The effect of anoxic selectors on the control of activated sludge bulking and foaming

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(ABSTRACT)

Laboratory scale activated sludge experiments were conducted on primary effluent municipal wastewater to evaluate the effects of anoxic selectors on controlling activated sludge bulking and foaming. These experiments were conducted with two pilot plants; a three stage anoxic selector preceding a complete mix system (experimental unit) and a complete mix system (control unit). Successful selector operation requires balancing two conflicting requirements; obtain a high substrate concentration in the selector while achieving a high substrate removal efficiency in the selector. The high substrate concentration enables rapid substrate uptake to occur predominately by floc forming microorganisms while the high substrate removal efficiency ensures that a feed-starve cycle is created whereby filamentous microorganisms are selected against.

The reported metabolic mechanisms responsible for substrate uptake in the selector are the formation of internal storage products and high rate metabolism. As presented by Jenkins *et al.*, (1993) small amounts of substrate are oxidized in the selector during the formation of internal storage products. Hence, large quantities of substrate can be removed while reducing only small amounts of the terminal electron acceptor. The internal stores are metabolized in the main biological reactor only after the exogenous substrate has been exhausted. High rate metabolism in the selector results in larger amounts of substrate oxidation. Consequently, for successful selector operation large quantities of the terminal electron acceptor must be reduced.

The anoxic selector pilot unit successfully reduced activated sludge settleability and biological foams relative to the control unit. Results from this study indicate that the mode of substrate removal was influenced by the initial selector floc load. This is in general agreement with the findings by Goel and Gaudy (1968) and Gaudy and Gaudy (1988) on oxidative assimilation in activated sludge treatment. The floc load depicts the instantaneous organic loading in the selector irrespective of hydraulic retention time. Results from this study further indicate that for lower floc loadings substrate storage is predominate. Alternatively, at higher floc loadings high rate substrate metabolism is predominate. Therefore, it is hypothesized that for selector zones with high enough F/M ratios to promote rapid substrate uptake, the mechanism predominately responsible for substrate removal is influenced by the floc loading.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I. INTRODUCTION

FOREWORD

New concepts or innovative applications of existing concepts usually gain increasing popularity throughout the engineering and scientific community as pilot scale data and ultimately as full scale data become available. It is the widespread use of these concepts which generally leads to significant findings that further aid in understanding the fundamental principles of these concepts. Data that conflict with the proposed hypothesis can be as useful or more so than data which conform to it. Herein lies the need for pilot testing the effectiveness of anoxic selectors on controlling activated sludge bulking and foaming given some of the conflicting results from full scale applications which utilize selectors to control activated sludge bulking.

BACKGROUND

A complete mix municipal wastewater treatment facility that has historically exhibited severe activated sludge bulking and foaming problems is faced with strict new effluent ammonia nitrogen requirements. In light of the new permit limits, the POTW's desire to expand the facility by 25 percent, and given the extreme space limitations on the existing site, increased process control is required to allow higher operating MLSS concentrations to achieve the desired treatment. Statistical analysis of historical influent data coupled with an extensive testing program for influent nitrogen constituents and optimization of the existing inline equalization facilities, yielded the following design values: wastewater temperature - 10 degrees C, peak flow factor - 1.8, BOD_5 - 175 mg/l, TKN - 35 mg/l, Inert suspended solids - 35 mg/l and pH 7.2 (through adjustment). A kinetic design based upon IAWQ activated sludge Model Number 1 methodology, with a safety factor of 1.2, produced the following biological design criteria for year round nitrification: Oxic MCRT - 10 days, MLSS - 2,700 to 3,000 mg/l, oxic HRT - 10 Hrs.

The design MLSS concentration was derived from existing site limitations, which provide a 10 hour HRT by utilizing existing tanks for biological reactor volume. To achieve increased process control two measures were simultaneously embarked upon.

Significant industrial users of the collection system were closely monitored and the established Sewer Use Ordinance and local limits were administered. Secondly, the issue upon which this paper focuses, *i.e.*, biological selectors preceding activated sludge treatment, was investigated as the proposed process upgrade to increase process reliability through the control of filamentous organisms.

The existing biological reactors are configured as a complete mix system and are limited to MLSS concentrations of 1,800 to 2,000 mg/l because of the deleterious effects of sludge bulking and foaming at higher concentrations. Bulking occurs due to the predominance of nuisance (filamentous) organisms in the MLSS, which produces a less dense and poorly settling sludge. Bulking sludges are characterized by sludge volume indices (SVIs) greater than 150 to 200 mL/g. Over the past three years the POTW average SVI has been 245 ml/g with values as high as 450 ml/g. To ameliorate this, RAS chlorination procedures have been used extensively to maintain process control. The inherent low loading (F/M) bulking problems of complete mix activated sludge systems has been well documented (Tomlinson and Chambers, 1982) and the reasons for these problems form the fundamental rationale for the utilization of biological selectors.

THE SELECTOR EFFECT

Biological selection uses differential growth kinetics to promote the development of good settling (floc-forming) bacteria rather than filamentous bacteria. This is accomplished because most floc-forming bacteria grow faster than filamentous bacteria at higher BOD loading rates. Conversely, most filamentous organisms grow faster than floc-forming organisms at lower BOD loading rates (the reason for bulking in complete mix systems). Therefore, small, highly loaded reactors provide high growth rate environments where floc-forming bacteria predominate and are selected throughout the activated sludge system via a feed starve cycle over filamentous bacteria. Also, most filamentous bacteria are strictly aerobes, thereby enabling to kinetic and metabolic selection of floc-forming organisms through the use of anoxic or anaerobic selectors. The decision to investigate anoxic selectors was determined by the dual mode of selection as explained above, but also by the reported success of anoxic selectors in reducing biological foaming problems (Cha *et al.*, 1992).

High floc loadings in the selector zones provide rapid growth conditions where soluble substrate is quickly taken up by the floc-formers or any other microorganisms which can compete at these high growth rates. This is termed the feed portion of the cycle and is similar to the contact zone of a contact stabilization process where oxidative assimilation occurs. The two mechanisms that enable rapid substrate uptake are high rate metabolism and the production of storage products. High rate metabolism refers to the process where the electron donor (the energy source) is used directly for oxidative phosphorylation and biosynthesis. This does not imply, however, that the entire process occurs in the selector zones. Substrate storage occurs through the production of non-nitrogenous products within the cells assimilating the organic substrate. Typical storage products are poly-hydroxyl-alknaoates and carbohydrates (Gaudy and Gaudy, 1988). Microorganisms which completely metabolize the substrate remove approximately 8 mg/l of soluble substrate per mg/l of nitrate reduced (Jenkins *et al*., 1993). Storage capable microorganisms remove significantly larger amounts of soluble substrate per mg/l of nitrate reduced.

Chapter II. LITERATURE REVIEW

- Chambers, B. and Tomlinson, E. J. eds. (1982). *Bulking of Activated Sludge: Preventative and Remedial Methods.* Ellis Horwood Limited, Chichester, West Sussex, 279p.

Chapter 6 - *"Biosorption and prevention of bulking sludge by means of a high floc loading"* - D. H. Eikelboom. It is discussed that the occurrence of excessive filamentous microorganisms results from plant configuration. Complete mix activated sludge treatment facilities tend to have greater incidences of activated sludge bulking than plug flow (conventional) activated sludge wastewater treatment systems. This relationship is explained due to the inherent low substrate concentration in complete mix systems which kinetically favor filamentous microorganisms over floc forming microorganisms. Specifically, filamentous microorganisms grow faster at lower substrate concentrations than floc forming microorganisms and vice versa for high substrate concentrations. It is presented that either plug flow treatment or the use of highly loaded mixing zones prior to either complete mix or plug flow treatment will reduce or prevent activated sludge bulking.

The fundamental reasons for the control of sludge bulking in both cases is the same, that is for high substrate concentrations either for a short period, as for the initial mixing zone, or for prolonged periods, as for plug flow treatment, floc forming bacteria become predominate because they can grow faster at higher substrate concentrations. The separation of exogenous substrate uptake and endogenous respiration is essential to induce a feed-starve cycle which can significantly eliminate the filamentous bacteria from the system.

The term floc loading is defined as a control parameter in evaluating different equilibrium substrate concentrations (loadings) and their impact on biosorption. It is shown that rapid substrate uptake achieving high removal efficiencies of soluble substrate can occur in relatively short periods (10 minutes) for some activated sludges. It is also noted that the rate of biosorption increases for decreasing floc load. An increase in the overall sludge loading (F/M) reduces the biosorption capacity. If the F/M loading becomes too great the endogenous phase no longer exists and the biosorption capacity diminishes since it can not be regenerated. In the absence of oxygen it was discovered that rapid substrate uptake also occurred. In this case it was not apparent if conditions were anoxic or anaerobic. In general, detention periods of ten minutes were adequate to obtain 70 percent removal of the soluble COD in pilot studies of aerobic selectors cited in this literature.

Chapter 7 - *"Theory and practice of accumulation regeneration approach to the control of activated sludge filamentous bulking"* - J. Chudoba, P. Grau, and M. Dohanyos. The authors explain kinetic selection of floc forming microorganisms through substrate accumulation, storage and subsequent metabolism. This concept is explained with respect to the contact stabilization process where as in the contact basin substrate is taken up by the microorganisms with resulting increases in biomass without substantial increases in the number of cells. Cell division (replecative growth) which is associated with protein syntheses occurs later in the stabilization basin at the expense of the accumulated or stored substrate. This statement is in general agreement with Gujer and Jenkins (1975), "COD removed in the contact basin is not entirely associated with cell growth".

Substrate uptake can be accomplished by either accumulation or storage. Typical storage capacities were reported as 2 g/g where as accumulation capacities were reported to be 0.3 to 0.4 g/g. It was hypothesized that mostly accumulation and some storage were responsible for the rapid substrate uptake. It was suggested that optimal selector designs would incorporate multiple basins to account for varying flow and loadings over the life of a facility to provide the optimal conditions for kinetic selection of floc forming microorganisms. Successful use of anoxic selectors for bulking suppression were also reported.

- Gaudy, A. F., Jr and Gaudy, E. T. (1988). *Elements of Bioenvironmental Engineering.* Engineering Press, Inc., San Jose, CA, 592p.

Chapter 10 "Aerobic Metabolism" discusses oxidative assimilation as an unbalanced growth condition where microorganisms under certain conditions convert soluble substrate into non-nitrogenous inter cellular products (stores). The energy to incorporate the substrate into internal stores is obtained through oxidizing very small portions of the substrate, therefore, this process is termed oxidative assimilation. This process is commonly known as biosorption and is responsible for soluble substrate removal in the contact zone of a properly sized contact stabilization activated sludge wastewater treatment process. The stabilization zone (as will be discussed later) regenerates the microorganisms enabling them to continually perform biosorption processes. Contact stabilization has been used for decades with varying degrees of success. The lack of knowledge and understanding of biosorption and the coupled relationships with the processes occurring in the stabilization zone are the primary causes of improperly functioning systems.

During oxidative assimilation growth, an increase in biomass through the production of intra- cellular products (carbohydrates and lipids), is commonly referred to as non-replicative growth (or non-proliferating system). It is termed this since during oxidative assimilation soluble substrate is taken up so rapidly that carbohydrate synthesis out paces protein synthesis. Therefore, under these conditions new cell material can not be produced (since protein synthesis does not occur proportionally to substrate uptake) and the microbes metabolize (convert) the substrate to internal stores until conditions are present where replicative growth can occur. In works cited in this chapter the anthrone test was used for cell carbohydrate analysis. During oxidative assimilation the carbohydrate content of the cells increased while the protein content of the cells remained essentially constant. Gaudy and Gaudy say:

> It should be noted that neither sorbitol nor glycerol reacts in the anthrone test for carbohydrate, which is used to measure the carbohydrate content of the cells. Therefore, the observed increase in the amount of cellular carbohydrate could not have been due to the sorption, or simple uptake, of

> these substrates. Rather, they were metabolized and converted to material that was carbohydrate in nature. (458)

When replicative growth occurs, either because of the presence of an adequate nitrogen supply or in the case of selectors because most of the exogenous substrate has been removed, the microbes autodigest the internal stores as they would an exogenous substrate and produce protein. The text presents graphs, as mentioned above, that show during storage capacity regeneration the cell content increasing with respect to protein and decreasing with respect to carbohydrate, *i.e.* internal stores are used for protein synthesis (replecative growth).

Oxidative assimilation was initially investigated for nitrogen deficient wastes. It was discovered that soluble substrate could be removed from nitrogen deficient wastewater through nonreplecative growth (oxidative assimilation). The microorganisms would then be regenerated by exposing them to an adequate nitrogen supply to allow for replecative growth. Since the regeneration stage is necessary for continuous oxidative assimilation it became of great interest. It was first thought that during the regeneration stage the internal storage products were essentially all respired ("burned off"). Obviously, if this were true, there would be great advantages to this process, lower sludge yield and etc. However the following article by Goel and Gaudy "Regeneration of Oxidative Assimilation Capacity by Intracellular Conversion of Storage Products to Protein" proves that in order to obtain continuous oxidative assimilation microbe regeneration via protein synthesis (replecative growth) through autodigestion (the use of internal stores for protein synthesis) is required.

Given the correct conditions of biomass and substrate concentrations it was discovered that oxidative assimilation occurred <u>even when</u> adequate nitrogen was present. The microorganisms autodigested the internal stores when the exogenous substrate had been exhausted. The mechanisms for this are explained above. During rapid substrate uptake carbohydrate synthesis occurs much faster than protein synthesis thus allowing nonreplecative growth to occur even in the presence of adequate nitrogen. This text presents laboratory results which illustrate that for decreasing S/X ratios (S=substrate concentration, X=biomass concentration) the rate of oxidative assimilation (non-replicative growth) increases. This relationship correlates with the findings of Eikelboom (Tomlinson and Chambers, 1982) that for increasing biomass concentrations (decreasing floc load or decreasing S/X) the rate of oxidative assimilation increases.

Gaudy and Gaudy also state that it is not the capacity of the microorganism to oxidatively assimilate which is limited by the S/X ratio (or floc loading) but the rate which it occurs (*i.e*. if it will occur at specified conditions and how fast it will occur if the conditions are adequate). Thus, high initial substrate concentrations (*i.e*. short selector zone HRT) at low S/X ratios enable phenomenal rapid soluble substrate uptake to occur.

This offers explanation and correlation to the selector effect as explained by Jenkins *et al*., (1993) where rapid soluble substrate uptake occurs in selector zones with high initial substrate concentrations (short selector zone HRT). In this process very little substrate is actually oxidized since the substrate is converted into internal stores. Later in the treatment process, when conditions for replecative growth occur, the microbes are regenerated by autodigesting the internal stores for protein synthesis.

There are basically two types of stores, carbohydrates and PHB. Carbohydrate stores can be readily converted to proteinacous matter when the exogenous substrate concentration decreases. It has been shown that for microbes using PHB as the internal store the exogenous substrate must be almost entirely exhausted before internal stores are converted to proteins. This lends to the effect of the over all treatment scheme (*i.e*. what the effluent objectives are) as to what type of internal storage products can actually be perpetuated. For instance, if the effluent substrate concentration objective is above that required to allow regeneration of the PHB storing bacteria then these bacteria will not proliferate and thus the carbohydrate storing capable microorganisms will have to provide kinetic selection via a feed starve cycle.

The above correlation of oxidative assimilation to the explanation of kinetic selection procedures of selectors by Jenkins *et al*, (1993) infers beyond the work of Gaudy and Gaudy (1988) for anoxic and anaerobic selectors. This is to say that Gaudy and Gaudy (1988) explained oxidative assimilation strictly to occur in aerobic environments. In Chapter 11 “Anaerobic Metabolism” Gaudy and Gaudy (1998) explain that “Many of the Pseudomonas species known to accumulate non-nitrogenous storage products do not denitrify, whereas many of the species capable of denitrification do not make the major non-nitrogenous storage products, i.e., poly-B-hydroxybutyrate or polysaccharides…”. These statements would lend one to believe that anoxic and anaerobic selectors would not enable substrate storage. This is later shown not to be the case (with respect to date of findings) by Tomlinson and Chambers (1982) and Jenkins *et al*. (1993). In all cases aerobic, anoxic and anaerobic selectors can use an exogenous carbon substrate to produce internal carbon stores which are in turn later used for protein synthesis. In the case of anaerobic selectors energy from breaking the high energy polyphosphate bonds are additionally used for internal carbon storage in the anaerobic zone which is accompanied by a release of orthophosphate. In the aerobic phase polyphosphate bonds are made thus requiring orthophosphate uptake which is part of the enhanced biological phosphorus removal process.

- Goel, K. C. and Gaudy, A. F., Jr. “Regeneration of Oxidative Assimilation Capacity by Intracellular Conversion of Storage Products to Protein.” *Applied Microbiology*, September, 1352-1357 (1968)

This research investigated the regeneration of microorganisms that convert soluble substrate into non-nitrogenous inter cellular products (stores) and the effects of continuous regeneration. Significant portions of this work have been presented (reviewed) above and will not be repeated here in the interest of limiting redundant information.

It is noted however, that this article represents the original work of Gaudy and Gaudy (1988) depicting the relationships of carbohydrate and protein synthesis during oxidative assimilation and regeneration phases, respectively.

Pilot results of this study showed that during oxidative assimilation of a nitrogen deficient waste the soluble substrate concentration decreased rapidly while the cell carbohydrate content increased and the cell protein content remained constant. The microorganisms were able to be continuously regenerated by adding a nitrogen source after the exogenous substrate was exhausted. Adding the nitrogen source during the regeneration phase allowed protein syntheses (replecative growth) to occur which resulted in the cell protein content increasing at the expense of the carbohydrate stores (resulting in a carbohydrate content decrease). This work showed that these two steps could be separated in a nitrogen deficient wastewater without effecting treatment performance. This leads into the explanations of the contact stabilization process as previously explained. (It was later discovered that oxidative assimilation would occur without a deficiency of nitrogen at low S/X ratios, as previously explained).

