PERFORMANCE EVALUATION OF THE BIOLOGICAL AERATED FILTER

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ABSTRACT

The Biological Aerated Filter is a novel biological wastewater treatment process consisting of an activated sludge zone followed by an unstratified sand filter for solids separation. Three evaluation studies of the BAF to date have yielded results indicating low solids production or possibly total oxidation. On the basis of these studies, Tymflo Process Limited, the patent holding company, claimed up to 50% cost savings for wastewater treatment as there would be no excess biological solids produced, and therefore no sludge disposal costs. The object of this report was to evaluate the BAF capabilities to treat degritted municipal sewage with respect to the above claims.

Two pilot scale BAF units were operated at the Canada Centre for Inland Waters continuously for 97 days treating degritted Burlington Skyway sewage at various operating conditions. The conclusions of the tests are that the BAF cannot be operated as a total solids retention system treating degritted municipal sewage on a 24 hour cycle at a 12 hour hydraulic detention time. The inert fraction of the influent is retained in the system resulting in high mixed liquor concentrations which overload the filter thereby decreasing treatment time. The system is capable of 88% COD removal, essentially complete nitrification and 97% SS removal. The system yields are in the order of 0.24 gm MLVSS/gm COD removed at organic loadings of approximately 0.08 gm COD removed/gm MLVSS day.

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Lastly, to my wife, Nardi, without whose patience and understanding this project would have been unbearable, I dedicate this work.

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1. INTRODUCTION

During the past 20 years, researchers have debated but failed to resolve conclusively the controversy of the issue of total oxidation of wastes by the activated sludge process, until Gaudy *et al.* (1970), published 3 years of experimental data as evidence that total oxidation is feasible on a bench scale system. Total oxidation, as defined by Forney *et al.* (1958) is the assimilation of substrate by a mixed microbial population or activated sludge and the eventual conversion of the substrate to oxidized nitrogen compounds, carbon dioxide and water, without any increase or decrease in the total weight of the biological mass or activated sludge in the system.

The above definition applies directly only to systems in which the substrate is in soluble form and there are no inert solids in the influent. In a system treating municipal sewage, the definition must be modified and coupled with two underlying assumptions:

1. the incoming volatile suspended solids are a portion of the substrate and are converted to biomass, and
2. the MLVSS are a measure of the biomass portion of the activated sludge.

Consequently, for systems treating municipal sewage, total oxidation is defined as the assimilation of substrate by the biomass portion of the sludge without an increase or decrease in the total weight of the biomass portion of the activated sludge in the system, commonly measured as mixed liquor volatile suspended solids (MLVSS).

A Canadian innovation, the Biological Aerated Filter, (BAF), invented by Mr. G. Tymoshchuk, United States patent number 3,968,034 has showed promise as a wastewater treatment process capable of attaining total oxidation in a single unit. To date there have been three studies (CPAR Project 177-1, (1974), CPAR Project 378-1, (1976), Tymflo Process Limited, (1976)) carried out to evaluate the capabilities of the process. Results have indicated low solids production or possibly total oxidation.

The BAF consists of an activated sludge zone followed by a sand filter for solids separation. The activated sludge zone has the same function as the aeration tank in an activated sludge system. Untreated wastewater enters this zone, and biochemical conversion of organics to biological solids, energy, carbon dioxide and water, takes place. Unlike conventional treatment schemes, the BAF system depends on a combination moving and fixed bed downflow sand filter for solids separation, thereby eliminating sludge carry-over problems associated with sedimentation. Periodically the sand filter is backwashed to return the solids captured in the filter to the activated sludge zone.

The objectives of this project, were to evaluate the performance of the BAF in treating degritted municipal sewage and specifically to delineate:

1. the biomass equilibrium concentration for total oxidation,
2. the biomass production in the event total oxidation is not a feasible operating condition,
3. the removal of suspended solids, COD, and nutrients, and
4. the required filter media size.

The study was subject to the following system constraints:

1. a minimum of 24 hours of filter operation between backwashes, and
2. a maximum hydraulic detention time of 12 hours.

2. LITERATURE REVIEW

2.1 Previous BAF Evaluations

The BAF process, invented in 1970, was first tested in 1971 on a municipal-industrial wastewater. The testing indicated that the system was capable of producing a high quality effluent in a relatively short 2-3 hour detention time (Tymflo Processes, 1976).

In 1974, Beak Consultants Ltd., sponsored by the Cooperative Pollution Abatement Research program, (CPAR Project Report 177-1, 1974), evaluated a pilot-scale BAF unit as a high rate biological process for treating kraft mill effluent. Operating 5 days per week, at loadings of 1.0 to 3.2 kg BOD_5/kg MLSS day, a 2½ hour detention time and at 16-27°C, the process achieved 70-85% BOD_5 removal and 56% suspended solids removal. During the course of the study no excess biological solids were reported at the high loadings, compared to 40-70 kg of solids per 100 kg of BOD_5 removed with conventional high rate systems. Under cold temperature operations between 5-14°C and similar loadings, the system BOD_5 removal deteriorated to 46% and the suspended solids removal improved to 60%.

In 1976 Beak Consultants Ltd. submitted a second report, CPAR Project Report 378-1, (1976), summarizing 77 days of bench scale testing of the BAF under controlled laboratory conditions using a synthetic feed consisting of glucose, glumatic acid and yeast extract. The results of the experimentation are summarized in Table 1.

Sludge never was purposely wasted during the course of the study. The results indicated biomass production during high loading conditions and biomass digestion during periods of lower organic loading. The

TABLE 1

BAF RESULTS TREATING SYNTHETIC FEED

(CPAR Project Report 378-1)

DETENTION TIME (hr)	ORGANIC LOADING g COD Removed / g MLSS day	INFLUENT COD g /day	COD % REMOVAL	AVERAGE EFFLUENT SS mg/l	YIELD g Solids / g COD Applied
16	0.34	33.0	95	72	0.09
28	0.21	26.8	91	256	0.16
28	0.12	13.4	89	110	-0.034
28	0.04	3.1	78	30	-1.37

existence of a equilibrium biomass concentration was suggested in the organic loading range between 0.21 and 0.12 g COD removed/day g MLSS.

The activated sludge was examined periodically during the course of the study and only bacterial forms were in evidence. The floc was completely dispersed pin floc, incapable of gravity separation without chemical flocculation. As a result, the filter was not capable of producing a high quality effluent with respect to suspended solids. The study recommended in situ testing to verify the existence of an equilibrium biomass concentration.

The most recent evaluation of the BAF was conducted at the Ontario Ministry of the Environment Brampton research facility on clarified municipal sewage (Tymflo Process Ltd., 1976). The 80 day field trial of the pilot scale BAF, operating as a total solids retention system (no sludge wasting) did not prove total oxidation was possible on the BAF but did indicate that the system was capable of better than 90% BOD_5 removal and 80% suspended solids removal while treating municipal sewage. Operating at 3.5 and 4.2 hour detention times for a combined period of 60 days, no significant increase in the biomass was noted, but at a detention time of 7.5 hrs operated for 10 days, the biomass in the system exhibited a positive growth trend.

On the basis of these studies, Tymflo Process Limited, claimed up to 50% cost savings for wastewater treatment as there would be no excess biological solids produced, and therefore no sludge disposal costs. The object of this report is to evaluate the BAF capabilities with respect to the apparent conflict of claims.

2.2 Review of the Theory of Total Oxidation

The theory of total oxidation is attributed to Porges et al., (1953), who on the basis of Warburg respirometer studies on dairy waste, theorized that total oxidation was possible under the proper conditions. Investigating the feasibility of batch treatment of dairy wastes, using fill and draw experiments at an approximate ratio of substrate to cell weight of 1:2, Porges observed that 62.5% of the initial COD was converted to cell material and the remainder completely oxidized for energy in a 6 hour assimilative phase. The cells which assimilated the waste had an endogenous respiration (oxidation of their own tissues for energy) which was approximately one-tenth the rate of the assimilation phase. The researchers concluded that at a constant loading, should the endogenous respiration proceed at a rapid enough rate, the auto-oxidation of the micro-organisms would bring about a biomass equilibrium with no sludge accumulation.

Forney and Kountz (1958), following up the work of Porges, supported this theory on the basis of their experiments with a continuous flow activated sludge pilot plant treating skim milk at the rate of 0.76 kg dry skim milk powder per day. For 44 days, they maintained a solids equilibrium of 9.1 kg of biomass in the reactors with a constant 0.06 kg of biomass per day going over the effluent weir and concluded "had these cells not been lost, the effect would simply have been to have increased the total weight of cells in the system". Their conclusion was that total oxidation for skim milk was established at an equilibrium ratio by weight of activated sludge to skim milk of 12:1. Measurements of the carbon dioxide evolved by their system established that 82% of the influent COD was initially assimilated and only 18% immediately oxidized for energy. Their reasons for the deviation from Porges' work was that their system was operated at a much lower loading of substrate to cells and therefore had a lower metabolic rate.

Symons and McKinney (1958) studied the biochemistry of nitrogen in the synthesis of activated sludge using bench scale fill and draw aeration units. The experiments were conducted using sodium acetate as a carbon substrate and nitrogen salts at various concentrations as the nitrogen source. The researchers observed a gradual increase in the polysaccharide material in the sludge mass as the amount of nitrogen fed decreased. They concluded that batch fed or conventional activated sludge systems cannot operate without wasting or a gradual solids build-up, unless some solids escape with the effluent. The build-up of solids in a total solids retention system is due to the bacterial production of non-degradable polysaccharides, which is most pronounced in nitrogen deficient systems.

In 1959, Kountz and Forney revaluated their previous work in light of Symons and McKinneys' findings, and reversed their stand on the theory of total oxidation. They concluded that total oxidation was not possible within reasonable detention times since residual material, equivalent to 20-25% by weight of the new activated sludge produced, was non-biodegradable. Taking into account the mass of solids lost in the effluent and the incoming ash, the equilibrium weight of activated sludge is 14 times the substrate weight per day.

Busch and Myrick (1960), attempted to delineate the limitations of total oxidation using glucose fed bench scale batch and continuous systems. Marked differences were noted in biological solids characteristics between the two systems. In neither environment though, was an equilibrium biomass concentration reached even after as long as 103 days of operation at BOD loadings of 0.05 kg/kg MLVSS. They concluded that theoretically, total oxidation is unsound and practically impossible unless effluent carryover of solids is disregarded.

In 1962, Washington and Symons published data of extensive research on the volatile sludge accumulation in bench scale activated sludge systems. Using sodium acetate, glucose and glycine in different experiments, they concluded that the volatile sludge accumulates at approximately 10 to 15 percent of the ultimate BOD of the substrate removed under equilibrium conditions. They defined equilibrium as the region of operation wherein the active population which can survive under the given conditions was a maximum. The equilibrium condition is attained in a volatile solids accumulating system when a constant fraction of the incoming substrate is completely oxidized. The accumulated inert volatile solids were analyzed to be mainly polysaccharide in nature with significant amounts of organic nitrogen.

Washington and Rao (1964) investigated the long-term adaptation of activated sludge organisms to the accumulated sludge mass grown on a glucose carbon source. They discovered that after the typical sludge accumulation phase which lasted 9 months, the volatile solids were gradually reduced for a period of five months and then continued to accumulate at which time the study was ended. The micro-organisms responsible for the digestion of the accumulated volatile solids were successfully innoculated into other glucose fed activated sludge systems with similar results.

Washington and Rao's results prompted Gaudy to pursue the investigation of auto-digestion and total oxidation.

In 1970, Gaudy et al. published three years of data on their studies of the operational stability of the extended aeration process using a bench scale unit and glucose as a carbon source. Ensuring a total solids retention system by centrifuging the effluent, they demonstrated conclusively that biological solids would not continually build-up, but exhibit a cyclic trend of accumulation, digestion, followed by accumulation without biochemical failure. The conclusion of the study was that total oxidation in the form of extended aeration activated sludge plants was possible for soluble organic industrial wastewaters without sludge wasting with reasonably good biochemical efficiency.

Obayashi and Gaudy (1973) investigated the aerobic digestion of microbial polysaccharides as a rebuttal to Symons and McKinney (1958) conclusions regarding the inertness of extracellular polysaccharides. Using five different polysaccharides as the sole carbon source to acclimitized micro-organisms,Obayashi and Gaudy established that the polysaccharides were readily amenable to biological treatment and therefore cannot be classified as biologically inert.

Although the above work would appear to have concluded the twenty year theoretical dispute regarding the total oxidation of soluble organic matter, designers of waste treatment plants also have had their problems with respect to the application of the theory.

Some designers of small treatment plants treating dairy wastes followed the lead of Porges et al. (1953) and designed treatment plants with long aeration detention times and no sludge handling facilities

(Horton and Trebler, 1953). For the small flows 10,000 to 12,000 liters per day (2,700-3,200 gpd) and soluble wastes, the small solids losses over the effluent weir, sufficed to prevent sludge build-up within the systems at small cost to biochemical efficiency.

Treatment plants designed along similar principles to treat municipal wastes were not as successful.

Pfeffer (1966), reviewed the applied developments of total oxidation in the form of the extended aeration process. The true extended aeration process consists of a large aeration tank and a settling tank. The process is designed to minimize sludge production to the biologically inert fraction which normally would pass out in the effluent resulting in slightly lower biochemical efficiency than normal activated sludge plants. Many manufacturers of package extended aeration plants did not provide for sludge disposal. Since there was no primary sedimentation or grit removal, most systems after a few years operation, became overloaded with solids consisting mainly of inorganic silt and grit. In some package plants, the mixed liquor volatile solids decreased to as low as 45 to 50 percent. The settling and drying characteristics of such a sludge were superior to anaerobically digested activated sludges, because of the high inert fraction which increased the sludge density and porosity. As a result, the most economical methods of disposal were sand drying beds, where land use and climate permitted, or vacuum filtration.

Realizing the problem of inorganics in most waste streams, Gaudy et al. (1976) addressed the problem of biological treatment of a high ash content waste with respect to the total oxidation process. In order to control the mixed liquor concentration in the total oxidation extended aeration system without solids wasting, Gaudy et al. (1971) developed what was called a "hydrolytic assist". Hydrolytic assist is the chemical hydrolysis of a portion of the sludge in order to aid the autodigestive process in maintaining a psuedo steady-state mixed liquor concentration. The process consists of acid hydrolysis at pH 1.0 for five hours at 15 psi and 121°C, followed by neutralization and recycle to the head of the system.

Operating a bench scale extended aeration plant with hydrolytic assist, Gaudy treated hydrolyzed trickling filter sludge with an ash content of 50-60% for a period of one and one-half years without biochemical failure or a continual inert solids build-up in the system. In fact, it was observed that the high ash content of the mixed liquor in the bench scale plant enhanced settling in the final clarifier.

2.3 Activated Sludge Filtration

To date there has been no published attempts to filter activated sludge mixed liquor using a sand media filter in a continuous process excluding the reports on the BAF. As a result the only comparable literature is based on the filtration of secondary effluent following sedimentation.

The conventional water treatment sand filter of United States design is not suited to handle high solids loads (Cleasby and Baumann, 1974) as the media is backwashed at a rate sufficient to expand the bed, and stratify the media. Since normal operation is downflow filtration, the solids encounter the finest media first, causing surface blinding which prevents in depth filtration. As a result dual media filters have been developed in the United States to encourage in depth filtration and thus achieve longer filter cycles with higher influent solids loads. The most common dual media filter bed is composed of a coarser layer of crushed anthracite coal over a layer of finer sand. Since coal has a lower specific gravity than sand, when sized properly it remains on top during backwashing if the backwash rate is sufficient to achieve full fluidization and some bed expansion.

European filtration practice tends towards deeper filters of coarse sand, referred to as single media unstratified filters. The backwashing of such filters is normally a combined air and water wash without significant bed expansion, in order to prevent stratification of the media. The BAF filter is of this type.

In order to compare the run length potential of various filters treating different solids loading, a standard unit of measure, the solids capture capacity of the filter bed, has been defined. Solids capture, measured as a weight of suspended solids captured per unit area of filter surface per unit of headloss build-up, excluding the clean-bed headloss, is the best measure of the solids that can be stored in a filter bed during a run.

The advantage of coarser media size is greater solids capture capacity. The disadvantage is that with the larger porosity greater in depth filtration occurs, requiring deeper filter beds to prevent run termination from solids breakthrough.

Dahab and Young (1977) have completed a thorough study of single-medium unstratified bed filters. The conclusions of the study which are applicable to the BAF are:

1. unstratified bed filters having the same effective size medium as used in the top layer of dual-media filters, provides essentially the same quality effluent and run length as can be obtained from the dual-media filter,

2. the use of unstratified beds with combined air-water wash permits the use of larger filter media sizes than normally used in dual or other multimedia filters,

3. increasing the size of the filter media improves in depth filtration, and increases the solids capture capacity of the filter bed thereby increasing the run length if solids breakthrough of the filter does not occur,

4. backwash rates needed for effectively cleaning an unstratified bed filter are lower than the rate needed to fluidize the media,

5. combined air-water wash essentially eliminates mudball formation, and

6. suspended solids removal efficiency of single-medium, unstratified bed filters is not reduced greatly by increasing the effective size of the media from 1 mm to about 2 mm and when operating at filtration rates of 5 m/hr-10 m/hr (2 gal/min/sq ft-4 gal/min/sq ft).

