SECTION 4

BAF PILOT TESTING - RESULTS AND DISCUSSIONS

Results specific to the BAF pilot and DAFT bench testing are discussed in this section. The discussion spans results acquired from Phase I and II, beginning with the need for Biofor-N to achieve the desired effluent quality. This is followed by discussions on the following topics:

- Compliance with anticipated secondary treatment standards, including a discussion on items that may impact meeting secondary treatment standards;
- Effect of hydraulic and organic loading, including an assessment of the response to diurnal loading;
- Backwash requirements, including air requirements, solids generation rate, and characterization of the backwash water;
- The use of DAFT for thickening generated backwash water;
- Management of recycle streams from a thickening process;
- Air and power requirements;
- Performance under stress conditions;
- Headloss development along the height of the column;
- Fate of phosphorus along the BAF column;
- Ability of the BAF to remove bacteria and viruses;
- Toxicity of the effluent produced by the BAF pilot units; and
- Evaluation of the biomass.

Performance evaluation of the Densadeg pilot unit is presented in Section 5.

The Need for Biofor-N

The City requested proposals from IDI and Krüger in early 2003 for a full-scale BAF system that can treat CEPT effluent to secondary treatment level at the PLWTP. Both companies were given the design criteria listed in Table 4.1.

Table 4.1. Initial Influent and Target Effluent PLWTP Wastewater Quality Provided to BAF Manufacturers

Parameter	Influent (Advanced Primary Effluent)	Target BAF Effluent
Maximum Monthly Average Flow	360	---
Peak Wet Weather Flow	432	---
$TBOD_5$	116	<20
TSS	52	<20
Minimum Temperature	21.8	---

IDI's proposal suggested using 64 Biofor-C cells and 32 Biofor-N cells in a staged arrangement—each cell 12.1 feet deep with 1,571 square feet of filter area. Krüger proposed a single-stage system. IDI felt that the stringent $TBOD_5$ effluent target required some nitrification to lower nitrogenous BOD. It was later discovered that, to guarantee achieving the target BAF effluent at all times, both vendors submitted preliminary designs that aimed for effluents with 15 mg/L $TBOD_5$ and TSS concentrations. This approach was considered to be too conservative, and the vendors were asked to provide new proposals based on effluent $CBOD_5$ and TSS concentration targets of 25 and 30 mg/L, respectively (i.e., secondary effluent standards). At the same time, a 4-year data set provided by the City of San Diego to Brown and Caldwell indicated that the maximum monthly average peaking factor (maximum monthly average/average annual daily flow) was 1.1, or 264 mgd. With the revised information, both manufacturers returned proposals with reduced footprint requirements. This time, IDI proposed only one stage, or 64 Biofor-C cells; Krüger proposed a reduced number of cells. The treatability of the CEPT effluent produced by the PLWTP was still uncertain. Therefore, IDI strongly suggested pilot testing both Biofor-C and Biofor-N.

To assess whether the effluent from the Biofor-C process must be treated in the Biofor-N process to meet secondary treatment standards, the 30-day running average concentrations for the permit constituents (i.e., $TBOD_5$, $CBOD_5$ and TSS) of the Biofor-C and Biofor-N pilot plant effluents were determined. The maximum values for both are shown in Table 4.2. These data indicate that Biofor-C process alone provides sufficient treatment to consistently meet permit limits and that, if needed, the Biofor-N process can be added to the treatment train to improve effluent quality. The complete Biofor-N data are presented in Appendix E. The remaining discussions focus on Biofor-C and Biostyr data.

Table 4.2. Comparison of Secondary Treatment Standards versus Maximum 30-Day Running Average Concentration Measured during Phase I

Parameter	Secondary Treatment Standards 30-d Running Average Concentration (mg/L)	Maximum 30-d Running Average Concentration (mg/L)	
		Biofor-C Effluent	Biofor-N Effluent
$TBOD_5$	30	21.0[(a)]	16.7[(a)]
$CBOD_5$	25	12.1	8.8
TSS	30	15.9	9.5

(a) Excludes data collected between March 3 and March 19, 2003, a period when Biofor-N was not fully acclimated and produced effluent with very high $TBOD_5$.

Compliance with Anticipated Regulatory Standards

The performance of each BAF pilot unit relative to anticipated regulatory limits for solids (measured as TSS) and organic pollutants (measured as $TBOD_5$ or $CBOD_5$ depending on the negotiated permit) were plotted over the course of the study. Figures 4.1 to 4.12 show the 30-day and 7-day running average daily influent and effluent $TBOD_5$, $CBOD_5$ and TSS concentrations. Figures 4.1 through 4.6 represent data obtained during Phase I; Figures 4.7 through 4.12 represent Phase II. The anticipated permit limits described in Section 1 are superimposed on each figure to provide a benchmark for performance. The results shown on these figures are discussed below.