This research also pointed out that there is a minimum solids concentration which allows oxidative assimilation to occur, and that for higher biological solids concentrations the greater the removal rate of soluble substrate. This was the beginning of the substrate to biomass (S/X) ratio as previously discussed. This work also pointed out that non-carbohydrate substrates showed a tendency to resist continuous regeneration of the microorganisms, however, this was later disproved by Goel and Gaudy (1968).

- Diagger, Glen, T., Nicholson, Gordon, A. "Performance Of Four Full-Scale Nitrifying Wastewater Treatment Plants Incorporating Selectors." *Research Journal of the Water Pollution Control Federation*, July/August, 676-683 (1990)

This article presents four long term case studies on the use of selectors for controlling filamentous microorganisms in wastewater treatment. The study indicates that selectors in conjunction with aeration basin configuration were effective in controlling activated sludge bulking. Similar performance was obtained from aerobic, anoxic and anaerobic selector systems.

The Upper Occoquan Sewage Authority (UOSA) Regional Water Reclamation Plant (RWRP) is a 27 mgd high performance advanced wastewater treatment facility which discharges directly into a drinking water reservoir. Prior to the last expansion the complete-mix facility exhibited severe bulking problems which reduced treatment capacity. The predominate filamentous microorganism was identified as *Microthrix parvicella*.

An aerobic selector (DO greater than or equal to 2 mg/l) was constructed as part of the facility expansion to 27 mgd. The plug flow aerobic selector receives both primary effluent and recycled activated sludge and has a hydraulic retention time of 11 minutes. Installation of the selector coupled with the new and existing aeration basins being operating in series has significantly improved activated sludge settleability and eliminated *M. Parvicella* from the system. It was reported that approximately 60 percent of the soluble BOD (sBOD) and approximately 45 percent of soluble COD (sCOD) were removed in the selector. It was also determined that approximately 0.1 mg of O_2 was utilized per mg sBOD removed. Such low levels of terminal electron acceptor reduction indicates that storage rather than oxidation is the predominate mechanism responsible for the removal of soluble organic substrate in the selector.

The Northside WWTP is a 27 mgd wastewater treatment facility which has effluent ammonia-nitrogen requirements. The facility has exhibited severe activated sludge bulking problems which reduced nitrification capability. The predominate filamentous microorganism was identified as *Microthrix parvicella*.

An aerobic selector (DO less than 2 mg/l) was constructed as part of the facility upgrade. The plug flow aerobic selector receives both primary effluent and recycled activated sludge and has a hydraulic retention time of 16 minutes. New complete mix aeration basins were constructed identical to the existing basins. Unlike at UOSA the new and existing aeration basins operate in parallel. This configuration has not proved successful in reducing sludge settleability and thus has not eliminated *M. Parvicella* from the system. It was determined that similar to UOSA approximately 60 percent of the sBOD was removed across the selector. However greater amounts of substrate were oxidized in the selector relative to UOSA findings. This indicates that high rate metabolism not storage is the predominate mechanism responsible for substrate removal across the selector.

The Fayetteville WWTP was an existing complete mix activated sludge treatment facility that was upgraded to provide ammonia-nitrogen and biological phosphorus removal. The existing facility had consistently experienced sludge bulking and required continuous application of chlorine to maintain adequate sludge settleability in the solids-liquid separation process.

The anaerobic zone required for biological phosphorus removal also served as an anaerobic selector. The selector consisted of six complete-mix zones in series followed by four complete-mix aeration zones in series. The hydraulic retention time of the selector was 99 minutes, with a total system HRT of 9.5 hours similar to the HRT of both UOSA and Northside WWTP's. Since facility start up good sludge settleability has been achieved with SVI's averaging 86 ml/g.

The Tri-City WWTP is a 13.5 mgd facility which provides advanced secondary treatment during warm months (10 mg/l BOD and TSS) and normal secondary treatment during cold months (30 mg/l BOD and TSS). Anoxic selectors were installed to combat both alkalinity deficiency and activated sludge bulking in the complete mix basins.

The anoxic selectors have been extremely successful in eliminating sludge bulking at the facility. The anoxic selectors have been so effective in eliminating filamentous bacteria that periodic low intensity aeration is applied to the selectors to promote the growth of some low DO filaments. This practice provides a back bone for the sludge floc and reduces turbidity in the secondary clarifier effluent.

In summary, this article concludes that aerobic, anoxic and anaerobic selectors can be effective in improving sludge settleability as measured by the SVI. Differences between the different types of selectors was relatively small. Based upon the long term operating histories selectors can be expected to produce activated sludges with SVI's between 60-90 ml/g regularly with variations no higher than 150 ml/g. The mechanisms responsible for rapid soluble substrate uptake were identified as substrate storage, or high rate metabolism. Kinetic selection of floc forming microorganisms, which is a byproduct of rapid substrate uptake in the selector and leads to the feed starve cycle, is also accompanied by metabolic selection when anoxic and anaerobic selectors are utilized.

- Gabb, D. M. D., Still, D. A., Ekama, G. A. Jenkins, D. and Marais, F. v. R. "The Selector Effect on Filamentous Bulking in Long Sludge Age Activated Sludge Systems." *Water Science and Technology*, Volume 23, 867-877 (1991)

A widespread survey of long sludge age bio P and N removal wastewater treatment facilities in South Africa showed extensively the occurrence of low F/M bulking. Literature suggested that low F/M bulking can be controlled in complete oxic systems by installing a selector. The selector effect is described by inducing a high substrate gradient in the selector zone which stimulates floc forming microorganisms with high substrate uptake and storage rates which allows them to proliferate (out compete) over the filamentous microorganisms through the resulting feed-starve cycle.

In the first stage of the research long sludge age fully aerobic systems both with, and with out, aerobic selectors were operated to evaluate activated sludge bulking. Selectors were simulated by using highly loaded selector zones and also using an intermittently fed, fill and draw system. Both types of systems (the non-selector and both selector systems) failed to bulk due to low F/M filaments even though they were all started with a low F/M bulking sludge.

The second stage of the research investigated long sludge age denitrification/nitrification systems both with, and without, anoxic selectors to reduce low F/M bulking. The control system was a continuous flow completely mixed (CFCM) reactor with alternating oxic and anoxic zones. The second system was a sequencing batch reactor, as previously described, which alternated under oxic and anoxic conditions. The selector effect was achieved due to the high initial substrate concentrations in the SBR under anoxic conditions. Aerobic selectors were not investigated since denitrification efficiency would be greatly reduced since the large amount of substrate taken up in the aerobic selector zones could not be used for denitrification. It was determined that anoxic selectors exhibited an equally high uptake rate of readily biodegradable COD (selector effect) to that of aerobic selectors.

Both systems were seeded with a low F/M bulking sludge. The DSVI rapidly increased in the anoxic/oxic CFCM but this was due to *S. natans* not low F/M filaments. The proliferation of *S. natans* was a result of seeding from pilot unit feed lines. The DSVI of selector unit stayed at 100 ml/g. Even though *S. natans* were identified in the selector unit they did not become predominate. To this point of the research low F/M bulking had not occurred. It was known that bio P and N plants exhibited low F/M bulking but the authors could foresee many problems in simulating a five stage Bardenpho or modified UCT without disrupting the process. However is was also known that Carrousel type plants exhibited low F/M bulking. Therefore, pilot units were constructed to investigate low F/M bulking in simulated Carrousel plants. An important aspect of the Carrousel type plant is that the anoxic period is almost twice as long as the oxic period.

Two CFCM reactors were operated (non-selector) with intermittent aeration to simulate a Carrousel type plant. Ammonia was added to ensure high levels of nitrification and also to ensure nitrate was present during all cycles. Low F/M filaments proliferated in both systems. One system was switched to continuous aeration operation which resulted in a decrease in the DSVI to below 80 ml/g within one sludge age. The other unit remained unchanged in operation and continued to have DSVIs greater than 300 ml/g.

Upon establishing a pilot system that exhibited low F/M bulking the effects of aerobic selectors could now be investigated. Two identical CFCM systems, as described above (oxic and anoxic cycles established by intermittent aeration), were operated. Low F/M bulking occurred in both systems with a DSVI of 340 ml/g by day 21. On day 21 one of the systems was installed with an aerobic selector preceding the main treatment basin. After a period of time the selector effect of the experimental (selector) unit was verified by the MLSS having a high substrate uptake rate (greater than two times of the control unit) and that 98 percent of the readily biodegradable COD was removed in the selector zone. After five and a half sludge ages (day 114) both units had DSVIs of 320 ml/g. The predominate filaments in both units were *M. parvicella*, 0092 and 0914. After day 117 the aeration pattern in the control unit was changed from intermittent to continuous. The DSVI decreased rapidly to 103 ml/g by day 132. During the same periods the DSVI in the experimental (selector) unit remained above 400 ml/g. Gabb *et al*., state:

> The above described experiments lead to the following conclusions: 1. Irrespective of the presence or absence of a selector effect, the fully aerobic systems and the particular anoxic-aerobic system (1 hour anoxic and 3 hour aerobic) did not support the growth of low F/M filaments, even when these systems were started up with low F/M bulking sludges from

full scale plants. 2. In laboratory long sludge age single reactor continuous constant feed systems with intermittent aeration (6-7 minute anoxic, 3-4 min aerobic) which simulate ditch type systems, low F/M filaments proliferated, in particular *M. parvicella* and type 0092. Changing the aeration pattern from intermittent (anoxic/aerobic) to continuous (fully aerobic) ameliorates the low F/M bulking and controls low F/M filament growth to DSVI's below 100 ml/g in the absence of a selector. 3. Incorporation of aerobic selectors receiving the influent and underflow streams at the head of an intermittently aerated main reactor system (to simulate low F/M filament proliferation) and which stimulated a selector effect, did not control the proliferation of the low F/M filaments *M. parvicella*, 0092 and 0914 in the system.

At this stage it is believed that it is the anoxic-aerobic alternation that leads to the low F/M filament proliferation because this is a common feature in N and P removal and completely mixed ditch type N removal systems. No answers are available at this stage as to the effects of magnitude of anoxic mass fraction, length of anoxic retention time (actual or nominal), duration of the anoxic-aerobic cycles in intermittent aeration system, concentration of nitrate during the anoxic periods, frequency of alternation between anoxic and aerobic periods and the effect of the low DO concentrations which arise from the "lead-in" to anoxic conditions. (876)

In summary this research discovered that low F/M bulking does not occur in pure aerobic or pure anoxic conditions but proliferates in intermittently aerated systems. To this end since low F/M conditions were not the cause of the proliferation of *M. parvicella* and types 0092 and 0041 filamentous microorganisms these types of filaments were renamed aerobic-anoxic (AA) filaments since it is the switching of environments which stimulates their predominance. The conclusion of this research leads directly into the next article "A Hypothesis for the Causes and Control of Anoxic-Aerobic (AA) Filament Bulking in Nutrient Removal Activated Sludge Systems" by Casey *et al*., (1994).

- Casey, T. G., Wentzel, M. C., Ekama, G. A., Loewenthal, R. E. and Marais, GvR. "A Hypothesis for the Causes and Control of Anoxic-Aerobic (AA) Filament Bulking in Nutrient Removal Activated Sludge Systems." *Water Science and Technology*, Volume 29; Number 7, 203-212 (1994)

Working from the previously reviewed research the authors first investigated the causes of AA filaments. Gabb *et al*. (1991) showed that aerobic and anoxic selectors do not conclusively control low F/M bulking. This brought to light that low F/M conditions were not the primary cause for this type of bulking. The previous research and review of the literature again concluded that low F/M bulking does not occur in pure aerobic or pure anoxic conditions but proliferates in intermittently aerated systems. To support these findings a continuous flow intermittently aerated (single reactor) nitrification-denitrification (IAND) system and a two reactor continuous flow nitrification-denitrification (2RND) system were operated both with aerobic mass fractions of 30 percent. An aerobic mass fraction of 30 percent was determined the critical (highest propensity) point for AA filament proliferation. The IAND system averaged DSVIs of 200 ml/g while the 2RND system averaged DSVIs of 150 ml/g. The dramatic differences between the two systems was unexplainable and thus resulted into further investigations where the 2RND system was modified to approximate the IAND system. These modifications did not lead to AA bulking in the modified 2RND system thus focus of AA bulking was directed to the IAND system. The TKN/COD ratio was increased in the IAND system to ensure the presence of nitrate at the end of the anoxic period. This led to AA filament bulking which led to the conclusion that the presence of nitrate and nitrite at the end of the anoxic period leads to AA filament bulking. At this time it was not clear if either nitrate or nitrite had the most impact.

To get back to systems which emulate full scale nutrient removal treatment plants that bulk two MUCT pilot units were constructed to investigate the impacts on the presence of nitrate and nitrite at the end of the anoxic period on AA filament bulking. The control unit was operated with a high TKN/COD ratio (0.13) and the other with a low ratio of approximately 0.9. The results from these investigations showed that the conditions for AA filament bulking result from aerobic-facultative heterotrophs in ND and NDBEPR systems which are exposed to alternating anoxic and aerobic conditions with the presence of certain (mainly nitrite) denitrification intermediates in the anoxic zone subsequent to entering the aerobic zone. When these conditions occur floc forming aerobic-facultative heterotrophs are inhibited to some degree in the aerobic zone which reduces their competitiveness over filamentous microorganisms thus resulting in the proliferation of filamentous microorganisms. This results from the differences in metabolic denitrification pathways between floc forming and filamentous microorganisms. Floc formers completely denitrify nitrate to nitrogen gas (NO_3^- - NO_2^- - NO - N_2O - N_2) with some intracellular accumulation of NO (a denitrification intermediate) under anoxic conditions. Casey *et al.*, state:

> When a floc former with some intracellular NO is subjected to aerobic conditions the NO inhibits the utilization of oxygen (and concomitantly the utilization of substrate). Furthermore, while NO is present under aerobic conditions, the floc formers continue to respire with NO_2^- (i.e. aerobic denitrification) albeit at a much reduced rate to that under anoxic conditions. (207)

Filamentous microorganisms which can denitrify only convert nitrate to nitrite and thus do not accumulate NO intracellularly and are not inhibited in the subsequent aerobic zone. In nutrient removal the above described conditions are common which lend to AA filament proliferation and bulking.

AA filament bulking in ND and NDBEPR systems can be prevented in basically three ways. Design the treatment system to ensure that all nitrate and nitrite are removed before leaving the anoxic zone or entering an aerobic zone. Given varying loadings and flow rates over the design life of a treatment facility this option seems very difficult. Alternatively, since it has been shown that in the presence of readily biodegradable COD (RBCOD) NO does not accumulate in floc formers, small aerobic or anoxic zones can be placed between the anoxic and main aerobic reactor to which a small fraction of primary effluent is fed.

The presence of small anoxic zones between the anoxic zone and the main aerobic zone while introducing small amounts of primary effluent has proven to be successful in eliminating NO accumulation and thus eradicating aerobic denitrification which inhibits aerobic metabolism. This procedure has proven successful in eliminating AA filament bulking from long sludge age nutrient removal systems. This hypothesis and research clarifiers to some degree the irregularity of results from anoxic and aerobic selectors on controlling low F/M filaments. From this it is deduced than anoxic selectors preceding fully aerobic systems will not induce aerobic denitrification (floc former inhibition) since the anoxic selector zone will have a high RBCOD substrate concentration with no other anoxic zones later in the treatment process.

- Kappeler, Jurg and Brodmann, Rene. "Low F/M Bulking and Scumming: Towards a Better Understanding By Modeling." *IAWQ Water Science and Technology*, Volume 31, Number 2, 225-233 (1995)

This paper is basically a recapitulation of the concepts of above papers, NO accumulation in aerobic facultative floc forming microorganisms cause inhibition under subsequent aerobic conditions. Evidence is given to support, "Excessive growth of Actinomycetes may be suppressed by aerobic selectors at low solids retention times and by anoxic selectors at all solids retention times."

- Patoczka, Jerzy and Eckenfelder, W. W. "Performance and Design of a Selector for Bulking Control." *Research Journal of the Water Pollution Control Federation*, March/April, 151-159, (1990)

The authors cite a long list of references stating that low F/M bulking has been shown to be controlled with a small initial chamber receiving return sludge and influent wastewater (selector zone) which precedes main biological treatment. To this end, this research developed a mathematical model to optimize aerobic selector performance to control low F/M bulking. It was noted that in order to achieve optimum selector performance two conflicting relationships have to be met in the selector; a high substrate concentration in the selector accompanied with a high substrate removal efficiency in the selector.

The goal of a selector is to achieve a zone with a high substrate concentration with a high degree of substrate removal. The authors state that the fundamental reasons for selection in the selector zones occur either because the floc formers (Zoogloeal bacteria) have a higher affinity for substrate at high substrate concentrations (*i.e.*, high Ks) or that the floc formers are able to rapidly uptake substrate through biosorption and subsequently store and metabolize the substrate. The authors basically state that the mechanism of selection or combination thereof is irrelevant for their model since both cases require the two aforementioned principles must be met (*i.e.*, the selector zone must have a high substrate concentration and a high removal efficiency).

The model was developed to optimize the selector system for resistance to bulking based upon the average substrate concentration in the selector (biosorption concentration, Cb) at which substrate was removed. Zone settling velocities below 0.6 m/hr (2ft/hr) were used as an indicator of sludge bulking. The Cb value is based upon the available substrate concentration in the selector, fraction of substrate removed in the selector, biodegradable substrate concentration in the aeration basin and the fraction of substrate removed in the selector. All values except the substrate concentration in the aeration basin are calculated from system parameters, a mass balance and a semi-empirically defined selector zone reaction rate which has the form of the Monod equation with a maximum reaction rate and half velocity rate. For given system parameters the model determines the optimum recycle rate for selector performance. In summary, the authors state: "The optimum sludge recycle rate results in a substrate concentration in the selector equal to one-half of the influent concentration. The optimum recycle rate is always less than 100 percent and approaches this value for small values of the system constant."

