EFFECT OF CHLORINATION ON FILAMENTOUS GROWTH AND NITRIFICATION IN BATCH FED AND CONTINUOUS ACTIVATED SLUDGE SYSTEMS

by

Thomas Marstaller

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ABSTRACT

Filamentous bulking is a prevalent problem in the treatment of waste water using activated sludge. Continuous-flow stirred-tank reactors (CFSTR) operated in the initial pilot phase of this research suffered from severe sludge bulking. Chlorination was implemented as a control method for the filamentous bulking in the CFSTRs. Possible causes of this problem were the P:MLSS ratio in the reactors and the reactor configuration. These were investigated in laboratory scale after the completion of the pilot scale research. Further studies were conducted to determine the response of the nitrifying bacteria to chlorination.

The study found that a P:MLSS ratio of 2.4 percent was desirable to avoid filamentous bulking regardless of the reactor configuration used. Increasing the P:MLSS ratio above 2.4 percent provided little improvement in sludge settleability. Sequencing batch reactors (SBR) were found to be more effective in controlling filaments than CFSTRs.

Chlorination successfully controlled filaments and improved sludge settleability in the short term. When the reactors were operated for several days without chlorine addition, the filamentous bacteria returned in even greater numbers. The next-day-effluent-suspended solids (NDESS) concentration was found to be proportional to the once-a-day batch dose applied. Lower sustained once-a-day batch doses were found to be equally effective in controlling filaments

than single once-a-day batch doses, even though they required several days to be effective. Microscopic observation (MO) number was determined to be a better indicator than sludge volume index (SVI) of impending mixed liquor suspended solids loss in the effluent due to extreme proliferations of filamentous bacteria. Nitrifying bacteria were found to be inhibited by a single once-a-day batch chlorine dose of 1.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$; while the filamentous bacteria required sustained once-a-day batch doses of 2.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ for two days followed by doses of 1.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ for six days.

Caution must be exercised in selecting reactor configurations and maintaining nutrient requirements if sludge bulking is expected to be a concern. Also, if nitrification must be maintained while chlorination is practised for filamentous bulking control, pilot tests should be carried out to determine what dose can be safely used to control the filaments without adversely affecting the nitrifying bacteria.

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PREFACE

At the beginning of man's time on Earth he paid little attention to the need for the treatment of the wastes that his existence produced. These wastes were able to be treated naturally through dilution. As man's numbers grew he was able to overpower the earth's ability to assimilate the wastes produced; leading to pollution of the earth.

In response to this unfortunate circumstance, man has developed technologies, such as activated sludge, to keep these wastes from reaching and destroying nature. These technologies, however, are not without their own problems. One of the problems that can occur with activated sludge treatment is filamentous bulking. If the bulking is not controlled it can lead to increased and unnecessary pollution of the environment. Therefore, this thesis intends to provide further information of this problem and some of the methods that can be used to combat it.

1. INTRODUCTION

1.1. HISTORY OF ACTIVATED SLUDGE

In 1893 Sir Thomas Wardle was operating a fill and draw reactor with only aeration and no chemical precipitation. He noted that a medium was formed from the precipitated impurities that accumulated in the tank which clarified the influent. The phenomenon observed by Wardle was later given the name activated sludge in studies carried out by Arden and Lockett in 1914-15 at the Waste Treatment Plant in Manchester, England.

Many fill and draw style operations were built in the period between 1914-1920. Almost all of these plants were converted to continuous flow operations in the following decade. Reasons for this trend included the high discharge flow rate relative to that of the influent; and the clogging of diffusers because of the periodic settlement of the sludge in the fill and draw systems. Increased operator attention was required due to the need for switching valves and cleaning diffusers. Therefore, the capital and operating costs of the continuous flow system were less than those for the fill and draw system (Irvine et al, 1985; Ganczarczyk, 1983). Regardless of the form or configuration, activated sludge had become the main form of biological waste treatment used in North America by the 1940's (WPCF, 1987).

1.2 ACTIVATED SLUDGE DEFINITION

Activated sludge treatment has been defined as an aerobic biological treatment process that uses the metabolism of microorganisms to degrade organics present in a waste water in order to produce a quality secondary effluent (WPCF, 1987). According to Richard (1989) activated sludge is defined as a consortium of micro- and macro-organisms which transform inorganics and organics to environmentally acceptable forms. By allowing biologically active solids to come in contact with the waste water, this transformation can be accomplished. Metabolism of degradable organic constituents by the bacterial solids releases less harmful products into the treated waste water.

In the activated sludge treatment process, the waste water is brought into contact with an aerobic bacterial culture maintained in suspension to form mixed liquor (Metcalf and Eddy, 1991). Aeration is the supply of sufficient oxygen to the mixed liquor to allow metabolism to proceed. The biological mass present, known as mixed liquor suspended solids or mixed liquor volatile suspended solids, converts the dissolved and colloidal biodegradable organics in the waste water to new cells and oxidized end products such as nitrates, sulphates and phosphates (Ganczarczyk, 1983; Metcalf and Eddy, 1991). Clarification involves the separating of solids from the mixed liquor to be returned to the aeration portion of the system or to be wasted from the system for further treatment before final discharge to the environment. The efficiency of the clarification and aeration unit operations determines how well the entire treatment system works (EPA, 1987).

1.3 CONVENTIONAL ACTIVATED SLUDGE PROCESS DESCRIPTION

The most widely used configuration of the activated sludge treatment process consists of two tanks: one for aerating the biological solids; and one for separating the biological solids from the treated effluent by gravity (Figure 1.1). Waste water is brought into contact with the biologically active solids and an oxygen source in the aeration basin. Oxygen can be supplied by mechanical aerators, a pure oxygen system, or an air compressor (WPCF, 1987). After the metabolic reaction has taken place, the mixed liquor suspended solids (MLSS) are discharged to the clarifier. The clarifier serves the dual function of clarification and thickening. A portion of the separated solids are returned to the aeration tank as return activated sludge (RAS) through underflow piping. This procedure is done to maintain a high concentration of MLSS in the aeration tank. Due to the constant synthesis of new cell material in the aeration basin, a means of manual or mechanical sludge wasting must be provided to remove the waste activated sludge (WAS) from the system (Metcalf and Eddy, 1991). The treated effluent is then sent to further treatment or discharged to the receiving water.

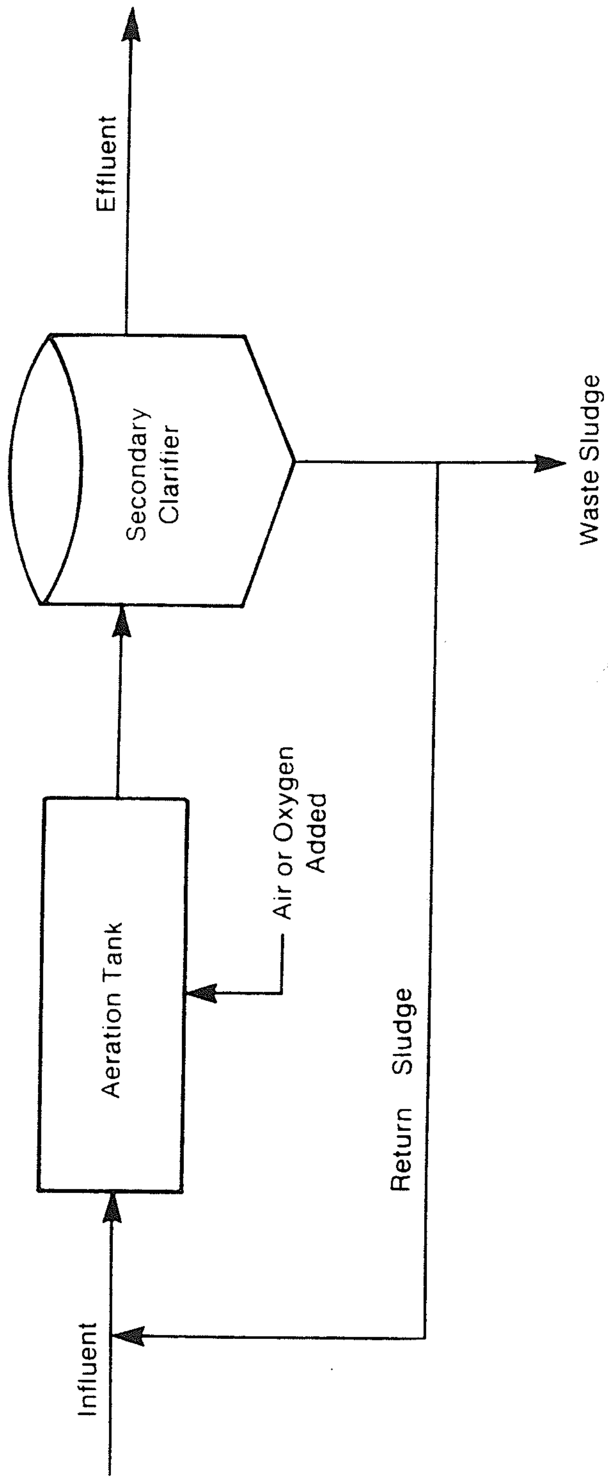

Figure 1.1. Conventional activated sludge process.

1.4 SEQUENCING BATCH REACTOR CONFIGURATION

As mentioned above, the first activated sludge reactors had a fill and draw configuration. This configuration was later abandoned in favour of systems that operated on a continuous basis. Irvine and Ketchum (1989) stated that the prevalence of CFSTRs in the United States was a stumbling block to the implementing sequencing batch reactor (SBR) technology in the 1970's. Introduction of electronic control systems for SBRs reduced the labour costs, making SBRs economically feasible. They have proven to be an appropriate technology for smaller waste water flows.

The main difference that exists between sequencing batch reactors and conventional technologies is that SBR's are oriented in time and conventional treatment is oriented in space. SBR's, therefore, have an advantage because their relative tank volume dedicated to any one of the phases of the cycle can be easily redistributed by adjusting the mechanism that controls the length of each phase. SBR's can therefore be operated as a labour intensive, low energy, high sludge yield system or a minimal labour, high energy, low sludge yield system using the same equipment (Irvine and Ketchum, 1989).

SBRs are operated on a cycle, generally 4 to 12 hours long. Each cycle consists of four or five components (Figure 1.2) including fill, draw, react, settle and if necessary, idle (Irvine and Busch, 1979).

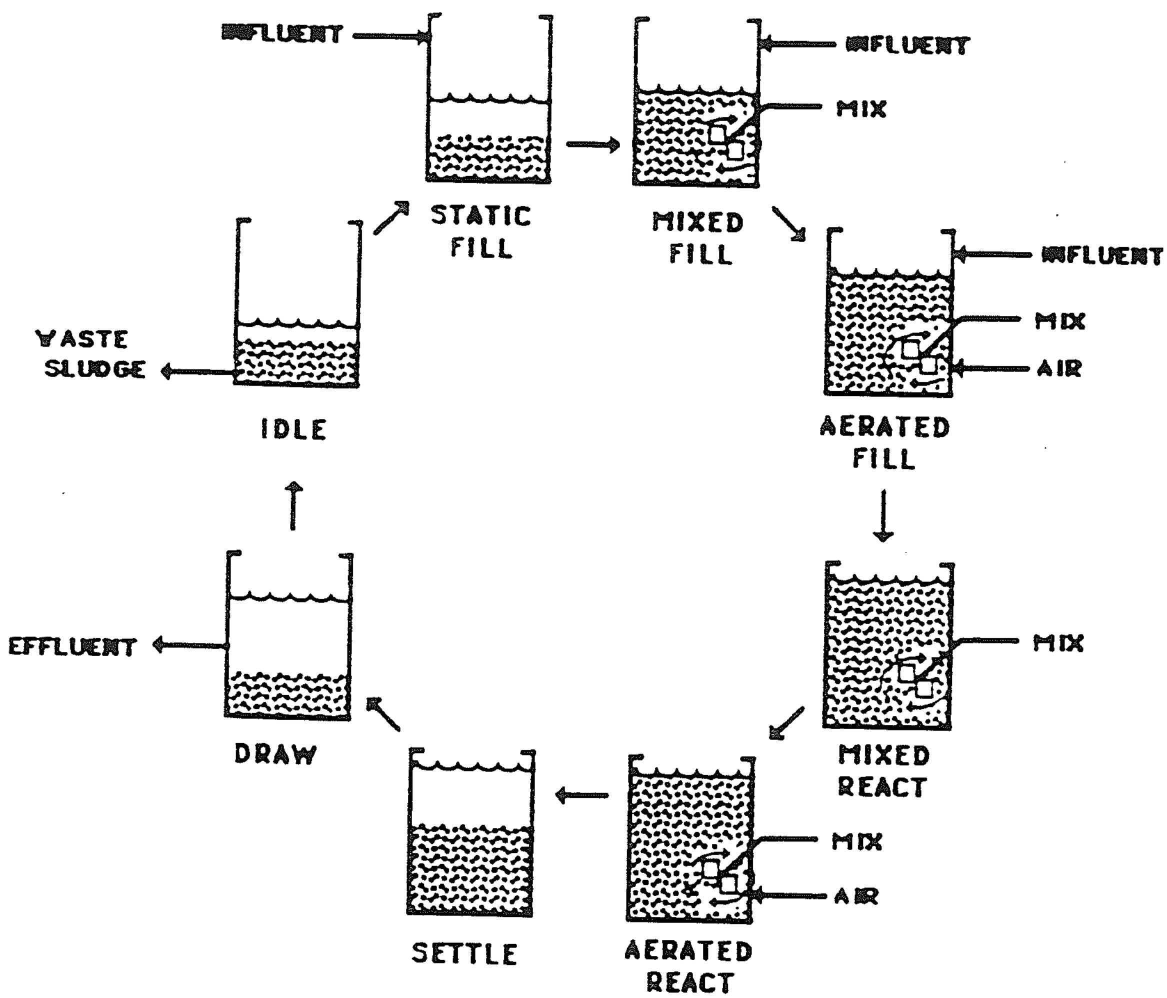

Figure 1.2. The five cycle components of an SBR reactor including FILL (STATIC, MIXED, and AERATED), REACT (MIXED and AERATED), SETTLE, DRAW, and IDLE.

During fill, the waste water is added to the biomass which has remained in the reactor from the previous cycle. Fill can be accomplished in the presence or absence of aeration or mixing, depending on the function that the reactor is intended to serve. Any metabolic reactions initiated in the fill phase will be completed in the react phase.

Depending on the intended mode of operation, the react period may be only mixed or mixed and aerated or a combination of the two. Sludge wasting is normally carried out during this phase of the operating cycle.

The settle period occurs under quiescent conditions in the same basin that was employed during the react phase. Using the same basin eliminates the need for the underflow hardware that exists in conventional activated sludge systems. Near the end of the settle period, sludge wasting can be achieved with higher solids concentrations which require smaller volumes.

After the sludge in the reactor has settled sufficiently, the clarified effluent is removed during the draw phase of the cycle. The length of draw should not be overly extended in order to avoid possible problems with rising sludge.

Idle is the length of time between the end of the draw period and the beginning of the fill stage. If an idle period is used, it's length may range from no time at all to as much as an hour depending on the influent flow rate (Irvine and Ketchum, 1989).

2. FILAMENTOUS BULKING

2.1 FILAMENTOUS BULKING DEFINITION

Activated sludge consists of a consortium of both micro and macro organisms which metabolize inorganics and organics in the waste water. Among these organisms are two basic types. The first type are bacteria that stick together to form the microstructure of the flocs. These flocs are the basis of the activated sludge process. Filamentous bacteria are the other type. In small amounts, the filaments are beneficial as they form the backbone or macrostructure of the activated sludge floc (Figure 2.1a). A complete lack of filaments will result in small dispersed flocs known as pinpoint floc and a turbid effluent (Figure 2.1b). A good balance between floc formers and filaments will result in larger flocs which settle better and remove small particles effectively. On the other hand if they become prolific (Figure 2.1c), normal settling of the sludge will be interrupted (EPA, 1987; Richard, 1989).

Due to the widespread use of the term "bulking" to describe any problem occurring with the separation of the biological solids from the mixed liquor, considerable variation in definition of this term is possible (Tomlinson, 1982). In the United States Environmental Protection Agency (EPA) manual, Jenkins (EPA, 1987) described bulking as the overabundance of filaments in an activated sludge that extend from the floc and interfere with the compaction and settling

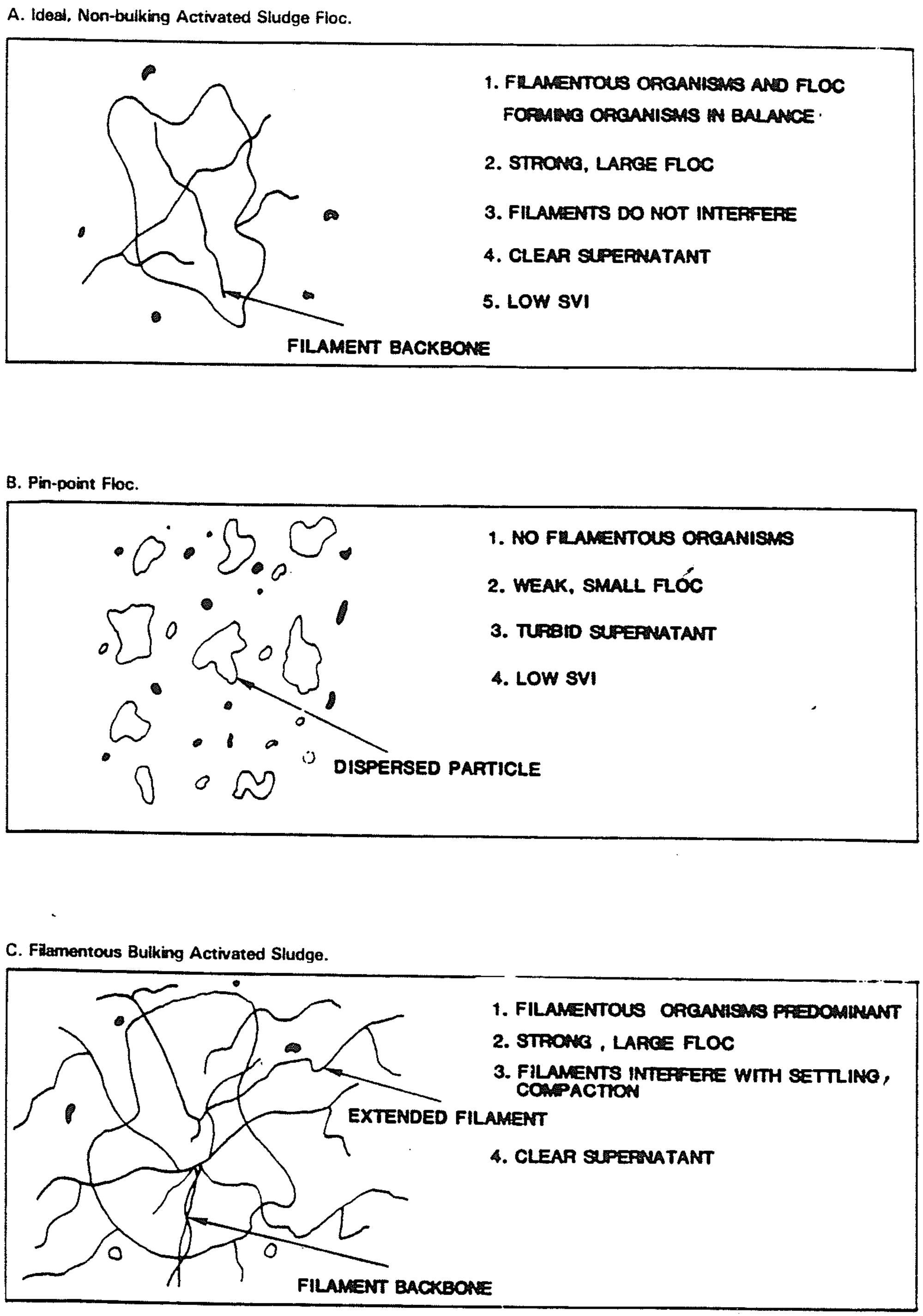

Figure 2.1. Effect of filamentous microorganisms on activated sludge floc structure.

of the sludge. Tomlinson (1982) stated that bulking occurred when the sludge occupies an excessive volume and does not settle readily, so that the effluent contains an excessive amount of suspended matter. These definitions outline the problem of bulking that will be investigated in this thesis.

Filaments are able to interfere in the clarification process in two ways. Open floc structure can result from flocs that grow around the filamentous bacteria leaving large internal voids. The second form of interference is interfloc bridging where the filaments grow and connect between the existing flocs. Both of these occurrences increase the area of the floc and cause it to settle more slowly.

A more practical approach to defining a bulking sludge is to set an acceptable sludge volume index (SVI) for the sludge. Jenkins (EPA, 1987) states that an acceptable SVI is in the range between 70 and 150 $mL \cdot g^{-1}$. According to Richard (1989), a bulking sludge is generally one with an SVI greater than 150 $mL \cdot g^{-1}$ but can be less than 100 $mL \cdot g^{-1}$ or greater than 300 $mL \cdot g^{-1}$ depending on the system. A further suggestion put forward by Pujol and Boutin (1989) is an SVI greater than 200 $mL \cdot g^{-1}$. In this research it was assumed that an SVI of greater than 150 $mL \cdot g^{-1}$ represented a sludge that was bulking.

2.2 OPERATIONAL IMPLICATIONS OF FILAMENTOUS BULKING

From an operational standpoint bulking only becomes a problem when the clarifier is no longer able to contain the sludge. This problem, however, leads to several severe operational predicaments. Among the problems that can occur are: solids carryover; high SVI; low sludge concentrations in both the reactor and the recycle with their incident high recycle rates; hydraulic overloading of the solids handling systems; and poor effluent quality (Richard, 1989; EPA, 1987). Tomlinson (1982) stated that when the secondary clarifier capacity is exceeded, the effluent BOD will initially increase in proportion to the amount of sludge lost in the effluent. As the sludge age decreases due to the loss of sludge, nitrification will be lost. If the decrease in sludge inventory continues, carbonaceous oxidation will be lost. Ultimately the process' ability to effect treatment will be lost.

If filamentous sludges can be contained in the secondary clarifier, they will result in higher effluent quality because they have higher specific substrate removal rates. Filaments will also act as a net to trap small particles (Chudoba et al, 1973). Chudoba also found that high BOD removals were achieved in his reactors regardless of the presence of filaments. Any effluent BOD was normally associated with suspended solids that escaped the clarifiers.

2.3 FILAMENTOUS BULKING PREVALENCE

Problems with bulking due to filamentous bacteria did not exist in the initial activated sludge systems due to their plug flow and fill and draw configurations. Donaldson (1932a, b) who called filamentous bacteria the "weeds of activated sludge" was the first to mention the problem of filamentous bulking. Presently one of every four activated sludge plants in France suffers from a bulking problem (Pujol and Boutin, 1989). Wagner (1982) stated that roughly 45% of the 315 German activated sludge plants he analyzed suffered from bulking sludge. In the United Kingdom 41 of 65 plants researched by Tomlinson in 1976 had sludge that bulked. Even though the true occurrence of bulking in activated sludge plants in the United States has not been quantified, bulking has been estimated to affect at least 60 percent of plants either intermittently or continuously (Richard, 1989). Work recently completed by Richard in Colorado determined that filamentous bulking occurred in at least eighty percent of the plants at some point during the year.

2.4 PARAMETERS FOR QUANTIFYING FILAMENTOUS BULKING

2.4.1 SLUDGE VOLUME INDEX

Sludge volume indices (SVI) has long been used to measure the ability of a sludge to settle or its lack thereof. The SVI is determined from the suspended solids concentration and the volume of the sludge after thirty minutes of settling using the following formula:

$$\text{SVI } (\text{mL}\cdot\text{g}^{-1}) = \frac{\text{settled sludge volume } (\text{mL}\cdot\text{L}^{-1})}{\text{suspended solids } (\text{mg}\cdot\text{L}^{-1})} * 1000 \qquad \textbf{(2.1)}$$

Although the SVI is not supported theoretically (Finch and Ives, 1950), widespread experience has shown it to be useful for routine process control.

2.4.2 MICROSCOPIC OBSERVATION

The microscope is an underrated tool in controlling activated sludge and bulking problems. Many researchers have recommended the use of microscopic techniques to determine the health of activated sludges (Chudoba et al, 1973; Eikelboom, 1982; EPA, 1987; Gabb et al, 1989; Richard, 1989; WPCF, 1987). A parameter that measures the sludges health in terms of the number of filaments present is the microscopic observation (MO) number. Using a phase contrast or normal light microscope at 100 x magnification, the sludge is viewed to determine the number of filaments present. Quantifying the filaments using the MO number is subjective but has been proven to be reproducible to within one category. The categories used are outlined in Table 2.1 below.

An overall rating of very common or higher for an activated sludge indicates that bulking is occurring. If an individual filament is found to have a rating of very common or greater it is said to be the dominant filament. Secondary filaments are present at a level of common or less, but in insufficient numbers to cause problems. It is important to observe the causative filament early in the bulking episode (Richard, 1989) because once failure has occurred many

Table 2.1. Categories used in determination of microscopic observation number.