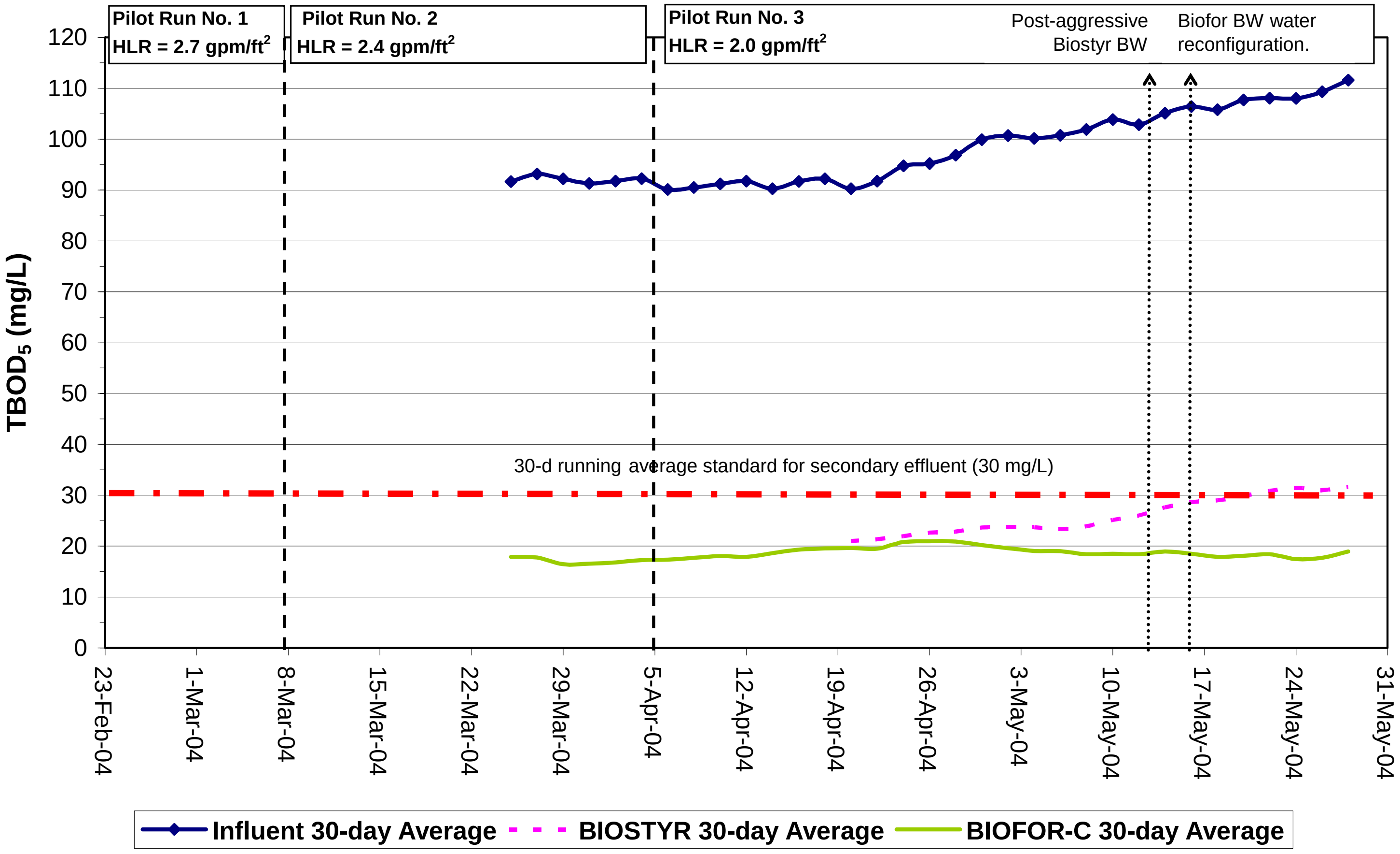


Figure 4.1. 30-Day Average TBOD$_5$ Concentration during Phase I of BAF Pilot

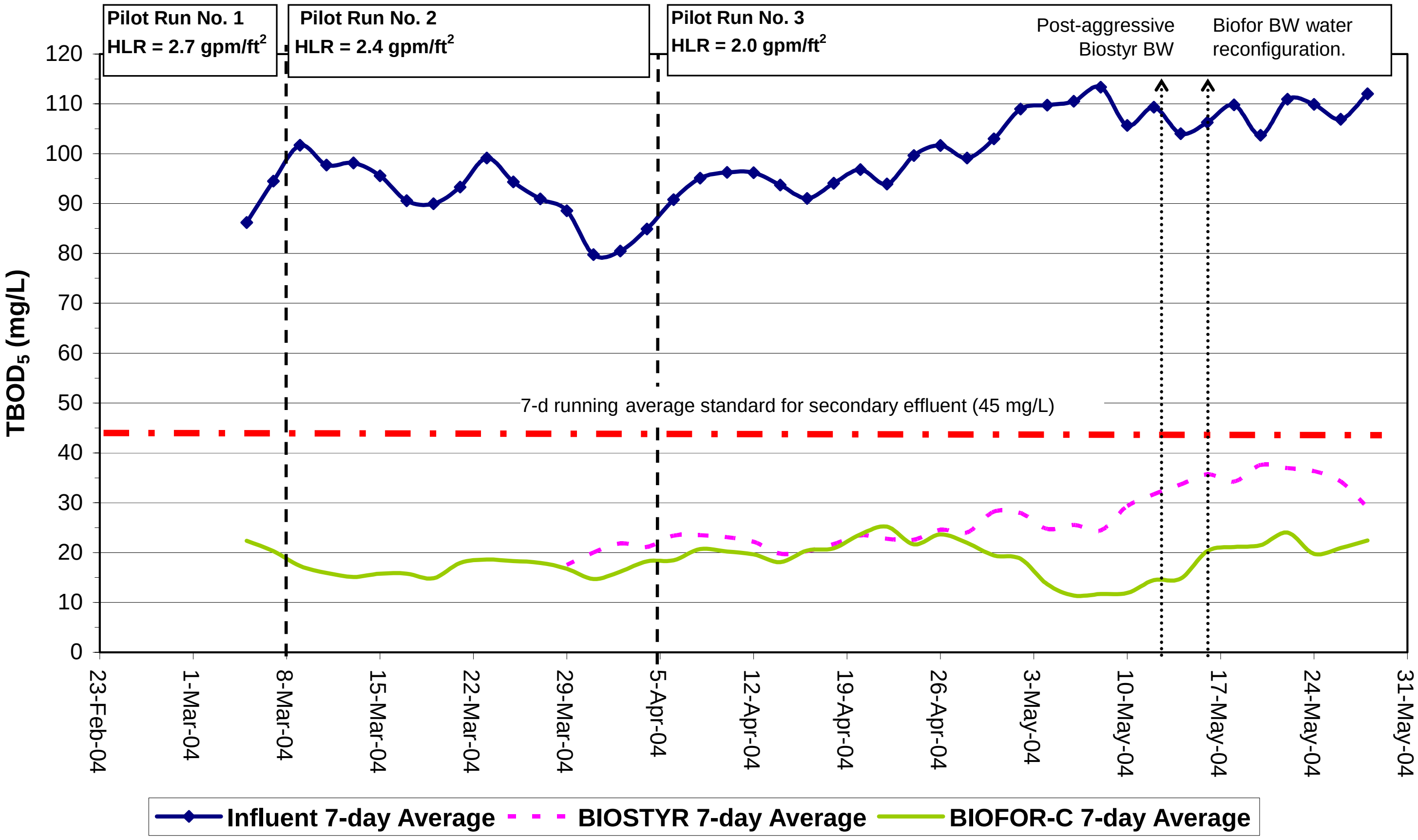


Figure 4.2. 7-Day Average TBOD$_5$ Concentration during Phase I of BAF Pilot

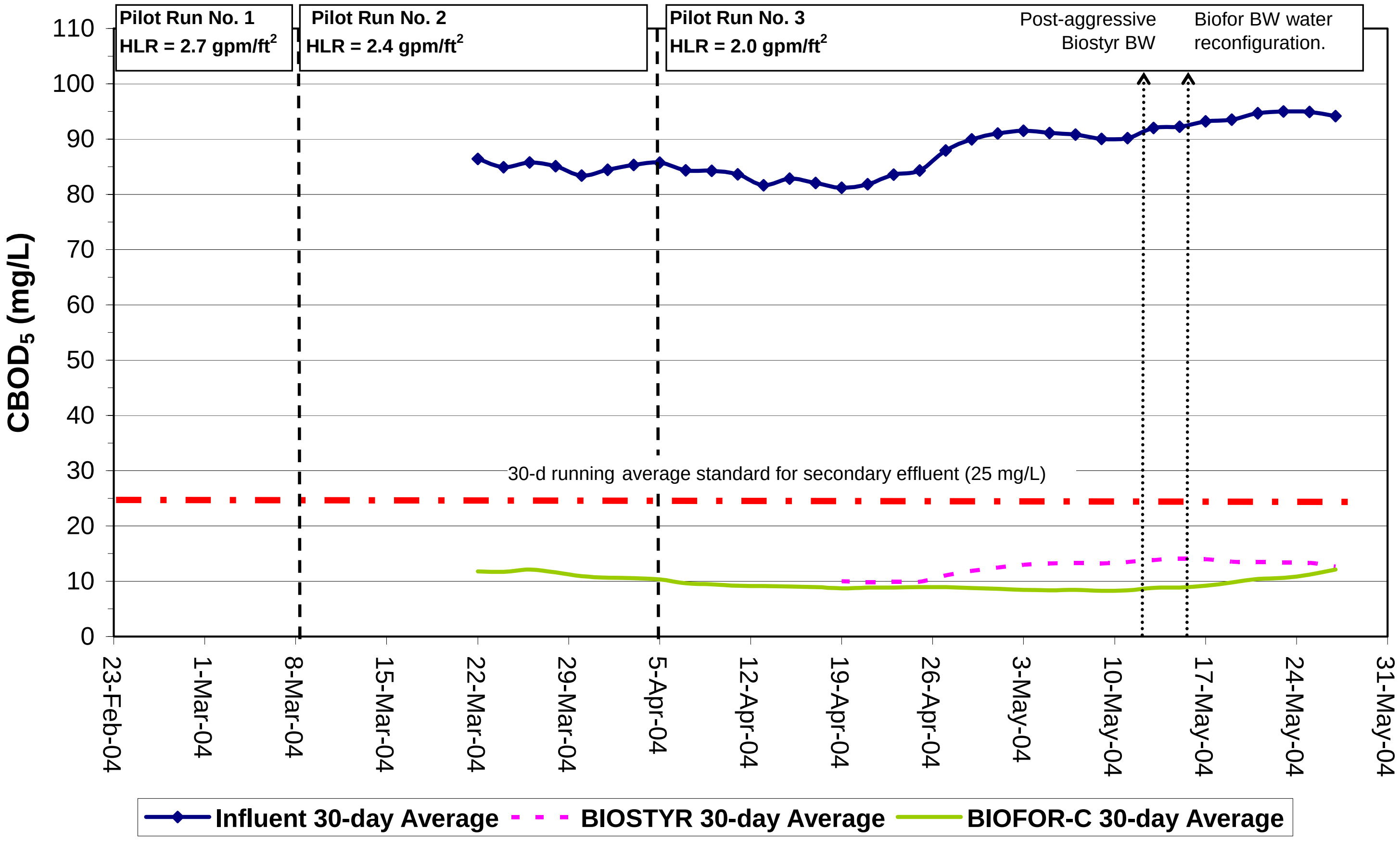


Figure 4.3. 30-Day Average CBOD$_5$ Concentration during Phase I of BAF Pilot

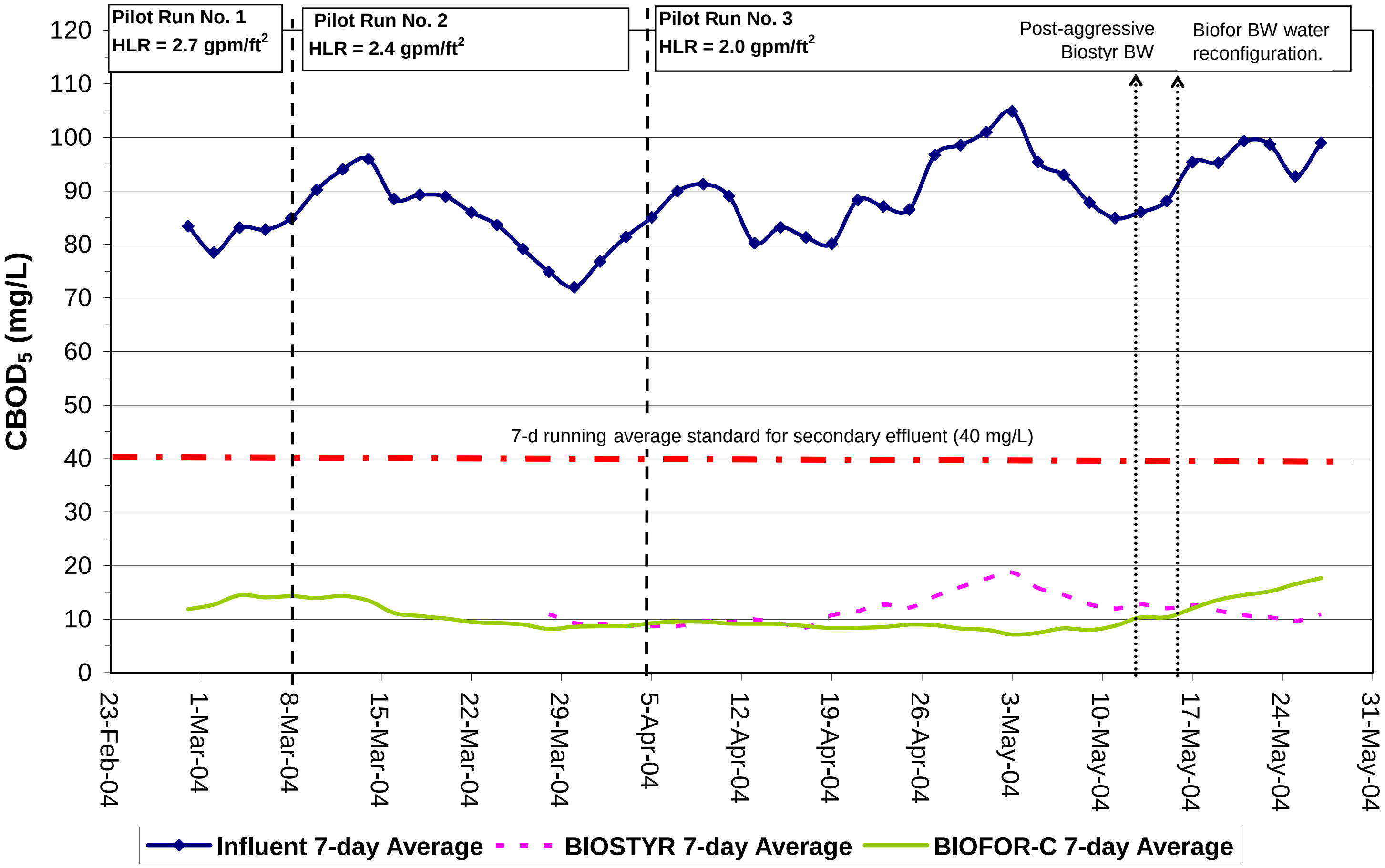


Figure 4.4. 7-Day Average CBOD$_5$ Concentration during Phase I of BAF Pilot

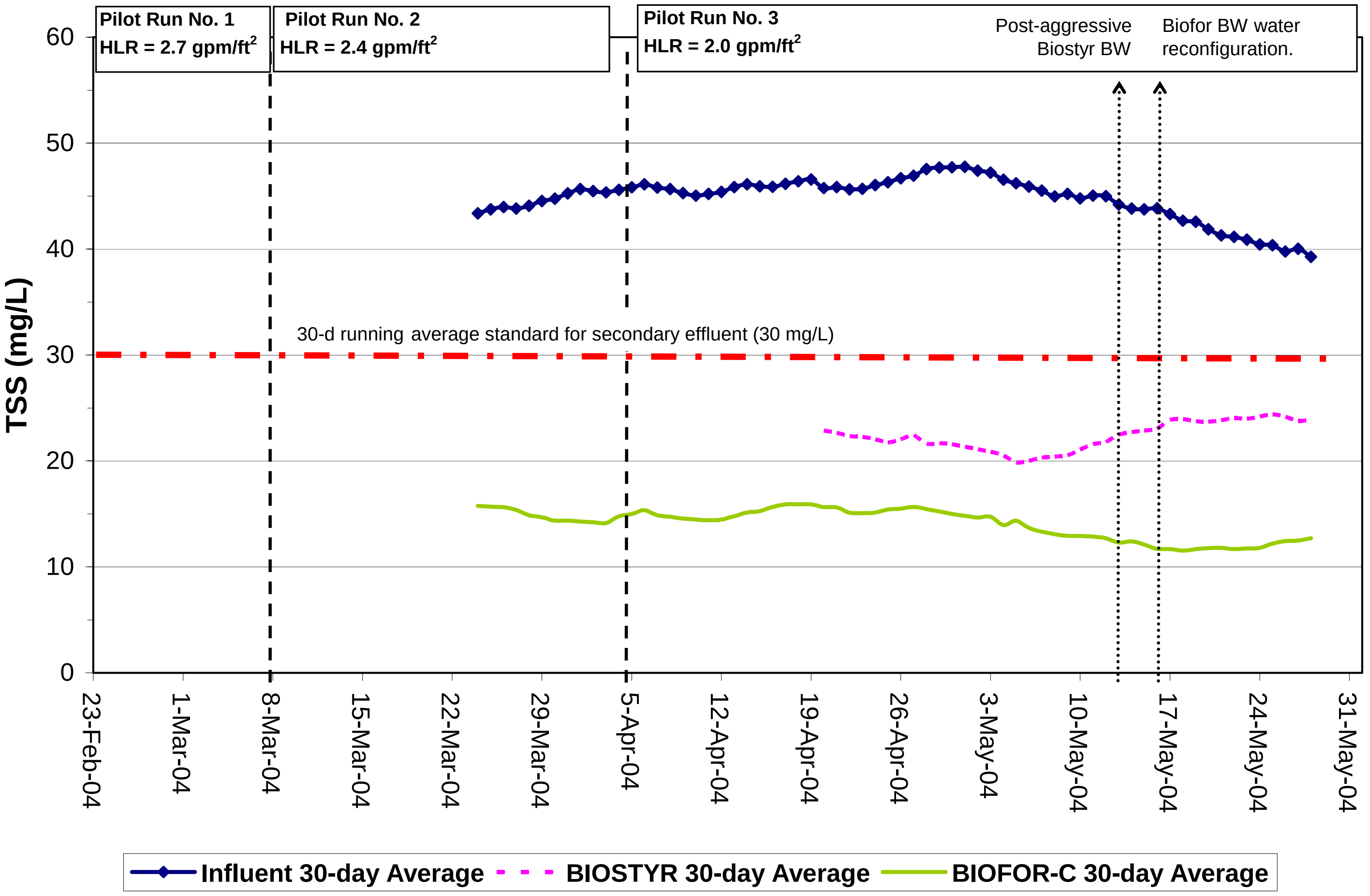


Figure 4.5. 30-Day Average TSS Concentration during Phase I of BAF Pilot

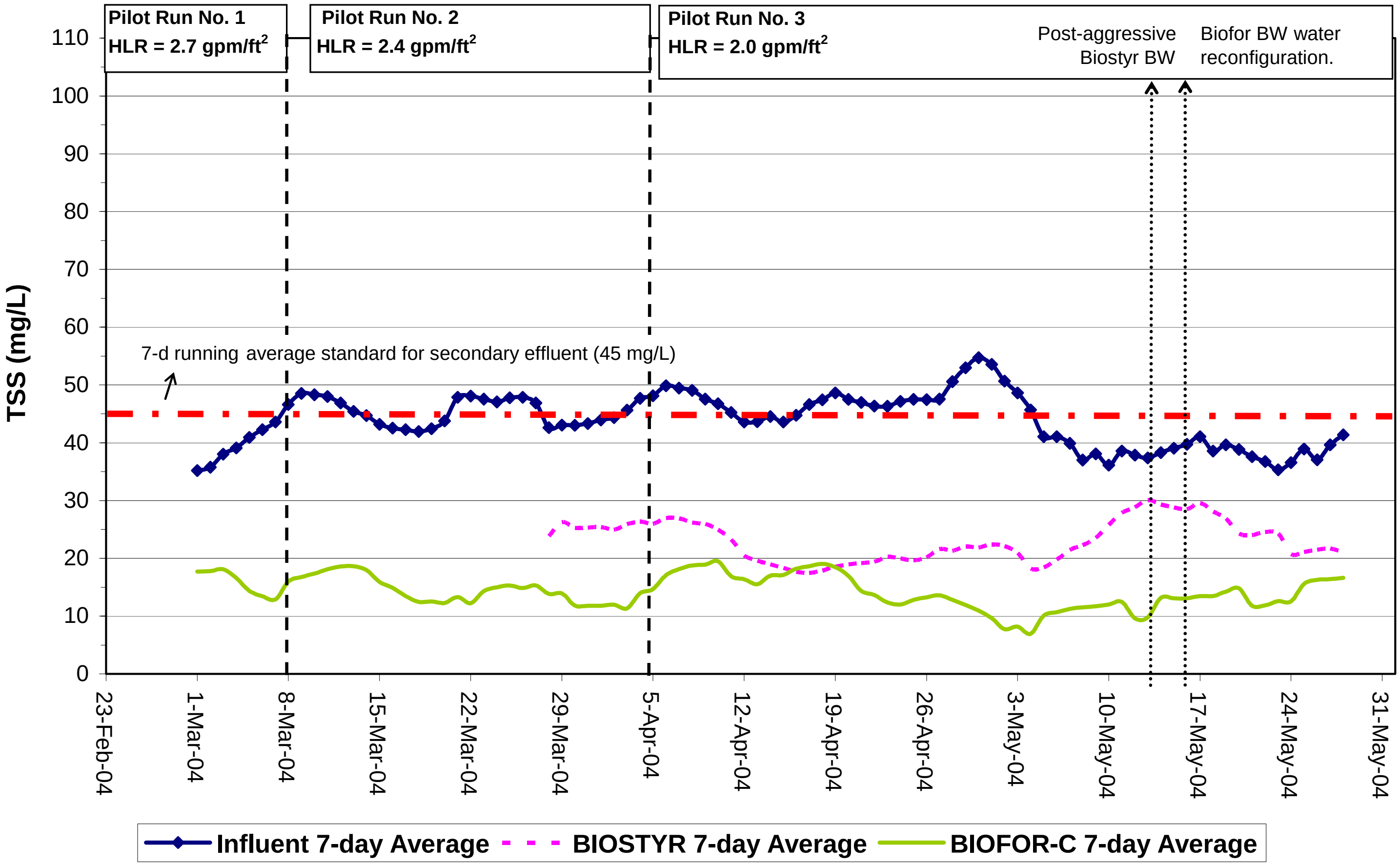


Figure 4.6. 7-Day Average TSS Concentration during Phase I of BAF Pilot

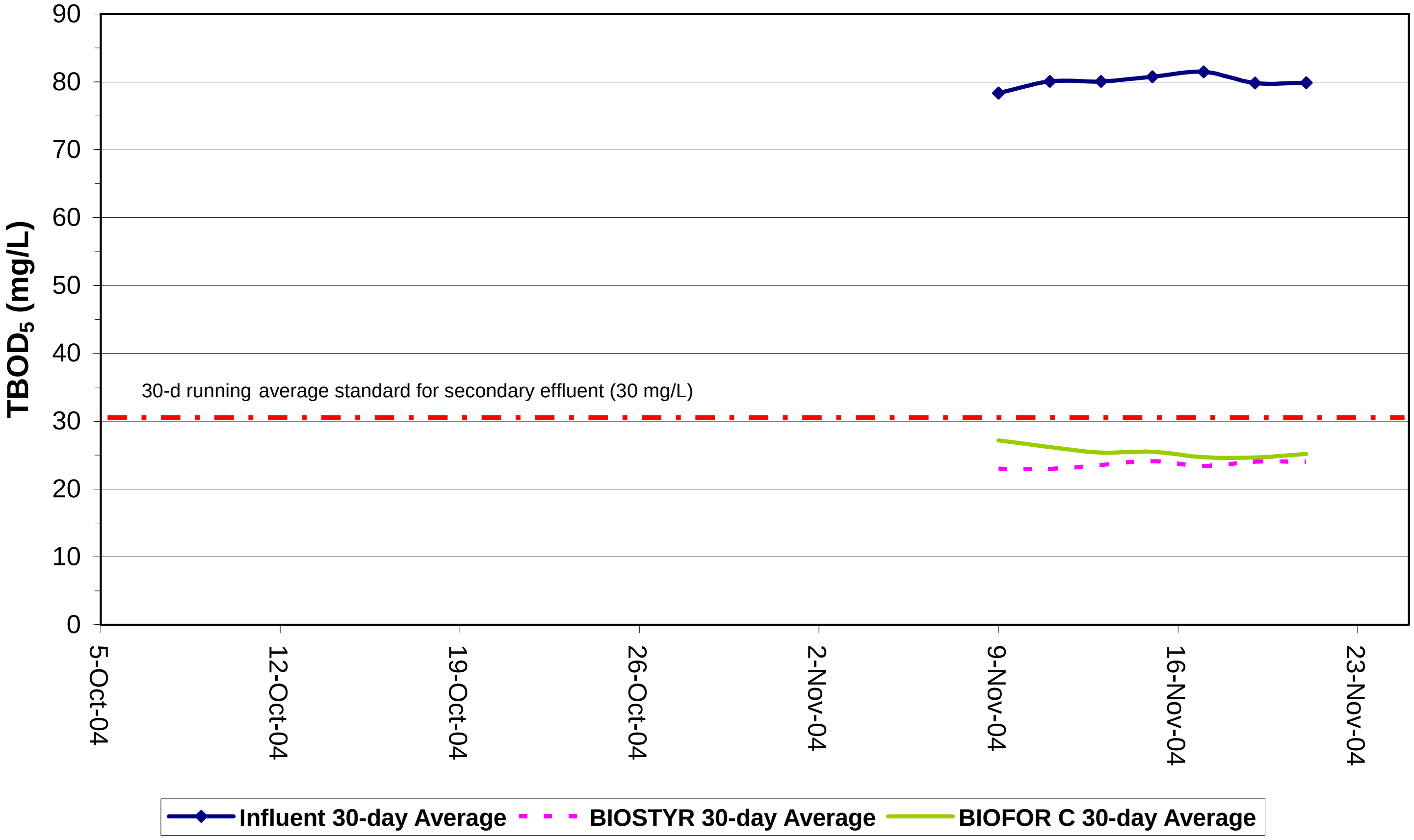


Figure 4.7. 30-Day Average $TBOD_5$ Concentration during Phase II of BAF Pilot

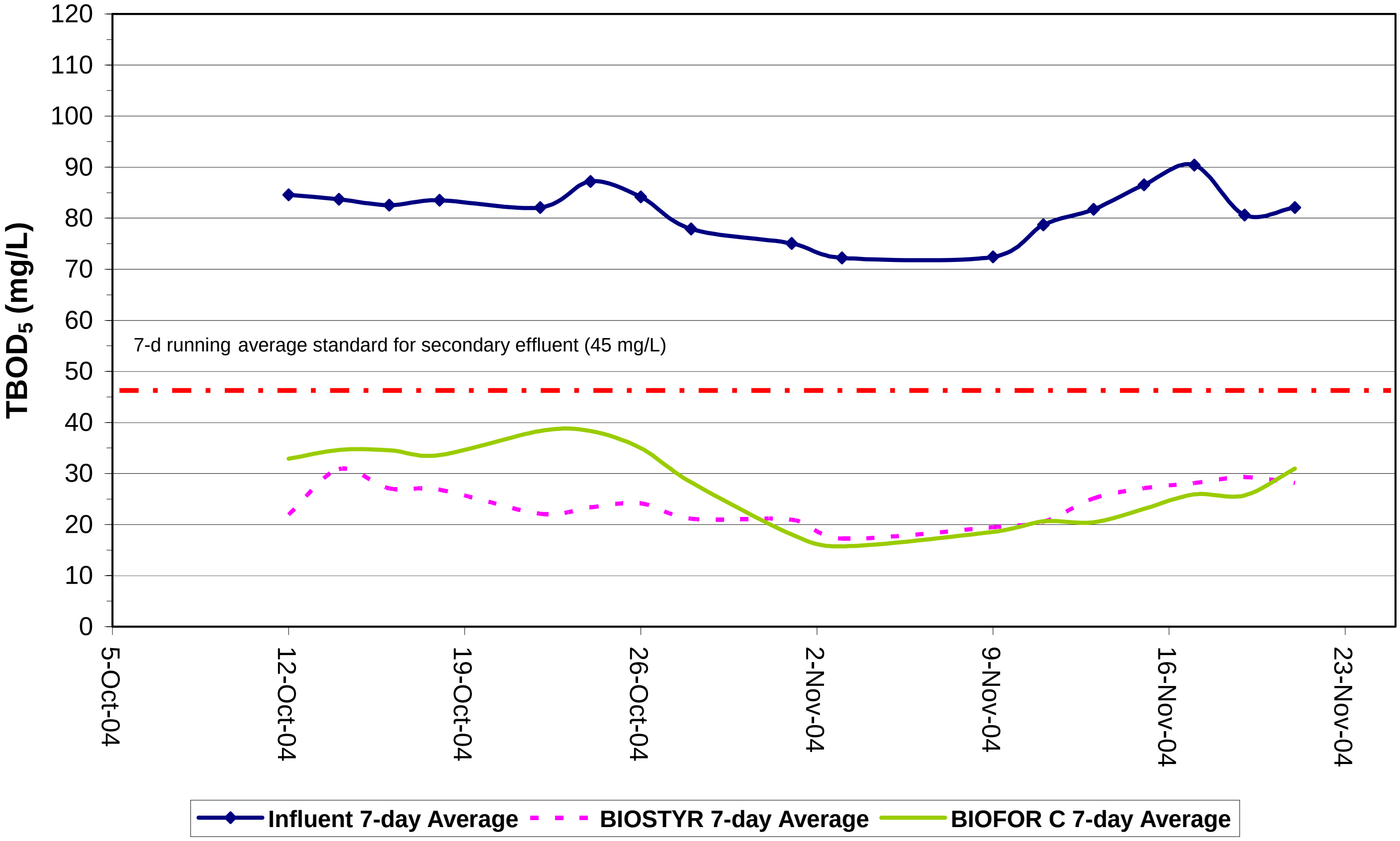


Figure 4.8. 7-Day Average TBOD$_5$ Concentration during Phase II of BAF Pilot

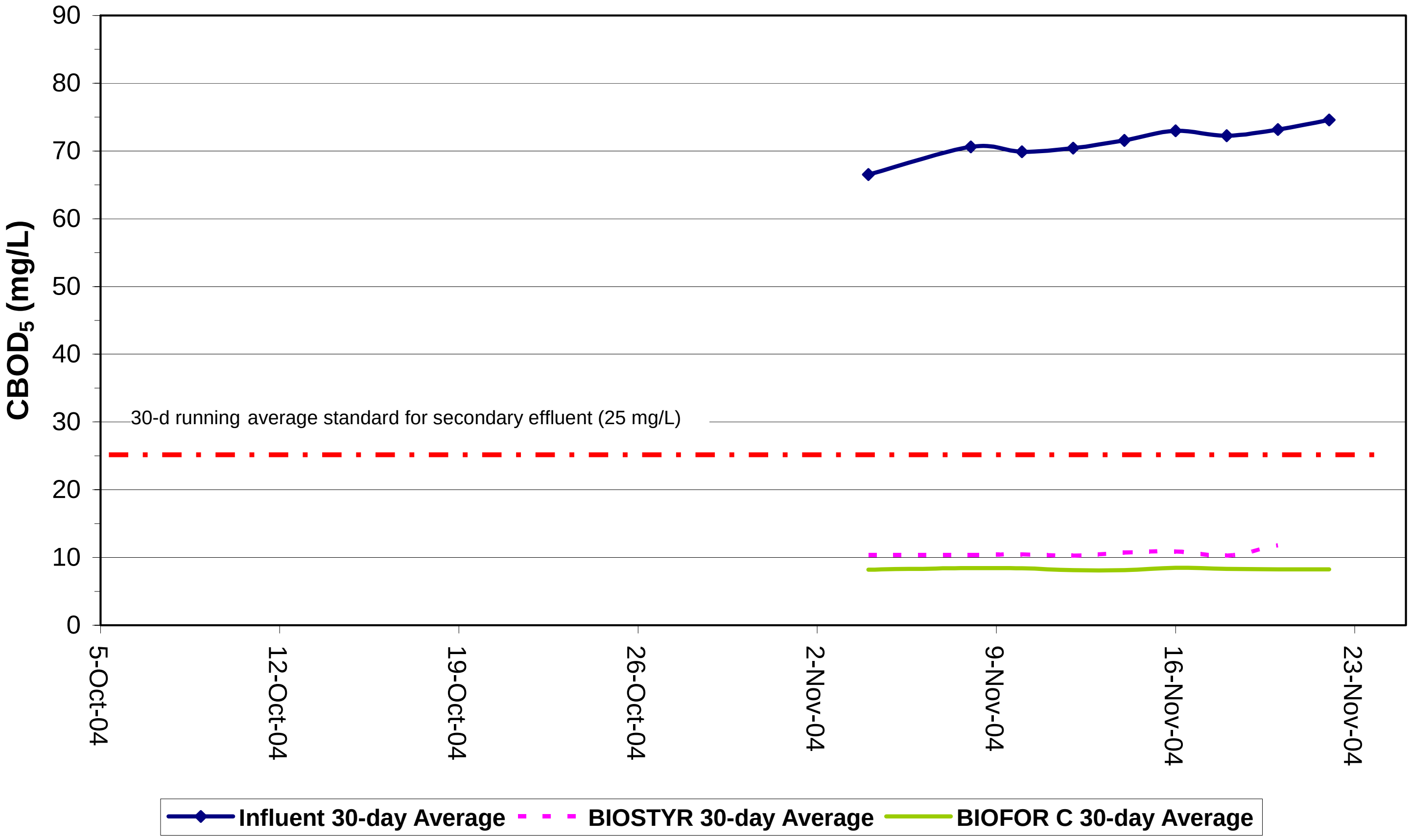