- Pujol, R. and Canler, J. P. "Contact Zone: French Practice with Low F/M Bulking Control." *Water Science and Technology*, Volume 29; Number 7, 221-228 (1994)

This research was based upon full scale application of selectors at twelve separate extended aeration wastewater treatment facilities in France to control low F/M bulking

(*Microthrix p*., type 0092, type 0041 and *Nostocida I*) and foaming (*Microthrix p*., and Nocardia sp.). The wastewaters were mostly of domestic origin with significant food processing wastewater contributions. The goal of the selector zone was described as establishing a high substrate zone where the floc formers ability to rapidly uptake and store substrate is stimulated. The stored substrate would subsequently be metabolized in the main aeration basin thereby lending to the proliferation of floc formers over the filamentous microorganisms which cannot store substrate.

The selector zones were designed on three basic premises: to have a contact time of ten minutes based upon peak flow, and return flow, to introduce primary effluent and return activated sludge together simultaneously, and to provide adequate mixing with aeration being optional. It is noted that since all of these experiments were performed on extended aeration activated sludge systems a non-aerated selector most likely resulted in an anoxic selector. Selector zone loadings ranged from 100 mg COD/g MLSS/hr to 300 mg COD/g MLSS/hr.

The following results and conclusions were obtained from the study of twelve extended aeration wastewater treatment facilities incorporating selectors. It was observed that the presence of oxygen in the selector zones is not required. This correlates to the findings of Jenkins *et al*., (1993) and Gabb *et al*., (1991). The impacts of selectors is gradual and may take as long as two to three MCRTs to become stable and in some cases longer periods are required. For example one plant in the study took two years for the initial SVI of 800 to be reduced to 100 ml/g. The selectors were successful in improving the SVI in 91 percent of the cases and foaming was controlled in 75 percent of the cases studied (Type 0041 and *M. parvicella* were the predominate filaments). It was also stated that selectors are not effective in controlling all filamentous microorganisms. For instance, they cannot control *Beggiatoa* which is a sulfur oxidizing bacteria.

- Diagger, G. T. and Roper, R. E. Jr., "The Relationship Between SVI and Activated Sludge Settling Characteristics", *Journal of the Water Pollution Control Federation*, Volume 57, 859-866 (1985)

This article presents simplified graphical methods to estimate activated sludge settling characteristics which unlike previous work are applicable over a broad range of sludge settleability. From this secondary clarifier design and performance evaluations can be accomplished for an expected range of SVI's given the solids loading rate and the corresponding underflow concentration. Using this approach the effects of selectors on reducing the average and maximum SVIs can be readily incorporated into secondary clarifier design and performance evaluations. Although this approach appears generalized site specific data is required for verification.

- Crabtree, K., Boyle, W., McCoy, E. and Rohlich, G. A. "A Mechanism of Floc Formation By Zoogloea Ramigera." *Journal of the Water Pollution Control Federation*, Volume 38; Number 12, 1968-1979 (1966)

This research presented a theory for bio-flocculation of the floc forming microorganism *Zoogloea Ramigera* which is commonly found in activated sludge treatment systems. The absence (or lack of a predominate presence) of floc forming microorganisms can lead to dispersed growth conditions of the activated sludge floc. Dispersed growth is an unfavorable condition in activated sludge treatment which favors poor settleability and inturn can lead to reduced treatment capacity by limiting the ability of the solids liquid separation processes to maintain desirable MLSS concentrations in the biological treatment basins.

Early flocculation theory postulated that bacteriological slime was responsible for floc formation, however, studies to the date of this article have yet to conclusively prove this. Additionally, this research showed that slime producing bacteria grown in conjunction with dispersed bacteria did not produce floc formation. Therefore, the bacteriological slime theory has been rejected as being the mechanism for floc formation of *Z. ramigera*.

Having disproved the former flocculation theory this research investigated specific mechanisms found within zooglocal microorganisms which would promote floc formation. It was discovered that flocs of *Z. ramigera* were bound together by a polymer termed poly hydroxybutyrate (PHB). It was found that during exogenous growth on a soluble organic substrate *Z. ramigera* would rapidly metabolize the substrate and produce a PHB store through estirification. During the phase of exogenous growth the cells would not replicate (divide). This was attributed to the rapid synthesis of PHB under exogenous growth conditions rather than other possible limiting conditions. It was shown that the cell weight increased in direct proportion to the substrate metabolized without an increase in population.

This correlates to oxidative assimilation (non replicative growth) theory as explained by Gaudy and Gaudy (1988) whereby rapid substrate uptake occurs in a selector zone where high initial exogenous substrate concentrations exist which enable PHB formation to out pace protein thesis in the floc forming organisms. The formed PHB stores would create conditions where the individual bacteria would stick together to form flocs of bacteria which settle rapidly. Within these flocs other bacteria would become entrapped within the floc. It was also determined that even after a period of agitation the flocs laden with PHB would reform flocs and settle rapidly.

The substrates which enabled PHB store formation are soluble substrates such as glucose and more than 30 sugars and related substrates and various peptides. The substrate has to lend to rapid uptake by the microorganism to enable PHB store formation. It should be noted that the impact of S/X ratios was not investigated.

Internal stores of PHB ranged from 12 - 50 percent by dry cell weight, with 12 percent being that of a normal cell. PHB formation was found not to occur at pHs less than 5.5 or greater than 8.5.

Thus, PHB production by floc formers in selector zones not only eliminates filamentous microorganisms through kinetic selection but also provides enhanced settling through bioflocculation.

- Hoffman, H., "Influence Of Oxic And Anoxic Mixing Zones In Compartment Systems On Substrate Removal And Sludge Characteristics In Activated Sludge Plants." *Water Science and Technology*, Volume 19, 897-910 (1987)

This research investigated sludge settleability and dewatering characteristics on plug flow and complete mix activated sludge systems with and without anoxic selectors. The F:M ratio was varied for all experiments while the total number of compartments was varied for the plug flow experiments. Results were verified by producing similar test results from a second and drastically different wastewater.

Two parallel pilot plants, one complete mix and the other plug flow, each with their own secondary clarifier were utilized for the experiments. The pilot units were initially fed primary clarified effluent from the municipality of Holzkirchen (in southern Germany). The Holzkirchen wastewater had significant contribution from two breweries and had historical sludge bulking problems. Test results on the Holzkirchen wastewater were verified using the township of Freising wastewater where historical bulking problems were known to occur due to the presence of numerous milk processing wastewaters.

Pilot results revealed that plug flow treatment with four compartment systems had significantly better settling sludges than complete mix reactors for sludge loadings of 1.8 kg BOD_5 (m^3/day) and less. For loadings equal to or greater than 2.0 kg BOD_5 (m^3/day) plug flow treatment could not prevent sludge bulking because of inadequate regeneration time. However, the introduction of an anoxic selector for sludge loadings of 1.0 kg BOD_5 (m^3/day) or less further improved plug flow treatment sludge settleability over completely mixed treatment. The effective loading in the anoxic selector was 4.0 kg BOD_5 (m^3/day). Sludge settleability was further improved when the selector loading was increased to 6.7 kg BOD_5 (m^3/day).

In conclusion this research demonstrated that the substrate gradient found in plug flow systems creates optimum growth conditions that prevented sludge bulking. Moreover, it was determined that highly loaded anoxic selector zones could further improve sludge settleability over the plug flow system alone. Increased sludge settleability allows higher operating MLSS concentrations and thus reduces the amount of biological and secondary clarifier volume required.

- Gaudy, A. F. Jr., Obayashi, A. and Gaudy, E. T. "Control of Growth Rate by Initial Substrate Concentration at Values Below Maximum Rate." *Applied Microbiology*, December, 1041-1047 (1971)

This research presents findings on the relationships of substrate concentration and specific growth rates in batch systems that contradict two assumptions fundamental to Monod kinetics as interpreted today. (1) The Monod equation "represents an instantaneous equality, i.e., that a change in S during growth results in an immediate change in μ if S is at a level below that which allows μ_{max}". (2) "The second which is corollary of the first, is that stated by Herbert et al., that exponential growth (μ and t_d are constant) can occur in a batch culture only when μ is equal to μ_{max}". Both of these assumptions have gained wide acceptance with out vigorous proof. Also of significance is that the authors state that these findings of batch kinetic behaviors are accurate for continuous flow systems under transient state conditions.

This research began on the basis that data from Monod and Schaefer, which indicate that growth with a constant value of μ occurred at initial substrate concentrations significantly less than that required for maximum growth rate conditions. This contradicts the fundamental assumptions of how we apply Monod kinetics to continuous flows systems today. This data in itself violates the two above identified assumptions.

Experiments conducted by the authors support that the above identified data of Monod and Schaefer which revealed that exponential growth could be achieved for substrate concentrations less than that required for maximum growth. This led to the conclusion that the Monod equation "does not accurately describe the relationship between μ and S during growth of batch culture and therefore probably should not be expected to predict behavior of a continuous culture during a severe transient". Moreover, it was concluded that equal concentrations of the initial substrate S_o and the substrate concentration at time t (S_t) do not produce equal specific growth rates. Gaudy and Gaudy state that this led to the working hypothesis that:

> In batch systems, the specific growth rate, μ, as shown herein, is determined by the concentration of external substrate initially present. The exponential rate of growth, once established, is not readily changed by changing external concentrations of growth-limiting nutrient in either batch or continuous flow systems. Thus, the culture exhibits a considerable inertia, or resistance to change in rates of synthetic processes. This suggests that the resistance to change in growth rate in a batch culture, and possibly in a continuous flow culture as well, is explained by control of the number of “permeation sites” by the concentration of external substrate to which the cell is exposed during the period when adjustment of the rates of all synthetic processes for achievement of balanced and orderly growth is occurring, *i.e.*, during the lag phase in a batch culture or during steady-state growth in a continuous culture. The cell thus established a steady-state internal concentration of the growth limiting nutrient, and the growth rates thus established can be maintained despite a significant decease in external concentration of that nutrient. (1046)

The authors also note that Monod kinetics as presently interpreted is adequate for continuous flow steady state systems or continuous flow systems with little change in load, *i.e.*, non-transient state.

This paper and presented topics are applicable to the current research herein this document because of the kinetic selection mechanisms present in anoxic selectors. Kinetic selection is only effective in situations where floc forming microorganisms can out compete filamentous organisms at higher growth rates. The current article may lend support to the hypothesis that the feed starve cycle created in the selector zones may continue for considerable time after leaving the selector zones.

- Lau, A. O., Strom, P. F. and Jenkins, D. "The competitive Growth of Floc-Forming and Filamentous Bacteria: A Model for Activated Sludge Bulking." *Journal of the Water Pollution Control Federation*, Volume 56, 52-61 (1984)

This research used computer modeling to predict bulking conditions by investigating competitive growth rates between filamentous bacteria (*sphaerotilus natans*) and floc forming bacteria (*Citrobacter sp.*) with varying DO concentrations and organic loading. The model incorporated a double Monod growth kinetic (substrate and DO) expression and also included diffusion of the substrates through the floc. The model uses a volume-weighted growth rate to account for conditions inside and/or outside the floc as dictated by the type and/or growth condition of the bacteria. For a set of conditions the model estimates both substrate concentrations (DO and soluble organic matter) with respect to the location within the sludge floc. It is shown that aerobic conditions (DO = 2.0 mg/l) may be present in bulk solution, however depending on the bulk solution organic loading and floc size, inside the floc may be anoxic and may have a significantly different organic substrate concentration. When predicting the higher growth rate between the filamentous and floc former microorganism both environments, within the floc and that of bulk solution, have to be considered. This line of reasoning may lend partial explanation as to why it takes a greater bulk solution DO to cure low DO bulking than it takes to prevent low DO bulking. Prior to the proliferation of filamentous bacteria both microorganisms (floc formers and filamentous) are living within the floc with the floc former being predominate. For example, as the organic load increases, given a constant bulk DO concentration, growth conditions within the floc may favor the filamentous bacteria. As the filamentous bacteria proliferates the filaments extend (for *S. natans*) outside the floc which results in the bacteria growing with respect to the bulk solution substrate concentrations. Therefore, as the organic loading decreases to the initial non-bulking loading the required bulk DO concentration required to increase the growth rate of the floc former, which is within the floc, greater than the filamentous bacteria, which is mostly outside the floc, is significantly larger since diffusional resistance across the floc has to be overcome. The magnitude of this difference in large part is dependent on the size of the floc. In summary, high bulk organic substrate concentrations (as opposed to within the floc), low bulk DO concentrations and spherical shaped floc favor the growth of *S. natans* over *Citrobacter sp*.

- Gabb, D. M. D., Ekama, G. A., Jenkins, D. and Marais, G. v. R. "Incidence of Sphaerotilus Natans in Laboratory Scale Activated Sludge Systems." *Water Science and Technology,* Volume 21, 29-41 (1989)

This research investigated the effects of aerobic selectors on the control of low F/M activated sludge bulking through two separate pilot programs receiving wastewater from the San Jose/Santa Clara Water Pollution Control Plant and from Mitchell's Plain WWTP in Capetown in South Africa. The San Jose/Santa Clara plant is a two stage activated sludge plant with separate stage nitrification which operates with a 12 to 14 day sludge age. The pilot units at the University of Cape Town Laboratory, treating Mitchell's Plain wastewater, were a single sludge nitrification and denitrification systems which had an MCRT of 20 days.

The situation occurred in both pilot programs where *S. Natans*, a low DO filament, which had never been identified in the full scale plant became dominant in the control. Process control strategies were undertaken to investigate the predominance of the *S. Natans* for two reasons: (1) The purpose of the control is to simulate full scale status quo conditions. If the control exhibits characteristics atypical of the full scale plant relative measurements between the selector unit and the control could not be made to determine the effects of selectors on low F/M bulking control. (2) To investigate control strategies to remedy bulking due to *S. Natans*.

As a result of these investigations the following were determined. The large surface area to volume ratio of pilot units as compared to full scale treatment facilities can make *S. Natans* attached growth become significant and predominate in the MLSS population in pilot units through seeding. Seeding occurs due to abundant *S. Natan* growth on pilot unit surfaces and feed lines. This growth can be reduced by scrubbing daily all wetted surfaces and routine replacement of all tubing/piping. Bulking due *to S. Natan* seeding can be corrected with high DO concentrations for complete mix systems, aerobic selectors or anoxic/anaerobic compartments preceding main biological treatment. If seeding is too excessive the control methods may not be successful.

- van Niekerk, A. M., Jenkins, D. and Richard, M. G. “A Mathematical Model of the Carbon-Limited growth of Filamentous and Floc-Forming Organisms in Low F/M Sludge.” *Journal of the Water Pollution Control Federation*, Volume 60, 100-106 (1988)

This paper presented a methodology for predicting the performance of aerobic selectors in controlling low F/M activated sludge bulking through mathematical modeling. The model predicts growth competition between a floc forming organism (*Zoogloea ramigera*) and a filamentous organism (type 021N) for a single carbon limiting substrate. Type 021N is a filamentous organism commonly found in low F/M CSTRs. *Z. ramigera* is a common floc forming organism found in SBR’s and aerobic selector low F/M activated sludges.

The model, using mass balance equations, predicts the net growth rate for each organism given certain conditions. Thus, the model enables the predominate organism to be identified and thus the status of bulking can be determined. Both Monod and Blackman kinetics were initially utilized in the model. For the short chain organic acid substrate Blackman kinetics were found to be more accurate in predicting the dominate organism. Modeling results were verified through full scale testing of municipal wastewaters.

Modeling results agreed with two previously observed characteristics of aerobic selectors. If selectors are sized too small a large portion of the soluble substrate is transported into the main aeration basin thus allowing filamentous bacteria to predominate given their higher affinity for substrate at lower concentrations. Conversely, if the selectors are oversized the substrate gradient is not high enough to induce rapid soluble substrate uptake which also leads to large amounts of soluble substrate entering the main aeration basin thus enabling the filamentous organisms to become predominate.

For the conditions outlined in the paper the optimum aerobic selector detention time was determined to be 14 minutes with an acceptable range of 12 to 20 minutes. Pilot testing confirmed the results of selectors being too small and too large for detention times of 7.5 and 30 minutes, respectively. Another important factor which arose from modeling simulations and from pilot testing was that relatively short periods (1 to 2 sludge ages) are required for bulking to be established if aerobic selectors are taken off line in low F/M CSTRs. On the other hand relatively long periods (5 to 8 sludge ages) are required for aerobic selectors to reduce low F/M bulking. This phenomena is termed “the slow bulking sludge response”.

Since optimum selector size is dependent on the influent substrate concentration and flow rate a minimum 3 compartment selector design is recommended to allow for varying concentrations and flows over time. Each individual compartment can be sized for different expected conditions. Additionally this research showed that floc loading, which is used by many people for sizing selectors, incorrectly neglects substrate uptake rates. However, as will be discussed later, floc loading can influence the mechanism responsible for substrate removal in the selector (*i.e*., storage or high rate metabolism).

- Pagilla, K. R., Jenkins, D., Kido, W. H. “Nocardia Control in Activated Sludge by Classifying Selectors.” *Water Environment Research*, March/April, 235-239 (1996)

This research investigated the effects of controlling Nocardia sp. in activated sludge through the promotion of surface foam and subsequent removal from the system. Foaming problems in activated sludge due to Nocardia and other bacteria from the actinomyces genus can lead to effluent deterioration (Pitt and Jenkins, 1990). Waste activated sludge containing high amounts of Nocardia when fed to anaerobic digesters can cause surface foam buildup leading to solids profile inversion, tipping of digester floating covers, and clogging of gas collection systems (Pitt and Jenkins, 1990). In activated sludge systems Nocardia foaming enhancement occurs due to higher wastewater temperatures, higher sludge ages, surface foam trapping in the secondary treatment system, recycle of secondary scum and also has an optimum pH of 6.5 (Pitt and Jenkins, 1990; Cha *et al*., 1992; Jenkins *et al*., 1993). It has been reported that at low concentrations surfactants can have a synergistic effect on Nocardia foaming in activated sludge.