MO VALUE	ABUNDANCE	DESCRIPTION
0	none	
1	few	filaments present but only observed in an occasional floc
2	some	filaments commonly observed but not present in all flocs
3	common	filaments observed in all flocs, but at low density (e.g.,1-5 filaments per floc)
4	very common	filaments observed in all flocs at medium density (e.g.,5-20 filaments per floc)
5	abundant	filaments observed in all flocs at high density (e.g.,20 filaments per floc)
6	excessive	filaments present in all flocs - appears more filaments than floc and/ or filaments growing in high abundance in the bulk solution

Source: EPA manual

secondary filaments will appear, thus making the cause difficult to diagnose. Eikelboom (1982) stated that he was able to observe more clearly a shift in floc populations to filamentous bulking at an earlier stage by an increase in the MO number rather than waiting for the SVI to increase.

2.4.3 EFFLUENT SOLIDS

When extreme bulking occurs, the SVI will become inadequate as an indicator of how catastrophic the problem has become. A good alternative parameter is the effluent solids. Increases in the effluent solids when normal sludge wasting is being practised indicate a worsening of the filamentous bulking in the reactor.

2.5 CAUSES OF FILAMENTOUS BULKING

As problems with bulking were realized in activated sludge plants, researchers analyzed plant design, operating conditions and waste water characteristics in search of the cause. Therefore, at various times bulking was associated with overloading or underloading, overaeration or underaeration, short circuiting, nutrient imbalance, high or low pH values, high temperatures, and sewage septicity. Publication of this information led to much confusion for those attempting to solve bulking problems.

Following this, efforts were made to try and relate sludge settleability to fundamental observations of micro-organism type and surface chemistry characteristics. Two schools of thought evolved from these observations. One believes that bulking results from the excessive growth of certain filaments. The second school believes that bulking results from the presence or absence of certain physico-chemical conditions on the surface of the micro-organism (Tomlinson, 1982). Pujol and Boutin (1989) and the WPCF Task Force On Waste Water Biology (1990) determined that filaments due to their high surface to volume ratio were favoured by nutritional deficiencies, an aeration tank shape that induced complete mixing, operation at a low organic loading in the presence of simple sugars and organic acids, presence of a primary settling tank and the treatment of diluted waste water. Two other conditions that resulted in filaments being selected were limiting dissolved oxygen and substrate concentration.

2.5.1 NUTRIENT DEFICIENCY BULKING

Low concentrations of phosphorus resulted in catastrophic sludge losses due to severe sludge bulking in the reactors operated by Greenberg et al (1955). Wagner (1982) found that bulking sludges generally had unbalanced nutrient compositions. Filamentous sludges exhibited high concentrations of carbon and nitrogen and a deficiency of phosphorus. Ericsson and Eriksson (1988) also found that insufficient phosphorous in the feed for their activated sludge reactors resulted in increased SVI and increased filamentous organism growth.

Forster (1985) stated that the nutritional balance of a waste water affects the dominant species of bacteria present. Changes in the phosphorus concentration caused a shift in the microbial population to occur in the system operated by Ericsson and Eriksson (1988). Filamentous bacteria were favoured by a lack of easily assimilable phosphates.

Their system experienced severe bulking when too much phosphorus was removed from the waste water by a high pre-precipitation dose. Sludge quality improved rapidly after the pre-precipitation dose was returned to the optimal concentration. In the research conducted by Greenberg et al (1955), healthy sludges that were subjected to low phosphorus concentrations quickly deteriorated. The quality of phosphorus deficient sludges recovered rapidly when sufficient phosphorus was added.

Wagner (1982) hypothesized that filamentous bulking in the absence of sufficient phosphorus occurs because micro-organisms satisfy their phosphorus demands by exploiting the surrounding environment. Large bacterial surface areas must be developed to utilize small concentrations of dissolved phosphates. Filaments are therefore favoured due to their large surface to volume ratio.

Several authors (Benefield and Randall, 1980; Eckenfelder and O'Connor, 1961; EPA, 1987; Metcalf and Eddy, 1991; Peavy et al, 1985) have stated that a biochemical oxygen demand to nitrogen to phosphorus ratio of 100:5:1 will usually insure adequate nutrition for sludge production. In the series of papers by Helmers et al (1950, 1951, 1952), the maximum phosphorus requirement for cotton kiering, rag rope and brewery waste waters was proven to be 0.45 kg of phosphorus per 45 kg of BOD removed which concurs with the ratio above.

Systems that employ long sludge ages will require smaller amounts of nutrients because they possess lower specific growth rates. Some of the nutrient requirements for sludge production will be met by nutrient recycling due to endogenous decay of the activated sludge (EPA, 1987). Figure 2.2 (Benefield and Randall, 1980) shows that as SRT gets longer, the nutrient requirements decrease.

Greenberg et al (1955) postulated that the amount of phosphorus needed per amount of BOD present was related to the rate of sludge solids development; which is in turn related to the applied BOD loading and inversely proportional to SRT. Concentrations of 0.0 to 5.4 $mg \cdot L^{-1}$ of phosphorus were added in the synthetic waste fed to batch reactors containing 1500 $mg \cdot L^{-1}$ of mixed liquor suspended solids. Those reactors that received less than 0.8 $mg \cdot L^{-1}$ of phosphorus were whitish in colour, had a strong tendency to bulk and possessed sludge consisting mainly of filamentous organisms. When the synthetic waste contained 0.8 $mg \cdot L^{-1}$ or greater of phosphorus, a sludge with the typical colour and microbial population was produced. These sludges also settled well. At the loading used in this study, a BOD:P ratio of 100:0.44 was found to be sufficient to avoid filamentous bulking. The authors concluded that the bulking was due to the deficiency of phosphorus in relation to the BOD present.

Two formulae exist for determination of the phosphorus requirements of an activated sludge system. Benefield and Randall (1980) based their nutrient requirement calculations on the amount of phosphorus required in the biomass produced to satisfy the chemical formula of $C_{60}H_{87}O_{23}N_{12}P$. The following formula for phosphorus requirements resulted:

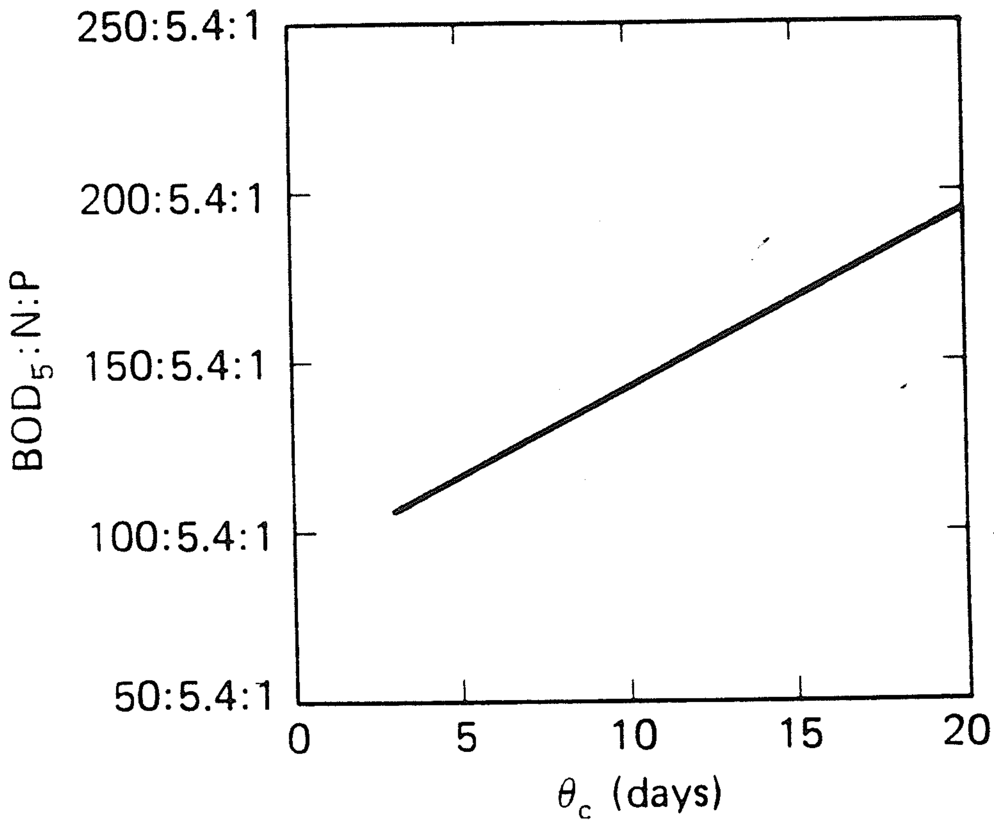

Figure 2.2. Effect of solids retention time, θ_c, on activated sludge nutrient requirements.

$$\text{PHOSPHORUS REQUIRED } (kg \cdot d^{-1}) = 0.023 \Delta X \tag{2.2}$$

where ΔX = biomass produced per day ($kg \cdot d^{-1}$)

Another formula used to determine the phosphorus requirements has been suggested by AWARE Inc (1974). Considered in the formula is the fact that activated sludge produced generally contains 2.6 percent phosphorus, but as the SRT gets longer and the biomass becomes endogenous the phosphorus content of the sludge will decrease to approximately one percent. Only the biodegradable organic fraction of the sludge produced is accounted for in the formula given below:

$$\text{PHOSPHORUS REQUIRED } (kg \cdot d^{-1}) = \frac{0.026 x \Delta X_v}{0.77} + 0.01 \frac{(0.77 - x) \Delta X_v}{0.77} \tag{2.3}$$

where x = biodegradable decimal fraction of the MLVSS
ΔX_v = biomass produced per day ($kg \cdot d^{-1}$)

Both of these relationships are plotted in Figure 2.3. The AWARE Inc. formula was plotted assuming the biodegradable fraction of the MLVSS to be 50 and 100 percent. Significant variations in the amounts of required phosphorus occur as the biodegradable portion of the MLVSS increases. No upper limit in the sludge production and the resultant amount of phosphorus required is accounted for in these calculations.

The role of phosphorus in the activated sludge process was studied by Wu and Okrutny (1982). Data for a non bulking

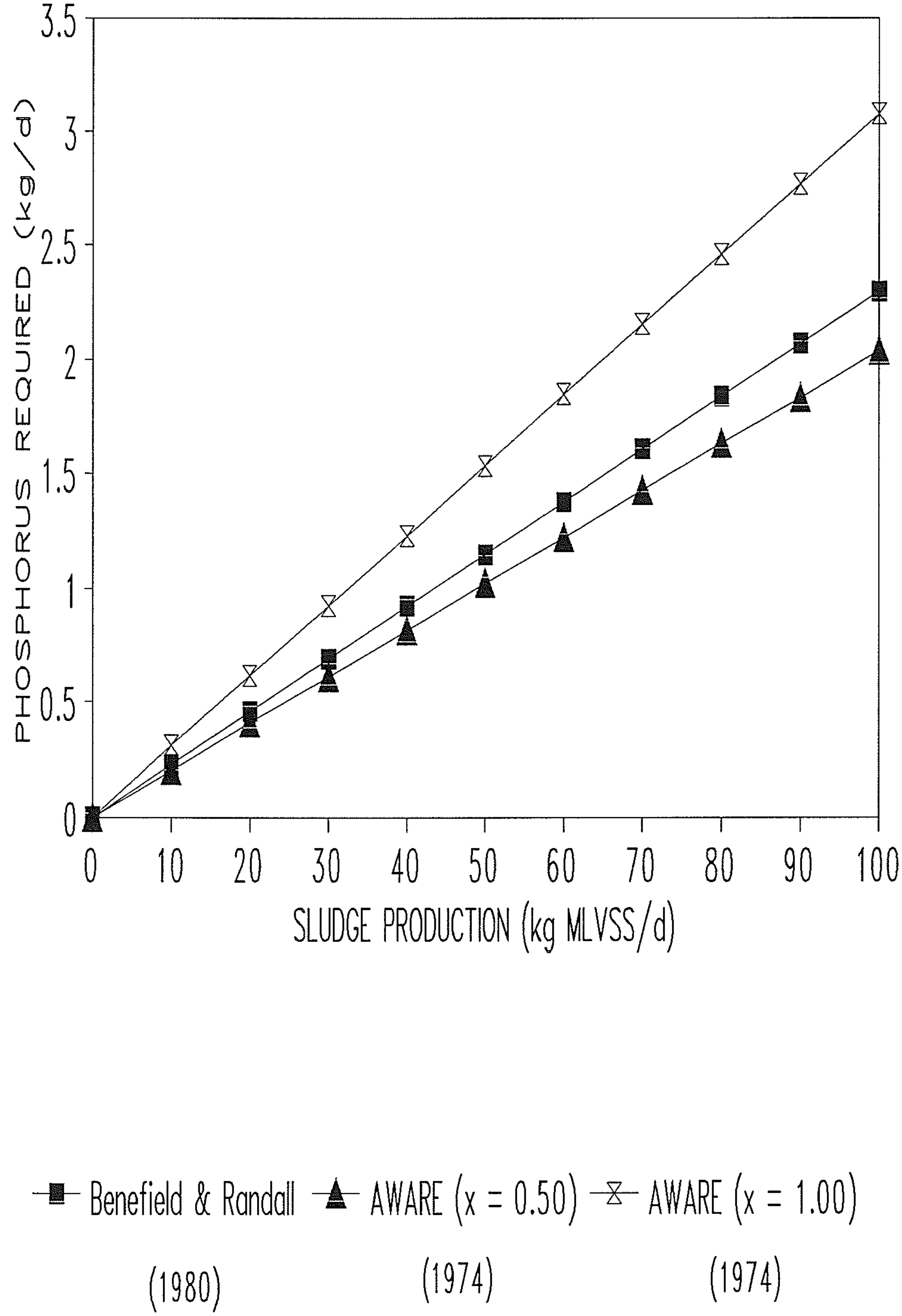

Figure 2.3. Effect of sludge production on the calculated amount of phosphorus required using the Benefield and Randall (1980) and the AWARE Inc. (1974) formulae.

sludge is plotted in Figure 2.4. It shows the effect of

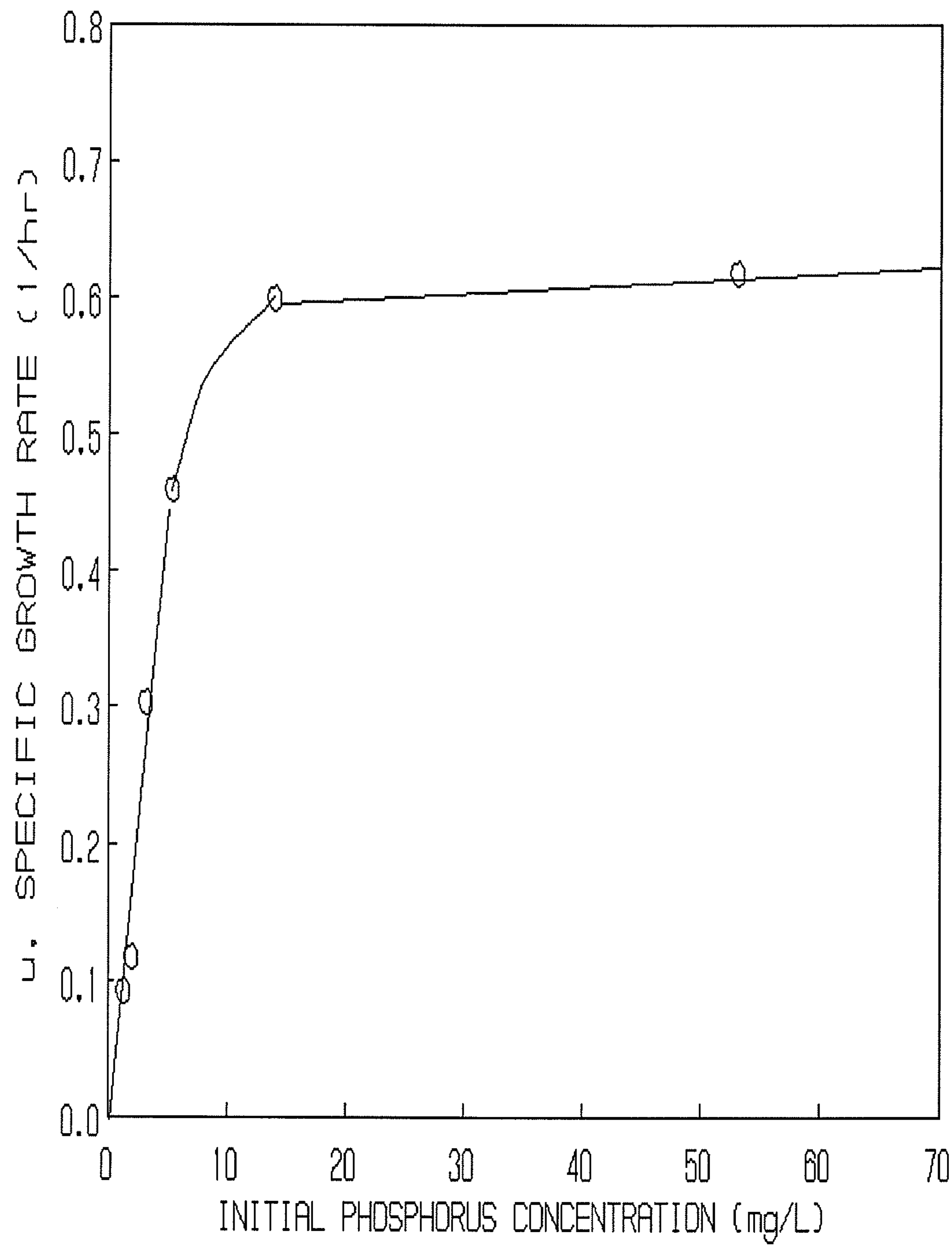

Figure 2.4. Effect of initial phosphorus concentration on the specific growth rate, u. After Wu and Okrutny (1982).

initial phosphorus concentration on the specific growth rate, u. A maximum in sludge production was reached at a concentration of 15 $mg \cdot L^{-1}$ of phosphorus. Increases in the initial phosphorus concentration beyond this level resulted in only a minimal increase in sludge production. This means that once the minimum phosphorus requirement is met any increase in the phosphorus concentration will result in insignificant benefits.

Helmers et al (1952) noted that once the nitrogen concentration in their reactors reached a certain level, no additional BOD removal was derived from further increases in nitrogen concentration. It is assumed that the BOD removal would be dependent on phosphorus as it had been on nitrogen. Maximum BOD removal would result in maximum sludge production in the presence of sufficient nutrients. This assumption corroborates the findings of Figure 2.4.

Wagner (1982) found that a relationship exists between the SVI and the ratio of phosphorus to organic MLSS. As indicated in Figure 2.5, when the P:MLVSS ratio decreased below three percent the sludge was likely to become highly filamentous. If the ratio was greater than three percent, bulking rarely occurred.

Forster (1985) stated that various ratios of nutrients have been used in the past based on the rationale that the nutrient conditions would suppress filaments. He reinvestigated the data presented by other authors to

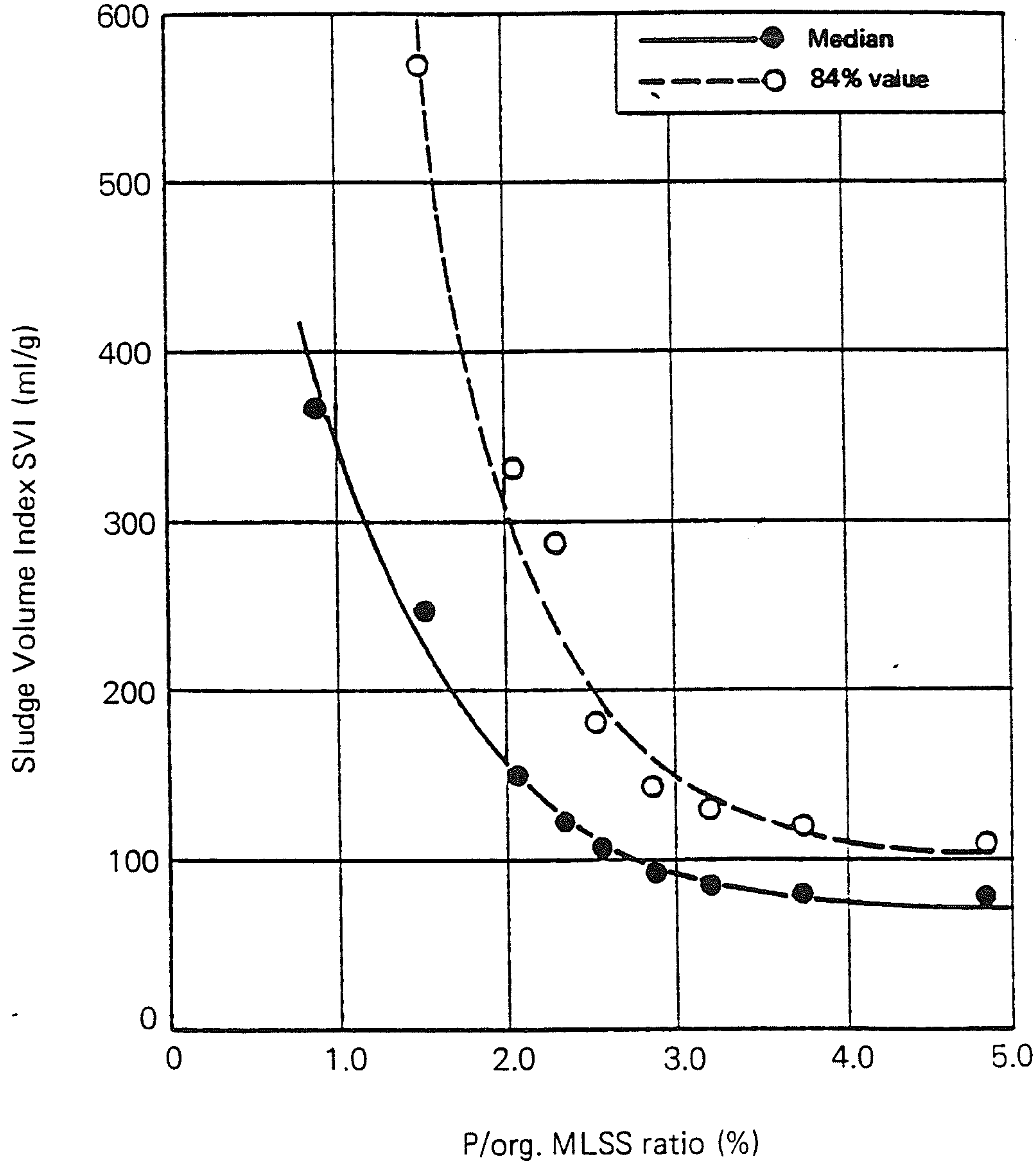

Figure 2.5. Wagner's graph showing the effect of P:org. MLSS on SVI.

determine if there existed a ratio, such as Wagner's P:MLVSS ratio, that could be correlated to the data from all of the studies analyzed. No positive statement could be made due to the insufficient data presented in some of the studies and the assortment of settling parameters used in the research analyzed.

2.5.2 BULKING INDUCED BY REACTOR CONFIGURATION

Initially, when fill and draw type reactors were employed in great numbers, no problems with filamentous bulking were reported. As time progressed, more and more waste treatment plants were being converted to complete mix configurations in order to address the problem of toxics (Tomlinson, 1982). In complete mix systems the influent mixes rapidly throughout the entire basin creating a dilution effect. This is helpful in the treatment of toxics because their concentration will be immediately diluted in a complete mix system. Activated sludge at the head end of plug flow reactors, on the other hand, would be significantly inhibited by the undiluted concentration of the toxicant. A recent study by Chudoba et al. (1991) has proven this conversion to be unnecessary because plug flow systems were able to effectively treat toxics. Unfortunately, many systems have been changed to a complete mix configuration which has resulted in filamentous bulking problems. Chudoba et al. (1973) suggested that complete mixing was detrimental to filament control. This view is supported by Richard (1989) who stated that sludges from complete mix systems were more susceptible to bulking than intermittently fed and plug flow systems.

2.6 BULKING CONTROL METHODS

Many researchers have stated that the onset of bulking is more rapid than its cure (Richard, 1989). A general approach to solving filamentous bulking problems involves four basic steps. First, the filament must be identified using microscopic observation techniques. Next, the probable cause of the bulking must be determined. Third, immediate operational changes must be investigated to see if the problem can be rectified. Finally, it must be determined if the treatment plant requires major operational or design changes which may require some time to implement (EPA, 1987).

The methods used to control sludge bulking can be classified as short term or long term solutions. When using short term solutions only the symptoms of the problem are being treated. Whereas, a long term solution deals with the cause of the problem. The short term control methods are required until the long term solutions can be implemented.

Jenkins et al. (1982) stated that any bulking control approach should consist of two steps. First, the filamentous bacteria extending from the sludge flocs must be selectively killed off. The second stage involves the determination of the source of the bulking problem and initiating the remedy.

When operational changes are made to an activated sludge system two to three solid retention times (SRT) will be required for the system to adjust (EPA, 1987).

Tomlinson (1982) states that the difficulties experienced in relating the fundamental characteristics to design strategies, operating conditions and waste water characteristics has led researchers to search for empirically-based solutions. It is important to remember that any solution found in one plant may not work elsewhere. Wagner (1982) stated that bulking control is confined to dealing with isolated problems and that the achievement of the desired objective was not guaranteed by applying control measures that were successful elsewhere. This view is echoed by Eikelboom (1982) who stated that no universally applicable bulking control method exists.

2.6.1 CHLORINATION

The most widely used toxic reagent employed in filamentous bulking control has been chlorine. Chlorine is widely used because of its availability at most waste water treatment installations, its relatively low cost and its widespread previous use in filamentous bulking control. Even though it can be used as a long term solution, chlorination has been most widely used as a short term solution.