3. EXPERIMENTAL PROGRAM

3.1 Pilot Plant Equipment

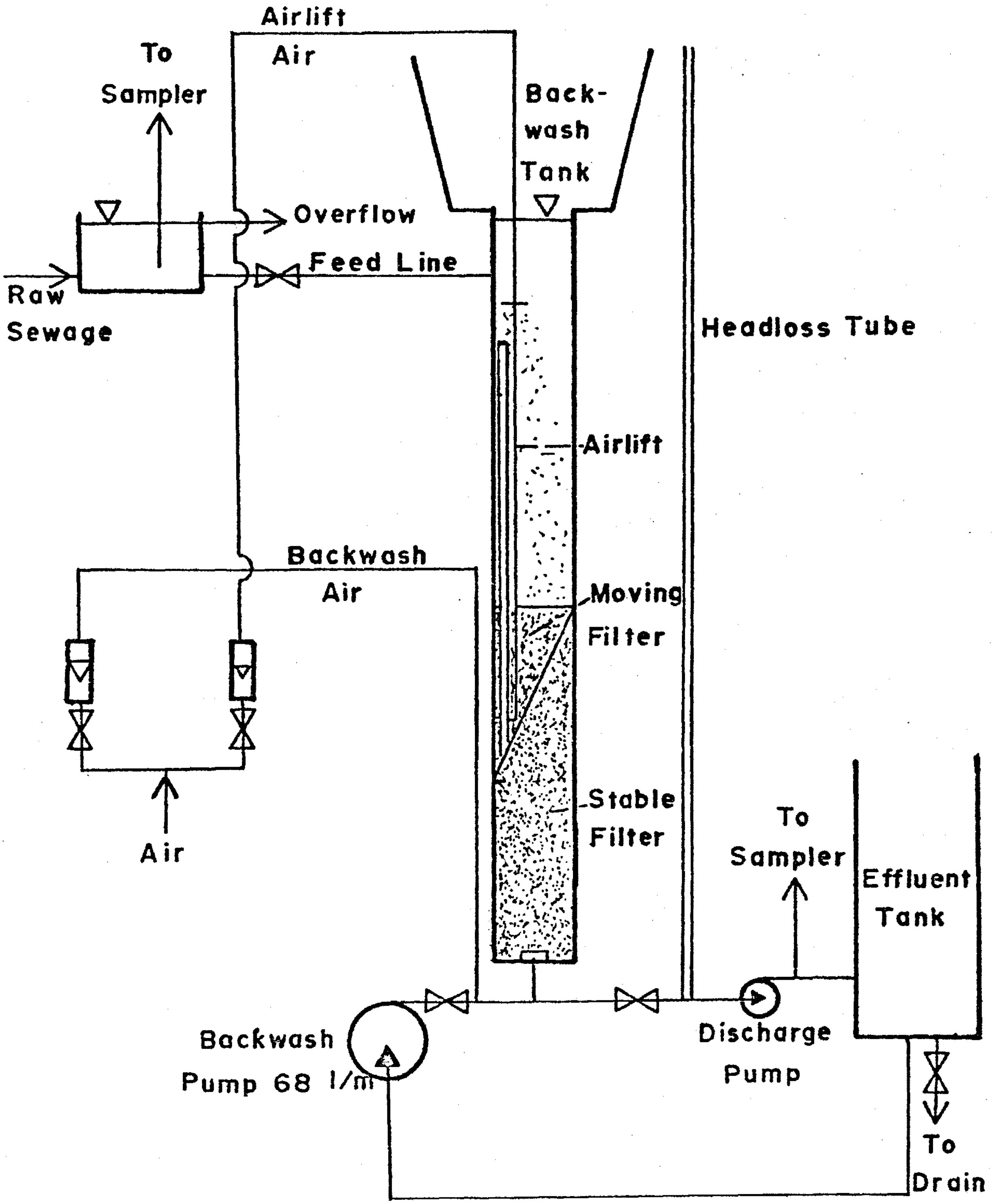
The performance of the BAF pilot plant was evaluated on two identical units located at the Canada Centre for Inland Waters, Wastewater Technology Centre, Burlington, Ontario. Each of the pilot scale systems used for this study consisted of a 3.05 m high column, 14 cm inside diameter, topped by a 68 liter tank, as illustrated in Figure 1. Under normal downflow operating conditions, filter sand occupied the lower 1.4 m of the column, and activated sludge the upper zone to the 3 m height. A 1.4 m long airlift was imbedded in the filter to depths of up to 76 cm, serving as the aeration device and also circulating a portion of the filter media creating a moving filter bed (MFB), and a stable filter bed (SFB). The wastewater treatment cycle of the BAF pilot scale system was limited by either a 3 m headloss or deterioration of effluent quality caused by solids breakthrough of the filter. Upon treatment run termination, the filter was backwashed with treated effluent and air, injected through the diffuser in the bottom of the column.

The pertinent measurements of the pilot unit are:

Volume of activated sludge zone	24.2 ℓ
Column cross-section	153 cm^2
Available head	3 m
Combined filter depth	1.4 m

FIGURE I

Biological Aerated Filter Schematic



Design filter medium

Effective size (D_{10})	1.28 mm
Uniformity Coefficient	1.42
Porosity	0.43
Specific Gravity	2.65

3.2 Influent Characteristics

The wastewater treated by the BAF was degritted municipal sewage from Burlington Skyway Pollution Control Plant. The sewage was pumped through a 1.5 mile long force main to the Wastewater Technology Centre where it was degritted in a highrate clarifier. The sewage characteristics are summarized in Table 2. The methods of analysis are outlined in Appendix A.

The concentration of COD, TKN as N, TP as P and suspended solids fed to the systems can be approximated by normal distributions as indicated by the linear relationship on arithmetic-probability paper (Appendix B). The sample populations of suspended solids and TP as P were culled of four and three data points respectively, as the rogue points did not fit the best fit line for the remaining data. The high suspended solids concentrations are probably random occurrences of solids sloughing off the force main or waste activated sludge from the Skyway treatment plant. The complete set of analyses performed on the influent to the BAF systems are presented in Appendix C.

3.3 Experimental Outline

The following experimental outline was followed:

Part 1: Beginning with the design filter media, the hydraulic detention times were set at 3.5 and 7.0 hours on Column A and Column B

TABLE 2

INFLUENT CHARACTERISTICS

	MEAN (mg/l)	S.D.	NO. OF OBSERVATIONS
SS	151	30	37
Total COD	318	111	41
Total TKN as N	25.8	5.76	41
Total TP as P	5.2	1.28	38
pH	7.1-8.2		
Filtrable COD	96	31	41
Filtrable TKN as N	18.5	3.72	41
Filtrable T as P	2.9	1.21	41
Filtrable NO_2+NO_3 as N	0.4	0.56	41
Filtrable NH_3 as N	14.2	3.64	41
$\frac{\text{Filtrable COD}}{\text{Total COD}}$	30%	% Volatile SS = 74.5	
$\frac{\text{Filtrable TKN}}{\text{Total TKN}}$	72%		
$\frac{\text{Filtrable TP}}{\text{Total TP}}$	56%		

respectively, and increased when the constraint regarding 24 hour filter operation was violated, to the limit set by the second constraint.

Part 2: As it became evident the system could not operate as a total solids retention system, (no wasting of solids), Column A was operated at a constant MLSS concentration with solids wasting, and Column B was restarted to verify yield data.

Part 3: The filter media in Column B was replaced with a silica sand D_{10}=2.1 mm, D_{60}/D_{10}=1.23, and a porosity of 0.44 in order to evaluate the effect of media size on BAF operation. The media was tested in parallel with the original media at 6,8,10, and 12 hour detention using Column A as control.

4. PROCEDURES

4.1 Start Up

Waste sludge from an activated sludge pilot plant was added to the activated sludge zones of both columns to make the final concentration of the activated sludge zone approximately 5,000 mg/l. The discharge metering pumps were set to give a 3.5 hour detention time in Column A and a 7 hour detention time in Column B. Sampling was initiated 24 hours later.

4.2 Operation

4.2.1 Treatment Mode

The treatment mode of the BAF pilot scale system consisted of a complete stirred reactor followed by a downflow filter. The total available head was 3 m. As the treatment run proceeded, the stable filter was penetrated by solids causing increased headloss and eventually flow reduction or solids breakthrough. As stated, the two absolute modes for termination of the treatment run were:

1. headloss through the filter attaining 3 m, or
2. solids breakthrough of the filter.

Secondary treatment interruptions were:

1. the need to estimate solids in the system at the end of a sampling run, and
2. insufficient head for an additional 24 hours of treatment.

4.2.2 Backwash

When the treatment mode was terminated for any of the above reasons, the filter of the BAF system was backwashed in order to restore the available head and to allow the estimation of the systems solids. The backwash sequence was as follows:

1. the feed and effluent valve were closed, headloss, moving filter bed and treated volume measured,
2. the filter was pulsed 12 times with backwash air at the rate of 4.25-5.66 m^3/hr in order to break up the filter bed and mudballs,
3. the backwash water (effluent) was introduced to flush the bed of loose solids at the rate of 30 l/min for approximately 10 seconds,
4. steps 2 and 3 were repeated three to four times until the filter was purged of solids and air,
5. the backwash tank was sampled for MLSS and MLVSS, and the backwash volume recorded,
6. the effluent valve was opened and the filtration of the backwash water begun, and
7. when the liquid level in the column reached 3 m, the feed valve was opened and the treatment run begun.

4.3 Sampling Procedure

Raw feed and effluent sampling for suspended solids, COD, and nutrient analysis was carried out from approximately 9:30 A.M. to 9:00 A.M.

the following day, starting Sunday, Tuesday and Thursday. The samplers were refrigerated composite samplers set to take 100 ml samples twice hourly. The samples were dated according to the end date of the sampling period. The MLSS and MLVSS were estimated on a grab sample taken approximately 90 seconds after the end of the filter backwash. Grab samples of mixed liquor were used to determine weekly Oxygen Utilization Rates. Periodically, temperature and pH were measured on the raw influent and DO, pH and temperature on the effluent and mixed liquor.

4.4 Media Evaluation

The effect of the media size was evaluated using Column A as the control column with the original filter media and Column B with a silica sand of the following properties:

D_{10}	2.1	mm
D_{60}/D_{10}	1.23	

porosity = 0.44

For the experiments at 6,8,10, and 12 hour detention times, the solids and backwash volumes in the two columns were balanced for each run, and the headloss versus time plotted to termination at 3 m of headloss. Solids penetration of the filter and solids remaining in the activated sludge zone were measured.

4.5 Calculations

4.5.1 MLSS and MLVSS Concentrations

Since the backwash volumes for the two pilot systems were not always equal and varied from day to day, the method of reporting the solids (MLSS and MLVSS) was standardized to be the concentration of the solids if all the solids were contained in the activated sludge zone. The calculation consists of three terms:

Term 1. solids in the backwash water,
Backwash volume (l) * measured MLSS (mg/l)

Term 2. Solids in the activated sludge zone, and
((Operating height - sand height (m))*
(cross-sectional area) (m^2)* 1,000 l/m^3)*
measured MLSS (mg/l)

Term 3. solids in the pore spaces in the moving filter bed.
(MFB (m) * cross-sectional area (m^2)) * porosity *
1,000 (l/m^3) * measured MLSS (mg/l).

The concentration of solids (mg/l) assuming all the solids were in the activated sludge zone, was equal to the total solids divided by the activated sludge zone volume. The equation for calculating the MLSS was a standardized to the format:

$$\text{MLSS (mg/l)} = \left[(\text{BWV(l)} + 24.2\text{(l)} + \text{MFB(m)} * 6.58 \text{ (l/m)}) * \frac{\text{MLSS (mg/l)}}{24.2\text{(l)}} \right]$$

The MLVSS concentration (as mg/l) was the product of the percent volatile solids in the sample times the calculated MLSS.

4.5.2 Detention Time

The detention time of the BAF system was based on the volume of the activated sludge zone plus the pore volume of the filter. The volume of the activated sludge zone was approximately 24.2 l and the volume of the pores in the sand filter were approximately 10.1 l. Consequently the reactor liquid volume was approximately 34.3 l. Table 3 summarizes the flows and detention times employed.

TABLE 3

DETENTION TIMES AND FLOWRATES

DETENTION TIME (hr)	FLOWRATES ml/min	l/hr	Igpd
3.5	163	9.80	51.7
5.0	114	6.86	35.9
6.0	95	5.72	30.1
7.0	82	4.90	25.9
7.5	76	4.57	24.1
12.0	48	2.86	15.1

5. RESULTS AND DISCUSSION

5.1 Overall Performance

5.1.1 Solids Production and Detention Times

The MLSS and MLVSS for the two pilot plants are plotted in Figures 2 and 3 with the hydraulic detention times superimposed. Detention times were progressively increased since the systems failed to meet the minimum 24 hour filter run constraint as the headloss exceeded 3 m. Table 4 lists the frequency of complete headloss for the various operating conditions.

As illustrated in the figures, particularly for the operating periods day 31-73 Column A and day 25-52 Column B, the inert non-volatile solids accumulated in the BAF system at a constant rate. This phenomenon was caused by the combination of the non-volatile fraction of the incoming sewage (approximately 25%) and the high efficiency of the filters. The MLVSS for the same periods increased at a very low rate, hinting that a MLVSS equilibrium was possible. However, total oxidation was not achieved. The MLSS overloaded the filters at the longest detention time without meeting the 24 hour filter run constraint. As a result, at day 52, when both columns had failed repeatedly, the primary objective of attaining total oxidation biomass equilibrium was abandoned. The remainder of the operating period was devoted to defining the system yield at a feasible operating condition and to investigate the performance of the system at extremely high inert solids - low volatile solids conditions.