Laboratory and full scale experiments were conducted to measure the effects of classifying selectors on controlling Nocardia foaming. Three CSTR pilot units were used, one as the control and two as classifying selector units. The control unit utilized a subsurface withdrawal method to transfer MLSS to the secondary clarification system which represented foam trapping in the aeration basin. The classifying selector units were equipped with a foam window which allowed excess foam to be wasted into a foam collector. In both selector units influent and RAS flows were stopped once per day for approximately ten minutes while high rate aeration was performed. At the end of this period the excess foam was manually scrapped through the foam window into the foam collector. In one of the selector pilot units a readily biodegradable nonionic surfactant was introduced prior to the high rate aeration period.

Full scale experiments were conducted at the Sacramento Regional Wastewater Treatment Plant a 150 mgd pure oxygen activated sludge system. An existing RAS channel was retrofitted as a continuously operating classifying selector.

Results of the investigations showed that pilot and full scale classifying selectors were effective in reducing foam over the control unit. Introduction of a readily biodegradable nonionic surfactant prior to foaming (the high rate aeration period of the classifying selector), in the pilot unit only, further reduced Nocardia levels below that of the classifying selector with out surfactant addition.

- Cha, D. K., Jenkins, D., Lewis, W. P. and Kido, W. H. "Process Control Factors Influencing Nocardia Populations in Activated Sludge." *Water Environment Research*, January/February, 37 - 43 (1992)

In an effort to reduce the deleterious effects of Nocardia through process control of activated sludge this research investigated the following; washout MCRT of Nocardia in activated sludge, the effect of foam recycle on Nocardia populations in activated sludge, the effect of pH on Nocardia populations in activated sludge, and the ability of aerobic and anoxic selectors on controlling Nocardia in activated sludge systems. All investigations were performed in continuous flow pilot-scale units which received primary effluent from the Sacramento California Regional Wastewater Treatment Plant.

It was determined that Nocardia generally increases with increasing MCRT over the range of MCRT's tested (1.5 to 15 days). The washout MCRT of Nocardia was found to fit the Arrhenius relationship with temperature. However, activated sludge systems which employed either foam trapping in the aeration basins or between the aeration basins and secondary clarifiers and/or did not remove secondary foam (scum) from the process could not significantly washout Nocardia. Secondary scum removal could occur by directly removing the scum from the secondary clarifiers or from utilizing dissolved air flotation devices for WAS thickening. The data show that foam recycle increased Nocardia filaments by approximately 10 times over those systems that did not recycle foam. Foam recycle was approximated in the pilot units by using a sub-surface withdrawal scheme in both the aeration basin and the secondary clarifier. The optimum pH for Nocardia growth was determined to be 6.5.

Aerobic selectors are effective in reducing Nocardia from activated sludge systems with MCRTs of approximately 5 days. Aerobic selectors were found not to be effective for activated sludge systems with 10 day MCRTs. The reasons for this are unknown and warrant further research since the growth relationships between *N. amarae* and *Z. ramigera* in aerobic conditions show the substrate uptake rate of *Z. ramigera* is greater than *N. amarae* at higher growth rates. Conversely, the substrate uptake rate of *N. amarae* is greater than *Z. ramigera* for low growth rates. Therefore, the high substrate concentration present in the aerobic selector should present conditions where *Z. ramigera* out competes *N. amarae* and thus be predominate for all sludge ages.

Anoxic selectors were found to be effective in controlling Nocardia populations in nitrifying activated sludge systems with a 12 day MCRT. This is in agreement with the pure culture data which showed that the denitrification rate of *N. amarae* was 2 to 3 orders of magnitude less than *Z. ramigera*. It is noted that *N. amarae* only denitrifies nitrate to nitrite rather than to nitrogen gas.

- Other Works Reviewed

Jenkins, D., Richard, M. G. and Daigger, G. T. *Manual on the Causes and Control of Activated Sludge Bulking and Foaming*. Lewis Publishers, Chelsea, MI, 184p., 1993

Randall, Clifford W., Barnard, James L., Stensel, H. D., eds. *Design and Retrofit of Wastewater Treatment Plants For Biological Nutrient Removal.* Technomic Publishing, Lancaster, Pennsylvania, 417p., 1992

Higgins, Matthew, J. and Novak, John, T. "The effect of cations on the settling and dewatering of activated sludges: Laboratory results." *Water Environment Research, 69*: 215-224 (1997)

Higgins, Matthew, J. and Novak, John, T. "Dewatering and settling of activated sluges: The case for using cation analysis." *Water Environment Research, 69*: 225-232 (1997)

CHAPTER III. MATERIALS AND METHODS

Overview

Two pilot activated sludge units were constructed to evaluate the effects of anoxic selectors on controlling activated sludge bulking and foaming. The experimental (anoxic selector) pilot unit was identified as Pilot A while the control unit was identified as Pilot B. Both the experimental unit and the control were constructed to simulate the proposed full scale upgraded and expanded facility with the only difference being that pilot A had a three stage anoxic selector zone preceding the main biological reactor while Pilot B did not.

Experimental Design

The following historical values were used in the kinetic design of the full scale facility: BOD_5 175 mg/L (maximum week), TKN 35 mg/l N (maximum week) Inert suspended solids 30 mg/l (maximum week), temperature 10 C, peak flow factor 1.8, pH 7.2 su (corrected through alkalinity addition) and a 1.2 nitrification safety factor. Results from kinetic modeling indicated that the proposed full scale activated sludge facility would require a 10 day oxic MCRT and a 10 hour oxic HRT which results in a MLSS of 3,000 mg/l to achieve the stipulated ammonia-nitrogen limits during winter months.

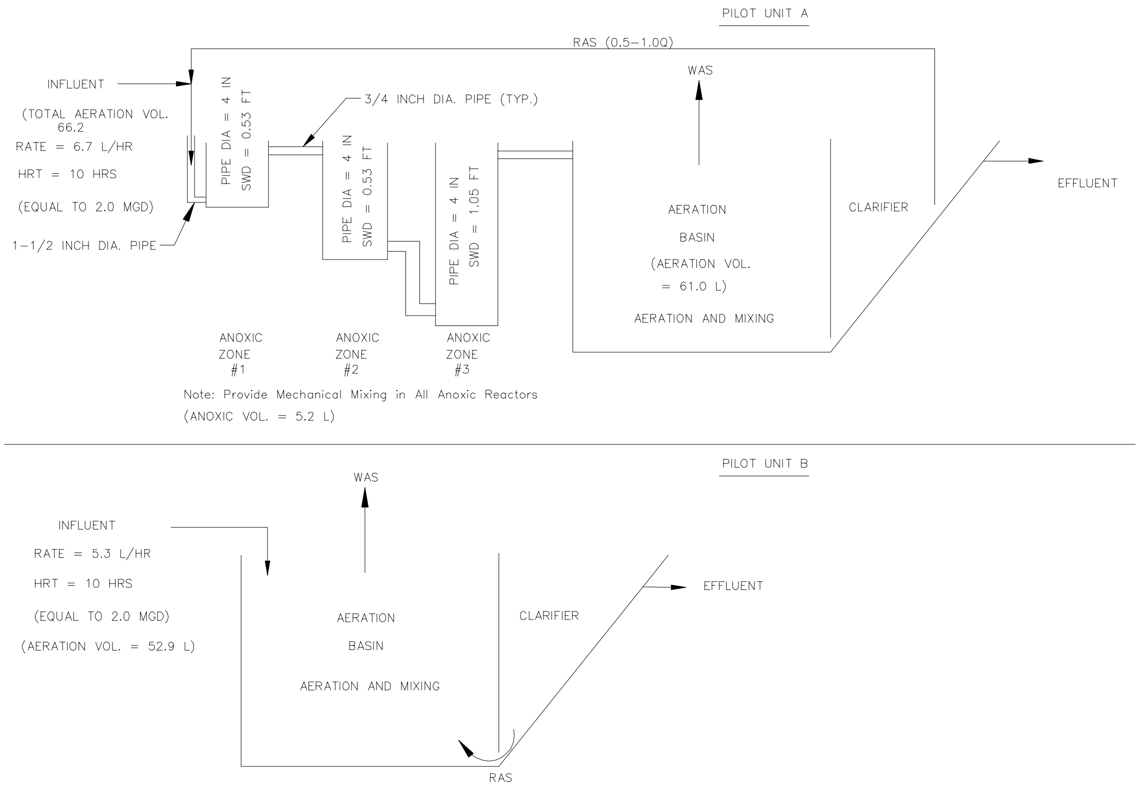
The three stage anoxic selector was designed with a decreasing F/M ratio of 12, 6 and 3 kg BOD_5 / kg MLSS-day based upon average influent loadings. The selector had a total HRT of 25 minutes. The first two selector zones were equal in size with the third zone being equal to the first two.

Pilot Program

The pilot program consisted of two individual process trains located at the treatment facility and was operated by plant staff with daily direction by the author. Figure 1 presents a schematic of the pilot program.

Figure 1

Pilot Program Schematic



One process train was the control (Pilot B) for the study and modeled the existing secondary treatment process of the full scale activated sludge treatment facility. The other process train (Pilot A) simulated the proposed anoxic selector activated sludge process. The biological process following the selectors was a complete mix system. The complete mix system was used instead of the proposed plug flow regime due to the availability of the complete mix units. The need to begin the pilot program immediately was because of a consent order deadline for a preliminary engineering report to be filed less than three months from the start of the pilot program. The pilot testing program is presented in Table 1. Microorganism examinations were performed weekly using a 1000X phase contrast microscope and Gram and Neisser staining procedures were also performed.

Table 1

PILOT PLANT TESTING & SAMPLING PROGRAM

Location	Test	Sample Frequency	Method of Collection	Testing Party	Pilot Unit: Pilot A	Pilot Unit: Pilot B
Pilot Influent						
	Flow	7 Days/wk	Continuos	City of Bedford	✓	✓
	pH	7 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	Temperature	7 Days/wk	Insitu	City of Bedford	✓	✓
	Alkalinity	7 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	COD	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	SCOD	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	BOD5	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	SBOD5	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	TSS	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	TKN	M,W,TH	24 hr Comp.	Olver Labs	✓	✓
	Ammonia	M,W,TH	24 hr Comp.	Olver Labs	✓	✓
	Nitrate	M,W,TH	24 hr Comp.	Olver Labs	✓	✓
	Nitrite	M,W,TH	24 hr Comp.	Olver Labs	✓	✓
	Inert Suspended Solids	M,W,TH	24 hr Comp.	Olver Labs	✓	✓
Anoxic Selector 1 Effluent						
	Dissolved Oxygen	7 Days/wk	Insitu	City of Bedford	✓	
	SBOD5	5 Days/wk	24 hr Comp.	City of Bedford	✓	
	MLSS	7 Days/wk	Once Per Day	City of Bedford	✓	
Anoxic Selector 2 Effluent						
	Dissolved Oxygen	5 Days/wk	Insitu	City of Bedford	✓	
	SBOD5	5 Days/wk	24 hr Comp.	City of Bedford	✓	
Anoxic Selector 3 Effluent	Dissolved Oxygen	5 Days/wk	Insitu	City of Bedford	✓	
	SBOD5	5 Days/wk	24 hr Comp.	City of Bedford	✓	
	Nitrate	M,W,TH	24 hr Comp.	Olver Labs	✓	
Activated Sludge						
	pH	7 Days/wk	Insitu	City of Bedford	✓	✓
	Temperature	7 Days/wk	Insitu	City of Bedford	✓	✓
	Dissolved Oxygen	7 Days/wk	Insitu	City of Bedford	✓	✓
	MLSS	7 Days/wk	Once Per Day	City of Bedford	✓	✓
	MLVSS	5 Days/wk	Once Per Day	City of Bedford	✓	✓
	SVI	5 Days/wk	Once Per Day	City of Bedford	✓	✓
	Oxygen Uptake Rate (OUR)	Once Per Week		City of Bedford	✓	✓
Clarifier Effluent						
	pH	7 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	Temperature	7 Days/wk	Insitu	City of Bedford	✓	✓
	Alkalinity	7 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	COD	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	SCOD	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	BOD5	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	SBOD5	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	TSS (Effluent, RAS, WAS)	5 Days/wk	24 hr Comp.	City of Bedford	✓	✓
	TKN	M,W,TH	24 hr Comp.	Olver Labs	✓	✓
	Ammonia	M,W,TH	24 hr Comp.	Olver Labs	✓	✓
	Nitrate	M,W,TH	24 hr Comp.	Olver Labs	✓	✓
	Nitrite	M,W,TH	24 hr Comp.	Olver Labs	✓	✓

Both pilot units were fed equalized primary effluent. The sludge age of the pilot units were kept constant at 10 days, and controlled hydraulically by wasting (via submerged withdrawal procedure) three times daily directly from the aeration basins.

Speed controlled peristaltic pumps fed each of the pilot units and a peristaltic pump was used for Pilot A to return RAS from the clarifier to the first anoxic zone. A separate return sludge pump was unnecessary for Pilot B since the settled sludge in the clarifier would naturally return under the center partition wall to the aeration basin. Clarifier effluent was withdrawn by gravity from approximately two inches below the water surface level in the clarifier.

All tests were performed following the procedures of the latest edition of Standard Methods. The contract laboratory instituted a quality control and assurance program which consisted of routine duplicate and replicate samples and tests. Any results which fell outside normal and/or expected values were re-tested. Periodic replicate tests were performed for all in plant testing procedures.

CHAPTER IV. RESULTS

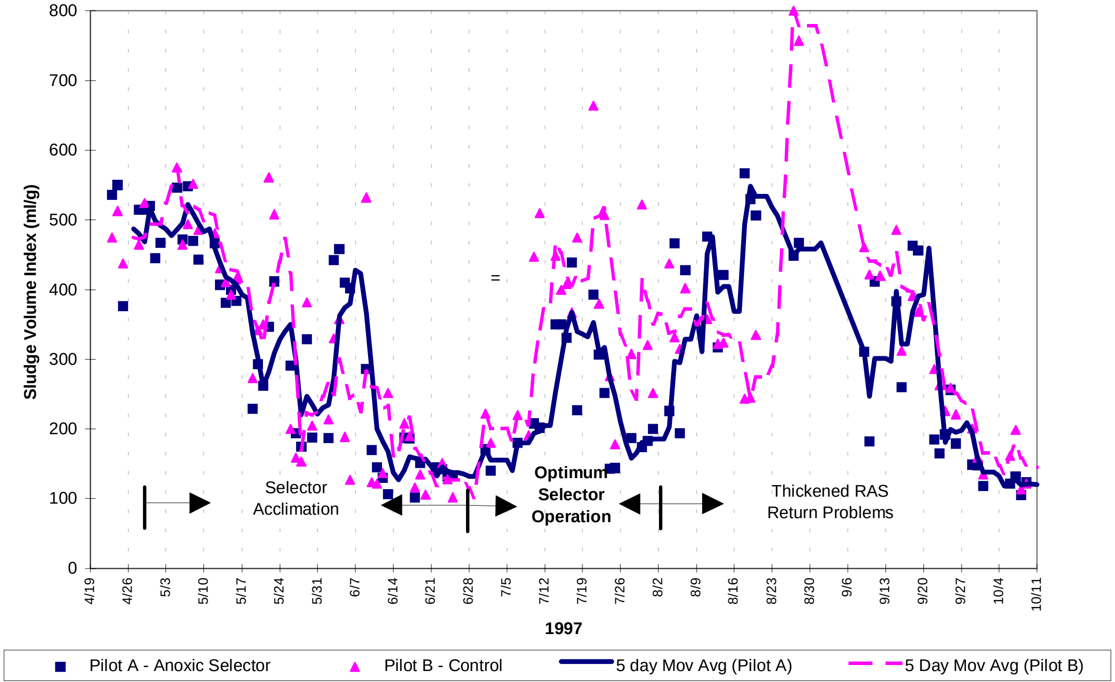
Introduction

In this section pertinent results and relationships from the pilot program will be presented to illustrate the effects of anoxic selectors on controlling activated sludge bulking and foaming, and the underlying principles and mechanisms at work. Except for Figure 2, all other figures, tables and data analyses have been performed only on data measured during the optimum selector operational period as defined in Figure 2.

The effect of anoxic selectors on the SVI

The SVI (conventional) from both pilot units are presented in chronological order in Figure 2. The figure has been segmented into three separate periods, which were determined by actual selector operation: selector acclimation, optimum selector operation, and thickened RAS return problems. Note the sudden increase in SVI in both pilot units from July 12^{th} to 26^{th}. Significant variation in the SVI can occur from day to day since the SVI can be influenced by daily variations in influent waste characteristics. To this end, a five day moving average has been used to represent system performance. It generally takes a few MCRTs (Jenkins *et al*., 1993) for the selector to "select" floc forming microorganisms over filamentous microorganisms. Thus, during the acclimation period rapid substrate uptake occurs in the selector identical to that during the optimum selector operational period. It is important to note here that the optimum selector operational period was determined by the differences in the SVI and the identified filamentous microorganisms between the experimental unit and the control.

FIGURE 2
PILOT PROGRAM SLUDGE VOLUME INDEX (CONVENTIONAL)



The effect of floc load and F/M on biosorption in the selector

The relationships between selector floc loading and F/M to total selector biosorption are presented in Figure 3. Figure 4 portrays the relationship between floc loading and the first selector F/M to substrate removal rate in the first selector.