2.6.1.1 CHLORINATION STRATEGY

Jenkins et al (1982) stated that chlorination has been successful in controlling a wide variety of filaments even though the relative susceptibility of each of the filaments was not yet known. Chlorine was the chemical of choice in the research investigating the effect of toxic reagents on filamentous bacteria.

The EPA (1987), Jenkins et al (1982) and Richard (1989) outlined a set of guidelines for chlorinating activated sludges for bulking control. First, a target SVI or other settleability parameter must be set. It is recommended that the target parameter be set as high as possible without allowing the MLSS to be carried over the effluent weir, as this will result in a clearer effluent due to the ability of the filaments to strain out small particles. Second, chlorination should only be undertaken when the target value is consistently exceeded.

Third, the chlorine dose must be known, controlled and added where it will mix efficiently. An important factor that must be known is whether once-a-day batch dosing or continuous in-basin chlorination will be used as they result in the activated sludge facing two different sets of conditions. When once-a-day batch doses are applied the activated sludge will face a high chlorine dose which will be rapidly consumed as it attacks the filaments. Continuous in-basin chlorination, on the other hand, will result in a lower dose being applied for a longer period of time. Therefore, the once-a-day batch doses use the acute toxicity of a large dose acting over a short time period while the continuous in-basin chlorination uses the chronic toxicity effect of low chlorine concentrations over longer time periods to inhibit the growth of the filamentous bacteria.

Fourth, chlorine should be added where the raw waste water concentration is at a minimum, because chlorine reacts rapidly with the organics in the waste water leaving little or no chlorine residual for killing filaments.

Fifth, the dosing point must be selected using the following four criteria. The dose has to be low enough so that it does not kill all of the organisms in the immediate area. Chlorine should be added at a location where the sludge is concentrated. Sufficient mixing must be present at the dosing location; because if the location selected has inefficient mixing a great deal of chlorine may be consumed in attaining only minimal amounts of bulking control. The entire sludge inventory should be exposed to the chlorine at least once per day.

Four locations are recommended for the addition of the chlorine. They are: direct addition of chlorine to the aeration tank; addition into a dedicated chlorination loop connected to the aeration tank; addition to the RAS line and; addition to the line that connects the aeration tank to the secondary clarifier. Dosing to the RAS line has been the most effective and is the most widely used. In plants with long hydraulic retention times (HRT), the daily solids flux is too low to allow RAS chlorination. Petchul et al. (1991) added chlorine at the aerator to allow for proper mixing of the chlorine with the activated sludge in their long SRT plant.

Finally, control analyses must be done to monitor the progress of the chlorination program. Tests should include a measure of the sludge settling rate, a measure of the final effluent turbidity and microscopic observation of the sludge (EPA, 1987).

2.6.1.2 METHOD BY WHICH CHLORINATION AFFECTS BACTERIA

Both the filamentous and floc forming bacteria are adversely affected by chlorine. Chlorination exposes activated sludge to chlorine levels which damage the filament while leaving the floc largely untouched. The dosage is lethal at the floc surface but is consumed as it penetrates the floc and reduced to sublethal concentrations (Richard, 1989). Use of chlorine only controls the extension of filaments from flocs. If the cause of the bulking has not been investigated and corrected the filaments will return in even greater numbers when chlorination is terminated.

The direct effects of chlorination on the filaments include loss of any sulphur granules that may be present, cell deformity and cytoplasm shrinkage, and filament break-up and lysis in which the filament detaches from the sheath and "balls" up. Gaps will start to appear in the sheath due to cell disappearance. The sheaths, however, will remain because they are not destroyed by the chlorine. Settling will remain poor until they are washed out through sludge wasting. Chlorination should be halted once the empty sheaths are visible in the sludge. Continuing the addition of chlorine until the SVI decreases will result in overchlorination (EPA, 1987; Richard, 1989). In his earlier work, Jenkins et al. (1982) stated that once stabilization began with a coincidental reduction in SVI the dose should be slowly decreased to zero. This means that once the target SVI is approached the chlorine dose should be zero.

The manifestations of overchlorination include turbid effluent due to the destruction of the flocs into pin floc and a reduction in the reactor's ability to remove BOD. If large once-a-day batch doses are used to control the filaments the effluent will turn milky due to the large amount of debris formed when the flocs were destroyed. This results in a high effluent solids value. After twenty-four hours the turbidity should clear up and the settleability of the sludge should improve markedly.

An argument against chlorination is the possible formation of chlorine by-products. This is highly unlikely because the chlorine reacts very rapidly with the ammonia and micro-organisms present and is used in only very small doses.

2.6.1.3 CHLORINATION DOSING PARAMETERS

Four chlorine dosing parameters exist. They are defined below:

Overall mass dose rate, T:

$$T\ (g\ Cl_2 \cdot g\ SS^{-1} \cdot d^{-1}) = \frac{M}{V_1\ x_1 + V_c\ x_c} \tag{2.4}$$

Dosed chlorine concentration at the chlorine dose point, C:

$$C\ (g\ Cl_2 \cdot L^{-1}) = \frac{M}{Q} \tag{2.5}$$

Local mass dose rate at the chlorine dose point, T_m:

$$T_m\ (g\ Cl_2 \cdot g\ SS^{-1}) = \frac{M}{Qx_q} \tag{2.6}$$

Exposure frequency of activated sludge to chlorine dosing, f:

$$f\ (d^{-1}) = \frac{Qx_q}{V_1\ x_1 + V_c\ x_c} \tag{2.7}$$

where M = chlorine application rate ($g\ Cl_2 \cdot d^{-1}$)
x = suspended solids concentration ($g \cdot L^{-1}$)
V = volume (L)
Q = flow rate of stream into which chlorine is dosed ($L \cdot d^{-1}$)
$_c$ = clarifier
$_1$ = aeration basin
$_q$ = stream into which chlorine is applied.

According to Richard (1989) the two most important of these parameters are the overall chlorine dosage and the frequency of exposure of the activated sludge to the chlorine. Concentrations of chlorine used are expressed as a dose rather than as a residual because the residual will depend on the situation. Dose determination should begin with a low dose and increase gradually (Neethling et al, 1987). The sludge condition should improve within one to three days if the correct dosage is being applied. In dosing the RAS line, most plants can expose the activated sludge inventory to chlorine three or more times per day. Required dosing frequency is a function of the relative growth rates for filaments and floc formers and the dose effectiveness. The frequency of chlorination required to control filamentous bacteria is plant specific. Jenkins et al (1982) stated that long SRT systems with typical overall mass dose rates, T, will have a high dosed chlorine concentration at the dose point, C and low exposure frequencies, f, due to the large sludge inventory present. Large sludge inventories may not allow RAS chlorination to work. Petchul et al (1991) found this to be the case in their activated sludge system which was operated at an HRT of 3 to 4 days and an SRT of 20 to 40 days. Therefore, they added chlorine on a continuous basis directly to the aeration basin at a rate that corresponded to a dosage of 5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$.

Effective chlorine doses are in the range of 1 to 10 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ (Richard, 1989). Jenkins stated that chlorine doses of 2 to 15 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ have been used to successfully control filaments. A small full-scale reactor that experienced filamentous bulking was discussed in a paper by McCartney (1991). Excessive doses of 22 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ were required to bring the bulking under control. Therefore, defining the magnitude of the chorine dose required for sludge bulking control is difficult due to the large number of factors involved.

2.6.2 PLANT CONFIGURATION

In order to understand how reactor configuration affects filamentous bulking, the principle of microbial selection must first be explained. At low concentrations of substrate, nutrients or dissolved oxygen, filamentous bacteria are favoured over floc formers due to their higher surface to volume ratios (Figure 2.6). Once the filaments have begun to stick out into the bulk liquid they are subjected to higher concentrations of substrate than available in the floc interior where diffusion and competitive uptake reduce the available substrate. Therefore, the filaments grow even faster (WPCF, 1990). At higher concentrations of substrate, nutrients and dissolved oxygen, the floc formers will be favoured because they have a more economical metabolism of their reserve materials as compared to the filaments (Van den Eynde et al, 1982).

Chiesa and Irvine (1985) proposed in their hypothesis on filamentous bulking that intermittently fed systems are able to provide specific conditions which are unfavourable for the growth of all types of filaments. The effectiveness of the intermittent feeding pattern is dependent on the proper balancing of feast and famine conditions so that the physiological weaknesses of the filamentous microbes can be selectively exploited. Systems that have an intermittent feeding pattern have the potential to extend the reliable operating range of activated sludge facilities in not only the

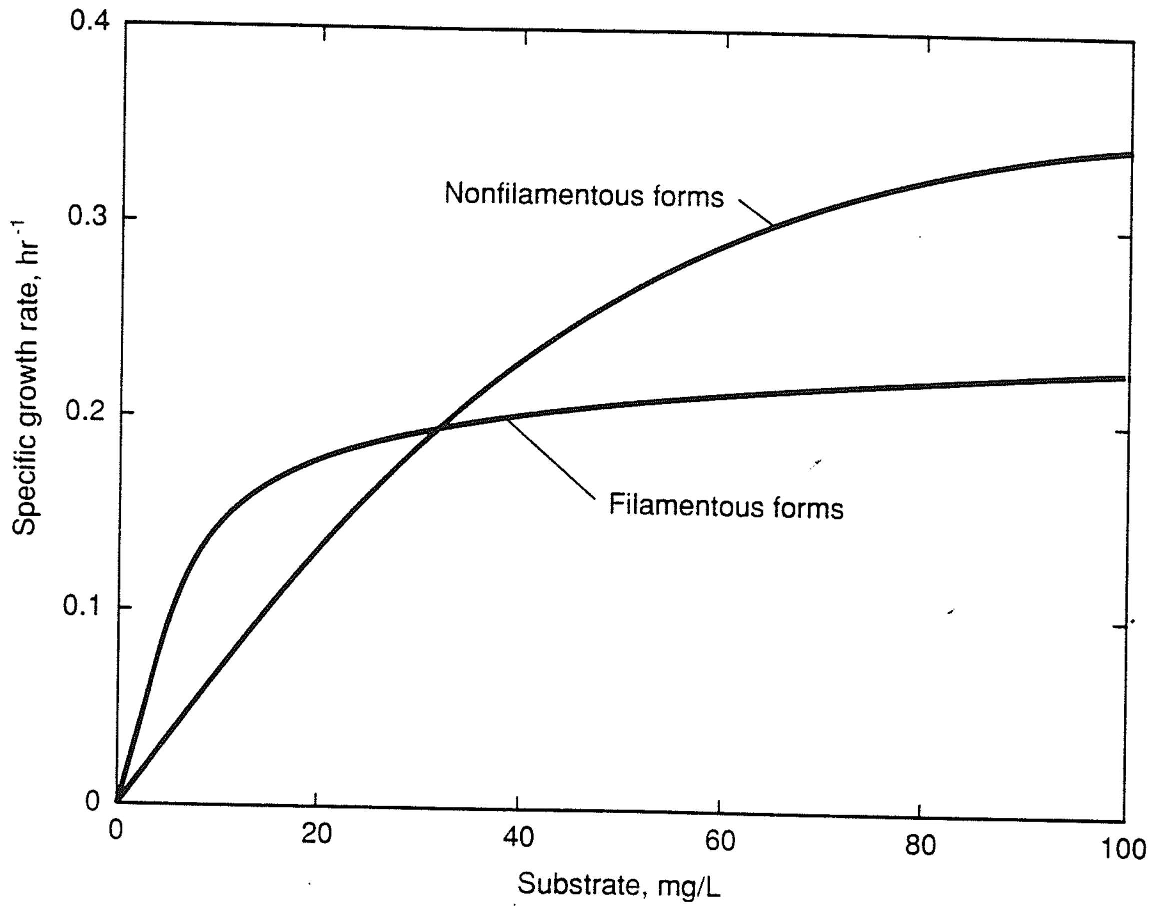

Figure 2.6. Typical growth curves for filamentous and non-filamentous organisms.

cases of domestic waste waters but also those that are synthetic or industrial in nature. Therefore an intermittent feeding pattern can be used to combat a wide range of different filament problems caused by different physiological conditions. Research conducted by Clesceri (1963) found that the intermittent feeding of substrate improved the settling characteristics of an activated sludge, which agrees with the hypothesis of Chiesa and Irvine (1985).

Chudoba et al (1974) and Lee et al (1982) warn that a specific reactor configuration or an observed substrate concentration will not guarantee a good settling sludge. This view was reinforced by the findings of Chudoba et al (1973), who stated that the primary cause of selection is the actual concentration of substrate at the tank inlet which is determined by the degree of mixing. Therefore, a concentration gradient with little or no mixing was required. Then, Chudoba et al (1982) showed that a substrate gradient was not sufficient to eliminate filaments. Filament suppression required that intermittent feeding be initiated. Pujol and Boutin (1989), however, stated that activated sludge plants in France have been successful in overcoming bulking problems by resorting to load gradients which concentrate more of the feed at the beginning of the reactor.

According to Chambers (1982), the remedy for continuous flow stirred tank reactors is to make them more like one of the systems that exhibits reduced bulking. Compartmentalization of the tank, batch feed operation and the intermittent feeding of the waste water are means by which this conversion can be accomplished. He found that long retention times were required to achieve good settling if a high degree of longitudinal mixing was present in the activated sludge reactor. Chambers determined that plug flow configurations produced better sludges than CFSTR configurations.

The findings of Chambers are further supported in a paper by Chudoba et al (1991). They determined that compartmentalized systems which very closely approximate a plug flow configuration had a greater potential to suppress filamentous bulking as indicated in Figure 2.7. The advantage of the compartmentalized system over the CFSTR in controlling filamentous bulking is clearly evident. A compartmentalized system differs from a CFSTR in that the exogenous and endogenous periods are alternated. Therefore, strong selection pressures are exerted on the micro-organisms which favour those with the capability to accumulate and store substrate. Selection pressures allow the floc forming bacteria to be selected over the filamentous bacteria.

When the transition from batch to continuous systems began in the 1920's, the first reactors were plug flow in character (Tomlinson, 1982). Plug flow reactors generally had very high length to width ratios which ensured that the BOD was fully oxidized by the time the waste water reached the

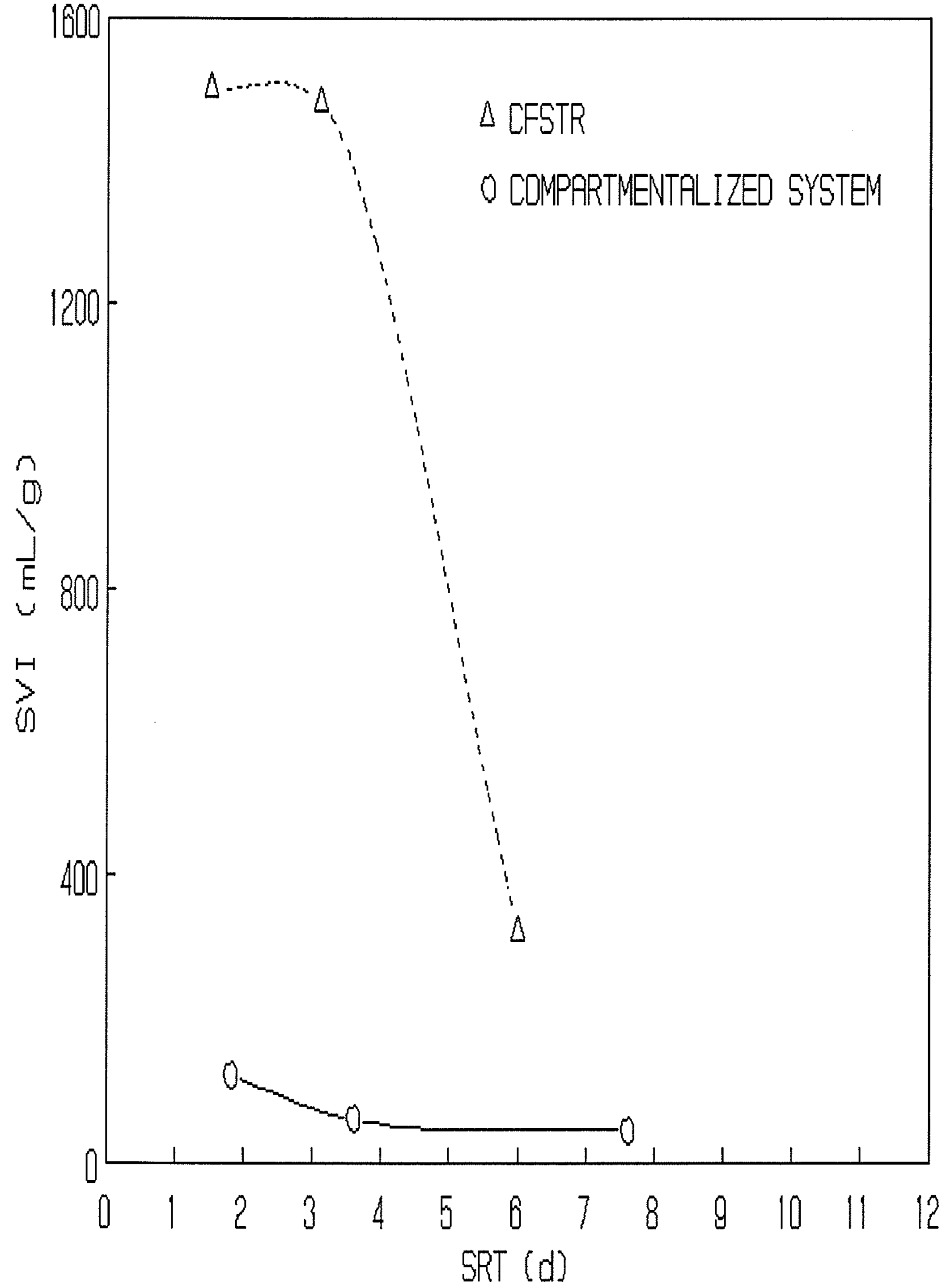

Figure 2.7. Effect of solids retention time (SRT) on sludge volume index (SVI) for continuous flow stirred tank reactor (CFSTR) and compartmentalized systems. After Chudoba et al (1991).

reactor outlet. Therefore, a high BOD concentration was brought in contact with the sludge that favoured the floc formers. Waller et al (1982) expressed their belief that plug flow configurations produced sludges of superior quality to those produced in a CFSTR.

Continuously fed systems can also be designed to control filamentous growth. The range over which these systems can be reliably operated, however, is narrower than that for intermittently fed systems operated under the same general conditions (Chiesa and Irvine, 1985).

Several means of controlling the length of feast and famine periods exist. One of these is conversion to an SBR system. This system can be adjusted to meet seasonal, daily and hourly changes in flow and waste strength by simple adjustment of the relative time dedicated to unaerated fill. In the initial fill and draw systems a large volume of sewage was combined with a small amount of sludge in a short time period which selected floc formers over filamentous bacteria (Tomlinson, 1982). Tomlinson found that similar sludges were produced by fill and draw and highly plug flow systems.

Dennis and Irvine (1979) noted that the settling characteristics for organisms developed in a SBR depend upon the fill:react ratio, which in turn affects the maximum concentration in the reactor. SBR's are capable of very rapid improvements in settling characteristics, as shown in the full scale study carried out at Culver, Indiana. Chudoba et al

(1973) found that systems that run in a batch mode had noticeably fewer filaments than those operated in a continuous mode. The case for using SBR's to control bulking is reinforced by these findings.

2.6.3 NUTRIENT ADDITIONS

Nitrogen and phosphorus have been found to be growth limiting when they are deficient; as in the case of some industrial wastes. Other nutrients such as sulphur and iron have also been pinpointed as having nutrient deficiencies in some cases of sludge bulking. Nutrients can be added to the incoming waste or directly to the aeration basin.

Only in combined domestic and industrial treatment should influent ammonia and phosphates be used to determine the nutrient availability. The organically combined nitrogen and phosphorus present may not be hydrolysed fast enough to keep up with BOD use, resulting in a nutrient deficiency, which will in turn cause filaments. Nutrient addition rate should match influent BOD as much as possible, including spikes which could cause the aeration basin to become nutrient limited for short periods of time (Richard, 1989; WPCF, 1990). Smaller surface areas are necessary for adequate nutrient assimilation when higher concentrations of dissolved phosphates are present in the waste water. Floc formers will therefore be favoured by these conditions.

3. NITRIFICATION

Nitrification occurs in two steps. The first step results in the conversion of the ammonia to nitrite by the bacteria Nitrosomonas. Nitrobacter convert the nitrite to nitrate in the second step of this process. The reactions involved in both steps of the nitrification process are given below:

Reaction for Nitrosomonas

$$55NH_4^+ + 76O_2 + 109HCO_3^- \rightarrow C_5H_7O_2N + 54NO_2^- + 57H_2O + 104H_2CO_3 \tag{3.1}$$

Reaction for Nitrobacter

$$400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- \; 195O_2 \rightarrow C_2H_7O_2N + 3H_2O + 400NO_3^- \tag{3.2}$$

McCartney (1988) determined that nitrification followed zero order kinetics.

Ganczarczyk (1983) stated that nitrification rates are affected by dissolved oxygen concentration, pH, temperature, BOD_5 to total Kjeldahl nitrogen (TKN) ratios and differing sludge ages. Even when nitrification is carried out in a separate activated sludge reactor the nitrifying bacteria constitute only 10 percent of the microbiological population.

Nitrification is characterized by substantial oxygen requirements because the nitrifying bacteria have higher DO requirements than do other bacteria (Richard, 1989). Nitrifying bacteria have a stoichiometric oxygen requirement of 4.57 g $O_2 \cdot (g\ NH_3\text{-}N)^{-1}$, excluding the role of microbiological synthesis which decreases the requirement by eight percent. Ganczarczyk (1983) reported that the influence of DO on nitrification is not well understood. Data from combined carbon oxidation and nitrification systems indicates that the process can be carried out at DO concentrations as low as 0.5 $mg \cdot L^{-1}$. Increased concentrations of DO enhanced the process kinetics.

Nitrification is also characterized by the decrease in waste water alkalinity that it causes. Stoichiometric requirements are 7.14 g $CaCO_3 \cdot$(g NH_3-N oxidized)$^{-1}$. This requirement is affected only marginally by biosynthesis and may result in a drop in pH. Optimum pH's are in the range of 7.5 to 8.5. Moderate pH drops are inhibitory but not toxic. Nitrifying bacteria can be acclimated to pH values outside this range. When waste waters low in ammonia are treated, the pH should be maintained between 7.6 and 7.8 to allow any carbon dioxide produced to escape. Heavy metals are strongly inhibitory in ionic form. If the pH is maintained within the optimal range, the heavy metals are relatively insoluble and do not affect nitrification at concentrations of 10 to 20 $mg \cdot L^{-1}$.

Temperature effects on the nitrification follow the Van't-Hoff Arhenius rule fairly well between 4°C and 35°C. The presence of free ammonia affects Nitrobacter more than Nitrosomonas. Concentrations at which free ammonia becomes inhibitory are affected by temperature, the number of nitrifying bacteria and prior exposure to the inhibitor (Ganczarczyk, 1983).

Nitrifying bacteria have a net growth rate only five to ten percent that of the BOD removing bacteria. Therefore nitrifying bacteria require sufficiently long SRT to proliferate. Systems with short SRT values will have difficulty nitrifying while those with longer SRT will be able to achieve complete nitrification.

It is desirable in activated sludge systems to maintain low numbers of filamentous bacteria and nitrification simultaneously. Therefore, the result of chlorine addition to activated sludge must be investigated.

Unpublished observations have suggested that nitrifying bacteria populations are not associated with the larger sized flocs in an activated sludge. This could result in a nitrifying bacteria population which is not "floc-protected" from chlorine. Therefore, nitrifying bacteria are more susceptible to inhibition than the bacteria responsible for the oxidation of the carbonaceous substrate present.

It is reported in the literature (Neethling et al, 1985) that when chlorine is added to an activated sludge possessing the correct amount of ammonia to result in a Cl_2:NH_3-N ratio less than 2.5 g $Cl_2 \cdot (g\ NH_3\text{-}N)^{-1}$, monochloramine will form. Measurements by Neethling et al (1987) have shown that the activated sludge solids are responsible for more than 87 percent of the total chlorine demand when free chlorine reacts with activated sludge solids and essentially 100 percent when monochloramine is used. Monochloramine has been reported to be quite stable in the presence of oxidizable material in potable water disinfection applications (AWWA, 1990; Kinman and Layton, 1976). However, the monochloramine residual was consumed in a matter of minutes due to its diffusion through the cell wall in a filamentous bulking control application (Neethling et al, 1985). Several factors determine the rate at which the reaction proceeds including the chlorine residual type, the suspended solids concentration, pH and the presence or absence of reducing compounds such as ammonia, nitrites or sulphides. Recommended doses of chlorine for nitrifying plants with typical municipal configurations are less than 5.0 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ (Jenkins et al, 1982).

4. OBJECTIVES

4.1 PORTAGE LA PRAIRIE PILOT PLANT OBJECTIVES

Due to the severe filamentous bulking problems that occurred in the activated sludge reactors used in the Portage La Prairie study, the main objective of this phase of the research was to determine the cause of the filaments. The effects of chlorination, as a short term solution to the bulking problem, were also investigated. The usefulness of microscopic observations as an indicator of filamentous bulking was also studied in this phase of the research.

4.2 SEQUENCING BATCH REACTOR STUDY OBJECTIVES

One goal of the second phase of the research was to determine the cause of the filamentous bulking that occurred in the Portage La Prairie pilot plant. The other goal of the research was to investigate the effects of low once-a-day batch doses of chlorine for filamentous bulking control on nitrifying bacteria present in the sludge.

