ACTIVATED SLUDGE BULKING IN MASSACHUSETTS:
THE MAGNITUDE OF THE PROBLEM AND
AN ENGINEERING EVALUATION OF
REMEDIAL CONTROL MEASURES

5903

A Master's Project

Presented by

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Submitted to the Department of Civil Engineering of the

University of Massachusetts in partial fulfillment

of the requirements for the degree of

MASTER OF SCIENCE

May 1990 3

Environmental Engineering Program

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ACKNOWLEDGEMENTS

This research was supported through the Research and Demonstration Program of the Massachusetts Division of Water Pollution Control (Project No. 88-08). I wish to acknowledge the assistance of the Technical Assistance Training Center in Millbury for their help in making this project possible.

I would like to thank Dr. Michael S. Switzenbaum for his assistance and support throughout the course of this project. I also would like to thank my other two committee members, Dr. David Reckhow and Dr. James Male. I am also grateful for the assistance and cooperation of all the operators who took the time to respond to the survey; and a special thanks to the operators who provided the plant data and assistance for the case studies in this report.

ABSTRACT

Filamentous bulking is considered to be a major problem encountered at most activated sludge facilities throughout the Commonwealth. A significant amount of research has been devoted to establishing a cause-effect relationship of these problems. A determination of the cause of bulking has led to an increase in remedial control actions capable of eliminating settleability problems associated with filamentous organisms.

The objectives of this research were twofold. The first portion was conducted to assess the magnitude of filamentous bulking in Massachusetts. The second part consisted of engineering evaluations of remedial control strategies for four treatment plants who were willing to participate in case studies. Remedial actions were evaluated based on ease of implementation, technical feasibility, level of effectiveness, and financial feasibility. Based on these results, a control strategy, or a combination thereof, was recommended to the treatment staff.

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CHAPTER I

INTRODUCTION

1.1 Background

There are several mechanisms available for the secondary treatment of wastewater. However, the activated sludge process is the one most commonly used (Metcalf & Eddy, 1979). In fact, 87% of treatment plants in Massachusetts reporting secondary treatment use the activated sludge process (Operators Assoc., 1984). Despite its widespread use, the activated sludge process has become prone to many physical, chemical, biological, and other operational problems. More specifically, poor settling characteristics have comprised a significant portion of the operational problems associated with the activated sludge process.

The activated sludge process consists basically of a two-stage system; the first stage is an aerated, mixed reactor commonly known as the aeration basin and the second stage is a combination clarifier-thickener, known as the secondary sedimentation basin. The performance of the activated sludge process is limited by the ability of the secondary sedimentation basin to separate and concentrate the activated sludge flocs from the treated effluent (Sezgin *et al.*, 1978). Poor solids separation will inevitably lead to reductions in effluent quality and treatment removal efficiencies.

Physical properties within an activated sludge floc often limit its ability to settle rapidly and to develop a thick, compact underflow. There are several types of solids separation problems which stem from both physical and microbial causes. Among the problems related to the microbial population are dispersed growth, viscous bulking, pinpoint floc, filamentous bulking, blanket rising, scum formation, and foaming.

One of the most commonly encountered types of solid separation problems is filamentous bulking. Filamentous bulking occurs when the predominant microbial population of an activated sludge system shifts from floc-forming organisms to filamentous organisms. This results in a condition where the sludge becomes very light, increases in volume, and decreases in terms of settleability. An overabundance of filamentous bacteria will lead to a hyperextension of filaments from the floc structure and into the bulk solution, thereby interfering with the settling and compaction of the floc particles. Consequently, this interference will more than likely decrease the hydraulic capacity of the clarifiers and will also decrease the solids concentration in the return and waste sludges. In addition, filamentous bulking may also overload the existing solids handling and dewatering devices.

There are several environmental conditions which favor the growth of filamentous bacteria. These conditions may include low dissolved oxygen (DO), low food to microorganism ratio (F:M), low nutrient concentration (nitrogen or phosphorus), low pH, and septic wastewater.

Identifying "bulking" sludges over the past years has caused considerable confusion. This is largely due to the fact that instances of sludge bulking are often highly subjective and plant-specific. As a result, it became evident that a unified, quantitative means of measuring a bulking sludge would be necessary. One attempt has been the sludge volume index (SVI). The sludge volume index was first introduced in 1934 as a measure of the physical characteristics of activated sludge solids (Mohlman, 1934). SVI is defined as the volume occupied by one gram of the activated sludge after settling the aerated liquor for 30 minutes (Dick and Vesilind, 1969). From this measure, a "bulking" sludge was proposed as being any sludge which has an SVI of greater than 200 ml/g with a 30-minute settled volume of less than 1000 milliliters (Pipes, 1969). Other researchers have suggested that a bulking sludge is that with an SVI of 150 ml/g or greater (Blackbeard *et al.*, 1986). Although an SVI of 200 ml/g or higher is generally indicative of a bulking sludge, some plants have operated quite well with SVI's matching or exceeding this proposed limit.

1.2 Recent Advances

Several advances have been made in recent years which have lead to a better understanding of the causes and control of filamentous sludge bulking. Advances in microscopic identification techniques have led to some encouraging forecasting and control strategies used to predict and alleviate bulking episodes. Researchers have developed methods to classify the types of filamentous organisms that occur in activated sludge systems as opposed to species (Eikelboom, 1975a, 1975b). Additional research has also shown that the predominance of certain filamentous organisms are often indicative of specific environmental pressures such as those mentioned earlier. There has also been considerable research performed on the control of sludge bulking. Technology has evolved from using non-selective control measures to achieve filamentous destruction to using environmental modifications which aim to discourage filamentous predominance. Non-selective measures such as chlorination, hydrogen peroxide addition, and polymer addition have proven to be effective measures in controlling bulking on a short-term basis. However, recent shifts to control bulking on a long-term basis, or "specific" control strategies, have become evident. These include the addition of nutrients, an increase in the dissolved oxygen concentration, an increase in the F:M ratio, the installation of a selector, and a number of other process modifications.

1.3 The Problem

The magnitude of the bulking problem is significant enough to warrant extensive research in this field. Microscopic inspection of about 3500 sludge samples from 315 activated sludge plants in Germany showed that extensive filamentous microorganism growth occurred in at least 45% of them (Wagner, 1982). In South Africa, bulking was reported to have occurred in 56% of the plants responding to a recent survey

(Blackbeard *et al.*, 1986). Similar numbers have been reported in the United Kingdom and France (Tomlinson, 1982; Pujol and Boutin, 1989). Recently in the United States, the results of a survey in Colorado reported that 92% of the plants surveyed experienced a filamentous episode within the past year (Richard, 1989). A summary of these surveys is shown in Table 1.

Table 1. Summary of Activated Sludge Bulking Surveys

Location	% Bulking	Source
W. Germany	45	Wagner, 1982
S. Africa	56	Blackbeard *et al.*, 1986
France	25	Pujol and Boutin, 1989
United Kingdom	63	Tomlinson, 1982
Colorado, USA	92	Richard, 1989

1.4 Research Objectives

This project was conducted to fulfill the following objectives:

1. To define the magnitude, duration, and impact of sludge bulking on activated sludge facilities in the Commonwealth of Massachusetts.
2. To analyze several engineering strategies available to reduce or eliminate sludge bulking for four treatment plants experiencing bulking in Massachusetts.
3. To integrate these engineering evaluations into a handbook for plant operators which will be developed by the principal investigator of the grant which supports this project (Switzenbaum *et al.*, 1990). These case studies, in conjunction with filamentous identification techniques, will be provided within the handbook in an effort to produce a more interesting and application-oriented document.

CHAPTER II

LITERATURE REVIEW

2.1 The Emergence of Sludge Bulking

Generally, the term bulking has been used to describe a wide variety of solids separation problems for the activated sludge process. Consequently, the lack of a precise definition for the term bulking has created some distress for those attempting to define exactly when it first emerged. There is no indication in the literature to suggest that problems of poor settleability occurred when the first experiments with activated sludge were performed in the early part of this century. However, several instances of settleability problems in activated sludge were reported in the early 1920's (Tomlinson, 1982). It was not until 1928 when filamentous organisms were shown to be a cause of sludge bulking (Morgan and Beck, 1928).

2.2 Approaches to the Problem

The phenomenon of filamentous bulking has been researched for over 60 years. A great deal of progress has been made in the past few decades on the causes and control of sludge bulking. However, filamentous bulking is still considered to be a major problem at many activated sludge plants.

Initially, attempts were made to analyze plant design data, operating conditions, and wastewater characteristics. Based on this information, researchers attempted to correlate these conditions with the settleability of the activated sludge. This particular approach yielded causes and solutions to unique and specific problems. Unfortunately, much conflicting information was published at this time which subsequently rejected the possibility of devising universal solutions to general problems. It became apparent that there were other variables involved which had not yet been addressed.

It was soon recognized that the settleability of activated sludge was highly dependent on the characteristics of its microflora. Several scientifically-rigorous approaches ensued which addressed both the surface chemistry and types of microorganisms present in an activated sludge (Tomlinson, 1982). From these observations, two distinct schools of thought developed; those which believed bulking was a result of an overabundance of filamentous organisms and those which believed bulking was a result of physio-chemical conditions on the surfaces of the microorganisms (Tomlinson, 1982). Both hypotheses obtained positive reinforcement which led researchers to believe that both were relevant theories in establishing the causes of filamentous bulking.

2.3 The Development of the Activated Sludge Process and its Relation to Bulking

The earlier activated sludge systems consisted of "fill-and-draw" units or batch reactor systems. Typically this consisted of filling a tank with sewage over a one hour period, aerating the contents for three hours, and then allowing quiescent settling for two hours. Finally, the clear supernatant was drawn from the reactor and the sludge was left for the next batchwise cycle (Tomlinson, 1982). Under such conditions, no problems of poor settling were reported. However, the need for a continuous flow process was clearly evident. Thus, the continuous activated sludge system was developed.

The continuous flow systems employed separate tanks for aeration and settling. Sewage was fed continuously to the aeration tank while the sludge from the settling tank was recycled to the aeration tank. Several modifications of this system were developed and it was at this time when a considerable amount of settling problems originated. In fact, it is now evident that the problem of bulking sludge emerged concurrently with the evolution of the fill-and-draw or batch reactors to continuous flow designs (Albertson, 1987).

The original fill-and-draw units exposed a relatively small amount of microflora to a high volume of sewage in a relatively short time (Tomlinson, 1982). Therefore, the microorganisms experienced high levels of carbonaceous substrate initially, but lower levels as oxidation proceeded throughout their detention time.

The original continuous flow tanks mimicked the fill-and-draw units in that they had high length to width ratios which effectively accomplished the same initial high levels of substrate (Duckworth, 1915). Systems of this type were more commonly referred to as "plug flow" configurations which were characterized by a low degree of dispersion or longitudinal mixing. However, a departure from the plug flow configuration to the so-called "completely-mixed" configuration occurred sometime during the 1940's. Within a complete-mix system, the microbial population experiences only one concentration of carbonaceous substrate, that being the very low concentration remaining in the treated sewage (Tomlinson, 1982). This was considered to be an advantage because of the immediate dilution of toxic substances or other inhibitory materials. The proliferation of the complete-mix system was also affected by the increased popularity of vertical-shaft, mechanical aerators during the 1950's (Tomlinson, 1982).

Mixing characteristics within aeration tanks became a topic of much research in terms of evaluating the settleability of an activated sludge. In 1932, Donaldson suggested that "short-circuiting" in aeration tanks could cause bulking and that the installation of baffle walls would prevent the problem (Donaldson, 1932a, 1932b). Baffle walls will help to reduce longitudinal mixing and, therefore, will effectively simulate the conditions encountered in plug flow reactors. Pasveer (1969), the developer of the well-known oxidation ditch, provided additional evidence to support this argument. Early versions of his oxidation ditch were operated in the fill-and-draw mode; however, upon conversion to completely-mixed systems, several settleability problems arose. Further experiments showed that aeration during extended fill periods, while operating in the fill-and-draw mode, would also produce poor settleability (Heide and Pasveer, 1974).

In summary, it has been observed that continuous-fed, completely-mixed systems are more prone to bulking than intermittently-fed, plug flow systems. However, the fact is that a number of existing activated sludge plants operate in the complete-mix mode; therefore, these plants will inevitably produce sludges with poorer settling characteristics. As a result, the systems which operate in this mode, and experience bulking, will be forced to consider remedial control methods which aim to increase plug flow conditions.

2.4 Filament Identification Techniques

Several advances have been made in recent years which have lead to a better understanding of the causes and control of filamentous sludge bulking. One particular advance using microscopic identification techniques has brought about some encouraging control strategies. As was mentioned previously, Eikelboom has developed a method for classifying the types (as opposed to species) of filamentous organisms that occur in activated sludge systems based on the size, morphology, and response of the organism to standard staining techniques (Eikelboom, 1975a, 1975b). Furthermore, additional research has shown that the predominance of certain filamentous organisms are often indicative of specific environmental pressures such as low dissolved oxygen, low F:M, low nutrients, low pH, and septic wastewater (Richard *et al.*, 1982; Strom and Jenkins, 1984). Table 2 presents these five conditions and the filaments associated with the persistence of these conditions. Therefore, microscopic investigation of the mixed liquor may provide treatment personnel with important insight as to the condition causing an overabundance of filamentous organisms. Furthermore, specific remedial methods needed to shift the microbial population back to floc-forming predominance may be evident at this time.

In addition, there have also been several mechanisms and theories which have been suggested to explain why filamentous organisms predominate under these five suggested causative conditions. A more detailed discussion on these theories and mechanisms will be presented in later sections of this report.

Table 2. Dominant Filament Types as Indicators of Conditions Causing Sludge Bulking.

Suggested Causative Conditions	Indicative Filament Types
Low DO	type 1701, *S. natans*, *H. hydrossis*
Low F:M	*M. parvicella*, *H. hydrossis*, *Nocardia sp.*, types 021N, 0041, 0675, 0092, 0581, 0961, 0803
Septic Wastewater/ Sulfides	*Thiothrix sp.*, *Beggiatoa*, and type 021N
Nutrient Deficiency	*Thiothrix sp.*, *S. natans*, type 021N, and possibly *H. hydrossis* and types 0041 and 0675
Low pH	fungi

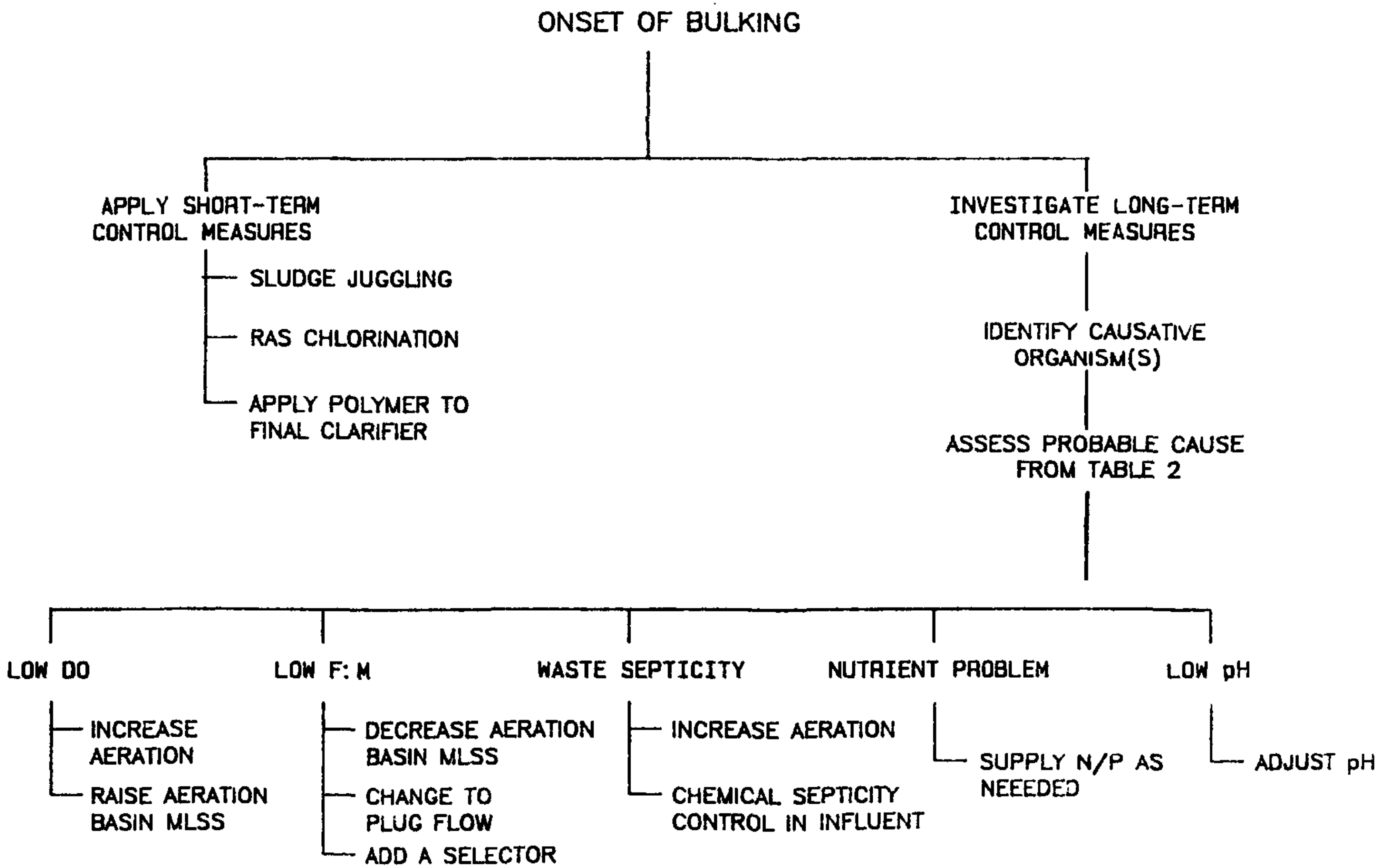
Richard *et al.*, 1982; Strom and Jenkins, 1984.

2.5 Control of Sludge Bulking

There are several methods used to control filamentous bulking. Although proper treatment plant design is the most effective method to prevent bulking (Jenkins *et al.*, 1986), many existing plants do not have this luxury. Therefore, existing plants utilize changes in operation and/or the addition of chemicals to overcome bulking episodes. Several methods have been used; however, some are more practical and more proven methods. In any case, a good general approach to controlling bulking problems is as follows: (1) identify the filamentous organisms causing the bulking, (2) using Table 2 and correlating this with plant data, determine the causative condition, (3) determine if the problem can be rectified immediately by operational changes, and (4) determine if major operational or design modifications are necessary (EPA, 1987).

Richard has subdivided control measures into two main categories: "long-term" solutions and "short-term" solutions (Richard, 1989). Short-term solutions include sludge manipulation, polymer addition, and toxicant addition (chlorine and hydrogen peroxide). Long-term solutions include control of pH, nutrient concentration, or waste septicity; also included are changes in aeration, biomass concentration, or waste feeding pattern. Richard's approaches to solving sludge bulking are shown in Figure 1 and will be presented later in subsequent sections of this report.

FIGURE 1. PRACTICAL APPROACHES TO BULKING CONTROL.
(AFTER RICHARD, 1989)



2.5.1 Short-Term Remedial Action (Non-selective Control)

These methods will not solve chronic bulking problems but will help alleviate immediate upsets during intermittent bulking episodes. It is important to note that short-term solutions do not involve the identification of filamentous bacteria and aim to treat the symptoms of bulking. Short-term solutions have often been referred to as "non-selective" control measures.

2.5.1.1 Sludge Manipulation

Two methods of sludge manipulation are changing the return activated sludge flow rate (RAS) and changing the aeration basin feed point. Increasing the RAS flow rate during a bulking episode will prevent solids loss to the effluent (Richard, 1989). Changing the operational mode of the activated sludge process to a step feed configuration will reduce the mixed liquor suspended solids concentration (MLSS) in the clarifier without reducing the MLSS inventory. This results in a reduction of clarifier loading (WPCF, 1987; Richard, 1989). Several design calculations should be addressed before process modifications are attempted. There are several pieces of literature available which explain these operations and their effects on the activated sludge system (EPA, 1987; WPCF, 1987; Jenkins *et al.*, 1986).

2.5.1.2 Polymer Addition

Synthetic, high molecular weight, cationic polymers used alone or in combination with an anionic polymer can overcome the physical effects of filaments on sludge settleability (Richard, 1989). Proper dosages and types of polymers are best determined by jar tests (WPCF, 1987). Inorganic coagulants such as ferric chloride have also been used but are not recommended where increases in sludge volumes would exceed or limit the capacity of the sludge handling devices (Richard, 1989). In general, the addition of polymers for bulking control is expensive compared to chlorination -- chemical costs of up to \$119/1000m^3 (\$450/MG) have been experienced (Jenkins *et al.*, 1986).

2.5.1.3 Toxicant Addition

Two toxicants, chlorine and hydrogen peroxide, have been used successfully to control filamentous organisms and to stop bulking episodes (Richard, 1989). Chlorine is used widely for bulking control because it is relatively inexpensive and is generally available on-site at most treatment facilities. Chlorination has been used for many years (Smith and Purdy, 1936; Tapleshay, 1945) and has recently found widespread use in the United States (Jenkins, 1980).

There is a wealth of information on the use of chlorination for bulking control (Smith and Purdy, 1936; Tapleshay, 1945; Frenzel and Safert, 1971; Frenzel, 1977;

Jenkins, 1980; Neethling *et al.*, 1982; Anon, 1983; Bode, 1983; Jenkins *et al.*, 1986; EPA, 1987; Richard, 1989). The use of hydrogen peroxide is not as widespread, but has been shown to be equally as effective as chlorine. There is also a wealth of information on the use of hydrogen peroxide for bulking control (Anon, 1973; Cole *et al.*, 1973; Keller and Cole, 1973; Caropreso *et al.*, 1974; Anon, 1976; Strunk and Shapiro, 1976; EPA, 1987).

2.5.2 Long-Term Remedial Action (Selective Control)

Long-term solutions involve filament identification and treat the cause of sludge bulking. Long-term solutions are often referred to as "selective" control measures. In other words, the cause of bulking is known and is selectively eliminated.

2.5.2.1 Aeration Basin pH Control

The aeration basin pH should be maintained between pH 6.5 and 8.5 to allow for proper microbial growth and to avoid low pH fungal growth (Richard, 1989). pH adjustment is accomplished through acid/base addition; guidance is available in operational handbooks (WPCF, 1987).

2.5.2.2 Waste Septicity

Influent septicity is usually indicated by strong odors or black-colored wastewater. Septic wastes contain elevated amounts of sulfides and low molecular weight fatty acids, both of which tend to encourage the growth of certain filamentous organisms (Richard, 1989).

Septic wastes are more common in systems in warmer climates, with large collection systems, or with unaerated flow equalization basins (Richard, 1989). Waste septicity is most commonly treated by chemical oxidation (with chlorine, hydrogen peroxide, or potassium permanganate) or with preaeration. Chemical precipitation has also been used to alleviate waste septicity with chemicals such as ferric chloride.

2.5.2.3 Nutrient Addition

Nitrogen and phosphorus can be growth-limiting if not present in sufficient amounts in wastewaters. In addition, trace elements such as iron and sulfur have also been shown to be growth-limiting (Carter and McKinney, 1973; Wood and Tchobanoglous, 1974; Richard, 1989).

Much of the current knowledge concerning nutrient additions is based primarily on the work of Sawyer and his colleagues between the late 1930's and early 1950's (Sawyer, 1940; 1941; 1942; Helmers *et al.*, 1951; 1952). The establishment of the BOD_5:N:P ratio (Five-day biochemical oxygen demand : Nitrogen : Phosphorus) of 100:5:1

was a result of this work. However, this approximate ratio is highly dependent on operating conditions, specifically solids residence time (SRT), which other researchers have summarized (Sherrard and Schroeder, 1976; Broderick and Sherrard, 1985). Determining the proper quantities of nutrients to add is very specific and is outlined in Appendix B (WPCF, 1987).

2.5.2.4 Changes in Aeration

Filamentous organisms maintain a competitive advantage over floc-forming organisms under low DO conditions partly due to the filamentous organism's higher surface area to volume ratio (relative to the floc-forming organism's). This property allows the filamentous organism to maintain higher exchanges with the bulk liquid which will effectively increase the organism's overall exposure to the limiting DO.