FIGURE 2

MLSS and MLVSS vs TIME COL. A

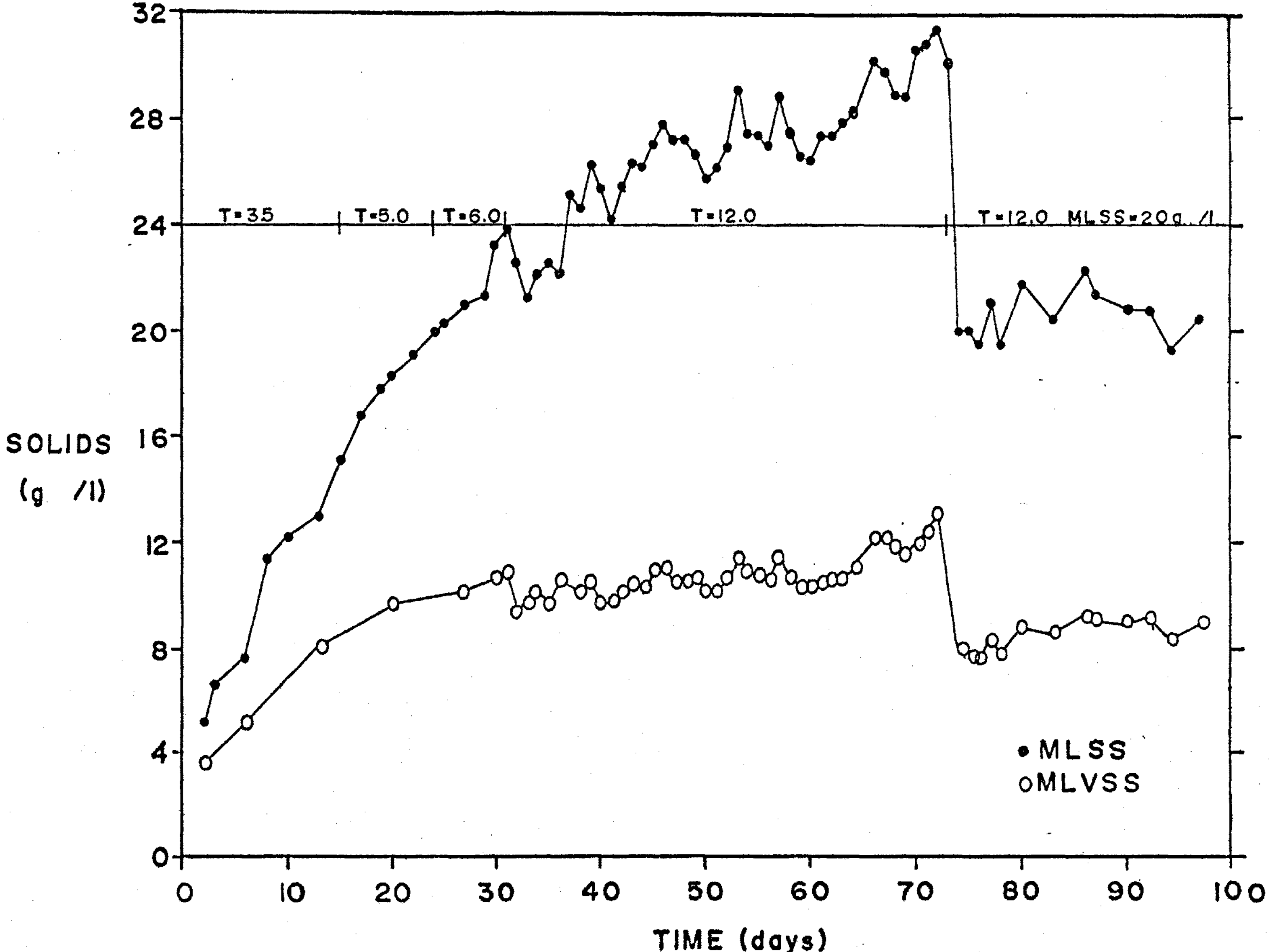


FIGURE 3

MLSS and MLVSS vs TIME COL. B

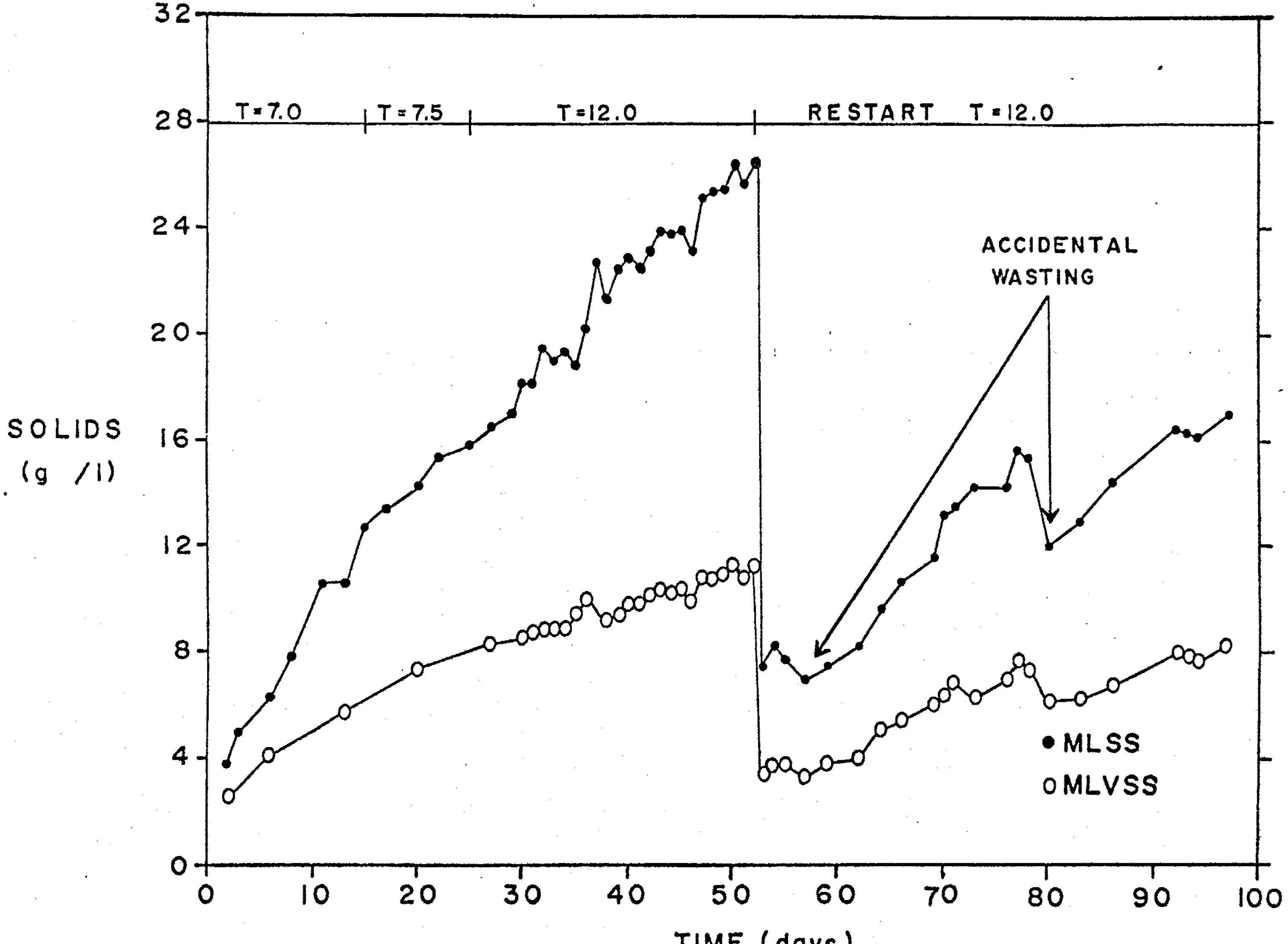


TABLE 4

FREQUENCY OF COMPLETE HEADLOSS

COLUMN	OPERATING CONDITION	PERIOD days	# OF TIMES HEADLOSS EXCEEDED 3m	
A	T = 3.5 hr	0 - 14	4	out of 14
B	T = 7.0	0 - 14	2	14
A	T = 5.0	15 - 24	10	10
B	T = 7.5	15 - 24	7	10
A	T = 6.0	25 - 30	6	6
A	T =12.0	31 - 73	21	43
A	T =12.0	74 - 97	1	24
	wasting to maintain 20,000 mg/l MLSS			
B	T =12.0	25 - 52	12	28
B	T =12.0	53 - 97	7	45
	restart at 7,000 mg/l MLSS			

T = hydraulic detention time

The inert solids build-up became an acute problem in a much shorter time than in the extended aeration plants reported by Pfeffer (1966), since the BAF system was designed as a total solids retention system. The sludge produced in the BAF system at the latter stages of the high solids operation, consisted of only 39% volatile solids, and exhibited good settling and relatively easy sample filtration. According to Pfeffer, such a low percent volatile sludge is very stable and readily amenable to dewatering without anaerobic digestion.

5.1.2 Removal Characteristics

Table 5 summarizes the average percentage removals of suspended solids, COD, TKN and TP for 82 days of operation.

The above summary does not include the first two weeks of operation, as Column A was losing excessive solids from solids breakthrough of the filter. At higher detention times and solids loading the breakthrough phenomenon ceased.

The effluent characteristics of the two pilot systems with respect to total and soluble COD and nutrients are tabulated in Table 6. The soluble effluent data was averaged over the last 68 days, because Column A did not completely nitrify for the first 25 days due to high solids losses through the filter. The effluent means with respect to filterable COD, TKN and NH_3 are statistically the same for the period of comparison. As a result, it was concluded that the systems removal characteristics are equal with respect to COD removal and nitrification, for the operating conditions employed. The probable reason the unfiltered COD and TKN were different is due to the difference in solids loading on

TABLE 5

AVERAGE PERCENTAGE REMOVALS

	COLUMN A		COLUMN B	
	$\bar{x}$	S.D.	$\bar{x}$	S.D.
SS	97	1.3	98	0.6
COD	87	5.7	88	5.6
TKN	85	8.8	89	6.8
TP	48	17	53	18

TABLE 6

EFFLUENT CHARACTERISTICS

PARAMETER	COLUMN	$\bar{x}$	S.D.	n	days	$\bar{x}_a=\bar{x}_b$ at 95% CONFIDENCE
Tot. COD	A	40.6	25.6	35	17-97	reject
	B	32.4	9.9	35	17-97	
Tot. TKN as N	A	3.63	2.10	35	17-97	reject
	B	2.78	1.79	35	17-97	
Tot. TP as P	A	2.92	0.98	35	17-97	reject
	B	2.48	0.70	35	17-97	
Filt. COD	A	33.7	8.1	35	17-97	accept
	B	31.3	13.6	35	17-97	
Filt. TKN	A	2.10	0.91	30	29-97	accept
	B	2.08	0.92	30	29-97	
Filt. NH_3	A	0.47	0.40	30	29-97	accept
	B	0.59	0.64	30	29-97	
Filt. NO_2+ NO_3 as N	A	15.6	4.05	30	29-97	reject
	B	12.8	5.09	30	29-97	
Filt. TP as P	A	2.50	0.82	35	17-97	reject
	B	2.07	0.91	35	17-97	
Suspended Solids	A	3.1	2.13	30	17-97	reject
	B	1.5	0.70	33	17-97	

pH 7.2-8.0
temperature 22-28°C
DO (mg/l) 0.2-2.0

Note: all parameters reported as mg/l

the filters and the resultant difference in effluent suspended solids. Dahab and Young (1977) cited higher solids loading on a filter as a major factor affecting the deterioration of filter effluent quality with respect to suspended solids.

The effluent filterable phosphorus was different for the two pilot plants, because solids production varied due to different modes of operation. Sherrard and Schroeder (1972) observed similar results when investigating cell yield at various mean cell residence times and concluded, providing the stoichiometric formula of cellular composition did not change, less nitrogen and phosphorus would be removed at longer mean cell residence times.

In general, the BAF has better suspended solids removal than conventional activated sludge systems employing sedimentation as the means of solids separation. In fact, the BAF effluent is equal to effluents from activated sludge plants or trickling filters followed by rapid sand filtration and easily meets the Environmental Protection Agency effluent criteria of 10 mg/l suspended solids, without chemical addition.

The EPA have established a BOD_5 effluent standard of 10 mg/l following tertiary filtration. The BAF performance evaluation was based on COD. Only four sets of BOD_5 determinations were made on the BAF effluents. These samples were from the third month of operation and ranged from 2-12 mg/l BOD_5 with an average of 7 mg/l BOD_5. Based on the above results, it would appear that the BAF treating degritted municipal sewage and operated at a 12 hour hydraulic detention time can meet the EPA tertiary filtration standard cf 10 mg/l BOD_5, 10 mg/l suspended solids.

5.1.3 Operational Difficulties

The main operating problem was maintaining as large a filtering area as possible. The filtering area was increased by increasing the slope of the moving filter - stable filter interface as close to the vertical as possible while maintaining the deepest operable airlift depth. The filtering area in the pilot scale system was affected by the airlift depth, air-flow and airlift size. The least amount of air required to operate the airlift was sufficient to maintain a DO level greater than 2 mg/l in the aeration zone. Therefore setting the minimum air-flow with maximum airlift depth was the objective. A slight decrease in air-flow after a large interface was formed, resulted in airlift plugging, cross-sectional filter face and rapid headloss.

On the other hand, increased in air-flow also affected the system. Air-flow directly affected the rate of circulation of the moving filter and as a result, at increased air-flows, such as occurred on weekends, the moving filter eroded the high inclined filtering surfaces to the normal angles of repose of the media. The reduction of filtering area resulted in higher headloss rates.

5.2 Physical Performance

5.2.1 Filtration Rates

The filtration rates presented in Table 7 are based on a horizontal filtering face in the BAF column. In actual fact, the filtering face was the interface between the moving filter and the stable filter, which was 2 to 3 times larger than the cross-sectional area. As a result the actual filtration rates were proportionally smaller. This actual interface area in the BAF was a function of

TABLE 7

FILTRATION RATES

DETENTION TIME (hr)	FLOWRATE		FILTRATION RATE	
	ml/min	Igpm	1/min-m^2	Igpm/ft^2
3.5	163	.036	10.7	.218
6.0	95	.021	6.21	.127
7.5	76	.017	4.97	.103
8.0	72	.016	4.70	.097
10.0	58	.013	3.78	.079
12.0	48	.011	3.14	.067

column diameter, airlift depth, air-flow, airlift size and media size.

In order to avoid excessive headloss, it was imperative to try and maintain as large an interface as possible. The increased filtering surface and scouring action of the moving filter were the main factors which allowed the relatively long filtration runs of the BAF relative to horizontal single medium unstratified filters. In the latter period of operation (days 80-97), Column B operated for up to five consecutive days without backwash without the headloss exceeding 3 m.

The interfacial area was not specifically optimized in this project since the systems operated were pilot scale and therefore the optimum operating conditions for a full-scale plant will be significantly different due to geometric differences. The airlift depth and airflow were adjusted to maximize the interfacial area for the pilot scale systems by a trial and error approach.

5.2.2 Solids Capture Capacity and Solids Penetration

Table 8a summarizes the solids capture capacity and solids penetration of the design filter media, D_{10}=1.28 mm, operated at a 12 hour detention time. Detailed calculations are presented in Appendix F. Table 8b lists literature values of solids capture capacities of various single medium unstratified filters treating secondary effluent.

The filtration rates at which the reference experiments were conducted are 26 times greater at the lowest rate, and are based on treating wastewaters with 30-100 mg/l suspended solids, therefore absolute comparisons are not valid. A general conclusion is that the BAF filter has a greater solids capture capacity than comparable media size and type filters treating secondary effluent.

TABLE 8a

SOLIDS CAPTURE CAPACITY AND PENETRATION

DAY	PENETRATION m	SOLIDS IN FILTER kg/m^2	CAPTURE CAPACITY kg/m^2-m of Headloss
44	0.52	19.2	12.6
45	0.42	18.2	17.1
57	0.61	20.6	10.4
58	0.62	21.1	7.7
60	0.42	17.6	9.1
61	0.42	16.1	9.6
62	0.50	17.0	8.8

Note: Filtration Rate = 0.19 m/hr

Ave. 10.4 S.D. 3.19

kg/m^2 * .204 = lb/ft^2

kg/m^2-m * .063 = $lb/ft^2/ft$

TABLE 8b

(Dahab and Young, 1977)

FILTRATION RATE m/hr	gpm/ft^2	D_{10} mm	CAPTURE CAPACITY kg/m^2-m of Headloss
20	8	2.31	5.0
20	8	1.82	4.2
20	8	1.49	2.4
20	8	0.97	1.6
5	2	2.31	3.7
5	2	1.82	3.0
5	2	1.49	1.76
5	2	0.97	0.96

5.2.3 Effect of Media Size

The results of the effect of media size experiments are summarized in Table 9 and Figure 4. The headloss rates were determined by a least squares straight line fit of the headloss vs time measurements for each run and the averages of two runs at similar conditions reported in Table 9. The solids penetration and solids capture capacity data presented, are also the average of two determinations. The calculations are presented in Appendix F.

Figure 4 indicates that the D_{10}=1.28 mm media has a higher headloss rate than the large media, though the difference at the longer detention times is not significant. The effect of media size on solids penetration and solids capture capacity, as shown by Figures 4b and c, is that the larger media (D_{10}=2.1 mm), allows significantly increased penetration and has a higher solids holding capacity, than the smaller media.

Comparing the effect of media size results to the work of Dahab and Young (1977), the trends with respect to solids holding capacity versus media size and filtration rate agree. Increased filtration rates result in increased solids capture capacity and penetration while a larger media size at the same filtration rate yields greater solids capture capacity and penetration.

Comparing the solids capture capacity of the D_{10}=1.28 mm media at the 12 hour detention time in Table 9 to Table 8a, an important effect of the size of the interfacial area is illustrated in the decreased solids capture capacity of the same media at the same filtration rate. The solids capture capacities in Table 8a, were measured under normal operating conditions which entailed operating the system with a maximum

TABLE 9

EFFECT OF MEDIA SIZE

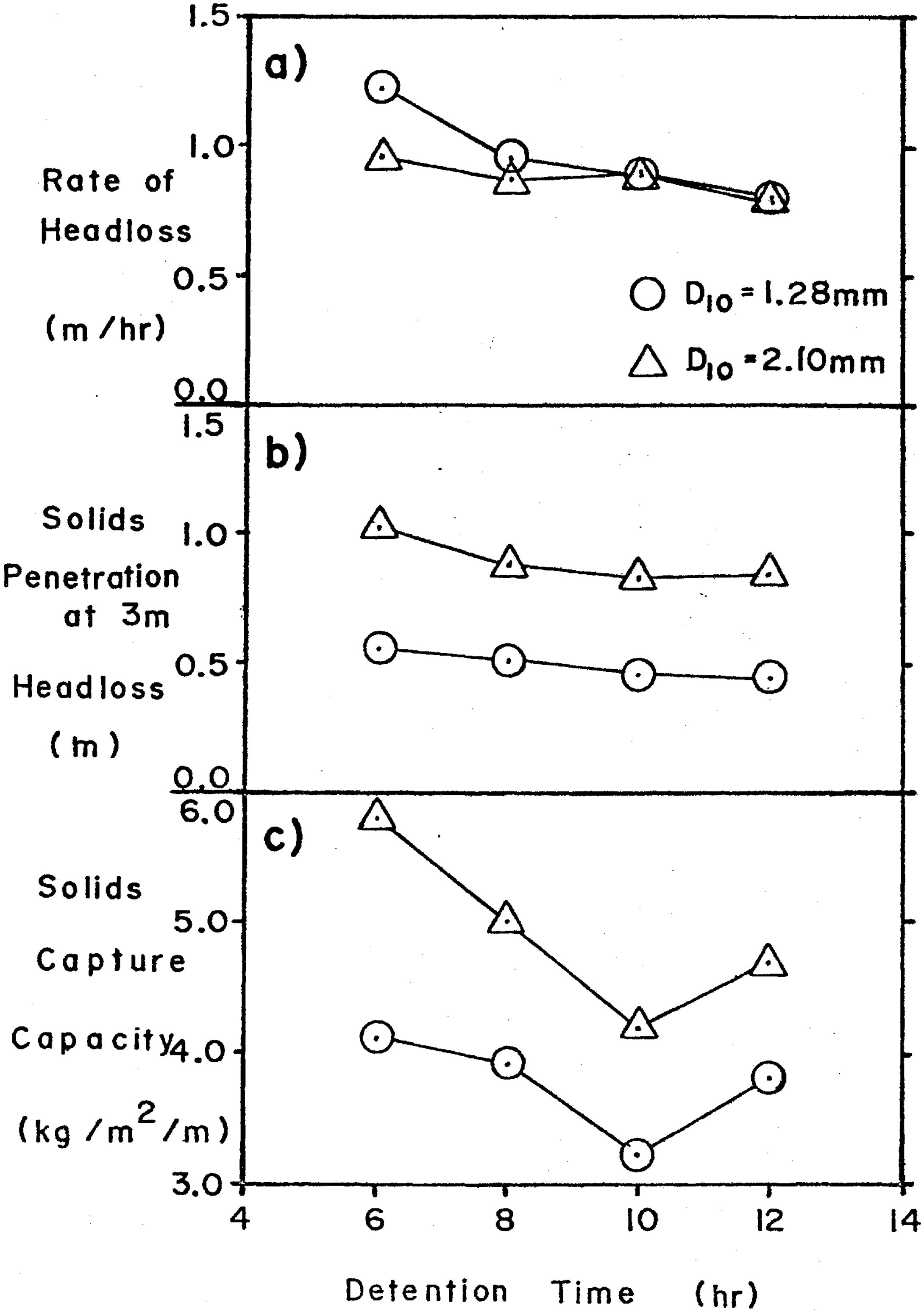
DETENTION TIME hr	HEADLOSS RATE m/hr		SOLIDS PENETRATION at 3m HEADLOSS m		SOLIDS CAPTURE CAPACITY kg/m^2-m		EFFLUENT SS mg/l	
	COLUMN A	COLUMN B	COLUMN A	COLUMN B	COLUMN A	COLUMN B	COLUMN A	COLUMN B
6	1.34	0.86	0.60	1.05	4.1	5.8	3	4
8	0.64	0.69	0.51	0.77	3.9	5.0	3	2
10	0.73	0.75	0.43	0.65	3.2	4.2	2	3
12	0.55	0.53	0.41	0.71	3.8	4.7	2	2

Note: Column A D_{10} = 1.28 mm

Column B D_{10} = 2.10 mm

FIGURE 4

Effect of Media Size



interfacial area in order to decrease headloss rate and maximize the treatment time. The effect of media size experiments on the other hand, were operated at a minimum stable interfacial area in order to minimize the experiment duration. The average solids capture capacity calculated for the larger interfacial area is 2.8 times greater.