5. MATERIALS AND METHODS

Two distinct phases existed in the research which was conducted. The first consisted of a pilot scale treatability study of anaerobically-pretreated vegetable processing wastes combined with municipal waste water in Portage La Prairie, Manitoba. The second phase included SBR treatment of two waste waters: one was the anaerobically-pretreated vegetable processing waste water combined with a synthetic domestic sewage and; the second was the synthetic domestic sewage alone.

5.1 PORTAGE LA PRAIRIE PILOT PROJECT

Portage La Prairie has a population of roughly 15 000 people and is located in south central Manitoba. Its industrial park contains three major waste water contributors. Potato and pea processing waste discharges were sent to an industrial park lift station. From here, the wastes were conveyed to the municipal treatment plant. These two sources produced eighty percent of the total BOD load of 12 900 $kg \cdot d^{-1}$ and only twenty percent of the present hydraulic load of 14 900 $m^3 \cdot d^{-1}$ (Oleszkiewicz et al, 1989). The third waste water contributor was a soup producer. Waste waters from this plant were discharged directly to the municipal sewer system. These waste waters presently overload the deep shaft reactor used in Portage La Prairie (Oleszkiewicz and Mateja, 1987). It has been proposed that some form of anaerobic pretreatment be installed for the two industries that discharge to the installed for the two industries that discharge to the industrial park lift station. The configuration chosen was a covered anaerobic lagoon under the trade name Bulk Volume Fermenter (BVF). The pilot scale system, as outlined in Figure 5.1, was assembled in the Sixth Avenue lift station in Portage La Prairie.

5.1.1 INDUSTRIAL TREATMENT TRAIN

The industrial wastes were pretreated by a pilot scale BVF whose performance has been described elsewhere (McCartney et al, 1990). During shut downs at the vegetable producers, frozen samples of effluent stored in metal drums were used to feed the BVF. The effluent from the BVF was pumped into a 1 L pre-aeration tank by a Masterflex peristaltic pump. An air to liquid ratio of roughly 100 L air$\cdot$L liquid^{-1} was maintained in the pre-aeration tank using a diffuser stone and an Aircadet pump. Effluent from the pre-aeration tank flowed by gravity into the 9 L industrial clarifier. The clarifier was made from 100 mm diameter plexiglass pipe. Hydraulic loading on the 1140 mm high clarifier was 0.74 $m^3\cdot(m^2\cdot h)^{-1}$. Solids were removed manually once a day by opening a drainage valve. Clarified waste water was discharged by gravity to the 150 L activated sludge feed tank. The feed tank was mixed by a submersible pump. A sampling pump collected a 24-hour composite sample from this container and conveyed it to a refrigerated container.

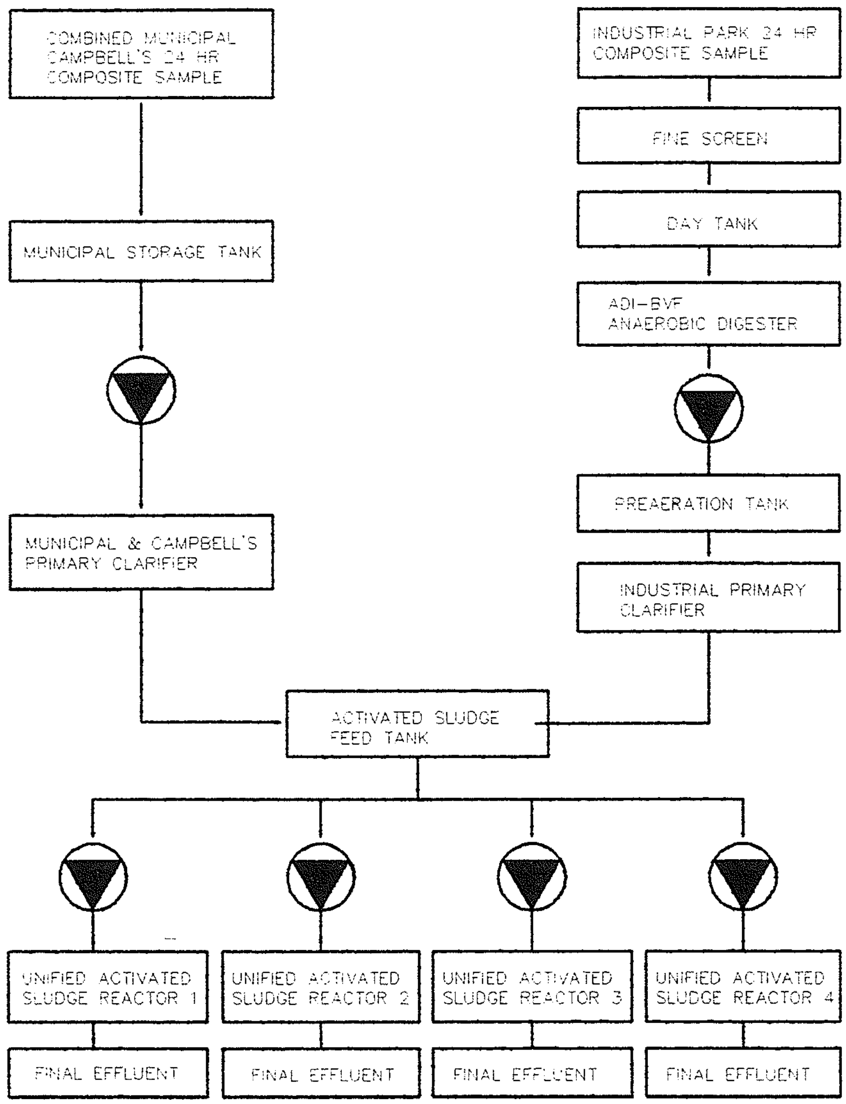

Figure 5.1. Portage La Prairie pilot plant layout.

5.1.2 MUNICIPAL TREATMENT TRAIN

Municipal waste water was collected from a ball valve tap on the force main in the Sixth Avenue lift station. The waste water was allowed to flow under pressure to a 250 L municipal storage tank. This tank was kept mixed by a large magnetic stirrer. From here, the waste water was pumped to the municipal clarifier using a Masterflex peristaltic pump. The clarifier was identical to the industrial clarifier in size and operated at an overflow rate of 1.41 $m^3 \cdot (m^2 \cdot h)^{-1}$. Effluent from the clarifier was discharged to the activated sludge feed tank using gravity flow.

5.1.3 ACTIVATED SLUDGE TREATMENT TRAIN

Industrial and municipal waste waters were mixed in the activated sludge feed tank using a sump pump. The combined waste water was pumped by Masterflex peristaltic pumps to the unified reactors which were modelled after Eckenfelder cells. The unified reactors had moving baffles which were designed to allow variable clarification and reactor volumes. Initially, a plexiglass baffle divided the reactor into a clarifier with a volume of 15 L and an aeration basin of 26 L volume. The reactors were aerated with a 0.75 hp oil-less air compressor. Each reactor also had an Aircadet pump and an aquarium diffuser to provide additional turbulence to keep the solids in suspension. All four reactors were contained in a water bath whose temperature was maintained at 16°C +/- 1°C using a

Brinkmann water circulator. The effluent from each reactor was discharged to an individual 200 L effluent container which was emptied daily.

5.1.4 TREATMENT TRAIN STERILIZATION

During steady state operation, the entire system was sterilized once a week. All of the tanks and clarifiers in the municipal and industrial treatment train were drained, sterilized with diluted chlorine bleach solution, and rinsed with copious amounts of water. The Tygon tubing joining the various tanks, clarifiers and pumps was also sterilized with a diluted chlorine bleach solution followed by a water rinse. This was done to avoid repeated contamination by the undesirable filamentous bacteria.

5.1.5 EXPERIMENTAL DESIGN

The steady state portion of the study consisted of two periods. First, an optimum solids retention time was sought. This was accomplished by operating the reactors for 24 days at a constant hydraulic retention time of 8 hours and SRTs of 3, 5, 8 and 12 days. The second phase of the study attempted to determine an optimum HRT for a pre-selected SRT. For 11 days, the reactors were operated at an SRT of 12 days and HRTs of 4,6,8 and 10 hours. Throughout the steady state operation of the reactors, it was necessary to undertake a chlorination program in order to control the growth of filamentous organisms. Operation of the pilot plant in Portage La Prairie in the initial months was unstable. Upsets and failures of the aeration system accounted for the lack of steady state process data until the twenty-third week of the study.

5.1.6 CHLORINATION PROGRAM

Chlorination was carried out with a 5.25 % sodium hypochlorite solution. The initial once-a-day batch doses of 5 and 10 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ were intended to rapidly attack the filaments present. Following the initial high once-a-day batch doses, doses of less than 5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ were applied. A timetable showing the magnitude of the once-a-day batch doses added to the reactors can be found in Appendix A.

5.2 SEQUENCING BATCH REACTOR STUDY

The second phase of this research was carried out in SBR's due to their ability to be controlled mechanically, reducing substantially the need for operator attention.

5.2.1 REACTOR CONFIGURATION

Four reactors containing sludge from Winnipeg's South End Treatment Plant were used in this portion of the study. They were 2 L in volume and constructed from clear plexiglass tubes 75 mm in diameter (Figure 5.2). Masterflex peristaltic pumps were used to feed each of the reactors and decant the supernatant after settling. Aeration was provided in the form

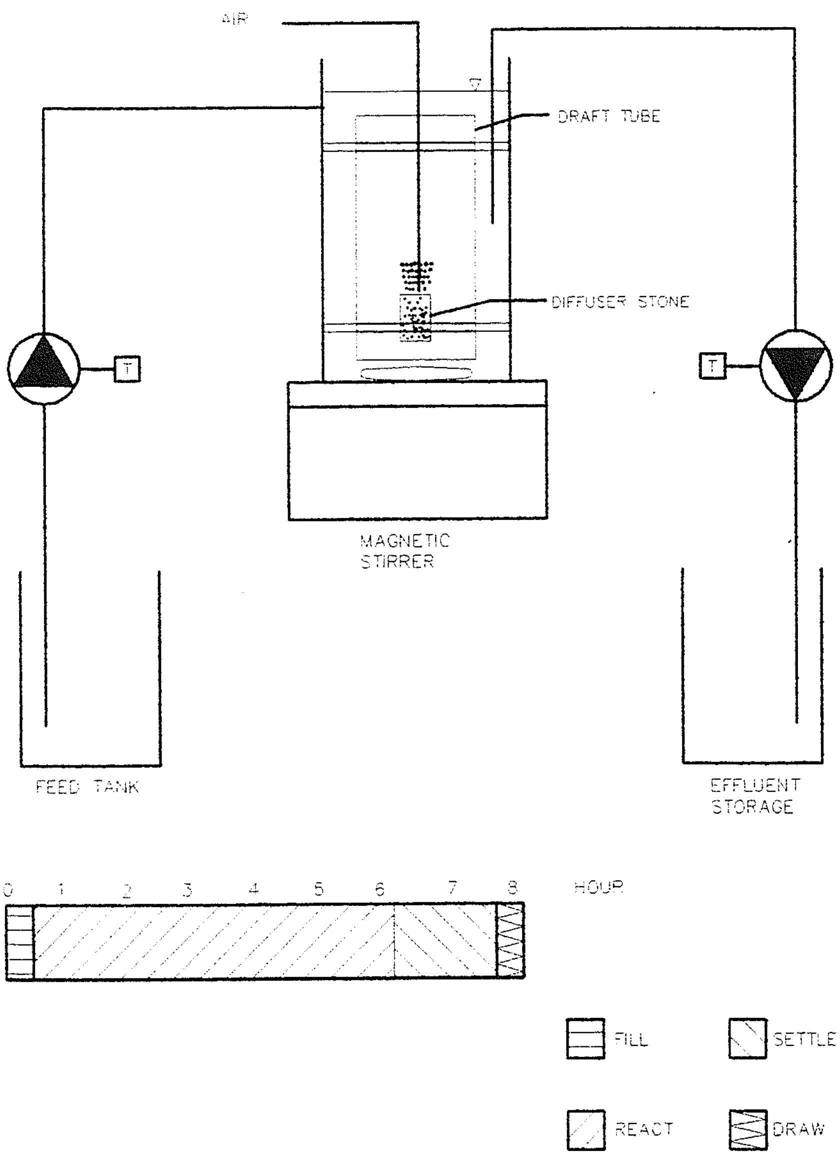

Figure 5.2. Sequencing batch reactor schematic.

of house air supplied by an air compressor. Diffuser stones were used in each reactor.

Mixing was provided in two forms. First, magnetic stirrers were placed below each of the reactors. Mixing was also provided in the form of draft tubes as illustrated in Figure 5.2. The aeration diffuser was placed inside the tube at the bottom which caused the liquid within the tube to rise thereby drawing more liquid through the opening at the bottom of the tube.

The SBR's were operated on an eight hour cycle. It began with a fifteen minute fill period. A six hour react period was initiated following the fill period. Settling of the sludge occupied the 90 minutes following the react portion of the cycle. Supernatant was removed in the last fifteen minutes of the eight hour cycle. The pumps and aeration system were turned off and on as required using a logic controller.

Sludge wasting was carried out manually. A valve on the side of the reactor was opened and the appropriate amount of sludge was allowed to flow out by gravity.

The entire experiment was housed in an environmental chamber maintained at 20 °C except for the feed for the reactors which was maintained at 4 °C in a neighbouring environmental chamber.

5.2.2 EXPERIMENTAL DESIGN

5.2.2.1 CAUSE OF FILAMENTOUS BULKING STUDY

Of the four reactors used, two were operated at an SRT of 3 d while the other two were set to an SRT of 12 d. The HRT was maintained at 16 hours in all of the reactors throughout the study. Two different feeds were fed to the reactors. One reactor at each of the SRT's was fed only synthetic waste prepared following the recipe of McCartney (1988). Components of this feed are outlined in Table 5.1. The other two reactors were fed combined BVF effluent and synthetic waste at a ratio of 1:2.8 starting on day 48. On day 61 the proportion of BVF effluent was increased to obtain a ratio of 1:1.9. The parameters of the BVF effluent are given in Table 5.2. Table 5.3 contains some of the monitored parameters for the two wastes fed to the SBRs.

5.2.2.2 EFFECT OF CHLORINATION ON NITRIFICATION STUDY

After it had been determined that the effluent from the BVF had resulted in few filaments, even at the ratio with more BVF effluent, the effects of low once-a-day batch doses of chlorine on nitrification were studied. Only the two reactors operated at the SRT of 12 days were used as the ones operated at shorter solids retention times did not exhibit nitrification.

Chlorine was added in the form of 5.25 percent sodium

Table 5.1. Synthetic waste components.

ELEMENT	CHEMICAL FORMULA	STOCK SOLUTION ($g \cdot L^{-1}$)	DILUTION
Casein hydrolysate	$C_8H_{12}N_2O_3$	38.33	1:200
Dextrose	$C_6H_{12}O_6$	200	1:800
Sodium acetate	$CH_3COONa \cdot 3H_2O$	111.2	1:200
Nitrogen	$(NH_4)_2SO_4$	12.76	1:100
Alkalinity	Na_2CO_3	26.5	1:100
Phosphorus	KH_2PO_4	26.37	1:1000
	K_2HPO_4	33.75	1:1000
Calcium	$CaCl_2 \cdot 2H_2O$	11.01	1:1000
Manganese	$MnSO_4 \cdot H_2O$	4.61	1:1000
Magnesium	$MgSO_4 \cdot 7H_2O$	42.58	1:1000
Iron	$FeCl_3 \cdot 6H_2O$	4.84	1:1000
Micronutrients Nickel	$NiCl_2 \cdot 6H_2O$	0.810	1:2000
Cobalt	$CoCl_2 \cdot 6H_2O$	0.808	1:2000
Copper	$CuSO_4 \cdot 5H_2O$	0.786	1:2000
Boron	H_3BO_3	1.144	1:2000
Zinc	$ZnSO_4 \cdot 7H_2O$	0.880	1:2000
Molybdenum	$(NH_4)_6Mo_7O_{24} \cdot 4H_2O$	2.576	1:2000
Aluminum	$AlCl_3 \cdot 6H_2O$	1.790	1:2000

hypochlorite solution. Once-a-day batch doses of 1.0, 1.5, 2.0, and 2.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ were used in the reactors. The chlorine was added to the surface of the sequencing batch reactor at the beginning of the second six hour react period

Table 5.2. BVF effluent parameters.

	MEAN ($mg \cdot L^{-1}$)	STANDARD DEVIATION ($mg \cdot L^{-1}$)
Soluble COD	940	280
Soluble BOD	590	145
Total organic carbon	378	not determined
Ammonia	202.1	not determined
Total Kjeldahl nitrogen	205.7	not determined
Total phosphorus	21.8	not determined
Sulphate	26.7	not determined

each day to determine its effect on the nitrification process.

5.3 ANALYSES

Both studies required the performance of a substantial

Table 5.3. Comparison of the synthetic and combined waste waters.

	SYNTHETIC WASTE	COMBINED WASTE BVF:MUNICIPAL	
		1:1.9	1:2.8
pH	9.06	8.44	8.09
SOC ($mg \cdot L^{-1}$)	160.5	142.8	135.2
NO_2-N ($mg \cdot L^{-1}$)	0	0	0
NO_3-N ($mg \cdot L^{-1}$)	0	0	0
NH_3-N ($mg \cdot L^{-1}$)	22.1	nd	76.5
TKN ($mg \cdot L^{-1}$)	36.2	nd	92.8

nd denotes analysis not performed.

amount of analyses. BOD, COD, SOC, TSS, VSS, DO, OUR, pH, orthophosphorous, total phosphorus, alkalinity and ZSV analyses were all performed in accordance with Standard Methods (APHA, 1989). SVI analyses in the first phase of the research were calculated from SSV values obtained in 100 mL graduated cylinders. For the SBR study, the SSV was determined insitu in the 2 L reactors and divided by two to determine the SSV for one litre. MO number determinations were carried out in both studies using the method outlined in Section 2.4.2 of this thesis.

The relative health of the nitrification process was monitored through influent total Kjeldahl nitrogen (TKN) and ammonia as well as effluent TKN, ammonia, nitrite and nitrate determinations. Influent nitrite and nitrate were monitored at first but were consistently found to be zero, allowing these determinations to be suspended. TKN and ammonia analyses were performed on a Kjeltec autoanalyzer while the nitrite and nitrate concentrations were determined on a Technicon autoanalyzer. All of the analyses were done in accordance with Standard Methods (APHA, 1989).

6. RESULTS AND DISCUSSION

6.1 CAUSES OF FILAMENTOUS BULKING

All four of the complete mix reactors in the first pilot phase of the research suffered from severe sludge bulking. Interfloc bridging resulted in SVI values of greater than 150 $mL \cdot g^{-1}$, which were considered high. Filamentous bulking was the cause of the high solids carry over and poor effluent quality that occurred. When investigating an activated sludge bulking problem, the first step is to determine the possible cause. Upon initial consideration of the data, nutrient deficiencies and reactor configuration looked to be the most likely of the filamentous bulking causes as mentioned by Pujol and Boutin (1989) and the WPCF (1990).

6.1.1 NUTRIENT DEFICIENCIES

The data obtained in the initial phase of the study indicate that phosphorus deficiencies could be responsible for the filamentous bulking that occurred. All four of the reactors were receiving excess amounts of phosphorus resulting in higher P:BOD ratios than the widely quoted P:BOD ratio of 1:100 (Metcalf and Eddy, 1991), as indicated in Figure 6.1. Near the bottom of the graph, there is a solid line indicating this ratio. Phosphorus additions were not sufficient, however, to meet the requirements quoted by Wagner (1982). Figure 6.2 shows the P:MLSS ratios calculated from the data obtained between 10 January and 30 March. The ratios were

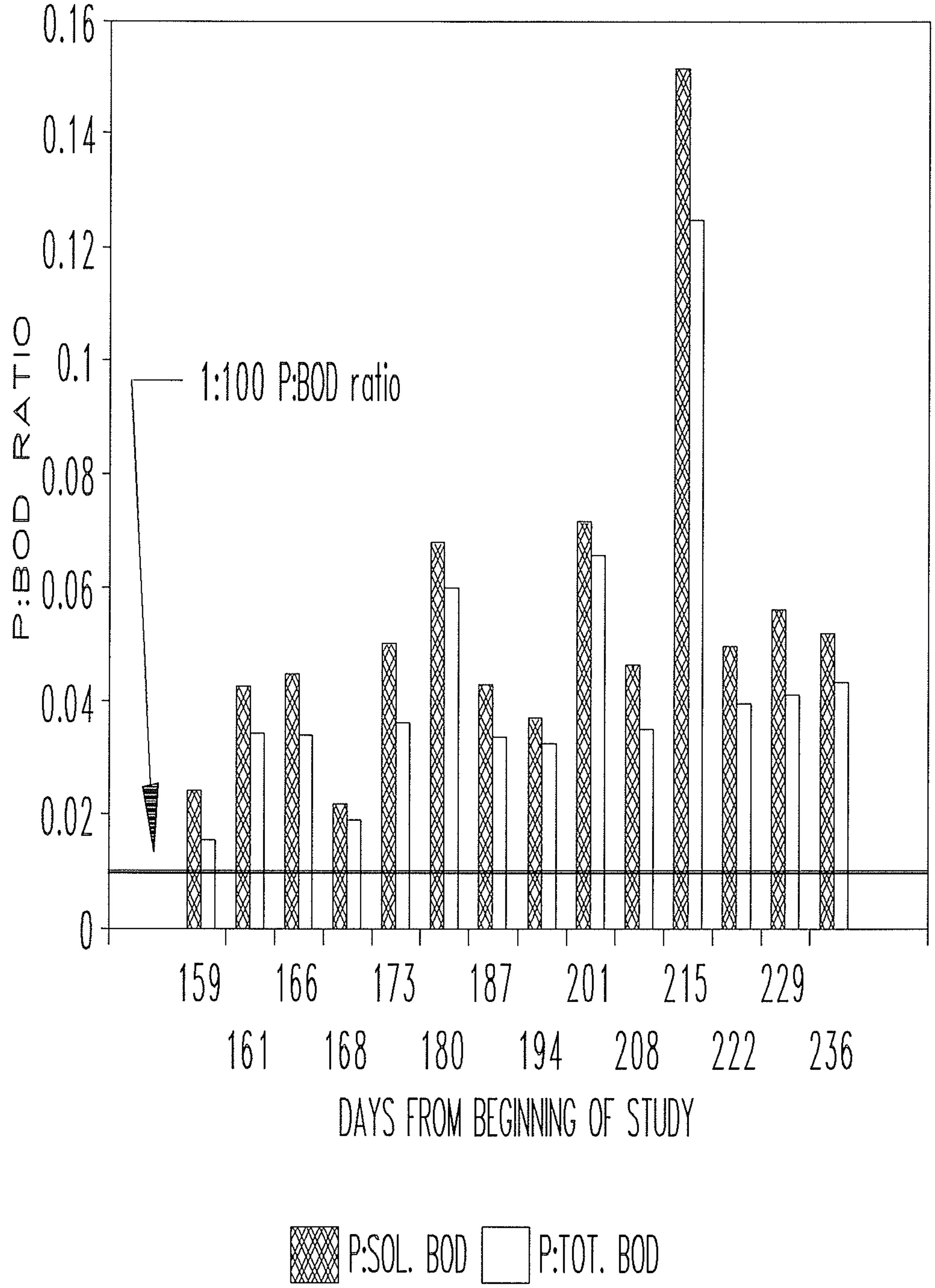

Figure 6.1. Influent P:BOD ratios for the initial phase of the study.