The required aeration basin dissolved oxygen concentration to prevent low DO bulking is not a constant; rather it is a function of the F:M rate (Palm *et al.*, 1980). This is shown graphically in Figure 2. Higher bulk DO is required to prevent the growth of these types of filaments as the F:M increases because of oxygen depletion through the floc and the need to maintain aerobic conditions in the interior of the floc (Richard, 1989). Although a bulk DO concentration of 2.0 mg/l is recommended for F:M values up to 0.5 kg BOD_5/kg mixed liquor volatile suspended solids per day (MLVSS*d) (Palm *et al.*, 1980; Parker and Merrill, 1976; Richard, 1989), plants

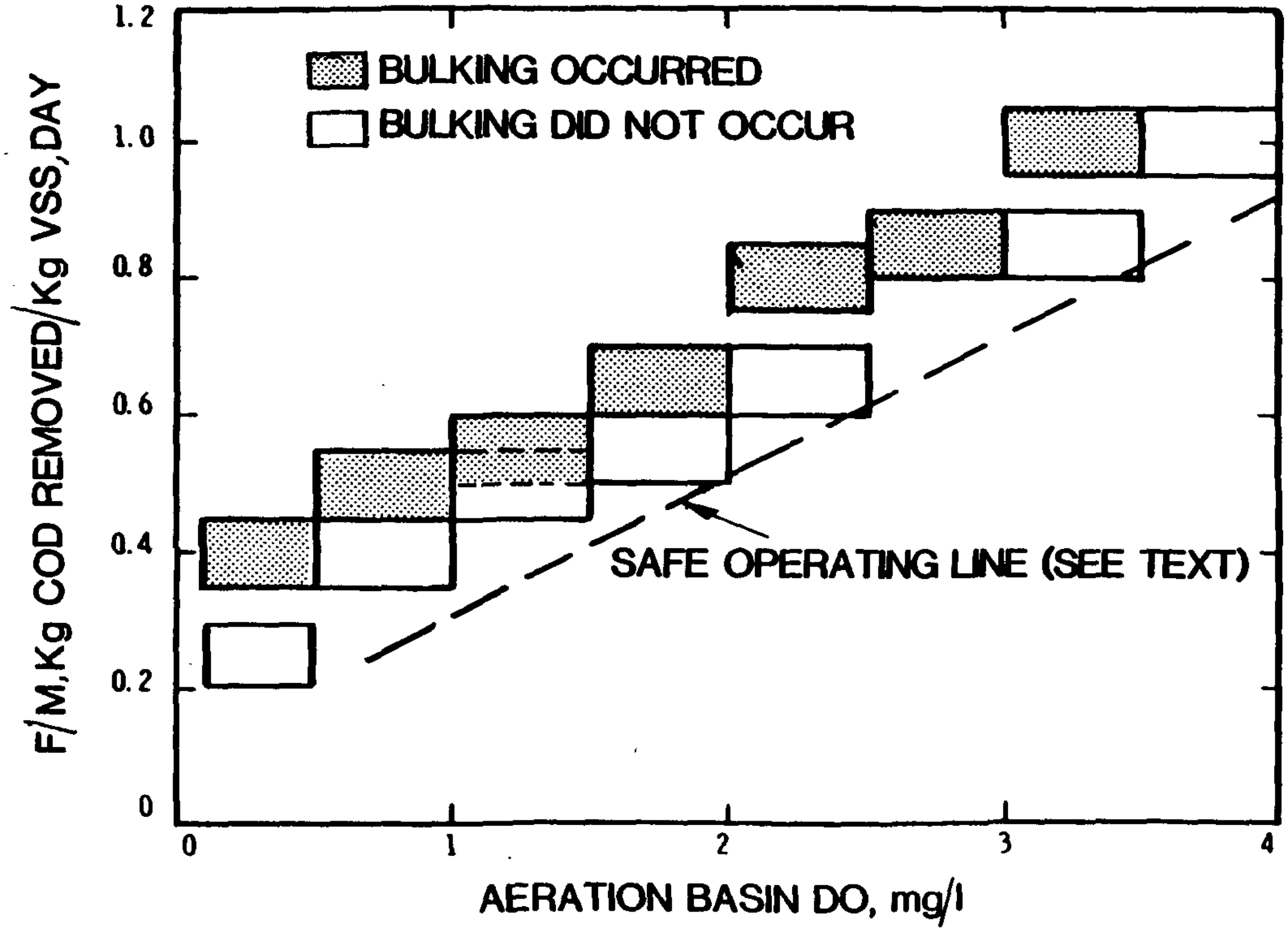


Figure 2. Combinations of F/M and aeration basin dissolved oxygen concentrations where bulking and non-bulking sludges occur (Palm *et al.*, 1980).

operating at higher F:M ratios have been shown to bulk at DO concentrations ranging from 12 to 14 mg/l (Jenkins *et al.*, 1986). Therefore, microscopic observation of low DO filaments should be trusted rather than the aeration basin DO values (Richard, 1989).

Low DO bulking is controlled by raising the aeration basin DO concentration or by lowering the F:M ratio (increasing MLSS). Raising the DO concentration may require the installment of new aeration equipment; either mechanical systems or diffused air systems. Example calculations used to evaluate existing oxygen transfer efficiencies of each system are presented in Appendix C (EPA, 1989a). In addition, manuals to design new aeration systems are also readily available and are presented elsewhere (EPA, 1985; 1989a; 1989b). However, it should be noted here that modifications of this type are extremely expensive and further consideration should be given to economic cost-benefit analyses.

2.5.2.5 Changes in Biomass Concentration and Waste Feeding Pattern

Filamentous bulking is common in completely-mixed, continuously-fed, low F:M activated sludge systems. In general, it can be stated that systems that are continuously-fed and have completely-mixed aeration basins produce poorer settling activated sludge than systems that are either fed intermittently or have aeration basins where there is a relatively high local concentration of wastewater at the point where the RAS and influent wastewater enter the basin (Heide and Pasveer, 1974; Rensink *et al.*, 1982; Tomlinson, 1982; Chiesa and Irvine, 1982). Basically, there are two theories which have been proposed to explain why intermittently-fed or plug flow systems produce sludges with better settling characteristics. The first theory proposes that floc-forming organisms possess higher maximum growth rates and higher saturation constants (μ_{max} and K_s, respectively) than filamentous organisms (Chudoba *et al.*, 1973). Therefore, where systems provide elevated initial substrate concentrations (plug flow and intermittently-fed reactors), floc-forming organisms will outcompete filamentous organisms due to their higher growth rates and saturation constants. This is represented graphically in Figure 3. The second theory proposes that floc-forming organisms are more capable of storing intracellular substrates for later use under substrate-starved conditions (van Niekerk *et al.*, 1986). If elevated substrate concentrations are provided initially, floc-forming organisms are able to store excess substrate for use during the starve condition realized at the end of plug flow or intermittently-fed reactors. This will insure floc-forming proliferation in the secondary clarifier and will therefore produce a better quality sludge.

Systems which are completely-mixed often suffer from low F:M bulking. Changing the biomass concentration or changing the waste feeding pattern (there are several possibilities to accomplish this) are two methods to combat this particular type of bulking. A discussion of these alternatives follows.

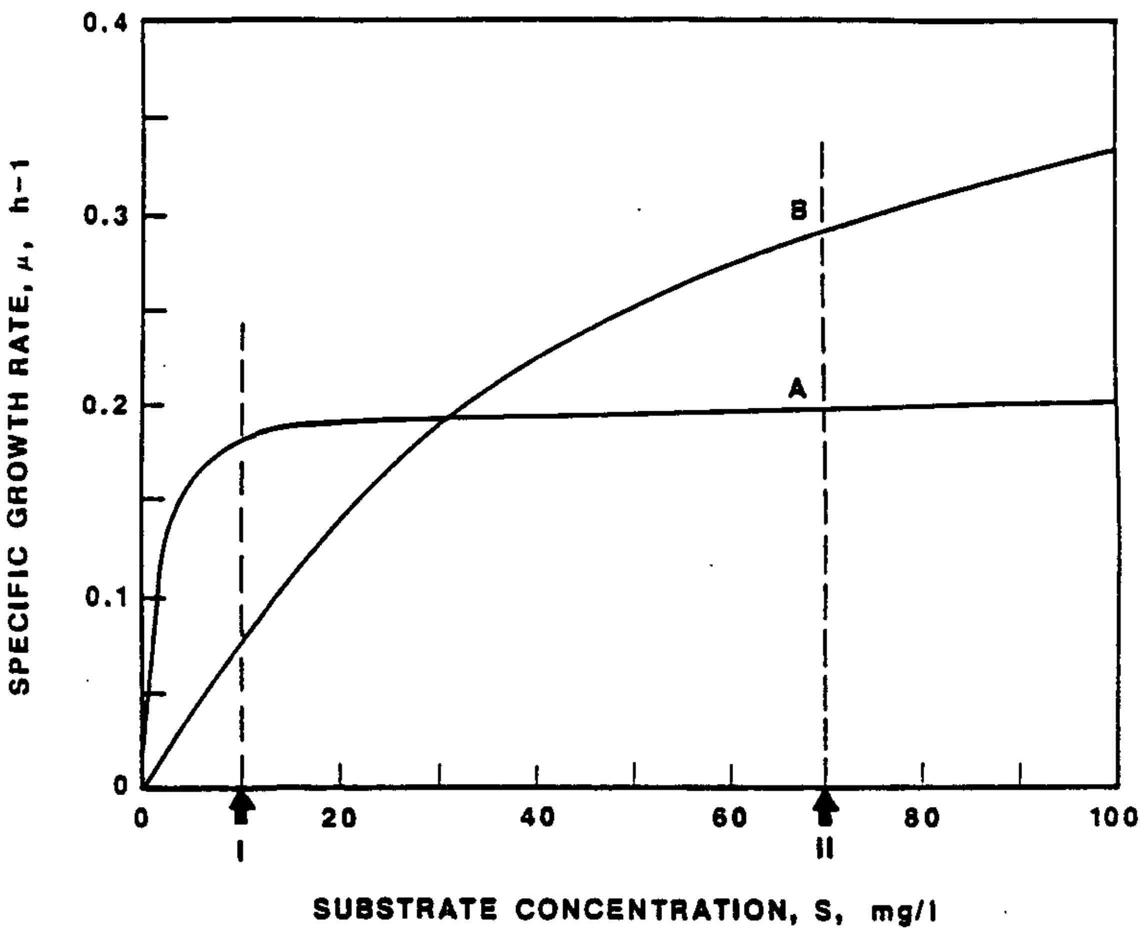


FIGURE 3. GRAPHICAL PRESENTATION OF THE PRINCIPLE OF SELECTION OF MICROORGANISMS IN MIXED CULTURES. A-FILAMENTOUS BACTERIA, B-FLOC FORMERS (AFTER CHUDOBA ET AL., 5)

Low F:M bulking can be controlled by lowering the MLSS concentration in the aeration basin. This will effectively increase the F:M ratio. However, lowering the MLSS concentration may not be suitable for some plants because it may result in the loss of nitrification and an increase in waste sludge production (Richard, 1989).

Low F:M bulking may also be controlled by a host of changes in waste feeding pattern. These changes include the compartmentalization of aeration basins (see Figure 4), the introduction of plug flow characteristics to the aeration basins (see Figure 5), intermittent feeding of wastes, batch-fed operation, and the use of a selector (see Figure 6). The "selector" concept has recently gained notoriety as a long-term strategy to control bulking episodes under low F:M conditions. The term selector has been used because this type of concept affects the selection of non-filamentous organisms. Within this process, return activated sludge is mixed with influent wastewater before application to the aeration basins. Single selector units have been effective as well as several contact chambers in series. The elevated initial loading in the selector, along with the extended endogenous conditions realized in the complete mix reactor, establish a growth environment capable of effectively controlling filament growth and sludge settleability (Linne and Chiesa, 1987).

Control of low F:M bulking through the use of these measures has been obtained consistently in laboratory or pilot-scale systems but less effectively in full-scale systems. Futhermore, these types of measures have been successful because they produce

FIGURE 4. PLUG FLOW MODIFICATION USING COMPARTMENTALIZATION

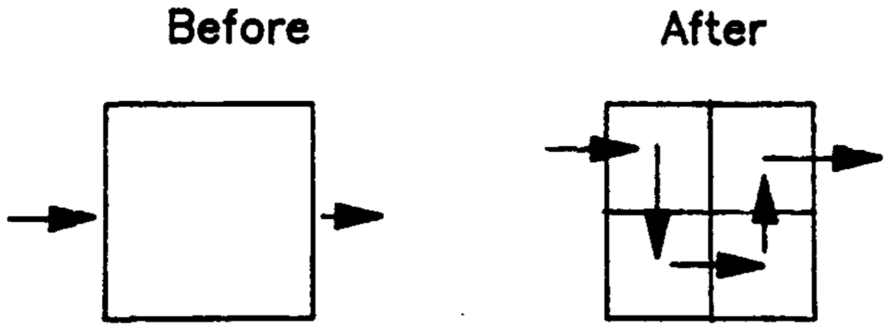


FIGURE 5. PLUG FLOW MODIFICATION USING BAFFLE WALLS

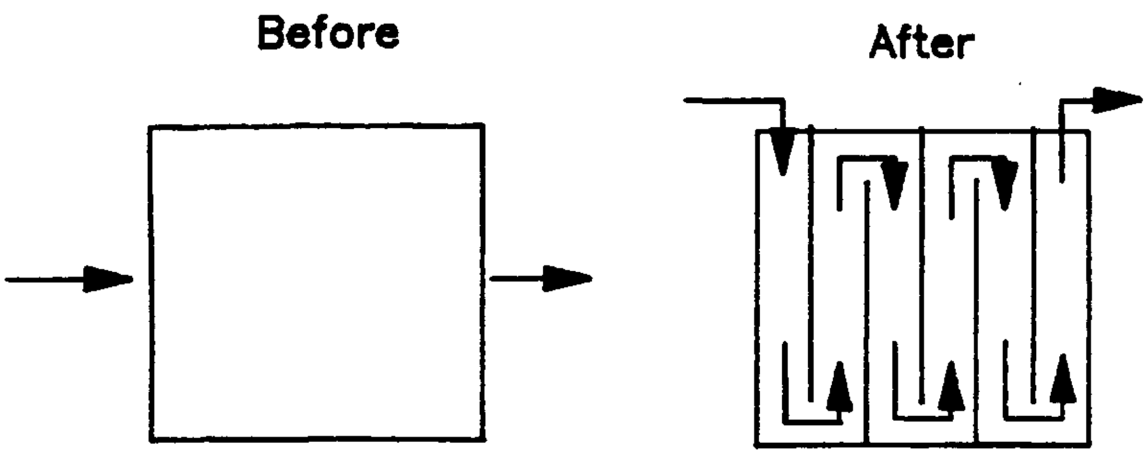
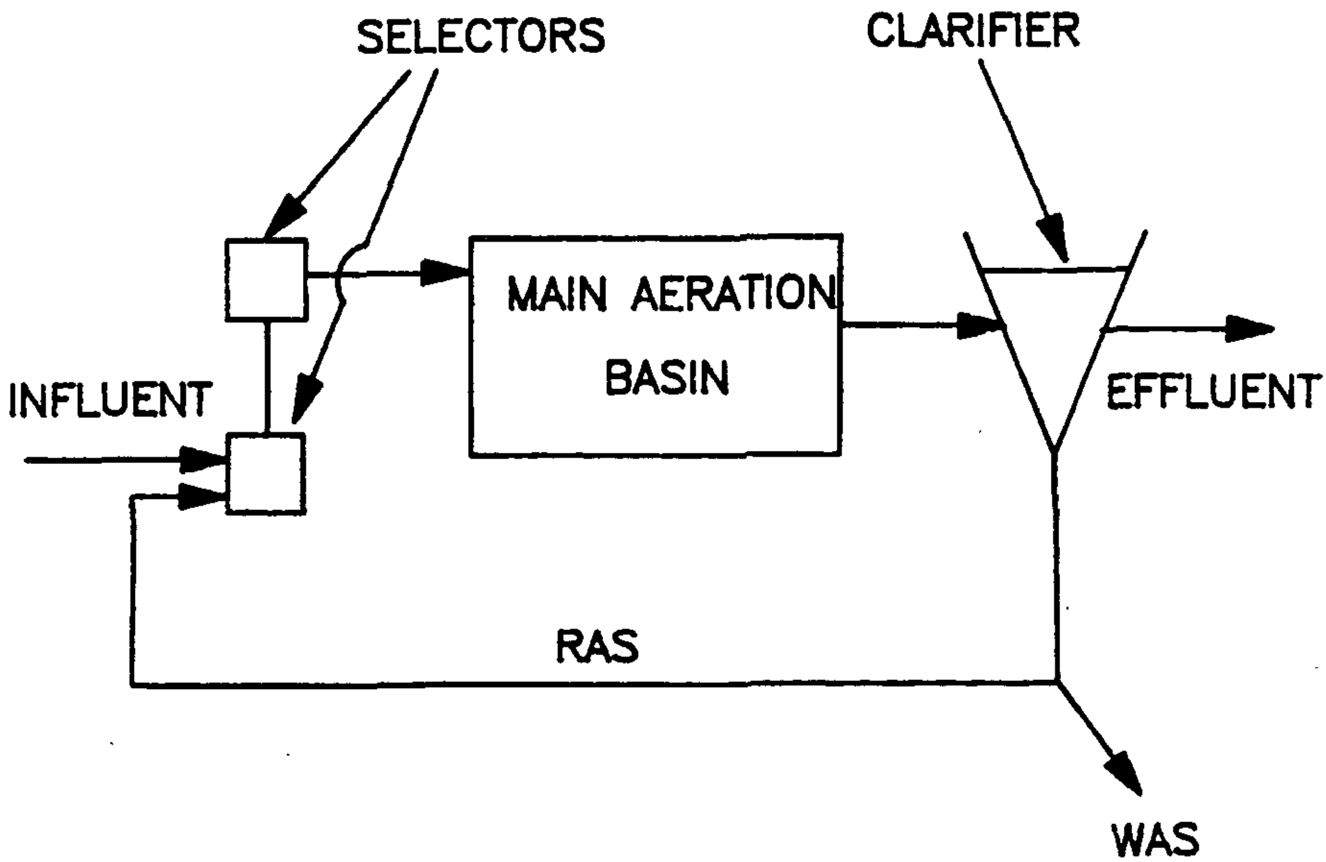


FIGURE 6. SCHEMATIC OF A SELECTOR SYSTEM.



a carbonaceous substrate concentration gradient in the aeration basin or a high substrate concentration at the point where return sludge and influent waste enter the aeration basin system (Jenkins *et al.*, 1986).

There has been extensive research on the five aforementioned control strategies, namely the compartmentalization of the aeration basins (Chudoba *et al.*, 1973a; 1973b; 1974), the introduction of plug flow characteristics to the aeration basin (Rensink *et al.*, 1982; Eikelboom, 1982), intermittent feeding of wastes (Houtmeyers, 1978; Houtmeyers *et al.*, 1980; Verachtert *et al.*, 1980; van den Eynde *et al.*, 1982a; 1982b), batch fed operation (Goronszy and Barnes, 1979; Goronszy, 1980; Barnes and Goronszy, 1980; Chiesa and Irvine, 1982), and the use of a selector (Lee *et al.*, 1982; Grau *et al.*, 1982; Wheeler *et al.*, 1984; Daigger *et al.*, 1985; Chudoba, 1985; Chudoba *et al.*, 1985; Linne and Chiesa, 1987; Shao and Jenkins, 1988; Wakefield and Slim, 1988; Patoczka and Eckenfelder, 1988; Pujol and Boutin, 1988; and Salemah and Malina, 1989).

In reference to selectors, there is no current literature which presents specifics about design guidelines for the prevention of low F:M bulking. However, authors have compiled useful design generalities (Jenkins *et al.*, 1986; Patoczka and Eckenfelder, 1988), and hopefully specific criteria for the design of selectors are in the near future.

2.6 Summary

There are several mechanisms which have been suggested to explain exactly why filamentous organisms predominate under certain conditions. These have been compiled and are presented in Table 3. It is important that these mechanisms are understood if a bulking problem is to be controlled properly. There is a wealth of information available for the control of filamentous bulking. Filament identification is extremely important to properly assess the problem and to define possible control strategies. Short-term control methods are often used to quickly control bulking episodes. Quite often, short-term approaches are necessary to temporarily control bulking episodes before long-term solutions to the problem can be implemented. Short-term solutions may be cheaper where complex process modifications are required to achieve long-term control of bulking. However, the best approach is for a plant to achieve long-term control of bulking. Although long-term solutions are preferred, technological or financial constraints often limit their implementation.

2.7 Costs

Limited information is available on cost-related data, especially or those remedial actions which involve complex process modifications. However, for control with chemical treatment, some information is available. Chambers and Tomlinson have compiled cost data for chemical treatment (toxicants and flocculating agents) which are useful for estimations (1982). Costs for nutrient additions are also available but on a limited basis (Broderick and Sherrard, 1985).

Table 3. Mechanisms Contributing to Filamentous Predominance Under Specified Conditions.

Environmental Pressure Causing Filamentous Predominance	Suggested Mechanism or Filament Characteristic
Low DO	1. Lower μ_{max} and K_s values. 2. Higher surface area to volume ratio.
Low F:M	1. Lower μ_{max} and K_s values. 2. Higher surface area to volume ratio. 3. Ability to store substrates intracellularly.
Septic Wastewater/ Sulfides	1. Use of reduced sulfur compounds as energy sources.
Nutrient Deficiency	1. Lower μ_{max} and K_s values. 2. Higher surface area to volume ratio. 3. Ability to store substrates intracellularly.
Low pH	1. Filamentous resistance to acidic conditions. 2. Presence of certain filamentous fungi.

CHAPTER III

METHODS AND MATERIALS

3.1 Introduction

Basically, there were two phases of this research. The first phase involved the determination of the extent of the bulking problem in Massachusetts. As was stated earlier, this was accomplished through the use of a survey. The second phase of this project involved the engineering evaluation of remedial control measures for four plants experiencing bulking problems.

3.2 Fabrication of a Sludge Bulking Survey

The objective of this portion of the research was to establish the magnitude of the bulking problem in Massachusetts. The goals of the survey were to gather wastewater characteristics, operational parameters, and design parameters from activated sludge plants in the Commonwealth. The list of activated sludge plants was based on material from the Massachusetts Wastewater Treatment Plant Operator's Association (1984), the Massachusetts Department of Environmental Quality Engineering (1987), and the Massachusetts Division of Water Pollution Control (1982). The survey was three pages in length and was designed to take only a few minutes to complete (See Appendix D). The survey was mailed to activated sludge plants in Massachusetts based on the current addresses provided by the previously-mentioned literature.

Approximately six weeks after the first survey was sent, a follow-up letter was sent to those plants who had not yet responded. The results of the survey will be presented in Chapter IV of this report.

3.3 Survey Interpretation

The data collected from the survey was statistically compiled and reviewed to observe correlations among those plants experiencing bulking problems. Those plants who reported having bulking problems within one year of the survey were contacted with regard to a potential on-site consultation. A total of ten plants responded that they would like to meet with us to discuss their bulking problems. The availability of plant data and the significance of the bulking problem were reviewed at this time. Sampling and filament identification were performed as a related portion of this project. From the filament identification, the severity of the bulking problem was evaluated (Plante, 1990). Based on this information, a total of four plants were chosen to be part of the case-study portion of this research.

3.4 Engineering Evaluation of Remedial Control Measures

Based on filament identification (Plante, 1990), and on correlations with available plant data, the condition causing the bulking problem was determined. Strategies to control the problem were compiled based on the type of condition encountered and by what strategies which had been successful in curing similar problems in other treatment plants. The techniques which were currently being used to suppress filamentous growth were also reviewed at this time. Both short-term and long-term control strategies were evaluated. These strategies were evaluated based on relative effectiveness, applicability to the plant-specific characteristics, ease of implementation, and economic feasibility. Other consideration was given to problems with compliance and nuisance creation.

Cost-benefit analyses were performed on all the strategies which were considered to be viable alternatives for bulking control. Financial expenditures for the current method used to control bulking were gathered through conversations with plant operators and also from plant data sheets. Costs for alternative measures were gathered from telephone conversations with local distributors, cost indexes for construction of new structures (or modifications to existing structures), and from the most current literature.

The best alternative was chosen for each plant in this study based on the previously-mentioned criteria. However, significant weight was given to economics because it obviously plays an important role in the selection of bulking control measures.

3.5 Jar Test Procedure

In one particular case study, jar tests were used to evaluate the effectiveness of hydrogen peroxide (H_2O_2) on filament destruction and oxygen supplementation. The protocol for these experiments will now be discussed.

A mixed liquor sample was obtained from the treatment plant and was transported in a plastic carboy to the laboratory where it was aerated with a porous stone diffuser. Two jar tests were performed to determine the optimal dose of H_2O_2 to be added. A total of six 600 ml beakers were filled with 500 ml of the mixed liquor sample. These six beakers were placed one at a time under a Phipps and Bird (Richmond, VA) paddle stirrer, at which time, five beakers were dosed with varying volumes of H_2O_2. The sixth beaker was used as a control. Paddle dimensions were 1 inch by 3 inches. The samples were stirred at 85 revolutions per minute (rpm) for 15 minutes. Following this period, the samples were allowed to settle quiescently for 30 minutes. Blanket depth, as well as qualitative supernatant descriptions, were recorded during the 30-minute settling time for each 5-minute interval. Approximately one hour after the addition of the H_2O_2, all six samples for each run were analyzed for dissolved oxygen content (DO) using a YSI (Yellow Springs, OH) DO meter.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Introduction

The results of the sludge bulking survey were compiled and reviewed. The results and discussion of each are presented in the following sections. In addition, a general summary of the results of the case studies evaluating remedial control measures will also be reviewed. However, Chapter V will contain a presentation of each case study and will outline the results of each in much greater detail.