FIGURE 3
SELECTOR ORGANIC LOADING VS BIOSORPTION

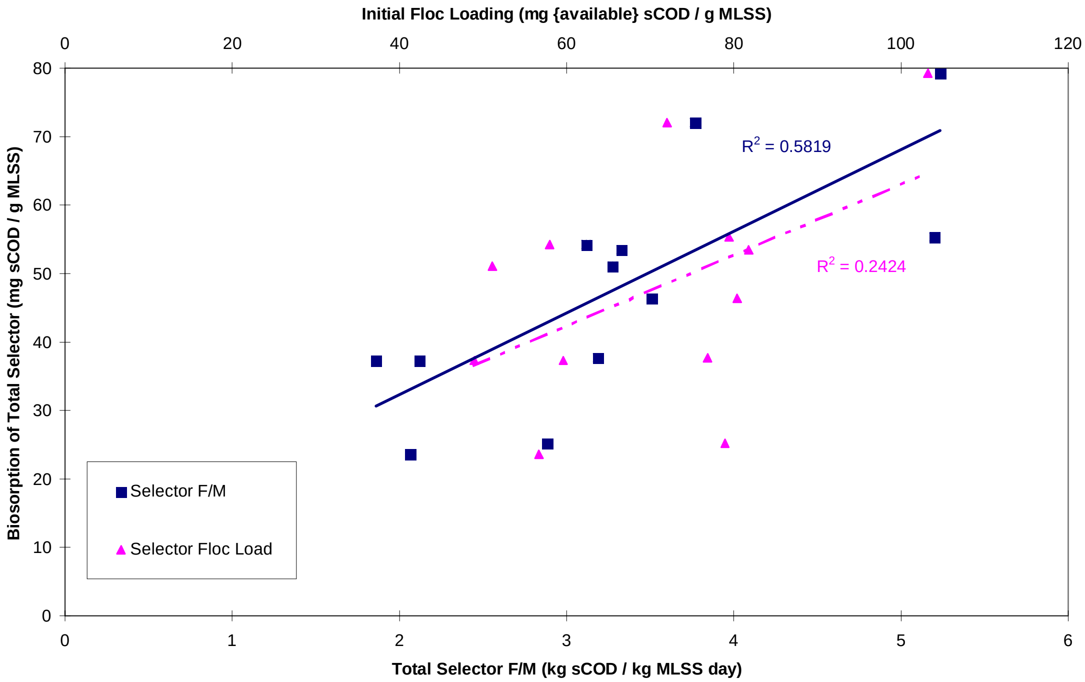
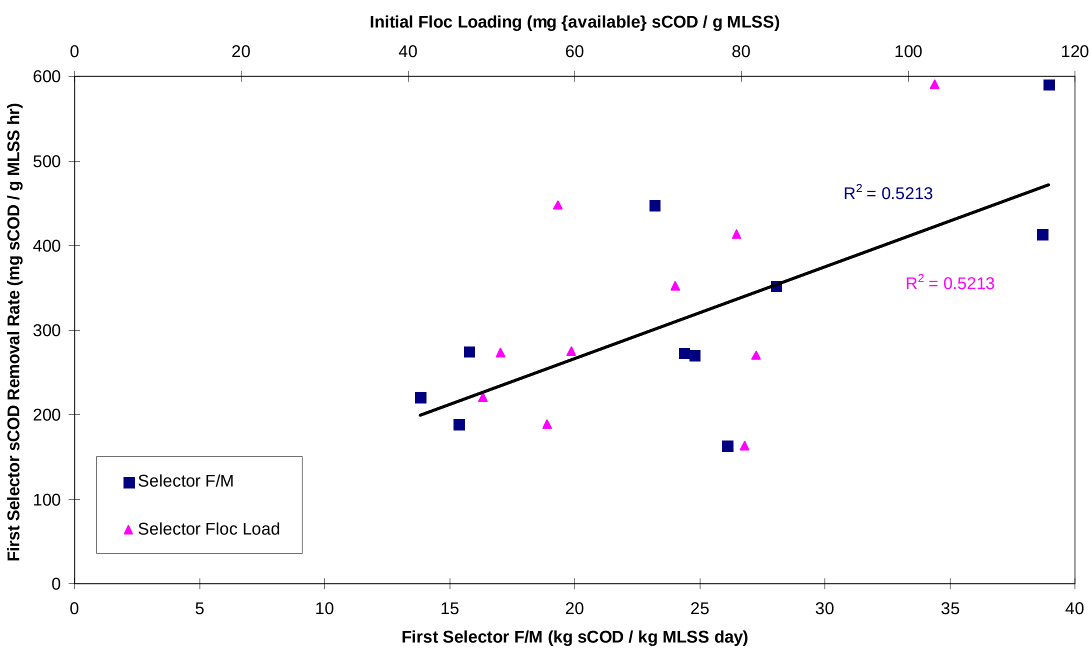


FIGURE 4
FIRST SELECTOR ZONE ORGANIC LOADING VS SUBSTRATE REMOVAL RATE



The impact of F/M on selector removal efficiency and mass of substrate removed

Figure 5 presents the total selector F/M vs. total selector removal efficiency and total mass of substrate removed. Figure 6 presents the total selector F/M by week vs. the total selector removal efficiency. Figure 7 presents the total selector F/M by week vs. the total mass of substrate removed. Chronological presentation or grouping the data by date is used here to filter out the effects of influent wastewater variation during the study period.

FIGURE 5
SELECTOR ORGANIC LOADING VS TOTAL SELECTOR REMOVAL EFFICIENCY AND MASS OF SUBSTRATE REMOVED

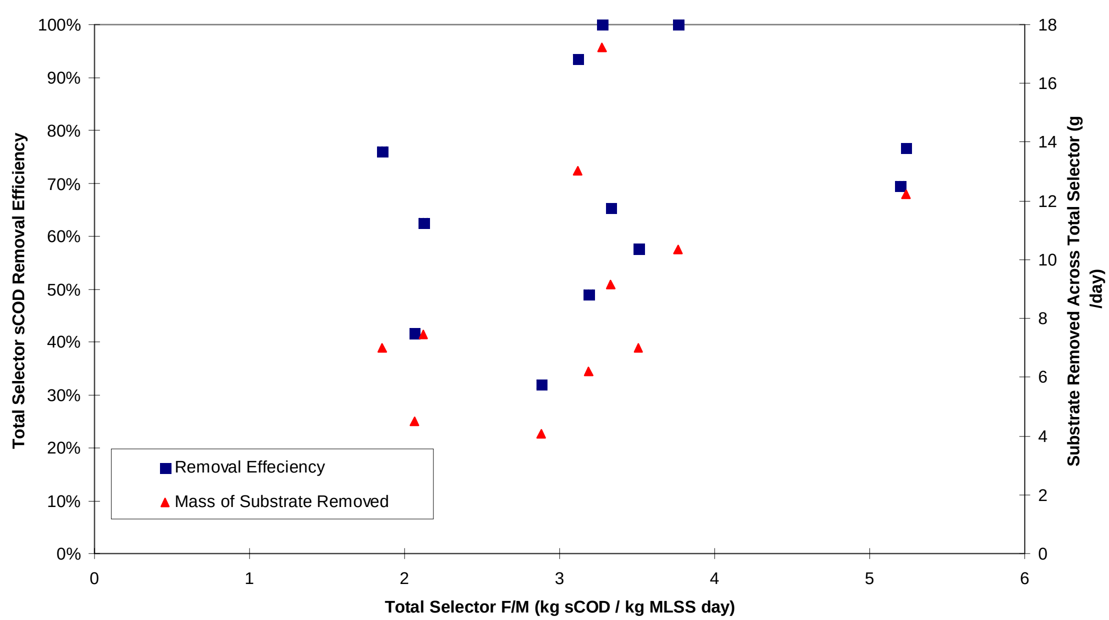


FIGURE 6
SELECTOR ORGANIC LOADING BY WEEK VS SELECTOR REMOVAL EFFICIENCY

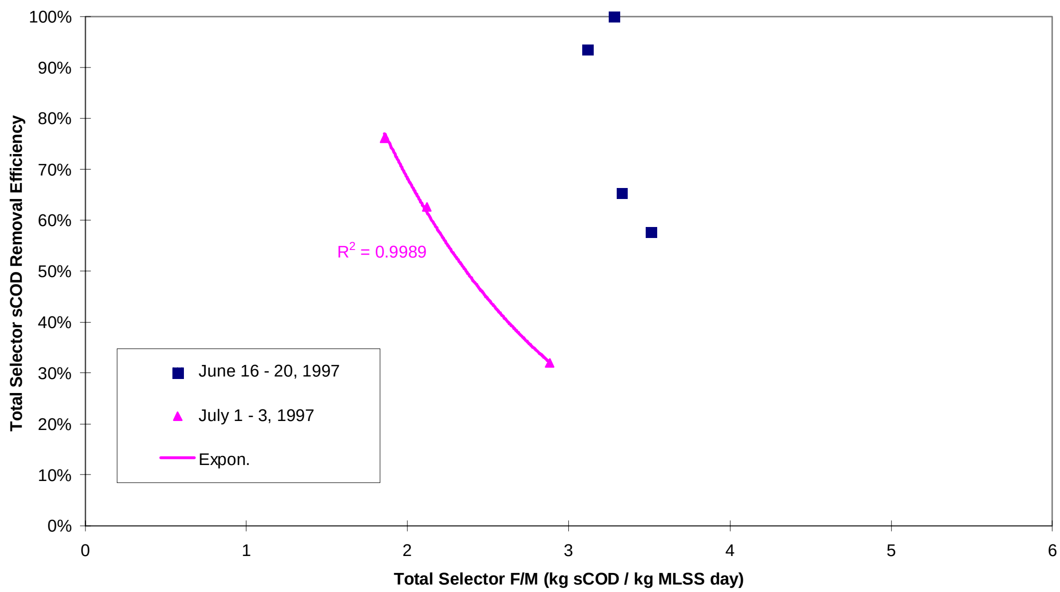
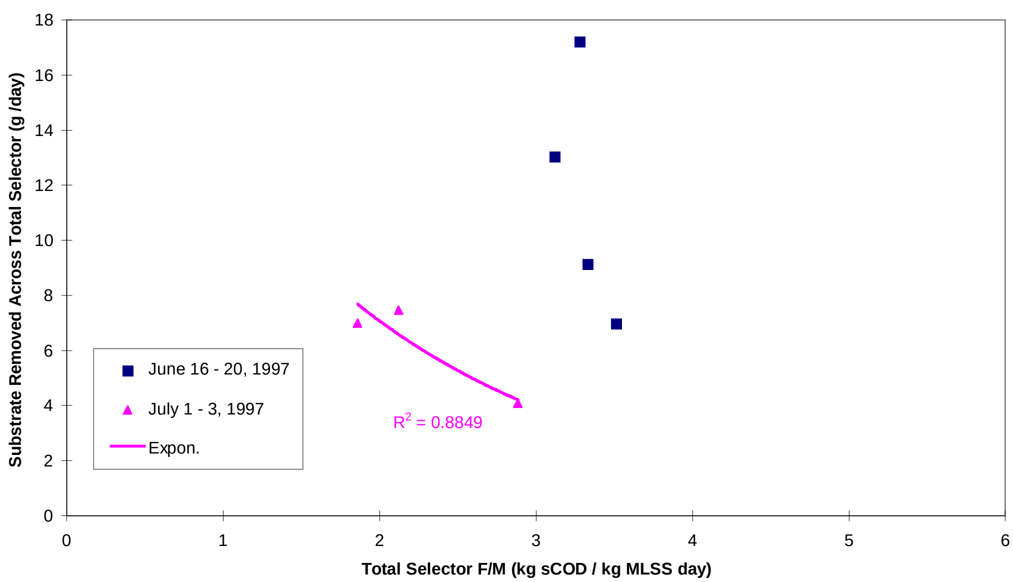


FIGURE 7
SELECTOR ORGANIC LOADING BY WEEK VS MASS OF SUBSTRATE REMOVED



The impact of selector floc load on selector removal efficiency and mass of substrate removed

Figure 8 presents the selector floc load vs. total selector removal efficiency and total mass of substrate removed. Figure 9 presents the selector floc load by week vs. the total selector removal efficiency. Figure 10 presents the selector floc load by week vs. the total mass of substrate removed. Again, chronological presentation or grouping the data by date is used here to filter out the effects of influent wastewater variation during the study period.

FIGURE 8
SELECTOR FLOC LOADING VS TOTAL SELECTOR REMOVAL EFFICIENCY AND MASS OF SUBSTRATE REMOVED

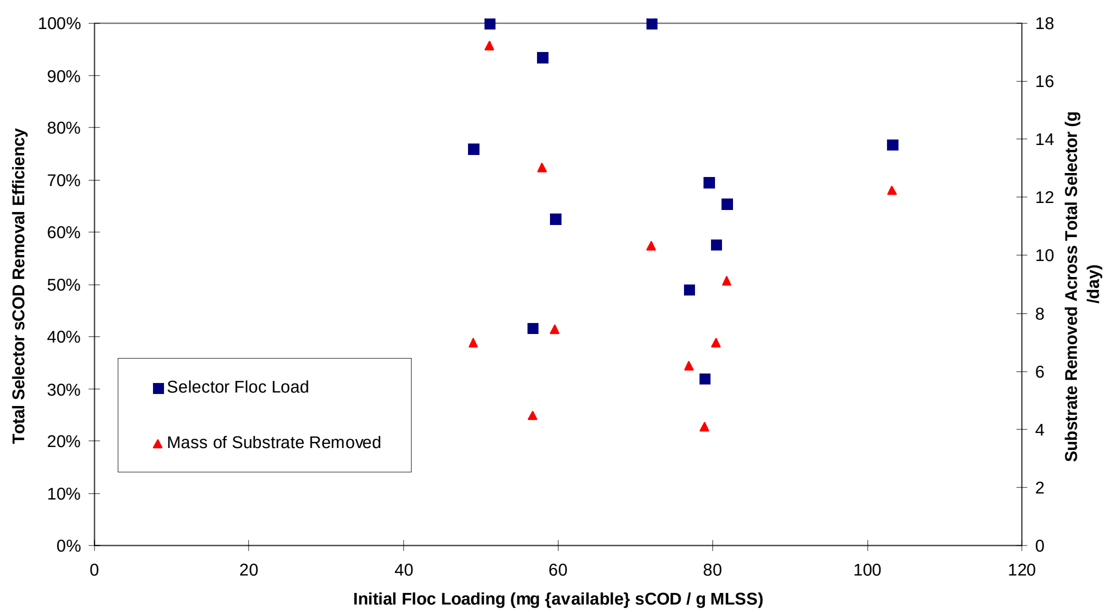


FIGURE 9
SELECTOR FLOC LOADING BY WEEK VS SELECTOR REMOVAL EFFICIENCY

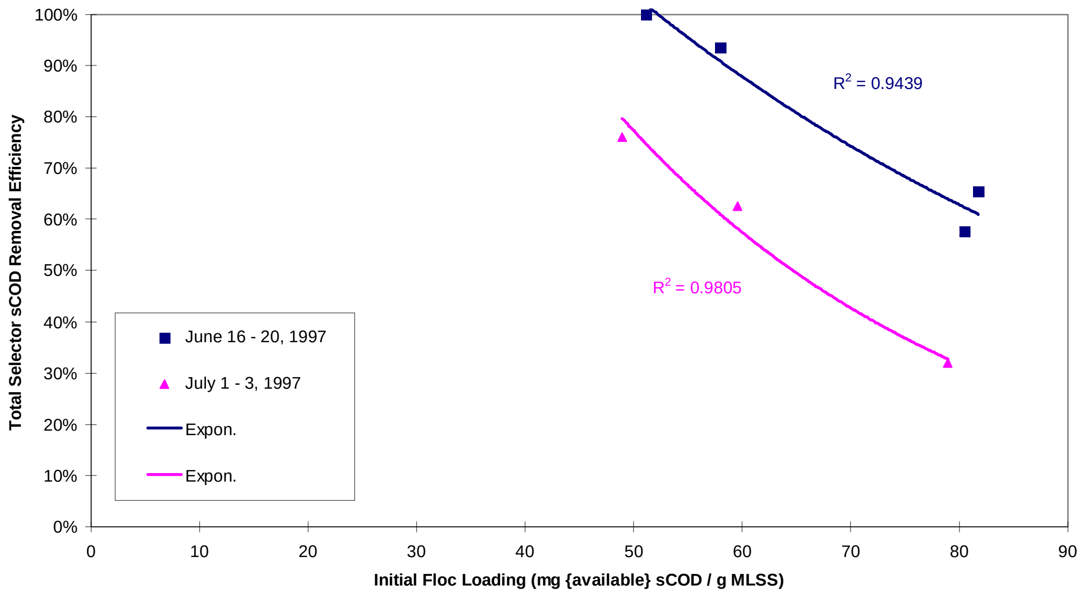
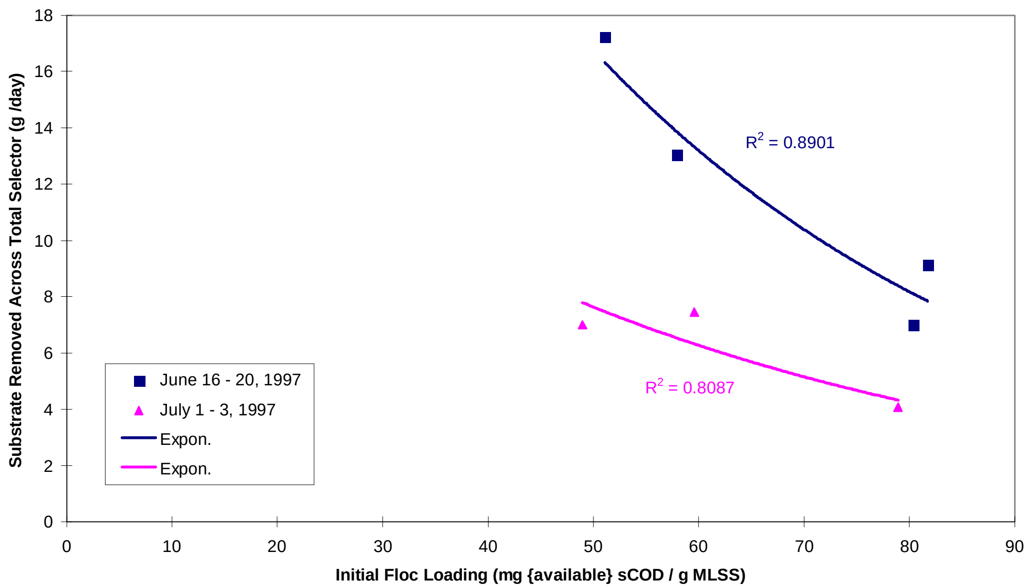


FIGURE 10
SELECTOR FLOC LOADING BY WEEK VS MASS OF SUBSTRATE REMOVED



The relationships between floc loading and substrate storage, substrate removal efficiency and mass of substrate removed

Table 2 summarizes pertinent data used to determine the mechanism predominately responsible for substrate removal in the anoxic selector zones. Only three sets of samples were obtained during the optimal period because both COD and total nitrogen analyses are required on the same day to present these relationships. Logistic issues, limited testing moneys and scarce manpower led to this reality. Note that the data are not presented in chronological order and nitrification inhibition did not occur during this period. It is important to note that the nitrate concentration leaving the third selector for the largest value of substrate removed per nitrate utilized (of both data series) was 3.7 mg/l N and for both the second largest and smallest values the nitrate concentration leaving third selector was non-detectable.