The last two columns in Table 9 summarize the effluent suspended solids for the effect of media size experiments. The effluent quality with respect to suspended solids was not affected by the media size. Dahab and Young (1977), found that as media size increased, D_{10}=0.97 mm to D_{10}=2.31 mm, effluent quality decreased slightly at filtration rates of 5-20 m/hr (2-8 gpm/ft^2), but the media grain size caused fewer variations in effluent suspended solids than changes in influent suspended solids concentrations.

Since filter depth in the BAF system should be kept to a minimum in order to increase the overall capacity of the BAF system, the conclusions of the media size experiments are:

1. At short detention times (6-8 hr) the larger media will increase treatment run time but will require deeper filter beds than the smaller media.
2. At longer detention times (10-12 hr) the larger media will not increase treatment run time, but will require deeper filter beds than the smaller media.
3. Under the test conditions, the larger media attained the same suspended solids removal as the smaller media.
4. The larger media has substantially higher solids capture capacity.

5.3 Biological Performance

5.3.1 Yield Assumptions

As raw sewage is a wastewater composed of soluble and solid organics and inorganics, and most research work regarding biological systems is carried out using strictly soluble substrates, there is a need to define the underlying assumptions of such parameters as yield and organic loading when dealing with composite feeds.

In this report, influent volatile solids were judged to be a portion of the substrate to the system and were measured by the COD analysis on the unfiltered influent sample. The influent volatile solids were assumed to be biodegradable and therefore eventually converted to biomass, CO_2 and water. Should the influent volatile solids have not been immediately digested, the same fraction of undigested solids would have been present throughout the calculation period, since the systems were operated continuously and the initial start-up period rejected for yield calculations.

It was assumed that the MLVSS were a representative measure of the biomass concentration of the system. Effluent volatile solids were not added to the increase in MLVSS for a calculation period, as the COD of the solids was measured as effluent COD and subtracted from the influent COD to estimate the COD removed. The TP and TKN balances, by the same reasoning were not corrected for effluent solids.

A comparison of the yields as calculated based on the above assumptions and secondly based solely on the removal of soluble COD assuming total influent volatile solid build-up is summarized in Table 10. The methods are the two extremes, one assuming total influent volatile solid biodegradation and the second assuming no biological degradation

TABLE 10

EFFECT OF ASSUMPTIONS ON YIELD

Example: Column B, Days 80-97

1. Assuming complete volatile solid biodegradation:

$Y = \Delta$ MLVSS/Total COD Removed

Δ MLVSS = 3.94 g /day

Total COD Removed = 16.5 g /day

$$\therefore \text{Yield} = 0.24 \frac{\text{g MLVSS}}{\text{g COD removed}}$$

2. Assuming no influent volatile solid degradation:

$Y = (\Delta$ MLVSS − Influent VSS)/Soluble COD Removed

Δ MLVSS = 3.94 g /day

Influent VSS = 7.68 g /day

Filtered COD = 4.06 g /day

$$\therefore \text{Yield} = -0.92 \frac{\text{g MLVSS}}{\text{g Filt. COD removed}}$$

of the volatile solids. The actual system most likely does allow a small amount of volatile solid build-up. One possible component of such a build-up within a total solids retention system, is high lignin content cellulose as stated by Hurwitz *et al.* (1961) and Edberg and Hofsten, (1975).

Normally yield is based on the above assumptions (Lawrence and McCarty, 1970), and this will be used throughout this report.

A second definition of yield in this report termed "gross yield", is an estimate of the total amount of solids produced per unit of substrate removed. The gross yield includes the inorganic inert solids associated with the influent substrate. The gross yield therefore is the total amount of solids produced per unit of substrate removed and represents the total solids requiring ultimate disposal.

5.3.2 BAF Yields

Since a MLVSS equilibrium concentration was not reached, it was necessary to define the system yields and feasible operating conditions. The 12 hour detention time was selected as the best operating condition to study system yields as it offered the highest chance of fulfilling the 24 hour filter run constraint at high solids levels.

The yield results, corrected for sampling, for five different periods are summarized in Table 11a. Table 11b reports the gross yields for the same five periods. Detailed calculations are presented in Appendix G.

The yields were calculated over periods where no known unaccountable operational upsets or losses occurred. The average mean cell residence time was calculated from the sum of the mean cell residence

TABLE 11

BAF YIELDS

11a YIELD

$Y = \Delta$ MLVSS/Δ COD   F/M = Δ COD/MLVSS

COLUMN	DAYS	$\frac{\Delta \text{ MLVSS}}{\text{day}}$ g /day	$\frac{\Delta \text{ COD}}{\text{day}}$ g /day	AVERAGE MLVSS g	YIELD	AVE. T_P	AVE. F/M
A	48-73	2.22	13.4	306	.17	138	.045
A	74-97	3.29	15.5	219	.21	67	.071
B	25-52	3.01	12.3	247	.25	82	.052
B	57-78	5.16	21.2	138	.24	27	.178
B	80-97	3.94	16.5	179	.24	45	.095

11b GROSS YIELD

$Y = \Delta$ MLSS/ΔCOD

COLUMN	DAYS	Δ MLSS/day g /day	GROSS YIELD
A	48-73	4.70	.35
A	74-97	5.68	.37
B	25-52	10.46	.85
B	57-78	11.28	.53
B	80-97	8.02	.49

times at the beginning and end of a calculation period. The organic loading was calculated similarly. Both the mean cell residence time and the organic loading, were constantly changing from beginning to end of a calculation period, even for the constant MLSS run.

Figures 5 and 6 are plots of the yield versus organic loading and yield versus mean cell residence time respectively. The best fitted lines through the data, as calculated by least squares regression, have considerable scatter about them, but indicate general trends. The yield is an increasing function of organic loading. If the range of organic loadings under which the systems were operated did not affect the yield, the average yield would be 0.22 ± 0.041 g MLVSS/g COD removed at the 95% level of confidence.

Comparing the BAF yields to the three year study of total oxidation by Gaudy <u>et al.</u>, (1970), the BAF system produced a significant yield, relative to Gaudy's claimed total oxidation. While both systems were operated at similar organic loadings, the BAF treated degritted municipal sewage while Gaudy's bench scale system treated a single substrate glucose.

The yield versus mean cell residence time (T_B) at a constant mass loading was shown to be a first order decay function of the mean cell residence time for the range 0-20 days by Sherrard and Schroeder (1972). The equation fitted for their data is:

$$Y = 0.406 \exp (-0.067\ T_B).$$

At the longer mean cell residence times under which the BAF was operated, the yields appear to be a zero order function of the mean cell residence

FIGURE 5

Yield vs Organic Loading

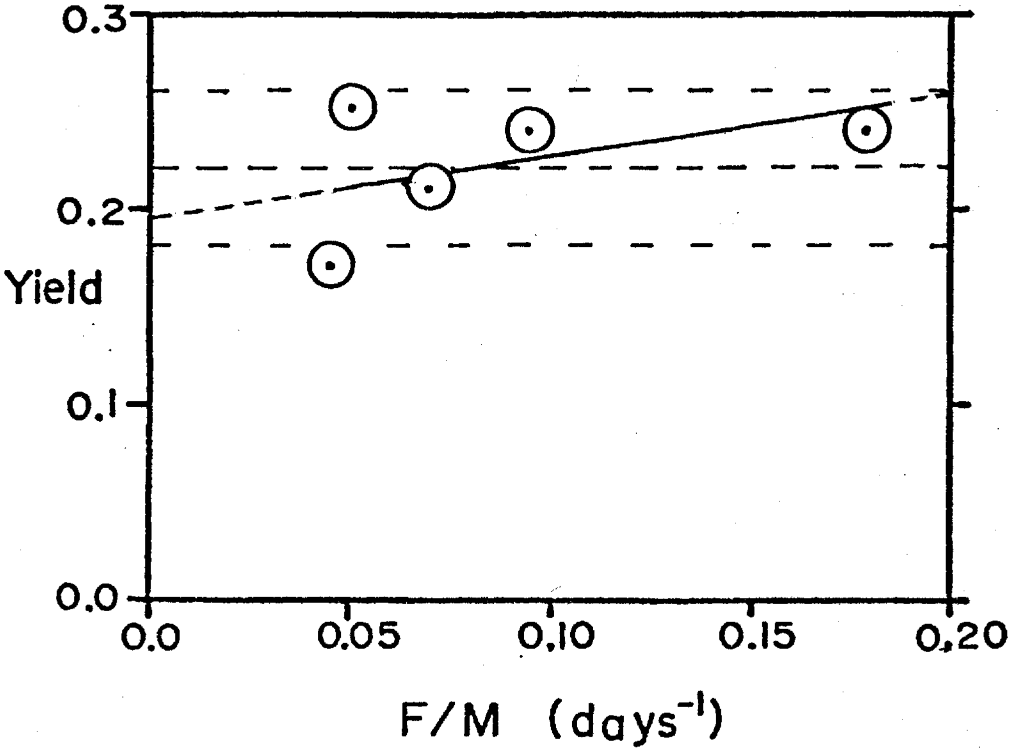
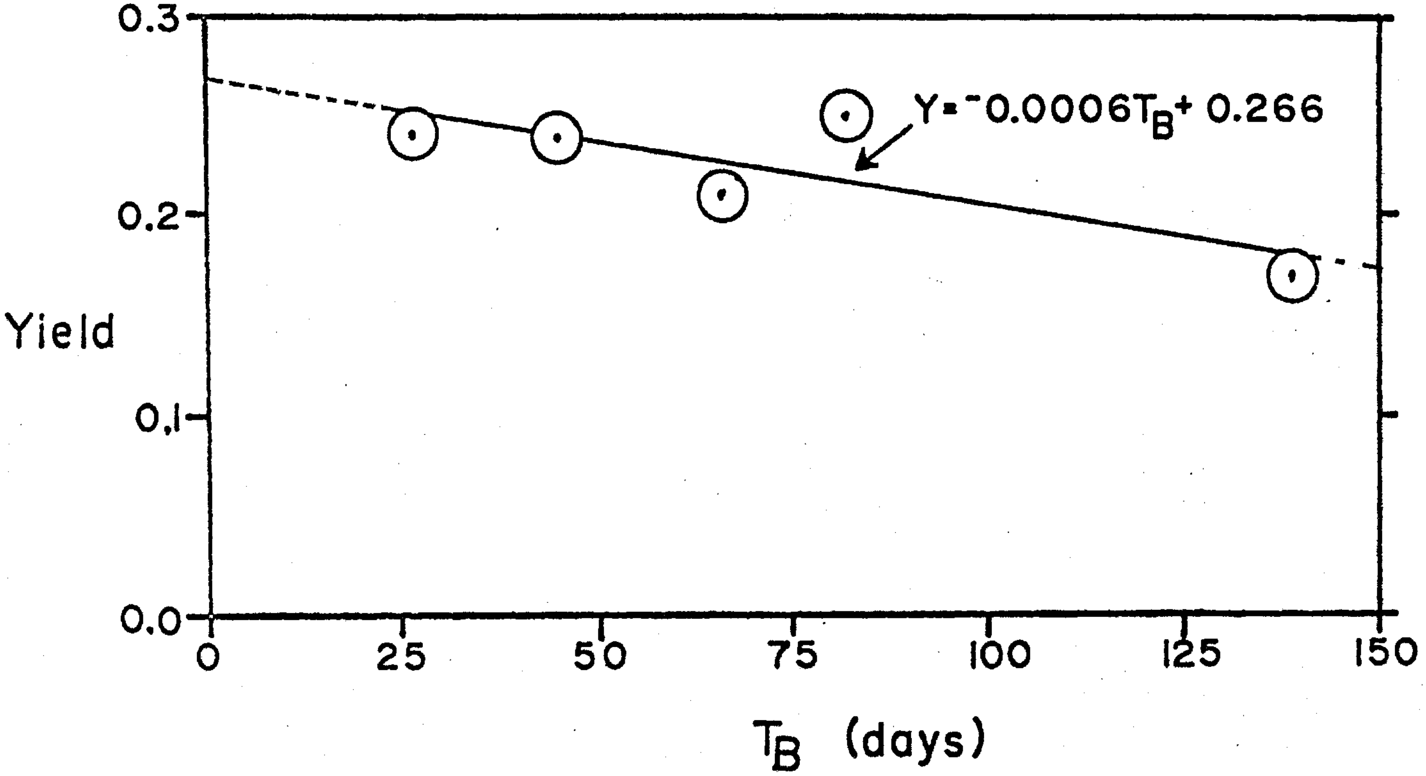


FIGURE 6

Yield vs Mean Cell Residence Time
(Assuming Constant Mass Loading)



time and may be expressed by the equation:

$$Y = -0.0006\ T_B + 0.266.$$

This equation is not valid in the region of 0-20 days as it predicts a 0.27 yield at zero T_B. This yield, based on COD, is definitely too low for sewage. It may be that the function can be approximated by a zero order equation at long mean cell residence times because first order curves tend to be nearly linear as they approach the asymptote. A possible explanation is that the loadings are so low, that the easily biodegradable substrate is immediately assimilated and the more resistant substrates such as cellulose are limited to zero order kinetics. The extrapolation of the data, predicts a zero yield at a mean cell residence time of 440 days. This linear estimate would give a minimum value, as a first order function which would be asymptotic to the absicca in this region, would predict a much larger mean cell residence time.

In Figure 7, when the organic loading versus mean cell residence time data was plotted in the linear form of $1/T_B$ versus F/M, the data was best fitted to the expression:

$$1/T_B = 0.214(F/M) - 0.0003$$

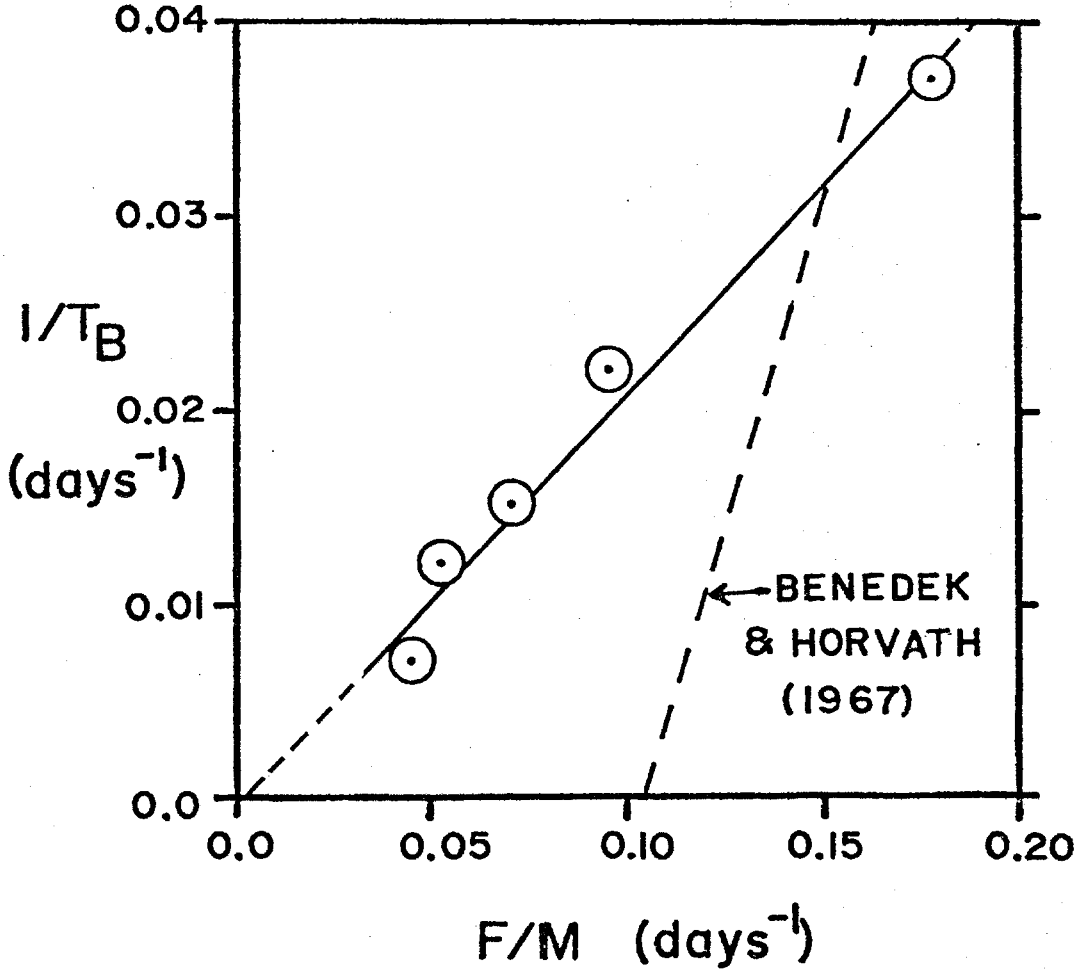
where 0.214 is the true yield constant, and

0.0003 is the maintenance energy coefficient or decay constant.