4.2 The Results of the Survey

4.2.1 The Extent of the Problem

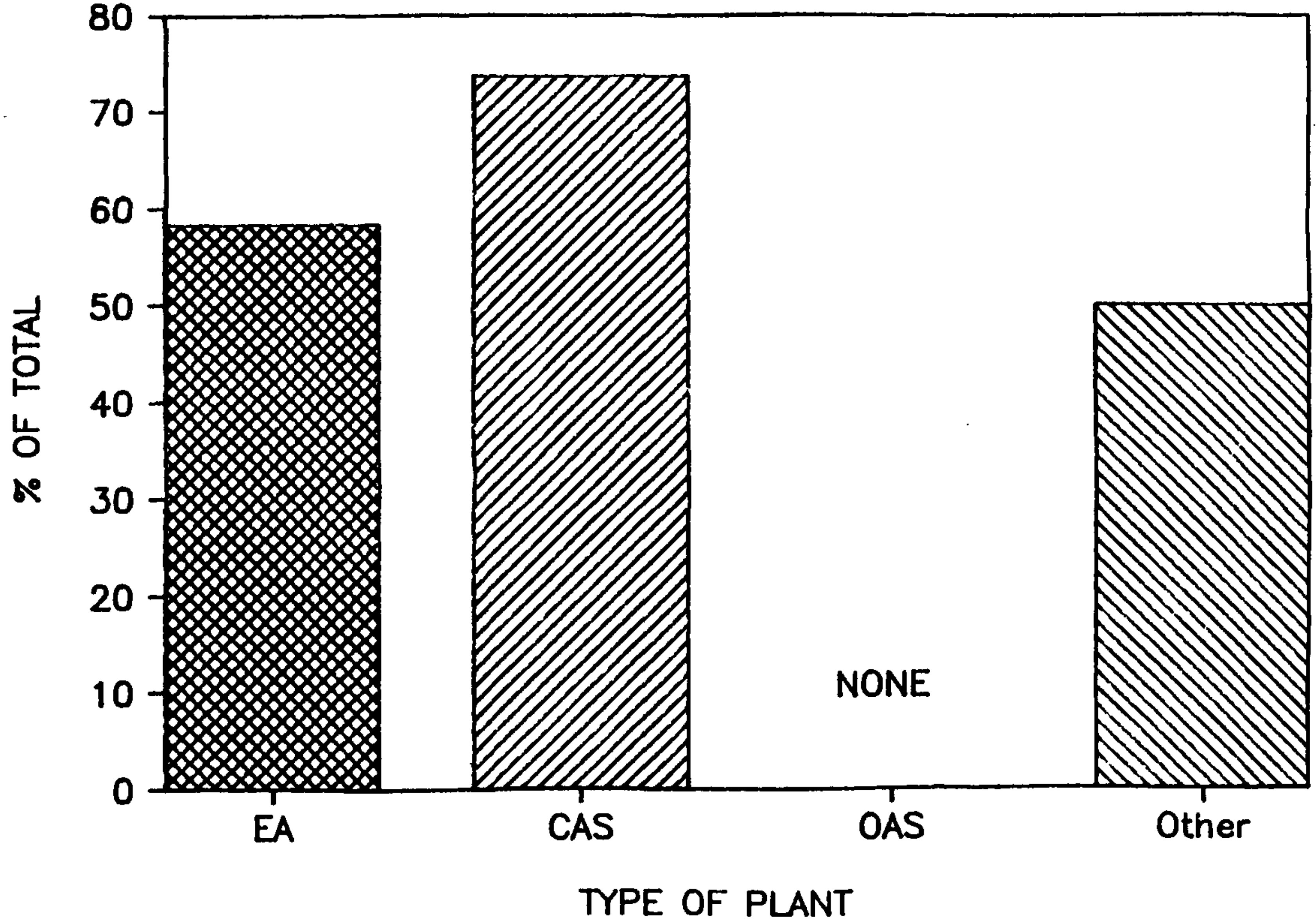
Based on the most current literature, there are a total of 112 wastewater treatment plants in Massachusetts, of which 83 operate in some form of an activated sludge mode. A plant was regarded as being activated sludge if it was categorized as any one of the following: conventional activated sludge, oxygen activated sludge, contact stabilization, extended aeration, or oxidation ditch.

A total of 83 surveys were sent, of which 50 (60%) were returned. The distribution of responses by plant type is shown in Table 4. Of the 50 surveys returned, a total of 30 (60%) reported that the plant had experienced bulking episodes within the last year. The distribution of plant types reporting bulking is as follows: 75% of the conventional plants (either completely-mixed or plug flow), 58% of the extended aeration plants, 50% of the contact stabilization or oxidation ditch plants, and none of the oxygen activated sludge plants. This is further illustrated in Figure 7.

Table 4. Summary of the Distribution of Plant Types Responding to Survey.

Plant Type	% of Responses
Extended Aeration (EA)	48%
Conventional Activated Sludge (CAS)	40%
Oxygen Activated Sludge (OAS)	4%
Contact Stabilization (CS)	2%
Oxidation Ditch (OD)	2%
Other	4%

FIGURE 7. PERCENTAGE OF PLANT TYPES REPORTING BULKING.



An investigation of the conventional activated sludge systems was conducted to test the hypothesis of completely-mixed systems being more prone to bulking than plug flow systems. A total of 60% of the plants operating in the complete-mix mode experienced bulking problems compared to only 45% of the plug flow systems.

Additional statistics were compiled based on SRT, F:M ratio, and DO concentration to see what effect, if any, these parameters had on the occurence of sludge bulking. The results of these evaluations are presented in Tables 5 through 7.

Table 5. The Role of SRT on the Frequency of Sludge Bulking.

SRT range (days)	0 - 3	4 - 12	13 - 25	≥26
% of responses in range	5	46	23	26
% of above reporting bulking	0	78	44	50

Table 6. The Role of the F:M Ratio on the Frequency of Sludge Bulking.

F:M range (kg BOD_5 per kg MLVSS*d)	0 - 0.12	0.13 - 0.25	≥0.26
% of responses in range	52	37	11
% of above reporting bulking	61	71	69

Table 7. The Role of DO Concentration on the Frequency of Sludge Bulking.

DO range (mg/l)	0 - 1.2	1.3 - 2.5	≥2.6
% of responses in range	9	45	46
% of above reporting bulking	80	55	59

4.2.2 Reported Control Measures

A majority (60%) of the respondents who indicated that the plant experienced bulking reported that the problem was controlled by using chlorination. Other reported control measures included the use of process/operational modifications (30%), the addition of settling enhancers (17%), the addition of nutrients (7%), and the addition of hydrogen peroxide (3%). Based on these results, it was clearly evident that a vast majority of the plants were using rapid, non-specific control techniques on a regular basis. The distribution of control measures is presented in Table 8.

Table 8. Summary of the Distribution of Reported Control Measures.

Reported Control Measure	% of Responses Reporting Bulking
Chlorination	60%
Process/Operational Modifications	30%
Settling Enhancers	17%
Nutrient Addition	7%
Hydrogen Peroxide	3%

4.2.3 Additional Observations

Case study analyses and filament identification procedures revealed that a significant number of the plants sampled were suffering from nutrient-deficient bulking. However, based on the results of the survey, only 34% of the respondents reported that they monitored nutrient concentrations on a regular basis.

Only a few monthly National Pollutant Discharge Elimination System (NPDES) permits were violated. However, daily total suspended solids (TSS) and BOD_5 limits were reported to be exceeded by a large fraction of the plants who responded to the survey.

A majority of the plants responding to the survey did indicate that the settling problems at the plant were caused by filamentous organisms. However, only 17% of the respondents identified that bulking was caused by a specific filamentous organism (indicated by a name or number). Several other causative conditions were listed and are summarized in Table 9.

Table 9. Summary of Reported Causes of Poor Solids Separation.

Reported Cause	% of Responses
Filamentous Organisms	57%
Seasonal Changes	20%
Nutrient Deficiency	7%
Septage/Septic Conditions	3%
Hydraulic Overload	3%
Unknown	10%

4.3 Summary of Results for the Case Studies

Four plants were chosen for case studies of remedial control measures. For each study, the filament causing bulking was identified (Plante, 1990); consequently, the suggested causative condition was determined using Table 2. These four particular plants were chosen from a total of ten plants which were sampled for filament identification. It was originally desired to choose one plant for each specific causative condition (recall there are five conditions, see Table 2). However, filaments indicative of low pH and septic wastewater were not identified at any of the ten plants sampled. Therefore, three plants were chosen to represent the three remaining categories which are low dissolved oxygen, low nutrient concentrations, and low F:M ratio. In addition, one other plant was chosen as a potential for the installation of a selector to combat low F:M bulking. Furthermore, these plants were chosen as a result of their established data bases, the severity of the bulking problem, and the cooperation and enthusiasm of the plant personnel toward curing the problem. Chapter V of this report is devoted to the discussion of the four case studies.

4.4 Discussion

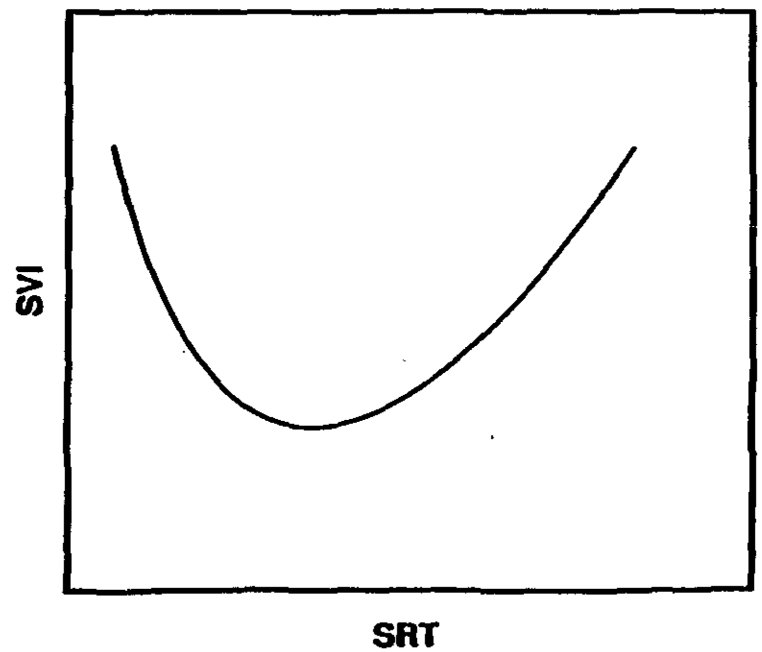
4.4.1 Interpretation of the Survey

Recall that 60% of the respondents indicated that the plant had experienced problems with bulking within one year of the survey. This figure was considered to be significant in that it clearly indicates that sludge bulking is a problem. The 60% bulking rate was consistent with the results of similar surveys elsewhere. However, it is possible that an inherent bias exists for this survey. Because the survey was clearly dealing with bulking, it is possible that only those operators experiencing problems with bulking, or familiar with the phenomenon, would return the survey. This would unavoidably result in an inflated frequency of reported bulking episodes. Therefore, the 60% bulking rate is possibly a little higher than what would be expected if all the plants had returned the survey, including those which did not experience bulking or did not know of the condition. However, it is unlikely that this figure would vary more than 10 to 15%. Even if the remainder of the surveys were returned and reported that bulking was not a problem, the bulking rate would still be 36% (30 of 83 plants report bulking). This would still be considered to be significant.

Plants operating in the plug flow configuration were compared to those operating in the completely-mixed mode. Recall that plug flow and completely-mixed systems have bulking rates of 45% and 60%, respectively. Although the hypothesis that completely-mixed systems are more prone to bulking than plug flow configurations has been strengthened by these results, one would have expected the difference between the two to be much greater. There are two possibilities why this may have occurred. The first is that in full-scale, practical applications it is extremely difficult to simulate true plug flow conditions as defined theoretically. Since this hypothesis is primarily based on pilot and bench-scale experiments, it is unlikely that the results of full-scale operation would appreciably parallel these experimental results. Therefore, in full-scale operation, the difference between the two modes may not be as significant. Another reason to explain the conflict may lay in the definition of plug flow and completely-mixed configurations. Since many plants operate in a wide variety of modes, it is possible that actual operation might lay somewhere between the two modes; therefore, the differentiation between the two would be more difficult for operators to identify.

There was some concern that the condition known as "dispersed growth" would be improperly identified by plant personnel as filamentous bulking. The settling characteristics of a sludge are highly influenced by the value of the SRT (see Figure 8). At low SRT's, the condition of dispersed growth may sometimes appear to be caused by filamentous organisms. Dispersed growth occurs because the physiological state of the microorganisms is such that the high growth rates result in decreases in the amount of exocellular polymer produced by these organisms. Therefore, the organisms form smaller individual clumps, as opposed to large flocs, which are sometimes improperly identified as bulking. Since this survey relied entirely on the subjective identification of bulking episodes by plant personnel, it was necessary to eliminate a bias in the bulking rate which included dispersed growth conditions. To safeguard against this, the plants who responded to the survey were placed in groups based on SRT (see Table 5). If dispersed growth was improperly identified as being filamentous bulking, this would appear in the number of plants with low SRT's which reported bulking. However, none of the plants operating at low SRT's reported bulking, thereby eliminating the potential bias caused by dispersed growth. From Table 5, one can see that a majority of the plants that operate with an SRT in the range of 4 to 12 days experience the highest frequency of reported bulking episodes (78%).

Figure 8. The Influence of SRT on SVI



The plants were also categorized based on the F:M operating range (see Table 6). As a result of this grouping, it can be deduced that F:M did not play a significant role in determining the frequency of sludge bulking; this is shown by the relatively small fluctuation in cases of bulking reported for each range of F:M. However, one would expect that plants operating in the lower range would have a higher frequency of bulking, but this was not reflected by the data.

Based on the DO levels established in the aeration basin, the plants were also grouped into three categories (see Table 7). As expected, a majority (80%) of the plants operating in the lower DO range reported instances of sludge bulking.

CHAPTER V

CASE STUDIES

5.0 Introduction

Engineering evaluations of remedial control measures were investigated for a total of four plants. Based on the results of filament identification (Plante, 1990), control strategies were evaluated for each specific cause of bulking. Table 10 is a brief summary outlining the four case studies and the condition believed to be causing the bulking problem. This chapter is devoted to discussing the four case studies in more detail.

Table 10. Summary of Conditions Believed to be Causing Bulking at the Four Plants in This Study.

Facility Designation	Condition(s) Believed to be Causing Bulking
Plant A	Low Nutrients
Plant B	Low DO/Low F:M
Plant C	Low F:M
Plant D	Low F:M/Low Nutrients

5.1 Plant A

5.1.1 Background

Plant A treats an average daily flow of 3,785 m^3/day (1.0 MGD), which constitutes approximately 56% of its average daily design flow of 6,815 m^3/day (1.8 MGD). The plant operates in the plug flow, step feed mode with diffused aeration. Approximately 80% of the flow is domestic wastewater; the remaining 20% is from a papermill which comprises 90 to 95% of the influent solids load. The average influent BOD_5 and TSS concentrations are approximately 440 mg/l and 730 mg/l, respectively. However, BOD_5 and TSS concentrations are highly dependent on the papermill operation and have been shown to be as high as 1040 mg/l and 2300 mg/l, respectively.

Plant A has had a history of bulking problems and, in the past, has relied heavily upon chlorinating the return sludge to control filamentous bulking. However, during episodes where filamentous organisms were extremely predominant, the plant experienced problems with over-chlorination. This resulted in the destruction of floc-forming organisms rather than filamentous organisms. In March and April of 1989, the plant violated its NPDES monthly average discharge limit of 30 mg/l for both BOD_5 and TSS. At this time, the bulking problem became significant enough to warrant further attention.

5.1.2 Filament Identification

In April of 1989, a sample was microscopically analyzed, at which time the SVI was 282 ml/g and the sludge was considered to be bulking. *Thiothrix II* were observed to be "abundant" while *Sphaerotilus natans* were considered to be secondary; significant amounts of interfloc bridging and free filaments were also observed (Plante, 1990).

As shown in Table 2, these organisms are indicative of a nutrient deficiency. Furthermore, it has been shown that nutrient deficient wastewaters are a common problem where paper mill wastes are combined with domestic wastewater.

5.1.3 Data Analysis and Interpretation

Unfortunately, the plant did not monitor nutrient concentrations at this time, making the immediate correlation between existing data and filament identification impossible. However, in March of 1989, the wastewater was analyzed for nitrogen and phosphorus content. Primary effluent and secondary effluent prior to chlorination were tested. Nitrogen levels in both samples were observed to be satisfactory; however, the secondary effluent sample analyzed for phosphorus content was found to contain only 0.2 mg/l total phosphorus. One method to insure against phosphorus-deficient wastewaters is to maintain approximately 0.2 mg/l of soluble PO_4- P in the effluent at all times (Richard, 1989; Jenkins *et al.*, 1986). Because soluble PO_4- P for this plant is obviously much lower than the recommended value, the plant was confirmed as being deficient in phosphorus.

As a result of this determination, the plant began to add phosphorus in late March of 1989. Phosphorus was obtained from a local lawn care company in a powdered form (42-50% H_3PO_4, 20.4% Ca, and 11.9% S). Primary effluent from the plant is transported to the aeration basins via two screw pumps located downgradient. It was at this point, specifically the screw pump wet wells, to which the mixture was added. Initially, relatively small doses were added which were eventually increased as to meet a secondary effluent orthophosphate residual of 1 - 2 mg/l. Generally, average monthly dosages range from 32 kg/day to 55 kg/day (70 - 100 lbs/day).

Commonly, nutrient additions are controlled based on concentrations found in the primary effluent. Once this concentration is determined, the exact amount of nutrient to be added is calculated in such a way as to limit overdosing (See Appendix B). However, recall that this plant receives 20% of its flow from a papermill which regularly discharges large volumes of colored dyes. Because a colorimetric test is used at the plant to determine orthophosphate concentrations, these dyes interfere with the analysis. Secondary treatment reduces the dye concentrations significantly enough so that their presence in small quantities does not cause an interference in the results. Therefore, the plant personnel rely on secondary orthophosphate residuals to determine influent phosphorus doses.

Since the commencement of the phosphorus additions, the plant has had success in maintaining stable, good quality sludges. Very good results have also been consistently obtained in reference to effluent quality (See Figures 10 and 11). Return sludge chlorination has ceased except in cases where highly filamentous conditions persist (See Figure 12).

5.1.4 Economic Analysis of Existing Remedial Actions

Based on the success of nutrient additions in controlling bulking episodes at the facility, it became necessary to evaluate the relative costs of adding nutrients versus the cost of using chlorination. Two ten-month periods in two successive years were analyzed (4/88 - 1/89 versus 4/89 - 1/90). It should be noted that longer time frames would be more desirable, however the available data did not permit a longer correlation to be made. The use of the same ten-month periods in two successive years will hopefully eliminate any bias caused by seasonal changes.

From April 1988 to January 1989, the plant spent a total of $620 on chlorination to control filamentous bulking. From April 1989 to January 1990, the plant spent a total of $1750 to control bulking. This figure represents the sum of the costs for phosphorus addition ($1516), and also the use of chlorine ($234) to alleviate extreme cases of bulking. The results are also expressed in tabular form in Table 11.

Figure 9. Plant A: SVI vs. Time.

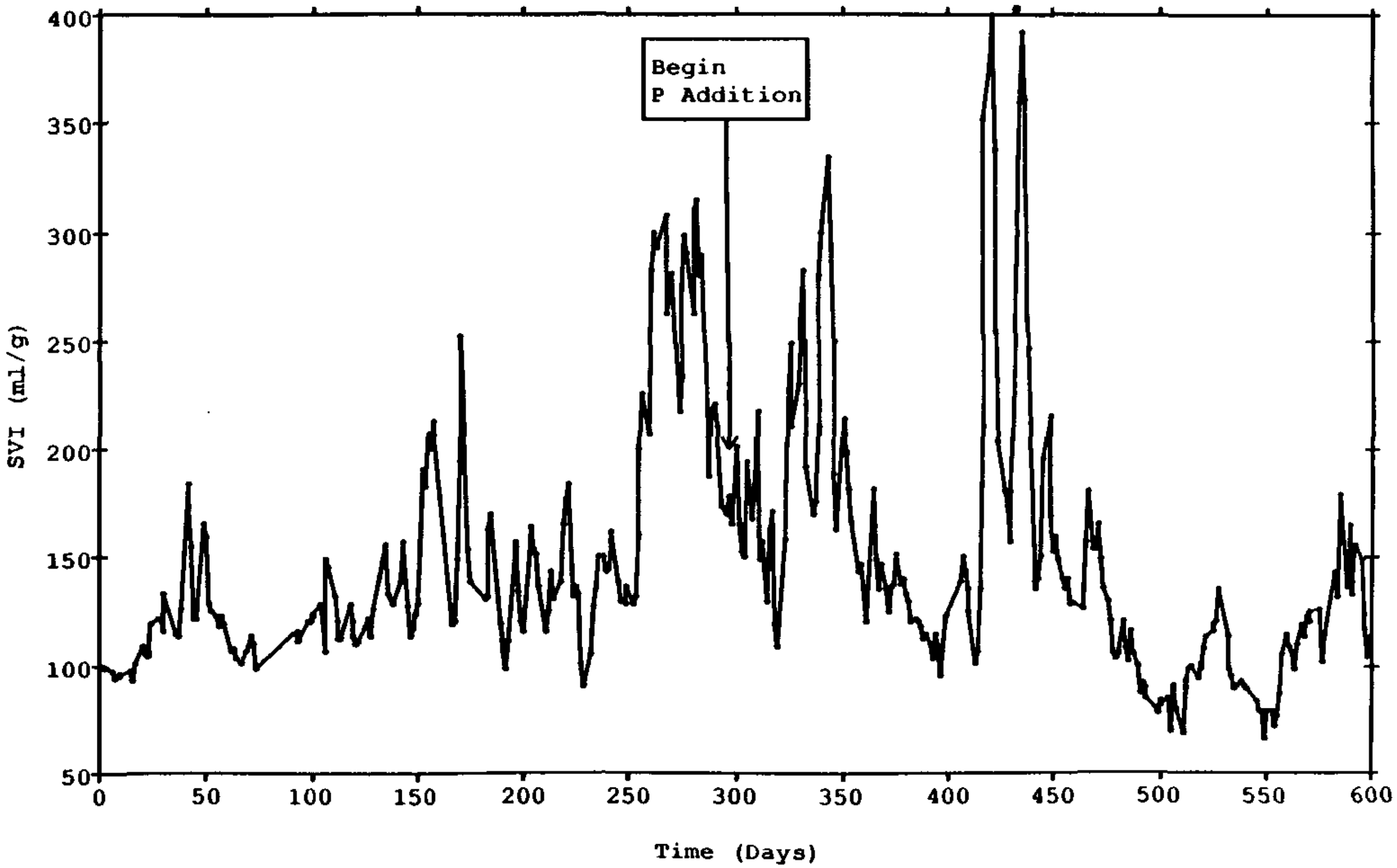


Figure 10. Plant A: Effluent BOD vs. Time.

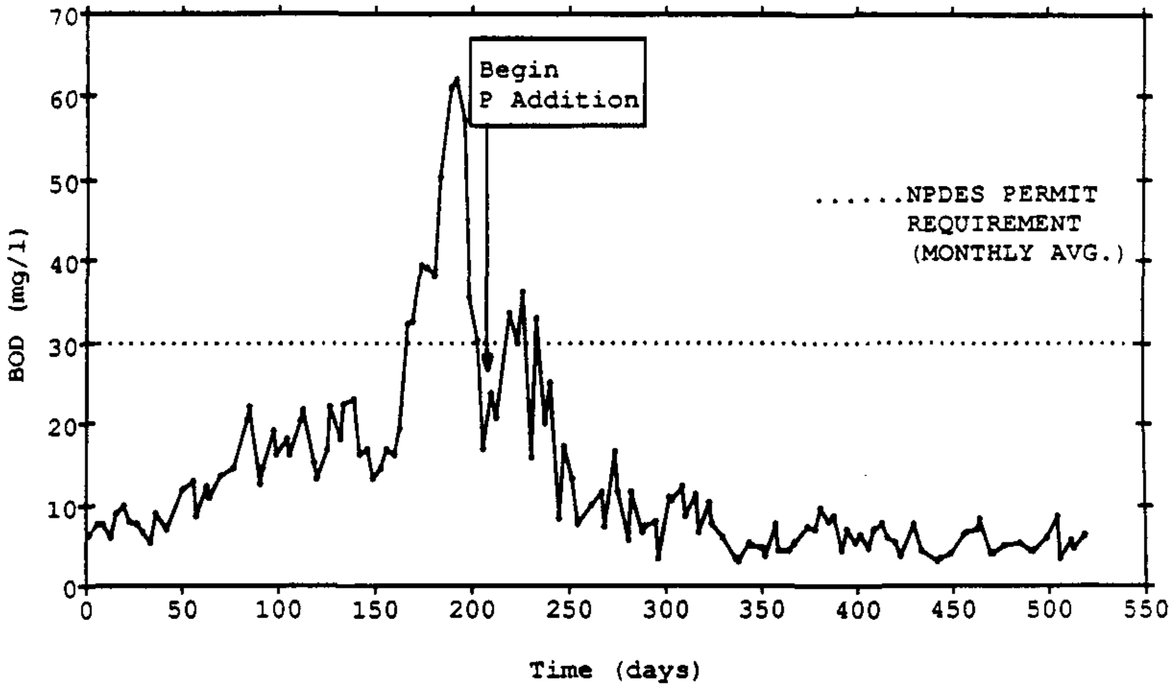


Figure 11. Plant A: Effluent TSS vs. Time.

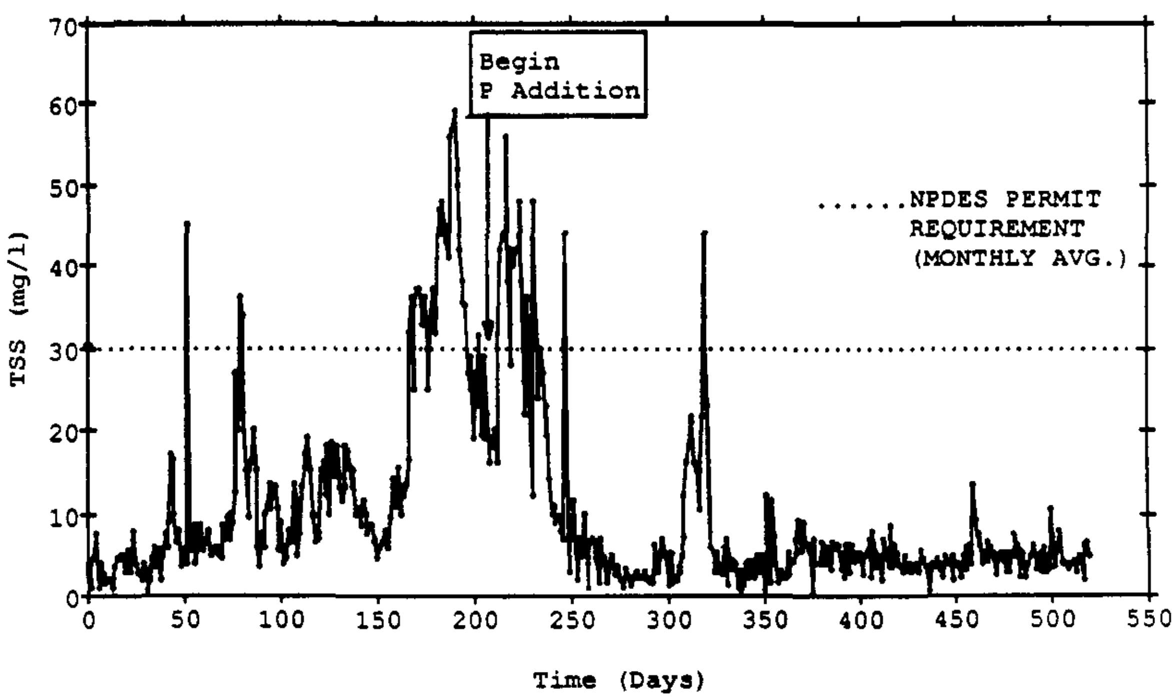


Figure 12. Plant A: RAS Chlorination vs. Time.