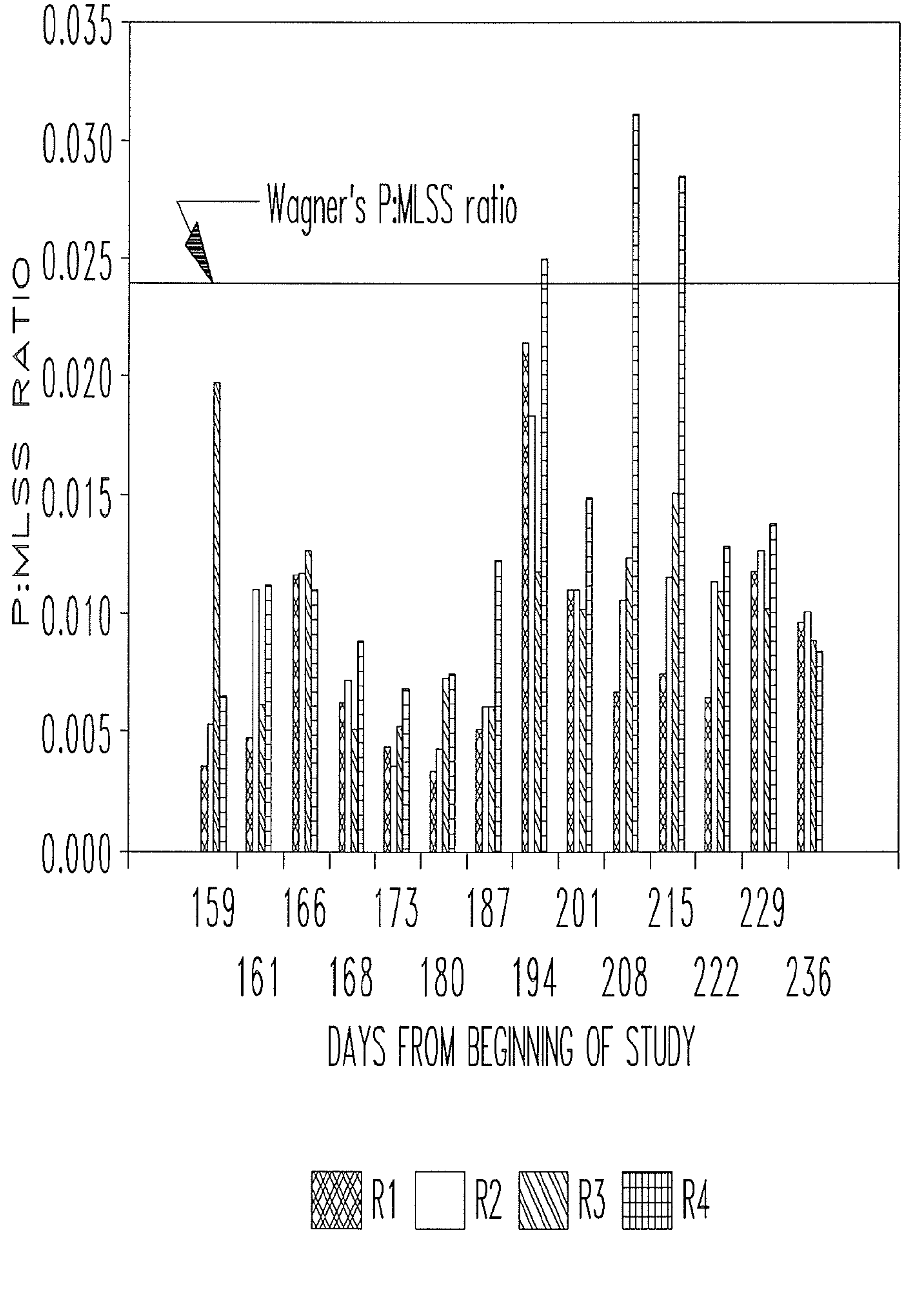

Figure 6.2. P:MLSS ratios for the four complete mix reactors in the initial phase of the study.

calculated as the total mass of phosphorus per day to the total inventory of sludge present in the reactor. Wagner (1982) stated that the ratio of phosphorus to organic mixed liquor suspended solids had to be three percent or greater to avoid bulking. In order to make a more direct comparison between this ratio and the data generated in this study, the ratio was converted to a P:MLSS ratio assuming that the MLVSS was eighty percent of the MLSS present. A solid line indicates the required P:MLSS ratio in Figure 6.2.

Table 6.1 supports the hypothesis that low P:MLSS ratios result in high SVIs and poorly settling sludge. P:MLSS ratios presented in Table 6.1 are each an average of four data points

Table 6.1. P:MLSS ratios and SVIs for the reactors in the initial phase of the study.

	P:MLSS RATIO (%)	SLUDGE VOLUME INDEX ($mL \cdot g^{-1}$)
R1	0.65	317
R2	0.88	321
R3	1.09	343
R4	0.94	406

from day 159 to day 168. No chlorination occurred during this time period. The SVI values are averaged from the ten sets of SVI analyses performed during the same time period. No correlation of the P:MLSS ratio to the MO number was possible because they were not performed until after chlorination had begun on day 189.

The P:MLSS ratios for the second phase of the research and the resultant SVIs are given in Figures 6.3 through 6.6. On each of the graphs are indicated three distinct phases which correspond to changes made to the feed for SBRs 3 and 4. During period A which lasted from day 1 to day 47, all four of the reactors were fed 36 mg of phosphorus daily. On day 48, period B began and the feed to SBR3 and SBR4 was modified to deliver 59.5 mg of phosphorus each day while the feed to SBR1 and SBR2 remained unchanged. When period C began on day 61, the amount of phosphorus added daily to SBR3 and SBR4 was increased to 68 mg. Figure 6.3 indicates that SBR1 met the suggested P:MLSS ratio regularly. SBR2 never reached a P:MLSS ratio of 2.4 percent (Figure 6.4). From Figure 6.5 it is clear that the suggested P:MLSS ratio was met all of the time in the last two periods of the study and most of the time in the first. The fourth SBR did not attain the suggested ratio at all in the first two periods and only seldomly in the third (Figure 6.6). The SVIs indicated in these figures never reached 150 $mL \cdot g^{-1}$ which was assumed to represent a bulking sludge.

Table 6.2 below gives the average values of P:MLSS ratio and SVI for each of the three periods. It is clear that the SVIs never reached bulking levels even though SBR1 and SBR2 had values that increased significantly during the study period. Correlations were attempted with MO numbers but no relationships could be determined.

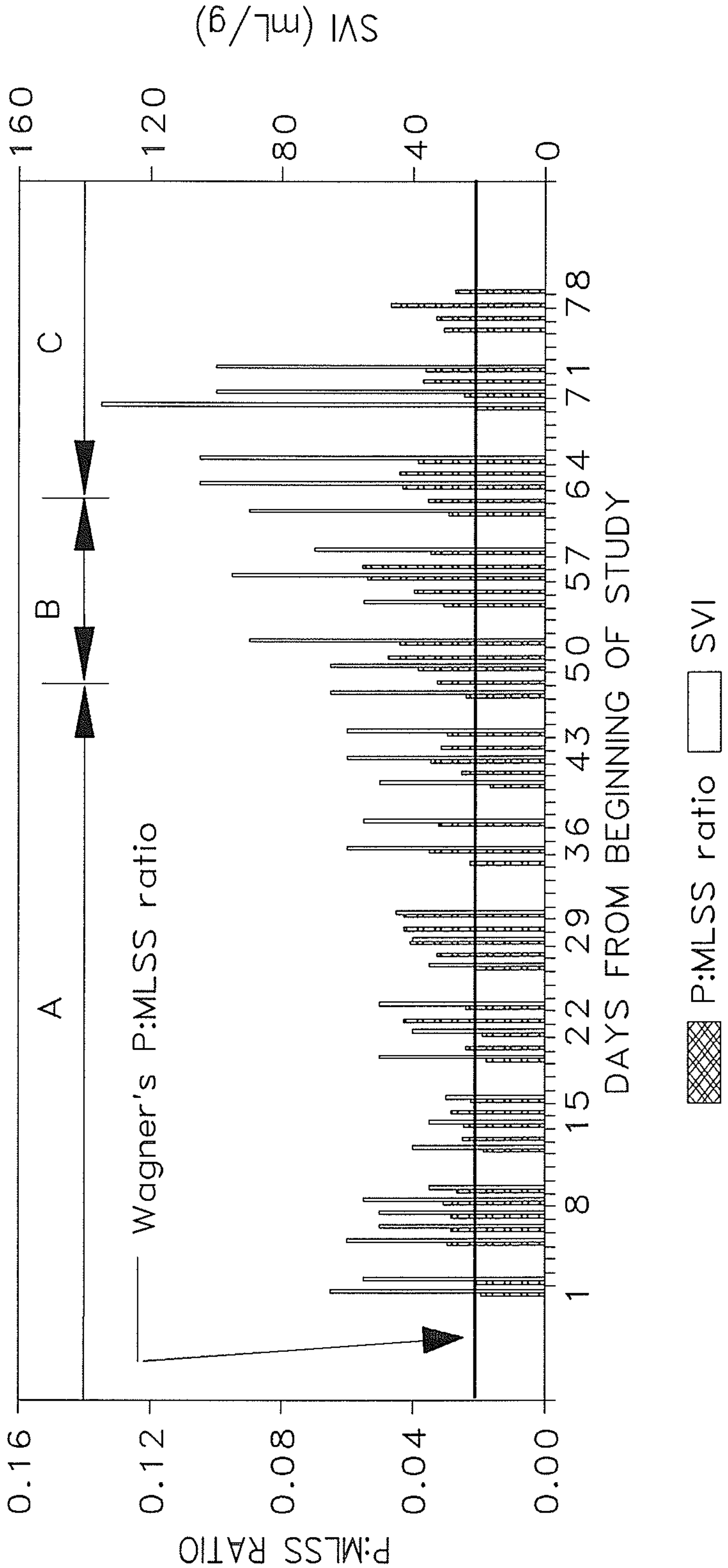

Figure 6.3. Sequencing batch reactor 1 P:MLSS ratios and resultant SVIs.

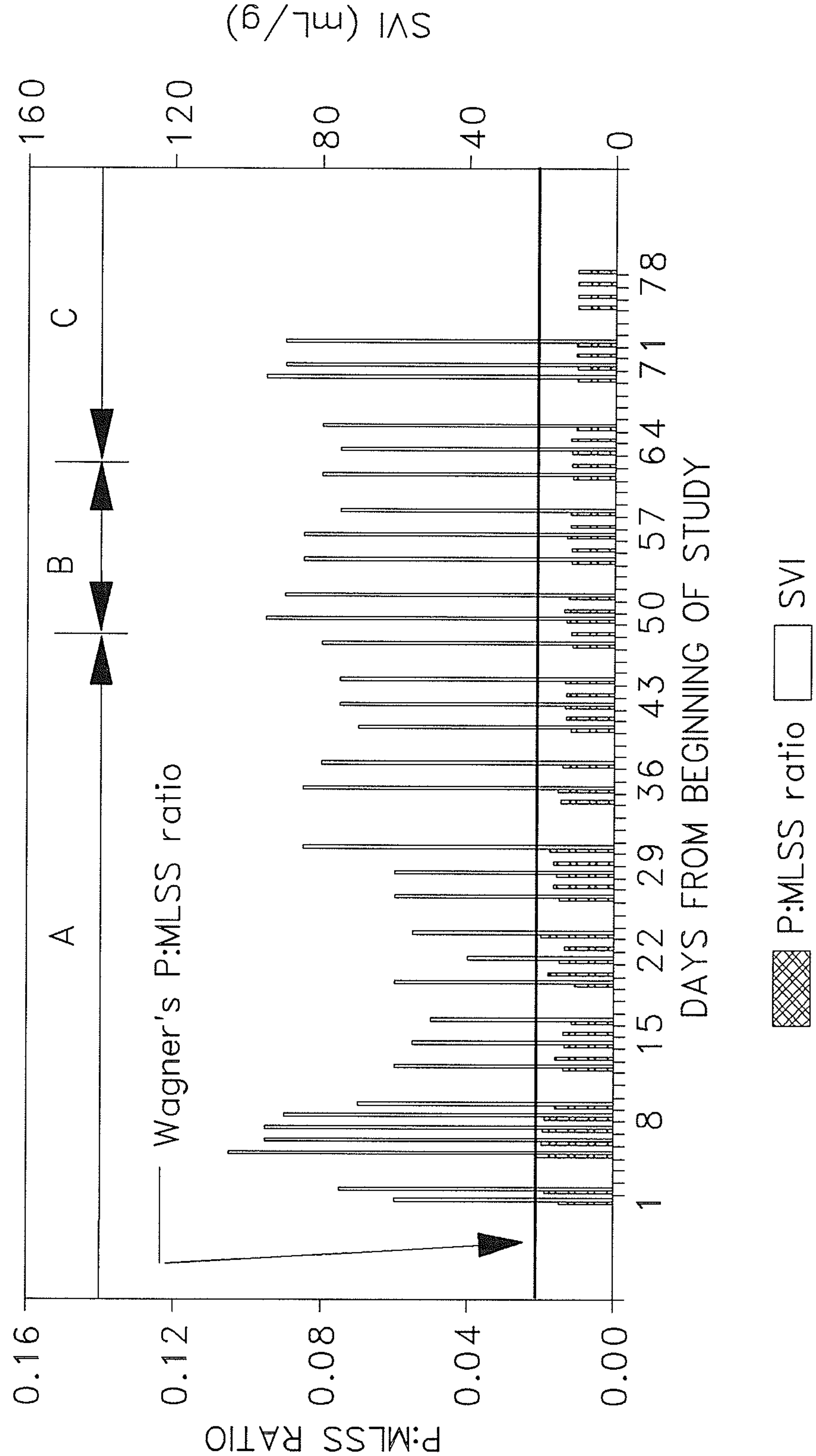

Figure 6.4. Sequencing batch reactor 2 P:MLSS ratios and resultant SVIs.

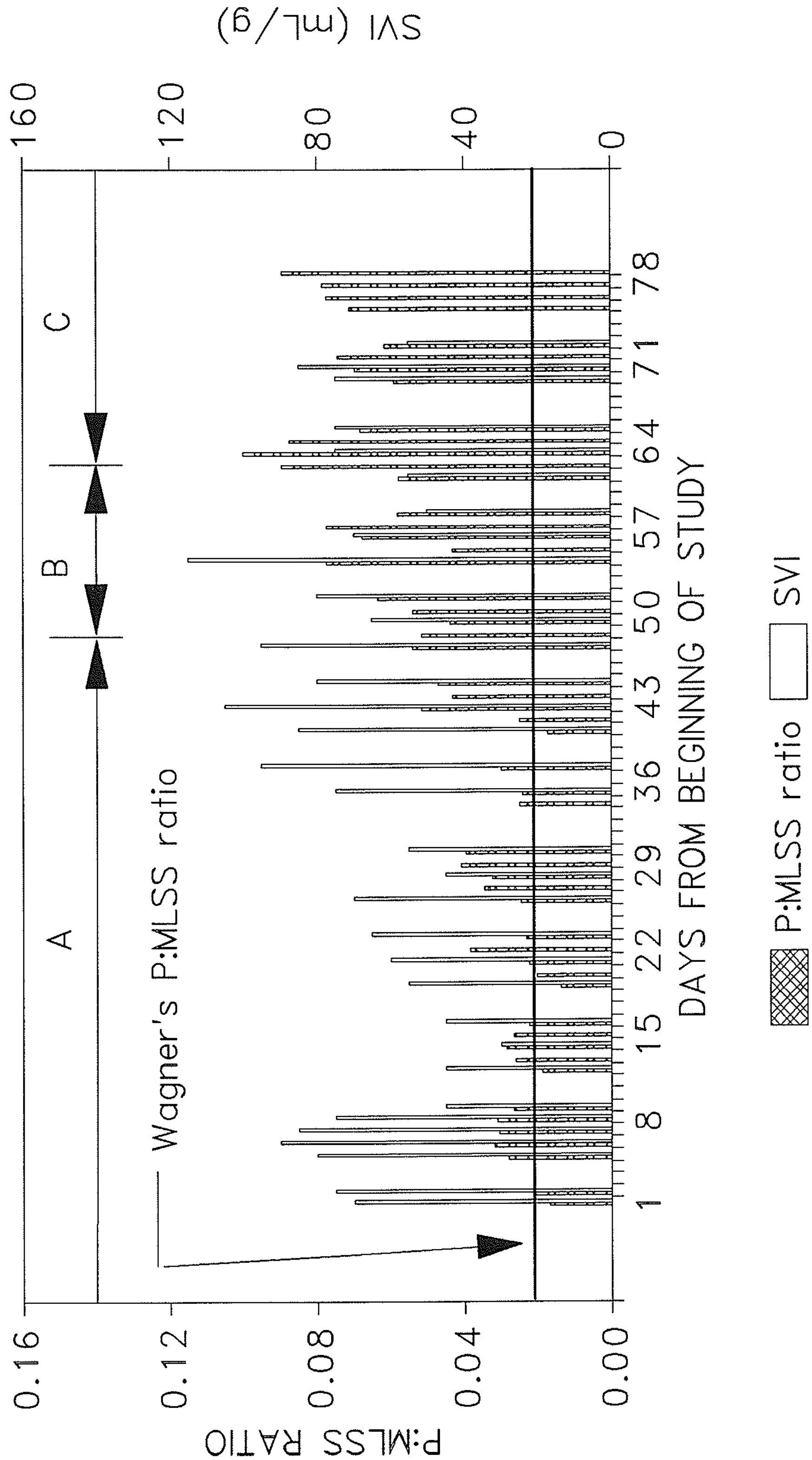

Figure 6.5. Sequencing batch reactor 3 P:MLSS ratios and resultant SVIs.

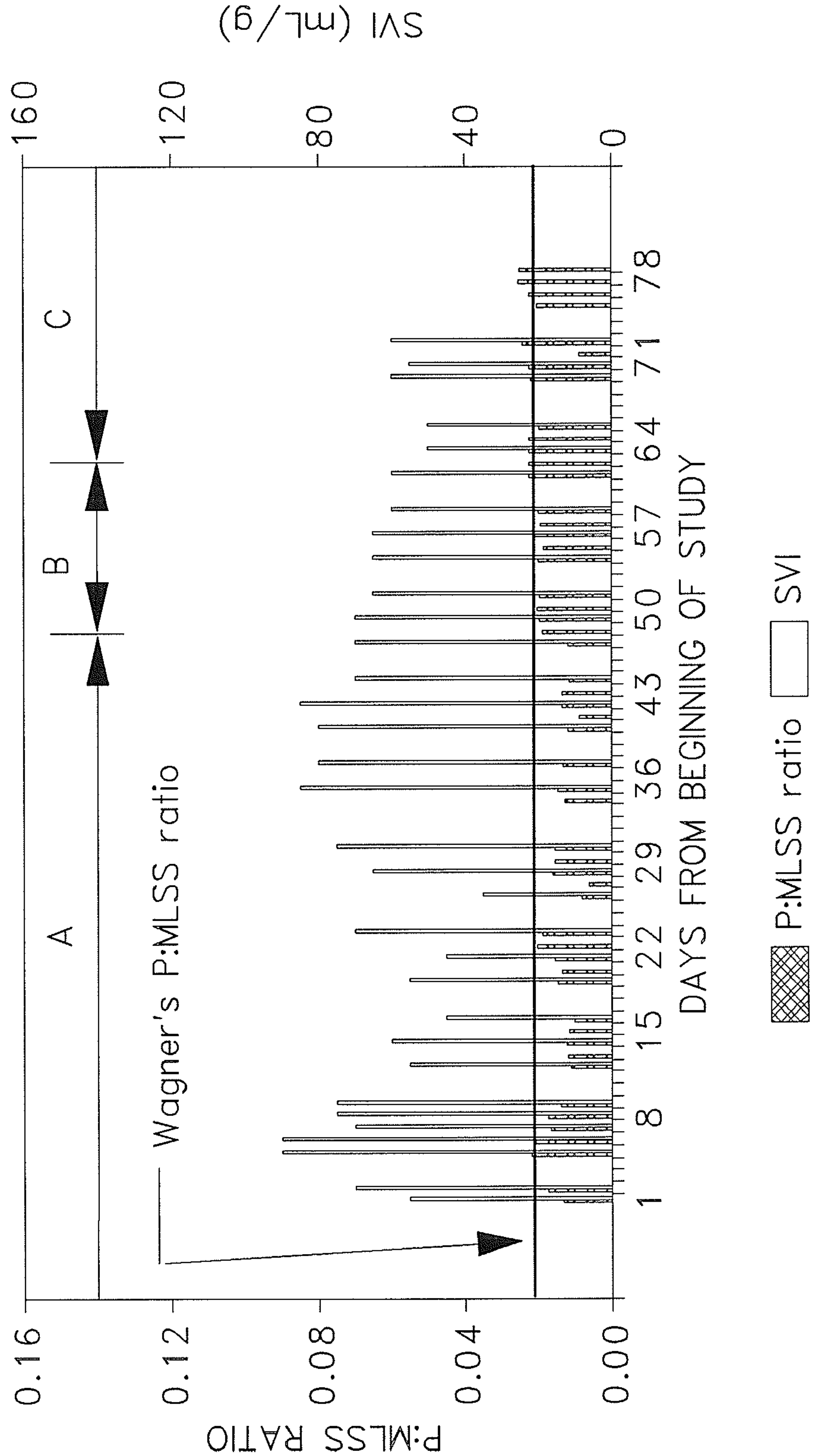

Figure 6.6. Sequencing batch reactor 4 P:MLSS ratios and resultant SVIs.

Table 6.2. P:MLSS ratio and sludge volume indices (SVI) for the four sequencing batch reactors in the second phase of the research.

	SBR1		SBR2		SBR3		SBR4	
	P: MLSS	SVI	P: MLSS	SVI	P: MLSS	SVI	P: MLSS	SVI
A	2.76	49	1.52	72	2.94	69	1.38	68
B	4.18	75	1.24	86	5.94	76	1.95	65
C	3.42	106	1.07	85	7.55	70	2.13	56

Data from Tables 6.1 and 6.2 are plotted in Figure 6.7. The points connected by the solid line in the Figure represent the curve shown in Figure 2.2 converted to a P:MLSS ratio from the P:MLVSS data assuming that the MLSS is eighty percent organic (Metcalf and Eddy, 1991). Extrapolation of the curve to higher P:MLSS ratios than reported by Wagner was performed to allow further comparison of the data to the curve. In the upper left portion of the graph, there are the points from the Portage La Prairie study. They are labelled R1 through R4. The remaining points on the graph labelled 1A through 4C represent the four SBRs in each of the three periods of operation.

All four of the CFSTRs fit closely to the curve that Wagner suggested. High SVIs resulted from the low P:MLSS ratios found in these reactors. SBR1 followed the general trend on the extrapolated curve. The deviations of the points 1A and 1C from the curve can be attributed to experimental variability. If the curve is extended to the right, SBR3 fit

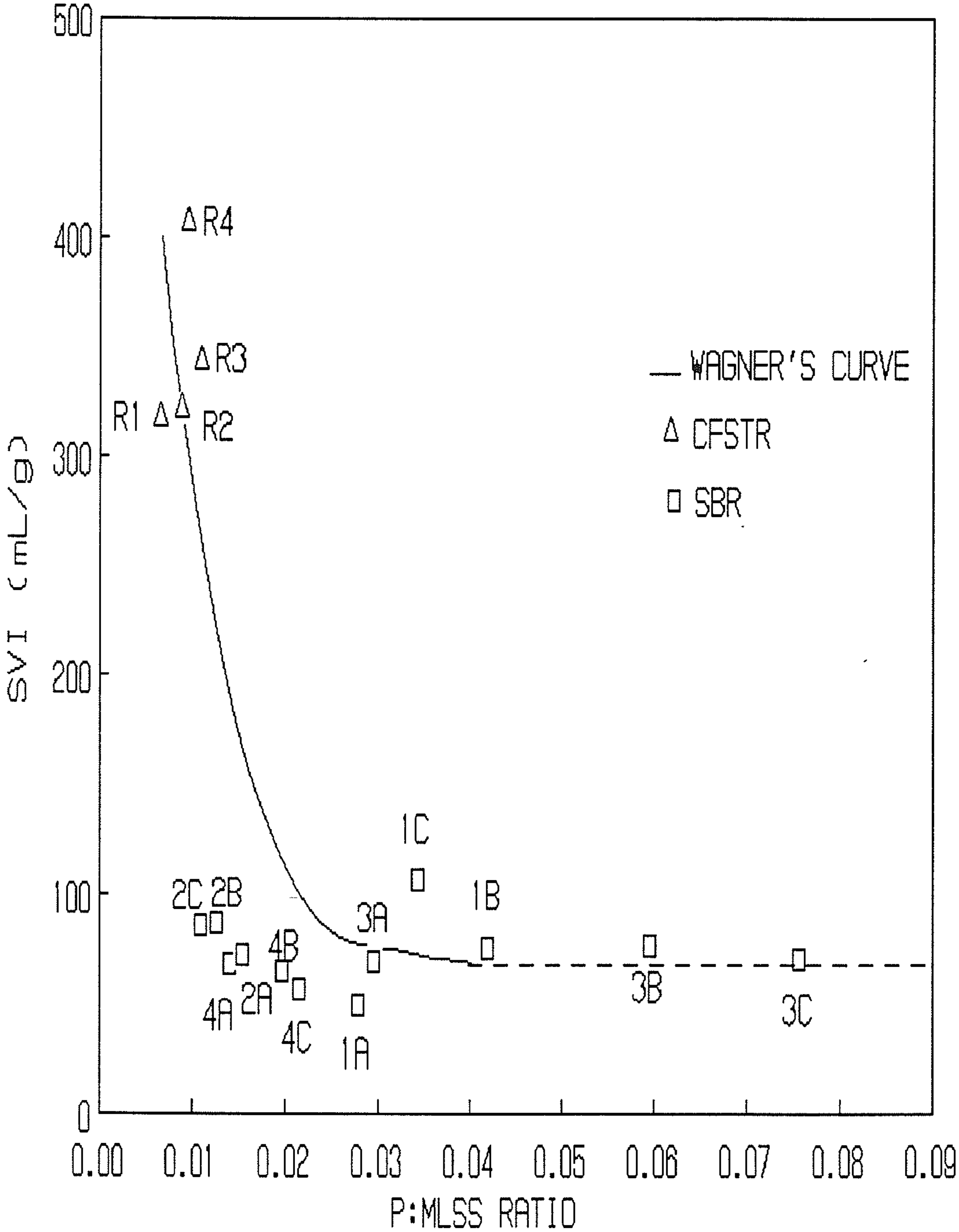

Figure 6.7. Effect of P:MLSS ratio on sludge volume index (SVI) including a comparison of the data to Wagner's extrapolated curve.

the curve as expected. Insignificant variation between the average SVIs for the points 3A, 3B and 3C indicate that once the P:MLSS ratio gets beyond 2.4 percent little or no additional benefit will be derived from increases in the P:MLSS ratio at short SRTs.