Figure 4.9. 30-Day Average $CBOD_5$ Concentration during Phase II of BAF Pilot

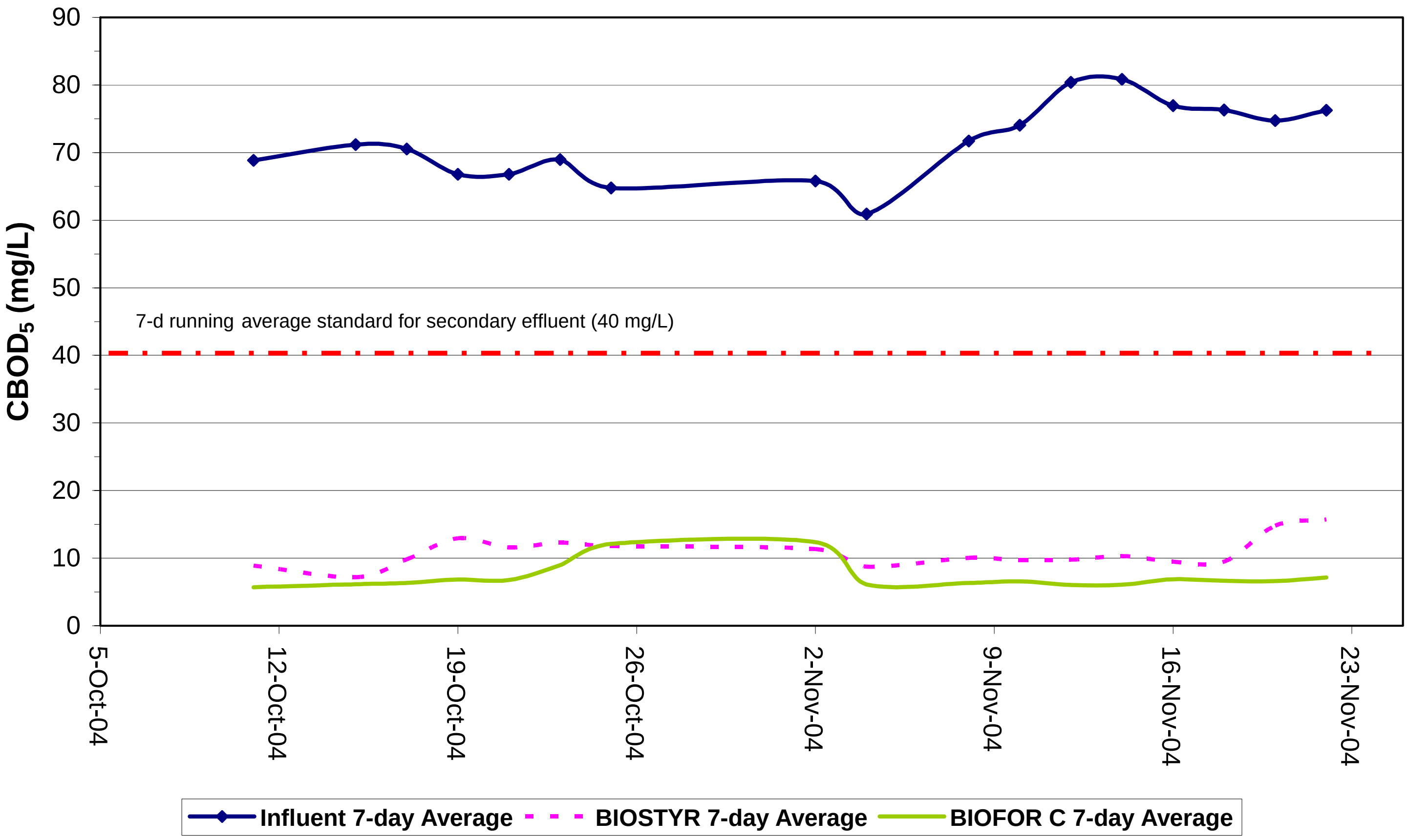


Figure 4.10. 7-Day Average CBOD$_5$ Concentration during Phase II of BAF Pilot

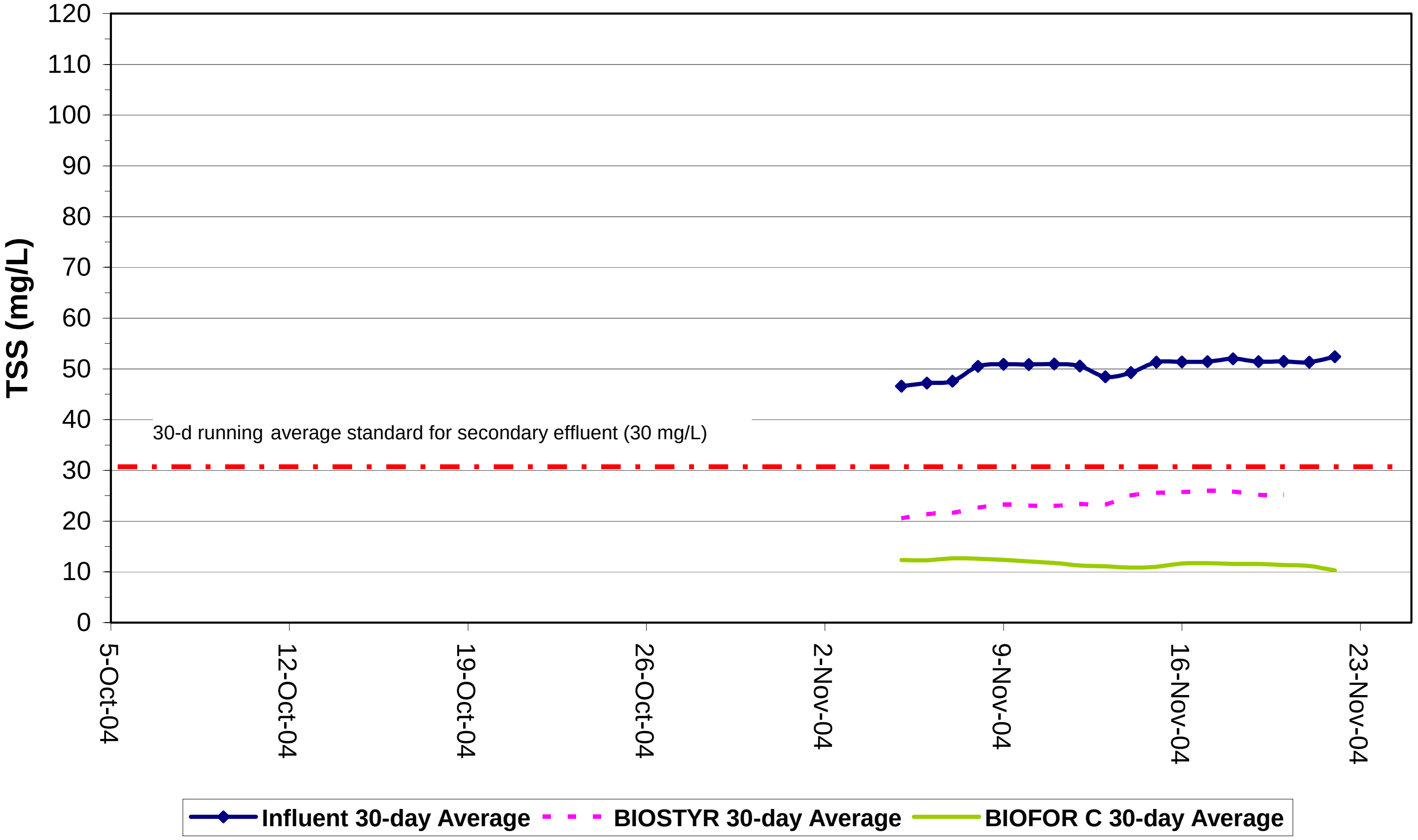


Figure 4.11. 30-Day Average TSS Concentration during Phase II of BAF Pilot

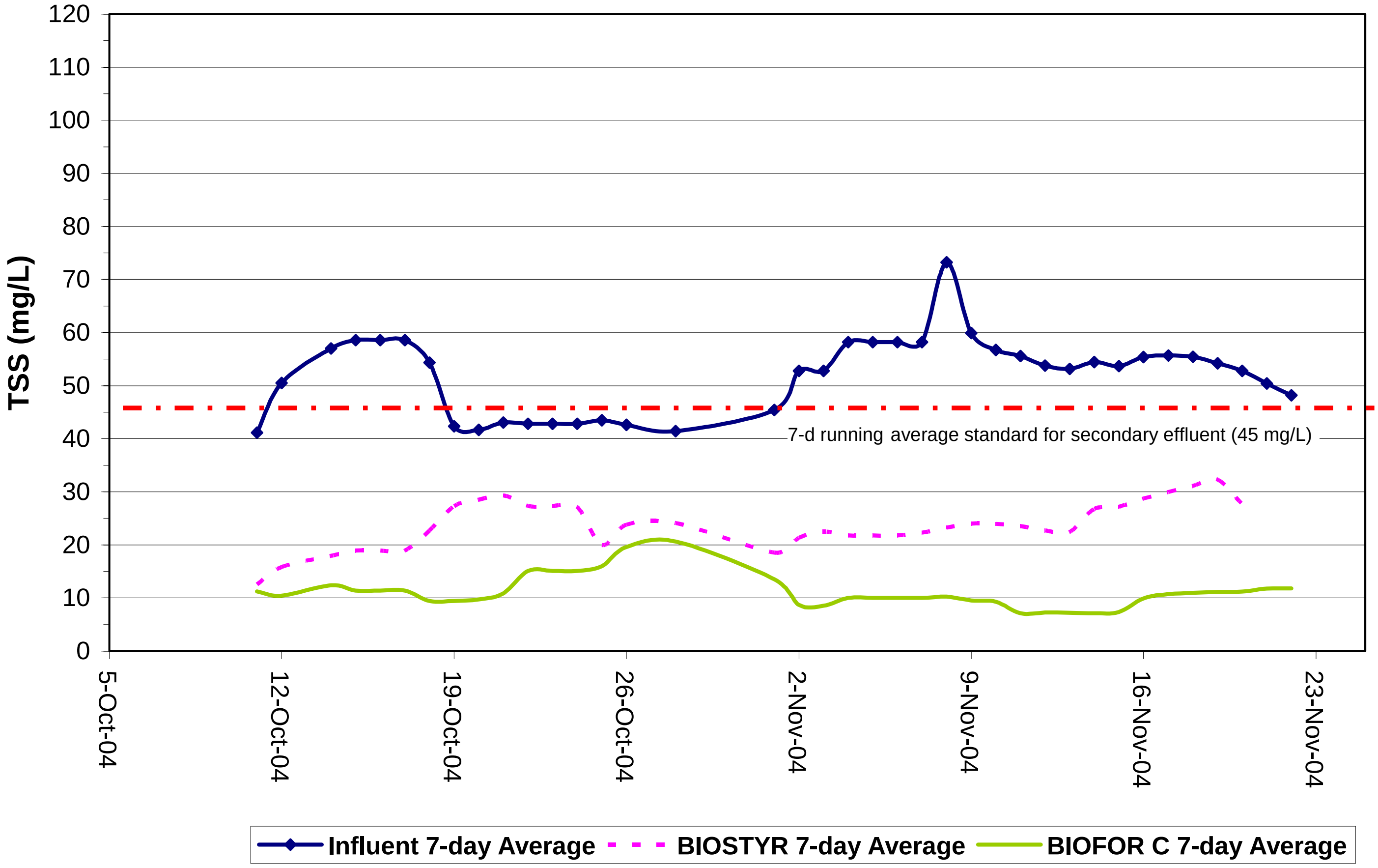


Figure 4.12. 7-Day Average TSS Concentration during Phase II of BAF Pilot

Biostyr Compliance with Projected Effluent Requirements. According to Figures 4.1 through 4.12, Biostyr effluent met the 7-day and 30-day running average secondary effluent requirements for $CBOD_5$ and TSS. However, the 30-day average effluent $TBOD_5$ concentration exceeded the permit requirement during the last month of operation in Phase I, as shown on Figure 4.1. During roughly the same period, BC staff observed the following:

- Media appeared black and clumpy through observation window.
- Spent backwash water had a septic odor.
- Spent backwash contained black colloidal solids that did not settle.