Table 2

Data Depicting Predominate Mode of Substrate Removal

Date (1997)	Floc Load (mg sCOD / g MLSS)	Substrate Removed (g sCOD/day)	Nitrate Utilized (g N/day)	Substrate Removed / Nitrate Utilized
June 18	51	17.2	0.5	35
June 16	58	13.0	0.7	19
June 19	80	7.0	1.0	7

General Notes: 1. Nitrification inhibition did not occur during this period.

Figure 11 presents the relationships of selector floc load vs sCOD removed per nitrate utilized and selector removal efficiency for the week of June 16 through 19, 1997.

FIGURE 11
SELECTOR FLOC LOAD VS sCOD REMOVED PER NITRATE UTILIZED AND TOTAL SELECTOR REMOVAL EFFICIENCY FOR WEEK OF JUNE 16 - 19, 1997

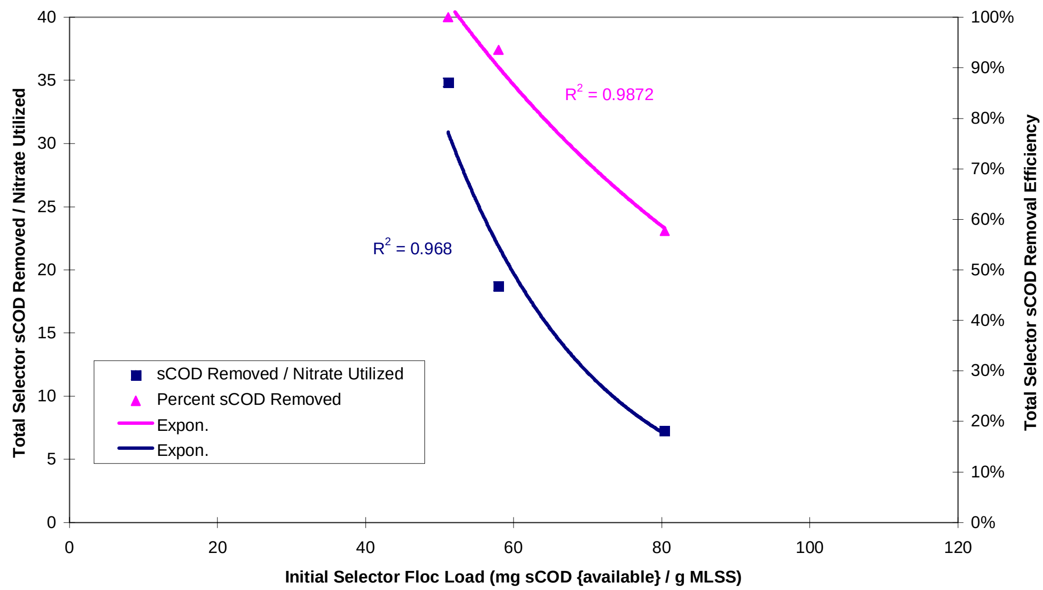


Figure 12 presents the relationship between total selector sCOD removed per nitrate utilized and total selector sCOD removal efficiency.

FIGURE 12
TOTAL SELECTOR sCOD REMOVED / NITRATE UTILIZED VS TOTAL SELECTOR REMOVAL EFFICIENCY

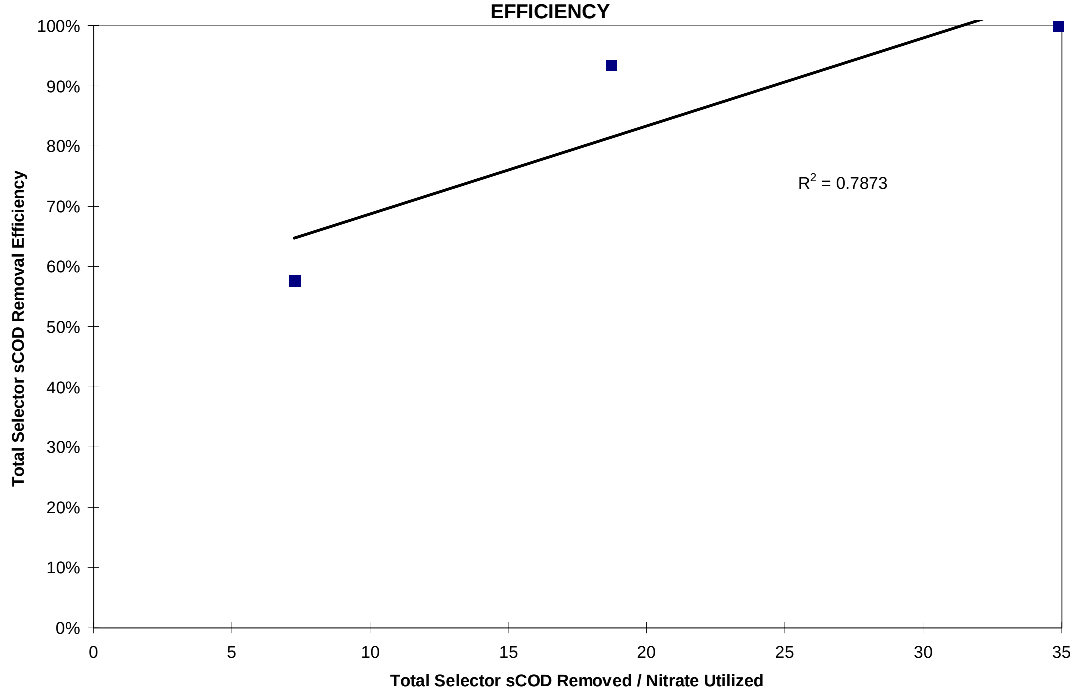


Figure 13 presents the relationship of selector floc load vs sCOD removed per nitrate utilized and mass of substrate removed for the week of June 16 through 19, 1997.

FIGURE 13
SELECTOR FLOC LOAD VS sCOD REMOVED PER NITRATE UTILIZED AND MASS OF SUBSTRATE REMOVED FOR WEEK OF JUNE 16 - 19, 1997

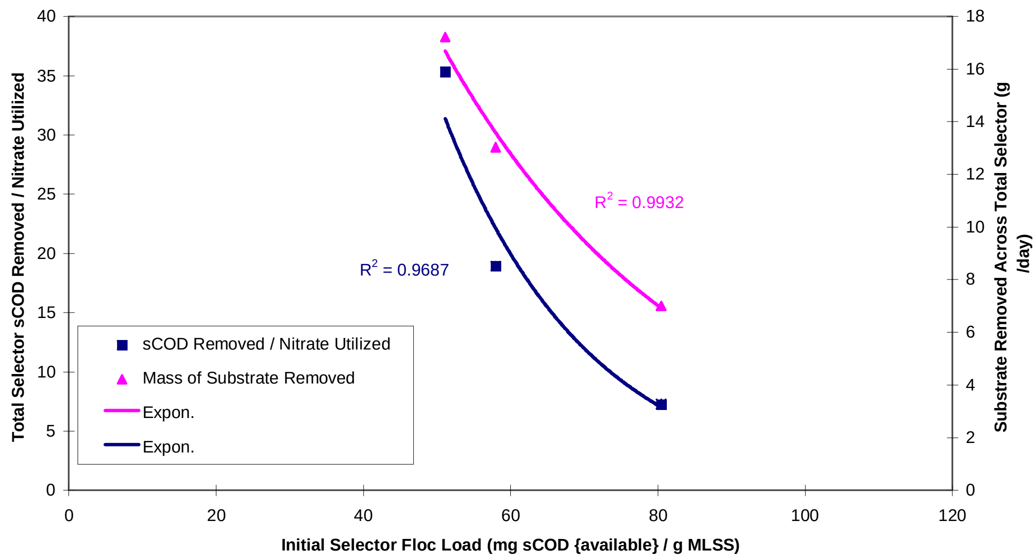
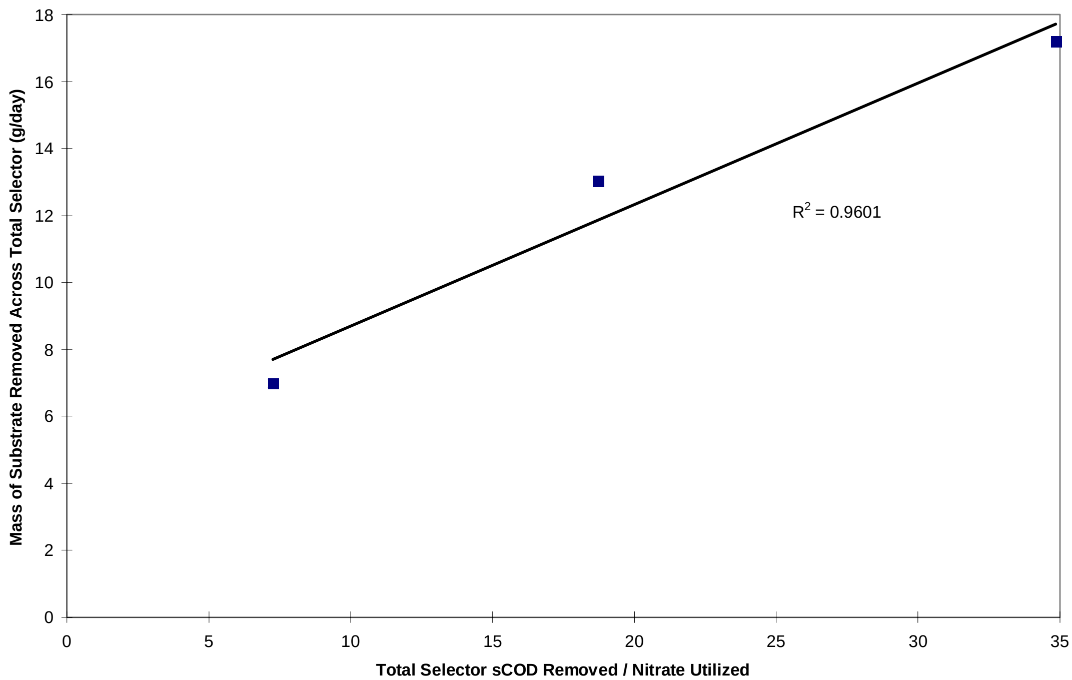


Figure 14 presents the relationship between total selector sCOD removed per nitrate utilized and total mass of sCOD removed in the selector.

FIGURE 14
TOTAL SELECTOR sCOD REMOVED / NITRATE UTILIZED VS MASS OF sCOD REMOVED



Significant characteristics of the waste stream

Surfactants

The frequent presence of a thin white film on the pilot feed barrel (primary clarifier effluent) with spectacular periodic white foaming events on the in-line (aerated) equalization basin led to the suspicion of surfactants being present in the plant influent. Both MBAS and CTAS tests were conducted on the pilot feed for six months and the results revealed an average concentration of 5 and 3 mg/l of MBAS and CTAS, respectively. Values as high as 15 and 10 mg/l were observed for MBAS and CTAS, respectively.

BOD toxic response

One, three and five day BOD tests with five dilution series each were conducted three times per week for 30 weeks to further quantify the toxic responses frequently observed at the POTW. One, three and five day soluble BOD tests with five dilution series each were also conducted for the last six weeks of the intensive toxic response testing. Of the 82 test days, 55 days resulted in a toxic response for at least one of the BOD tests. In most cases where a toxic response was identified, both the 3 and 5 day tests showed the characteristic toxic response. In the last six weeks of the testing both soluble and total BOD tests were performed. Of the 14 test days which displayed a toxic response from the total BOD test, only four days showed a toxic response in the soluble BOD tests.

Monovalent to divalent cation ratios

During the week of July 12th 1997, the SVI in both pilot units increased. Microscopic investigations revealed that a diffuse floc structure was present in both pilot unit sludges. Pilot A (the anoxic selector unit) predominately had a diffuse floc structure while Pilot B had significant filaments extending beyond the diffuse floc structure. A micro nutrient scan performed on the influent during this time revealed that the monovalent to divalent cation ratio was 3.7 and the magnesium concentration was 0.11 meq/l.

CHAPTER V. DISCUSSION

The effect of anoxic selectors on the SVI

Microscopic examinations of pilot unit A during the optimum performance period showed an increase in floc-forming organisms and free-swimming and attached ciliates, and a decrease in the number of filamentous organisms relative to pilot unit B, which was the control.

The predominate filaments during the optimum period shown in Figure 2 were identified as type 021N and *M. parvicella*. Type 021N is a Group II filamentous organism which has been reported to be controlled by anoxic selectors (Jenkins *et al*., 1993). *M. parvicella* is a Group IV filamentous organism which has no known successful selector control strategy. The significantly lower SVI in pilot A compared to B during this period is believed to be attributable to the successful feed-starve cycle instituted by the anoxic selectors.

Gabb *et al*., (1989) warned researchers that pilot units themselves could develop favorable growth conditions for *S. natans*. Thus, the selectors could give a false positive result for the control of filamentous organisms thought to be indigenous to the full scale facility. To this end, the pilot units were operated with a high dissolved oxygen concentration (> 4.0 mg/l) to prevent favorable growth (low D.O.) conditions for *S. natans*. Additionally a rigorous maintenance program was established which involved weekly scrubbing of the reactor walls with bleach and replacement of feed lines. Other than one instance when the air supply (to both pilot units) failed over a weekend, *S. natans* were never dominate in either pilot unit.

It should be noted that a diffuse floc structure was observed during certain high SVI periods. As will be further discussed later the bulking associated with the diffuse floc structure may have been associated with the presence of nonionic surfactants or an imbalance in the cationic ratio in the influent. Sometimes it requires the action of the selector to eliminate one type of bulking to discover other types of bulking which have always been present.

The following presents a statistical analysis of the data contained in Figure 2 during the optimal performance period (as noted) of pilot operation.

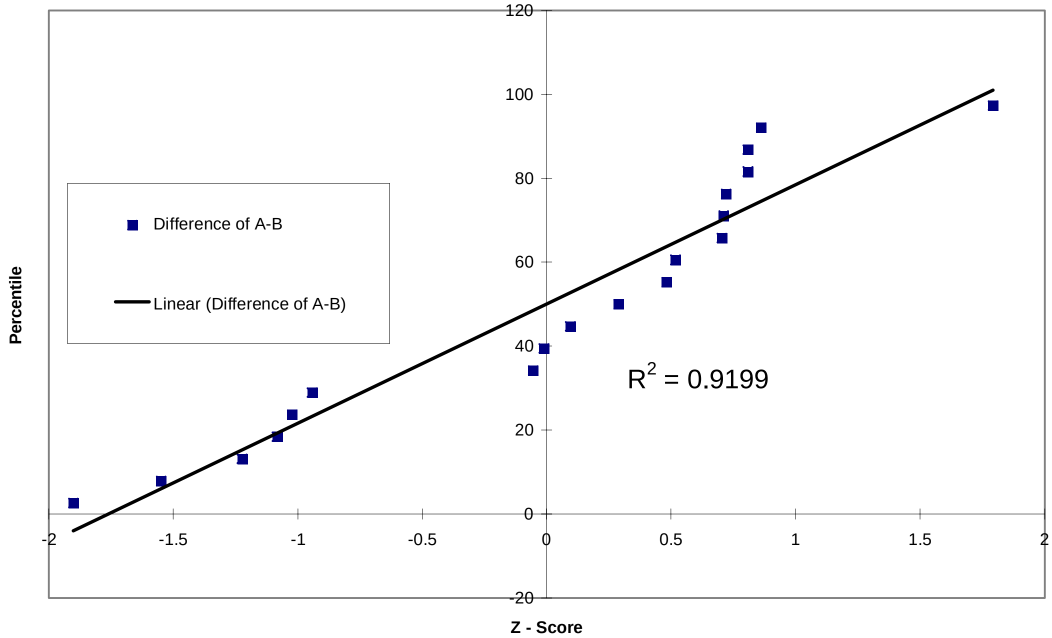
The inherent dependency of the SVI on influent wastewater characteristics lends to a natural pairing of daily SVI data points of each pilot unit. Data pairing in addition to identical and side by side operation of the pilot units eliminated variability between the two SVI data populations beyond that of the anoxic selectors. Thus, the paired *t* test was used to measure the difference between the average SVIs of the two pilot units.