The other two reactors, however, did not follow the expected behaviour and require some explanation. For both SBRs, the points plotted for all three periods fell below and to the left of the curve in Figure 6.7. According to Wagner (1982) these reactors had a high probability to bulk because of the low P:MLSS ratio they had. Lower SVIs than expected were realized. Jenkins stated in his EPA manual on filamentous bulking (1987) that reactors with longer sludge ages required less nutrients because less sludge is produced to consume nutrients and the endogenous decay of the bacteria will recycle nutrients. When the bacteria die, the cells are broken down and any phosphorus in the cells will be released for use by the remaining bacteria. SBR2 and SBR4 both had a SRT of 12 d which was four times longer than the SRT in SBR1 and SBR3. It is, therefore, assumed that the low SVIs achieved in the long SRT reactors in spite of low P:MLSS ratios were the result of recycled phosphorus and added phosphorus from the feed to attain a P:MLSS ratio greater than 2.4 percent.

The concept of longer SRT batch reactors requiring less phosphorus in the feed is further supported by the work of

Greenberg et al (1955) who stated that sludge production determined the amount of phosphorus required. He operated reactors at P:MLSS ratios much lower than 2.4 percent. His reactors had calculated SRTs that ranged from 14.4 to 32.6 days with P:MLSS ratios that ranged from 0.01 to 0.72 percent. All of these reactors produced sludges that settled well.

The effect of the P:MLSS ratio on the specific growth rate, u, was investigated for all four of the SBRs in three study periods. It was expected that a relationship similar to the one determined by Wu and Okrutny (1982) in Figure 2.4 would result. Figure 6.8 shows the SBR data as circles. P:MLSS ratios were used to allow comparison of a wide range of reactors with different MLSS concentrations. Data calculated from the work of Greenberg et al (1955) and Helmers et al (1951; 1952) are indicated as triangles and squares respectively. All of the points in Figure 6.8 represent batch reactors with SVIs less than 150 $mL \cdot g^{-1}$. The values of the maximum specific growth rate, u_{max}, and the half saturation constant, K_s, were found to be 0.30 d^{-1} and 0.625 percent respectively from the Figure. It is interesting to note that the plateau in the graph begins at roughly 2.4 percent which corroborates the finding from Figure 6.7 that once the P:MLSS ratio of 2.4 percent is achieved little additional benefit will be gained from increases in the influent phosphorus concentration. Since this graph represents only those reactors with sludge that had SVIs less than 150 $mL \cdot g^{-1}$, one

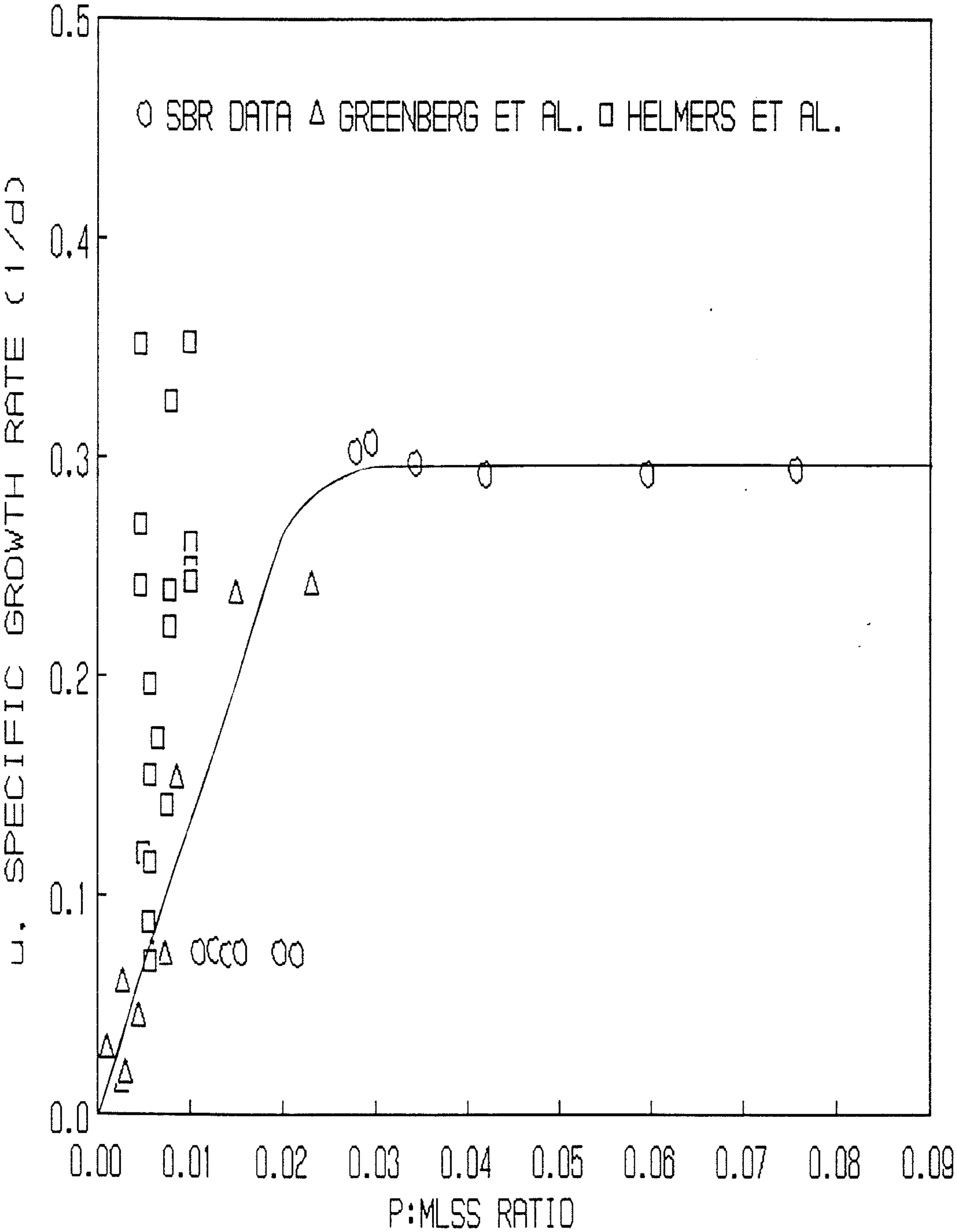

Figure 6.8. Effect of P:MLSS ratio on specific growth rate, u, for batch systems.

can assume that the specific growth rates shown represent mainly floc forming bacteria and their growth is a maximum when the P:MLSS ratio is at least 2.4 percent.

Even though Forster (1985) has stated that no single ratio works for all cases, the data presented in this study fits fairly well to Wagner's hypothesis with the exception that systems with long SRTs require less phosphorus in the feed because of less sludge production and their ability to get some phosphorus from the endogenous decay of bacteria.

6.1.2 REACTOR CONFIGURATION

It is apparent from the number of authors in agreement (Chambers, 1982; Chiesa and Irvine, 1985; Chudoba et al, 1973; Clesceri, 1963; Richard, 1989; and Waller et al, 1982) that CFSTR configurations are a poor choice if filaments are to be avoided. Due to the virtually instantaneous mixing that occurred in the reactors employed in the first phase of this research, the substrate that came into contact with the sludge inventory was quite dilute. Filamentous bacteria were favoured by presenting the sludge with low concentrations of substrate and phosphorus. Low concentrations of phosphorus resulted in nutrient deficiencies. Table 6.1 shows what effect the low concentrations of substrate and phosphorus had on the SVIs of the CFSTRs.

Figure 6.9 compares the data from the SBRs used in the second study phase to the data plotted in Figure 2.7. The SBR

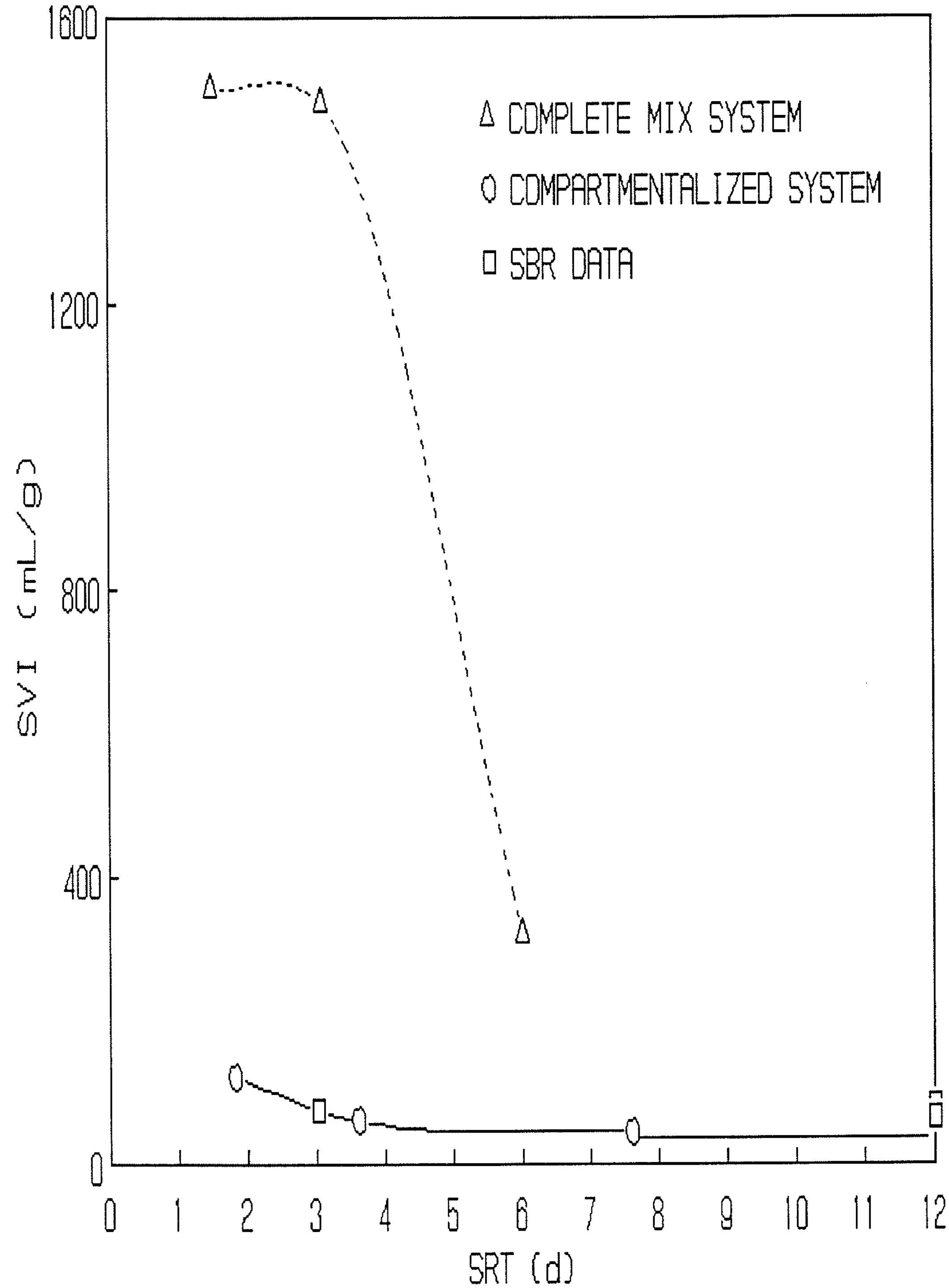

Figure 6.9. Effect of solids retention time (SRT) on sludge volume index (SVI) for batch, compartmentalized systems, and CFSTRS.

data closely fit the curve for the compartmentalized systems. SVI is affected similarly by SBRs and plug flow systems such as the compartmentalized system used by Chudoba et al (1991). The benefits of these systems over CFSTRs are obvious from the big difference in the SVIs reported at low SRTs. SVI data from the CFSTRs in the first study phase were not included in Figure 6.9 because the only time period when chlorination was not used, HRT instead of SRT was used as the control parameter.

Figure 6.10 illustrates the dependency of the MO number on SRT for the CFSTRs. One line in the Figure represents the final MO, which is the MO number after a week of operation without chlorination. Average MO numbers that were determined over a week of operation without chlorination make up the second data set. The reactors with longer SRTs had lower MO numbers which supports the general trend of the curve for the complete mix reactor in Figure 6.9.

6.2 SOLUTIONS FOR FILAMENTOUS BULKING PROBLEMS

6.2.1 NUTRIENT ADDITIONS

From the material presented so far, it would seem obvious that nutrient addition should have been attempted to solve the bulking problems. If the nutrient deficiencies had been discovered during the operation of the CFSTRs, nutrient additions could have been implemented. Unfortunately,

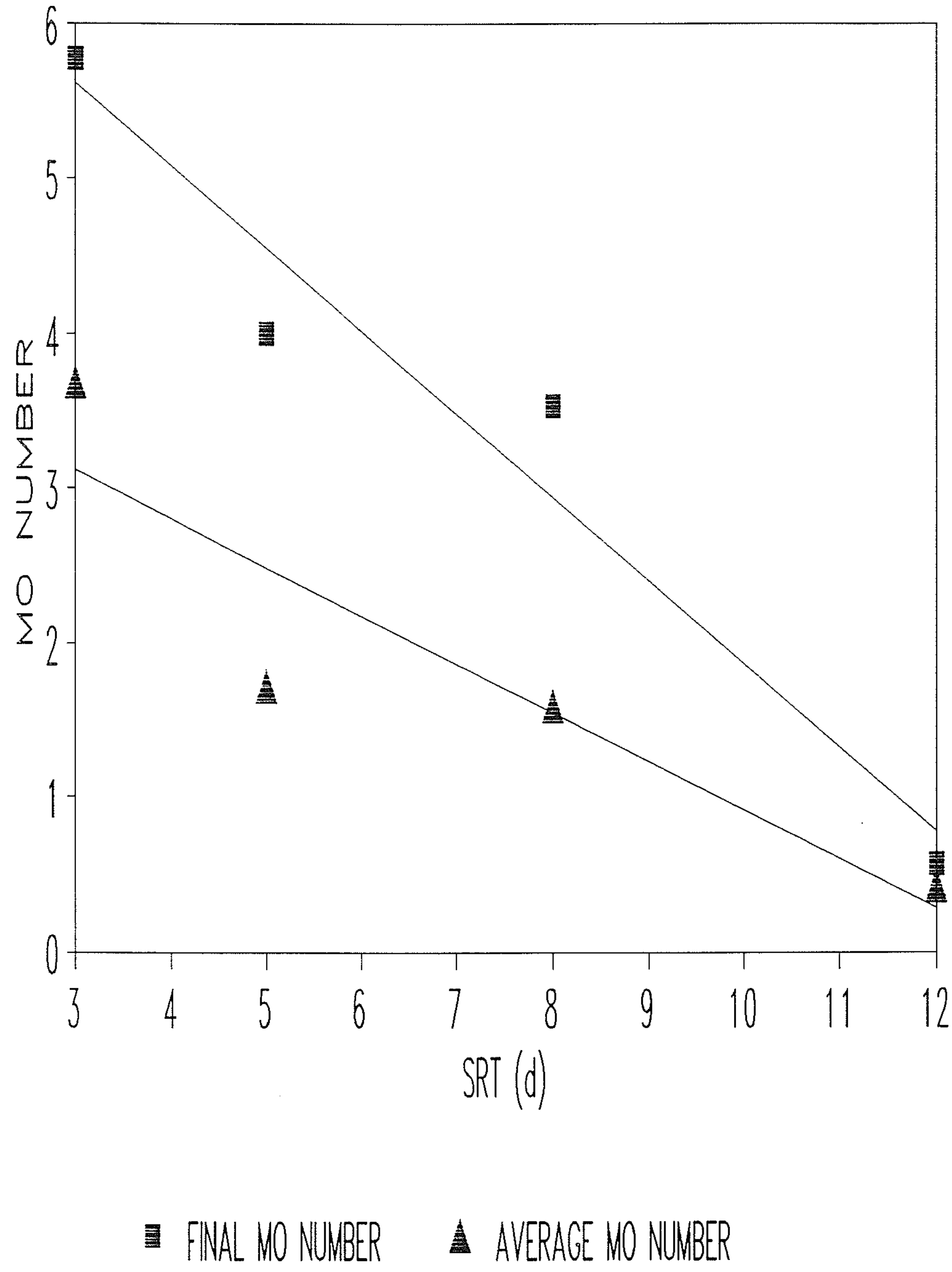

Figure 6.10. Effect of solids retention time (SRT) on microscopic observation (MO) number.

isolation of nutrient deficiencies as the cause of the filamentous bulking was only achieved upon perusal of the data after the research had been completed. Therefore, the possibly simple solution of nutrient addition could not be implemented.

6.2.2 CHLORINATION

Severe bulking occurred in all four of the reactors in the initial phase of the study. Therefore, starting with the day 189 of the study, a chlorination program was implemented. Parameters, T and T_m, were essentially equal in the CFSTRs because the chlorine was dosed directly to the aeration basin once a day and mixed almost instantaneously throughout the reactor.

6.2.2.1 LARGE ONCE-A-DAY BATCH DOSES

Initially, large once-a-day batch doses of 10 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ were used. The effects of such a large dose on effluent solids are evidenced in Figure 6.11. Arrows indicate the day that chlorine was applied. Turbid effluent was expected for 24 h after the chlorine dose is added (EPA, 1987). Figure 6.11 proves that the effluent solids increased dramatically after a once-a-day batch dose of 10 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ for a 24 hour period before falling to lower levels on the second day after dosing.

Following the initial once-a-day batch doses of 10 mg

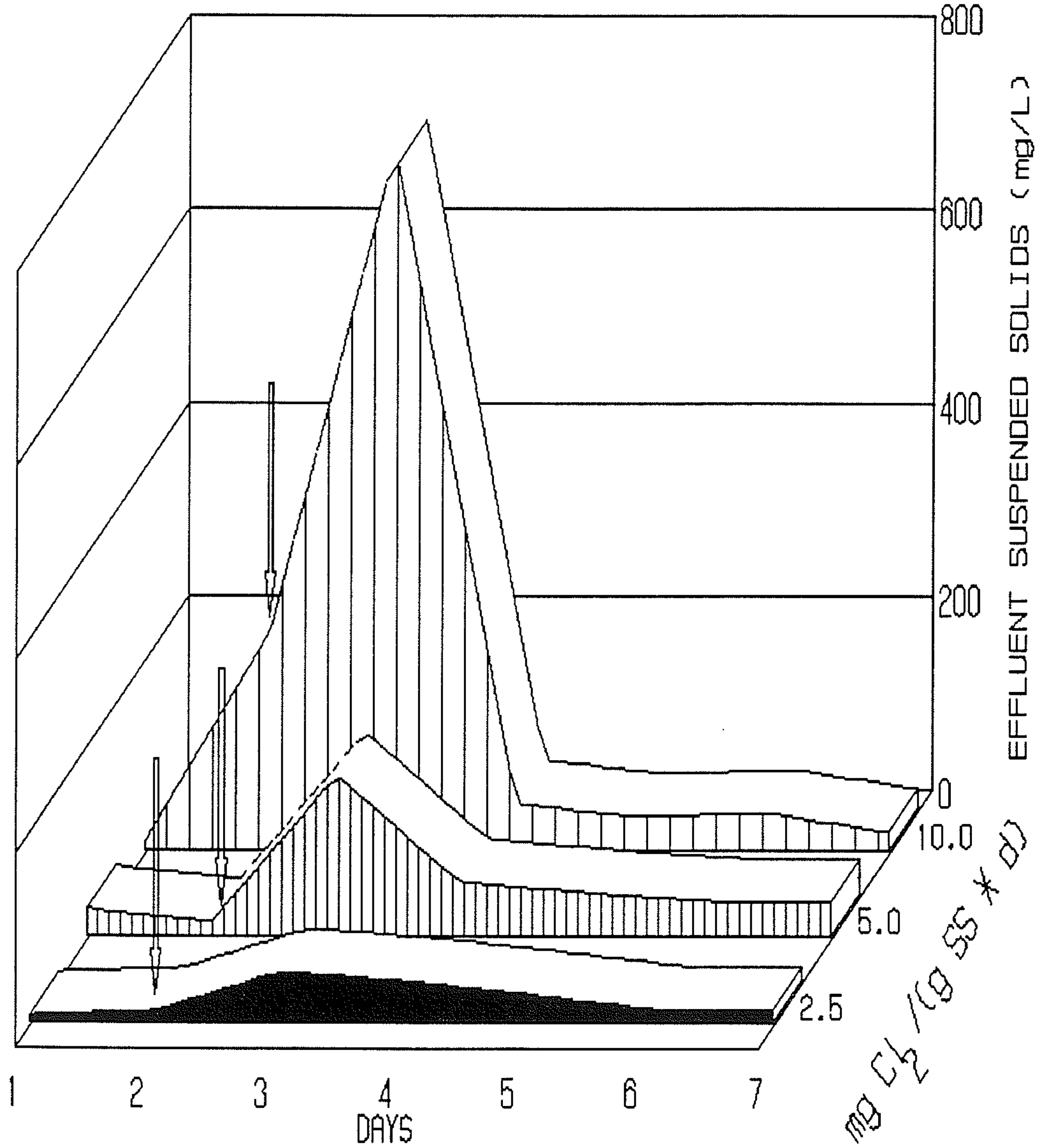

Figure 6.11. Effect of once-a-day batch chlorine doses on effluent suspended solids. The arrows indicate the day that chlorine was added.

$Cl_2\cdot(g\ SS\cdot d)^{-1}$, several once-a-day batch doses of 5 mg $Cl_2\cdot(g\ SS\cdot d)^{-1}$ were investigated. Figure 6.11 shows the effect of one such dose on the effluent solids from the reactor. Once again, the effluent suspended solids increased dramatically the day following dosing, then decreased rapidly on the second day and beyond.

Lower doses were investigated to see if the same improvements in sludge quality could be achieved without the dramatic sludge losses. Higher doses were not able to return the effluent solids to a level of 30 $mg\cdot L^{-1}$, which is standard for discharge permits in Manitoba. Occasionally, throughout the chlorination period, once-a-day batch doses of 2.5, 3 and 4 mg $Cl_2\cdot(g\ SS\cdot d)^{-1}$ were employed to control filamentous bulking. The repercussions of a once-a-day batch dose of 2.5 mg $Cl_2\cdot(g\ SS\cdot d)^{-1}$ are displayed in Figure 6.11. Here again, the solids increased substantially on the day following the chlorine dose. The recovery from this dose of chlorine was not as dramatic as with the higher doses. On the fourth day after dosing, the effluent solids fell below the 30 $mg\cdot L^{-1}$ level. Therefore, lower doses allow the effluent solids to be within discharge limits while the higher doses do not.

The once-a-day batch dose of 22 mg $Cl_2\cdot(g\ SS\cdot d)^{-1}$ reported by McCartney (1991) would be expected to have even more severe consequences in terms of effluent sludge loss than the doses shown in Figure 6.11. Actual effects of this once-a-day batch dose on effluent solids could not be plotted due to a lack of data.

Figure 6.12 shows the effect of chlorine dose, T, on the next day effluent suspended solids (NDESS) which were the concentrations of suspended solids in the effluent on the day following application of the chlorine dose. All of the values plotted in the Figure are once-a-day batch doses preceded and followed by at least one day without chlorination. The values displayed for the once-a-day batch doses of 5 and 10 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ are the average of four data points. Lower once-a-day batch dose values are derived from a single data point due to a lack of data, which was caused by the need to chlorinate the reactors regularly to maintain process control. The correlation between these two variables has an r^2 of 0.955 and confirms what one would intuitively suspect. As the chlorine dose increases, the amount of effluent solids lost due to cell destruction on the following day also increases.

6.2.1.2 SUSTAINED ONCE-A-DAY BATCH DOSES

Further experimentation was carried out with sustained once-a-day batch doses of 1.5 and 2.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$. Doses were applied as needed, for several days in succession, to determine their effect on effluent solids. One such trial is illustrated in Figure 6.13. Other trials in other reactors produced similar responses. In the long run, using sustained low doses of chlorine was just as effective as using the high shock doses illustrated in Figure 6.11.