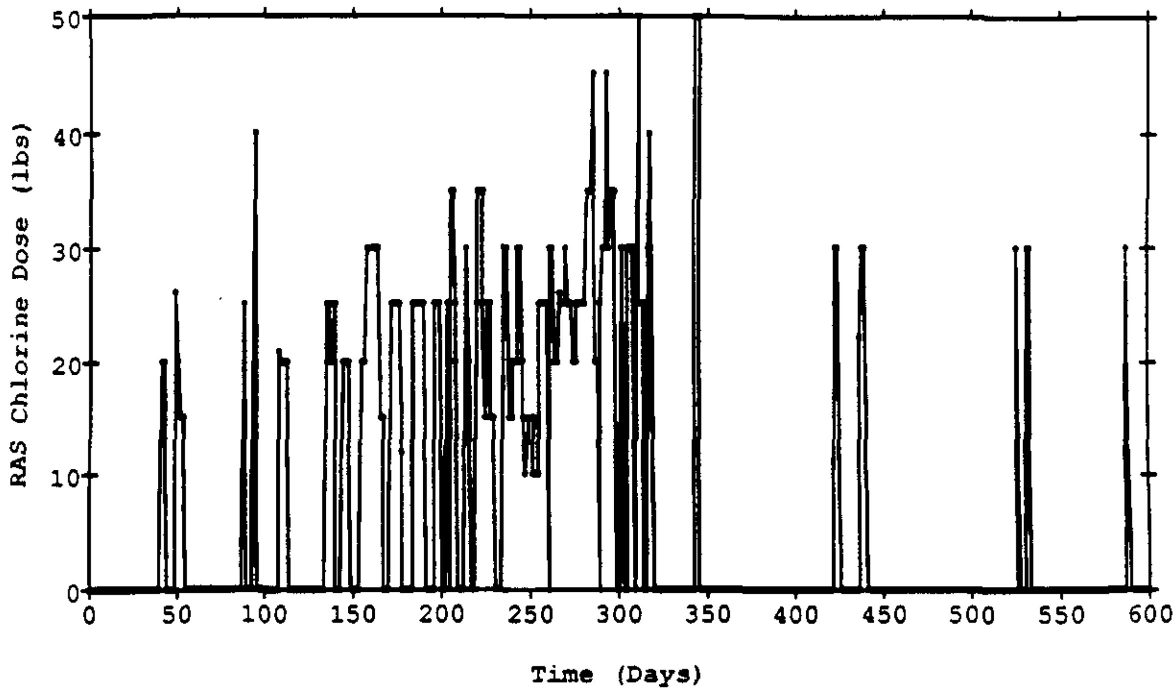
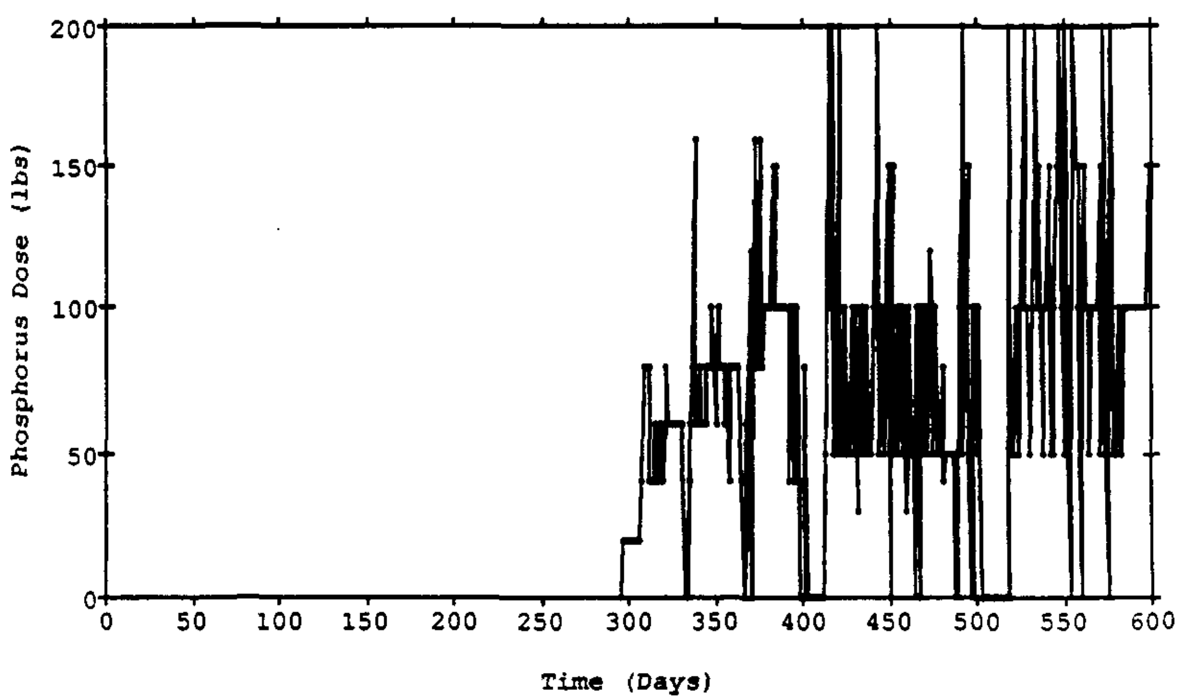


Figure 13. Plant A: Phosphorus Dose vs. Time.



In relative terms, the use of phosphorus and chlorine in combination costs approximately 2.8 times more than the use of chlorination as the single remedial action.

Table 11. Summary of Costs for Bulking Control at Plant A.

Time Period	4/88 - 1/89	4/89 - 1/90
Chlorine Expenditure (Dollars)	620	234
Phosphorus Expenditure (Dollars)	0	1516
TOTAL (Dollars)	**620**	**1750**

5.1.5 Discussion of Remedial Control Measures

In this particular case, there is no doubt that chlorination is far cheaper than the addition of a phosphorus compound. However, one has to recall that chlorination is treating the symptoms of bulking, whereas nutrient additions treat the cause of bulking. The addition of phosphorus has been shown to be very effective, not only in controlling the frequency and duration of bulking episodes, but also in producing a more stable biomass and a better quality effluent. Although no monetary values can be placed on these merits, it is imperative to include these considerations in the choice of remedial control alternatives. Operational problems and nuisances can play an important role in establishing remedial actions, and this plant is an excellent example where these factors should be addressed.

Now that the nutrient addition has proven to be effective, it would be beneficial to examine alternatives for the addition of the requisite phosphorus since adding a fertilizer purchased from a local lawn care company is probably not the most cost-effective solution. Although this method of application is well-suited for short-term, experimental operations, it is more than likely that this solution over a long period of time may be the least economical. Other factors which contribute to its inapplicability are the cost of labor to manually apply the chemical, the non-continuous means in which the chemical is applied, and the inability to purchase bulk quantities at a reasonable price. Chemical feed pumps which would supply the chosen chemical at a uniform, continuous dose are the obvious solution to this type of problem.

5.1.6 Economic Analysis of Remedial Alternatives

There are several compounds which are available as phosphorus sources for nutrient additions. To determine the chemical costs associated with nutrient additions requires that the current prices for the more commonly used compounds be compared on a normalized basis, such as cost per unit weight of phosphorus. Cost comparison at 1990 prices indicates that monoammonium phosphate is the most economical source for phosphorus (See Table 12).

Table 12. Present Day Phosphorus Costs.

Compound	Cost/ton (Dollars)	Cost/ton of P (Dollars)
Monoammonium Phosphate	135	965
Phosphoric Acid (53%)	164	980
Super Phosphoric Acid (70%)	242	1095
Diammonium Phosphate	126	1165

Compiled from *Chemical Marketing Reporter* (2/19/90)
Note: Quotes are for bulk quantities.

From April 1989 through October 1989 (ten months), the plant personnel added a total of 13,465 pounds of Triple Superphosphate (TSP). Based on yearly average use and daily average use, the plant personnel will add approximately 16,375 lb/year and 45 lb/day, respectively. This is equivalent to 4,030 lb/year or 11.0 lb/day as available phosphorus (P). If monoammonium phosphate were to be added in place of TSP on an equivalent weight of P basis, a total of 14,950 lb/year of monoammonium phosphate would be required. On a yearly basis, this would correspond to an expenditure of $1010. Comparing this to the extrapolated yearly cost of treatment with TSP, it would cost approximately 2.5 times more to use TSP than monoammonium phosphate. These chemical costs have been summarized and are shown in Table 13.

Table 13. Comparison of Existing Phosphorus Addition to Proposed Alternative.

Compound	lbs P added per year	lbs chemical per year	cost/ton of chemical	cost/yr (Dollars)
Triple Superphosphate (46% Available P)	4030	16,375	307[a]	2515
Monoammonium Phosphate (52% Available P)	4030	14,950	135[b]	1010

a - Actual cost paid by the facility.
b - Price obtained from *Chemical Marketing Reporter* (2/19/90).

It was desired to price a chemical feed system to apply the monoammonium phosphate on a continual basis proportional to flow rate. A dry feed system would cost approximately $8600 including installation, 6 cubic feet of hopper storage, and dust prevention (Rowden, 1990). Based on an interest rate of 8% and an analysis period of 10 years, it would cost approximately $1280/year for an annual equivalent payment (excluding chemical costs). Therefore, the total yearly payment including chemicals and equipment is projected to be $2290.

5.1.7 Recommendation of Remedial Alternative

Based on several month's data, the phosphorus addition has proven to be effective in controlling filamentous growth. The plant personnel recognize the cause of the problem and are willing to maintain the addition of phosphorus to control bulking episodes. As shown by the cost estimation, it would be more cost-effective for the plant to purchase monoammonium phosphate and the recommended feed system than to continue the manual application of TSP. In addition, the continual dose may be more effective than the current method of batch dosing. This may make the continual system with monoammonium phosphate even more economically attractive than it appears.

In summary, it is strongly recommended that the plant personnel purchase the feed system and monoammonium phosphate. Sufficient data is available to prove that this method of applying phosphorus would be the most effective and the most economical. However, as shown in Table 14, the most economical solution to the bulking problem would be to continue chlorination. Unfortunately, the bulking problem becomes uncontrollable when increases in chlorine added result in the destruction of floc-forming organisms. Over-chlorination will result in solids loss to the effluent as well. In addition, the implementation of new toxicity regulations may play an important role in limiting chlorine use in the future due mto the potential formation of chlorination by-products. Therefore, these limitations could mandate the use of alternative control measures other than chlorine despite the relatively low cost associated with its use.

Table 14. Summary of Bulking Control Options at Plant A.

Control Measure	Cost/yr ($)	Advantages	Disadvantages
RAS Chlorination	745	1. Inexpensive 2. On-site Availability 3. Continuous dosing	1. Overdosing 2. Treats symptoms
Triple Superphosphate (Batch-fed)	2515[a]	1. Treats cause, cures bulking	1. Expensive 2. Labor intensive 3. Non-continual 4. Storage
Monoammonium Phosphate (Continually-fed)	2290[b]	1. Treats cause, cures bulking 2. Automated	1. Storage

a - Chemical cost only.

b - Equipment and chemical costs (i = 8%, n = 10 years).

5.2 Plant B

5.2.1 Background

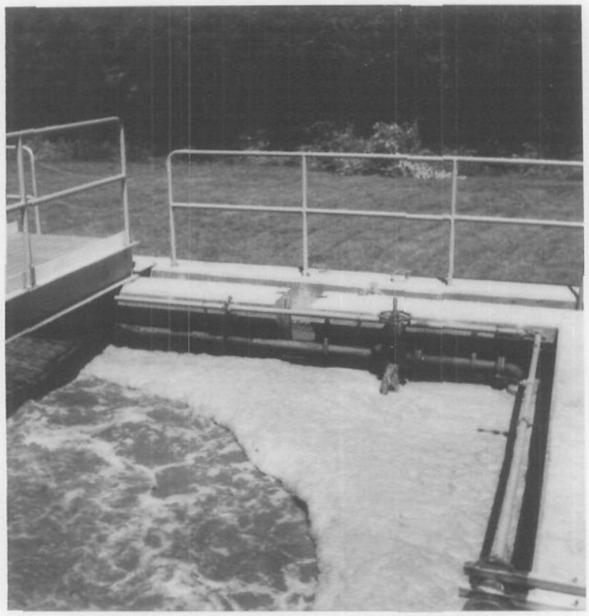
Plant B is a small extended aeration facility which treats an average daily flow of 430 m^3/day (0.113 MGD); this corresponds to 63% of its average daily design flow of 680 m^3/day (0.18 MGD). The plant operates in the complete-mix mode with mechanical aeration and without primary sedimentation. The surface aerators are operated intermittently (1.5 hours on and 0.25 hours off). Plant B maintains an average aeration basin DO concentration of 0.2 mg/l. The plant treats 100% domestic wastewater with no contribution from septage or industrial flows. However, it has been postulated by the operators that the plant may be receiving fairly high grease and fat concentrations from poorly maintained grease traps at local restaurants.

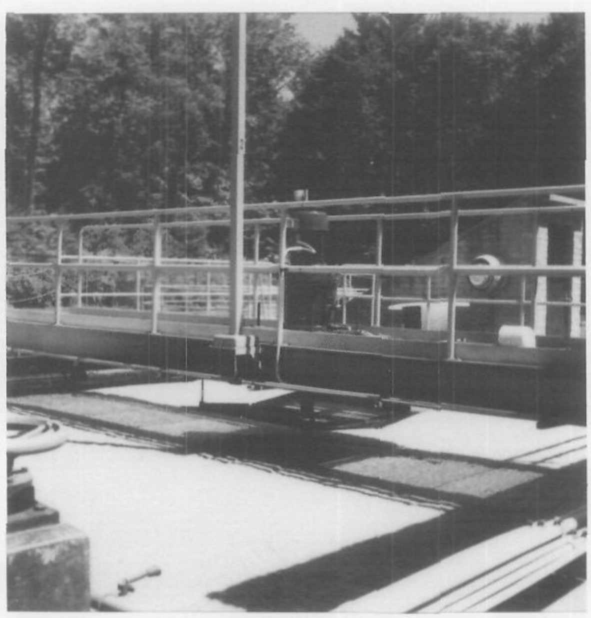
Plant B has had a history of bulking problems; high levels of foaming in the aeration basin (see Figure 14) and frequent blanket rising in the secondary clarifiers are two of the main operational problems which are regularly encountered. Foaming problems are believed to be a caused by both the influent grease and fat concentrations and also from the intermittent operation of the aerators. Blanket rising, caused by denitrification in the secondary clarifiers, is believed to be a result of the elevated SRT. In addition, solids are retained for longer periods during wet weather due to an inability to waste sludge from the system. Sludge processing at the plant is accomplished through the use of an aerobic digester. The digested sludge is then dried

Figure 14. Foam on the aeration basin at Plant B.

a). During 1.5 hr operation period.

b.) During 0.25 hr shut-off period.





on outdoor drying beds if weather permits. During wet weather, the sludge age is increased due to decreases in sludge wasting to the overloaded aerobic digester. In turn, this contributes to a high sludge blanket level in the secondary clarifiers which results in eventual solids loss to the effluent.

Currently, filamentous bulking is controlled by the addition of liquid sodium hypochlorite (NaOCl, 15% available Cl_2) to the return sludge. Approximately 25 gallons of NaOCl are added per day for the summer months (May - September). This corresponds to approximately 7.5 lbs available Cl_2 per day during these months.

5.2.2 Filament Identification

Both foam and mixed liquor samples were examined microscopically. The dominant organisms present were *Micothrix parvicella* and Type 0041, ranging from "abundant" to "excessive" in number (Plante, 1990). Further observation indicated that floc formation was dispersed and individual flocs were difficult to discern.

As shown in Table 2, the combined presence of these organisms is indicative of a low F:M condition. Furthermore, the presence of *M. parvicella* has also been associated with the existence of excess grease and fat concentrations.

5.2.3 Data Analysis and Interpretation

Operating data for Plant B are shown in Figures 15 through 18. Inspection of the data indicate that the plant appears to be suffering from a combination of low DO and low F:M conditions.

The mixed liquor DO concentrations are well below the recommended values of 1 - 2 mg/l. Currently, the mixed liquor DO is measured by transporting a sample from the aeration basin to the plant laboratory. This may result in a lower measured DO concentration because the relatively high concentration of MLVSS may add to the oxygen depletion. Although this may result in a reduced DO concentration, it is unlikely that the difference would be significant; especially since the initial DO concentration is very low from the start.

Visual inspection of the existing mechanical aerators helped to confirm the cause of the low DO condition. As shown in Figure 19, the aerators are well undersized and are barely submerged in the mixed liquor. It is also visually apparent that the aerators do not create sufficient agitation to promote efficient oxygen transfer. Furthermore, the depth of the aeration basins appears to be far too deep to insure for proper mixing and oxygen transfer. This observation was supported through discussions with the plant operator who revealed that the basins had a tendency to turn septic on occasion. In addition, the intermittent aeration pattern and the lack of a two-speed system also help contribute to low mixed liquor DO concentrations.

Figure 15. Plant B: SVI vs. Time.

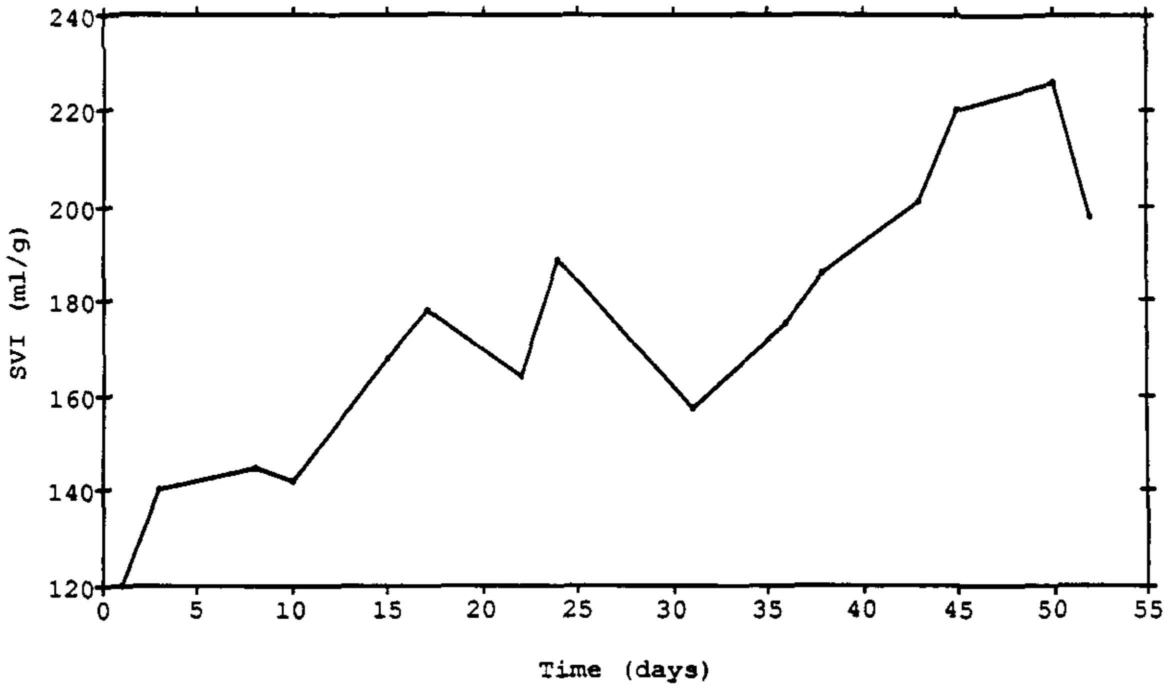


Figure 16. Plant B: Mixed Liquor DO Concentration vs. Time.

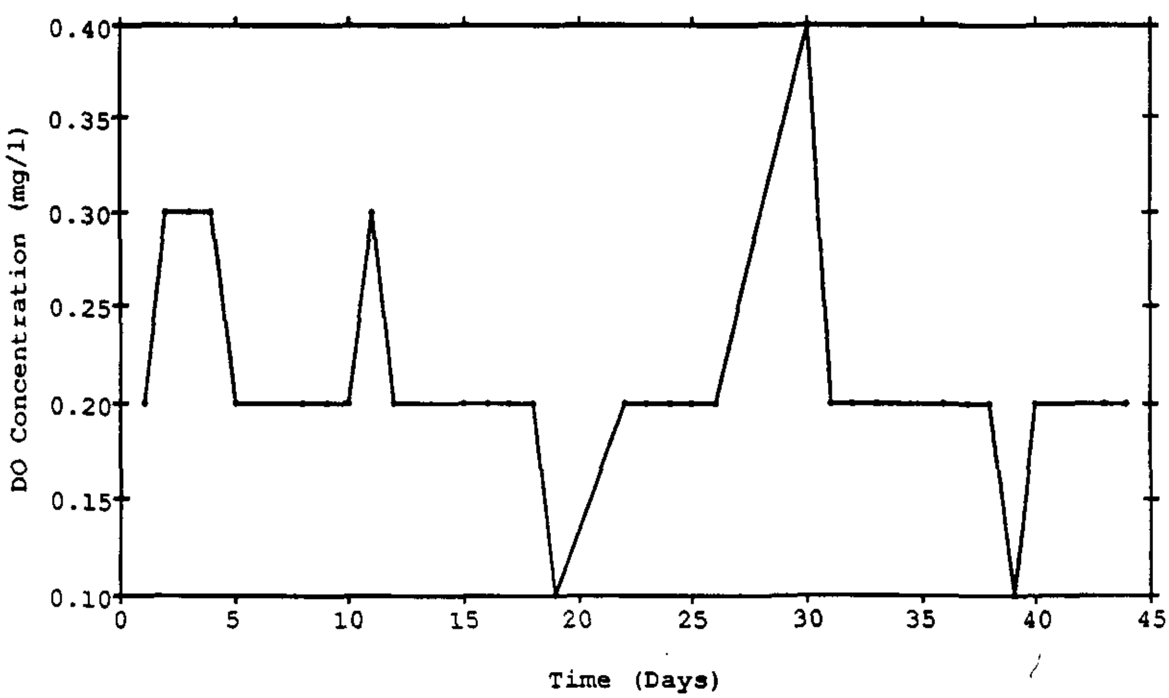


Figure 17. Plant B: MLSS Concentration vs. Time.

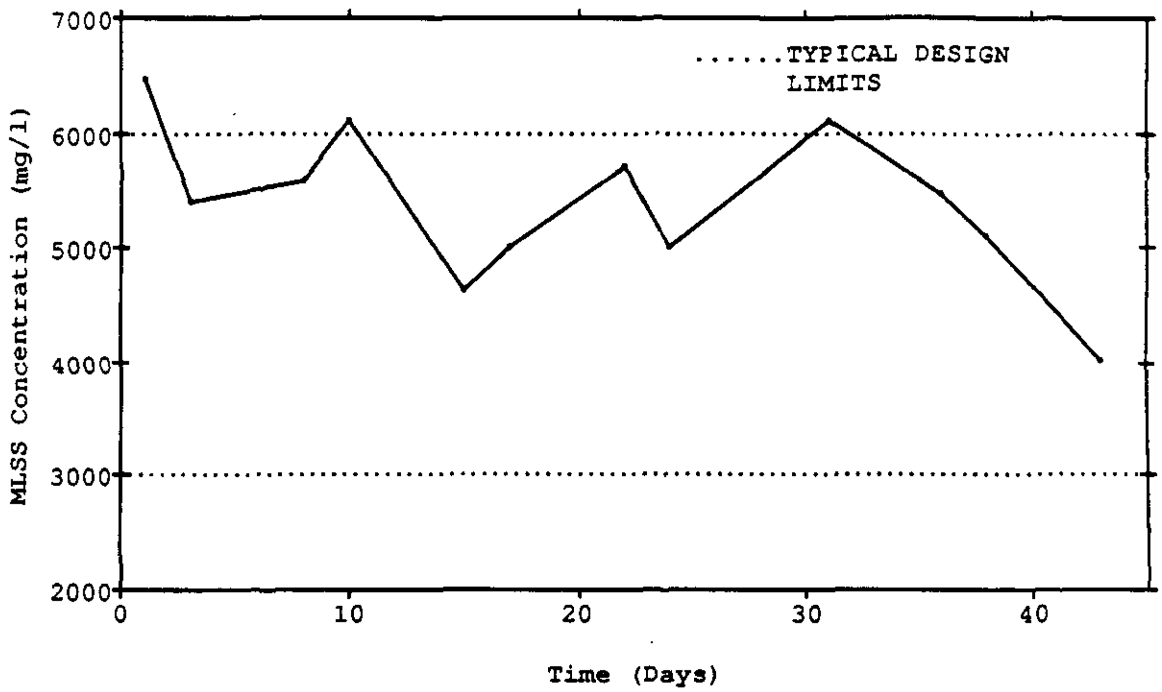


Figure 18. Plant B: F:M Ratio vs. Time.