Prior to the observations listed above, Krüger had lowered the air flow in the column from 2.0 to 1.7 scfm in preparation for off-gas testing, which was scheduled for the following week (documented in Appendix F). One theory to explain the high Biostyr effluent $TBOD_5$ is that a substantial portion of the biomass in the column became anaerobic during this period. After the observations were reported to Krüger, the air flow rate set-point was restored to 2.0 scfm. In addition, a vigorous backwash using potable water was performed to clear whatever anaerobic biomass may have accumulated.

Interestingly, during the same period the Biostyr effluent $CBOD_5$ only marginally increased and never threatened the projected $CBOD_5$ effluent limit, as shown on Figure 4.3. However, the increase in Biostyr effluent $TBOD_5$ shown on Figure 4.1 was accompanied by a similar increase in effluent TSS, shown on Figure 4.5. Considering these observations, a second theory is that the high $TBOD_5$ at the end of Phase I was caused by nitrogenous oxygen demand exerted by nitrifiers in the BOD bottle. As shown in previous studies, some amount of nitrifier growth is unavoidable with aerobic fixed film systems designed to meet secondary treatment limits. The higher $TBOD_5$ values could then have resulted from increased seeding of nitrifying bacteria (via the increased TSS) in the BOD bottle.

Biofor-C Compliance with Projected Effluent Requirements. According to Figures 4.1 through 4.12, the Biofor-C effluent met the 7-day and 30-day running average secondary effluent standards for $TBOD_5$, $CBOD_5$ and TSS during Phase I and Phase II operation. As indicated in the figures, Biofor-C effluent quality was better than Biostyr most of the time. This is exhibited by the TSS plots on Figures 4.5 and 4.6 for Phase I and on Figures 4.11 and 4.12 for Phase II. These results indicate Biofor-C appears to bio-flocculate solids more effectively than Biostyr. The constraints that BAF effluent TSS concentration place on meeting effluent limits is described below.

Constraints on Effluent Requirements. The SDRWQCB has indicated that the City would be able to choose between an effluent limit based on $TBOD_5$, and one based on $CBOD_5$. Note that the $TBOD_5$ concentration of a sample is the sum of the $CBOD_5$ that is exerted and the Nitrogenous Oxygen Demand NOD_5 concentrations exerted within the five day BOD test. In the previous section, it was suggested that the BAF effluent TSS could increase the NOD_5 and, therefore, the

$TBOD_5$ measurement. This section provides details on the impacts of NOD_5 and contains information supporting the selection of a $CBOD_5$ limit rather than a $TBOD_5$ limit. Also presented is a discussion on how the fraction of the TSS that exert a $CBOD_5$ (i.e., the particulate $CBOD_5$) can add a second constraint in meeting the organic discharge limit.

Nitrogenous Oxygen Demand. The presence of nitrifiers in the sample to be analyzed for 5-day BOD is expected to influence the results, causing higher values to be measured. The number of viable nitrifier colonies that persist in the BOD bottle has been shown to be related to the sample TSS concentration. In general, the data obtained during the pilot testing (e.g., ammonia removal, presence of nitrite and nitrate in the effluent) indicated that nitrification was occurring in both the Biofor-C and Biostyr reactors. Depending on process organic loadings, fixed film systems such as BAF and trickling filters undergo at least partial nitrification at the wastewater temperatures prevalent throughout the pilot test. The BAF effluent data also indicate that an increase in $TBOD_5$ concentration (sometimes over 30 mg/L) often coincided with an increase in TSS. However, during this same period, the $CBOD_5$ concentration remained consistently below 15 mg/L, indicating that the difference between the $TBOD_5$ and the $CBOD_5$ concentrations was due at least in part to the NOD_5 exerted by the nitrifiers seeded into the BOD bottle.

A test was devised to see if the calculated NOD_5 at the end of the five-day BOD test correlates with the TSS of the sample tested. For each of the pilot columns, an effluent sample was collected. The sample was filtered through Whatman GF/C glass-fiber filters (same filter paper used in the suspended solids analysis per Standard Methods). The sample was then split into five equal volumes. Each volume was spiked with a different calculated mass of suspended solids that were obtained from a continuously stirred fresh spent backwash sample. This created five samples for each reactor, each having the same $SBOD_5$ and $SCBOD_5$ but different TSS and particulate-$CBOD_5$. The resulting NOD_5, $TBOD_5$ and $CBOD_5$ values were then plotted against TSS; the presence of nitrifier seeding would manifest itself as increasing NOD_5 and $TBOD_5$ versus TSS.

Figures 4.13 and 4.14 show NOD_5, $TBOD_5$, $CBOD_5$ versus TSS for Biostyr and Biofor-C effluents, respectively for the experiment described above. In each case, there appears to be a linear correlation between TSS and both NOD_5 and $CBOD_5$. These results prove that seeding of the BOD bottle with viable nitrifying bacteria is occurring. Comparing Figures 4.13 and 4.14, it also appears that the NOD_5 fraction of the $TBOD_5$ is greatest in the Biofor-C data. For example, 40 to 55 percent of $TBOD_5$ is NOD_5 in the Biostyr effluent; whereas, NOD_5 makes up 70 to 80 percent of $TBOD_5$ in the Biofor-C effluent. One possible explanation for the high NOD_5 fraction in the Biofor-C is that more air was inadvertently provided to the Biofor-C column due to blower malfunctions and flow measurement inaccuracies that were later discovered during the off-gas testing. Air flow rates three times greater than the set-point flow were occurring in some instances. The lower air flow rate in the Biostyr could have prevented the growth of nitrifiers in some parts of the column.

The results shown in Figures 4.13 and 4.14 compare closely with the results from an evaluation performed by Brown and Caldwell at Windsor, Ontario (Parker, et. al. 1995). To analyze the effect of seeding, effluent TSS, $TBOD_5$ and $CBOD_5$ data were obtained from four pilot plants operated by the City of Windsor, including the trickling filter/solids contact (TF/SC) process, the activated sludge (AS) process, the rotating biological contactor (RBC) process, and the BAF process. Figure 4.15 shows the relationship between secondary effluent TSS and the NOD_5, where NOD_5 was calculated as the difference between the $TBOD_5$ and the $CBOD_5$. The plot clearly indicates that NOD_5 increases linearly with TSS in the effluent solids, again demonstrating the impact of nitrifier seeding on NOD_5.

Reexamination of Figures 4.13 and 4.14 also indicate that meeting the 30-day secondary treatment standard for TSS of 30 mg/L may not equate to meeting the $TBOD_5$ 30-day average limit of 30 mg/L. For both pilot units, the effluent $TBOD_5$ exceeds this limit when TSS reaches 30 mg/L. Meanwhile, the $CBOD_5$ concentration is shown to be 10 to 15 mg/L less than the 30-day average limit for $CBOD_5$ of 25 mg/L.

To protect the City from analytical or operational problems that cause NOD_5 to be exerted within the five day BOD test upon committing to secondary treatment for all or part of the flow to the PLWTP, permit applications should be for $CBOD_5$ rather than $TBOD_5$.

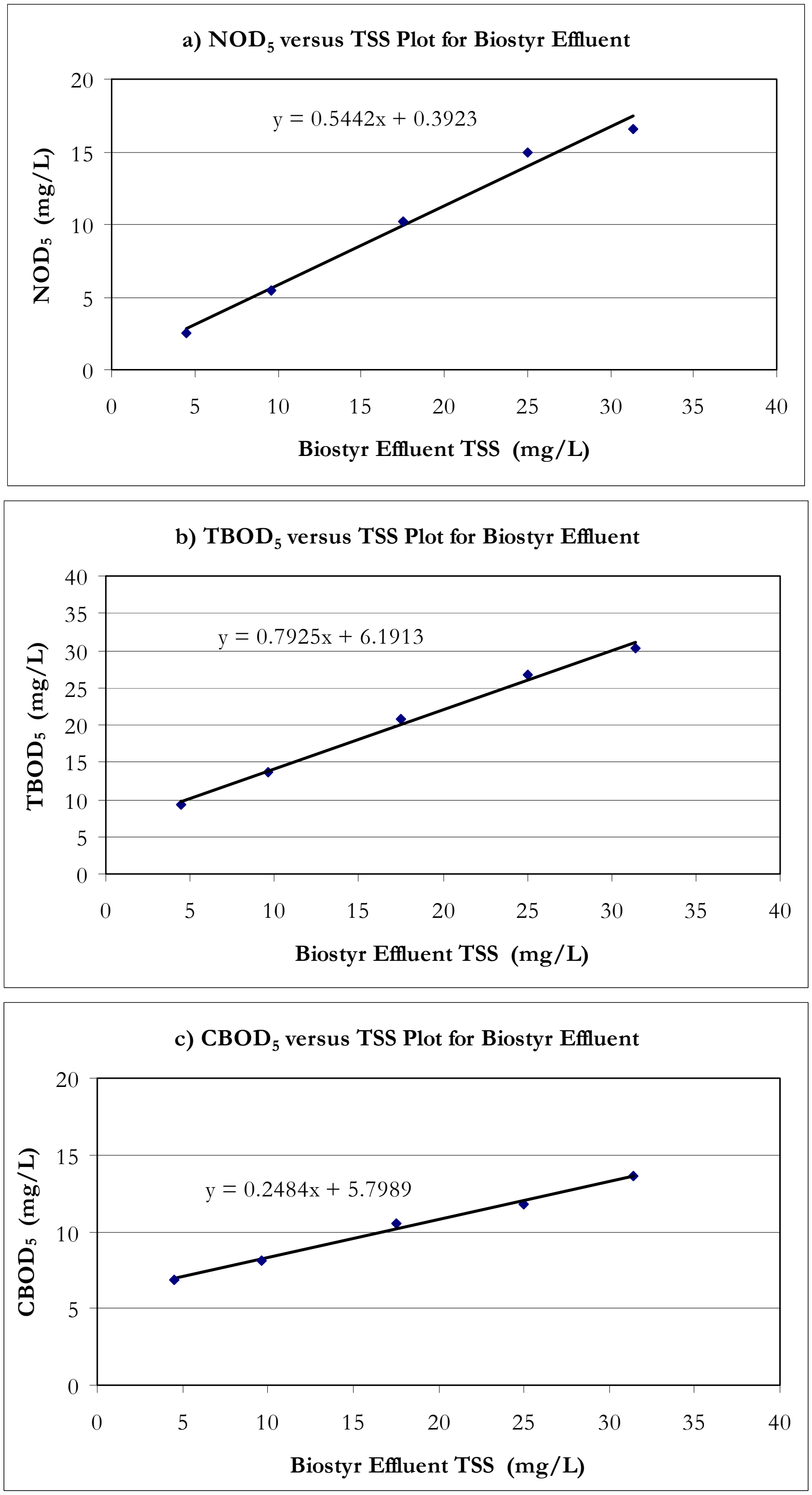
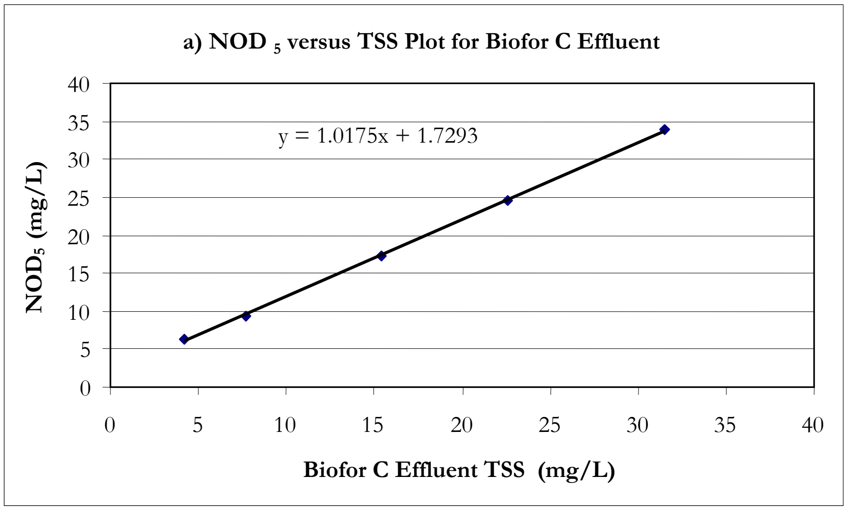
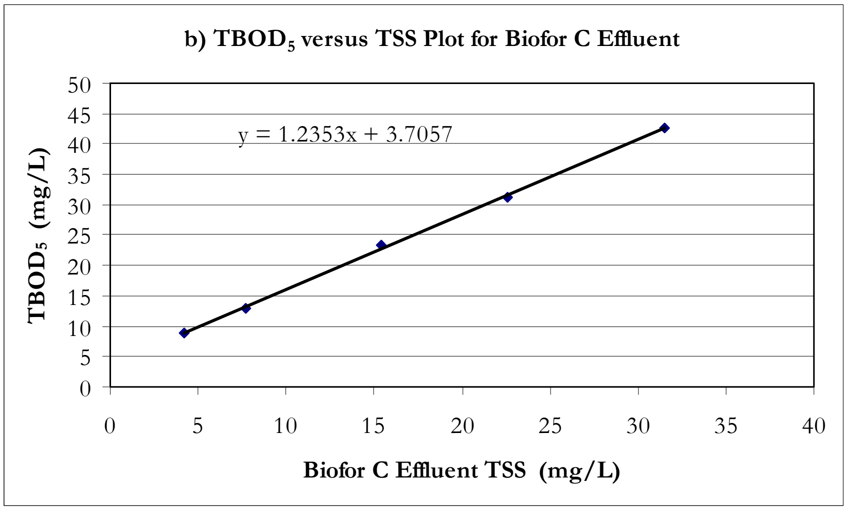


Figure 4.13. NOD_5 and $TBOD_5$ versus TSS for Biostyr Effluent





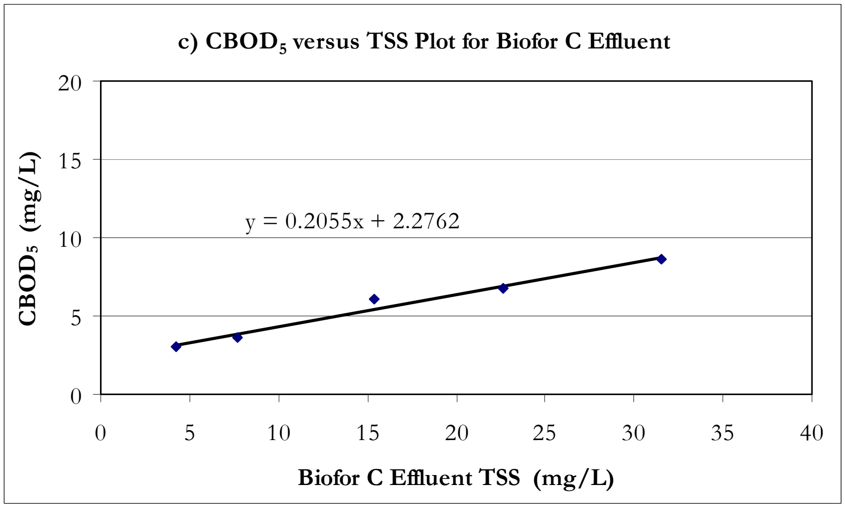


Figure 4.14. NOD_5 and $TBOD_5$ versus TSS for Biofor-C Effluent

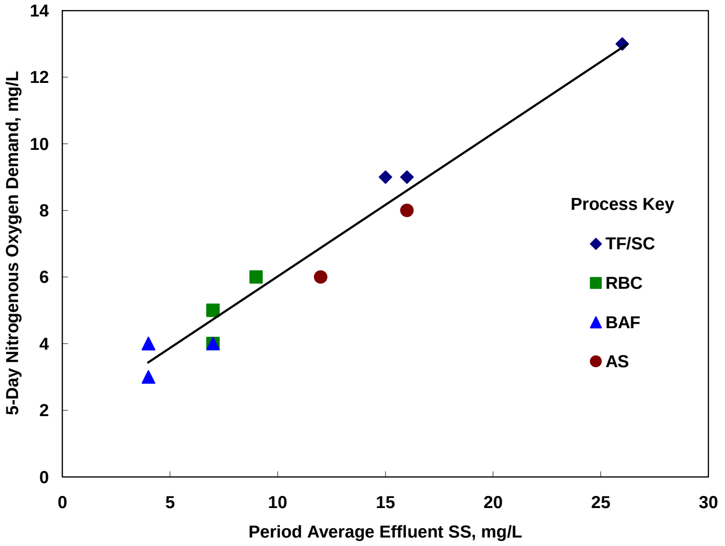


Figure 4.15. Relationship Between Nitrogenous Oxygen Demand and Effluent SS in a Pilot Study in Windsor, Ontario (after Parker et al., 1995)

Note: TF/SC = Trickling filter/solids contact
RBC = Rotating biological contactor
AS = Activated sludge
BAF = Biological Aerated Filter

Particulate and Soluble CBOD$_5$. Effluent particulate carbonaceous BOD$_5$ (pCBOD$_5$) is the difference between effluent CBOD$_5$ and effluent SCBOD$_5$. Dividing pCBOD$_5$ by effluent TSS concentration gives the particulate pCBOD$_5$ to TSS ratio. This number is important in understanding the contribution made by the effluent solids to the effluent TBOD$_5$. The average ratio of particulate CBOD$_5$ to TSS (pCBOD$_5$/TSS) was calculated in the Biostyr and Biofor-C effluent for Phase I and Phase II testing periods.