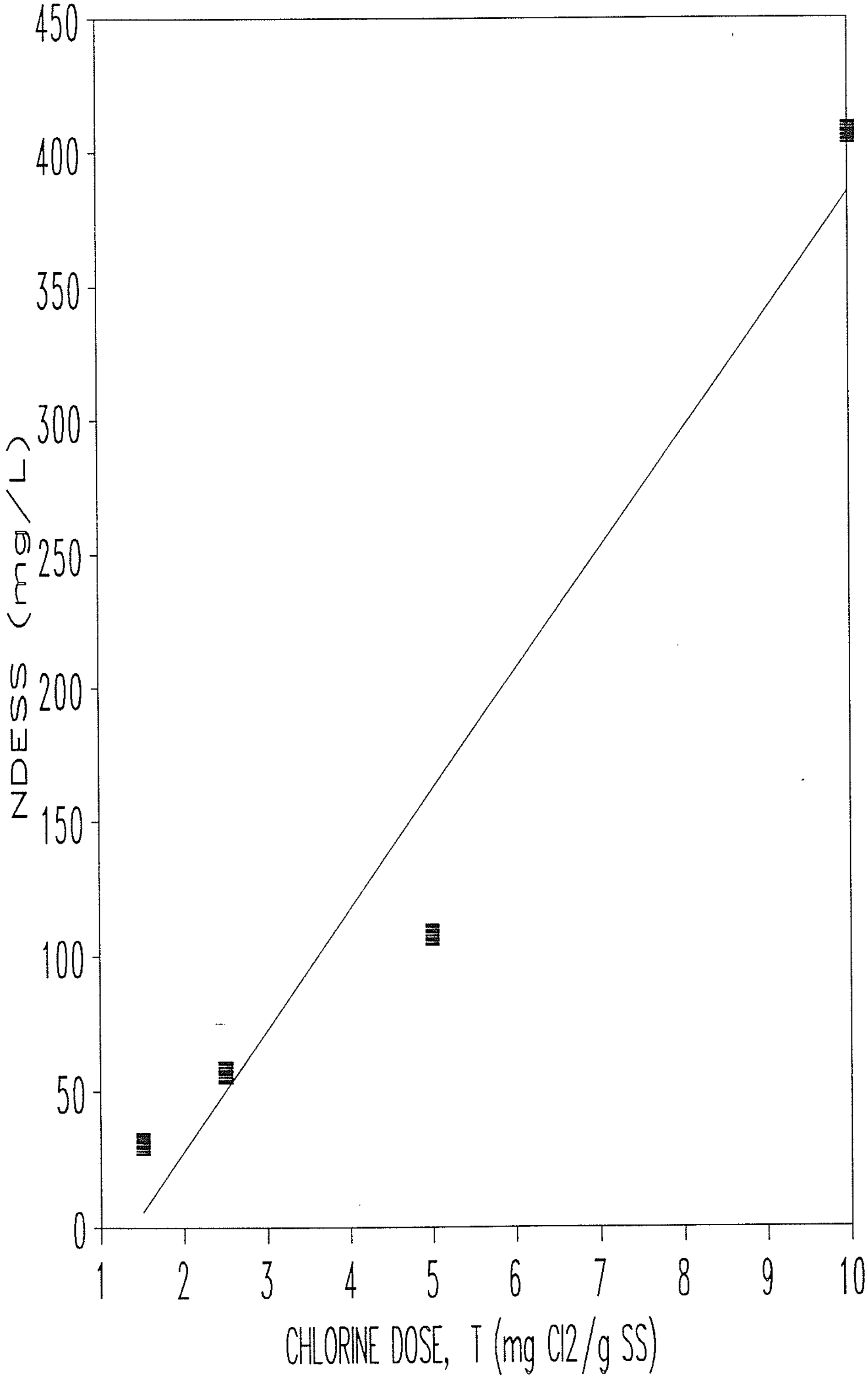

Figure 6.12. Effect of once-a-day batch chlorine dose on the next-day-effluent-suspended solids (NDESS).

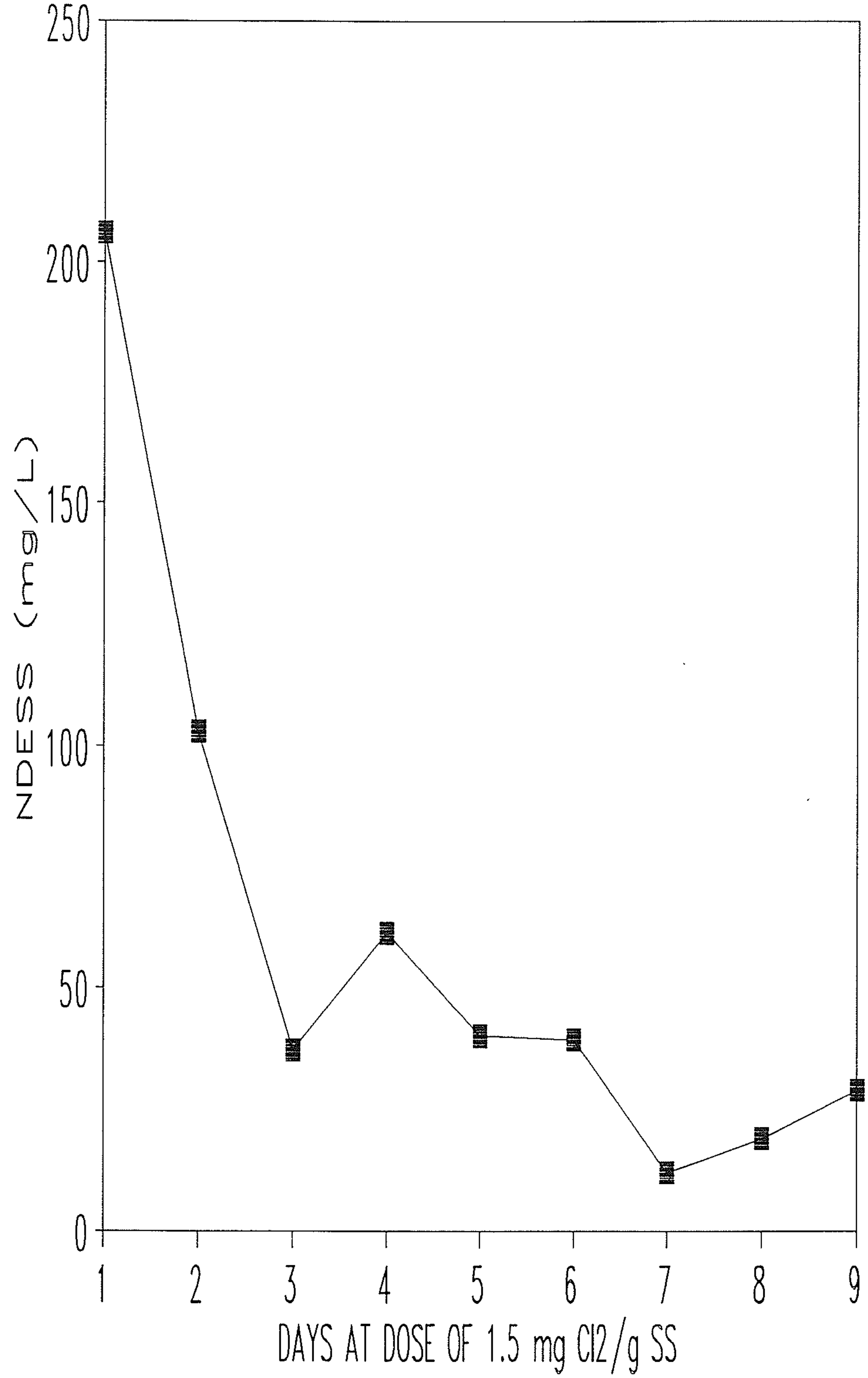

Figure 6.13. Effect of once-a-day batch doses of 1.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ applied several days in succession on next-day-effluent-suspended solids (NDESS).

In Figure 6.13, the first dose was added to the reactor on day 0. Following the first dose the solids increased from 82 $mg \cdot L^{-1}$ to 206 $mg \cdot L^{-1}$. The increase was too dramatic to be caused only by the destruction of cells and their washout. It is believed that the increase was the combination of two effects. Attack by low chlorine doses was not as effective as the higher doses allowing some of the filaments to survive the first dose. Cells that were attacked and destroyed flowed over the effluent weir, thus adding to the solids concentration. On day 2 the effluent solids began to decrease. The second dose was more effective in reducing the effluent solids than the first one because it further attacked filaments that had only been weakened by the previous dose. Effluent solids reported on the second day are likely caused by the washing out of the filaments. Seven doses were required to obtain effluent suspended solids below 30 $mg \cdot L^{-1}$. Therefore, one can conclude that low sustained chlorine doses are equally as effective as high once-a-day batch doses but require longer to achieve low effluent suspended solids.

Figure 6.14 shows the effectiveness of 2 doses of 2.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ followed by six doses of 1.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ on reducing the SVI and the MO number. The response chronicled in the Figure represents a single reactor even though more or less the same response occurred in the other reactors as well. Even after the application of the eight

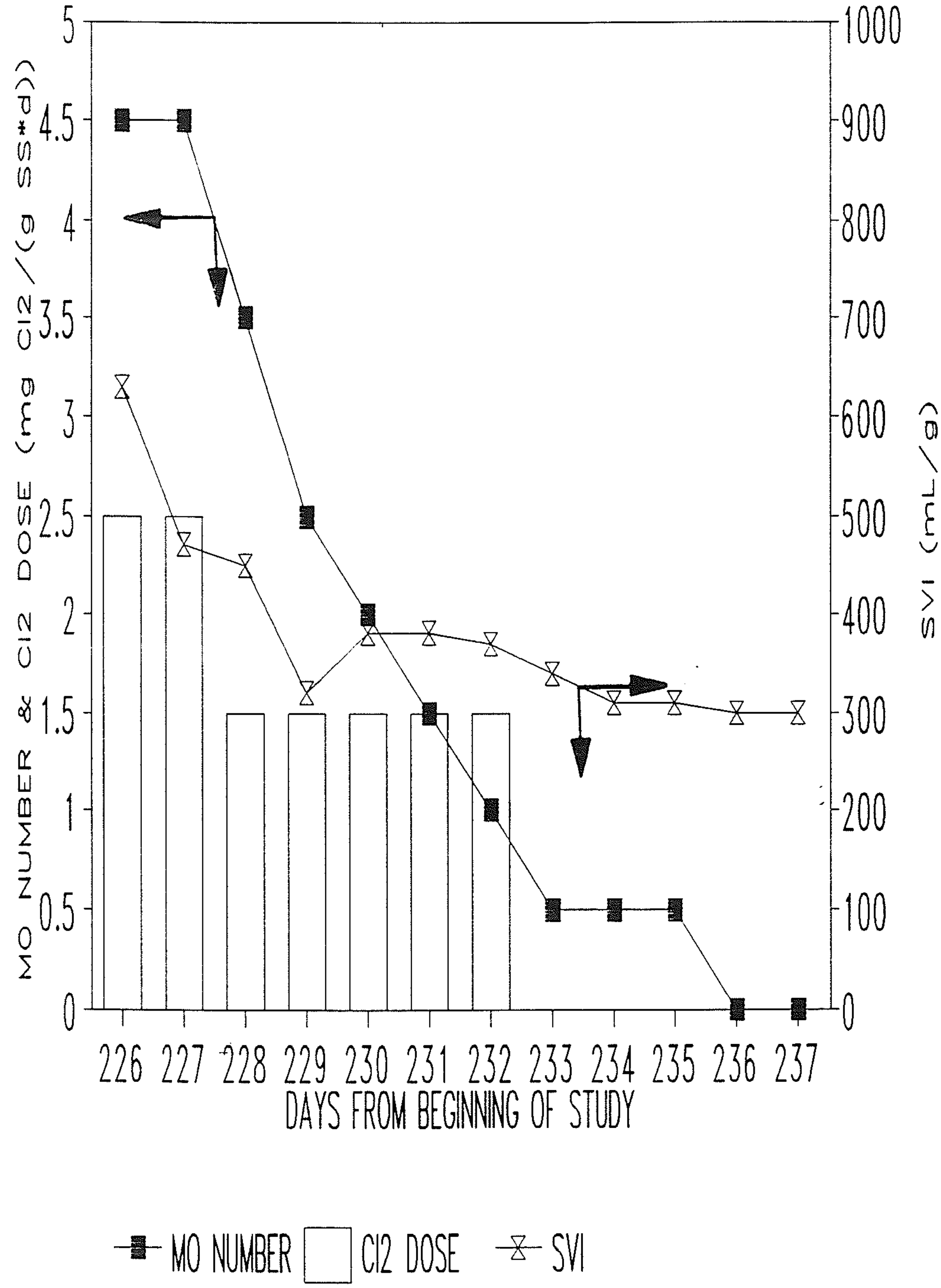

Figure 6.14. Effect of low sustained once-a-day chlorine doses on microscopic observation (MO) number and sludge volume index (SVI).

doses mentioned above, several days were required until improvements in the MO number were realized. SVI improvements were minimal because, even though the filaments were killed, the sheaths remained. Therefore, the SVI will not respond until they are washed out through sludge wasting. Richard (1989) and the EPA (1987) noted similar behaviour in other activated sludge chlorination situations. MO numbers increased again after only three days at 0.5. The increases in the MO number and the NDESS that occurred ten days after the chlorination was stopped were expected because the source of the filamentous bulking problem had not yet been found.

The effectiveness of low sustained once-a-day batch doses in controlling filaments is made clear in Figures 6.15 and 6.16. Before chlorination was initiated, the sludge was very filamentous (Figure 6.15). Figure 6.16 indicates the improvements that can be achieved with chlorination at low sustained once-a-day batch doses.

6.2.2.3 SLUDGE QUALITY INDICATORS TO USE DURING CHLORINATION

All of the comparisons made were done using effluent suspended solids because the SVI was unresponsive to chlorination and the recovery of the MO number after chlorination had a lag time associated with it. Further evidence of this is found in Figure 6.17. The response chronicled in the Figure represents a single reactor even though more or less the same response occurred in the other

Figure 6.15. Microscopic photograph of the activated sludge before chlorination was initiated.

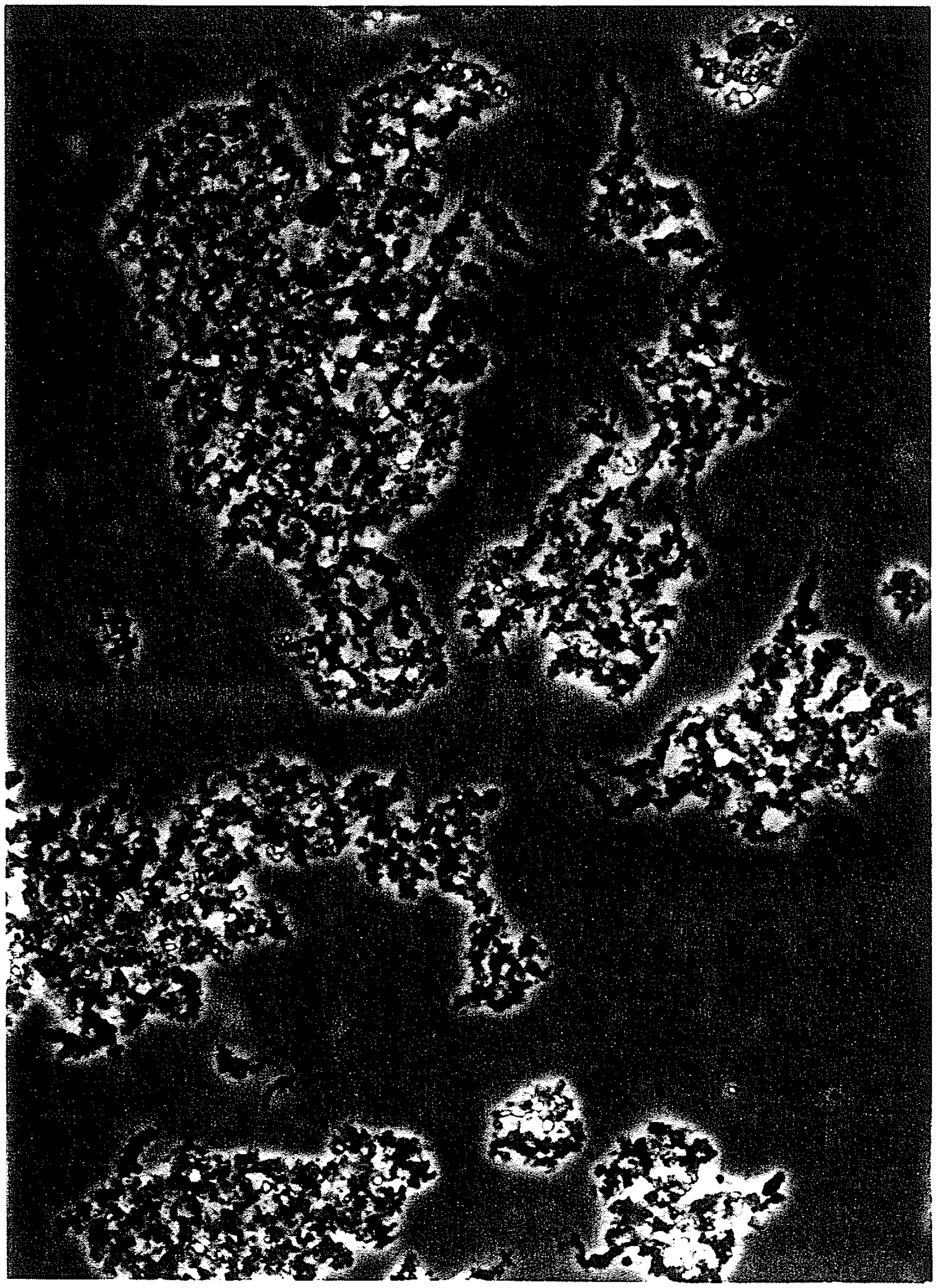

Figure 6.16. Microscopic photograph of the activated sludge after several days of chlorination.

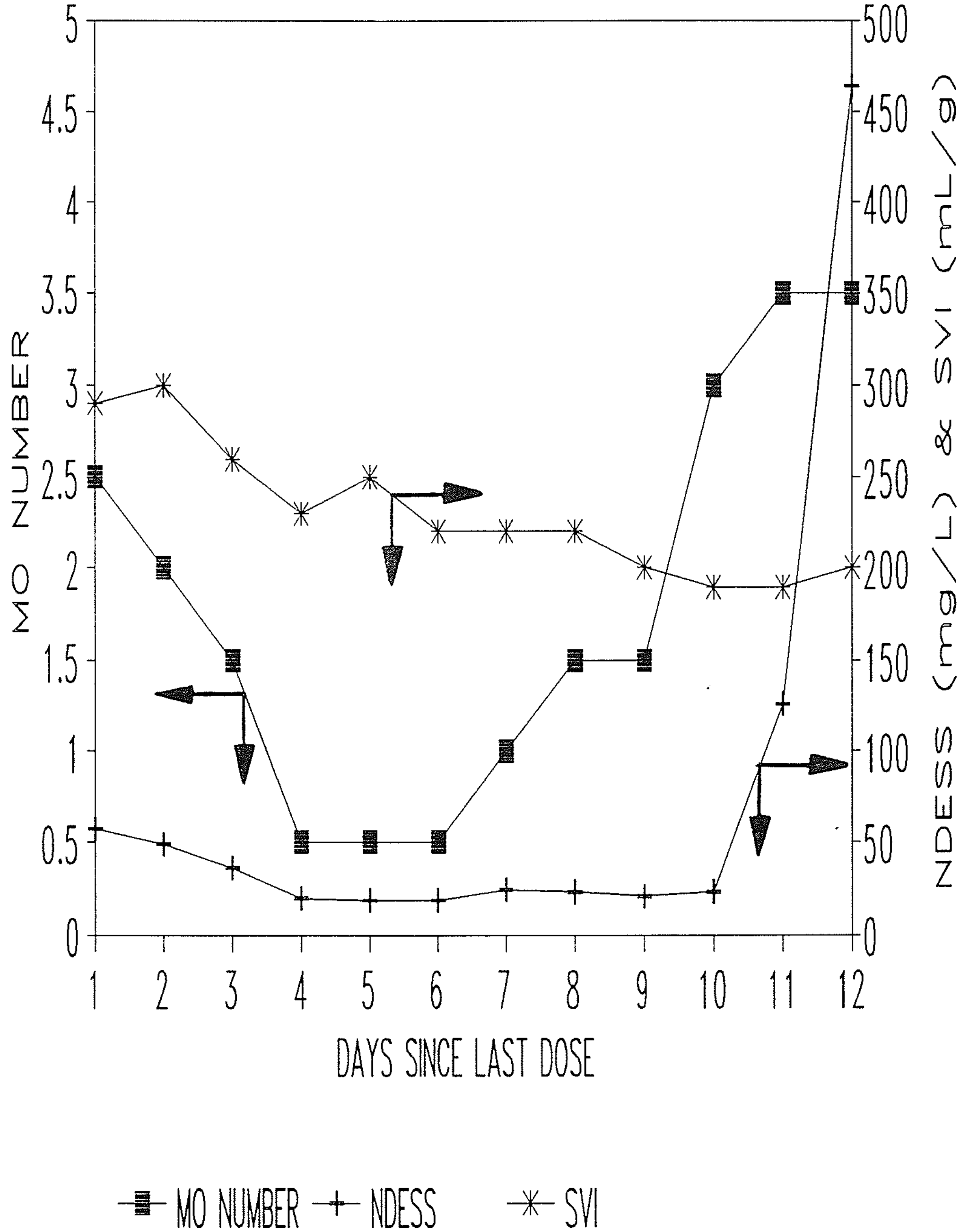

Figure 6.17. Effect of sustained low chlorine doses on microscopic observation (MO) number, next-day-effluent-suspended solids (NDESS), and sludge volume index (SVI).

reactors as well. SVI showed only minimal improvement after a few days because, even though the filaments were killed, the sheaths remained. Therefore, the SVI will not respond until they are washed out through sludge wasting. Richard (1989) and the EPA (1987) noted similar behaviour in other activated sludge chlorination situations. MO numbers required several days without chlorination to drop significantly further; supporting this explanation.

Figure 6.17 shows that the SVI gave no indication of the increase in effluent suspended solids concentration that was about to occur on the eleventh day after the last chlorine dose had been added. The MO number, on the other hand, increased to a value of 3 by the ninth day after the last chlorine dose. This gave more warning of the increased effluent suspended solids concentration which would come on the eleventh and twelfth days after chlorine was dosed for the first time. This conclusion is in agreement with Eikelboom (1982) who stated that MO numbers were more effective than SVIs for monitoring sludge quality.

Catastrophic sludge losses on the eleventh and twelfth days corroborate Richard's (1989) finding that chlorination only controls the symptoms of filamentous bulking. When chlorination is terminated the filaments will return in even greater numbers if the problem has not been corrected.

6.2.3 SBR REACTOR CONFIGURATION

Even though the SBRs operated in the second phase of the study treated the same BVF waste as the CFSTRs in the first phase, they still had much lower SVIs (Table 6.2). The reason for this is twofold. First, the combination of highly concentrated substrate with the sludge at the beginning of the aerated react period favours the floc formers. Second, the phosphorus added was not diluted immediately, creating a higher local P:MLSS ratio that would favour floc formers. Therefore, if filamentous bulking is expected, SBRs or intermittently fed or plug flow systems should be selected over CFSTRs.

6.3 EFFECT OF CHLORINATION ON NITRIFICATION

6.3.1 INITIAL STUDY PHASE

Even with all of the upsets that occurred in the initial phase of the research, the reactors achieved significant nitrification efficiency for the two week period before chlorination started on day 189 (Figure 6.18). Nitrification efficiencies were calculated using the following formula:

$$\text{NITRIFICATION EFFICIENCY (\%)} = \frac{[NO_2\text{-}N]_e + [NO_3\text{-}N]_e}{[NO_2\text{-}N]_e + [NO_3\text{-}N]_e + [NH_3\text{-}N]_e} * 100 \qquad (6.1)$$

where $[NO_2\text{-}N]_e$ = effluent nitrite nitrogen concentration ($mg \cdot L^{-1}$)

$[NO_3\text{-}N]_e$ = effluent nitrate nitrogen concentration ($mg \cdot L^{-1}$)

$[NH_3\text{-}N]_e$ = effluent ammonia nitrogen concentration ($mg \cdot L^{-1}$)

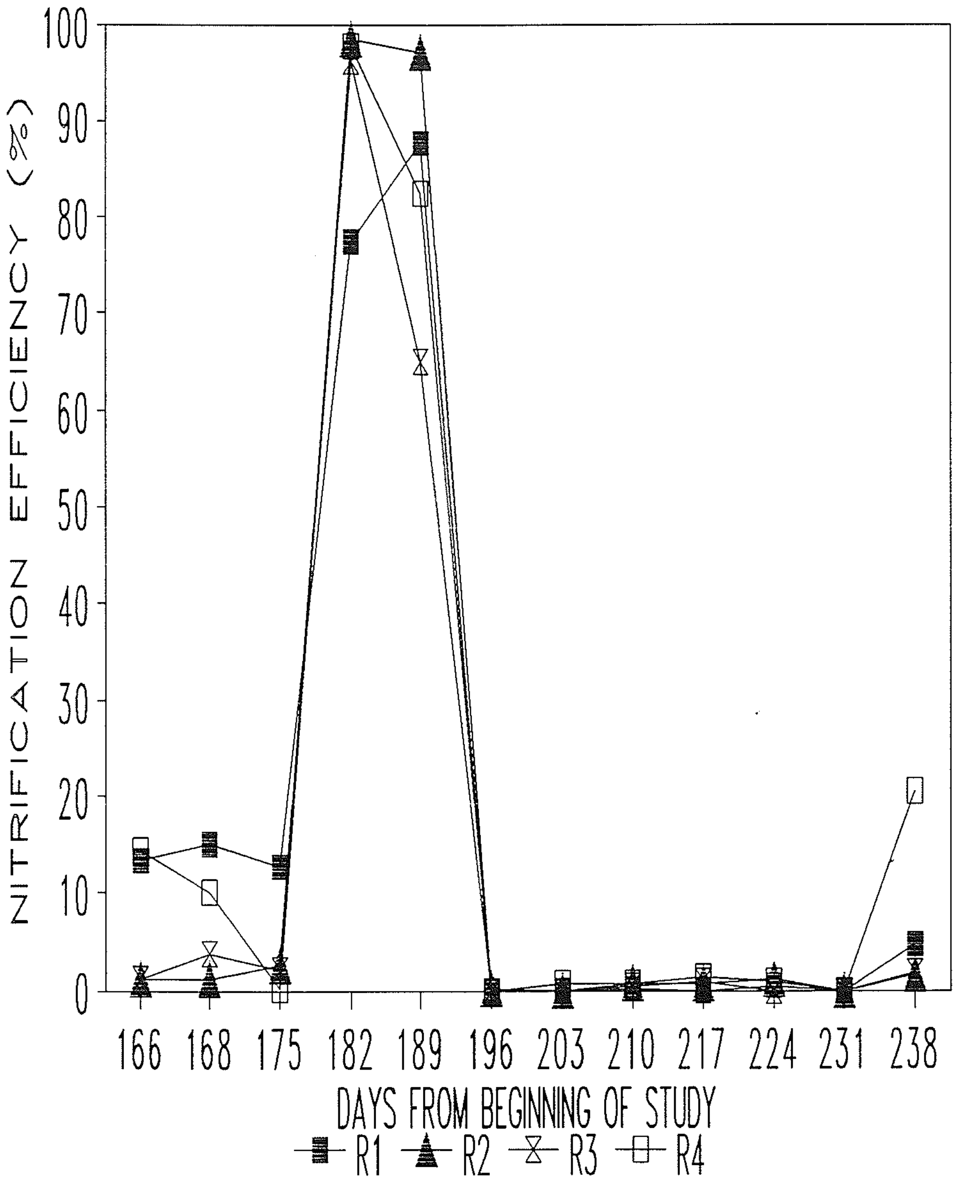

Figure 6.18. Nitrification efficiencies in the four reactors of the Portage La Prairie pilot study.