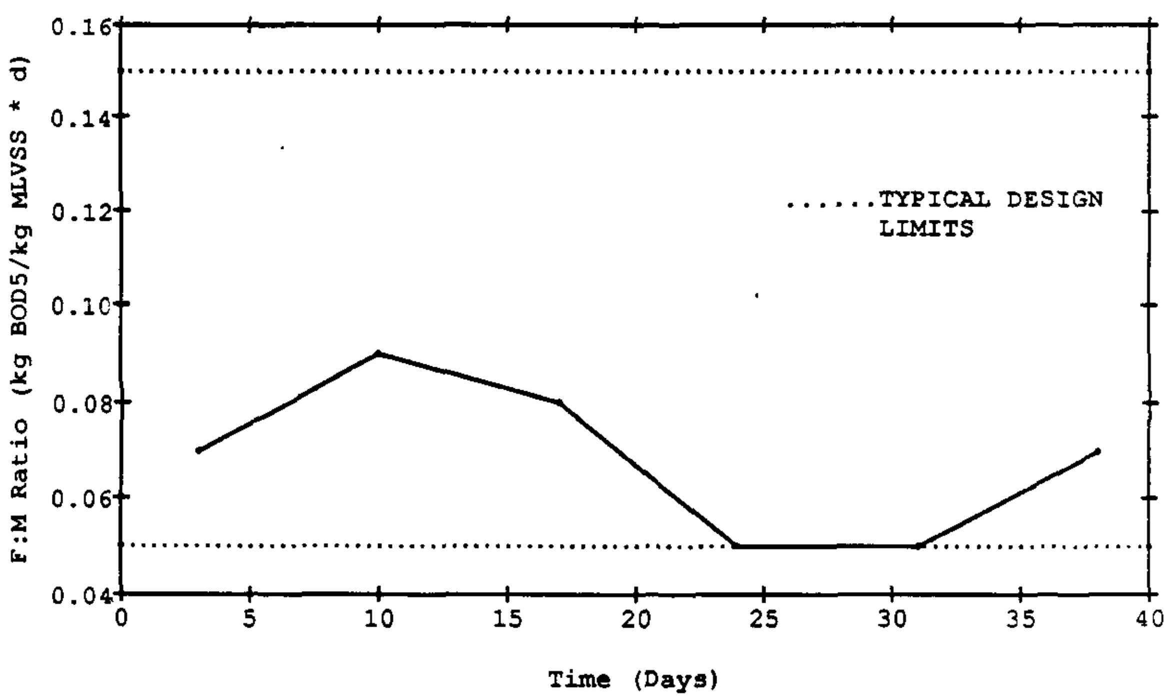


Figure 19. Existing Aeration System at Plant B.

a.) On-line Basin.

b.) Off-line Basin.

The oxygen transfer efficiency of the existing aeration system was evaluated to determine if sufficient oxygen was being transferred to accommodate the BOD_5 loading. This was done in accordance with the method presented by the EPA (EPA, 1989a). An example calculation is shown in Appendix C. For this particular system, the oxygen transfer capacity was calculated to be 1.08 kg oxygen per kg BOD_5. Generally, marginal oxygen transfer will be evident if the dissolved oxygen levels in the aeration basins can not be maintained at desired levels (1-2 mg/l), or if the oxygen transfer efficiency evaluation yields a transfer rate of less than 1.2 kg oxygen transfer capacity per kg BOD_5. In this particular case, both conditions exist making the plant suspect to having marginal oxygen transfer capacity.

The relatively low F:M ratios recorded are more than likely a result of the extended SRT's (> 25 days) and not of low influent BOD_5 concentrations. Elevated blanket levels in the secondary clarifiers are also a result of the extended SRT's, which lead to denitrification and eventual formation of nitrogen gas bubbles in the sludge blanket. This condition is more commonly known as rising sludge.

In addition, operational problems such as poor secondary clarifier design and inadequate waste sludge storage also contribute to the plant's inability to function properly.

5.2.4 Evaluation of Remedial Control Measures

Plant B suffers from a combination of several different types of problems. However, the most apparent and influential problem appears to be associated with the low mixed liquor DO concentration. If long-term control of filamentous bulking is to be achieved, the existing aeration system will inevitably have to be replaced by new mechanical aerators or by a new diffused air system. Long-term control by means of equipment modifications will be discussed in greater detail in subsequent sections of this chapter. Strategies which exclude the use of major equipment modifications are also viable solutions and should be addressed before major modifications are instituted.

Commonly, it takes a higher mixed liquor DO concentration to cure low DO bulking than it does to prevent it from happening in the first place (Richard, 1989). For this reason, many operators rely on short-term options to increase DO concentrations to a level which will temporarily suppress this type of bulking. There are several short-term options available to circumvent low DO bulking. Raising the MLSS concentration (decreasing F:M) is a method which is commonly used. Accordingly, a decrease in F:M will increase the SRT; as a consequence, the microbial growth rate will decrease and the instantaneous DO required will decrease as a result. However, since this plant operates on the lower F:M range already, it is likely that raising the MLSS concentration will result in compounding the bulking problem.

Raising the weir elevation is also commonly used to increase oxygen concentrations in the mixed liquor. This will result in an increase in aerator submergence and a potential for increase in oxygen transfer. However, weir elevations at Plant B can not be altered, and even if this were possible, it is unlikely that this method would increase DO concentrations substantially because the aerators are simply not capable of transferring more oxygen due to their size restriction.

Currently, the plant relies on chlorination of the return sludge to rectify bulking episodes. However, this short-term resolution is not always effective in suppressing filamentous growth. A more logical solution would be to use hydrogen peroxide as a non-selective control measure. It has been claimed that not only does hydrogen peroxide destroy filamentous bacteria, but it also produces oxygen as a by-product. Consequently, this oxygen becomes available for supplementation to the low DO concentration present. However, it is possible that the sludge may develop the ability to rapidly degrade the peroxide, resulting in a decrease in its availability for filamentous destruction.

The potential of using hydrogen peroxide instead of chlorination was evaluated through the use of jar tests. A series of two tests were run to determine the effects of hydrogen peroxide on the settling characteristics of the sludge and on the dissolved oxygen concentration in the mixed liquor (See Section 3.5 for methodology). The results of these tests are shown in Figures 20 through 23. Dissolved oxygen

Figure 20. Blanket Depth vs. Time For Varying Peroxide Dose.

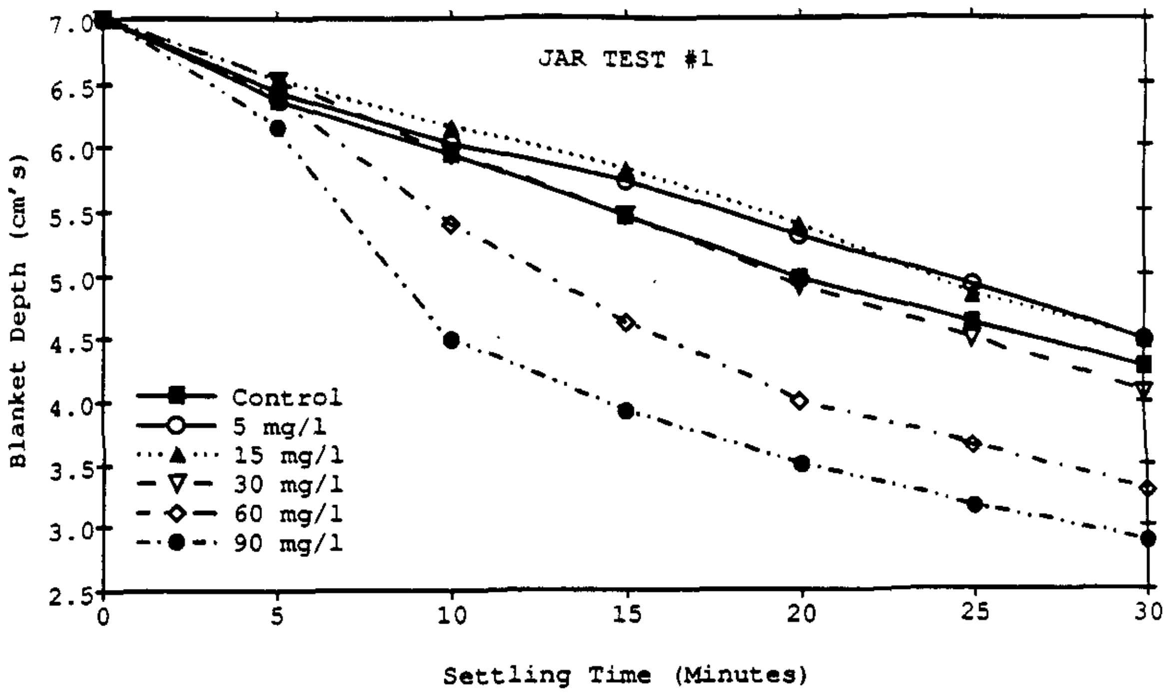


Figure 21. Blanket Depth vs. Time For Varying Peroxide Dose.

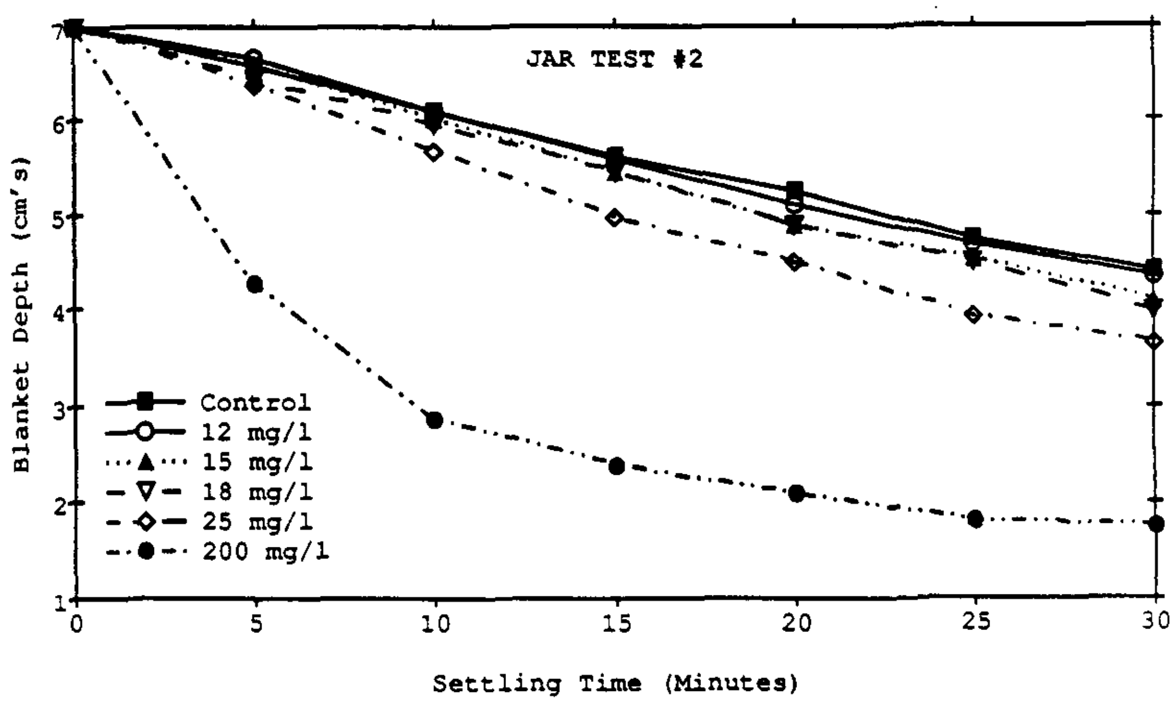


Figure 22. DO Concentration as a Function of Peroxide Dose.

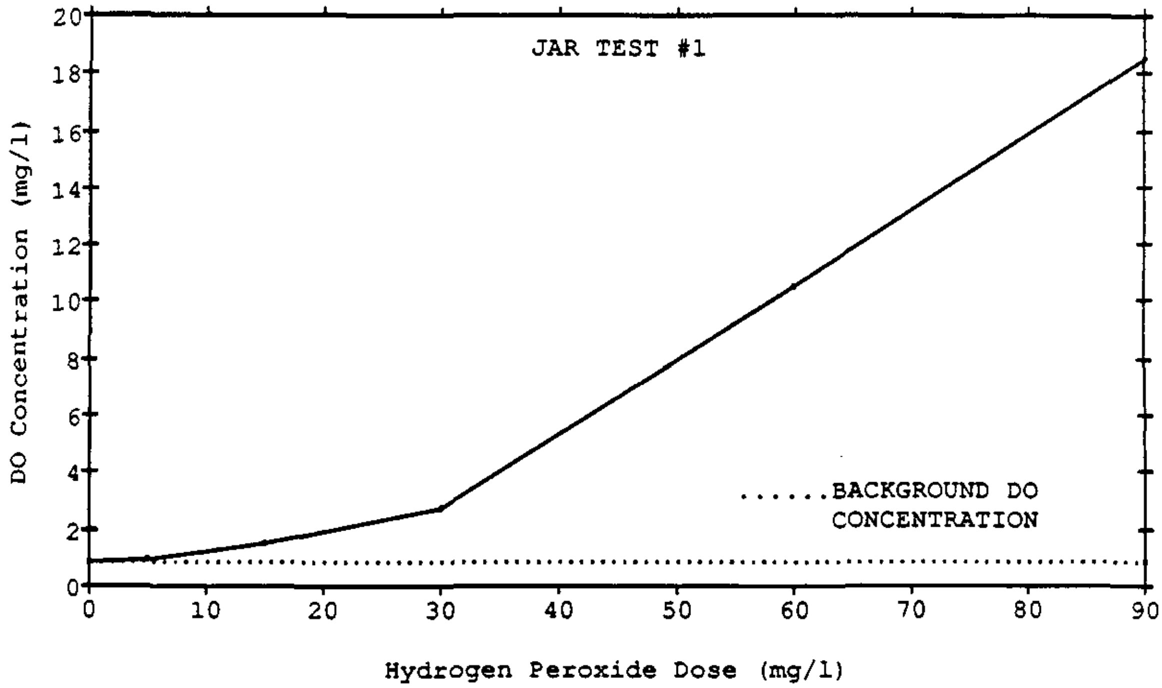
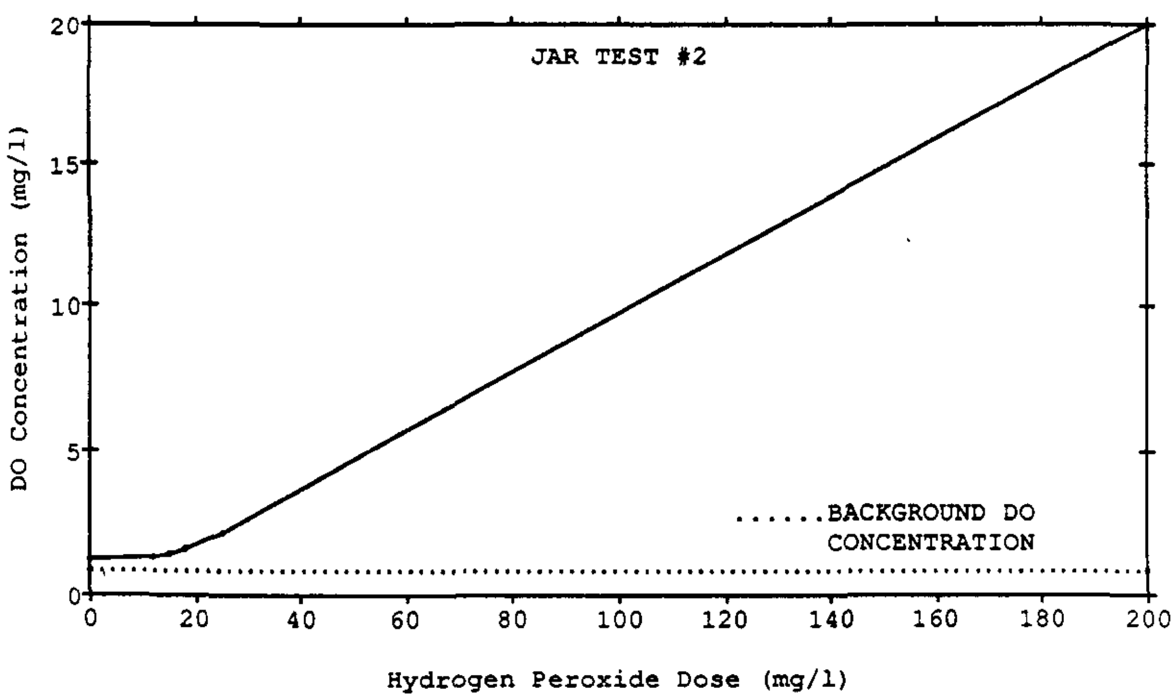


Figure 23. DO Concentration as a Function of Peroxide Dose.



concentrations and the accompanying supernatant descriptions are also provided in Table 15. The determination of the optimal dose was based on settling enhancement, DO increase, supernatant quality, and microscopic examination. Based on the results of these experiments, the optimal dose was found to be 18 mg/l (5.5 lb H_2O_2 per 1000 lb of MLVSS). The DO concentration for the 18 mg/l dose increased by 33% in jar test #2 above background DO levels (See Figure 23). The DO concentrations for the 15 mg/l dose increased by 88% and 21% in jar tests #1 and #2, respectively (See Figures 22 and 23). For illustration, one of the samples was overdosed (200 mg/l) to display the effects of hydrogen peroxide on filamentous bacteria. The results of the overdosing are shown in Figures 24 and 25. Microscopic observation reveals that many filaments appear to have been severed or broken. The action of H_2O_2 on filamentous bacteria has been reported to be one of attacking the sheath or cell wall of the organism (Caropreso *et al.*, 1973; Jenkins *et al.*, 1986). The broken appearance of the bacteria are a result of cell lysis from the H_2O_2.

Table 15. Hydrogen Peroxide Results -- DO Concentrations and Supernatant Descriptions.

H_2O_2 Dose (mg/l)	DO Conc. (mg/l)	Supernatant Description
Jar Test #1		
Control	0.80	Clear
5	0.95	Clear
15	1.5	Clear
30	2.7	Slightly cloudy, some broken flocs.
60	10.5	Cloudy, several broken flocs, some blanket rising evident.
90	18.5	Very cloudy, excessive broken flocs, viscous blanket at surface.
Jar Test #2		
Control	1.2	Clear
12	1.3	Clear
15	1.45	Clear with very few broken flocs.
18	1.60	Clear with very few broken flocs.
25	2.20	Slightly cloudy, some broken flocs.
200	20+	Very cloudy, floc destruction, and viscous blanket covering entire surface.

Figure 24. Hydrogen Peroxide Jar Test Results.
a.) From left: 0 mg/l, 12 mg/l, and 15 mg/l.
b.) From left: 18 mg/l, 25 mg/l, and 200 mg/l.

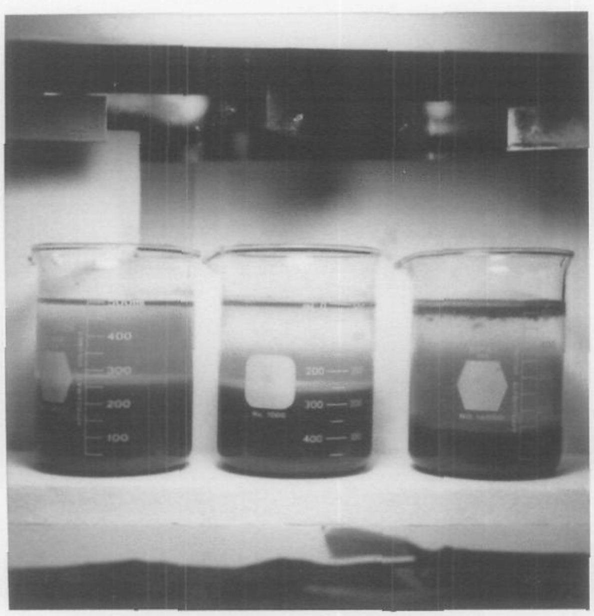
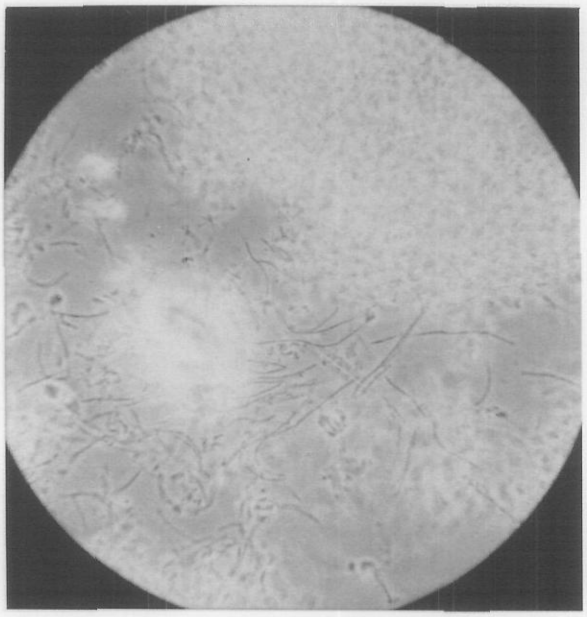
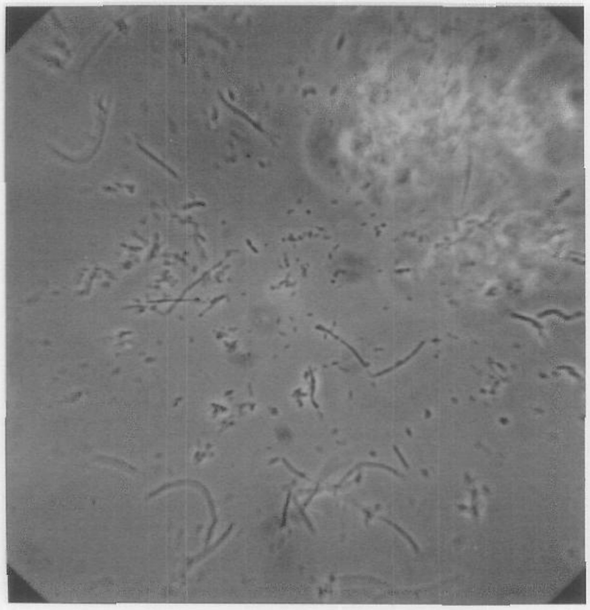


Figure 25. Microscopic Filament Observation at Plant B.

a.) 0 mg/l H_2O_2.

b.) 200 mg/l H_2O_2.





The relative costs of using sodium hypochlorite versus hydrogen peroxide were evaluated. The current dose of sodium hypochlorite (as Cl_2) added per day at the plant is 7.5 lbs. The projected cost per day for hydrogen peroxide was based on the optimal dose of 18 mg/l, also to be added on a continual basis. Given that the MLVSS concentration on the day of the jar test was 3278 mg/l and that the dose of H_2O_2 capable of suppressing filamentous growth was 18 mg/l, a mass to mass ratio of 5.5 lb H_2O_2/1000 lbs MLVSS was established. This ratio was used to determine the required mass dose per day of H_2O_2 for an average MLVSS concentration. The results of this analysis are shown in Table 16. Based on these results, it would cost approximately 1.7 times more to use sodium hypochlorite than it would if hydrogen peroxide were to be used.

Generally, it has been shown that hydrogen peroxide will require higher doses and longer contact times than chlorine (Jenkins *et al.*, 1986). However, the relative cost of hydrogen peroxide compared to the existing sodium hypochlorite addition is far cheaper. Furthermore, it has also been shown that hydrogen peroxide can alleviate bulking episodes more quickly than chlorine, making the overall hydrogen peroxide requirement even less than what it appears. Given the low DO conditions and its ramifications, the use of hydrogen peroxide is certainly a viable solution to the persistent bulking problems at Plant B.

Table 16. Comparison of H_2O_2 Costs versus Existing Chlorination Costs.

Compound Used For Control	Dose (lbs/day)	Cost/lb (Dollars)	Cost/Day (Dollars)
Existing Control Measure			
NaOCl	7.5[a]	5.35[b]	40.15
Proposed Control Measure			
H_2O_2(52%)	42.0[c]	0.57	24.10

a - Daily dose of available Cl_2 based on current application.
b - As available Cl_2.
c - Daily dose based on required lbs H_2O_2/1000 lbs MLVSS from optimal dose of 18 mg/l; MLVSS concentration based on average daily concentration.

5.2.5 Recommendation of Remedial Action

The main concern for plant B is to bring the filamentous bulking problem under control as soon as possible. It is recommended to accomplish this in two distinct phases. The first phase would involve the use of non-specific, rapid control measures to temporarily suppress filamentous growth. The second phase would involve specific control measures such as increasing mixed liquor DO which could be investigated as phase I control is implemented.

Based on the results of the jar tests and on existing literature, it is recommended that the plant begin to use hydrogen peroxide as a filament suppressant.

The existing system could be used to supply the peroxide in the same manner in which the hypochlorite is currently being added. If the current system is not amenable to H_2O_2 addition, a permanent system such as the one shown in Figure 26 could be constructed at a minimal cost to the plant. Economically, the addition of 50% hydrogen peroxide will be far cheaper than the current sodium hypochlorite addition. However, if for some reason the results of such experimentation prove to be unsuccessful, the current method of chlorination could be reinstated without much problem.

As was discussed earlier, sludge wasting during wet weather is a problem at the plant because of the inability of the outdoor drying beds to accept digested sludge. A short-term solution to this problem would be to temporarily store the digested sludge in a place other than the digester. This would result in a decrease in SRT and a subsequent increase in F:M. A temporary building could be constructed to store the sludge, from which it would be applied to the drying beds as weather permits. However, precautionary measures capable of reducing the risk of explosion from methane fermentation should be addressed if this method is used. A temporary building would be relatively inexpensive and would definitely help rectify settleability problems caused by the extended SRT's.