The equation constants are low relative to the 0.67 true yield constant and 0.07 decay constant for domestic waste on a COD basis reported by Benedek and Horvath (1967).

FIGURE 7

$1/T_B$ vs F/M



The gross yields for the BAF system reported in Table 11b, have considerable scatter most likely due to the variable inert solids accumulation. The average gross yield is 0.52 ± 0.28 g MLSS/g COD removed at the 95% level of confidence. The gross yield is very dependent on the inert fraction of the wastewater being treated and as a result comparable data is not readily available.

5.3.3 Mass Balances

Table 12 summarizes the results of six sets of analyses of the BAF activated sludge for COD, TKN and TP.

Only the percentage TP content of the sludge was the same for both columns at the 95% confidence level. The only balances attempted on the BAF system were nitrogen, phosphorus and inert solids.

Assuming the biomass composition $C_{60}H_{87}O_{23}N_{12}P$ used by Sherrard, (1976), is correct, the COD equivalent of the biomass would be 143%. The nitrogen content of the theoretical biomass would be 12.2%, and the phosphorus 2.3% by weight.

The observed COD equivalents of the BAF MLVSS are approximately 60% higher than the COD equivalent of the accepted biomass composition. For the ratio of COD:N:P observed, the empirical biomass composition would be $C_{57}H_{56}O_{23}N_3P$. It is possible this may be the result of the accumulation of small quantities of relatively inert organics such as cellulose which are oxidized in the COD test.

The phosphorus content of activated sludge under normal operating conditions reported by other researchers (Levin and Shapiro, 1965), is in the order of 2-3.5%.

TABLE 12

PERCENTAGE COMPOSITION OF BAF MLVSS

	COD		TKN		TP	
	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
Column A	206	17.8	4.67	0.80	3.48	0.46
Column B	196	5.0	5.35	0.51	3.38	0.21

With respect to those values, the phosphorus values calculated for the BAF sludge agree well. The calculated nitrogen contents though compose only 40% of the theoretical 12.4%. Kountz and Forney (1959) reported activated sludge contents of 8.5% in a system with a sufficiency of nitrogen. With respect to their data, the BAF sludge was nitrogen low. Sutton (1977) though, while investigating nitrification-denitrification systems found 5-6% nitrogen in pilot scale activated sludge systems.

Table 13 lists the percentages of nitrogen, phosphorus and inert solids not explained by the MLVSS and MLSS accumulation for the observed removals across the BAF system assuming no denitrification. The negative signs in the inert solids column represent the percentage excess inerts accumulated in the MLSS not accounted for by the inerts of the incoming sewage. The poor results are partially due to the incorrect sampling schedule for mass balances, and in the case of the nitrogen balance, the probable occurrence of denitrification. The last set of columns, list the percentage of nitrogen and phosphorus needed in the MLVSS in order to explain the nutrient removal across the columns. If the phosphorus content of the MLVSS had been in the range of 5%, 1.5% higher than the observed 3.5%, a phosphorus balance could have been obtained. The only perceivable loss could be precipitation with calcium or iron onto the sand particles. No measurements of this phenomena were made.In future studies, specific 5 day mass balance sampling periods should be carried out to ascertain that biological uptake of phosphorus is the only removal mechanism, and to delineate the extent of denitrification. Detailed calculations are listed in Appendix H.

TABLE 13

MASS BALANCE RESULTS

		PERCENTAGE LOSS			% COMPOSITION NEEDED	
COLUMN	DAYS	N	P	INERTS	N	P
A	48-73	87.4	48.5	-18	37	6.8
A	74-97	69.5	26.6	-19	15	4.7
B	25-52	57.5	27.8	-258	13	4.7
B	57-78	57.5	32.4	-87	13	5.0
B	80-97	77.8	34.1	-58	24	5.1

5.3.4 Oxygen Uptake Rates

Table 14 lists the oxygen uptake rates (OUR) measured on the BAF activated sludge accompanied by the approximate organic loadings for key days. The OURs are positively correlated with the organic loading and are generally much lower than conventional activated sludge or extended aeration plant uptake rates. Gaudy *et al.* (1970), during his three year study of total oxidation, using a bench scale extended aeration plant treating glucose, encountered OURs as low as 1.0 mg O_2/hr-g MLVSS with a first year average of 3.5 mg O_2/hr-g MLVSS. The F/M range employed was 0.017-0.02 g COD/g MLVSS-day.

In general the BAF mixed liquor was relatively inactive as indicated by the respiration rate, owing to the low organic loading and long cell residence time. Microscopic examination of the sludge supported the respiration data and indicated no higher forms of protists, only bacteria present and large amounts of debris. The BAF sludge was very similar in population and appearance to an aerobically digested sludge.

5.4 Discussion

5.4.1 Comparison of the BAF and Extended Aeration Processes

The basis of all comparisons of treatment alternatives are economics, removal efficiency, sensitivity, flexibility and excess solids production or yield. Depending on the effluent requirements and specific project constraints, the factors are weighted to reflect the particular project needs. This study was concerned with technical feasibility of the BAF concept and does not provide an economic evaluation.

TABLE 14

OXYGEN UPTAKE RATES

	COLUMN A		COLUMN B		TEMP
DAY	OUR*	F/M	OUR*	F/M	°C
13	11.6	0.19	6.3	0.16	23
20	7.7		6.7		24
27	5.5		3.9		24
34	3.6		2.5		26
41	2.8		2.5		24
48	1.8	0.05	4.9	0.04	27
55	3.0		6.6		25
62	2.8		7.6	0.25	26
69	3.8	0.04	7.0		26
76	2.7	0.08	4.6	0.12	24
83	3.7		4.4	0.11	23
90	5.7	0.07	6.2	0.08	27

---

*Units of OUR's are mg O_2/hr-g MLVSS

This study demonstrated the BAF removal capabilities are 97% for suspended solids, 88% for COD with essentially complete nitrification when operated at a constant 12 hour detention time treating degritted municipal sewage. Periodic BOD_5 sampling indicated that the BAF effluent quality under the controlled operating conditions meets the most stringent EPA standards of 10 mg/l BOD_5, 10 mg/l SS, set for tertiary filtration of secondary effluents in the United States. Extended aeration plants, the low yield design conventional activated sludge plant, are also capable of complete nitrification, but have difficulty in meeting the 15 mg/l BOD_5, 15 mg/l SS effluent standards set by the Ministry of the Environment, when operated at hydraulic detention times of up to 24 hours. The longer detention times employed in the extended aeration process infer substantially larger aeration tankage than would be required with the BAF, yet the effluent quality is generally inferior due to incomplete solids separation.

Sensitivity in the context of this report refers to the response of a system to a range of hydraulic and influent concentration conditions. The BAF can be definitely classified as a stable system over a wide range of hydraulic and organic loading conditions. No effluent quality deterioration occurred during the 97 day testing period. During evaluation of media size, the suspended solids removal in the BAF was not affected by detention time in the range of 6-12 hours. The COD removal, though not monitored for these specific experiments probably would be 88% based on the 97 day continuous testing. With the shorter detention times and higher hydraulic loadings, the BAF mixed liquor solids concentration must be decreased in order to achieve the same filter run as at the longer detention times. The lower solids concentration will most likely result in somewhat higher yields and solids disposal costs.

The extended aeration process on the other hand, can similarly operate over a large range of hydraulic detention times, and depending on the specific plant maintain BOD_5 removals in the order of 85-95% (Pfeffer, 1966). The effect of operating at shorter detention times are higher yields as with the BAF system. Unlike the BAF, the effluent quality normally deteriorates with increased hydraulic loading due to clarifier overloading and the resultant loss of solids over the effluent weir.

As the full scale BAF system will most likely be of a modular design, set up in battery formation, the system would have two distinct advantages over the extended aeration process. First with regards to sensitivity, toxic plugs or shock loads will not upset the whole plant since some of the modules would be in backwash mode. Secondly with respect to flexibility, the modular design will facilitate expansion as the need arises in a particular treatment scheme, compared to the current practice for extended aeration plants of overdesigning the initial installation, waiting until the system is overloaded and then twinning the plant or changing to the conventional activated sludge system with shorter detention times and higher yields.

The BAF yield is in the same range as yields for extended aeration as both systems are based on the principle of minimizing the biomass production to the relatively inert portion. In the BAF, the high MLVSS concentrations and resultant low organic loadings produce a very stable, highly oxidized residual MLVSS. In the extended aeration process the effluent suspended solids losses reduce the quantity of MLVSS in the system.

The gross yields for both systems depend on the pretreatment employed, the fraction of inerts in the influent, and the effluent suspended solids. Due to the higher efficiency of the BAF filter relative to the extended aeration clarifier, somewhat higher apparent gross yields will be experienced with the BAF.

The testing of the BAF to date, has demonstrated that the system has potential as a wastewater treatment process if it can be scaled up to a full size system. A major factor in the successful operation of the BAF was the high solids capture capacity of the stable filter in the pilot unit. Apparently the scouring action of the moving filter prevented accumulation of solids at the moving filter to stable filter interface and the attendant headloss. In the scale-up it will be necessary to develop and maintain the unstable filter interface formed by the moving filter. In the pilot BAF, this area was several times larger than the cross-sectional area of the column.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

1. The BAF system, treating degritted municipal sewage at hydraulic detention times ranging from 5 to 12 hours, is capable of meeting the most stringent EPA tertiary filtration standards of 10 mg/l BOD_5, 10 mg/l SS, and complete nitrification in the temperature range 20-28^oC. The percentage removals under the controlled operating conditions were:

SS	97%
COD	88%
TKN	87%
TP	50%

2. Total oxidation was not achieved and the estimated yield was 0.24 g MLVSS/g COD removed at an organic loading of approximately 0.08 g COD removed/g MLVSS day. Due to the inert fraction of the influent suspended solids which accumulated within the system, the gross yield for the above loading was approximately 0.5 g MLSS/g COD removed.

3. The actual filter face in the BAF system is the moving filter to stable filter interface, which is a function of column diameter, airlift, air-flow, airlift size, solids in the system and media size. The larger the filtration area the longer the filter run at a particular solids loading. The BAF filter has a much higher solids capture capacity than similar filters treating secondary effluents.

4. The BAF may be operated with the stated removals on a 24 hour cycle at a 12 hour detention time with 20,000 mg/l MLSS and a yield of approximately 0.24 g MLVSS/g COD removed. Lower MLSS concentrations should permit longer filter runs with slight increases in yield.

6.2 Recommendations

1. A full scale BAF plant should be designed and tested to demonstrate that the filter solids capture capacity observed in the pilot scale testing can be obtained with a prototype unit. Unless the unstable filter inferface can be maintained, economic operation of the BAF is unlikely. Once the capability of a full scale BAF has been demonstrated, an economic analysis will indicate the potential of the system as a wastewater treatment alternative.

2. Mass balance runs with daily composite sampling should be carried out to determine accurately the extent of denitrification and define the mechanism of phosphorus removal.

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APPENDIX A

ANALYTICAL TECHNIQUES

Sample Preparation

Unfiltered samples for analysis of COD, TKN, and TP were acidified with concentrated H_2SO_4 to a pH of approximately 2 and stored at room temperature for analysis. Filtered samples for analysis of COD, TKN, NH_3, NO_2, NO_3 and TP were filtered through pre-ashed Saratorius glass fiber filters and stored along with unfiltered BOD samples in a -5^oC freezer until analysis.

Chemical Oxygen Demand

The Chemical Oxygen Demand was done by the dichromate reflux method prescribed by "Standard Methods" (1975).

Nitrogen and Total Phosphorus Analyses

Nitrogen and Total Phosphorus were carried out by methods adapted to the Technicon Auto Analyzer as detailed in the "Manual of Methods for Chemical Analysis of Water and Wastes" (1974).

Suspended and Volatile Suspended Solids

Suspended solids determinations on the mixed liquor were made by filtering 10 ml samples through pre-ashed Saratorius glass fiber filters. The filter plus solids were dried at 103^oC for a minimum of 2 hrs and then dessicated for 15 minutes before weighing. The feed and effluent solids were done similarly using 25-50 ml and 500 ml samples respectively. The increase in weight of the dried filter was taken as a measure of the suspended solids. The volatile portion of the sample was determined as the difference in weight between the dry-weight at 103°C and the ash-weight after igniting the filter and sample at 550 °C for 20 minutes.

Oxygen Utilization Rate (Oxygen Consumption Rate)

Oxygen Utilization Rates (OUR) determinations were done according to the method described in "Standard Methods" (1975), using a Yellowsprings Instrument Co. Ltd. polarographic probe.

pH

pH was determined using an Orion Model No. 404 pH meter together with Fisher Combination electrode.

Particle Size Analysis

The particle size analysis of the silica sand filter media was done using Tyler sieves and a Reinhart Laboratory Shaker.

Porosity

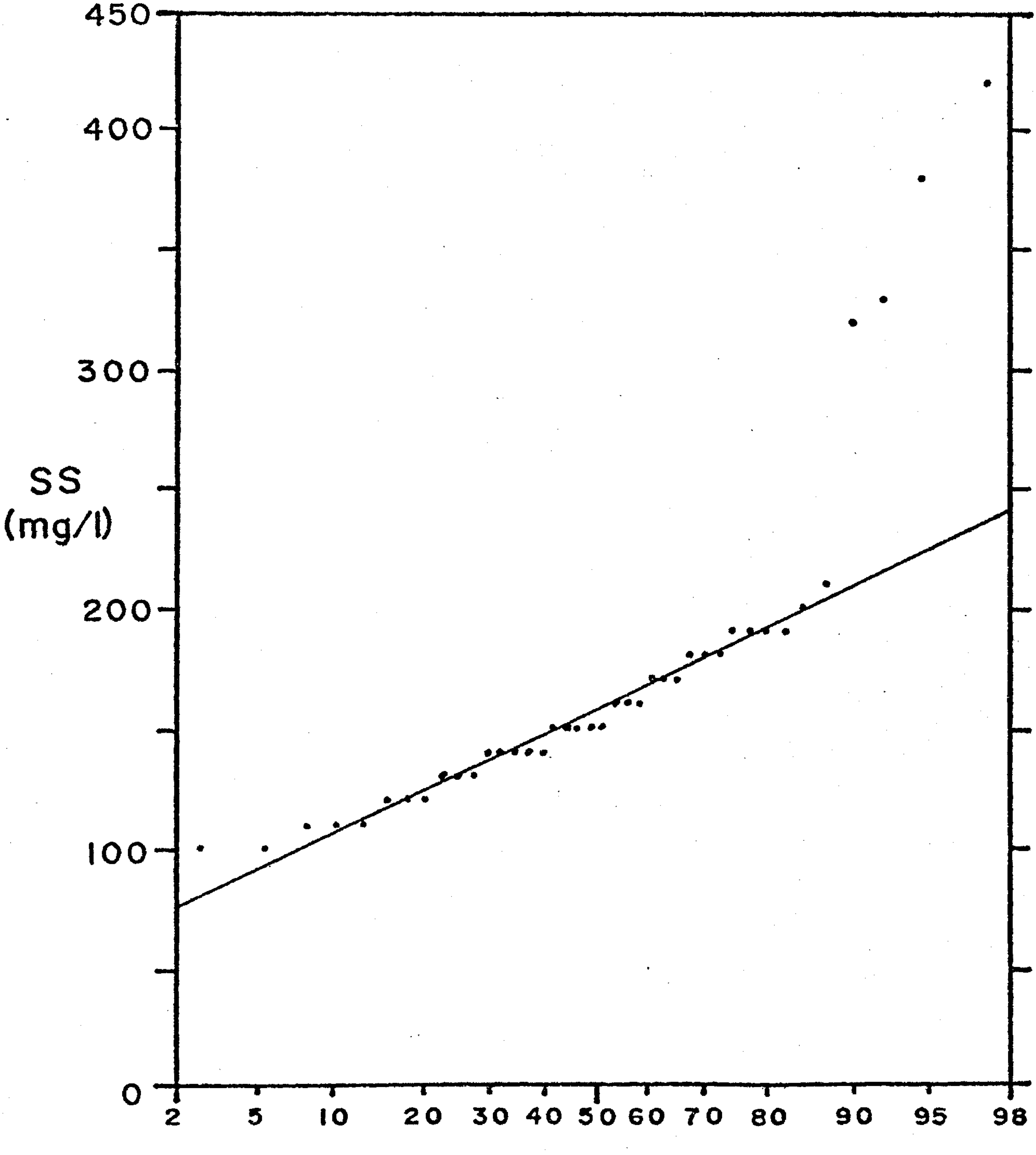
The porosity of the filter media was determined by the displaced volume technique in a 1 litre graduated cylinder and in situ.