The dramatic effect of the 10 mg $Cl_2\cdot(g\ SS\cdot d)^{-1}$ dose applied on day 189 on the nitrification efficiency is apparent from Figure 6.18. No significant nitrification occurred in the following six weeks due to the chlorination program. Nitrification efficiency began to increase in the following two weeks. It is not clear if the time without chlorine addition was sufficiently long to allow the nitrifiers to re-establish themselves or if the nitrifying bacteria had become sufficiently acclimated to the low sustained doses of chlorine to allow nitrification to proceed. A combination of these two is also a possibility.

6.3.2 SECOND STUDY PHASE

The inhibition of the nitrification process by chlorination left several questions unanswered. Therefore, an experiment was undertaken with lower doses of chlorine in the SBRs operated in the second part of the study. Only SBR2 and SBR4 were analyzed in this study because the other two reactors had too short of an SRT to sustain nitrification.

Chlorine addition resulted in monochloramine formation in the sequencing batch reactors because the Cl_2:NH_3-N ratio was much less than 2.5 g $Cl_2\cdot(g\ N)^{-1}$ for all of the doses given; as indicated in Table 6.3 below. Included in Table 6.3 are the calculated amounts of monochloramine produced, based on the following stoichiometric equation:

$$NH_3 + HOCl \rightarrow NH_2Cl + H_2O \tag{6.2}$$

Table 6.3. $Cl_2:NH_3$ ratios and calculated monochloramine concentrations for the chlorine doses used.

Dose mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$	$Cl_2:NH_3$ ratio		Calculated monochloramine concentration ($mg \cdot L^{-1}$ NH_2Cl)	
	R2	R4	R2	R4
1.0	0.08	0.04	2.56	2.43
1.5	0.17	0.05	3.84	3.32
2.0	0.19	0.06	5.17	3.89
2.5	0.22	0.07	6.43	4.91

It is assumed that these small amounts of monochloramine penetrated the large numbers of bacteria present in a matter of minutes. The biocidal potency of monochloramine is significantly less than that of hypochlorous acid.

SBR2 suffered adversely when the once-a-day batch chlorine dose increased to 2.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$, as illustrated in Figure 6.19. This was shown by the simultaneous increase in the ammonia and TKN concentrations accompanied by a decrease in the nitrate concentration. The other variations in TKN are likely just normal daily variations attributable to organic nitrogen, as they are not accompanied by an increase in ammonia which would indicate that the nitrification process is suffering.

The effects of the chlorine doses on the other reactor are chronicled in Figure 6.20. Even though all of the chlorine added was converted to monochloramine, its concent-

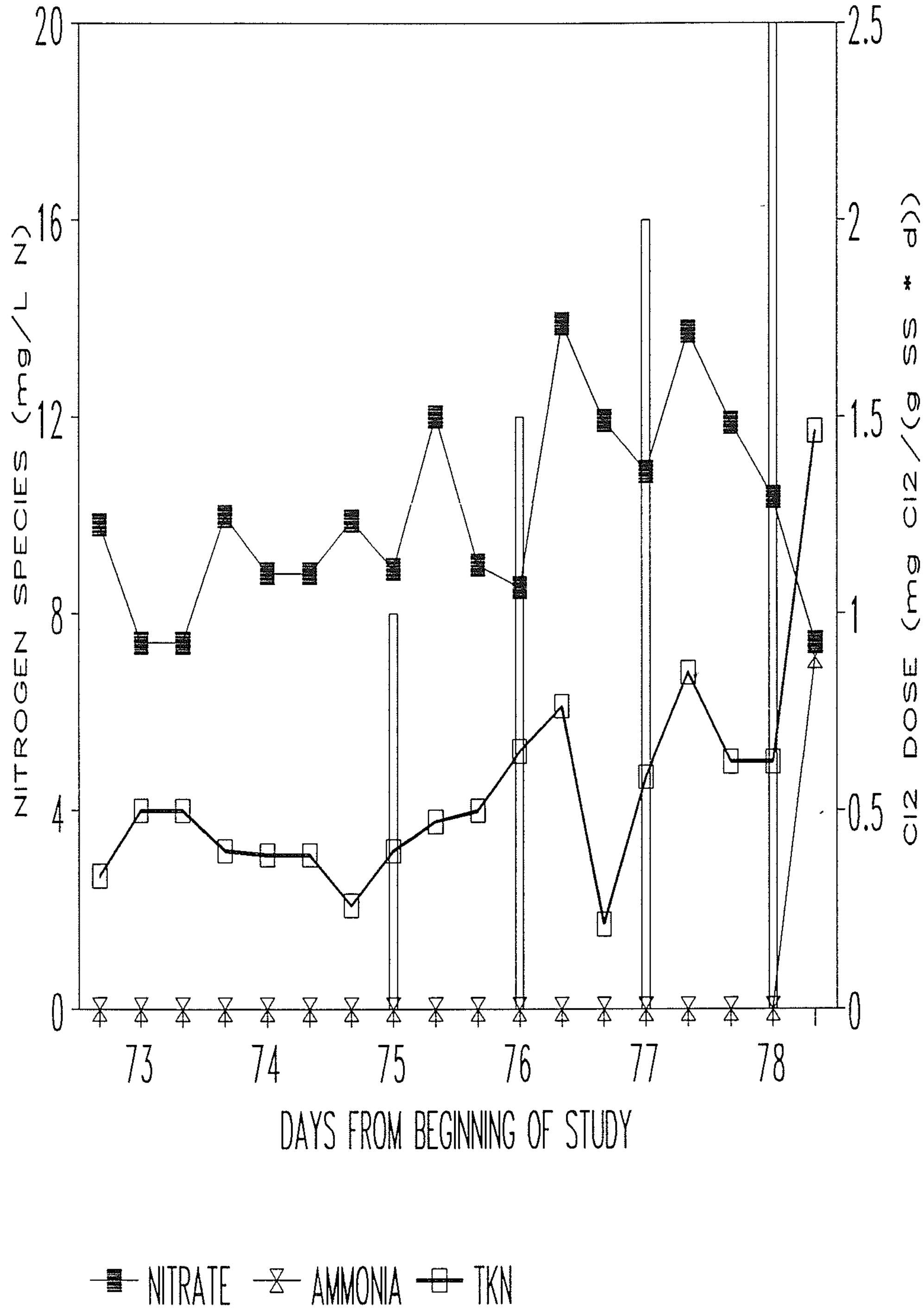

Figure 6.19. Graph showing the effects of chlorine dose on TKN, ammonia, nitrite, and nitrate concentrations in SBR2. The bars indicate the chlorine doses used.

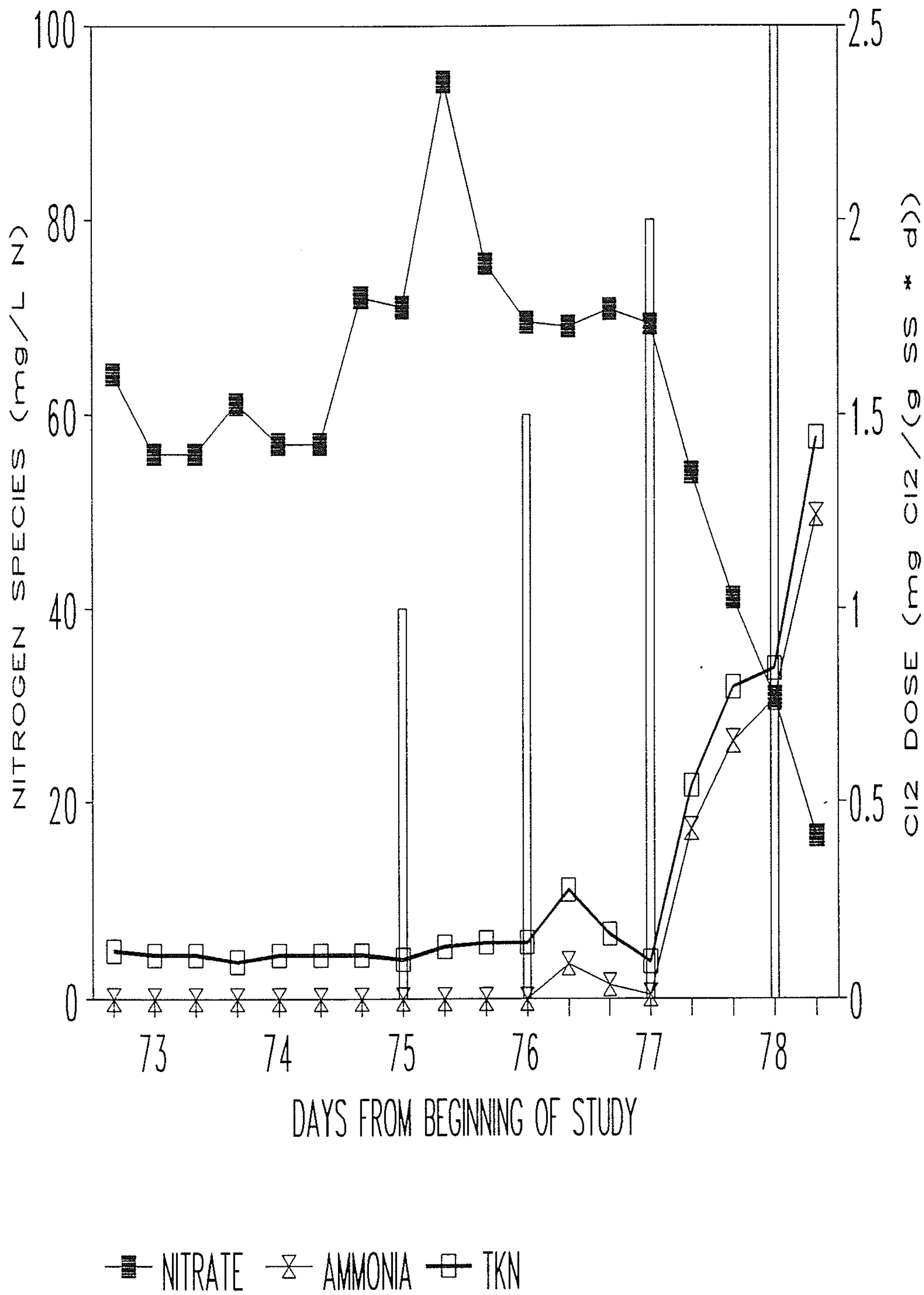

Figure 6.20. Graph showing the effects of chlorine dose on TKN, ammonia, nitrite, and nitrate concentrations in SBR4. The bars indicate the chlorine dose used.

ration was insufficient to have any effect on nitrification at a once-a-day batch dose of 1.0 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$. Eight hours after dosing the reactor with 1.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ the effluent ammonia and TKN increased slightly, indicating a slight nitrification sensitivity. Twenty four hours after this dose was added the effluent TKN and ammonia values had returned to their levels before chlorination. When the once-a-day batch dose was increased to 2.0 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$, more significant reductions in nitrification became evident. This is apparent from the reductions in the nitrate concentration and the coincidental increases in the ammonia and TKN concentrations in Figure 6.20. As the chlorine affected the bacteria less of the ammonia in the influent was converted to nitrite and nitrate resulting in a higher ammonia concentration in the effluent. Therefore, the TKN concentration will also increase because the TKN is the sum of ammonia and organic nitrogen. Concentrations of TKN and ammonia had begun to level off; indicating that the bacteria were starting to recover. The first measurements taken after the reactor was dosed with 2.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ showed that the TKN reduction had decreased to an efficiency of 40%. It was therefore assumed that a dose higher than 2.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ would result in a total shutdown of the nitrification process.

Figure 6.21 illustrates the effect of chlorine dose on nitrification efficiency. Nitrification efficiency was

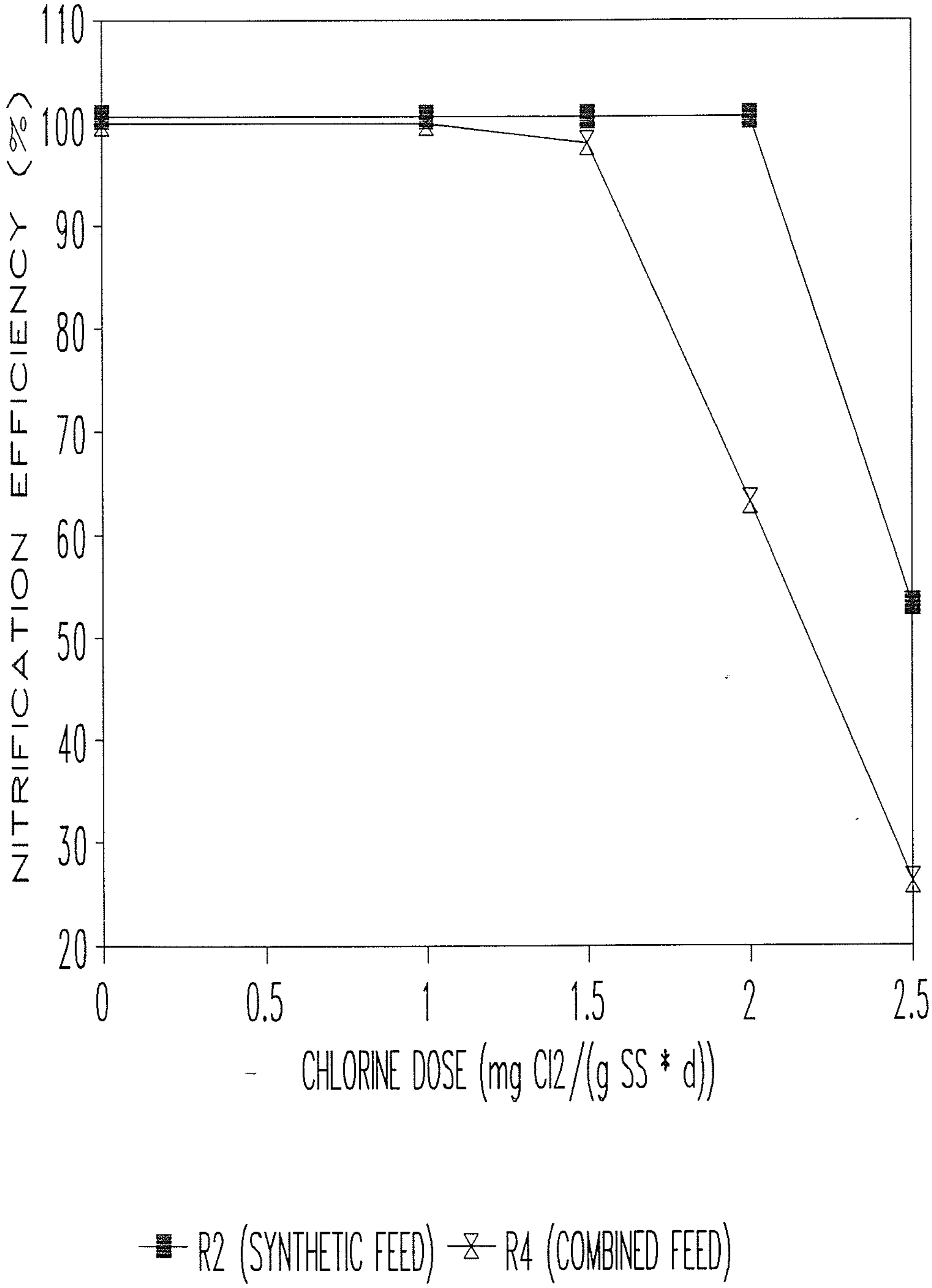

Figure 6.21. Effect of chlorine dose on nitrification efficiency.

calculated using formula **(6.1)**. It is apparent from Figure 6.21 that nitrification efficiency was not affected in either of the reactors at a dose of 1.0 mg $Cl_2\cdot(g\ SS\cdot d)^{-1}$. The nitrification efficiency in SBR2 remained unaffected until the maximum dose of 2.5 mg $Cl_2\cdot(g\ SS\cdot d)^{-1}$ was added, which reduced the nitrification efficiency to 53 percent. SBR4 was already beginning to show inhibition at a once-a-day batch dose of 1.5 mg $Cl_2\cdot(g\ SS\cdot d)^{-1}$. At the maximum dose of 2.5 mg $Cl_2\cdot(g\ SS\cdot d)^{-1}$, the efficiency of SBR 2 had decreased to 26 percent.

Common inhibitors of nitrification, such as temperature and pH (Ganczarczyk, 1983), did not play a significant role here because the temperature was maintained at 20 °C and the pH's were 7.0 and 7.3 respectively. Other operational parameters such as HRT, SRT, and F/M ratio were all maintained constant throughout the chlorination period.

The reasons for the difference in the magnitude of the inhibitory dose in the two reactors can be explained as follows. SBR4 was treating 76.5 $mg\cdot L^{-1}$ of ammonia as compared to SBR2 which was treating 22.1 $mg\cdot L^{-1}$ of ammonia. The removal rates given in Table 6.4 below were calculated using the following formula used by McCartney (1988):

$$\text{REMOVALRATE}\ (mgNH_3\text{-}N\cdot(mgVSS\cdot h)^{-1}) = \frac{[NH_3\text{-}N]_i - [NH_3\text{-}N]_e}{X\cdot t} \qquad \textbf{(6.2)}$$

where $[NH_3\text{-}N]_i$ = influent ammonia nitrogen concentration $(mg\cdot L^{-1})$

$[NH_3\text{-}N]_e$ = effluent ammonia nitrogen concentration $(mg\cdot L^{-1})$

X = MLVSS concentration $(mg\cdot L^{-1})$

t = time (h)

Table 6.4. Ammonia nitrogen removal rates in sequencing batch reactors from the second study phase.

DOSE mg $Cl_2 \cdot (gSS \cdot d)^{-1}$	R2 REMOVAL RATE mg NH_3-$N \cdot (g\ VSS \cdot h)^{-1}$	R4 REMOVAL RATE mg NH_3-$N \cdot (g\ VSS \cdot h)^{-1}$
0.0	1.15	5.09
1.0	1.27	4.56
1.5	1.15	4.34
2.0	1.27	4.00
2.5	1.00	2.30

The calculated rates are based only on an influent concentration and an effluent concentration after six hours and therefore do not give an indication of the actual rate. When the effluent ammonia concentration is zero, it is not known how much of the six hours was required to get to zero.

Assuming that the nitrification rate is the same in both reactors and follows zero order kinetics (McCartney, 1988), SBR4 which has the higher ammonia concentration will require roughly three times as long to achieve nitrification than SBR2. The addition of chlorine slowed the rate of nitrification in both reactors. Analyses for ammonia nitrogen were performed in the influent and at the end of the six hour react period. When the chlorine dose was zero, both reactors were able to achieve complete nitrification within the 6 h period. As the dose increased, the reactor with the lower influent concentration would still be able to nitrify all of the ammonia during the aeration period while the other reactor would have ammonia remaining at the end of 6 h. Therefore, it was concluded that both reactors were affected equally.

Nitrifying bacteria were more susceptible to inhibition from chlorine than the filamentous bacteria. Filaments required two once-a-day batch doses of 2.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ followed by once-a-day batch doses of 1.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ sustained for six days to be sufficiently inhibited to allow the sludge quality to improve. Nitrification was adversely affected by a once-a-day batch dose of 1.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$.

The findings of this study have important implications in plant operations. Since once-a-day batch doses of 2 to 22 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$ have been used to control filamentous growths it is obvious that batch chlorination once per day to control filaments could adversely affect nitrification. It is believed that continuous chlorination would have similar effects to once-a-day batch chlorination at the same dose. Therefore, pilot tests should be performed to determine what type and magnitude of dose can be applied for filamentous bulking control without inhibiting the nitrification occurring in the reactor.

7. CONCLUSIONS

Several conclusions can be drawn from this research. The conclusions relating to the cause of the filamentous bulking are:

1. A minimum phosphorus to mixed liquor suspended solids ratio (P:MLSS) of 2.4 percent was desirable to avoid filamentous bulking due to phosphorus limitations regardless of the reactor configuration with the combined wastes from the Portage La Prairie study. This may not be applicable to all waste treatment systems.
2. Little or no additional benefit in terms of increased sludge settleability was realized from increasing the P:MLSS ratio beyond 2.4 percent.
3. Sequencing batch reactor, intermittently fed, or plug flow configurations should be selected over continuous flow stirred tank reactor configurations if filamentous bulking due to low substrate concentration is expected.

Conclusions from the research into the effectiveness of chlorine as a short term bulking control measure are:

4. Next-day-effluent-suspended solids (NDESS) were found to be proportional to the once-a-day batch chlorine dose applied.
5. The use of large once-a-day batch doses of chlorine resulted in high NDESS.
6. Smaller sustained once-a-day batch doses of chlorine were equally effective as the large once-a-day batch doses but

several days of application were required to achieve filamentous bulking control.

7. Chlorination was able to control filamentous bulking in the short term.
8. The filamentous bacteria returned in even greater numbers after the chlorination stopped because the problem responsible for the bulking remained uncorrected.

The study of the usefulness of the microscopic observation number as a parameter to quantify sludge bulking resulted in the following conclusion:

9. MO number was found to be a better indicator of impending MLSS losses in the effluent due to extreme proliferations of filaments than the SVI.

Studying the effect of chlorination for filamentous bulking control resulted in the following conclusions:

10. Nitrifying bacteria were found to be more susceptible to chlorination than filamentous bacteria.
11. Nitrification efficiency was found to be significantly reduced at a once-a-day batch dose of 1.5 mg $Cl_2 \cdot (g\ SS \cdot d)^{-1}$.

8. ENGINEERING SIGNIFICANCE

The engineering significance of this research is far reaching. It gives further support to the use of chlorination as a short term control method of filamentous bulking until the cause can be found and rectified. It has shown that engineers must pay close attention to the nutrient balance in the waste waters being treated.

The research has also shown that chlorination can adversely affect nitrification. Engineers must rely on pilot plant studies to determine what type and magnitude of dose can be applied for filamentous bulking control without inhibiting the nitrification occurring in the reactor.

This research has shown the benefits that intermittently fed configurations, especially SBRs, can provide over continuous flow stirred tank reactors. Therefore, if engineers are faced with selecting a reactor configuration in an application where bulking may occur they should seriously consider an SBR or a plug flow configuration.

9. SUGGESTIONS FOR FURTHER STUDY

Further studies are required to shed more light on the causes of filamentous bulking, the use of chlorine and reactor configuration for bulking control and the effects of chlorination on nitrification. For better understanding of the causes of filamentous bulking, it is suggested that:

1. Parallel systems of sequencing batch and continuous flow stirred tank reactors (CFSTR) with the same P:MLSS ratios and similar operating characteristics should be operated to determine how important reactor configuration is in filamentous bulking control.
2. CFSTR's should be operated at varying P:MLSS ratios to determine the effect of P:MLSS ratios on specific growth rates in CFSTRs.

Suggested studies for the effects of chlorination on filaments and nitrifying bacteria include:

1. Further investigation of the amount of NDESS produced and the bulking control provided by once-a-day batch doses of chlorine.
2. Determination of differences, if any, in the effects on nitrifying bacteria and filaments between continuous and once-a-day batch chlorination.
3. Chlorination of a nitrifying, bulking sludge in a CFSTR should be studied to see if the effect on nitrifying bacteria is similar to that found in sequencing batch reactors.

4. Studies to determine if nitrifying bacteria can be acclimated to low once-a-day batch doses of chlorine.

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NOMENCLATURE

APHA - American Public Health Association
AWWA - American Water Works Association
BOD - biochemical oxygen demand
BOD:P - biochemical oxygen demand to phosphorus ratio
BVF - bulk volume fermenter
COD - chemical oxygen demand
CFSTR - continuous-flow stirred-tank reactor
d - day
DO - dissolved oxygen
EPA - United States Environmental Protection Agency
F/M - food to microorganism ratio
h - hour
HRT - hydraulic retention time
MLSS - mixed liquor suspended solids
MLVSS - mixed liquor volatile suspended solids
MO - microscopic observation
NDESS - next day effluent suspended solids
OUR - oxygen uptake rate
RAS - return activated sludge
SBR - sequencing batch reactor
SOC - soluble organic carbon
SRT - solids retention time
SS - suspended solids
SSV - settled sludge volume
TKN - total Kjeldahl nitrogen
TSS - total suspended solids
u - specific growth rate
VSS - volatile suspended solids
WAS - waste activated sludge
WPCF - Water Pollution Control Federation
ZSV - zone settling velocity