The null hypothesis for this experiment was; the average SVI of the experimental unit (Pilot A) is equal to the average SVI of the control unit (Pilot B) to the 0.05 significance level. The alternative hypothesis stated that the average SVI of the experimental unit is less than the average SVI of the control unit.

The paired *t* test required that the difference of the two populations be normally distributed and secondly that the differences themselves be randomly selected from the population (*i.e.* data points from each pilot unit be independent and identically distributed (IID)). Although there is some interdependence of the SVI from day to day this correlation is small and is unavoidable. Thus, the requirement of IID is assumed to be satisfied. All 19 paired data points (which represents six weeks of optimal operation) were used in the analysis.

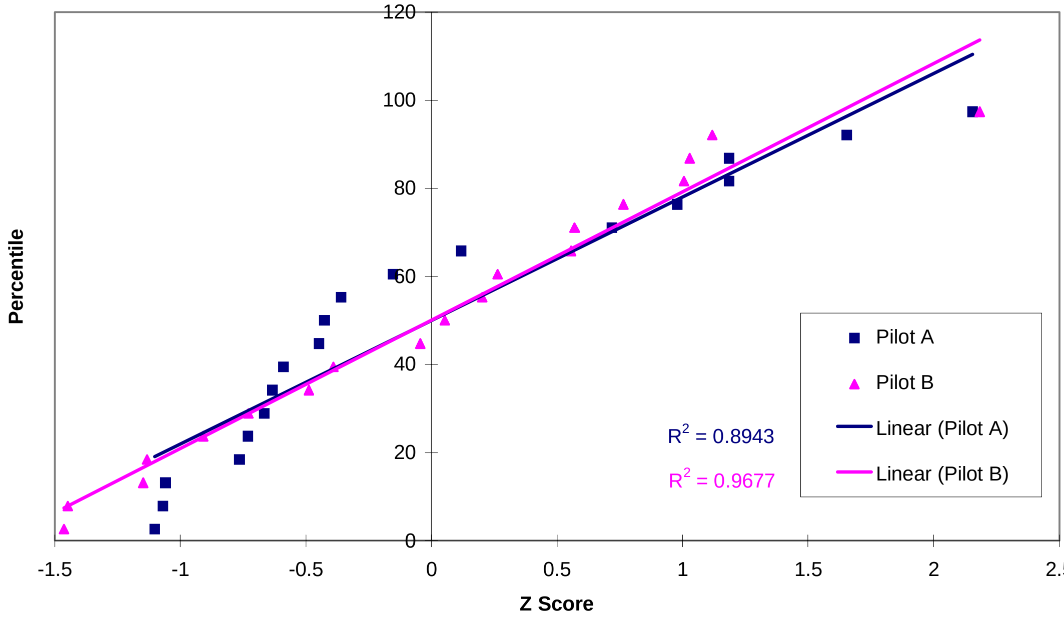
SVI data from each pilot unit were paired together for each day (19 test days) during the optimal operational period. The difference between each data set (SVIA - SVIB) was computed and then ranked from smallest to largest. A corresponding Z score was calculated using the average and sample standard deviation of the differences. To determine if the differences were normally distributed the Z score was plotted against the corresponding data percentile. A least squares linear regression resulted in an R^2 value of approximately 0.92. Thus, a normal distribution of the differences was verified. Figure 15 presents these findings.

FIGURE 15
PROBABILITY PLOT FOR THE Z SCORES OF SVI (A - B)



The question of normality was further investigated by creating a SVI Z score plot for each pilot unit during the optimal period. A least squares regression resulted in an R^2 value of approximately 0.96 for the control and approximately 0.89 for the experimental unit as depicted in Figure 16. From the closeness of the data it is reasonable for the two best fit lines to be essentially the same as presented in Figure 16. Because the experimental unit requires nitrification to occur, the periodic inhibition of nitrification due to influent toxicants (which occurred periodically throughout the pilot program) adversely affected the experimental unit SVI greater than the control unit SVI. The lower R^2 value for the experimental unit is therefore understandable and within reason. Thus, the underlying SVI populations for both pilot units are normally distributed.

FIGURE 16
Z SCORE PLOTS FOR PILOT PROGRAM SVIs
DURING OPTIMAL PERIOD



The single tail paired *t* test analysis with an 0.05 significance level resulted in a test statistic of -5.05 with a critical *t* value of -1.73. Thus, the null hypothesis was strongly rejected and the alternative hypothesis was accepted *i.e.*, SVI A is less than SVI B. The observed level of significance was approximately 0.00004, therefore, there is a 0.004 percent chance that the null hypothesis was rejected when in fact it is the true state of nature. In summary, this hypothesis test states that the population mean of SVIA (anoxic selector) is less than the population mean of SVIB (control) to the 0.004 percent significance level.

The F test with a 0.05 significance level was used to evaluate the variances of the two SVI populations. The F test requires the data be normal and be independent and identically distributed. As presented above the data during the optimal period meets both of these conditions. The hypothesis test was constructed such that the null hypothesis stated that the variance of SVIA equals the variance of SVIB. The alternative hypothesis stated that the variance of SVIA is less than the variance of SVIB. The one tail F statistic (alpha = 0.05) was calculated to be 0.47. The critical value was determined to be 0.45. Since 0.47 is not less than 0.45 the null hypothesis is not rejected, however this does not imply that the null hypothesis was accepted. The observed level of significance was 0.06 thus the null hypothesis would be rejected if the desired significance level were to be set equal to or greater than 0.06.

The effect of floc load and F/M on biosorption in the selector

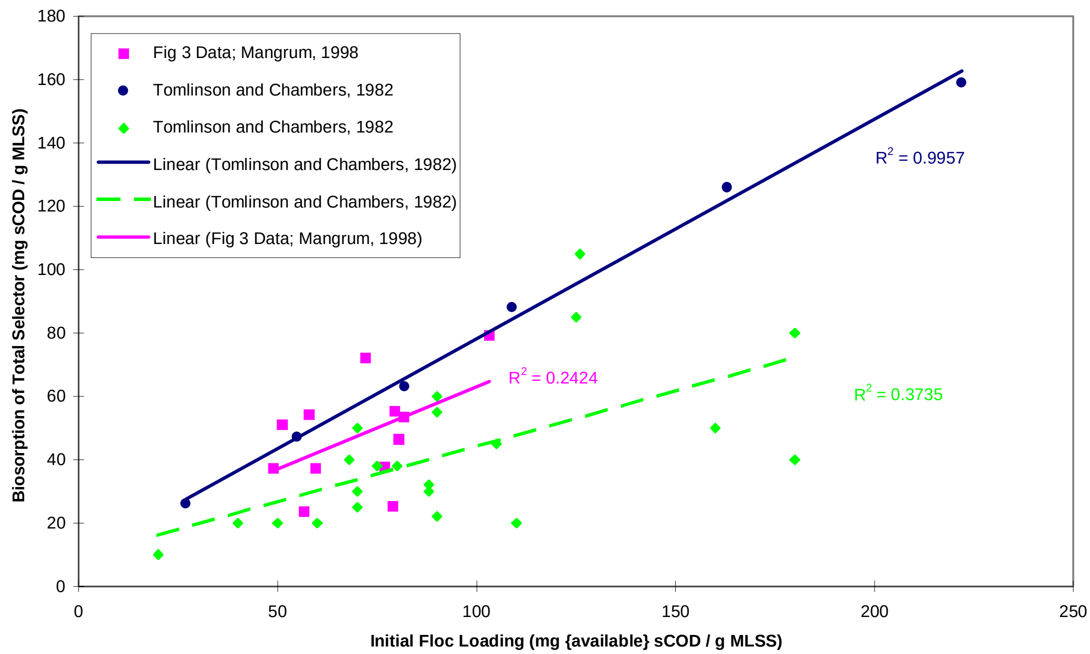
Floc loading and the F/M ratio are two methods used herein to measure selector zone organic loading. Floc loading represents an instantaneous organic loading irrespective of hydraulic retention time in the selector. This term was introduced and defined by Eikelboom (Tomlinson and Chambers, 1982) and is calculated by computing the instantaneous sCOD concentration in the first selector zone minus the recycle sCOD concentration (which represents non-biodegradable material) then dividing this by the RAS concentration. The F/M ratio is a well known term and does not warrant further discussion other than it is based solely on sCOD as is the floc load.

The relationships depicted in Figures 3 and 4 demonstrate that as the organic loading in the selector increased the substrate removal rate correspondingly increased. Figure 17 presents data from Tomlinson and Chambers (1982) with data from Figure 3. The first Tomlinson and Chambers data series ($R^2 = 0.9957$) was derived from batch experiments with constant influent wastewater characteristics. The second Tomlinson and Chambers series represents data from several full scale facilities. The significance in the second data series is that this data was taken from different sludges each seeing varying wastewater characteristics typical of full scale facilities and similar to that used to create the Figure 3 data. Given this, it is more than reasonable for the Figure 3 data to be between these other two data series with both high and low values similar to the other two data sets.

These principles are fundamental to kinetic selection of floc forming organisms with high specific growth rates. When the flocculant slurry of microorganisms is subjected to high growth rate conditions the higher specific growth rate microbes will out compete the slower specific growth rate microorganisms for the available substrate and are thus “selected” throughout the MLSS inventory (Jenkins *et al.*, 1993; Tomlinson and Chambers, 1982). This sequence of events is termed the feed portion of the feed-starve cycle. Both cycle portions are necessary for kinetic and metabolic selection of floc forming microorganisms.

The higher the substrate concentrations (*i.e*. higher floc load and higher F/M ratios) in the selector zones, the faster the microbes will grow (Jenkins *et al*., 1993; Tomlinson and Chambers, 1982; Gaudy and Gaudy, 1988).

FIGURE 17
SELECTOR FLOC LOADING VS BIOSORPTION



An important relationship that further defines the effectiveness of the selector is the actual substrate removal efficiency or mass of substrate removed across the selector. To effectively create the equally important starve portion of the feed starve cycle the selector has to remove all, or almost all, of the readily biodegradable substrate (Jenkins *et al*., 1993; Tomlinson and Chambers, 1982). In step with Monod kinetics, as the organic loading to the selector increases so does the removal rate per microorganism, but the equilibrium concentration of each selector zone correspondingly increases and thus the removal efficiency must go down. Herein lies the conflicting requirements of optimal selector operation (Jenkins *et al*., 1993; Eckenfelder and Patoczka, 1990) . This concept will be further discussed in the next section.

Obviously, selector performance closely relates to influent wastewater characteristics and upstream unit processes (Tomlinson and Chamber, 1982). For instance, if a waste stream (biological influent) has a low soluble COD fraction coupled with a high particulate fraction, the feed-starve cycle will not be effectively instituted with a conventional selector design. In order for the selector to be successful, high rate substrate uptake has to occur efficiently prior to the main biological reactor. This will ensure that the desired kinetic and metabolic microorganisms take up all the readily biodegradable material and leave very little carbon substrate for oxidation in the main biological reactor. For high particulate wastes, metal salts added to the primary clarifier can be used to reduce the particulate mass entering the biological reactor. Also, an anaerobic zone prior to the first selector can be used to produce volatile fatty acids (VFA), which will increase the soluble substrate concentration entering the selector zones.

The impact of selector floc load and F/M on selector removal efficiency and mass of substrate removed

As noted by Eckenfelder and Patoczka (1990), selector design requires balancing two conflicting requirements; obtain a high substrate concentration in the selector while achieving a high substrate removal efficiency in the selector. The high substrate concentration sets the high growth rate which enables rapid substrate uptake to occur predominately by floc forming microorganisms while the high substrate removal efficiency ensures that a feed-starve cycle is induced.

Based upon kinetic principles such that the effluent substrate concentration of a CSTR is controlled by the growth rate, which in turn is set by the F/M ratio, high substrate removal efficiencies coupled with high loading rates in theory are difficult to obtain. For example, as the organic load to a selector zone increases the equilibrium concentration (and the growth rate) in the selector zone will correspondingly increase, thus decreasing the selector removal efficiency. To this end, Tomlinson and Chambers (1982) state the following; as the substrate uptake rate in the selector increases the overall removal efficiency decreases.

Figures 3 and 4 illustrate that selector zone substrate uptake rates increase with increasing floc loading and F/M ratio. Again, this is intuitive based upon kinetic principles.

Eckenfelder and Patoczka (1990) proposed optimizing the biosorption concentration in the selector through manipulation of system parameters to simultaneously maximize substrate loading and removal efficiency in the selector. They defined the biosorption concentration as the average substrate concentration at which substrate is removed in the selector.

Figures 5 and 8 present the F/M ratio and floc loading, respectively, versus total selector zone substrate removal efficiency and mass of substrate removed. Substrate removal efficiency was calculated by dividing the amount of biosorption by the floc load for each respective day. The occurrence of industrial slug loads at the POTW is the reason for significant data scatter in Figures 5 and 8. Both nitrification and carbonaceous oxidation inhibition were associated periodically with these industrial slug loads. Data collected during known inhibition periods, which were shown in Figures 5 and 8, are not presented in further graphs.

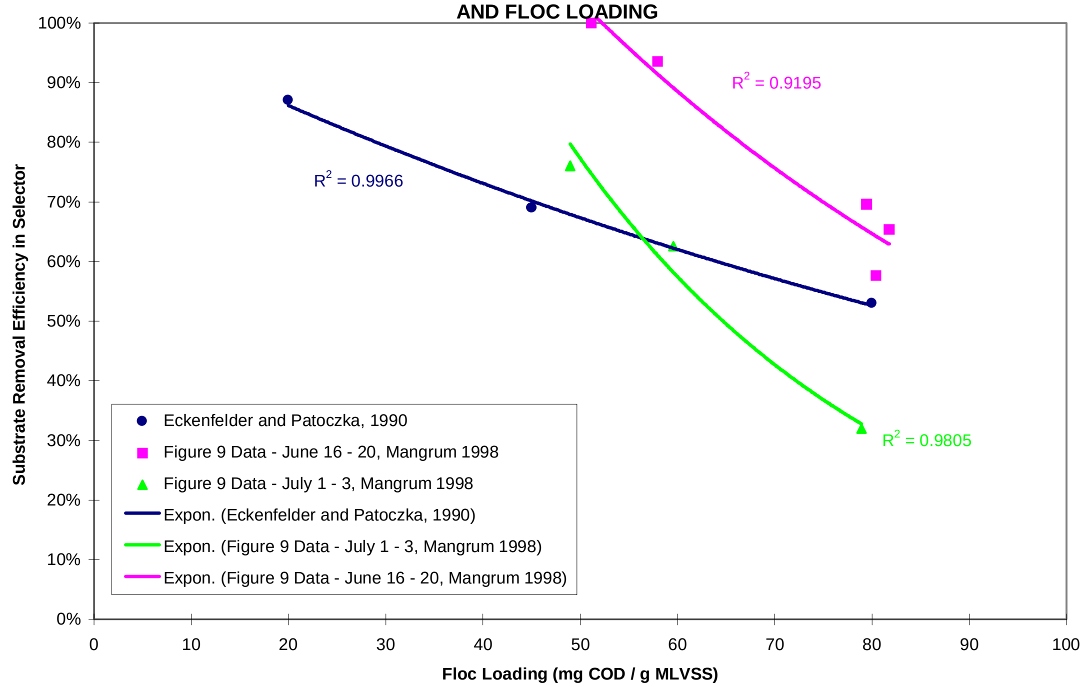
To account for weekly changes in the POTW influent as a result of industrial dischargers, Figures 6 and 9 present the data contained in Figures 5 and 8 (mass of substrate removed not shown), respectively by specific week. Again, the data collected during known inhibition periods are not presented. Figure 7 and 10 present selector F/M and floc loading vs. mass of substrate removed, respectively, for the same periods. The relationships displayed in Figures 6, 7, 9 and 10 agree well and support kinetic based relationships as defined above.

When comparing the F/M graphs (Figures 6 and 7) to the floc loading graphs (Figures 9 and 10) it is apparent that the floc loading graphs more consistently depict selector kinetics for the two weeks of data shown. The difference between the two data series in each figure is attributed to the varying influent wastewater characteristics as previously detailed.

It is important to note that as a result of varying degrees of success with returning high underflow concentrations in Pilot A RAS during the optimum period, the MLSS concentration in the selector zones at times were both high and low. Thus, resulting low and high F/M ratios and floc loadings were obtained.

Figure 9 agrees reasonably well with data presented by Eckenfelder and Patoczka (1990), as shown in Figure 18.

FIGURE 18
CORRELATION BETWEEN AVERAGE SUBSTRATE REMOVAL EFFICIENCY IN SELECTOR AND FLOC LOADING



The relationships between floc loading and substrate storage, substrate removal efficiency and mass of substrate removed

As explained by Gaudy and Gaudy (1988) non-replicative growth commonly known as oxidative assimilation or biosorption occurs under certain exogenous substrate to microorganism ratios (or floc loadings) where carbohydrate synthesis outpaces protein synthesis. Replicative growth, the creation of new cell matter, cannot occur without protienaceous matter, thus, substrate removal due predominately to carbohydrate synthesis results in the formation of internal storage products. Jenkins *et al*., (1988) also explain growth in a selector as an unbalanced growth condition.

During non-replicative growth very little substrate is oxidized because the formation of internal storage products requires only a small amount of energy (Jenkins *et* *al*., 1993). In step with this, small amounts of terminal electron acceptor are reduced during oxidative assimilation. As explained by *Jenkins et al*., (1993) when utilizing selector zones on predominately domestic wastewater, values close to 8 mg sCOD removed / mg nitrate utilized represents complete (high rate) metabolism is predominately responsible for substrate removal across the selector. Significantly higher values indicate storage (oxidative assimilation) is predominately responsible for substrate removal across the selector.