APPENDIX B

PROBABILITY DISTRIBUTION PLOTS

FIGURE B1

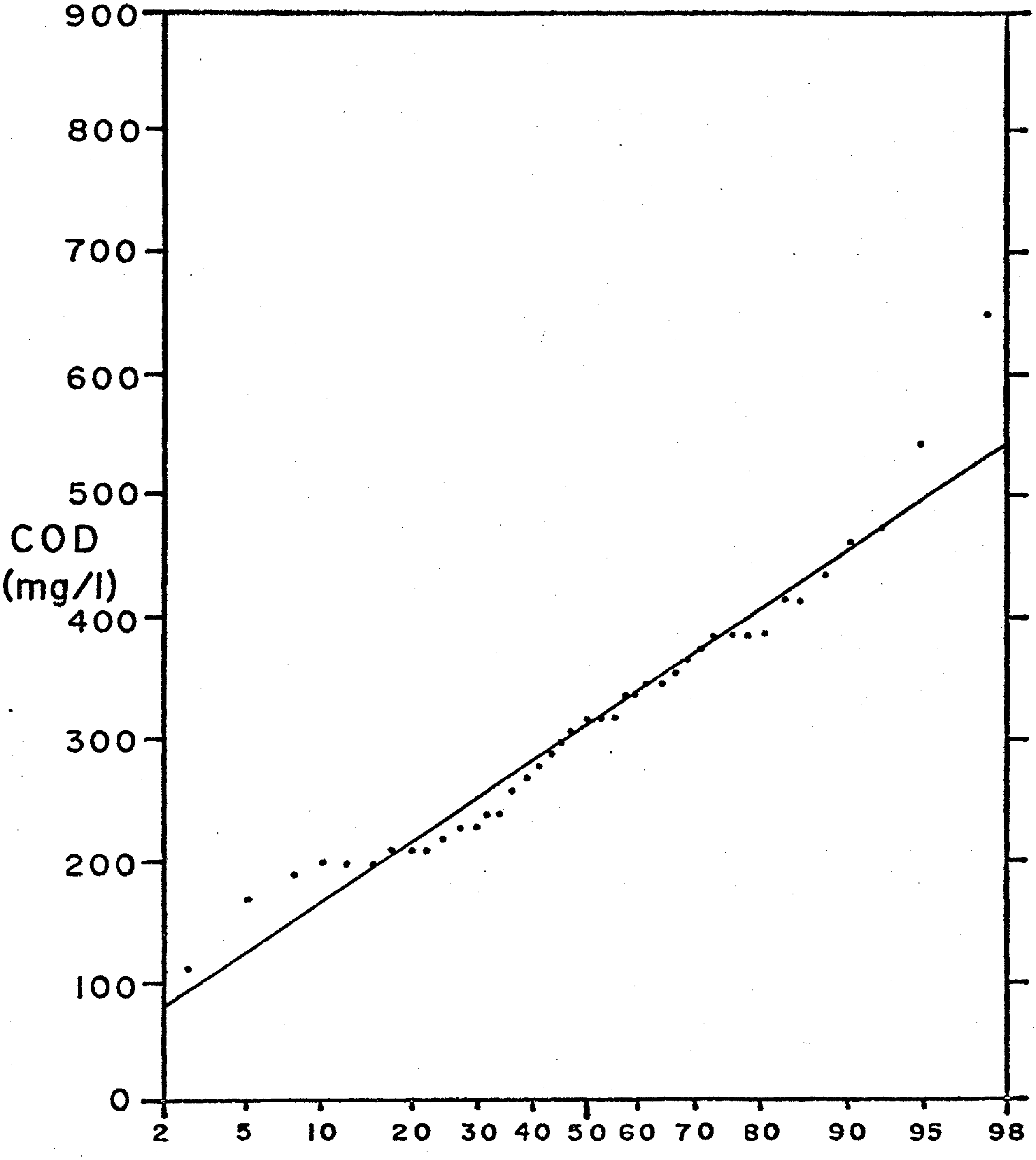
Probability Distribution for Suspended Solids Feed to BAF Units



% of Observations Less Than or Equal To Stated Value

FIGURE B2

Probability Distribution for COD Feed to BAF Units

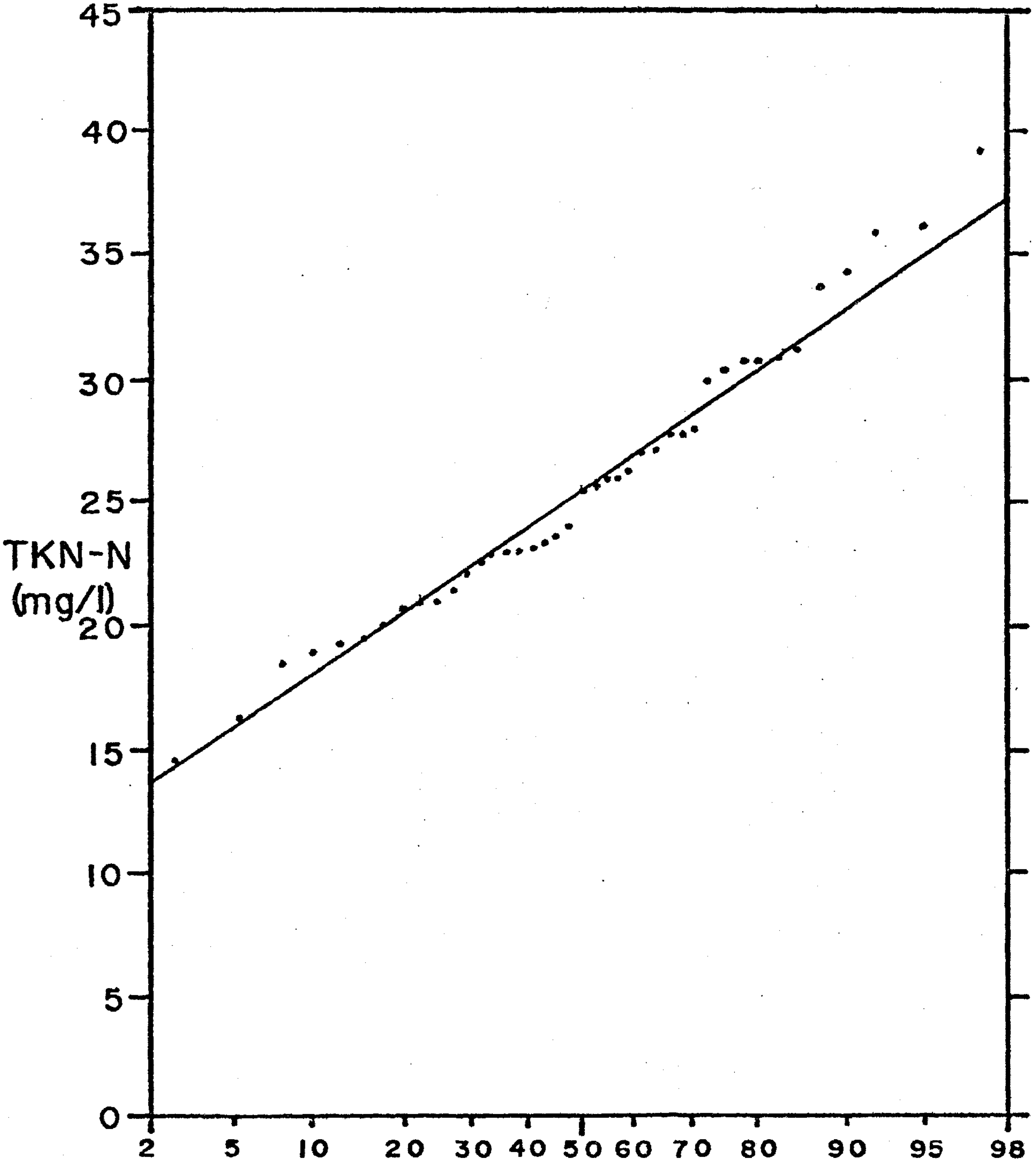


% of Observations Less Than or Equal To Stated Value

FIGURE B3

Probability Distribution for TKN - N

Feed to BAF Units

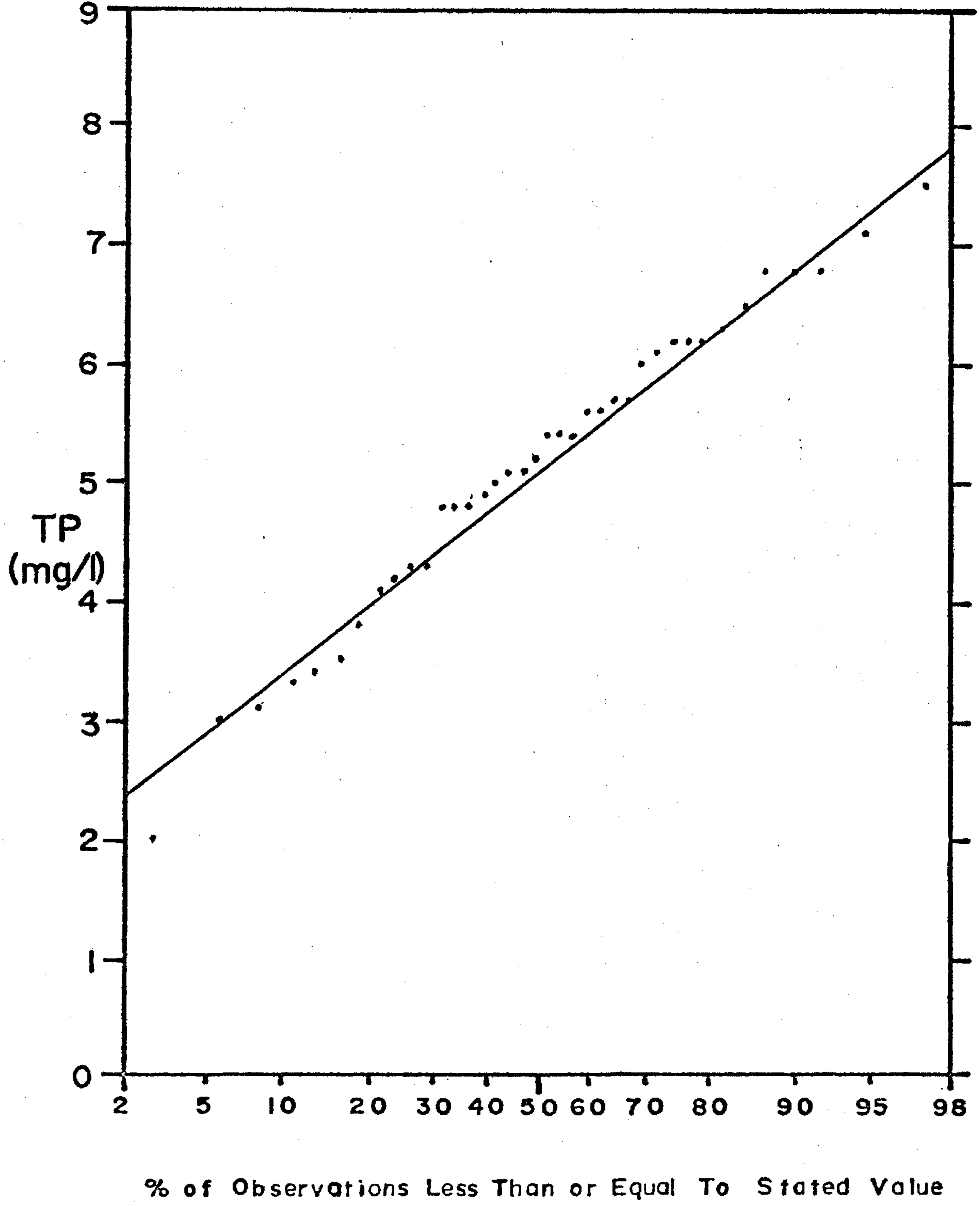


% of Observations Less Than or Equal To Stated Value

FIGURE B4

Probability Distribution for TP

Feed to BAF Units



APPENDIX C

BAF NUTRIENT ANALYSIS AND SOLIDS DATA

		UNFILTERED			FILTERED					
DAY	SAMPLE	COD	TKN-N	TP	COD	NH_3-N	NO_2-N	NO_3-N	TKN-N	TP
03	RAW	410	28.1	5.1	160	15.0	0.0	0.0	18.2	3.0
03	EFF A	220	21.1	3.6	160	13.0	0.0	0.0	20.1	3.2
03	EFF B	180	26.1	4.9	170	9.0	0.0	0.0	15.4	3.2
06	RAW	280	26.5	5.0	87	14.0	0.1	0.1	22.4	3.4
06	EFF A	83	16.6	5.0	75	12.0	0.0	0.0	21.1	4.1
06	EFF B	47	11.4	3.0	43	6.0	0.3	0.0	12.3	2.6
08	RAW	320	27.4	4.2	120	21.0	0.1	0.3	21.7	2.2
08	EFF A	63	16.6	3.4	72	14.0	0.5	0.1	16.6	2.1
08	EFF B	55	9.8	3.0	52	7.6	1.2	3.1	9.1	1.9
10	RAW	260	26.3	3.5	110	18.4	0.0	0.1	23.6	2.5
10	EFF A	210	21.0	3.0	54	13.2	0.1	0.0	19.7	2.2
10	EFF B	43	6.3	1.7	52	2.5	0.5	2.9	5.9	1.7
13	RAW	200	20.9	4.1	66	13.5	0.6	2.8	17.1	1.2
13	EFF A	190	27.1	5.5	50	15.0	0.1	0.0	18.6	2.8
13	EFF B	36	8.3	2.5	46	1.1	0.4	3.2	4.3	2.5
15	RAW	410	34.2	7.5	120	15.0	0.6	0.0	22.8	2.0
15	EFF A	130	20.0	3.6	56	7.0	0.0	0.0	15.9	3.0
15	EFF B	52	5.9	2.6	48	0.0	0.8	2.6	5.6	2.2
17	RAW	480	23.0	2.0	120	13.0	0.1	0.2	15.9	1.6
17	EFF A	56	11.0	2.3	46	4.0	0.1	0.4	5.9	2.1
17	EFF B	48	5.5	2.3	44	0.0	0.8	3.9	2.8	1.3
20	RAW	200	16.3	4.8	63	12.0	0.1	0.4	12.4	1.8
20	EFF A	52	5.6	3.2	44	3.0	0.6	2.0	5.1	3.0
20	EFF B	40	2.6	2.2	36	1.0	1.2	7.8	2.4	2.0
22	RAW	350	27.3	5.6	130	15.0	0.0	0.1	19.5	2.1
22	EFF A	43	6.9	3.5	43	4.0	0.9	2.4	6.4	2.5
22	EFF B	35	2.4	2.0	35	1.0	1.2	7.8	2.7	1.8
24	RAW	390	30.7	6.1	87	18.0	0.0	0.2	20.4	2.7
24	EFF A	35	7.3	3.2	35	4.0	0.9	3.9	6.8	2.7
24	EFF B	35	2.8	2.3	35	1.0	0.8	9.7	2.5	1.7
27	RAW	210	19.0	3.4	51	11.0	0.0	0.5	13.3	1.3
27	EFF A	47	4.3	2.5	35	2.0	1.2	10.3	3.4	2.9
27	EFF B	31	1.6	1.5	24	1.0	1.2	11.4	2.2	1.3
29	RAW	320	23.2	5.7	96	15.0	0.1	0.2	16.8	3.3
29	EFF A	40	4.1	2.7	40	1.0	2.5	10.8	2.2	3.2
29	EFF B	28	2.7	3.2	32	1.0	1.0	16.4	1.3	3.5
31	RAW	300	23.5	6.0	100	12.0	0.1	0.7	16.7	3.0
31	EFF A	36	5.0	2.3	40	1.0	1.0	15.3	2.5	1.7
31	EFF B	44	1.6	2.8	36	0.0	0.2	8.1	2.2	2.4
34	RAW	230	24.3	5.1	63	16.0	0.1	0.5	17.8	2.4
34	EFF A	48	3.8	2.7	44	0.0	0.9	10.8	3.1	2.4
34	EFF B	36	2.3	3.1	32	0.0	0.3	8.4	2.2	3.0
36	RAW	340	23.1	9.8	75	11.0	0.4	0.0	15.4	1.7
36	EFF A	30	2.7	2.9	35	1.0	0.5	12.9	1.7	1.9
36	EFF B	37	2.4	2.5	25	1.0	1.8	17.0	1.6	1.8