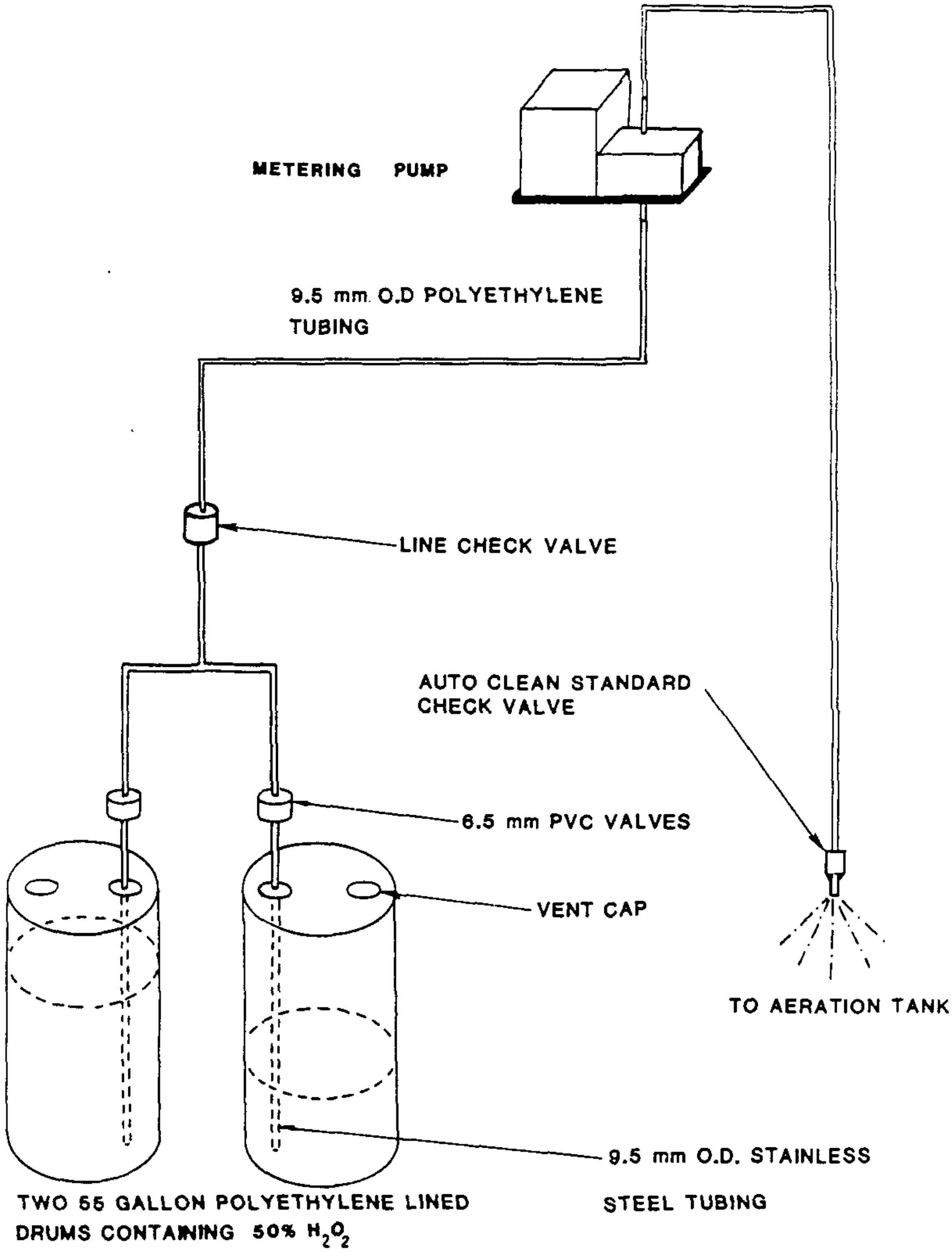


Figure 26. Recommended feed system for dosing hydrogen peroxide (Anon, FMC Corp., 1976).

The phase II investigation would involve a retrofit of the current aeration system. There are several reasons why the current aeration system should be replaced. These include poor oxygen transfer capability, inadequate mixing, inability to adjust the speed of the aerators, and the inability to terminate the intermittent aeration pattern. Two new systems were evaluated to determine their applicability to the condition at plant B. The capital cost of a replacement mechanical system was evaluated and was found to be approximately $7000. The capital cost of a new fine-bubble, diffused system was designed and estimated to be approximately $18,000. The operation and maintenance costs (O & M) of each system were also evaluated. Using estimated power curves for each system provided in an EPA costing manual (1980), it was possible to determine the power required for each system. Based on current electricity costs of $0.07/kWh and on labor and material estimates in the manual, the total annual O & M costs for the mechanical and diffused systems were estimated to be $9540 and $8820, respectively. Assuming an annual interest rate of 8% and a period of analysis of 10 years, an equivalent annual payment for both the mechanical and diffused systems were calculated to be $10,585 and $11,500 per year, respectively. The characteristics of both of these systems were compiled and are presented in Table 17.

Major modifications such as replacing the existing aeration system should generally be avoided if possible in an effort to minimize costs. However, it is obvious that this particular plant has major oxygen transfer deficiencies which

Table 17. Summary of Potential Aeration Changes at Plant B.

Diffused Aeration System (For one basin only)	
Type	Ceramic Disc, grid configuration
No. Discs	196 (7.0" Diam.), 14 rows of 14
Airflow/Disc	1.53 SCFM
Area Covered/Disc	4.6 ft^2
Blower size/type	Two 300 SCFM/15 hp, cast housing
O_2 Transfer Rqd. : O_2 supplied	346 lb/day : 375 lb/day
Est. Capital Cost[a]	$18,000
Est. O & M Cost[b]	$8820/yr
Equiv. Annual Payment[c]	$11,500/yr
Mechanical Aeration (For one basin only)	
Size/Type	10 hp floating unit w/ draft tube
Oxygen Transfer Rating	3 lb O_2/lb BOD_5 (clean water)
Approx. Capital Cost[d] (Incl. Installation)	$7,000
Est. O & M Cost[b]	$9,540/yr
Equiv. Annual Payment[c]	$10,585/yr

a - Capital cost estimate courtesy of D. Leidel, Aercor, Inc.
b - O & M cost estimated using EPA cost curves, EPA (1980).
c - Equivalent Annual Payment assumes 8% interest rate and 10 year analysis period.
d - Capital cost estimate courtesy of S. Schupbach, Aqua-Aerobic Systems, Inc.

exacerbate its chronic settling problems. Because the DO concentration is so low, it is possible that a replacement system will be the only alternative if target DO levels are to be achieved and if the bulking problems are to subside. The implementation of such a system, if effective, could pay for itself in a matter of a few years.

In summary, it would be wise for the plant to experiment with hydrogen peroxide. The relative costs between H_2O_2 and NaOCl will be more apparent once these experiments are completed. The benefits of installing new aeration equipment will also be more apparent once the effectiveness of H_2O_2 is determined. Should it be ineffective, the plant should strongly consider the installation of new aeration equipment. Specifically, the floating mechanical system is relatively inexpensive and its implementation would be rather simple. The installation of new aeration equipment certainly has the potential to pay for itself in a matter of years. However, on a yearly basis, the use of chemicals are the most cost-effective solution for this particular plant. Table 18 is a summary of the remedial options for bulking control at plant B.

Table 18. Summary of Bulking Control Options at Plant B.

Control Measure	Cost/yr ($)	Advantages	Disadvantages
RAS Chlorination (NaOCl)	6025[a]	1. Automated 2. On-site Availability	1. Expensive 2. Treats symptoms 3. Does not address O_2 deficiency
H_2O_2 (50%)	3615[a]	1. Inexpensive 2. Automated 3. O_2 Supplementation	1. Treats symptoms
<u>Aeration Equipment</u>			
Mechanical Aeration	10,585	1. Treats cause, cures bulking 2. Easy to retrofit	1. Fairly expensive
Diffused Aeration	11,500	1. Efficient 2. Treats cause	1. Requires detailed installation

a - Based on use during summer months only (approx. 150 days).

5.3 Plant C

5.3.1 Background

Plant C treats an average daily flow of 18,925 m^3/day (5.0 MGD), which constitutes approximately 70% of its average daily design flow of 26,875 m^3/day (7.1 MGD). However, it is important to note that the plant treats wastewater from a local state university and the flow tends to vary significantly depending the flux of the students and the time of year. Within the past year and a half, the flow has been as high as 49,210 m^3/day (13 MGD) and as low as 9,465 m^3/day (2.5 MGD). The plant operates in the complete-mix mode with mechanical aeration and with the option to operate in the step feed mode. Approximately 95% of the flow is domestic wastewater and the plant accepts less than 1% of its flow as septage.

Plant C has had a long history of bulking problems, most of which have been controlled without much problem because of the plant's excess capacity. The plant has operated successfully at SVI's at or exceeding 150 ml/g on a regular basis. SVI's in the range of 150-250 ml/g are considered to be normal. The majority of upsets at the facility are related to foam and scum formation, occasionally resulting in solids loss to the effluent. The plant has also had problems associated with seasonal temperature changes and influent surges directly related with the periodic influx of students at the university. However, during the period of this study, the plant did not violate its NPDES permit.

5.3.2 Filament Identification

A sludge sample was analyzed microscopically, at which time *Nocardia sp.*, Type 0041, and *Micothrix parvicella* were found to be dominant (Plante, 1990). The abundance of these filaments was recorded as being "very common" and diffuse floc structure was also evident at this time.

From Table 2, the predominance of *Nocardia sp.*, Type 0041, and *M. parvicella* are indicative of a low F:M condition. The presence of *M. parvicella* and *Nocardia sp.* are also believed to be the organisms responsible for causing the foaming conditions observed regularly at the plant.

5.3.3 Data Analysis and Interpretation

Figure 27 shows the extreme variations in flow received by the plant. Maximum flows are normally observed upon the return of the students from summer, winter, and spring vacations. Inspection of Figures 27 and 28 yields the observation that increased SVI's are encountered during peaks of average daily flow. Also evident from Figure 28 is the plant's tendency to operate at SVI's normally greater the 200 ml/g.

Operation of the plant at MLSS concentrations exceeding typical operating ranges of 1500 - 3000 mg/l (Metcalf & Eddy, 1979) prior to day 250 correlate well with the resultant decreases in F:M (See Figures 29 and 30). The plant also seems to

Figure 27. Plant C: Influent Flow vs. Time.

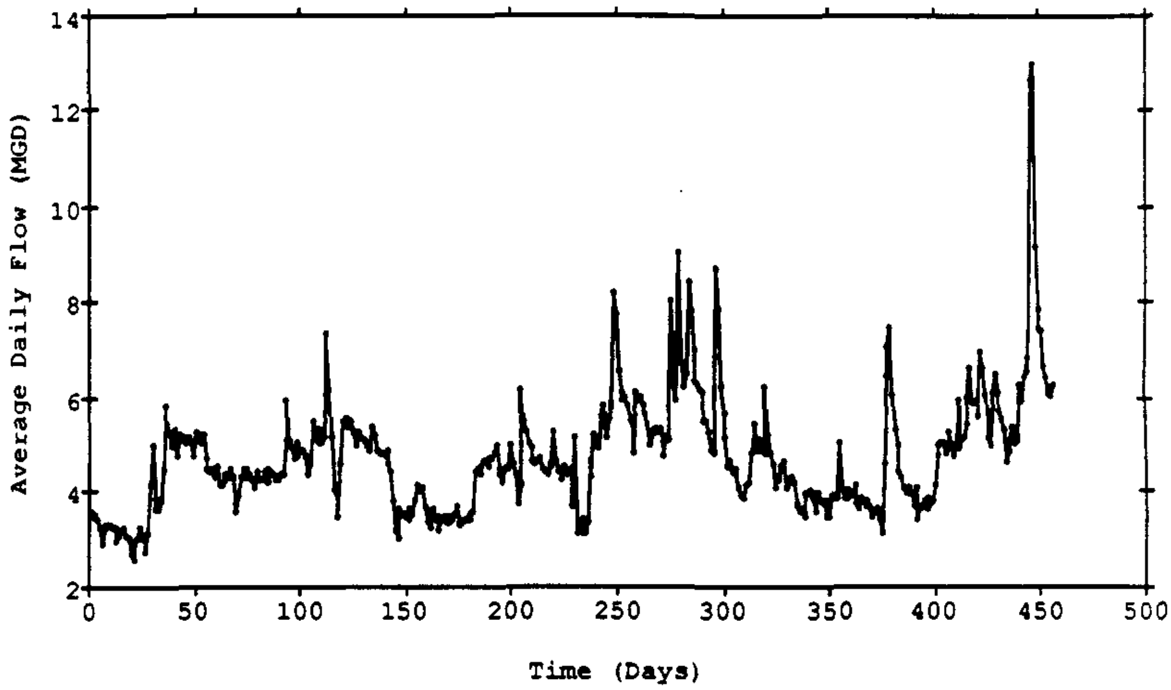


Figure 28. Plant C: SVI vs. Time.

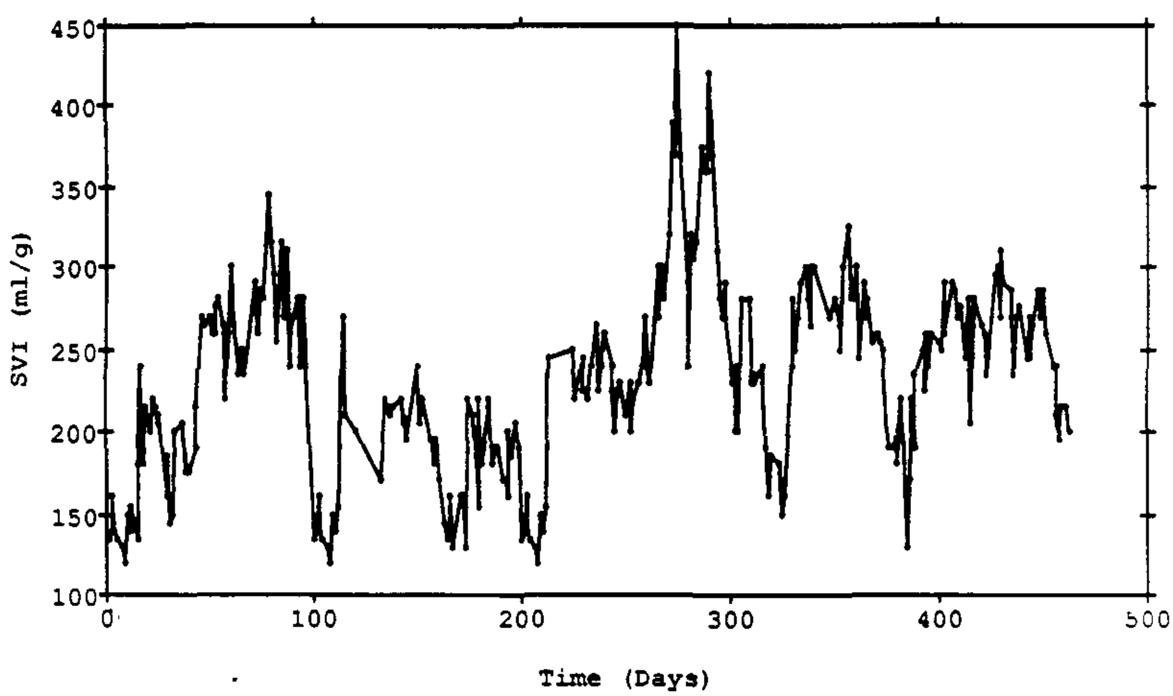


Figure 29. Plant C: MLSS Concentration vs. Time.

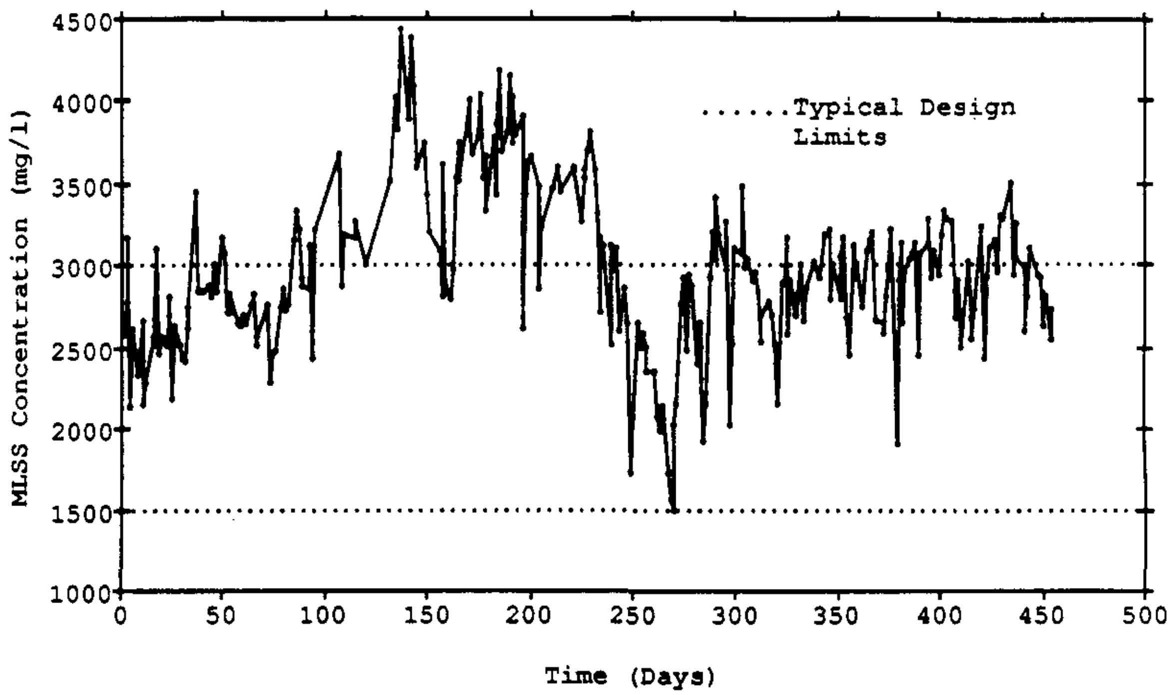
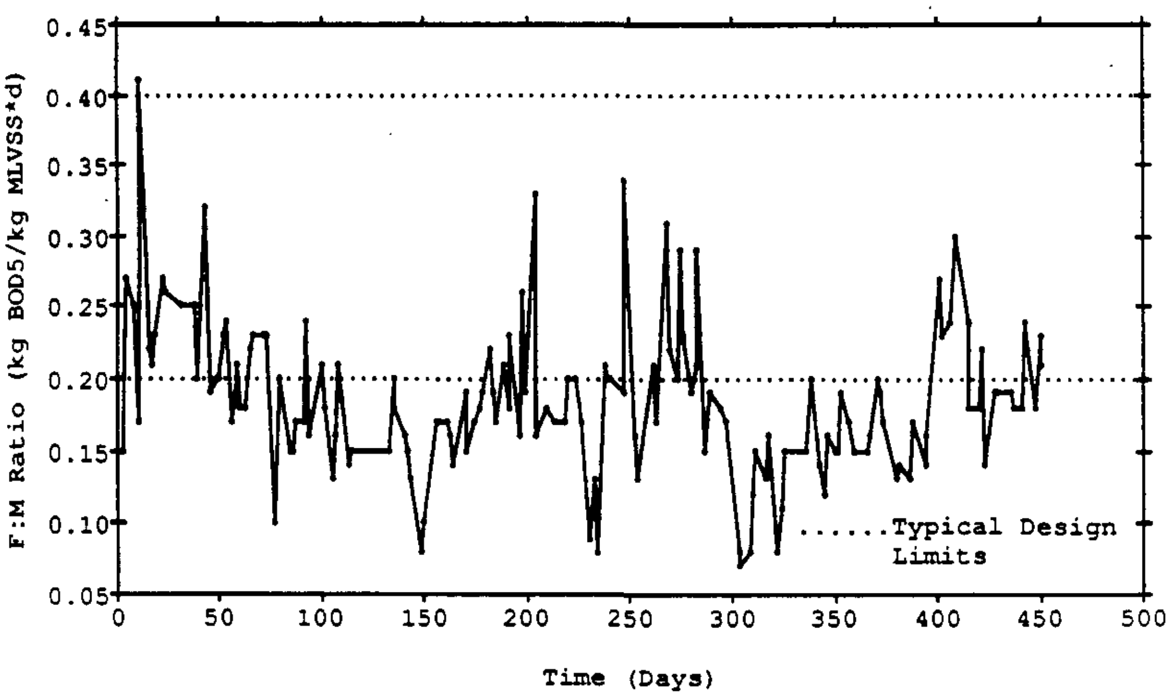


Figure 30. Plant C: F:M Ratio vs. Time.



operate at low values of F:M when compared to typical design ranges (See Figure 30). Based on this data and the results of the microscopic examination, the plant was confirmed as suffering from a low F:M condition.

5.3.4 Evaluation of Existing Remedial Control Measures

The main control strategy used by the plant to control filamentous bulking is to decrease the MLSS concentration which results in an increase in F:M. The plant has had success in controlling SVI with this particular practice as shown by Figures 28 and 29. The resultant increase in F:M is also shown in Figure 30. However, since a reduction in MLSS concentration leads to a decrease in SRT, more sludge must be wasted form the system. Sludge dewatering at the facility is accomplished by a dissolved air flotation unit (DAF) followed by vacuum filtration. The increase in sludge wastage has resulted in increased operation of this equipment. As a result, expenditures for chemicals, energy, and maintenance have increased substantially.

In addition to manipulating the MLSS concentration, the plant has the capability of chlorinating the return sludge. However, chlorination is rarely used to control filamentous bulking at the plant except during extreme filamentous conditions.

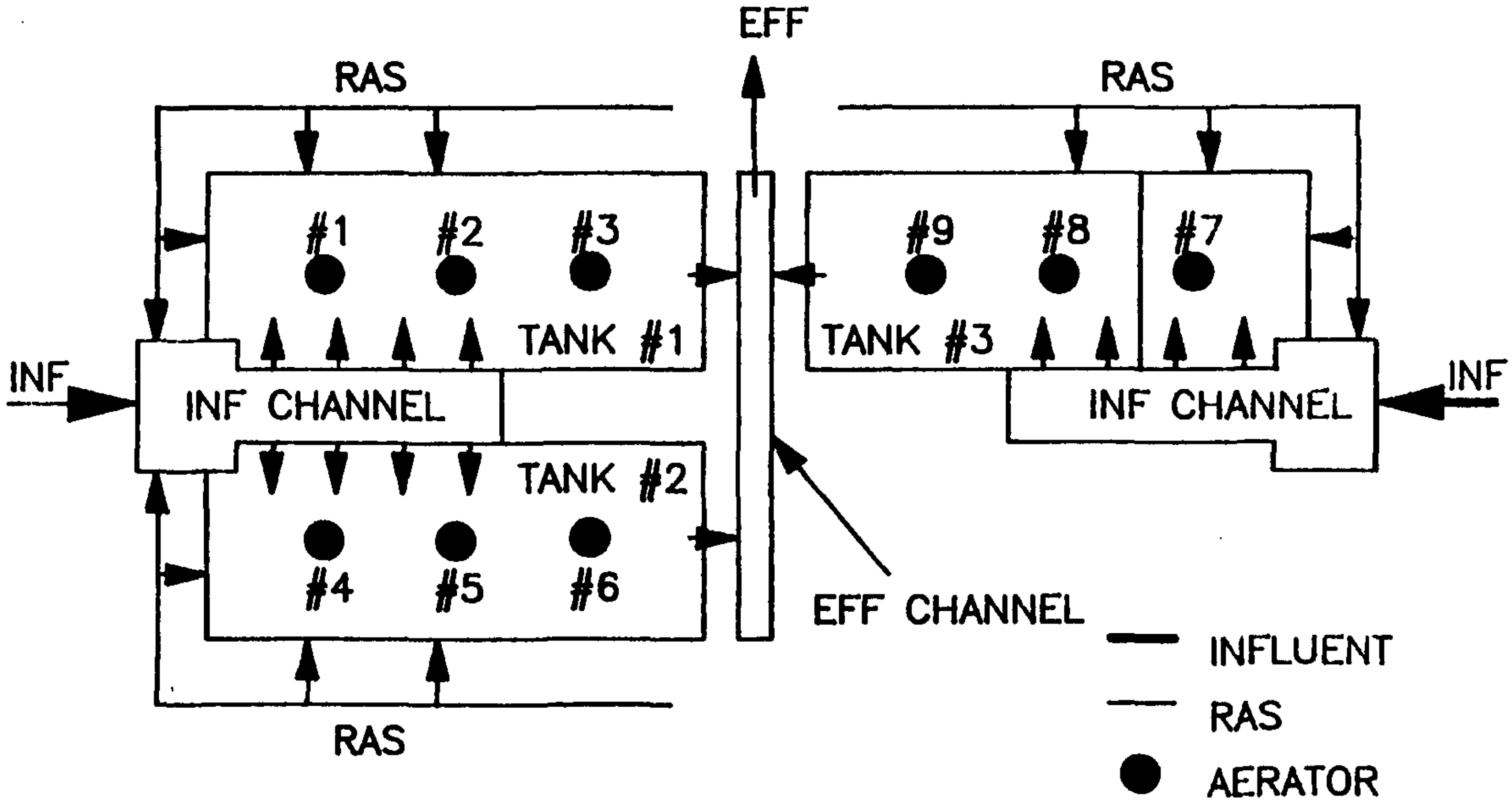
5.3.5 Evaluation of Alternative Remedial Control Measures

Excluding the use of reducing MLSS concentration, there is only one other general strategy used to control low F:M bulking. This strategy involves the introduction of plug flow characteristics to the aeration basins, or to otherwise increase the substrate gradient across the basins. Increasing the substrate gradient through the aeration basins would be a viable alternative to control bulking. However, operating the plant in a variety of modes other than the current configuration has not resulted in a significant enhancement in settling characteristics.

Another method used to increase the substrate gradient is to use a selector system as previously discussed. Design of selection systems for new treatment plants would be configured such that the selectors were considered as separate basins. However, retrofit designs normally do not incorporate separate selector basins unless adequate area and flexibility in pipe rerouting are available, and also with the provision that the magnitude of the problem mandates their incorporation (excluding the consideration of cost). Retrofit designs will normally involve aeration basin modifications or some other alterations capable of providing RAS and influent mixture with adequate detention time.

The flexibility in operation of the aeration tanks in certainly one of the strong points of plant C. There are a variety of modes in which the plant may be operated. A detailed schematic of the aeration tanks is shown in Figure 31.

FIGURE 31. AERATION BASIN CONFIGURATION AT PLANT C.



There are a total of three aeration tanks; each tank has three mechanical aerators. Furthermore, each large tank is comprised of three smaller tanks which are not physically separated by concrete walls; however, the initial compartment in each has the capability being operated as a separate entity. In fact, the initial basin in tank number 3 is compartmentalized as shown in Figure 31.

As was discussed earlier, the variation in flow requires the plant to operate in a variety of modes. The volume of flow dictates the number of aeration tanks that are kept on line, as well as the number of aerators in operation. Table 19 is a summary of aeration tank operation based on the volume of flow received.

Table 19. Existing Aeration Operation at Plant C.

