held constant throughout the experiments.

The model suggests a reduction in effluent suspended solids concentration with increasing detention period up to an optimum value, above which the concentration increases. The optimum detention period for the studied slurry was determined to be 5 hours by differentiating
the model equation with respect to detention period. The studied slurry was obtained from a facility operating in the extended aeration mode at a long solids retention time (26 days) and thus was completed nitrified. The surface overflow rate for the studied slurry was held constant at 200 gpd/ft². The parameter estimates associated with the selected model are specific to the studied slurry.

Evidence of denitrification activity was obtained through analysis of effluent and feed slurry grab samples. The results verified that the activated sludge was in a nitrified condition throughout the experiments, and further indicated that denitrification activity increased with increasing detention period.

Through application of the developed model, there is quantitative evidence to suggest that clarification efficiency for nitrified activated sludge can be impaired through use of detention periods beyond some optimal value. For the specific nitrified activated sludge slurry studied in this research program, this optimal detention period was determined to be 5 hours. Through visual evidence of rising sludge phenomena beyond the 5-hour period and the indication of increasing denitrification activity with increasing detention period, there is evidence to suggest that the impairment of clarification efficiency was due to denitrification within the experimental clarifier units.

**Engineering Significance**

Based on the findings of this research, the effluent suspended solids concentration from the final clarifier for nitrified activated sludge decreases with increasing detention period below a certain optimal period. Therefore, as long as the specified detention period is
below this optimum value, the design engineer can expect an improvement in clarification efficiency with increasing detention period. A qualitative evaluation of this optimum limit can be made by comparing the results of this research program to detention periods recommended by the GLUMRB (1973) for clarifier design, as well as to values derived from the utilization of deeper clarifiers as advocated by Parker (1983). The GLUMRB recommended clarifier design detention period for the extended aeration process, which is commonly used to achieve complete nitrification, ranges from 3 to 4 hours depending on plant design capacity. However, if increased clarifier depths (16 feet or greater) as advocated by Parker (1983) are coupled with surface overflow rates (300 to 600 gpd/ft²) recommended by the GLUMRB (1973) for the extended aeration process, then design detention periods ranging from 4.8 to 9.6 hours could be realized. In accordance with standard practice, these design detention periods are based on plant influent flow and disregard the recycle sludge flow component. However, this research program considered total detention period, which is based on the sum of plant influent flow and sludge recycle flow. The 5 hour optimum detention period can be theoretically converted to design detention periods for various sludge recycle rates. The GLUMRB recommends sludge recycle rates ranging from 50 to 150 percent for the extended aeration process. A listing of design sludge recycle rates and corresponding theoretical design detention periods for the 5 hour optimum value are presented in Table 11. It is not suggested that a direct numerical conversion of this optimum value to design detention period can be made in terms of actual design practice, since the optimum detention period determined by
### TABLE 11

**CONVERSION OF OPTIMUM TOTAL DETENTION PERIOD TO THEORETICAL DESIGN DETENTION PERIOD FOR VARIOUS SLUDGE RECYCLE RATES**

<table>
<thead>
<tr>
<th>OPTIMUM TOTAL DETENTION PERIOD (hr)*</th>
<th>PERCENT RECYCLE</th>
<th>THEORETICAL DESIGN DETENTION PERIOD (hr)</th>
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<tbody>
<tr>
<td>5.0</td>
<td>50</td>
<td>7.5</td>
</tr>
<tr>
<td>5.0</td>
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<tr>
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<td>11.25</td>
</tr>
<tr>
<td>5.0</td>
<td>150</td>
<td>12.5</td>
</tr>
</tbody>
</table>

*Based on a surface overflow rate of 200 gpd/ft².
this research is slurry specific, and various researchers including Marglo (1985) have established a significant relationship between the effluent suspended solids concentration and sludge recycle rate. However, a comparison is useful to the design engineer for evaluating the use of longer design detention periods for nitrified activated sludge without impairment of clarification efficiency due to denitrification activity.

A review of Table 11 indicates that the 5 hour optimum total detention period determined by this research program corresponds to theoretical design detention periods ranging from 7.5 to 12.5 hours for sludge recycle rates ranging from 50 to 150 percent. These theoretical design detention periods are well above the GLUMRB recommended design detention periods, and are near the upper limit of detention periods obtained through utilization of deeper clarifier sidewater depths. Therefore, it appears that increasing the design detention period to improve clarification efficiency for nitrified activated sludge can be practiced within reasonable limits without experiencing impairment of performance due to denitrification activity. An increase in clarifier depth, as opposed to surface area, to achieve longer detention periods is consistent with research results reported by Dietz and Keinath (1984) and Huguenard (1986). An economic analysis performed by Dietz and Keinath indicates that a deep clarifier with a small diameter is less expensive than a shallow clarifier with a large diameter, primarily due to the greater cost of the clarifier mechanism for the larger diameter unit. The use of deep clarifiers to achieve economy in design is supported by computer optimization modeling conducted by Huguenard.
Based on simulation results from the optimization modeling, Huguenard determined that the most economical method of providing an increase in detention period is to increase the clarifier depth.
CHAPTER VII
RECOMMENDATIONS FOR ADDITIONAL STUDY

This research program identified a 5 hour optimum detention period above which clarification performance was impaired, and the evidence suggests that this impairment was due to denitrification activity within the final clarifier. Additional research should be conducted with nitrified activated sludge to quantitatively verify these observations through the determination of steady-state nitrate concentrations as well as effluent suspended solids concentrations by replicate sampling. This research program was limited to two data points above the identified 5 hour optimum period. Therefore, it is suggested that the detention periods selected for study include a cluster of points near 5 hours in order to more accurately identify the point at which clarification performance begins to deteriorate. Random points scattered above and below 5 hours should also be included in order to verify the trend of improved clarifier performance up to a certain optimal detention period, with impairment of performance above this value.