Two values presented in Figure 11 (35 and 20 mg sCOD removed / mg nitrate utilized) indicate that significant storage occurred. According to Gaudy and Gaudy (1988) and Goel and Gaudy (1968) low substrate to MLSS ratios (low floc loadings) are necessary for non-replicative growth to occur. The trend presented in Figure 11 depicting decreasing storage values with increasing organic loading generally agrees with these findings. As the organic load increased the rate of protein synthesis increased (*i.e.*, began to match carbohydrate synthesis), which enabled replicative growth (high rate metabolism) to become increasingly significant. To this end, the ratio of sCOD removed / nitrate utilized decreased.

Figure 11 presents the selector floc load versus sCOD removed per nitrate utilized and the selector sCOD removal efficiency for selected days. Because both COD and total nitrogen analyses are required on the same day to present these relationships, only three data points were obtained during the optimal period. As shown in the figure, as the organic load increased the amount of sCOD removed per nitrate utilized decreased as did the removal efficiency.

The largest values in Figure 11 were obtained concurrently with the highest substrate removal efficiencies. As explained by Gaudy and Gaudy, (1988) and Tomlinson and Chambers (1982), the initial floc loading does not affect the storage capacity of the microorganisms, only the rate at which it occurs. Thus, for lower floc loadings (lower S/X ratios) the rate of oxidation assimilation and substrate removal efficiency will both increase.

It is important to note that if the entire system F/M ratio is increased the storage capacity will decrease as the regeneration period, which consists of endogenous respiration of the internal stores, is shorten by the increased loading (Tomlinson and Chambers, 1982; Gaudy and Gaudy, 1988; Gaudy and Goel, 1968). Thus, if inadequate endogenous metabolism occurs the storage capacity will not be fully restored and the storage function and thus the selector effect will be lost.

Each set of data in Figure 11 has a best fit exponential curve shown with the corresponding r^2 value. The r^2 values are 0.97 and 0.99, respectively, for the floc load vs sCOD removed / nitrate utilized and floc load vs substrate removal efficiency. The high r^2 values indicate that for this data a strong relationship exists between the floc load and sCOD removed / nitrate utilized and substrate removal efficiency. Figure 12 presents the relationship of total selector substrate removed per nitrate utilized vs. the total selector sCOD removal efficiency. A least squares linear regression resulted in a best fit line with an r^2 value of 0.79. Again, the relatively high correlation coefficient indicates a strong relationship between sCOD removed per nitrate utilized and substrate removal efficiency.

Figure 13 presents the floc load vs sCOD removed / nitrate utilized and mass of substrate removed. As expected the relationships in Figures 11 and 13 are similar. Each set of data has a best fit exponential curve shown with the corresponding r^2 value. The r^2 values are 0.97 and 0.99, respectively for the floc load vs sCOD removed / nitrate utilized and floc load vs mass of substrate removed. The r^2 values in Figures 11 and 13 are virtually equal. The high r^2 values indicate that for this data a strong relationship exists between the floc load and sCOD removed / nitrate utilized and mass of substrate removed across the selector.

Figure 14 presents the relationship of total selector substrate removed per nitrate utilized vs. mass of substrate removed across the selector. A least squares linear regression resulted in a best fit line with an r^2 value of 0.96. Again, the high correlation coefficient indicates a strong relationship between sCOD removed per nitrate utilized and mass of substrate removed across the selector.

Based upon the substrate removed per nitrate utilized data presented in the above referenced figures and in Table 2, it is surmised that the amount of substrate oxidized varied greatly between the largest and smallest data points. With regards to the data presented in Table 2; as the floc load increased the mass of nitrate utilized increased and the mass of substrate removed and the ratio of substrate removed per nitrate utilized decreased. The two largest data points (35 and 19) represent the formation of internal storage products and the smallest value represents complete (high rate) substrate metabolism. Again, this is supported based upon the bench mark detailed by Jenkins *et al*. (1993) which states that values significantly larger than 8 mg sCOD removed / mg nitrate utilized represent significant formation of internal storage products.

Thus, the mechanism predominately responsible for substrate removal across the selector changes with floc loading. It is important to note that apparently the mode of substrate removal can change from day to day depending on the floc loading present. The daily changes in the floc loading resulted from varying degrees of success in returning biomass from the secondary clarifier to the selector zones. When sludge return procedures were successful more biomass was returned to the selector zones which produced a lower floc loading and F/M ratio. Alternatively, when sludge return procedures were not as successful less sludge was returned which in turn produced higher floc loadings and F/M ratio.

At low floc loadings carbohydrate synthesis can outpace protein synthesis and thus the majority of the removed substrate is converted to non-nitrogenous stores. The kinetics of these relationships enables rapid and efficient uptake of soluble substrate. This process lends to the kinetic selection of high specific growth rate microorganisms (floc formers) which can form internal stores. The internal stores are utilized by the floc forming organisms in the main biological reactor when the exogenous substrate has been exhausted. It is postulated that selector zones are most effective in controlling filamentous microorganisms when oxidative assimilation (non-replicative growth) is the dominate mechanism of substrate removal across the selector.

This reasoning is based upon the fact that oxidative assimilation can occur rapidly at low floc loadings giving it a large capacity to remove substrate in a relatively short period of time. Secondly, as reported by Crabtree *et al*., (1968) the formation of poly-B-hydroxybuturate (PHB), a common storage product produced by floc forming microorganisms under non-replicative growth conditions, was suggested as a mechanism of biological floc formation. Crabtree *et al*., (1968) identified that rapid biosynthesis of PHB required carbon starvation conditions. In fact they postulated under the initial growth conditions in conventional activated sludge treatment that rapid PHB formation occurred in the presence of excess carbon substrate and terminal electron acceptor. This ties directly into the findings of oxidative assimilation, as explained herein, by Gaudy and Goel (1968) and Gaudy and Gaudy (1988).

According to Diagger *et al*., (1990) the selectors at UOSA and the Northside WWTP are similar in size, configuration and performance, however, the Northside plant has been unable to control its filamentous bulking problem. This could be attributed to the probability that greater amounts of substrate are oxidized in the Northside selector zones than in the UOSA selector zones. This suggests that the mechanism primarily responsible for substrate removal in the UOSA selectors is storage and high rate metabolism is the responsible mechanism at Northside. Thus, superior settling and floc formation may be a result of substrate storage and resultant PHB formation at the UOSA facility.

Effects of Increased floc loading

As the floc load increases protein synthesis also increases relative to carbohydrate synthesis and thus more substrate is oxidized to generate energy for the formation of increasing amounts of proteinacous matter (*i.e*., replicative cell growth). Thus, greater amounts of nitrate are required as storage (non-replicative growth) becomes less significant and replicative growth becomes more significant. Since the RAS ratio in these experiments was only 0.5 and without any additional nitrate recycle, as the floc load increased a greater proportion of substrate was oxidized which led to non-detectable nitrate values leaving the third selector zone.

Although a case may be made that the reason for the lower mass of substrate removed for the two lower values of Figure 11 is attributable to the partial presence of anaerobic conditions (which has slower growth rates), the data in Table 2 refute this. As revealed in Table 2, not only did the mass of substrate removed decrease with increasing floc load, but the mass of nitrate removed increased, which led to a decreasing ratio of substrate removed per nitrate utilized. This sequence of events lends support to metabolic transition from storage to high rate metabolism.

It is important to note that traditional Monod kinetics would explain the decrease of substrate removal with increasing floc load, but the corresponding increase in nitrate utilization indicates significant substrate storage was occurring. It is also important to note that the corresponding floc load depicted in Figures 11 and 13, which denotes the transition from substrate storage to high rate metabolism as described above, is not absolute and can vary with influent wastewater characteristics. It is believed that the actual floc load that corresponded to the "transition value" for this research was actually higher than displayed in Figures 11 and 13. This is believed to be the case because of the continual RAS return problems that were encountered during pilot testing. The MLSS values used in the foregoing calculations are believed to be higher than what was actually present for the period the values represent. Lower MLSS values correspond to "actual" higher floc loads present during the study.

Conditions that effect selector performance

Surfactants

The presence of surfactants in the waste stream can have a synergistic effect on activated sludge foaming (Cha *et al*., 1992; Jenkins *et al*., 1993; Pagilla *et al*., 1996). As previously presented, both cationic (MBAS) and nonionic (CTAS) surfactants were continuously detected in the plant influent. Kappeler and Brodmann (1995) found that the presence of nonionic surfactants increased the oxygen uptake rate of the filamentous microorganism *M. parvicella* (a dominate filament identified during this research). This would in effect increase the growth rate of the filamentous bacteria and would thereby greatly diminish the effect of kinetic selection procedures against this filamentous microorganism.

Although *M. parvicella* was detected in both pilot units, the anoxic selector unit had significantly less foam and *M. parvicella* was less dominate than in the control. It is important to note that both pilot units used identical foam trapping procedures (*i.e*. submerged wasting scheme and submerged withdrawal from the secondary clarifier). It also should be noted that the full scale plant historically has had severe foaming problems.

Nitric oxide - a harmful denitrification intermediate

Anoxic and aerobic selectors have historically had varying degrees of success in controlling low F/M bulking. Based upon kinetic selection principles it is intuitive that low F/M bulking can be prevented with the use of selectors. However, nitric oxide, a denitrification intermediate, has been found to inhibit floc formers.

Gabb *et al*., (1991) and Casey *et al*., (1994) explained that inhibition of heterotrophic aerobic-facultative microorganisms (floc formers) occurs when incomplete denitrification occurs and intracellular nitric oxide is utilized in the oxic zones by the floc formers (aerobic denitrification). This inhibits the floc formers to some degree. These conditions diminish the feed-starve cycle and allow the filamentous bacteria to be dominate throughout the sludge inventory. This sequence of events was responsible for some of the conflicting results obtained when using aerobic and anoxic selectors to control low F/M bulking in biological nutrient removal facilities.

Gabb *et al*. (1991) determined that the cause of filamentous bulking in these conditions was not the result of low F/M conditions but due to the presence of aerobic and anoxic conditions. Thus the name A-A bulking evolved. Casey *et al*., (1994) determined that anoxic conditions without a readily biodegradable organic substrate led to A-A bulking. Endogenous denitrification is common to most nutrient removal systems with effluent total nitrogen limits below 8 mg/l. In summary, small anoxic selectors do not cause A-A bulking since a readily biodegradable substrate is present.

BOD toxic response

Influent toxicants were sufficiently present to consistently produce characteristic BOD toxic responses on the pilot plant influent during periods of the pilot program. Both pilot units exhibited complete and partial nitrification inhibition and at times carbonaceous oxidation inhibition. The experimental pilot unit seemed to be more susceptible to nitrification inhibition as the wastewater temperature decreased. This seems logical since the high substrate concentration in the selector would expose the microorganisms in Pilot A to a much higher concentration of the toxicant than would be the case for the complete mix control unit (Pilot B). It should be noted that although Pilot A consistently had 15 to 25 mg/l more alkalinity than Pilot B both pilot units had effluent pHs of 6.6 - 6.9. Alkalinity addition and increased sludge age during colder wastewater temperatures may have significantly reduced if not eliminated the numerous cases of nitrification inhibition in Pilot A.

Monovalent to divalent ratios

During the week of July 12th 1997, the SVI in both pilot units increased. Microscopic investigations revealed that a diffuse floc structure was present in both pilot unit sludges. Pilot A (the anoxic selector unit) had a dominantly diffuse floc structure while Pilot B had significant filaments extending beyond the diffuse floc structure. A micronutrient scan performed on the influent during this time revealed that the monovalent to divalent cation ratio was 3.7 and the magnesium concentration was 0.11 meq/l. According to Higgins and Novak (1997) monovalent to divalent cationic ratios greater than 2.0 in the process influent were found to contribute to nonfilamentous bulking conditions. Additionally, magnesium concentrations less than 0.72 - 2.0 meq/l were found to contribute to nonfilamentous bulking. The findings of Higgins and Novak (1997) and others may lend partial explanation to the unexplained increases in SVI in both units (and the full scale plant) during the pilot study. It is important to note that two significant industrial users use sodium based chemicals to adjust pH and to increase alkalinity.

CHAPTER VI. CONCLUSIONS

The Effects of Anoxic Selectors on the Reduction of Filamentous Microorganisms

In conclusion, anoxic selectors were effective in reducing both the SVI average and variance relative to the control. Anoxic selectors were also successful in reducing foaming relative to the control.

Storage Vs. High Rate Metabolism

It was discovered that floc loading influenced the dominate mechanism responsible for rapid substrate removal in the selector (*i.e*., storage vs. high rate metabolism). At low floc loadings substrate storage dominates when store forming bacteria are significantly present and high rate metabolism dominates at higher floc loadings. The lower the floc loading the higher the substrate removal rate and efficiency across the selector.

Significant advantages result from substrate storage in the selector: 1. Under high growth conditions phenomenal substrate removal rates with high efficiencies (*i.e*., oxidative assimilation or unbalanced growth) create an effective feed-starve cycle which leads to the selection of floc forming microorganisms over filamentous microorganisms. 2. Improved bioflocculation resulting from the production of the polymer PHB, which is a common storage product produced by floc forming microorganisms (Crabtree *et al*., 1968).

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APPENDIX A -

Data

Pilot Unit: A
Testing Location: Activated Sludge; Figure 2-18 data

	COD												
Date	Pilot Influent Tot.	Pilot Influent Sol.	Selector 1 Efflent Sol.	Selector 2 Efflent Sol.	Selector 3 Efflent Sol.	Pilot A Effluent Tot.	Pilot A Effluent Sol.	Pilot B Effluent Tot.	Pilot B Effluent Sol.	A Sol dilute	% removed in selectors	amount removed	Recycle Ratio A
11-Jun	165	165	70	49	60	60	57	28	67	111	0.46	51	1
12-Jun	113	123	20	44	29	44	12	9	1	68	0.57	39	1
13-Jun	121	130	27	27	36	13	2	4	1	66	0.45	30	1
16-Jun	137	95	4	21	6	25	2	32	18	64	0.91	58	0.5
17-Jun	162	165	95	51	51	58	22	68	35	117	0.57	66	0.5
18-Jun	129	140	64	47	25	38	25	28	28	102	0.75	77	0.5
19-Jun		140	108	65	56	53	23	37	26	101	0.45	45	0.5
20-Jun	107	140	60	49	40	10	10	10	10	97	0.59	57	0.5
23-Jun	114	112	43	40	46	17	4	13	4	76	0.39	30	0.5
24-Jun	109	133	48	40	24	97	24	10	1	88	0.73	64	0.7
26-Jun	115	129	101	57	49	20	9	9	1	87	0.44	38	0.53
1-Jul	126	131	29	20	32	26	1	23	5	84	0.62	52	0.57
2-Jul	122	133	33	33	30	68	13	13	13	84	0.64	54	0.69
3-Jul	121	133	106	53	64	20	6	2	7	91	0.30	27	0.49
8-Jul	129	122	42	30	27	17	9	13	6	86	0.69	59	0.46

											Total Selector	1st sel	1st sel	total selector		
Date	MLSS A	Selector 1 MLSS	Selector 2 MLSS	Selector 3 MLSS	COD Conc Dil	Influent flow (l/min)	Total F/M (sCOD)	Floc Loading	Biosorption	Percent sCOD Removed	sCOD RE / NO3 utilized	Initial F/M (sCOD)	uptake rate mg/l hr	Mass Removed (g/day)	total selector F/M	Mass NO3 Removed (g/day)
16-Jun	1070	1260	910	940	64	0.156	3.1	58	54	0.94	19	23	479	13	3.1	0.69
17-Jun	1200	940	900	940	117	0.168	5.2	79	55	0.70		39	496			
18-Jun	1500	1600	1020	870	102	0.156	3.3	51	51	1.00	35	24	410	17	3.3	0.49
19-Jun	970	4200	2250	1630	101	0.108	3.5	80	46	0.58	7	26	158	7	3.5	0.96
20-Jun	1060	2210	2160	760	97	0.112	3.3	82	53	0.65		25	287	9		
23-Jun	1270	2890	1530	990	76	0.104	2.1	57	24	0.42		15	239	4		
24-Jun	890	860	720	540	88	0.112	3.8	72	72	1.00		28	313	10		
26-Jun	1020	3400	3550	1100	87	0.112	3.2	77	38	0.49		24	0	6		
1-Jul	1390	1450	610		84	0.1	2.1	60	37	0.63		16	382	7		
2-Jul	1450	1660	1480	1650	84	0.09	1.9	49	37	0.76		14	320	7		
3-Jul	0	1450	1080	330	91	0.104	2.9	79	25	0.32		21	0	4		
8-Jul	750	780	930	1100	86	0.143	5.2	103	79	0.77		39	443	12		

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July 1996 to present
Parsons Engineering Science, Consulting Engineers, Fairfax Virginia
Project Engineer for environmental studies and design of wastewater systems utilizing conventional and innovative collection, treatment and disposal techniques. Project experience includes advanced wastewater treatment pilot studies, modeling and design of nitrogen removal wastewater treatment systems and master planning.

January 1995 to July 1996
Olver Incorporated, Consulting Engineers, Blacksburg,Virginia
As a project engineer design and project management experience was gained in many aspects of environmental engineering. Project duties included the design of water and waste treatment facilities, pretreatment program development, effluent and construction permitting and computer modeling and design of distribution, collection and treatment systems.

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United States Public Health Service, Atmore, AL
Commissioned as an Ensign (O-1) and worked in the Sanitation Facilities Construction Branch of the U.S. Indian Health Service. Design and inspection experience was gained in facultative and mechanically aerated lagoons, pump stations and sanitary sewer lines. Presented bi-monthly reports which included design calculations, cost estimates and existing system analysis to the project engineer.

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Virginia Department of Transportation, Fairfax, VA
Employed as a Transportation Construction Inspector for three summers during which time experience was gained in variety of areas such as plans and specifications, bridge construction, material compaction and testing, surveying, pile driving, project layout and administration, change orders and claims. Inspected job activities and was directly responsible for safety, pay items and quality assurance of those activities.

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