Table 4.3 shows the pCBOD$_5$:TSS ratio for Biostyr and Biofor-C for Phases I and II. On average, the effluent TSS contribution to effluent CBOD$_5$ was higher for Biofor-C process (0.29) than for Biostyr (0.23) process. From these average values, the allowable effluent SCBOD$_5$ concentration, shown in Table 4.4, was estimated for a series of TSS concentrations using the following relationship:

Allowable SCBOD$_5$ in mg/L = 25 mg/L CBOD$_5$ – (pCBOD$_5$:TSS Ratio) * (TSS)

Note that the 25 mg/L CBOD$_5$ in the equation is the 30-day average limit for secondary treated effluents. This derivation points out that as the TSS concentration increases in the BAF effluent, the more important it is for the BAF to treat soluble CBOD$_5$ such that the effluent SCBOD$_5$ cannot exceed 16-18 mg/L under max loading conditions.

Table 4.3. Effluent Particulate $CBOD_5$ to TSS Ratio

Phase	Particulate $CBOD_5$:TSS Ratio (lb/lb)	
	Biostyr	Biofor-C
I	0.25	0.30
II	0.20	0.28
Average	0.23	0.29

Table 4.4. Effluent TSS Versus Estimated Allowable Effluent $SCBOD_5$

Effluent TSS (mg/L)	Allowable Effluent $SCBOD_5$ (mg/L)	
	Biostyr [(a)]	Biofor-C [(b)]
5	23.9	23.6
10	22.7	22.1
15	21.6	20.7
20	20.4	19.2
25	19.3	17.8
30	18.1	16.3

(a) Ratio of $pCBOD_5$ to TSS for Biostyr = 0.23
(b) Ratio of $pCBOD_5$ to TSS for Biostyr = 0.29

As noted above, the $pCBOD_5$ was calculated by subtracting the effluent $SCBOD_5$ concentration from the $CBOD_5$ concentration. It is also useful to consider the $SCBOD_5$ as a percent of the $CBOD_5$. This provides an understanding of the degree to which the $pCBOD_5$ contributes to the $CBOD_5$. Table 4.5 shows the average value and ranges of the $SCBOD_5$ as a percent of the $CBOD_5$. It is shown that the soluble portion of the $CBOD_5$ was greater on average for the Biofor-C during both phases of pilot testing. In addition, the soluble portion of the effluent $CBOD_5$ decreased in both cases from Phase I to Phase II. Although the cause it is not clear, it is worth noting that the BAF influent average $SCBOD_5$ was substantially higher during Phase I than during Phase II. This implies that hydrolysis reactions may be occurring in the existing CEPT basins, possibly the result of long sludge residence times needed to achieve the relatively high target sludge density (between 4 and 5 percent) as currently practiced at the plant. Finally, Table 4.5 shows that over the study the average soluble fraction of the $CBOD_5$ ranged from 36 percent (for Biostyr in Phase II) to 61 percent (for Biofor-C in Phase I). This shows that a substantial portion of the effluent $CBOD_5$ from each pilot was $pCBOD_5$. This highlights again the importance of proactive process control (e.g., automated controls for backwashing and aeration) to achieve an effluent with low TSS regardless of the effluent TSS regulatory limit. In addition, the City should reconsider the strategy of thickening in the primary sludge in the CEPT basins; pumping thinner sludge to an external thickening system could reduce the BOD loading on the secondary process.

Table 4.5. Average Value and Ranges of the $SCBOD_5$ as a Percent of the $CBOD_5$

Statistic		Percent of $CBOD_5$ that is soluble	
		Biostyr	Biofor-C
Phase I	Average (%)	49	61
	Range (%)	17 - 80	42 - 95
Phase II	Average (%)	36	48
	Range (%)	21 - 73	32 - 75

Effect of Hydraulic Loading Rate on BAF Performance

During the pilot test, the following target hydraulic loading rates (HLR) were selected to determine performance under maximum 30-day and peak wet weather loading conditions:

- 2.0 gpm/ft^2 for maximum 30-day conditions
- 3.0 gpm/ft^2 for peak wet weather flow (for 10-hour sustained period)
- 2.0 – 3.0 gpm/ft^2 during transition between rainy and dry periods.

These loadings were based on the proposed full-scale design information presented in Table 3.3.

Wet weather experiments were conducted to coincide with actual storm events so that the effects of inflow and infiltration into the sewage collection would be captured in the wastewater characteristics. As the rainy season ended (the season's last rain fell on March 2, 2004), the HLR was decreased but held between approximately 2.5 and 2.7 gpm/ft^2 through April 2, 2004. Wet weather testing resumed on September 2, 2004.

During the wet weather testing, each pilot was evaluated at the peak HLR of 3.0 gpm/ft^2, which represents the anticipated loading at a full-scale PLWTP flow of 432 mgd. The wet weather hydraulic loading conditions tested for each of the BAF pilot units are summarized in Table 4.6

Table 4.6. Summary of Wet Weather Hydraulic Loading Conditions Tested

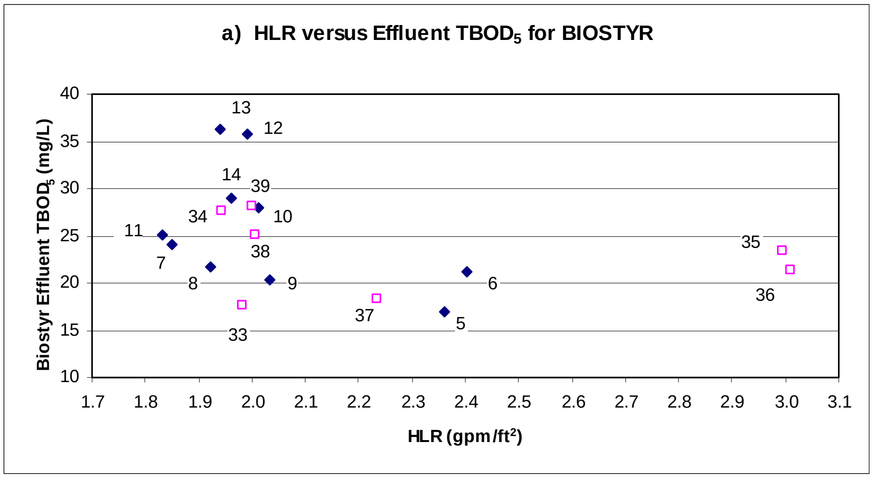
Wet Weather Hydraulic Loading Characteristic	Biostyr	Biofor-C
Average hydraulic loading (gpm/ft^2)	2.3	2.3
Range of hydraulic loading rates tested (gpm/ft^2)	1.8 – 3.0	0.7 – 3.1
Number of days tested	71	92
Number of days in which hydraulic loading exceeded 2.95 gpm/ft^2	15	5

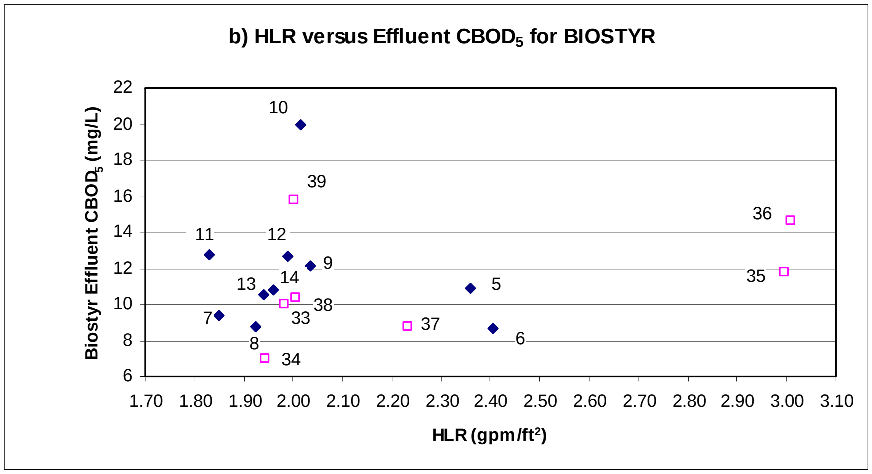
The dry season simulation began approximately April 5, 2004 and continued through the end of Phase I testing in June 2004. The dry weather hydraulic loading conditions tested for each of the BAF pilot units is summarized in Table 4.7. The effect of variation in HLR is discussed for the Biostyr and Biofor pilot units below.

Table 4.7. Summary of Dry Weather Hydraulic Loading Conditions Tested

Dry Weather Hydraulic Loading Characteristic	Biostyr	Biofor-C
Average hydraulic loading (gpm/ft^2)	1.9	1.9
Range of hydraulic loading rates tested (gpm/ft^2)	1.3 – 2.1	1.2 – 2.1
Number of days tested	54	54
Number of days in which hydraulic loading exceeded 1.95 gpm/ft^2	43	37

Biostyr Performance. Figure 4.16 shows the effect of higher hydraulic loading on Biostyr effluent $TBOD_5$, $CBOD_5$, and TSS concentrations. Each datum has been labeled to show the test week number represented. For example, by observing plots (a), (b), and (c), it can be seen that in Week 8, the weekly average hydraulic loading rate, effluent $TBOD_5$ concentration, effluent $CBOD_5$ concentration, and effluent TSS concentration were 9.2 gpm/ft^2, 21.7 mg/L, 8.72 mg/L, and 17.9 mg/L respectively. In addition, two different chart symbols were used on Figure 4.16 to distinguish between weeks in which BAF feed flow came from CEPT effluent (◆) or Densadeg effluent (□).


a) HLR versus Effluent $TBOD_5$ for BIOSTYR


b) HLR versus Effluent $CBOD_5$ for BIOSTYR

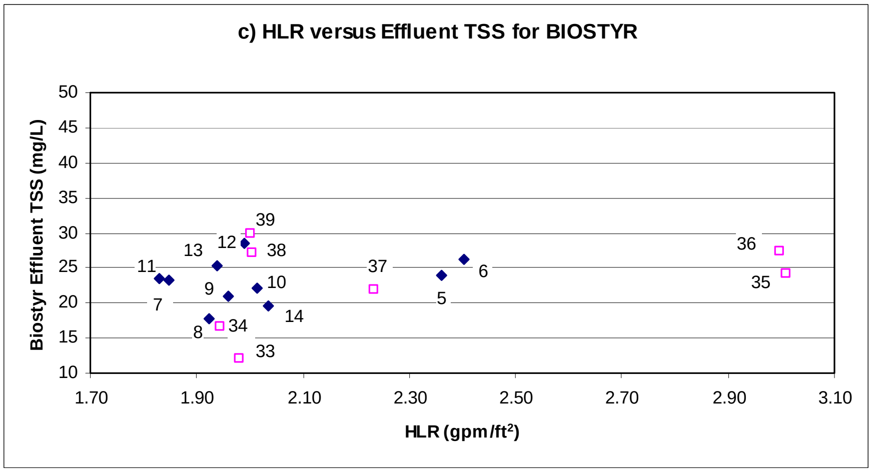

c) HLR versus Effluent TSS for BIOSTYR

Figure 4.16 Effect of HLR on Effluent $TBOD_5$, $CBOD_5$ and TSS Concentration for Biostyr
Note: Data presented are weekly averages. Numbers next to data points correspond to the week of operation.

◆ CEPT Effluent □ Densadeg Effluent

Parts (a) and (b) on Figure 4.16 show that increased HLR does not appear to correlate with increased effluent oxygen demand; however, effluent oxygen demand measured as $TBOD_5$ decreases slightly at the higher HLR.

Part (c) of Figure 4.16 shows the effect of increased HLR on Biostyr effluent TSS concentration. The TSS did not appear to increase with increased hydraulic loading to the Biostyr unit.

Biofor–C Performance. Figure 4.17 shows the effect of higher hydraulic loading on Biostyr effluent $TBOD_5$, $CBOD_5$, and TSS concentrations. As on previous figures, each datum has been labeled to show the test week number represented. These plots include wet and dry weather data. In addition, the same chart symbols are used to distinguish between weeks in which BAF feed flow came from CEPT effluent or Densadeg effluent.

The results for Biofor-C hydraulic loading indicate that the 7-day average regulatory limits for TSS, $TBOD_5$ and $CBOD_5$ were consistently met, even at loading rates of up to 3.0 gpm/ft^2. Part (a) shows no substantial increase of Biofor-C effluent $TBOD_5$ with increasing hydraulic loading. On Part (b), the two data points inside the boxed area represent Weeks 13 and 14 of the study. During this time, the source of backwash water for the Biofor-C was changed from Biofor-N effluent to Biofor-C effluent. This turned out to be a significant process change initially resulting in septic conditions in Biofor-C. The change in backwashing configuration was discussed previously.

Part (c) of Figure 4.17 shows the effect of increased hydraulic loading on Biofor-C effluent TSS concentration. TSS did appear to increase only slightly with increased hydraulic loading to the Biofor-C.

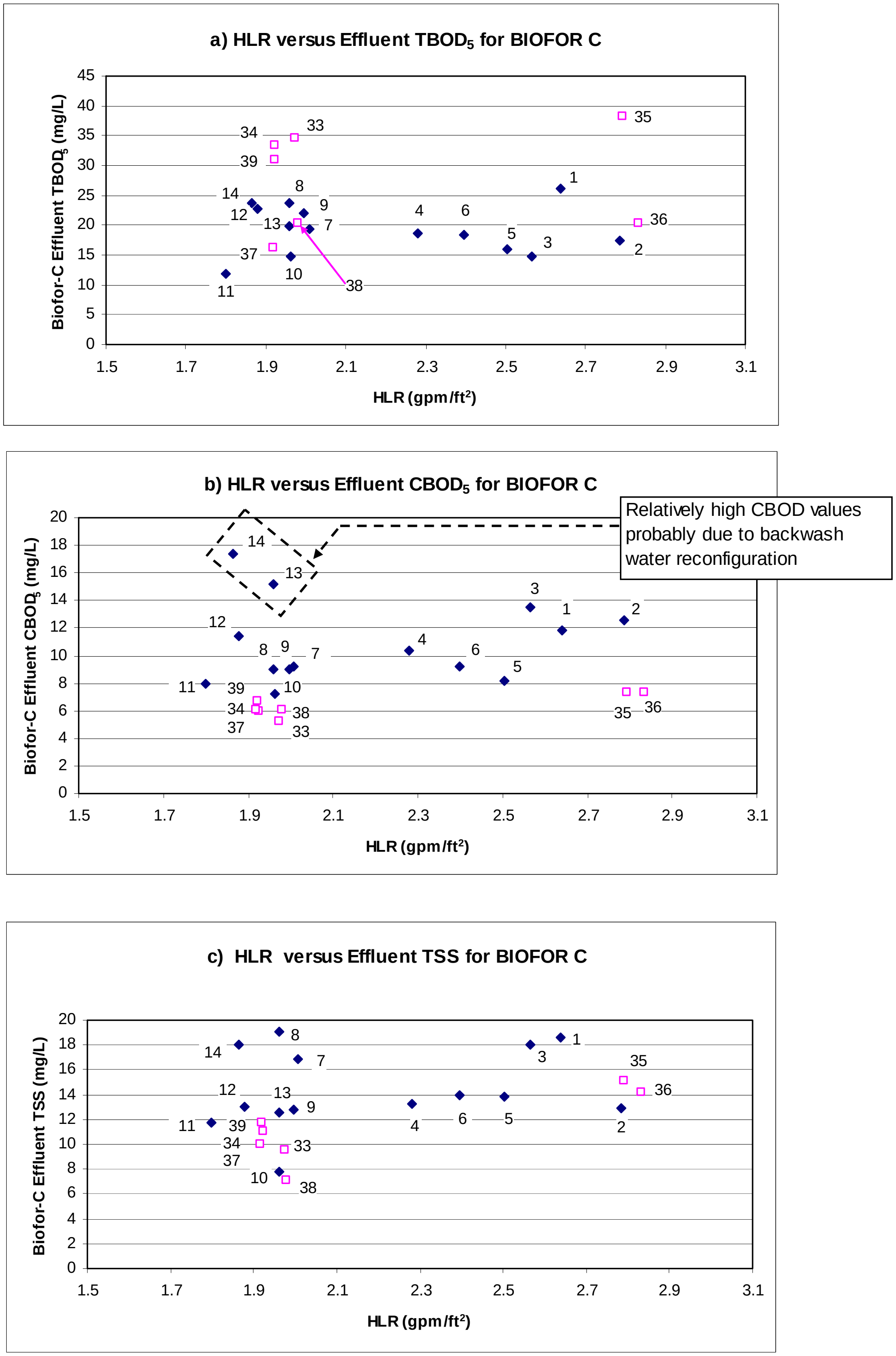


Figure 4.17. Effect of HLR on Effluent TBOD$_5$, CBOD$_5$ and TSS Concentration for Biofor-C

Note: Data presented are weekly averages. Numbers next to data points corresponds to the week of operation.