Time of Year	Flow (MGD)	Aeration tanks on line by #	Aerators on line by #
Summer	3.0 - 3.5	1	2,3
Fall	4.0 - 5.0	1,2	2,3,5,6
Spring (Average Flow)	5.0 - 6.0	1,2	1-6
Spring/Student Flux (High Flow)	>7.0	1,2,3	2,3,5-8

It was desired to investigate selection alternatives at the plant without resorting to major changes in operation or the implementation of major design modifications. Because the plant is non-nitrifying, the investigation of aerobic selection (aerated with DO present) is appropriate. The most obvious course of action would to be to operate tank #3 with the initial compartment functioning as a selector. However, based on the volume of the compartment (787 m^3 or 0.208 MG) and average flows (18,925 m^3/day or 5.0 MGD), the hydraulic residence time (HRT) would be slightly higher than desired. HRT's which have been found to be effective are in the range of 2 to 50 minutes (Chudoba *et al.*, 1973; Wheeler *et al.*, 1984; Daigger *et al.*, 1985; Patoczka and Eckenfelder, 1988; Salameh and Malina, 1989). Others recommend that 50 to 70% of available substrate be removed in about 10 minutes; best results were obtained with floc loadings between 50 and 150 mg chemical oxygen demand (COD) per gram of MLSS (Patoczka and Eckenfelder, 1988). Based on the literature and on the average influent BOD_5 of the plant, operating the initial chamber as a selector would more than likely be ineffective because of the low substrate concentration (high HRT). Further consideration was given to dividing the initial compartment into small chambers; however, factors such as the lack of tank drains and difficulties with aeration and mixing made this consideration physically impossible.

The influent channels of the aeration basins (see Figure 31) were also considered as selection mechanisms. There are two channels; the first channel has the flexibility to feed both tanks 1 and 2 while the second channel feeds only tank 3. Each channel is 80 feet in length, 4 feet wide, and 6 feet deep (wastewater depth). The initial mixing box is 4 feet by 6 feet; also 6 feet in depth. Total volume of both the channel and the mixing box is approximately 2064 cubic feet (15,440 gallons or 58 m^3). Each tank has four feed points, all of which are 1.5 feet wide by 1.0 foot deep sluice gates (See Figure 31). In order to maximize detention time in the channel, only the last sluice gate should be open. Based on the total volume of the channel and on a variety of flows, a series of HRT's were calculated and are compiled in Table 20. As a result, a wide range of flows could be maintained to bring the HRT within the desired range specified by the literature. However, because the fourth sluice gate would not be large enough to handle the requisite flows, a modification to the gate would have to be made. Either the existing sluice gate would have to be enlarged or another discharge mechanism capable of handling the flow would have to be installed.

Table 20. Influent Channel HRT Possibilities as a Function of Flow.

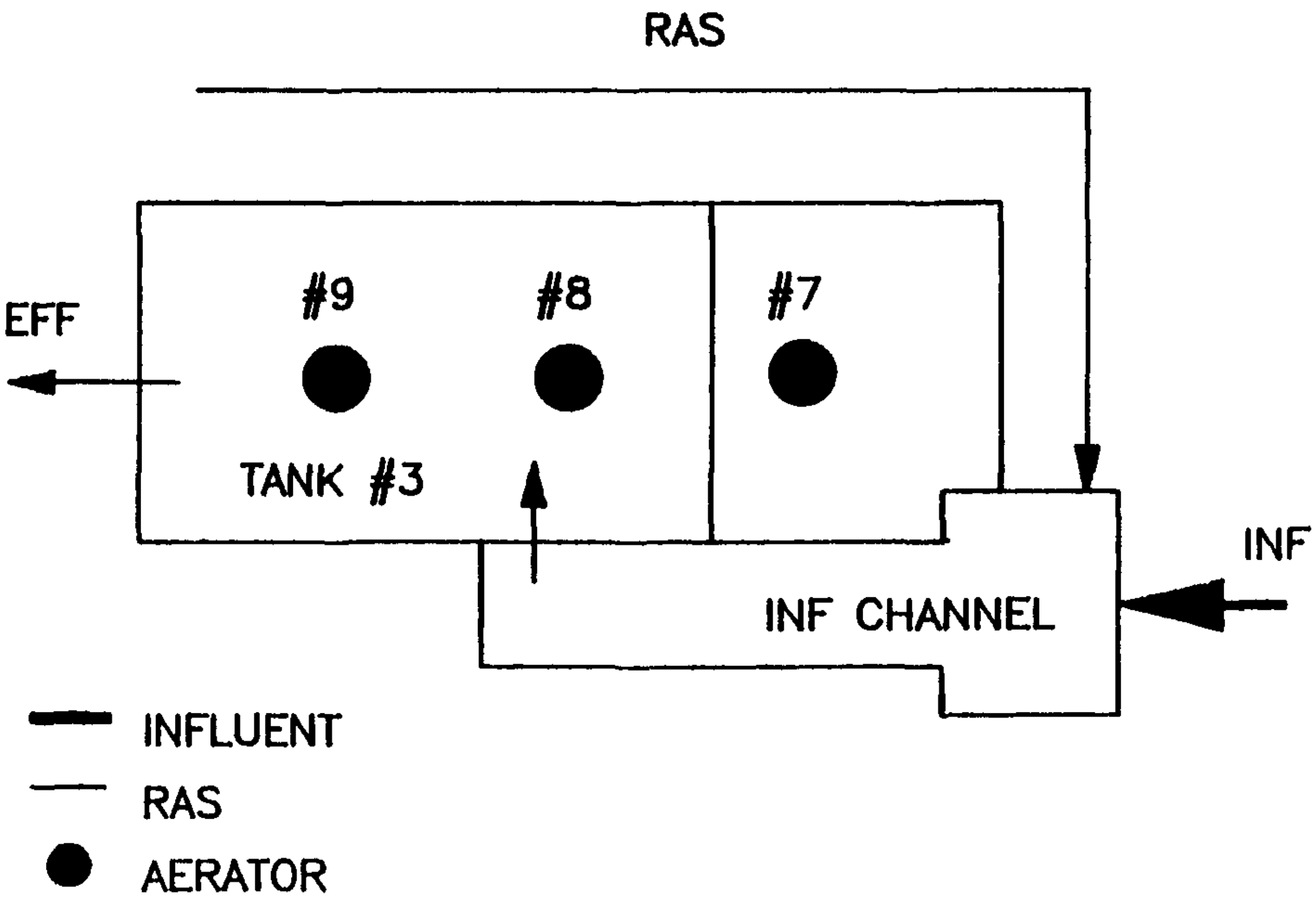
Flow (MGD)	HRT (minutes)
0.5	45
1.0	22
1.5	15
2.0	11
2.5	9
3.0	7.5
3.5	6.4

5.3.6 Recommendation of Remedial Action

As was stated earlier, the plant has had relatively good results in dealing with bulking problems by decreasing the MLSS concentration (increasing F:M). However, the increase in sludge wasting has resulted in an increase in chemical volumes, energy consumption, and maintenance requirements associated with the sludge dewatering process. Furthermore, the increase in the volume of dried sludge to be landfilled has not been taken lightly; local landfill space limitations have placed considerable pressure on the treatment plant to reduce sludge volumes. Increases in sludge volumes will certainly be even more undesirable in the near future due to these constraints.

It is recommended that the plant focus on strategies which involve the selector concept. Given the extreme flexibility of the plant, it seems only logical that a reduction in bulking episodes could be achieved with manipulation of the operational mode. The two selection alternatives are certainly viable solutions and should be implemented on an experimental basis. While the university is on recess, the system could be experimented with to determine the effectiveness of the two selection strategies. The plant could start by using the initial chamber of basin #3 as a selector. As was pointed out earlier, this may or may not be effective. If not, consideration should be given to the option of using the influent channel as a selector. In doing so, both the influent and RAS should be applied directly to the mixing box to insure for adequate detention time and a maximum substrate gradient (See Figure 32). A modification would have to made to the fourth sluice gate but this could be done rather easily in a number of ways. Once the channel is modified and placed on line, the system could be adjusted in such a way as to yield optimal conditions based on the required HRT. It should be pointed out that proper selection could take up to six sludge ages to achieve (Richard, 1989); this should be considered

FIGURE 32. PROPOSED FLOW CONFIGURATION OF TANK #3 AT PLANT C.



during the start-up period of this experimentation.

In terms of economics, the advantages and disadvantages of using the selection alternatives versus the current MLSS reduction strategy are extremely difficult to assess. However, it can generally be assumed that these selection alternatives will be more cost-effective than the MLSS reduction strategy although actual numbers are difficult to establish.

Bulking and foaming problems at the plant do not normally compromise treatment efficiency. The plant recognizes its settleability problems and has a competent staff capable of addressing these problems. However, it is recommended that the plant consider the selection alternatives as a means of reducing the cost associated with the current MLSS reduction strategy.

5.4 Plant D

5.4.1 Background

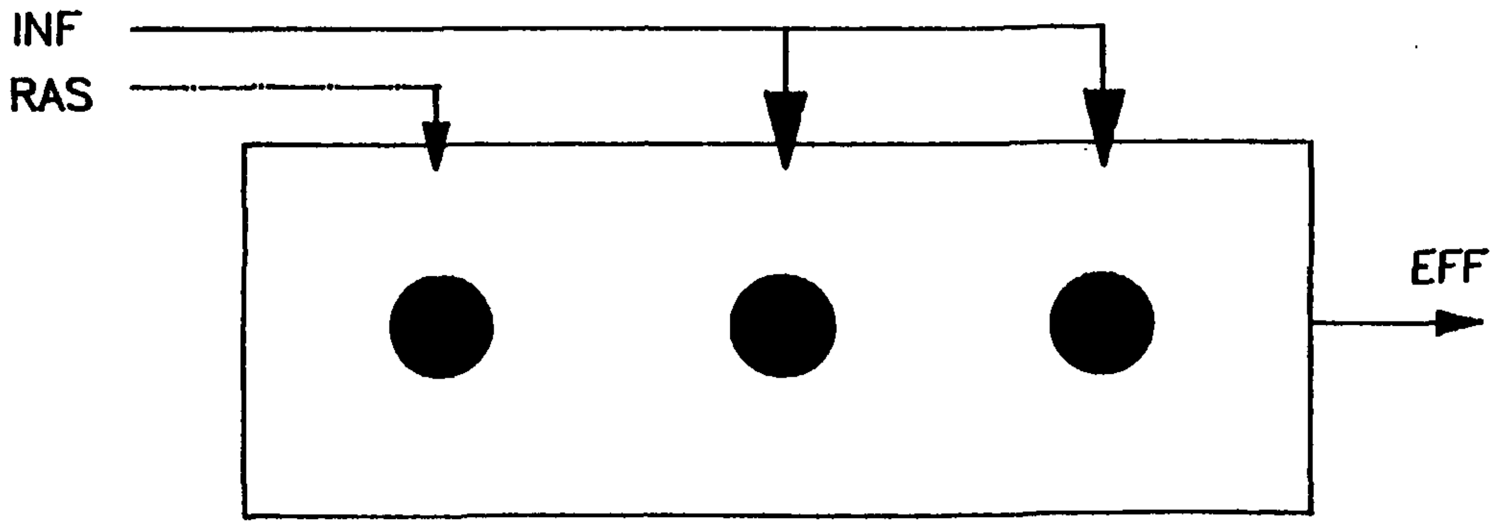
Plant D treats an average daily wastewater flow of 43,150 m^3/day (11.4 MGD), which is approximately 80% of its average daily design flow of 54,125 (14.3 MGD). Approximately 88% of the flow is domestic wastewater; the remainder is of industrial origin. A majority of the industrial flow (9%) is from a local paperboard manufacturer. The remaining 3% is from eleven circuit board manufacturers and also from a leather tannery. Average influent BOD_5 and TSS concentrations are both 220 mg/l. However, BOD_5 and TSS concentrations as high as 700 mg/l and 1800 mg/l, respectively, have been reported. The plant operates in the step feed mode with mechanical aeration (See Figure 33).

In the past, the plant has experienced foaming problems associated with the presence of *Nocardia sp.* During the time of this study, the SVI has increased steadily due to an increase in episodes of bulking and foaming.

5.4.2 Filament Identification

Mixed liquor samples were microscopically examined on two occasions for this particular plant. The first sample contained "excessive" numbers of *Micothrix parvicella,* Type 0041, and Type 1851 (Plante, 1990). *Nostocoida limicola II* and *Nocardia sp.* were also present but in lesser amounts. Type 0041 and *N. limicola II* are

FIGURE 33. TYPICAL FLOW CONFIGURATION AT PLANT C.



associated either with low F:M or nutrient deficient wastewater as shown in Table 2. *M. parvicella*, *Nocardia sp.*, and Type 1851 have been associated with low F:M conditions.

The second mixed liquor sample contained "abundant" quantities of *Nocardia sp.* and Types 0041 and 1851. Also present were *N. limicola II* and Type 0961 but in lesser amounts. Similarly, these filaments are indicative of both low F:M and nutrient deficient wastewaters.

5.4.3 Data Analysis and Interpretation

Operational data for plant D are shown in Figures 34 through 37. As was stated earlier, note the steady rise observed in SVI since the commencement of this study (See Figure 34).

As shown in Figure 37, the plant operates well below the typical F:M ranges of 0.2 to 0.4 kg BOD_5/kg MLVSS * d (Metcalf & Eddy, 1979). Also evident in Figures 36 and 37 is the success in increasing F:M by decreasing the MLSS concentration (after day 160). It should be noted, however, that this practice was not intentional; the reduction in MLSS concentration was a result of a ruptured seal in one of the secondary clarifiers which lead to a decrease in return sludge MLSS concentrations.

Based on the data available, the filament identification, and several discussions with plant operators, the plant was diagnosed as suffering from a low F:M

Figure 34. Plant D: SVI vs. Time.

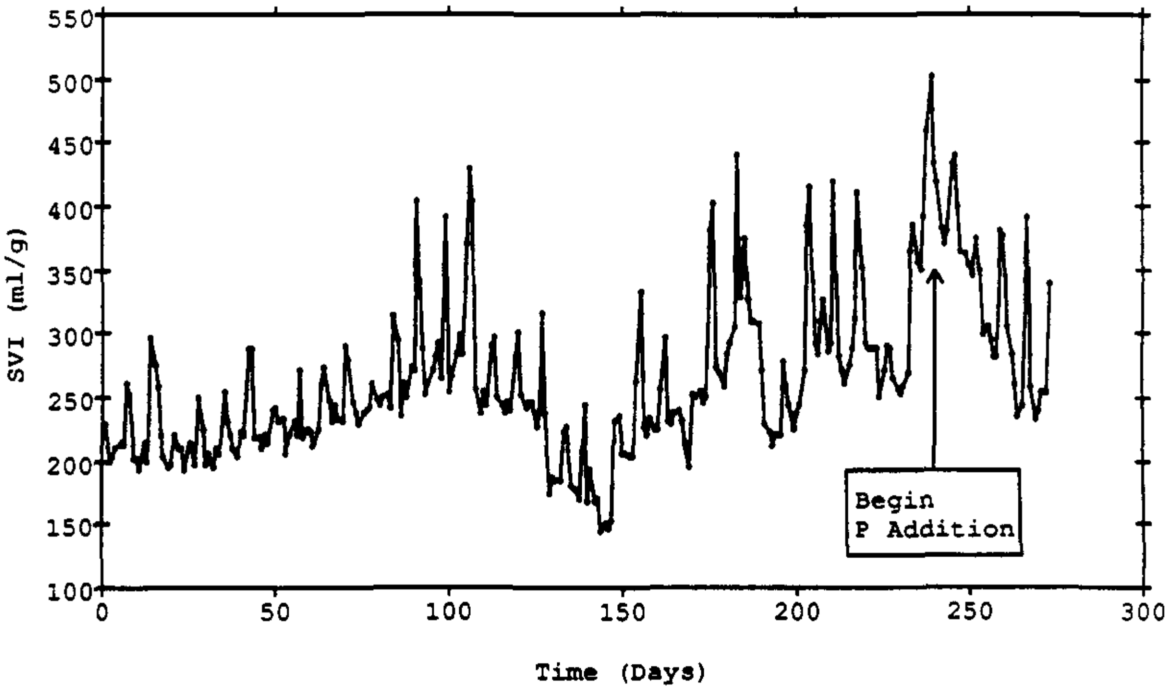


Figure 35. Plant D: RAS Chlorination vs. Time.

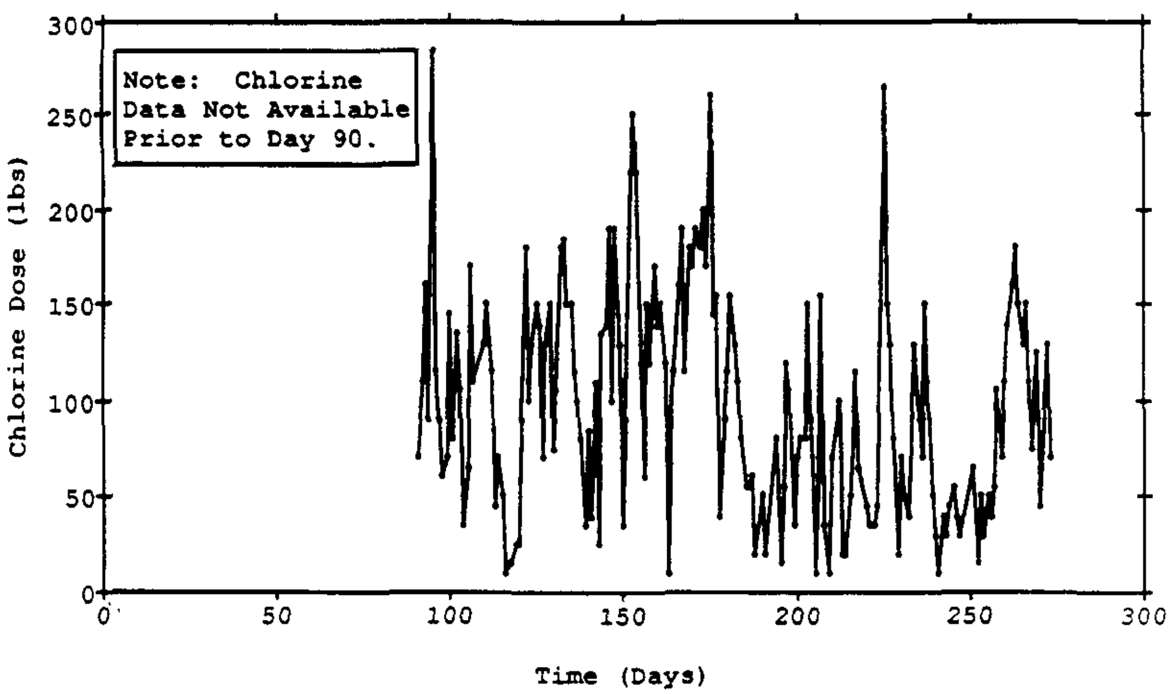


Figure 36. Plant D: MLSS Concentration vs. Time.

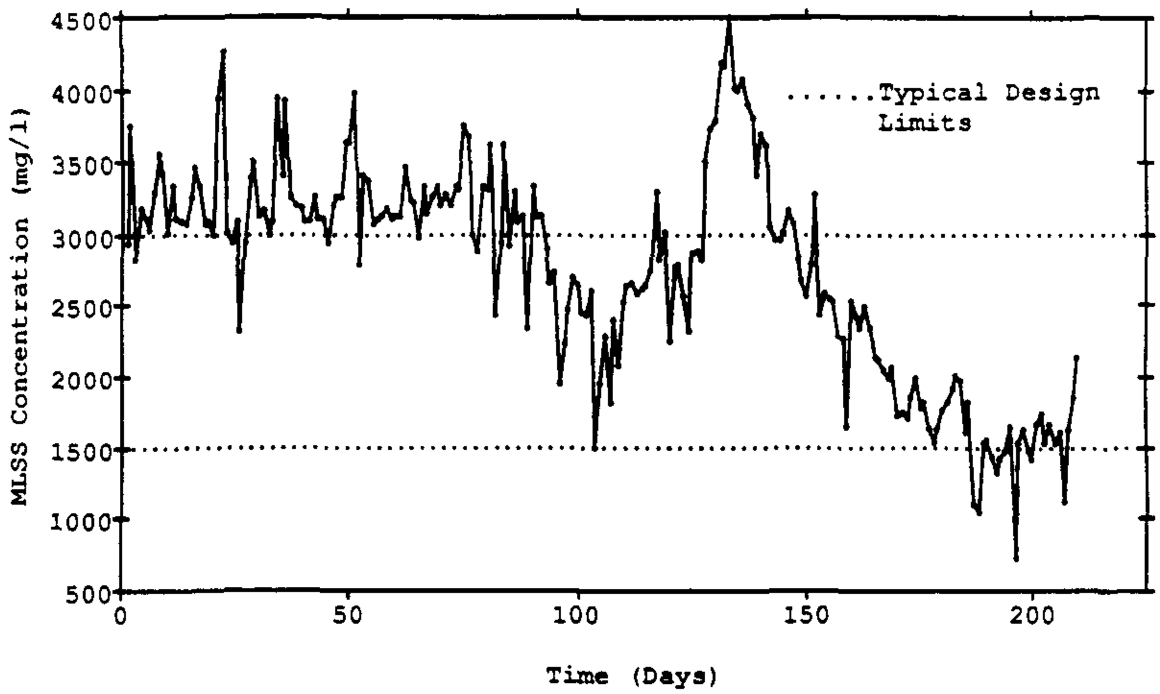
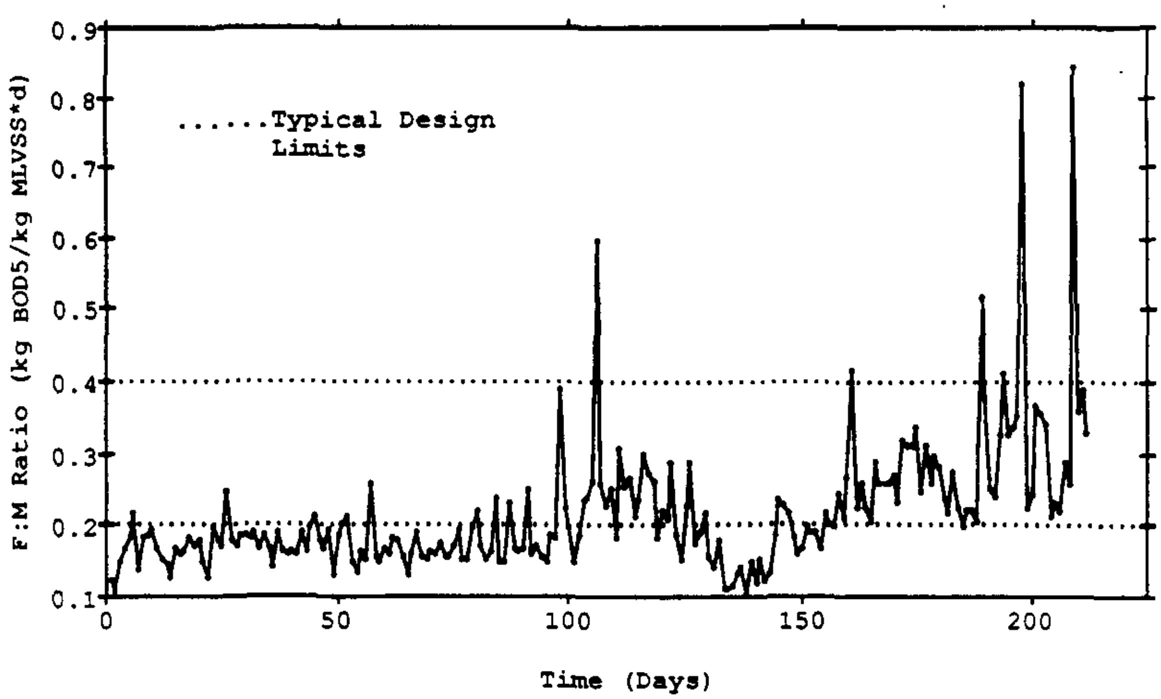


Figure 37. Plant D: F:M Ratio vs. Time.



condition. A secondary cause of bulking was determined to be a nutrient deficiency, a common problem associated with plants treating a mixture of domestic and papermill wastewaters. Further analysis by plant A personnel resulted in the determination that the limiting nutrient was phosphorus.

5.4.4 Evaluation of Existing Control Measures

Control of bulking episodes at the plant have been accomplished by chlorinating the return sludge (See Figure 35). However, chlorination of the RAS is limited in that destruction of floc-forming organisms is observed after about seven successive days of application. Prior to day 180, the plant chlorinated the return sludge with an average daily dose of 53 kg/day (116 lb/day). It was at about this time when plant personnel observed the destruction of floc-forming organisms. Subsequently, the operators reduced the daily dose to 29 kg/day (63 lb/day). As a consequence, the SVI has risen steadily since the reduction in RAS chlorination (See Figures 34 and 35).

In August of 1989 (day 240), the plant personnel decided to address the phosphorus deficiency by adding trisodium phosphate to the aeration basins. Approximately 45 kg/day (100 lb/day) were added directly to the basins for ten days. The addition of trisodium phosphate was terminated at this time due to high cost ($500/week), despite the noted reduction in SVI (See Figure 34). It would have been desired to continue the phosphorus addition for a longer period to determine its long-term effectiveness in controlling SVI. However, at this time, it is not known whether the observed reduction in SVI was a result of the phosphorus addition or of the increasing trends shown in the F:M ratio during that time (See Figure 37).

The detrimental effects of chlorination for periods longer than seven days make this alternative only moderately effective in controlling filamentous bulking. The use of trisodium phosphate could certainly be viable solution to bulking control, as well as several methods used to control low F:M bulking. Further consideration will now be given to these alternatives.

5.4.5 Evaluation of Remedial Control Alternatives

Because the plant suffers from a combination low F:M, phosphorus-limited condition, a host of control strategies are available. Obviously, the best alternative would be one that addresses both the low F:M and low nutrient conditions concurrently. However, it would be wise to first evaluate strategies to control each of the two deficiencies separately in an effort to assess the effectiveness of each particular method. Once this is done, an overlap of the best strategies may be more evident.