		UNFILTERED			FILTERED					
DAY	SAMPLE	COD	TKN-N	TP	COD	NH_3-N	NO_2-N	NO_3-N	TKN-N	TP
38	RAW	220	19.5	3.1	75	9.0	0.1	0.4	14.6	2.2
38	EFF A	30	1.8	2.5	25	0.0	1.3	12.6	1.3	2.4
38	EFF B	20	1.2	2.0	25	0.0	0.7	13.0	1.2	1.9
41	RAW	205	20.2	4.3	70	6.0	0.1	0.0	15.9	3.3
41	EFF A	30	2.7	3.0	26	1.0	1.0	12.5	1.5	2.2
41	EFF B	22	1.6	1.8	24	0.0	0.7	12.5	0.7	1.0
43	RAW	360	19.4	5.7	75	10.0	0.0	0.1	12.8	2.2
43	EFF A	37	1.6	2.9	30	0.0	0.6	13.5	1.0	2.8
43	EFF B	31	1.3	2.9	15	0.0	0.2	13.1	1.0	2.3
45	RAW	340	23.7	4.9	55	11.0	0.0	0.6	16.2	2.4
45	EFF A	27	4.4	2.9	22	0.0	0.7	18.9	4.0	2.6
45	EFF B	17	1.5	2.3	15	0.0	0.5	19.7	3.5	2.3
48	RAW	230	22.3	5.4	65	5.0	0.0	0.5	10.6	2.8
48	EFF A	25	1.5	3.0	22	0.0	0.2	16.0	0.9	2.6
48	EFF B	25	3.7	3.0	15	1.0	0.5	6.3	1.9	2.6
50	RAW	350	22.7	6.8	79	14.0	0.0	0.0	16.7	2.4
50	EFF A	33	3.1	1.5	28	1.0	0.4	16.6	2.5	2.8
50	EFF B	30	2.3	1.8	26	1.0	1.4	14.8	3.3	2.5
52	RAW	390	31.5	5.4	140	20.0	0.1	0.5	22.2	3.1
52	EFF A	31	3.1	1.5	33	1.0	0.2	15.6	2.0	0.7
52	EFF B	36	2.9	2.0	33	1.0	0.7	11.8	2.0	0.4
55	RAW	210	23.3	5.6	64	10.0	0.0	0.0	18.4	3.2
55	EFF A	31	0.5	4.1	31	0.0	0.4	10.8	0.5	3.4
55	EFF B	23	1.0	4.1	26	0.0	0.5	12.2	0.4	2.7
57	RAW	390	30.4	6.2	120	18.0	0.0	0.1	23.0	2.3
57	EFF A	33	6.6	2.7	37	0.0	1.2	17.5	3.0	2.3
57	EFF B	25	3.2	2.0	29	0.0	0.8	9.5	2.9	1.7
59	RAW	470	34.7	6.8	160	17.0	0.0	0.0	23.0	5.8
59	EFF A	22	3.3	2.0	38	0.0	1.2	24.2	2.9	3.7
59	EFF B	33	3.0	2.6	37	0.0	0.4	7.7	2.8	3.6
62	RAW	210	14.5	3.3	71	9.0	0.1	0.3	11.9	5.1
62	EFF A	25	2.3	2.7	37	0.0	0.8	13.8	2.0	4.6
62	EFF B	38	1.7	3.3	27	0.0	0.6	20.9	1.7	4.7
64	RAW	660	39.6	9.4	130	16.4	0.0	0.0	22.5	2.3
64	EFF A	30	1.3	2.4	18	0.7	0.7	11.7	2.1	2.0
64	EFF B	18	4.1	2.0	18	1.4	1.4	10.0	3.7	1.5
66	RAW	370	31.0	5.2	130	15.0	0.1	0.4	22.8	2.5
66	EFF A	21	1.2	2.1	26	0.9	1.1	26.0	1.0	0.8
66	EFF B	26	1.5	1.9	15	0.5	1.2	22.9	1.5	0.5
69	RAW	570	38.3	12.1	56	13.0	0.0	0.0	18.0	3.2
69	EFF A	81	4.5	4.1	32	0.7	0.2	9.1	2.3	2.3
69	EFF B	18	1.8	2.1	30	0.4	0.1	9.3	2.0	1.8
71	RAW	310	25.6	4.3	110	15.5	0.1	0.8	17.6	1.6
71	EFF A	54	1.6	2.5	38	0.7	0.1	18.9	1.2	1.9
71	EFF B	34	2.2	2.9	40	0.5	0.1	20.9	1.7	2.2

DAY	SAMPLE	UNFILTERED COD	UNFILTERED TKN-N	UNFILTERED TP	FILTERED COD	FILTERED NH_3-N	FILTERED NO_2-N	FILTERED NO_3-N	FILTERED TKN-N	FILTERED TP
73	RAW	190	21.5	5.4	61	12.5	0.1	0.7	14.1	2.6
73	EFF A	170	4.9	6.6	40	0.3	0.1	13.2	1.0	2.9
73	EFF B	38	2.4	4.3	37	0.6	0.2	14.9	1.6	3.2
76	RAW	240	18.7	6.6	84	16.0	0.1	0.8	17.6	2.3
76	EFF A	43	1.2	5.1	40	0.3	0.2	10.5	1.0	2.2
76	EFF B	29	1.4	1.8	43	0.8	0.1	8.5	1.2	1.4
78	RAW	240	21.0	3.8	66	11.7	0.1	0.1	15.9	2.2
78	EFF A	33	3.7	2.6	32	0.4	0.1	17.4	3.5	2.4
78	EFF B	29	3.0	2.4	29	0.2	0.0	14.7	2.5	2.4
80	RAW	290	26.2	6.2	110	16.0	0.0	0.2	21.0	4.0
80	EFF A	24	2.5	3.0	26	0.2	0.1	14.4	2.2	2.8
80	EFF B	27	2.3	2.7	16	0.5	0.1	14.7	2.1	2.3
83	RAW	110	21.2	4.8	67	15.4	0.0	0.1	17.6	3.3
83	EFF A	26	2.5	3.3	26	0.2	0.2	21.5	1.2	2.4
83	EFF B	30	1.9	2.9	23	0.3	0.1	11.6	1.1	2.0
85	RAW	170	28.3	3.0	118	16.0	0.0	0.9	20.4	2.0
85	EFF A	38	3.2	1.4	27	1.0	0.0	10.6	3.0	0.6
85	EFF B	35	4.0	1.8	32	2.9	0.0	6.6	3.0	0.9
87	RAW	390	36.5	6.2	125	12.4	0.0	0.1	18.9	5.5
87	EFF A	53	5.0	2.7	50	0.4	0.0	14.2	3.0	2.6
87	EFF B	52	3.9	1.4	47	1.1	0.0	6.2	3.8	1.4
90	RAW	320	28.2	7.1	95	17.0	0.0	0.1	23.6	5.7
90	EFF A	45	4.6	3.7	47	0.7	0.0	13.7	3.4	3.1
90	EFF B	47	2.9	3.3	35	0.7	0.1	15.2	1.3	3.0
92	RAW	440	31.2	6.8	140	19.8	0.0	0.1	22.4	5.0
92	EFF A	28	2.8	2.9	30	0.5	0.3	14.7	1.7	2.2
92	EFF B	17	4.1	3.3	31	1.5	0.2	10.9	3.6	2.4
94	RAW	380	31.1	6.3	130	19.0	0.0	0.1	24.8	5.3
94	EFF A	28	3.5	2.5	30	0.5	0.3	15.1	2.9	2.0
94	EFF B	45	3.3	1.5	24	0.7	0.1	7.5	2.4	0.7
97	RAW	270	25.9	4.8	89	17.6	0.0	0.0	22.0	3.0
97	EFF A	35	2.9	3.1	24	0.5	0.2	16.9	2.4	2.5
97	EFF B	56	4.0	2.8	37	0.7	0.1	3.1	2.6	2.3

EAF SOLIDS DATA

DAY	INF	COLUMN A MLSS	COLUMN A MLVSS	COLUMN A EFF	COLUMN B MLSS	COLUMN B MLVSS	COLUMN B EFF
02		5190			3820		
03	200	6680		65	5300		20
06	160	7620	5200	14	6270	4100	3
08	150	11400		16	7300		1
10	120	12200		170			1
11		0		190	10500		
12		0		130			
13	140	13100	8100	180	10500	5800	2
15	210	15100		120	12700		7
17	320	16800		7	13300		3
19		17800					
20	110	18300	9700	5	14300	7400	1
22	130	19100		4	15300		1
25	190	20300		4	15900		2
27	110	21000	10300		16500	8400	
29	330	21300		3	16900		1
30	254	23200	10700		18100	8600	
31	150	23900	10900	2	18100	8800	1
32		22500	9500		19400	8900	
33		21200	9700		19000	8900	
34	140	22100	10100	6	19300	8900	1
35		22500	9700		18800	9400	
36	170	22200	10600	3	20200	10000	1
37		25100			22700		
38	140	24700	10200	5	21400	9200	2
39	160	26300	10500		22400	9500	
40	110	25300	9800	420	22800	9700	2
41	100	24100	9800	10	22600	9900	
42	210	25500	10100		23100	10100	
43	190	26300	10500	3	23800	10300	20
44		26200	10400		23700	10200	
45	160	27000	10900	2	23800	10400	2
46	190	27800	11000		23100	10000	
47	120	26800	10600		25100	10900	
48	140	26800	10700	3	25300	10800	3
49	190	26700	10700		25400	10900	
50	180	25700	10200	2	26400	11400	1
51	150	26100	10100		25600	10800	
52	130	26900	10700	1	26000	11200	1
53	140	29000	11350		7500	3490	
54	110	27500	10900		8200	3790	
55	100	27300	10800	1	7800	3790	0
56	180	27000	10700				
57	190	28800	11400	1	7000	3430	0
58	140	27400	10700				
59	170	26500	10400	1	7500	3830	1
60		26400	10400				
61	100	27400	10600				
62	190	27300	10700	1	8300	4020	0
63	180	27900	10700				
64	380	28100	11100	1	9700	5090	1
65	160	0					
66	150	30100	12100	2	10700	5500	2
67	150	29700	12200	110			
68	500	28900	11700				

BAF SOLIDS DATA (Cont'd)

DAY	INF	COLUMN A MLSS	COLUMN A MLVSS	COLUMN A EFF	COLUMN B MLSS	COLUMN B MLVSS	COLUMN B EFF
69	420	28800	11600	75	11600	5990	1
70	260	30600	12000		13200	6410	
71	150	30800	12400	16	13500	6870	3
72	160	31400	13100	10			
73	120	30000		170	14300	6300	2
74		20000	8000				
75	120	20000	7800	130			
76	120	19500	7600	5	14300	6900	2
77	160	21100	8400		15700	7700	
78	130	19500	7800	3	15300	7300	3
79	140						
80	130	21700	8800	2	12000	5700	1
81	150						
82	110						
83	140	20400	8500	1	12900	6300	1
84	150						
85	160			1			1
86	170	22300	9300		14400	6800	
87	190	21400	9100	4			2
88	180						
89	160						
90	150	20800	8900	2			2
91	180						
92	190	20800	9200	2	16400	8000	2
93	200				16300	7900	
94	170	19200	8400	1	16200	7700	2
95	160						
96	110						
97	110	20400	9000	2	17000	8200	2

** ALL SOLIDS REPORTED IN MILLIGRAMS PER LITER

APPENDIX D

CALCULATION PROCEDURES

The calculation of the yield consists of two steps:

1. The slope of the MLVSS data was calculated by least squares assuming that the straight line was the correct model form. The concentration was converted to a mass of volatile suspended solids per day by multiplying by the activated sludge zone volume. The 95% confidence interval was calculated using the mean residual sum of squares as the estimate of the variance. The MLVSS increase per day was corrected for sampling by estimating the sampling volume and concentration, converting to an average loss per day and adding to the observed increase. The effluent solids were not included in the yield because the COD of the effluent solids was discounted in the COD removal calculation for that particular sample.

2. The mass of COD removed by the system was calculated from the COD influent and effluent data and the production data. The assumption was made that the thrice weekly samples represent the influent and effluent for the 7 day period. The mass of COD removed was reduced to an average mass of COD removed per day in order to maintain consistent units. The yield in terms of mass of MLVSS per mass of COD removed was calculated. Since there was no means of calculating the standard deviation on the mass of COD removed, the 95% confidence interval on the yield could not be calculated.

The gross yield in terms of MLSS per mass of COD removed was calculated in a similar manner.

MEAN CELL RESIDENCE TIME CALCULATION PROCEDURE

The mean cell residence time in this report was defined as the doubling time of the MLVSS mass. Therefore the mean cell residence time was calculated by dividing the MLVSS mass by the average MLVSS increase per day. Since the BAF was normally operated as a total solids retention system, the mean cell residence time was an increasing function of the MLVSS mass.

MASS BALANCE PROCEDURES

Nitrogen

The nitrogen balance for a nitrifying system with no denitrification was assumed to be:

$$\text{TKN} + \text{NO}_2 + \text{NO}_3 \text{ (in)} = \text{TKN} + \text{NO}_2 + \text{NO}_3 \text{ (out)} + \text{TKN fraction of MLVSS} * \text{MLVSS increase}$$

where TKN, NO_2 and NO_3 are reported as Nitrogen and TKN being done on an unfiltered sample.

Total Phosphorus

The TP balance for the BAF system was:

$$\text{TP (in)} = \text{TP (out)} + \text{TP fraction of MLVSS} * \text{MLVSS increase}$$

where TP is reported as P in an unfiltered sample.

Inert Solids

The Inert Solids balance for the BAF system was:

Inerts (in) = Inerts (out) + (MLSS increase - MLVSS increase)

APPENDIX E

HYPOTHESIS TESTING OF EFFLUENT CHARACTERISTICS

HYPOTHESIS TESTING OF EFFLUENT CHARACTERISTICS

HYPOTHESIS TESTING

$$H_0: \ \mu_1 = \mu_2 \text{ or } \bar{x}_1 = \bar{x}_2$$

$$\bar{x}_1 \neq \bar{x}_2$$

STEP 1. POOL VARIANCE

$$S_p^2 = \frac{(n_1 - 1 * S_1^2) + (n_2 - 1 * S_2^2)}{n_1 + n_2 - 2}$$

STEP 2. CALCULATE T

$$T = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{S_p^2}{n_1 + n_2}}}$$

STEP 3. Compare T to predetermined level of significance, e.g. 95% look up $t_{.025, n_1 + n_2 - 2}$

EFFLUENT CHARACTERISTICS HYPOTHESIS TESTING $H_0: x_1 = x_2$, $H_1: x_1 \neq x_2$
(Two sided t Test)

PARAMETER	COLUMN	DAYS	n	$\bar{x}$	S.D.	s^2	s_p^2	T	$t_{.025,n_1+n_2-2}$	RESULT
TOT COD	A	17-97	35	40.6	25.6	655.4	376.7	3.54	1.99	REJECT
	B	17-97	35	32.4	9.9	98.0				
TOT TKN	A	17-97	35	3.63	2.10	4.41	3.807	3.64	1.99	REJECT
	B	17-97	35	2.78	1.79	3.20				
TOT TP	A	17-97	35	2.92	0.98	0.95	.721	4.34	1.99	REJECT
	B	17-97	35	2.48	0.70	0.49				
FILT COD	A	17-97	35	33.7	8.10	65.6	125.3	1.79	1.99	ACCEPT
	B	17-97	35	31.3	13.6	185.0				
FILT TKN	A	29-97	30	2.10	0.91	.828	.837	.169	2.01	ACCEPT
	B	29-97	30	2.08	0.92	.846				
FILT NH_3	A	29-97	30	0.47	0.40	.160	.285	1.74	2.01	ACCEPT
	B	29-97	30	0.59	0.64	.410				
FILT NO_2^+	A	29-97	30	15.6	4.05	16.4	21.2	4.72	2.01	REJECT
NO_3	B	29-97	30	12.8	5.09	25.9				
FILT TP	A	19-97	35	2.50	0.82	.667	0.75	4.15	1.99	REJECT
	B	17-97	35	2.07	0.91	.834				
EFF SS	A*	17-97	30	3.1	2.13	4.54	2.53	6.11	2.00	REJECT
	B	17-97	33	1.5	0.70	0.70				

*Rejecting days 40,67,69,71,72,73, and 75

EFFLUENT CHARACTERISTICS HYPOTHESIS TESTING

T = 12 hrs   Col A 33-97   Col B 25-97

PARAMETER	COLUMN	DAYS	n	$\bar{x}$	S.D.	S^2	S_p^2	T	$t_{.025,n_1+n_2-2}$	RESULT
TOT COD	*A	34-97	25	32.2	8.04	64.69	84.6	.569	2.0	ACCEPT
	B	27-97	31	31.5	10.03	10.03	100.6			
TOT TKN	*A	34-97	25	2.87	1.37	1.88	2.71	.727	2.0	ACCEPT
	B	27-97	31	2.71	1.84	3.38				
TOT TP	*A	34-97	25	2.77	.795	.631	.587	2.33	2.0	REJECT
	B	27-97	31	2.53	.742	.551				
EFF SS	*A	34-97	24	2.29	1.45	2.13	1.36	4.89	2.01	REJECT
	B	27-97	28	1.50	.84	.704				
FILT COD	A	34-97	28	31.9	7.84	61.5	67.6	3.36	2.01	REJECT
	B	27-97	31	28.3	8.54	73.0				
FILT TKN	A	34-97	28	2.08	.944	.89	.858	.08	2.01	ACCEPT
	B	27-97	31	2.09	.910	.83				
NH_3	A	34-97	28	.429	.383	.147	.279	2.57	2.01	REJECT
	B	27-97	31	.606	.631	.398				
FILT TP	A	34-97	28	2.40	.831	.691	.809	2.39	2.01	REJECT
	B	27-97	31	2.12	.956	.914		2.39		
NO_2+NO_3	A	34-97	28	15.6	4.18	17.5	21.5	4.64	2.01	REJECT
	B	27-97	31	12.8	5.01	25.1				

* Days 69,71,73 rejected due to spotty breakthrough of the filter

APPENDIX F

SOLIDS CAPTURE CAPACITY AND EFFECT OF MEDIA SIZE

SOLIDS CAPTURE CAPACITY AND SOLIDS PENETRATION

DAY	HEADLOSS	TOTAL BIOMASS	HFB	MEASURED MLSS AT END	MASS IN FILTER		SOLIDS PENETRATION		LOADING	SOLIDS CAPTURE		CONC. IN PORES
	ft	g	in	g /l	g	lb	ft	m	lb/ft^2	$lb/ft^2/ft$	$kg/m^2/m$	g /l
44	5	675	10	14.7	295	.648	1.71	.52	3.93	.79	12.6	15.9
45	3.5	695	12.5	15.8	280	.615	1.38	.42	3.73	1.07	17.1	18.7
57	6.5	748	10	16.7	316	.695	2.00	.61	4.21	.65	10.4	14.5
58	9.0	705	10.5	14.7	323	.711	2.04	.62	4.31	.48	7.7	14.5
60	6.3	679	10	15.8	270	.594	1.38	.42	3.60	.57	9.1	18.1
61	5.5	705	10	17.7	247	.543	1.38	.42	3.29	.60	9.6	16.5
62	6.3	704	10	17.1	261	.575	1.63	.50	3.48	.55	8.8	14.8