◆ CEPT Effluent ☐ Densadeg Effluent

Effect of Organic Loading Rate on BAF Performance

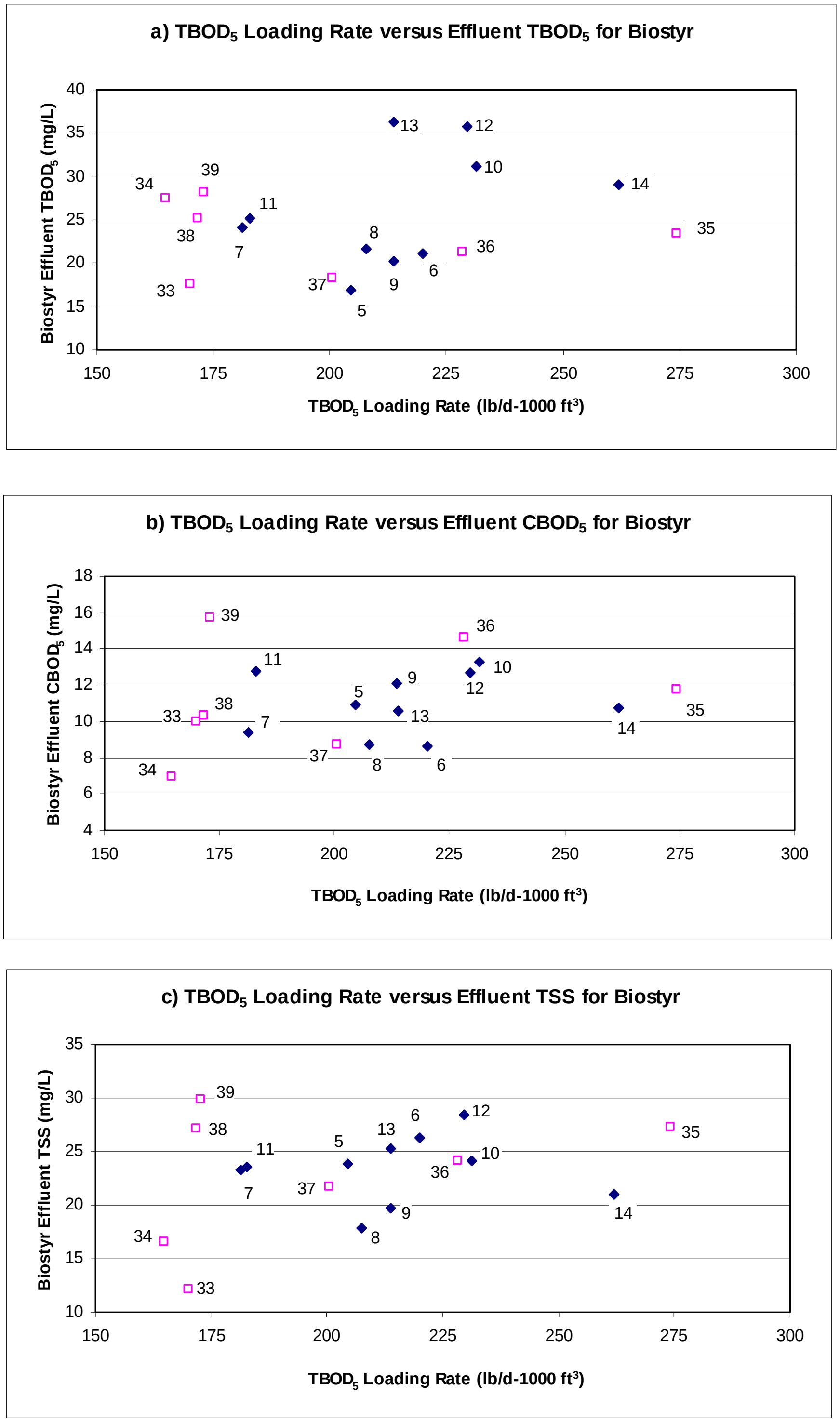
This section discusses the effects of variations in organic loading on BAF performance. The organic loading rates (OLR) observed during the test were not controlled directly during the experiment. In other words, the concentrations of carbonaceous material in the BAF influent was not augmented or supplemented in any way and depended only on the raw wastewater characteristics and removal efficiencies of the upstream treatment processes (i.e., preliminary and primary treatment). Although the hydraulic loading rates were controlled, the feed characteristics were observed to vary widely over the course of the study. The peak week hydraulic and $TBOD_5$ loadings, along with the week in which they occurred, are presented in Table 4.8.

Table 4.8. Peak Hydraulic and $TBOD_5$ Loading Conditions Tested

Loading Characteristic		Biostyr	Biofor-C
Peak week hydraulic loading	Value in gpm/ft^2	3.0	2.8
	Week occurred	35	35
Peak week $TBOD_5$ loading	Value in lb/day-1000 ft^3	279	276
	Week occurred	2	35

Biostyr Performance. Figure 4.18 shows the plots of organic loading (lb $TBOD_5$/day-1000 ft^3) versus each of the Biostyr effluent parameters mentioned above. Part (a) shows the effluent $TBOD_5$ and part (b) shows the effluent $CBOD_5$. In both cases, increased organic loading does not appear to cause an increase in effluent oxygen demand. During the latter part of Week 10, the automatic backwashing controls on the Biostyr failed and it was necessary to manually backwash the filters using approximately the same cycle as programmed for the automatic controller. In addition, the IDI and Krüger teams were instructed to optimize the aeration rates in preparation for off-gas testing. The Krüger team lowered the air flow rate from 2.0 standard cubic feet per minute (scfm) to 1.7 scfm during Weeks 11 and 12. Unfortunately, the Biostyr system appeared to become dissolved oxygen (DO) limited as a result of this adjustment. By the middle of Week 12, the Biostyr appeared to be going septic, as explained previously. The aeration rate was increased back to 2.0 scfm and an aggressive backwash performed to scour off the septic biomass. In Week 13, Biostyr's performance began to improve, although the weekly average $TBOD_5$ was still elevated. The situation appeared to be corrected by Week 14.

Figure 4.18b shows the OLR versus effluent $CBOD_5$ concentration. An increase of effluent $CBOD_5$ concentration was not observed with increasing $TBOD_5$ loading. No consistent trend of Effluent TSS is seen with OLR in Figure 4.18c.



a) $TBOD_5$ Loading Rate versus Effluent $TBOD_5$ for Biostyr

b) $TBOD_5$ Loading Rate versus Effluent $CBOD_5$ for Biostyr

c) $TBOD_5$ Loading Rate versus Effluent TSS for Biostyr

Figure 4.18. Effect of Organic Loading Rate on Effluent $TBOD_5$, $CBOD_5$ and TSS Concentration for Biostyr

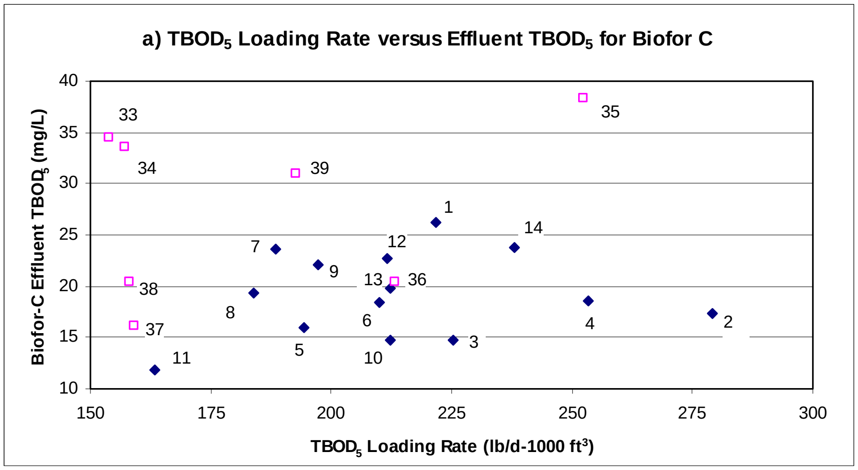
Note: Data presented are weekly averages. Numbers next to data points corresponds to the week of operation.

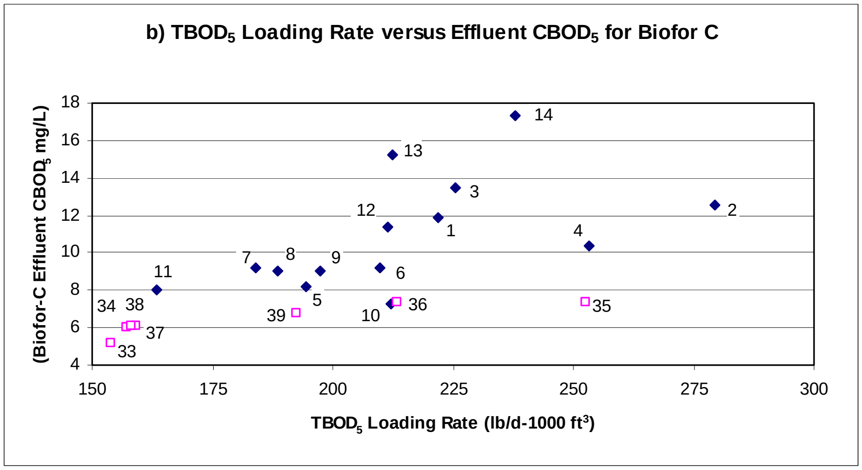
◆ CEPT Effluent ☐ Densadeg Effluent

Biofor-C Performance. The results for Biofor-C were similar to those described above for Biostyr. These results are shown in Figure 4.19, a three-part graph showing the plots of OLR versus each of the Biofor-C effluent parameters (TSS, $TBOD_5$ and $CBOD_5$). Part (a) shows the effect of variation in OLR on effluent $TBOD_5$ and Part (b) shows the effluent $CBOD_5$. In both cases, increased organic loading did not appear to cause an increase in the effluent oxygen demand.

Part (b) of Figure 4.19 shows the OLR versus Biofor-C effluent $CBOD_5$ concentration. The backwashing process configuration was changed in Weeks 13 and 14 such that the backwash supply water to the Biofor-C changed from Biofor-N effluent to Biofor-C effluent. Moreover, the Biofor-N effluent was rich in nitrate from the nitrification occurring in the column, the Biofor-C effluent was not. Weeks after the backwash configuration was changed (Weeks 13 and 14), the effluent $CBOD_5$ concentration was at its highest. It was initially surmised that the practice of backwashing Biofor-C with nitrate-rich Biofor-N effluent provided a biofilm water-chemistry environment that would suppress septic conditions in the biofilm. The reconfiguration may have temporarily upset the microbial environment within the column.

Part (c) of Figure 4.19 shows the OLR versus effluent TSS concentration. An increase of effluent TSS concentration was not observed with increasing $TBOD_5$ loading.





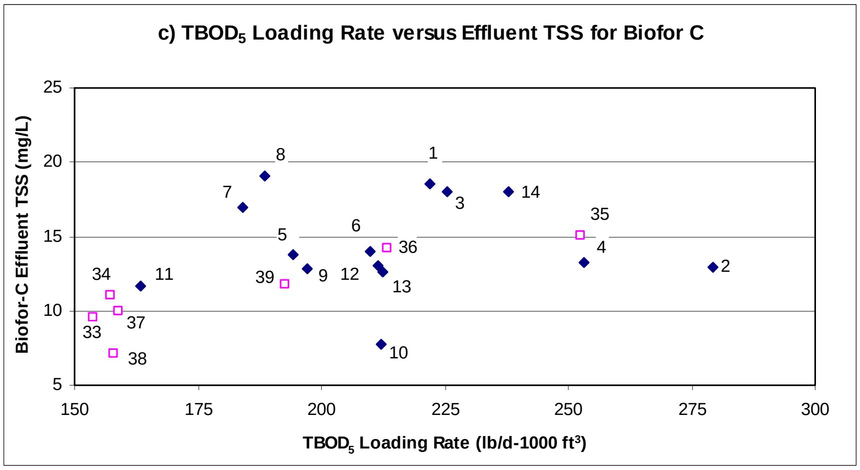


Figure 4.19. Effect of Organic Loading Rate on Effluent TBOD$_5$, CBOD$_5$ and TSS Concentration for Biofor-C

Note: Data presented are weekly averages. Numbers next to data points corresponds to the week of operation.

◆ CEPT Effluent ☐ Densadeg Effluent

Diurnal Organic Concentration Profiles

During Phase I, BAF influent (CEPT effluent) and effluent grab samples were collected over a 24-hour period using an automatic sampler with 12-bottle carousel. These samples were analyzed for $TBOD_5$, soluble BOD_5 ($SBOD_5$), $CBOD_5$ and $SCBOD_5$. The 24-hour profiles generated are discussed below.

Diurnal BAF Influent and Effluent $CBOD_5$ and $SCBOD_5$ Organic Concentration Profiles. Figure 4.20 shows the diurnal profiles of the BAF influent and effluent $CBOD_5$ and $SCBOD_5$; both Biofor-C and Biostyr effluent profiles are shown. The CEPT effluent (i.e., BAF influent) concentrations appeared to go through three distinct phases during the 24-hour period. During the morning hours, the CEPT effluent $CBOD_5$ and $SCBOD_5$ were approximately 65 and 45 mg/L, respectively. Starting about 2:00 pm, the $CBOD_5$ and $SCBOD_5$ began trending upward (a transitional period). From about 7:00 pm to 7:00 am, the $CBOD_5$ and $SCBOD_5$ appeared to be approximately 90 and 63 mg/L, respectively. This pattern is consistent with observations by pilot study staff that influent characteristics appeared to change in a similar fashion during most weekdays. This is noticeable because the concentration of dispersed black colloidal material appears to vary daily.

Figure 4.20 shows that both BAF pilot units appeared to perform well—with respect to $CBOD_5$ and $SCBOD_5$ removal—under all of the influent conditions presented during the diurnal testing with one exception. The Biofor-C effluent $CBOD_5$ appeared to spike from 9 mg/L at 13:00 to 20 mg/L at 15:00. This is considered to be an anomaly since the influent did not exhibit the same spike and the $CBOD_5$ returned to 9 mg/L for the remainder of the diurnal testing.

During the diurnal testing, pilot unit flows were not varied to match the diurnal flows typically experienced at the plant. Instead, the flows going to Biostyr and Biofor-C units were kept constant at the target average flows of 7.45 and 6.3 gpm.

Diurnal BAF Influent and Effluent $TBOD_5$ and $SBOD_5$ Organic Concentration Profiles. Figure 4.21 shows the diurnal profiles of the BAF influent and effluent $TBOD_5$ and $SBOD_5$. Note that both Biofor-C and Biostyr effluent profiles are also shown. Figure 4.21 shows that the CEPT effluent (i.e., BAF influent) concentrations appeared to vary only slightly over the 24-hour period.

Figure 4.21 shows that both BAF pilot units appeared to perform well—with respect to $SBOD_5$ and $SBOD_5$ removal—under all of the influent conditions presented during the diurnal testing with one exception: the 3:00 pm Biofor-C effluent $TBOD_5$ appeared to spike from approximately 15 to 23 mg/L. However, this is not viewed as important given that the following results appear to return to approximately 17 mg/L for the remainder of the diurnal testing.