In relation to observed denitrification activity within the final clarifier, it is recommended that models be developed which address the relationship between clarification efficiency and biological transformation in the final clarifier. It is also suggested that different activated sludge slurries be evaluated in order to verify the observed beneficial effects of detention period.
### TABLE 12
8-HOUR STEADY-STATE DATA

**EXPERIMENT 1**

**DATE:** 9/15/84  **OVERFLOW RATE:** 8.15 m/day  **RECYCLE RATE:** 8.15 m/day

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<td><strong>EFFLUENT SUSP. SOLIDS CONC. (mg/L)</strong></td>
<td><strong>UNDERFLOW SUSP. SOLIDS CONC. (mg/L)</strong></td>
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\[ \bar{x} = 1.83 \quad \bar{x} = 5645 \quad \bar{x} = 2798 \quad \bar{x} = 1.95 \quad \bar{x} = 5214 \quad \bar{x} = 3024 \]

\[ s = 0.37 \quad s = 174 \quad s = 66 \quad s = 0.63 \quad s = 201 \quad s = 78 \]

\[ C.I. = 0.95 \quad C.I. = 0.95 \quad C.I. = 0.95 \quad C.I. = 0.95 \quad C.I. = 0.95 \quad C.I. = 0.95 \]

\[ 1.57 < u < 2.09 \quad 5429 < u < 5861 \quad 2634 < u < 2962 \quad 4965 < u < 5464 \quad 2830 < u < 3218 \]
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**TABLE 13**

8-HOUR STEADY-STATE DATA

EXPERIMENT 2
### TABLE 14

8-HOUR STEADY-STATE DATA

**EXPERIMENT 3**

**DATE:** 10/13/84  
**OVERFLOW RATE:** 8.15 m/day  
**RECYCLE RATE:** 4.08 m/day

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<td><strong>C.I. = 0.95</strong></td>
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<td><strong>C.I. = 0.95</strong></td>
<td><strong>C.I. = 0.95</strong></td>
<td><strong>C.I. = 0.95</strong></td>
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<tr>
<td><strong>0.74 &lt; u &lt; 1.06</strong></td>
<td><strong>6848 &lt; u &lt; 7404</strong></td>
<td><strong>2402 &lt; u &lt; 2830</strong></td>
<td><strong>1.00 &lt; u &lt; 1.30</strong></td>
<td><strong>5776 &lt; u &lt; 9448</strong></td>
<td><strong>2299 &lt; u &lt; 2825</strong></td>
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### TABLE 15
8-HOUR STEADY-STATE DATA

#### EXPERIMENT 4

**DATE:** 11/10/84  
**OVERFLOW RATE:** 8.15 m/day  
**RECYCLE RATE:** 12.2 m/day

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- \( x = 2.59 \)
- \( s = 0.38 \)
- \( C.I. = 0.95 \)

- \( 2.32 < u < 2.86 \)
- \( 3713 < u < 3907 \)
- \( 2153 < u < 2501 \)
- \( 1.79 < u < 2.35 \)
- \( 3283 < u < 4009 \)
- \( 2151 < u < 2613 \)

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- \( x = 2.07 \)
- \( s = 0.39 \)
- \( C.I. = 0.95 \)

- \( 1.79 < u < 2.35 \)
- \( 3283 < u < 4009 \)
- \( 2151 < u < 2613 \)
**TABLE 16**

8-HOUR STEADY-STATE DATA

EXPERIMENT 5

DATE: 12/15/84

OVERFLOW RATE: 8.15 m/day

RECYCLE RATE: 4.08 m/day

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\[ x = 3.74 \quad \bar{x} = 5838 \quad \bar{x} = 2744 \quad \bar{x} = 3.55 \quad \bar{x} = 5052 \quad \bar{x} = 2691 \\
\[ s = 0.59 \quad s = 477 \quad s = 70 \quad s = 0.50 \quad s = 249 \quad s = 148 \\
\[ C.I. = 0.95 \quad C.I. = 0.95 \quad C.I. = 0.95 \quad C.I. = 0.95 \quad C.I. = 0.95 \quad C.I. = 0.95 \\
\[ 3.32 < u < 4.16 \quad 5246 < u < 6430 \quad 2570 < u < 2918 \quad 3.19 < u < 3.91 \quad 4743 < u < 5361 \quad 2323 < u < 3059 \]
REFERENCES


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Tuntoolavest, Musin; Miller, Eli; and Grady, C.P.L., Jr. "Factors Affecting the Clarification Performance of Activated Sludge Final Settlers." *Journal of Water Pollution Control Federation* 55 (March 1983): 234.