EFFECT OF MEDIA SIZE-SOLIDS CAPTURE CAPACITY AND SOLIDS PENETRATION

DETENTION TIME hr		BIOMASS TOTAL g	BIOMASS AT END g	BIOMASS IN FILTER g	BIOMASS IN FILTER lb	SOLIDS PENETRATION ft	SOLIDS PENETRATION m	LOADING lb/ft^2	SOLIDS CAPTURE CAPACITY lb/ft^2/ft		SOLIDS CAPTURE CAPACITY kg/m^2/m	EFF SS
6	COL A	528	359	169	.372	1.75	0.60	2.25	.25	>	4.1	2
	COL A	528	355	173	.381	1.88	0.60	2.31	.26			4
	COL B	526	273	253	.557	3.21		3.38	.38	>	5.8	4
	COL B	528	295	233	.513	3.17	1.05	3.11	.35			4
8	COL A	481	314	167	.367	1.54		2.22	.25	>	3.9	3
	COL A	532	367	165	.363	1.58	0.51	2.20	.24			3
	COL B	478	266	212	.466	2.17		2.82	.31	>	5.0	1
	COL B	537	327	208	.458	2.54	0.77	2.78	.31			3
10	COL A	506	380	126	.277	1.33		1.68	.19	>	3.2	2
	COL A	510	371	139	.306	1.29	0.43	1.85	.21			2
	COL B	540	397	143	.315	1.83		1.91	.21	>	4.2	2
	COL B	559	353	206	.453	2.13	0.65	2.75	.31			4
12	COL A	536	382	154	.339	1.21		2.05	.23	>	3.8	1
	COL A	534	374	160	.352	1.29	0.41	2.13	.24			3
	COL B	569	364	205	.451	1.96		2.73	.30	>	4.7	2
	COL B	539	345	194	.427	2.33	0.71	2.59	.29			2

NOTE: MFB = 7.5 inches
HEADLOSS 9'

EFFECT OF MEDIA SIZE

HEADLOSS VS TIME REGRESSION RESULTS COL A D_{10} = 1.28 nm

COL B D_{10} = 2.10 nm

COLUMN	DETENTION TIME (hr)	HEADLOSS RATE		% VARIATION EXPLAINED BY REGRESSION
		(ft/hr)	AVERAGE (m/hr)	
A	6	4.23		98
A	6	4.55	1.34	99
B	6	2.62		99
B	6	3.04	0.86	99
A	8	2.06		99
A	8	3.44	0.84	99
B	8	2.14		99
B	8	2.42	0.69	99
A	10	2.41		99
A	10	2.38	0.73	97
B	10	2.32		99
B	10	2.58	0.75	99
A	12	1.76		99
A	12	1.80	0.55	97
B	12	1.88		99
B	12	1.65	0.53	99

APPENDIX G

YIELD CALCULATIONS

YIELD CALCULATIONS

PART 1

LINEAR REGRESSION RESULTS

FOR YIELDS (SLOPE OF MLVSS DATA)

COLUMN	DAYS	N	SLOPE g /day	% VARIATION EXPLAINED BY REGRESSION
A	48-73	24	2.06	59
B	28-52	23	2.99	92
B	57-78	12	5.07	94
B	80-97	7	3.84	95

FOR GROSS YIELDS (SLOPE OF MLSS DATA)

COLUMN	DAYS	N	SLOPE g /day	% VARIATION EXPLAINED BY REGRESSION
A	48-73	25	4.30	66
B	25-52	26	10.19	95
B	57-78	12	11.15	97
B	80-97	7	7.82	97

Column A, days 74-97 was operated at 20,000 mg/l therefore yield was based on the mass of MLSS and MLVSS wasted and the increase in MLVSS within the system at constant MLSS.

Column A days 74-97

WASTING RECORD

DAY	VOLUME (l)	MLSS (mg/l)	MLVSS (mg/l)	MLSS (g)	MLVSS (g)	% VS
80	1.55	13.34	5.34	20.7	8.4	40.0
83	0.72	13.32	5.54	9.6	4.0	41.6
86	2.15	12.80	5.36	27.5	11.5	41.9
87	1.56	13.40	5.70	20.9	8.9	42.5
90	1.50	12.20	5.21	18.3	7.8	42.7
92	1.80	12.35	5.43	22.2	9.8	44.0
			SUM	119	50.3	

Change in MLVSS due to % VS increase = .04 x 20,000 x 25.74 = 20.6 g

Therefore, yield of MLVSS = 3.19 g /day
gross yield of MLSS = 5.17 g /day

PART 2

REMOVAL CALCULATIONS SUMMARY

			MASS REMOVAL					AVERAGE REMOVAL RATE				
COLUMN	DAYS	N	INF SS g	COD g	TKN g	TP g	NO_2+NO_3* g	INF SS g /day	COD g /day	TKN g /day	TP g /day	NO_2+NO_3* g /day
COLUMN A	48-73	25	210	336	38.5	3.75	18.0	8.4	13.44	1.54	0.15	0.72
COLUMN A	74-97	23	216	356	33.7	3.59	22.0	9.39	15.48	1.47	0.16	0.96
COLUMN B	25-52	27	216	332	26.7	3.75	16.4	8.00	12.30	0.99	0.14	0.61
COLUMN B	57-78	21	261	433	31.5	5.16	18.4	12.43	20.62	1.50	0.25	0.88
COLUMN B	80-97	17	175	280	26.2	3.43	10.0	10.29	16.47	1.54	0.20	0.59

*NO_2 + NO_3 is the increase across the system

YIELD CORRECTED FOR SAMPLING

COLUMN	DAYS	TOTAL SAMPLE VOLUME (l)	MLSS	% VS	SAMPLE CORRECTION MLSS g /day	SAMPLE CORRECTION MLVSS g /day	MLVSS SLOPE g /day	COD REMOVED g /day	YIELD
A	48-73	0.59	17.0	41	0.40	0.16	2.06	13.4	0.17
A	74-97	0.43	12.9	42	0.24	0.10	3.19	15.5	0.21
B	25-52	0.54	13.0	45	0.26	0.13	2.99	12.3	0.25
B	57-78	0.54	6.7	48	0.18	0.09	5.07	21.2	0.24
B	80-97	0.34	10.0	48	0.20	0.10	3.84	16.5	0.24
GROSS YIELD CORRECTED FOR SAMPLING									
A	48-73				0.40		4.30	13.4	0.35
A	74-97				0.24		5.17	15.5	0.37
B	25-52				0.26		10.19	12.3	0.85
B	57-78				0.18		11.15	21.2	0.53
B	80-97				0.20		7.82	16.5	0.49

REMOVAL CALCULATIONS

COL A days 48-73

	CONCENTRATION REMOVED						MASS REMOVED				
DAY	INF SS mg/l	COD mg/l	TKN mg/l	TP mg/l	NO_2+NO_3 mg/l	TREATED VOL (l)	INF SS g	COD g	TKN g	TP g	NO_2+NO_3 g
48	140					42					
49	190					30	5.70				
50	180	317	19.6	5.3	17.0	29	5.22	18.7	11.6	0.31	1.00
51	150					49	7.35				
52	130	359	28.4	3.9	15.2	46	5.98	34.1	2.7	0.37	1.44
53	140					52	7.28				
54	110					52	5.72				
55	100	179	22.8	1.5	11.2	51	5.10	27.7	3.53	0.23	1.74
56	180					50	9.00				
57	190	357	23.8	3.5	18.6	49	9.31	35.3	2.36	0.35	1.84
58	140					47	6.58				
59	170	448	31.4	4.8	25.4	45	7.65	41.2	2.89	0.44	2.34
60						52					
61	100					53	10.50				
62	180	185	12.2	0.6	14.2	50	9.00	28.7	1.89	0.09	2.20
63	180					48	8.60				
64	380	630	38.3	7.0	12.4	32	12.20	50.4	3.06	0.56	0.99
65	160					41	6.56				
66	150	349	29.8	3.1	26.6	51	7.65	32.1	2.74	0.29	2.45
67	150					46	6.90				
68	500					40	20.00				
69	420	489	31.8	8.0	9.3	44	18.50	63.6	4.13	1.04	1.25
70	260					50	13.0				
71	260	256	24.0	1.6	18.1	43	11.2	23.8	2.23	1.67	1.68
72	160					40	6.0				
73	120	20	16.6	-1.2	12.5	42	5.0	1.64	1.36	-.10	1.03
						SUM	210	336	38.5	3.75	17.96

COL A 74-97

	CONCENTRATION REMOVED						MASS REMOVED				
DAY	INF SS mg/l	COD mg/l	TKN mg/l	TP mg/l	NO_2+NO_3 mg/l	TREATED VOL (l)	INF SS g	COD g	TKN g	TP g	NO_2+NO_3 g
74											
75	120										
76	120	197	17.5	1.5	19.8	51	8.2	28.8	1.70	0.15	0.95
77	160					54	8.6				
78	180	207	17.3	1.2	17.3	45	8.1	20.5	1.71	0.12	1.71
79	140										
80	130	266	23.7	3.2	14.3	132	17.8	35.1	3.13	0.42	1.89
81	150										
82	110										
83	140	81	18.7	1.5	21.6	208	27.7	16.8	3.89	0.31	4.49
84	150					58	9.9				
85	160	130	25.1	1.6	9.7	57	9.1	15.0	2.89	0.18	1.12
86	170					65	11.0				
87	190	339	31.5	3.5	14.1	50	9.5	39.0	3.62	0.40	1.62
88	180										
89	160										
90	150	271	23.6	3.4	13.6	198	32.3	53.7	4.67	0.67	2.69
91	180										
92	190	412	28.4	3.9	14.9	122	22.6	50.3	3.47	0.48	1.82
93	200										
94	170	352	27.6	3.8	15.3	125	23.1	44.0	3.45	0.48	1.91
95	160					71	11.4				
96	110					77	8.5				
97	110	235	23.0	1.7	17.1	75	8.3	52.4	5.13	.38	3.81
						SUM	216	356	33.7	3.59	22.0

COL B days 25-52

	CONCENTRATION REMOVED						MASS REMOVED				
DAY	INF SS mg/l	COD mg/l	TKN mg/l	TP mg/l	NO_2+NO_3 mg/l	TREATED VOL (l)	INF SS g	COD g	TKN g	TP g	NO_2+NO_3 g
25	190										
26						49					
27	110	179	17.4	1.9	12.1	30	8.69	14.14	1.37	0.15	0.96
28											
29	330	292	20.5	2.5	17.1	104	34.3	30.37	2.13	0.26	1.78
30	254					39	9.91				
31	150	256	21.9	3.2	7.5	50	7.50	22.78	1.95	0.29	0.67
32						48					
33						44					
34	140	194	22.0	2.0	8.1	51	20.02	27.74	3.15	0.29	1.16
35						50					
36	170	300	20.7	7.3	18.4	45	16.15	28.50	1.97	0.69	1.75
37						50					
38	140	200	18.3	1.1	13.2	53	14.42	20.60	1.89	0.11	1.36
39						51					
40	110					50	11.11	18.48	1.88	0.25	1.32
41	100	183	18.6	2.5	13.1	46	4.60	8.42	0.86	0.12	0.60
42	210					50	10.5				
43	190	330	18.1	2.8	13.2	47	8.93	32.01	1.76	0.27	1.28
44						45					
45	160	319	22.2	2.6	19.6	55	16.0	31.90	2.22	0.26	1.96
46	180					50	9.0				
47	120					50	6.0				
48	140	210	18.6	2.4	6.3	49	6.86	31.30	2.77	0.36	0.94
49	190					52	9.88				
50	180	320	20.4	5.0	15.2	49	8.82	32.32	2.06	0.51	1.54
51	150					50	7.50				
52	130	354	28.6	3.4	11.9	43	5.59	32.92	2.66	0.32	1.11
						SUM	216	332	26.7	3.75	16.43

COL B 57-78

	CONCENTRATION REMOVED						MASS REMOVED				
DAY	INF SS mg/l	COD mg/l	TKN mg/l	TP mg/l	NO_2+NO_3 mg/l	TREATED VOL (l)	INF SS g	COD g	TKN g	TP g	NO_2+NO_3 g
57	190										
58	140										
59	170	437	31.7	4.2	8.1	120	18.6	52.4	3.80	0.50	0.97
60											
61	100										
62	180	172	12.8	0.0	21.1	206	37.1	35.4	2.64	0.00	4.35
63	180										
64	380	642	35.5	7.4	11.4	130	36.4	83.5	4.62	0.96	1.48
65	160										
66	150	344	29.5	3.3	23.6	132	20.5	45.4	3.90	0.44	3.16
67	150										
68	500										
69	420	552	34.5	10.0	9.4	208	74.2	114.8	7.18	2.08	1.96
70	260					62	16.1				
71	150	276	23.4	1.4	20.1	54	8.1	32.0	2.71	0.16	2.33
72	160										
73	120	152	19.1	1.1	14.3	127	17.8	19.3	2.43	0.14	1.82
74						54					
75	120					51	12.6				
76	120	211	17.3	4.8	7.7	54	6.5	33.6	2.75	0.76	1.19
77	160					53	8.5				
78	180	211	18.0	1.4	14.5	27	4.8	16.9	1.44	0.11	1.16
						SUM	261	433	31.5	5.16	18.4

COL B 80-97

DAY	INF SS mg/l	CONCENTRATION REMOVED COD mg/l	TKN mg/l	TP mg/l	NO_2+NO_3 mg/l	TREATED VOL (l)	INF SS g	MASS REMOVED COD g	TKN g	TP g	NO_2+NO_3 g
80	130										
81	150					60	9.00				
82	110					55	6.05				
83	140	77	19.3	1.9	11.6	58	8.12	13.32	3.34	0.33	2.01
84	150					55	8.25				
85	158	133	24.3	1.2	5.7	51	8.06	14.10	2.58	0.13	0.60
86	170					76	12.92				
87	190	340	32.6	4.8	6.1	47	8.93	41.82	4.01	0.59	0.75
88	180					76	13.68				
89	160					76	12.16				
90	150	269	25.3	3.8	15.2	76	11.40	61.33	5.77	0.87	3.47
91	180					76	13.68				
92	190	423	27.1	3.5	11.0	76	14.44	64.30	4.12	0.53	1.67
93	200					55	11.00				
94	170	335	27.8	4.8	7.5	56	9.52	37.19	3.09	0.53	0.83
95	160					70	11.20				
96	110					78	8.58				
97	110	214	14.6	2.0	3.2	75	8.25	47.72	3.26	0.45	0.71
						SUM	175	280	26.2	3.43	10.0

NOTE: INFLUENT VOLATILE SS = .75 * INF SS

REMOVAL CALCULATIONS

COLUMN B days 80-97 FILTERABLE COD

DAY	CONCENTRATION REMOVED FILTERABLE COD mg/l	TREATED VOL (l)	MASS REMOVED FILTERABLE COD
80			
81		60	
82		55	
83	44	58	7.61
84		55	
85	86	51	9.12
86		76	
87	78	47	9.59
88		76	
89		76	
90	12	76	2.74
91		76	
92	109	76	16.57
93		55	
94	196	56	11.77
95		70	
96		78	
97	52	75	11.60
		SUM	69.0

APPENDIX H

MASS BALANCE CALCULATIONS

1.0 MLVSS COMPOSITION

DAY	COLUMN	MLVSS (mg/l)	COD (mg/l)	TKN (mg/l)	TP (mg/l)	% COD	% TKN	% TP
84	A	6710	13,000	241	197	194	3.6	2.9
	B	2990	5,700	164	96	191	5.5	3.2
86	A	5750	11,000	335	224	191	5.8	3.9
	B	5490	11,000	279	171	200	5.1	3.1
89	A	5210	10,000	277	255	192	5.3	3.7
	B	5750	11,000	283	191	191	4.9	3.3
91	A	5400	11,000	221	162	204	4.1	3.0
	B	5000	9,600	267	179	192	5.3	3.6
94	A	5290	12,000	247	180	227	4.7	3.4
	B	4930	9,900	246	176	201	5.0	3.6
97	A	5640	13,000	255	223	230	4.5	4.0
	B	5000	10,000	314	175	200	6.3	3.5
				Col A	$\bar{x}$	206	4.67	3.48
					S.D.	17.8	0.80	0.46
				Col B	$\bar{x}$	196	5.35	3.38
					S.D.	5.0	0.51	0.21

NITROGEN BALANCE

COLUMN	DAYS	ΔMLVSS day g /day	ΔTKN day g /day	ΔNO_2+NO_3 day g /day	$\Delta TKN-\Delta (NO_2+NO_3)$ g /day	ΔMLVSS*%TKN g /day	% LOSS
A	48-73	2.22	1.54	0.72	0.82	0.104	87.4
A	74.97	3.29	1.46	0.96	0.50	0.154	69.5
B	25-52	3.01	0.99	0.61	0.38	0.161	57.5
B	57-78	5.16	1.50	0.88	0.62	0.276	57.5
B	80-97	3.94	1.54	0.59	0.95	0.211	77.8

TP BALANCE

COLUMN	DAYS	ΔMLVSS day g /day	ΔTP day g /day	ΔMLVSS*% TP day g /day	% LOSS
A	48-73	2.22	0.150	0.077	48.5
A	74-97	3.29	0.156	0.114	26.6
B	25-52	3.01	0.141	0.102	27.8
B	57-78	5.16	0.258	0.174	32.4
B	80-97	3.94	0.202	0.133	34.1

INERT SOLIDS BALANCE

COLUMN	DAYS	ΔMLSS day	ΔMLVSS day	INERT ACCUMULATION	INF SS day	% INERT	INERT SS day	% IN EXCESS
A	48-73	4.70	2.22	2.48	8.40	25	2.10	18
A	74-97	6.08	3.29	2.79	9.37	25	2.34	19
B	25-52	10.46	3.01	7.45	7.99	25	2.00	258
B	57-78	11.28	5.16	6.12	12.43	25	3.11	87
B	80-97	8.02	3.94	4.08	10.31	25	2.58	58