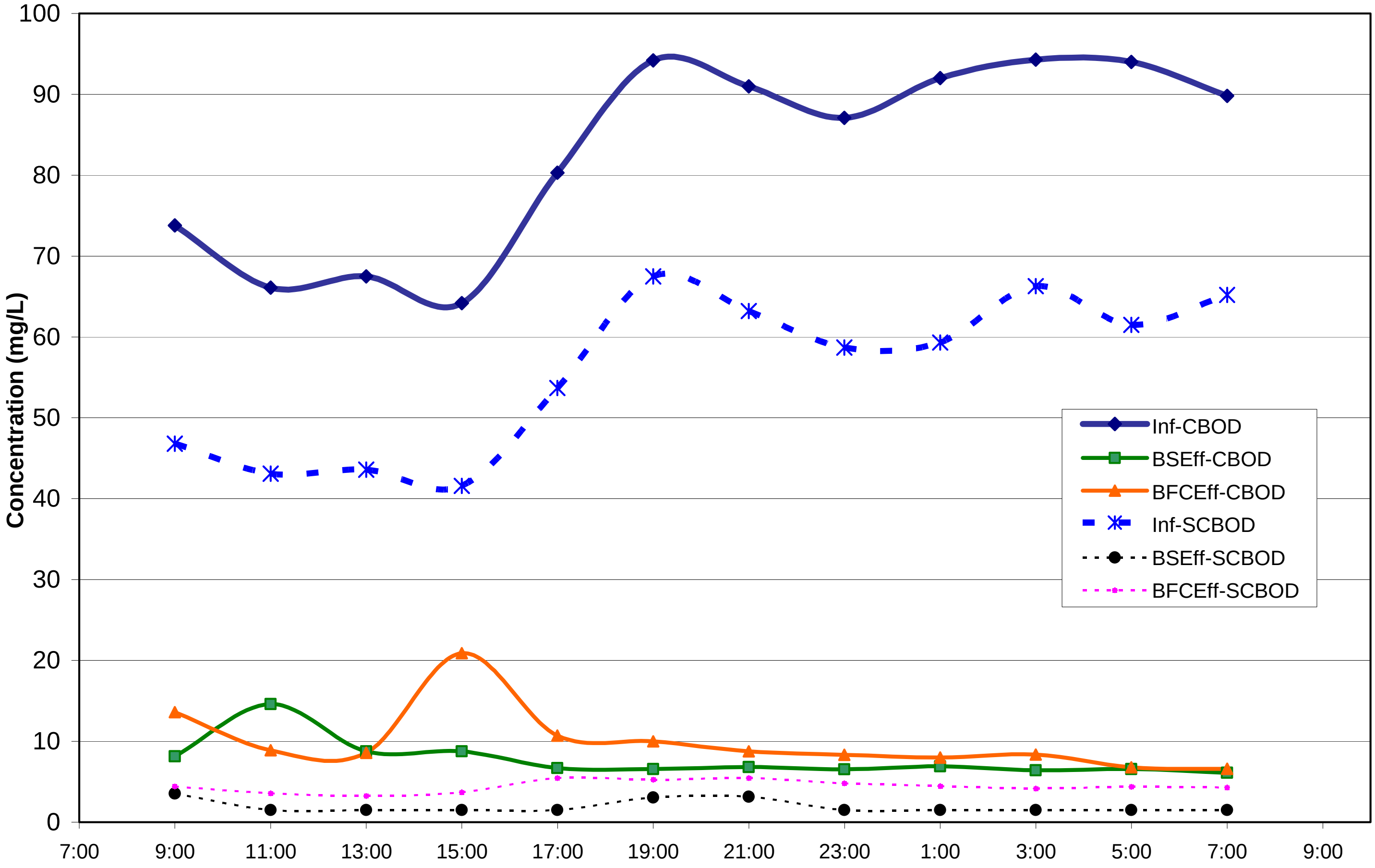


Figure 4.20. Diurnal CBOD$_5$, and SCBOD$_5$, Profile for April 15-16, 2004

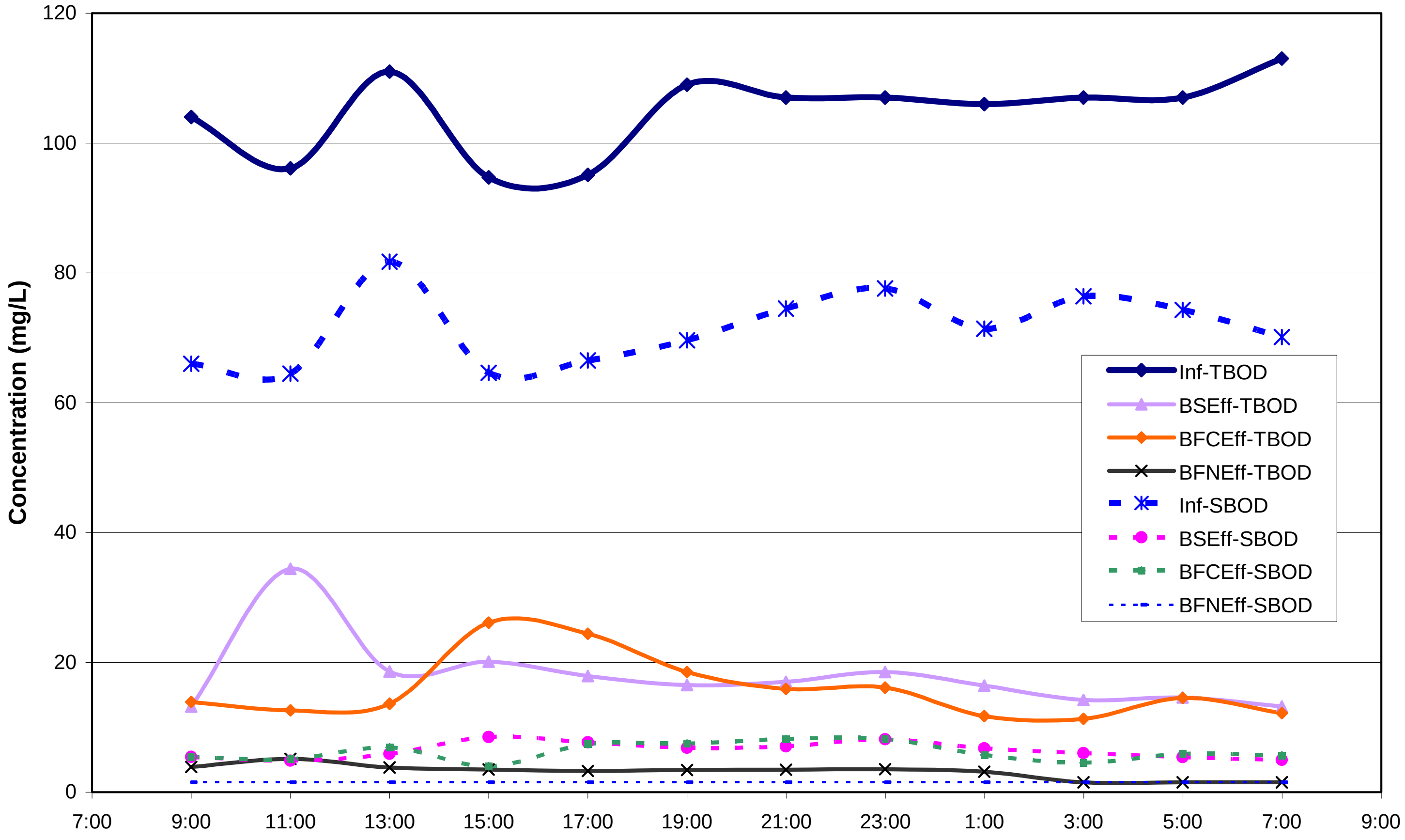


Figure 4.21. Diurnal TBOD$_5$ and SBOD$_5$ Profile for April 22-23, 2004

Backwash – Requirements and Solids Generation Rate

Every other day during the pilot, the backwash flow was diverted to a special tank where it could be collected, mixed (i.e., homogenized), and sampled. Tables 4.9 and 4.10 show the average backwash data derived from the pilot. Average values over the entire study are presented except as noted. Backwash flow and volume values for Biostyr, presented in parenthesis in Table 4.9, denote the average values after Week 12.

The results indicate that more than 90 percent of backwash $TBOD_5$ is particulate BOD_5.

Table 4.9. Spent Backwash Water Quality Based on Pilot Findings in Phase I

		Biostyr Backwash Water Percentile Values		Biofor-C Backwash Water Percentile Values	
Parameter	**Unit**	**50%**	**90%**	**50%**	**90%**
$TBOD_5$	mg/L	423	677	379	594
$SBOD_5$	mg/L	27	39	17	32
COD	mg/L	882	1396	869	1292
SETS	mg/L	32.3	82.6	36	68.2
TS	mg/L	2300	2625	2405	2912
VS	mg/L	802	1066	814	1185
TSS	mg/L	747	1136	738	1076
VSS	mg/L	594	946	580	817

Table 4.10. Spent Backwash Water Quality Based on Pilot Findings in Phase II

		Biostyr Backwash Water Percentile Values		Biofor-C Backwash Water Percentile Values	
Parameter	**Unit**	**50%**	**90%**	**50%**	**90%**
$TBOD_5$	mg/L	235	370	523	770
$SBOD_5$	mg/L	12	21	25	35
COD	mg/L	521	750	967	1430
SETS	mg/L	52	80	58	85
TS	mg/L	2117	2390	2519	3000
VS	mg/L	637	820	900	1200
TSS	mg/L	562	1000	869	1350
VSS	mg/L	430	750	651	1000

Backwash Frequency, Duration, and Volume Generated. Both Biostyr and Biofor-C pilot units normally required backwashing once every 24 hours. This frequency was established by the manufacturers at the beginning of the pilot testing; there was no evidence (such as excessive or reduced pressure buildup within the column) to warrant a change in backwash frequency. The average backwash duration for the Biostyr and Biofor-C were 15 and 68 minutes, respectively. The average volume of backwash generated per backwash cycle (i.e. per day) and the backwash flow as a percent of influent flow are summarized in Table 4.11.

Table 4.11. Daily Average Backwash Volume Generated by BAF Pilot Units

Parameter		Biostyr	Biofor-C
Average daily backwash volume (gallons per backwash event)	Phase I	1,069	704
	Phase II	1,451	741
Average daily volume treated (gallons)	Phase I	10,428	8,888
	Phase II	12,367	9,962
Backwash flow as percent of influent flow (%)	Phase I	10.3	7.9
	Phase II	13.9	7.4

Although both vendors provided preliminary full-scale design proposals (see Appendix B), only Krüger provided an estimate of backwash solids generation and backwash volumes at full-scale. The Krüger estimate for backwash flow was 31 mgd at a maximum month flow condition of 264 mgd. This equates to a backwash flow of 11.7 percent of influent flow. The pilot test results confirmed this estimate.

Air Requirements. Air is required in the BAF process during backwashing to scour or agitate the media. This agitation is necessary to strip off older biofilm and/or inert solids that adsorb onto the biofilm. Air scouring of this type is typically employed intermittently throughout the backwash cycle. In terms of the full-scale system, backwash aeration is not a substantial cost item but its characteristics are important for properly sizing blowers. Table 4.12 compares the average backwash air requirement (air flow per media cross sectional area) measured during the pilot test versus vendor-proposed figures.

Table 4.12. Backwash Air Requirement per Backwash Event

	Air Scour (scfm/ft^2)	
BAF process	Pilot study	Vendor-Proposed Rate
Biostyr	0.81 – 1.06	0.65
Biofor-C	5.09 – 5.20	5.35

The results in Table 4.12 indicate that Krüger underestimated the required backwash air capacity in their preliminary full-scale proposal and IDI overestimated this slightly. On the other hand, the results show that the backwash air capacity required to scour the sunken clay media (Biofor) is roughly five times the capacity required to scour the floating Styrofoam media. This seems to exhibit that the energy required to agitate relatively light Styrofoam may be less than that required for relatively heavy clay.

Solids Generation. This section presents the total solids generation rates that were calculated for the Biostyr and Biofor-C pilot units. The average solids generation rate was calculated for each unit using measurements of daily flow, backwash volume, and associated TSS laboratory analytical results. The raw data on which the solids generations rates are provided in Appendix E. Average total solids yields based on $TBOD_5$ removal were calculated based on the following equation:

$$\text{Total Solids Yield} = (\text{Effluent SS} + \text{Backwash SS})/(\text{Influent TBOD}_5 - \text{Effluent SBOD}_5)$$

The yield calculated by this equation gives total solids generation by the BAF units including solids in the effluent stream. The calculated total solids yield results are given in Table 4.13.

Table 4.13. Average Solids Yield (in lb TSS/lb $TBOD_5$ Removed)

Phase	Biostyr	Biofor-C
Phase I (1)	0.99	0.72
Phase II	1.21	1.15

(1) Phase I values calculated based in Experiment 3 data only. Experiment 1 and 2 backwash volume data were found to be inaccurate.

Daily total solids yield calculations for the Biostyr and Biofor-C pilot units were compared to determine if the observed differences were significant. Backwash solids and influent and effluent $TBOD_5$ were measured on alternating days typically. Daily solids yields were calculated using measured effluent and backwash solids on one day and measured $TBOD_5$ removal on the preceding day. Therefore, a maximum of 27 individual daily yield values could have been calculated for Phase I and 24 values for Phase II.

Figure 4.22 shows a log-normal probability plot for the Phase I. There were sufficient paired data to calculate 21 individual daily yield values for the Biostyr pilot unit and 22 values for the Biofor-C pilot unit. To determine if the two data sets were statistically different, daily average sludge yields for each reactor were calculated. The figure shows that the data sets for each of the two reactors can be described with a log-normal distribution as they tend to fall in a straight line. An unpaired t-test for two samples with unequal variances was used to determine if the difference in mean values (i.e., 50th percentile values) is significant given the variability in the values (i.e., slope of the distribution). The analysis shows that there is a significant difference (alpha < 0.05) between sludge productions for the two reactors.

A similar analysis could not be made for the Phase II data, as there were too few paired data to calculate a significant number of individual daily yield values.

The results shown in Table 4.13 indicate a substantial increase in solids yield from Phase I to Phase II for each pilot unit. In addition, the calculated Phase II solids yield values are greater than 1 pound TSS per pound of $TBOD_5$ removed, a value typically expected for advanced secondary treatment biological systems operated at relative short solids residence times. This result has led BC to a careful review the methods and calculations used to derive the yield values. Possible sources of error include:

- Volume calculations of spent backwash water
- Error in influent flow measurement

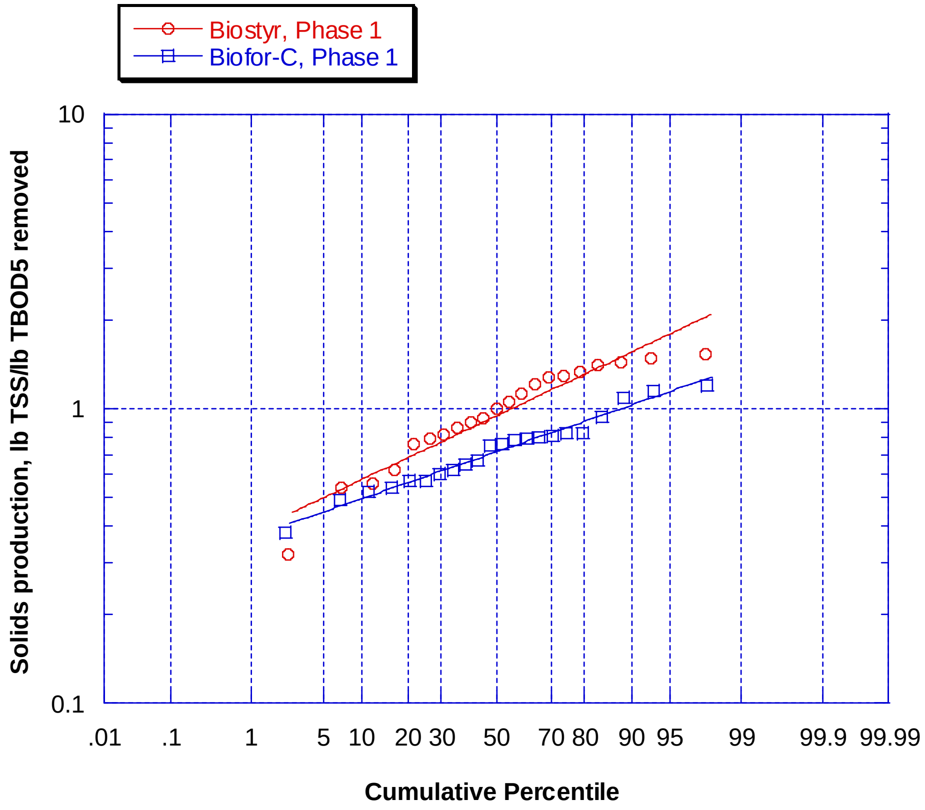


Figure 4.22. Phase I -Log Normal Probability Plots for Biostyr and Biofor-C Total Solids Production Data

The values reported in Table 4.13 are considered to be correct (measurement and analytical procedures and calculations were carefully reviewed; no errors were found that would explain the high solids yield values).