It would first seem logical to further evaluate the effectiveness of adding phosphorus. Unfortunately, the method used by the plant proved to be too costly. Therefore, it would be appropriate to investigate alternative measures which could be more cost-effective. As reported in section 5.1.6 of this report, monoammonium phosphate was determined to be the most economical source of phosphorus. The $500/week cost for the phosphorus addition could be substantially reduced if monoammonium phosphate were to be used. This would therefore allow for a longer observation period to be established to determine exactly how costly and effective its use would be. This could be accomplished on a trial basis for a short time (at least one month would be desirable), whereby the chemical could be added directly to the aeration basins. If at this time it proved to be successful, a permanent, continuous feed system could be installed at a capital cost of approximately $8600, in a similar manner to the system evaluated in section 5.1.6 of this report.

The next step in this evaluation is to consider the options associated with controlling low F:M bulking. Recall that there are basically three possibilities: a reduction in the MLSS concentration, an increase in the plug flow characteristics to the aeration basins, and the installation of a selector. Reducing the MLSS concentration to increase F:M has been practiced in the past (See Figures 36 and 37). However, the plant operators feel that the subsequent increase in load on the sludge dewatering equipment would be undesirable. Increasing the plug flow characteristics at the plant has also been practiced and deemed to be undesirable. Because the plant receives 12% of its flow from varied industrial sources, and increase in plug flow characteristics would result in increased susceptibility to toxic shock loads. The plant has the capability to operate in the plug flow mode and has done so in the past. However, this change did not have a significant effect in curing bulking problems while subsequently increasing the risk of damage from toxic shock loads. Apparently, the only alternative which has not been entertained has been the selector concept. Its applicability to this particular situation will now be addressed.

The selector concept has gained notoriety as a means of curing bulking problems stemming from low F:M conditions. It was desired to consider the selector as an option for controlling bulking at plant D. After some research, it was found that plants treating a mixture of domestic and paper wastes are often subjected to bulking episodes caused by both low F:M and low nutrients. A similar case study was reported by Jenkins *et al.* (1986). In this particular case, a selector was installed and a non-bulking condition was achieved. Not only was the initial F:M increased, but a higher initial nutrient loading was established as well. In this particular case, the selector system provided a cure for both limiting conditions. Because of the promise shown in the results of this study and from the results of others, it was desired to investigate the design of a selector for plant D.

Although there is a wealth of information available on the selector concept, there is a considerable lack of selector design information available. One of the most important design considerations is the hydraulic residence time in the reactor. If the residence time is too short, insufficient time may be available for microbial substrate uptake and storage. In addition, the condition known as "viscous bulking" may result. Viscous bulking is a condition where floc-forming organisms shunt carbonaceous substrate to exocellular polymers which decreases settleability and increases sludge dewatering costs (Richard, 1989). If the detention time is too long, insufficient substrate concentration may be available, thereby limiting the growth encouragement of floc-forming organisms while encouraging the growth of filamentous organisms. A wide range of detention times have been shown to be effective (Chudoba *et al.*, 1973; Wheeler *et al.*, 1984; Daigger *et al.*, 1985; Patoczka and Eckenfelder, 1988; Salameh and Malina, 1989). This range has been between 2 and 50 minutes with a majority of the residence times being around 15 minutes.

A separate selector basin was designed to handle one third of the average daily flow (there are three aeration basins at plant D). A residence time of 20 minutes was used for design. Due to a lack of available design literature, the selector was designed in the same manner as a post aeration system. It is important to note here that a series of pilot studies would be beneficial before the design and implementation of a separate selector basin is undertaken. However, for illustration and to estimate costs, this particular experimental design was used. Cost information was derived form "Innovative and Alternative Technology Assessment Manual" published by the EPA (1980). As was stated earlier, the selector was designed as a post aeration system based on an HRT of 20 minutes and an average daily flow of 14,385 m^3/day (3.8 MGD). Cost curves from the manual were used to estimate capital and O & M costs for the design and installation of one selector capable of serving flow to only one aeration basin. The costs were updated using an Engineering News-Record (ENR) index for March 1, 1990 of 4700. Using these resources, capital and annual O & M costs were estimated to be $810,125 and $26,000/yr, respectively. Assuming an 8% interest rate and a 25 year analysis period, equivalent annual payments of $101,830 would be required. Table 21 is a summary of these costs. In addition, a schematic of the proposed selector configuration is shown in Figure 38.

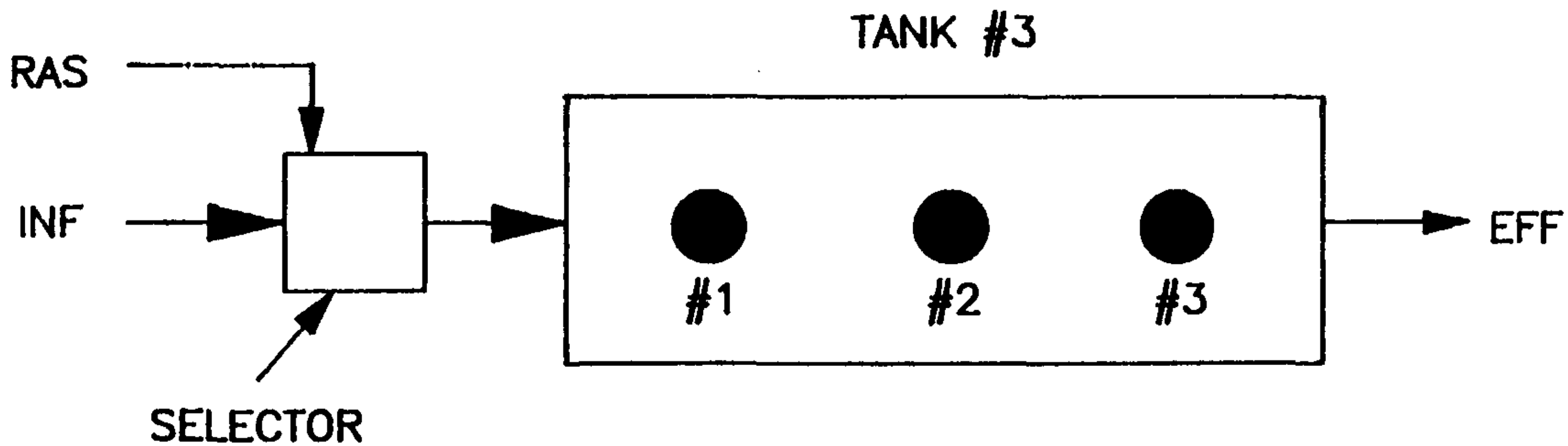
Table 21. Summary of Costs for the Installation of a Selector at Plant D.

Type of Cost	Cost (1990 Dollars)
Capital	
Construction	512,725
Piping (10%)	51,275
Electric (8%)	41,025
Instrumentation (5%)	25,640
Site Preparation (5%)	25,640
Engineering (15%)	76,910
Contingencies (15%)	76,910
Total Capital Cost	**810,125**
O & M	
Power[a]	10,500/yr
Labor	15,200/yr
Materials	285/yr
Total O & M Cost	**26,000/yr**
Equivalent Annual Payment[b]	**101,830/yr**

a - Based on power consumption of 150,000 kWh @ $0.07/kWh.

b - Based on interest rate of 8% and analysis period of 25 years.

FIGURE 38. PROPOSED SELECTOR SYSTEM AT PLANT D.



5.4.6 Recommendation of Remedial Action

From an operational perspective, the best alternative for plant D would be to install a selector. However, the yearly expenditures of over $100,000 would surely not be welcomed by the facility. Obviously, it would be advantageous for the plant to investigate the possibility of using phosphorus addition as an alternative. If the application of trisodium phosphate were to continue at the same rate as which it was applied for the ten-day period, it would cost the plant $26,000/year. However, it is likely that this cost could be substantially reduced if a dosing system were to be installed which could apply monoammonium phosphate continuously. Unfortunately, it would be difficult to determine the yearly cost for this system because only a limited amount of data is available to evaluate the phosphorus demand. This control method certainly warrants further attention and should be investigated as soon as possible.

It is recommended to begin adding phosphorus on a temporary basis in the form of monoammonium phosphate in order to determine its effectiveness in controlling bulking. The plant should allow for at least one month's time before characterizing its effectiveness. If the addition is effective, a continuous system such as the one provided in section 5.1.6 of this report could be installed. If not effective, the plant should seriously begin to consider the installation of a selector. Before doing so, it is also recommended that the plant begin pilot studies to determine the effectiveness of a selector system. The plant certainly has the staff and the facilities to conduct these studies. Furthermore, a temporary selector could be installed on a full-scale basis without disrupting current operation. An above ground basin, as well as temporary piping and aeration equipment, could be placed prior to one of the aeration basins. The system could be operated and evaluated as a separate entity.

In summary, this plant has had what is considered to be major bulking problems. In addition, the plant is operating close to capacity which results in a compromise in operational flexibility. Immediate attention should be given to the previously-mentioned actions before the problem becomes uncontrollable.

5.5 Summary of Case Studies

For illustration, the costs for each treatment alternative were analyzed based on the volume of wastewater treated. The results are shown in Table 22. Furthermore, the cost to implement the proposed alternatives at all four of these facilities is small relative to the total yearly operating costs. In light of these results and the results of the case studies, it is recommended that each facility consider these alternatives as long-term, economical solutions to bulking control.

Table 22. Costs for Treatment Based on Wastewater Volume.

Facility	Treatment/Modification	Cost/1000 m^3 ($)
Plant A	Phosphorus	1.66
Plant B	Hydrogen Peroxide	23.03
	Mechanical Aeration	67.44
	Diffused Aeration	73.27
Plant C	Selector Mode	Unknown
Plant D	Phosphorus	1.65
	Selector	19.41

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Filamentous bulking is the most commonly-encountered solids separation problem at activated sludge facilities. It is a problem that affects more than one half of all activated sludge facilities in the Commonwealth of Massachusetts, the country, and much of Europe. Practical control methods are first based on the fact that the solids separation problem is a result of filamentous organism predominance. If so, this is followed by the identification of the filaments responsible for the bulking problem. From the identification and through analysis of operational data, the condition(s) causing filamentous predominance can be determined. Once this has been established, the strategies available to control these conditions may be evaluated. A tiered approach can be instituted; economic feasibility, applicability to plant-specific characteristics, ease of implementation, and degree of effectiveness can all be used to evaluate each tiered approach.

Short-term strategies are often used to temporarily suppress filamentous growth whereas long-term methods are instituted to cure the causes of bulking, as opposed to treating the symptoms.

Several conclusions have been compiled as a result of this research. They are as follows:

(1) From the results of the survey, it is evident that bulking is a major problem in Massachusetts. A majority of the plants (60%) that responded to the survey indicated that they had experienced bulking-related problems in the past year.

(2) There is a wealth of information available on remedial control of filamentous bulking. Short-term solutions are the measures used by most plants and are generally considered to be the most cost-effective. Long-term solutions such as process modifications are generally very costly and are those which have not been widely implemented. Long-term solutions to bulking problems are preferred because they treat the causes of bulking and not the symptoms of bulking. However, technical and financial constraints often limit their implementation.

(3) Based on the survey, the identification of bulking problems is highly subjective and very plant-specific. There is no defined value of bulking in terms of SVI, although many researchers have placed the value in the range of 150-200 ml/g. Recently, many qualitative measures have been used to assess the magnitude of a bulking problem. Characteristics such as solids loss to the effluent are now playing increased roles in the evaluation of whether or not a bulking problem actually exists.

(4) Based on the results of the survey and on plant visits, The knowledge of treatment plant staff on filamentous bulking has been found to be a function of plant size. Generally, the larger the plant, the more was known about filamentous bulking. Manpower and financial considerations often play major roles in determining the knowledge and resources available for a plant to efficiently control its bulking problems.

(5) A need to spread the knowledge of filamentous bulking certainly exists. The publication of easy-to-read bulking manuals and the release of successful case studies are necessary if a better understanding of bulking is to be established.

(6) In terms of Massachusetts, the need for a centralized information resource on bulking control is very evident. Many bulking problems within the state have been ignored because technical expertise was not readily available to assist in curing these bulking problems.

(7) In terms of regulation, there is little incentive for plant personnel to control bulking problems since compliance with NPDES permit requirements has not been strictly enforced. More enforcement of these permits would mandate control of bulking episodes on a regular basis.

(8) The need for selector design criteria is certainly evident. Selection has proven to be effective in controlling low F:M bulking; a series of design

guidelines need to be established so that implementation of this control alternative will be more prominent.

As a result of this research, several recommendations for further research have also been compiled. They are as follows:

(1) A compilation of case studies which were effective in controlling bulking should be made available to treatment plant staff. It would be desirable to categorize these based on the type of bulking cured. Included in this information should be the costs associated with the implementation such that general economic ramifications can be estimated for plants considering the alternative.

(2) More research should be directed toward the design of selector systems. A series of design equations or guidelines could be compiled. Successful applications could also be gathered to display the effective measures used and also the costs associated with the design.

(3) An information center where plant personnel can obtain advice on filamentous bulking should be established and advertised. Filament identification should also be made available in an effort to reduce the costs of sending samples out-of-state.

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APPENDICES

APPENDIX A

A. List of Abbreviations

BOD_5 -- Five-day Biochemical Oxygen Demand

Ca -- Calcium

CAS -- Conventional Activated Sludge

Cl_2 -- Chlorine

COD -- Chemical Oxygen Demand

DAF -- Dissolved Air Flotation

DO -- Dissolved Oxygen

EA -- Extended Aeration

EPA -- Environmental Protection Agency

F:M -- Food to Microorganism ratio

H_2O_2 -- Hydrogen Peroxide

H_3PO_4 -- Phosphoric Acid

hp -- Horsepower

HRT -- Hydraulic Residence Time

K_s -- Saturation Constant

kWh -- Kilowatt Hours

μ_{max} -- Maximum Growth Rate

m^3 -- Cubic Meters

MG -- Million Gallons

MGD -- Million Gallons per Day

MLSS -- Mixed Liquor Suspended Solids

MLVSS -- Mixed Liquor Volatile Suspended Solids

List of Abbreviations (Cont.)

N -- Nitrogen

NaOCl -- Sodium Hypochlorite

NPDES -- National Pollutant Discharge Elimination System

O_2 -- Oxygen

O & M -- Operation and Maintenance

OAS -- Oxygen Activated Sludge

P -- Phosphorus

PFR -- Plug Flow Reactors

PO_4 -- Phosphate

RAS -- Return Activated Sludge

S -- Sulfur

SCFM -- Standard Cubic Feet per Minute

SRT -- Solids Retention Time/Mean Cell Residence Time

SVI -- Sludge Volume Index

TSS -- Total Suspended Solids

WPCF -- Water Pollution Control Federation

APPENDIX B

B. Determination of a Nutrient Addition to Correct a Nutrient Deficiency

EXAMPLE:

Given: Secondary influent BOD_5= 170 mg/l

Secondary influent TKN = 4.5 mg/l

Secondary influent P = 1.0 mg/l

Secondary influent Fe = 0.5 mg/l

Suggested ratio by weight, BOD_5/N = 100/5

Suggested ratio by weight, BOD_5/P = 100/1

Suggested ratio by weight, Bod_5/Fe = 100/0.5

Average daily plant flow = 7.5 MGD

Ammonia/nitrogen atomic weight ratio, NH_3/N = 17/14

Trisodium phosphate/phosphorus atomic weight ratio, Na_3PO_4/P = 164/31

Ferric chloride/iron atomic weight ratio, $FeCl_3/Fe$ = 162.5/56

Solution:

Step 1. Calculate the amount of nutrients needed to achieve the suggested ratios.

$$\text{Nutrient needed, mg/l} = \frac{\text{Secondary inf } BOD_5\text{, mg/l}}{\text{Suggested Ratio, } BOD_5\text{/nutrient}}$$

$$\text{N needed, mg/l} = \frac{BOD_5\text{, mg/l}}{\text{Ratio, BOD/N}} = 8.5 \text{ mg/l}$$

$$P\ needed,\ mg/l = \frac{BOD}{Ratio,\ BOD/P} = 1.7\ mg/l$$

$$Fe\ needed,\ mg/l = \frac{BOD}{Ratio,\ BOD/Fe} = 0.85\ mg/l$$

Step 2. Calculate the difference between the nutrients available and the nutrients needed. If the answer is 0 or negative, then no nutrient need be added.

Nutrient shortage, mg/l = (Nutrient needed) - (Nutrient Available)

N shortage, mg/l = 8.5 - 4.5 = 4.0 mg/l

P shortage, mg/l = 1.7 - 1.0 = 0.7 mg/l

Fe shortage, mg/l = 0.85 - 0.5 = 0.35 mg/l

Step 3. Calculate the weight of nutrients that need to be added.

Nutrient to add, lb/day = (Shortage, mg/l)(Q, MGD)(8.34 lb/Gall)

N to add, lb/day = (4)(7.5)(8.34) = 250 lb/day

P to add, lb/day = (0.7)(7.5)(8.34) = 43.8 lb/day

Fe to add, lb/day = (0.35)(7.5)(8.34) = 21.9 lb/day

Step 4. Calculate the weight of the commercial chemical to be added per day to supply the necessary nutrients.

$$Chemical,\ lb/Day = \frac{(Nutrient\ to\ add,\ lb/day)(Atomic\ weight\ ratio)(100\%)}{Concentration\ of\ chemical,\ \%}$$

For anhydrous ammonia, commercial grade solution, 80% concentration:

$$\text{Anhydrous Ammonia, lb/day} = \frac{(250)(1.2)(100)}{80} = 375 \text{ lb/day}$$

For trisodium phosphate, commercial grade solution, 75% concentration:

$$\text{Trisodium phosphate, lb/day} = \frac{(43.8)(5.3)(100)}{80} = 310 \text{ lb/day}$$

For ferric chloride, commercial grade solution, 39% concentration:

$$\text{Ferric Chloride, lb/day} = \frac{(21.9)(2.9)(100)}{39} = 163 \text{ lb/day}$$

APPENDIX C

C. Example Calculations -- Oxygen Transfer Efficiency

In Plant A there are four centrifugal blowers, each with a capacity of 1,550 acfm. Three are utilized, with one as standby. The standard oxygen transfer efficiency (SOTE) or efficiency of the coarse bubble diffusers is 12 percent at 15-ft water depth based on manufacturer's data. Plant A is located at 2,750 feet above sea level.

1. Convert SOTE = 12 percent to AOTE using:

$$AOTE = (SOTE)\alpha\left[\frac{\beta C_{sw} - C_L}{C_s}\right]\theta^{T-20}$$

Where,

AOTE = actual oxygen transfer efficiency at site conditions, percent.
SOTE = standard oxygen transfer efficiency at standard conditions in clean water, percent.
α = 0.85 for coarse bubble diffuser, from Table E-1.
β = 0.95 for domestic wastewater.
θ = 1.024
C_s = 9.17 mg/L oxygen saturation at standard temperature and pressure.
C_{sw} = $C_{14.7}$ (P/14.7), mg/L

Assume maximum summer wastewater temperature = 25°C at Plant A. From Table E-2, $C_{14.7}$ = 8.38 mg/L @ 25°C. From Figure E-1, P = 13.25 psia @ 2,750 ft above mean sea level. A potential depth correction can be applied to this term, as noted in Appendix E. However, to be more conservative in the evaluation, utilize atmospheric pressure:

$$C_{sw} = 8.38\ [13.25/14.7] = 7.55\ mg/L$$

C_L = 2.0 mg/L (mixed liquor DO concentration)

$$AOTE = \{(0.12)(0.85)\ [(0.95)(7.55)-2]\ 1.024^{25-20}\} \div 9.17$$

$$AOTE = 6.5\ percent$$

2. Convert blower output of 1,550 acfm to scfm:

$$acfm = scfm\ (T_a/T_s)(P_s/P_a)$$

Where,

acfm = 1,550 cfm.
T_a = 100°F + 460°F = 560°R (temperature at which manufacturer rated blowers).
T_s = 68°F + 460°F = 528°R (standard temperature).
P_s = 14.7 psia (standard pressure).
P_a = 13.25 psia (pressure @ 2,750 ft above mean sea level).

scfm = (1,550) (528/560) (13.25/14.7) = 1,317 cfm

3. Calculate lb O_2/d from 3 blowers using diffuser actual oxygen transfer efficiency of 6.5 percent and blower capacity of 1,317 cfm:

Peak air flow = 3 x 1,317 = 3,951 scfm

lb O_2/d = (scfm)(1,440 min/d)(23.2 lb O_2/100 lb air) x (0.075 lb air/cu ft air)(AOTE)

= (3,951)(1,440)(23.2/100)(0.075)(6.5)

= 6,435 lb/d

4. Therefore, 3 blowers @ 1,317 cfm each will transfer 6,435 lb O_2/d. Compare the oxygen transfer capability with the BOD_5 loading applied to determine the lb O_2/lb BOD_5 that the diffused air system can provide.

Note: After EPA, 1989a.

In Plant B there are two 50-hp surface mechanical aerators. Both units are utilized. The SOTR is 3 lb O_2/whp-hr based on manufacturer's data. Plant B is located at 2,750 ft above sea level.

1. Convert SOTR = 3 lb O_2/whp-hr to AOTR using

$$AOTR = (SOTR)\alpha\left[\frac{\beta C_{sw} - C_L}{C_s}\right]\theta^{T-20}$$

Where,

AOTR = actual oxygen transfer rate at site conditions, percent.
SOTR = standard oxygen transfer rate at standard conditions in clean water, percent.
α = 0.90 for surface mechanical aerator, from Table E-1.
β = 0.95 for domestic wastewater.
θ = 1.024
C_s = 9.17 mg/L oxygen saturation at standard temperature and pressure.
C_{sw} = $C_{14.7}$ (P/14.7), mg/L

Assume maximum summer wastewater temperature = 25°C at Plant B. From Table E-2, $C_{14.7}$ = 8.38 mg/L @ 25°C. From Figure E-1, P = 13.25 psia @ 2,750 feet above mean sea level.

C_{sw} = 8.38 [13.25/14.7) = 7.55 mg/L

C_L = 2.0 mg/L (mixed liquor DO concentration)

AOTR = {(3)(0.9) [(0.95)(7.55)-2] 1.024^{25-20}} ÷ 9.17

AOTR = 1.7 lb O_2/whp-hr

2. Determine surface mechanical motor power usage:

a. Determine whp of motor based on the assumption that whp is 75 percent of mhp.

whp = 0.75 (50 mhp) = 37.5 whp

b. Determine whp based on actual power measurements and assumption that power factor is 0.90, as shown in Appendix F.

Voltage measurement = 480 volts

Amperage measurement = 37.4 amps

kVA = (V) (A) $(3)^{1/2}$ ÷ 1,000 (3-phase power)
= (480) (37.4) $(3)^{1/2}$ ÷ 1,000 = 31.1kW

kW = kVA x PF = 31.1 (0.9) = 28 kW

whp = kW ÷ 0.746 = 28 ÷ 0.746 = 37.5 hp

Total whp = 2 motors x 37.5 whp = 75 whp

3. Determine oxygen transferred based on AOTR and whp:

O_2 transfer = (1.7 lb O_2/whp-hr) (75 whp) (24 hr/d)
= 3,060 lb O_2/d

4. Compare the oxygen transfer rate with the plant BOD_5 applied loading to determine the lb O_2/lb BOD_5 that the surface mechanical aeration system can provide.

Note: After EPA, 1989a.

APPENDIX D

D. Filamentous Bulking Survey

QUESTIONAIRE

I. DESIGN PARAMETERS

1. What are your design flows?
   a) average daily design flow__________
   b) maximum daily design flow__________
   c) peak design flow____________

2. What is your average daily flow? _____________

3. Under which plant specification would your facility be categorized? Please check one.
   _ conventional activated sludge
   _ pure oxygen activated sludge
   _ extended aeration
   _ contact stabilization
   _ oxidation ditch
   _ rotating biological contactor
   _ trickling filter
   _ other, please specify__________________________

4. What type of aeration system is currently being used at the facility?
   _ surface aeration
   _ diffused aeration
   _ other, please specify__________________________

II. OPERATIONAL PARAMETERS

1. What is the hydraulic residence time in the aeration basin?
   ____

2. What is the solids retention time?__________

3. What is the reactor type? Please check one.
   _ plug flow
   _ completely mixed
   _ step feed
   _ other, please specify _________________________

4. At what range of F/M ratios is the facility currently being operated?_____________________________________

5. At what range of mixed liquor suspended solids concentrations is the facility currently being operated?

____

III. WASTEWATER CHARACTERISTICS

1. What percentage of the total flow is industrial?__________

2. What percentage of the total flow is septic wastes?---------

3. For each of the following influent parameters, please indicate an average range encountered under normal operating conditions:
   a) pH ________________
   b) BOD __________________________
   c) nitrogen ________________________ (as total Kjeldahl N)
   d) phosphorus ______________________ (as total P)

4. What average range of dissolved oxygen concentrations is encountered under normal operating conditions within the aeration basin?____

IV. ADDITIONAL QUESTIONS

1. In the last two years, has your facility experienced any bulking-related problems? _______ If so, please answer the following:

   a) Specifically, what type(s) of problem(s) did you encounter and were you able to identify the causative condition(s)?

   ____
   ____

   b) Please briefly explain any remedial action taken to correct the bulking problem (For example, the addition of chlorine, hydrogen peroxide, etc.).______________________________

   ____
   ____

   c) As a result of the bulking problem, were you unable to meet your discharge permit? Please explain.

   ____
   ____
   ____

2. Did you experience any other solids separation problems?
______ Please check any of the following which may apply:
_ clarifier overloading
_ biological problems other than bulking
_ blanket rising
_ foaming
_ others, please specify ______________________

3. Please enter any additional comments that you may feel are specifically important to the operation and/or to the design of your facility which have not been addressed in this questionaire.______________________

In the space provided, please fill in a name, address, and telephone number of a person we may contact at your facility:

name ______________________
address ______________________
____
____
____
phone # ______________

In addition, we would greatly appreciate a brief process schematic highlighting the major components of the facility.

For your convenience, a self-addressed, stamped envelope has also been enclosed. Your quick response to this questionaire will be greatly appreciated. Thank you very much for your time and cooperation.