As a check on the data from each pilot unit in each phase, an inert suspended solids (ISS) balance was calculated across the BAF. ISS is the difference between the total and volatile suspended solids. Influent and effluent ISS should balance, unless the wastewater characteristics and processes within the BAF are generating inert solids. The ISS mass balance results showed that in both systems, more inert solids were exiting the columns than entering indicating an inert solids production in the BAF process. The average ISS produced was calculated for each pilot unit in each phase using the average of the minimum and maximum backwash solids and is summarized in Table 4.14.

Table 4.14. Estimated ISS Production for the Biostyr and Biofor-C Columns

Phase	Average ISS Produced, mg/L	
	Biostyr	Biofor-C
I	4.6	1.7
II	4.5	1.5

As backwash solids were measured every other day typically, a maximum and minimum effluent ISS range was calculated assuming the unmeasured backwash solids were equal to the maximum or minimum of the adjacent measured values. The calculated ISS balance showed that both units generated ISS, within the range of assumed backwash solids, and that the Biostyr pilot unit generated more ISS than the Biofor-C pilot unit.

The solids yield and ISS results presented above raise the following questions:

- Why were the resulting BAF solids yields high relative to other advanced biological treatment processes for $CBOD_5$ removal?
- Why were the solids yields for the two pilot units different?
- What caused the solids yields of both units to increase from Phase I to Phase II, and why was the Biofor-C increase proportionally higher than the Biostyr?

The results of this study do not answer these questions fully and more research would be required to address the unknowns completely. However, one probable cause for the difference in calculated solids yields between the two pilot units derives from the differing backwash methods for the two BAFs. Krueger finds that with their media they need to include several mini-backwashes between their regular backwash to clear accumulated influent solids from the first few inches of the column. There is no parallel to this for the Biofor-C unit. It is our interpretation that this influent material that does not penetrate the Biostyr column is not biodegraded, but it is recorded as backwash solids. Further, the "true influent" to the BAF is therefore less than the measured CEPT or Densadeg effluent $TBOD_5$, since some of this material is filtered out by the lower media layers of the Biostyr unit and is then sent directly to the backwash storage tank. The impact of this effect can be examined by means of the yield calculation as shown in the following equation:

$$\text{Total Solids Yield} = (\text{Effluent SS} + \text{Backwash SS})/(\text{Influent TBOD}_5 - \text{Effluent SBOD}_5)$$

In the equation above, the backwash SS for the Biostyr unit is increased by the influent solids that are trapped in the media and sent to the backwash tank via the several mini-backwash steps. These solids do not have the opportunity to be biodegraded in the Biostyr unit. Also, in the equation above, part of the measured influent $TBOD_5$ is not degraded in the BAF (and is sent to the backwash tank). If it were possible to distinguish between biological and influent solids, as well as measure the true influent to the Biostyr unit (after separation of filtered influent solids), then it is likely that the measured yield values for the BOD_5 treated in the two BAFs would be the same.

In addition, the apparent inert solids production might be caused by precipitation of oxidized iron salts in the BAF column. Moreover, it was postulated that the chemical doses used when operating the Densadeg in Phase II, which were substantially higher than doses typical of normal operations at the PLWTP (discussed in Section 5), might also explain the increase in solids yield observed from Phase I to Phase II. The increased iron could have led to increased precipitation of insoluble iron oxides in the BAF pilot units. The polymer dose during Phase II was increased by as much as a factor of 10. This could have resulted in flocculation of colloidal iron sulfides that were then measured as effluent suspended solids. To evaluate the influence of iron precipitation on BAF solids yield, consider that 160.6 mg of $FeCl_3$ produces 106.6 mg of $Fe(OH)_3$ sludge or 0.66 lb/lb. (Expressed on an iron basis, 55.6 mg of Fe produces 106.6 mg of $Fe(OH)_3$ sludge, or 1.92 lb/lb). However, from the ISS balance results shown Table 4.14, it appears that the Biofor-C difference is not due to a greater degree of iron oxidation/precipitation, as the average ISS increase across Biofor-C pilot unit does not change significantly between Phases I and II. Therefore, while iron precipitation is likely a substantial contributing factor to the higher than expected BAF solids yields in general, it does not explain the increase in calculated solids yield from Phase I to Phase II.

The effect of nitrifier growth on the solids yield was also considered. The average Biostyr ammonia removal was 13.5% in Phase I and 13.8% in Phase II - not a significant difference. The average Biofor-C ammonia removal increased from 8.4% in Phase I to 41.4% in Phase II. The Phase II Biofor-C removal corresponds to an absolute removal of 10.9 mg/L as N. Assuming a nitrifier yield of 0.3 lb VSS/lb NH_3-N removed (the high end of the range reported for (suspended growth) nitrification in the literature), this corresponds to an additional 3.3 mg/L VSS, or a cumulative total of 13.1 lb VSS over Phase II. This cumulative total is approximately 5.1% of the Phase II Biofor-C average cumulative VSS production of 256 lb. However, the calculated Biofor-C solids yield increased approximately 53% between Phase I and Phase II. Consequently, the nitrifier growth may have been one of several contributing factors, but it was not enough to explain the whole of the increased Biofor-C yield in Phases II.

Given the discussion above, more research is required before the various contributing factors to the solids yields can be identified and fully explained. In the mean time, the City should consider the yield values as conservative and suitable for preliminary design and cost estimation purposes until the questions above can be answered with greater certainty through addition research.

Based on the average solids yields shown in Table 4.13, full-scale Biostyr and Biofor-C sludge production at average annual daily flow conditions was calculated. This calculation was based on the following values:

- Average annual daily flow is 240 mgd.
- Average influent $TBOD_5$ concentration is 96 mg/L.
- Average effluent $SBOD_5$ concentration is 9.1 mg/L (Phase I) and 5.1 mg/L (Phase II) for Biostyr and 10.4 mg/L (Phase I) and 10.6 mg/L (Phase II) for Biofor-C, based on pilot unit performance.

- Average effluent TSS concentration is 22.6 mg/L (Phase I) and 27.3 mg/L (Phase II) for Biostyr and 14.0 mg/L (Phase I) and 13.6 mg/L (Phase II) for Biofor-C, based on pilot unit performance.

- Solids yields presented in Table 4.13 for both Phase I and Phase II.

Daily sludge production rates for estimating the sludge processing needs was calculated by only accounting solids in the backwash water. In other words, solids in the BAF effluent were subtracted from the total solids generation to estimate the sludge amount that needs to be processed further. The resulting estimated full-scale average sludge mass flows for each unit are summarized in Table 4.15. Even though the solids yield for Biofor-C is less than that for Biostyr, the Phase II sludge production for Biofor-C is greater because of the higher effluent TSS concentration for Biostyr (i.e., more of the solids generated are going out in the BAF effluent).

Table 4.15. Estimated Full-Scale Daily Solids Production for Further Sludge Processing Needs

	Full-Scale Solids Production Rate (lb/d)	
	Biostyr	Biofor-C
Phase I	127,000	95,300
Phase II	165,500	169,400

Based on Phase I and Phase II Solids Yield Estimates

Settleability of BAF Solids. The settleability of the BAF solids was characterized during the study using Imhoff cones. In addition, a dissolved air flotation thickener (DAFT) bench-scale system was used to assess how readily the BAF backwash solids could be thickened. The results of the Imhoff cone experiments are discussed below; the DAFT sludge thickening experiments are discussed in a subsequent section.

Figure 4.23. Photo of Sample Settling in Imhoff Cone

The sludge volume index (SVI) was calculated for BAF backwash solids and the resulting SVI values are summarized in Tables 4.16 and 4.17 for Phase I and Phase II, respectively. SVI values less than 100 indicate the settled material can form a dense sludge that can be easily separated from the bulk fluid. On the other hand, SVIs greater than 120 are indicative of thin sludges that may not be easily separable from the bulk fluid. As shown in Tables 4.16 and 4.17, on the average (i.e., at 50 percentile), solids generated by the Biostyr and Biofor-C form an easily separated dense sludge in the Imhoff cone (allowed to settle for 30 minutes).

A marked increase in the average SVI occurred between Phase I and II; this can be seen by comparing the results in Table 4.16 with those in Table 4.17. The difference is most striking for the Biostyr process which went from an average SVI of 30 in Phase I to an average SVI of 93 in Phase II. The use of the effluent from the Densadeg instead of the PLWTP CEPT was the only difference between Phase I and Phase II pilot operation may be the cause in changes observed in the backwash solids characteristics. The increase in SVI could be linked to the different polymer type and the higher chemical doses applied when using Densadeg.

The CEPT uses anionic polymer while the Densadeg used a low molecular weight cationic polymer. In addition, the polymer dose for the Densadeg was approximately 10 times greater than for the existing CEPT. The ferric chloride dosage was also over 30% higher when Densadeg was used. This change in BAF influent water chemistry may change backwash solids particle surface charge and flocculation properties. Of the two BAF units, the Biostyr appear to be more sensitive to this change in primary effluent quality. The SVI for the Biofor-C also increased from Phase I to Phase II; however, the increase was not as severe as for the Biostyr.

Table 4.16. BAF Backwash Solids SVI Values in Phase I

	Percentile		
	50%	90%	
Unit	SVI Values		Data Collected in
Biostyr	30	56	Week 5-14
Biofor-C	36	52	Week 5-11

Table 4.17. BAF Backwash Solids SVI Values in Phase II

	Percentile		
	50%	90%	
Unit	SVI Values		Data Collected in
Biostyr	93	140	Week 33-39
Biofor-C	67	95	Week 33-39

In addition to SVI, other important solids handling parameters are the supernatant quality and the backwash sludge solids content. To evaluate these, the sludge and supernatant from the Imhoff cone experiments were separated and analyzed. The results of these experiments are presented in Table 4.18 and 4.19 for Phase I and Phase II, respectively. Note that $TBOD_5$ was used in Phase I to measure the supernatant effluent oxygen demand while $CBOD_5$ was used in Phase II. By comparing the Phase I results shown in Table 4.18 with the Phase II results shown in Table 4.19, the following observations can be made:

- The average $TBOD_5$ values were roughly 2 and ½ times greater than the $CBOD_5$ values. In general, the difference between $TBOD_5$ and $CBOD_5$ is cause by nitrogenous oxygen demand.

- The supernatant TSS appeared to be similar between the two phases.

- The sludge density, measured as total solids (TS) content, varied between 0.5 to 2.3 percent (on average) in the case of the Biostyr and 0.5 to 1.5 percent for the Biofor-C.

- The backwash sludge densities decreased from Phase I to Phase II for both BAF pilot units. This confirms the changes in SVI described above and indicates a thinner and, perhaps, less easily separable sludge particles were produced by the BAFs during Phase II.

- The volatile solids (VS) content of the backwash solids decreased substantially between Phase I and Phase II. This would suggest greater loading of inert solids to the BAF units during Phase II than in Phase I. The lower VS content of the backwash solids produced during Phase II is perhaps connected to the higher ferric dose used for the Densadeg during Phase II.

Table 4.18. Backwash Supernatant and Solid Quality Data for Phase I

Parameter	Unit	Biostyr Backwash Percentile Values 10%	Biostyr Backwash Percentile Values 50%	Biofor-C Backwash Percentile Values 10%	Biofor-C Backwash Percentile Values 50%
Backwash Supernatant					
$TBOD_5$	mg/L	85	111	116	151
TSS	mg/L	115	166	165	198
VSS	mg/L	93	143	133	167
Backwash Solids					
TS	(%WT)	1.2	2.3	0.8	1.5
VS	(%TS)	72	75	67	72

Table 4.19. Backwash Supernatant and Solid Quality Data for Phase II

Parameter	Unit	Biostyr Backwash Percentile Values 10%	Biostyr Backwash Percentile Values 50%	Biofor-C Backwash Percentile Values 10%	Biofor-C Backwash Percentile Values 50%
Backwash Supernatant					
$CBOD_5$	mg/L	28	42	26	55
TSS	mg/L	85	150	85	213
VSS	mg/L	63	115	50	173
Backwash Solids					
TS	(%WT)	0.50	0.72	0.50	0.97
VS	(%WT)	53	59	60	65

Thickening BAF Backwash Water

A major consideration with the BAF process is the processing of the solids produced. Adequate separation of these solids from the bulk backwash fluid is required to minimize the size of the anaerobic digesters. An earlier study by Brown and Caldwell indicated that the PLWTP would need to thicken the digester feed sludge to at least 5.6 percent TS content to avoid the construction of additional digesters at the PLWTP. This estimate considered processing both BAF and primary sludge at wastewater flows projected for the buildout. The buildout annual average flow for the plant is 240 mgd compared to the 2004 annual average flow of approximately 173 mgd.

Dissolved air flotation thickening (DAFT) is a process widely used in municipal wastewater plants that is expected to be fully capable of producing the desired sludge thickness. As discussed in Section 1, a bench scale DAFT unit was used to evaluate the floatability of the two types of sludges, the thickness of the sludge blanket, the sludge rise rate, and the percent solids recovery. The evaluation was performed under batch conditions and designed to determine the feasibility of using flotation as a thickening process; it was not focused on deriving a set of design criteria. A larger pilot test unit must be run to obtain design-related parameters.

Two thickening experiments were performed to determine the polymer type and dose requirements, optimum recycle ratio and air to solids ratio. The experiments were as follows:

- Thickening of the BAF backwash solids alone (i.e., dedicated thickening of BAF backwash solids); and
- Thickening of the BAF backwash mixed with primary solids (i.e., co-thickening of BAF and primary solids).

The polymer dose requirements were established using jar testing in combination with the DAFT. The jar test data is provided in Appendix G. Three polymers were tested: one low-molecular weight cationic, one high molecular weight cationic, and one low molecular weight anionic polymer. For both the dedicated BAF and co-thickening experiments, the jar testing indicated that the low molecular weight cationic polymer (Nalco Optimer 7128) was superior for floc formation and for producing a clear subnatant. Note that for determining design parameters for the preliminary design, it is recommended that a more extensive jar testing be performed.

Another important operational factor for the DAFT process is the recycle ratio. The recycle ratio (recycle flow to influent flow) was varied to arrive at the optimum ratio for the bench-scale DAFT unit. The recycle ratio trial data for each experiment is included in Appendix G. The results of the DAFT testing are discussed for each of the two thickening experiments below.

Dedicated Thickening of BAF Backwash Solids. The polymer dose was determined by jar testing and the required recycle ratio was determined through trial and error, using a minimum A/S ratio of 0.04. The selected polymer dose was 1.5 mg/L as active polymer.

For the BAF backwash, very low recycle ratios (lower than allowable for conventional practice) were observed to be effective in floating the solids. Appreciable differences in the rise rates were not observed using recycle ratios of 0.10, 0.17, 0.33, and 0.50 (calculations of the recycle ratios are provided in Appendix G). The optimum recycle ratio was determined to be about 0.5. Photographs of the bench-scale DAFT unit with the thickened BAF backwash solids is shown in Figure 4.24

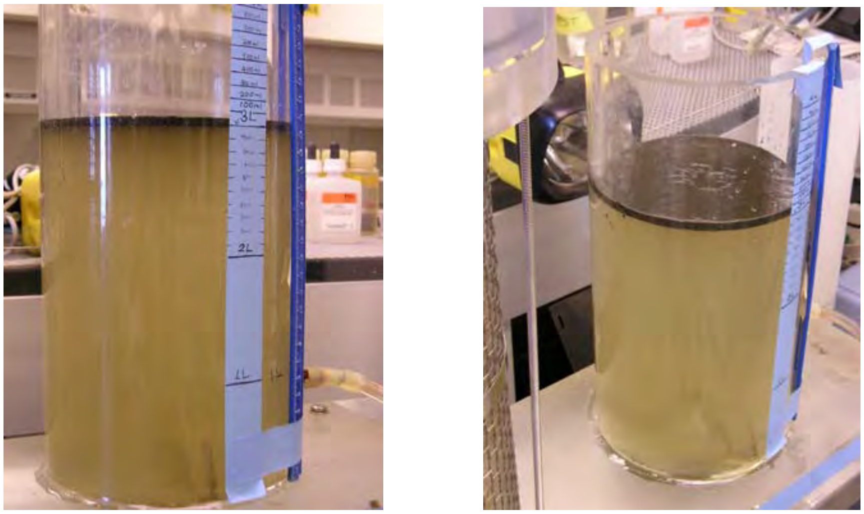


Figure 4.24. DAFT Bench-scale Unit With BAF Backwash

Three DAFT trials were run at the polymer dose and recycle ratio stated above. In each case the sludge rise rate was estimated to be approximately 0.5 inches per second. In addition, the following parameters were determined for each trial:

- Influent turbidity
- Influent TSS
- Influent $CBOD_5$
- Subnatant turbidity
- Subnatant TSS
- Subnatant $CBOD_5$
- Sludge TS content
- Sludge VS content
- Solids removal efficiency

The results of the three trials are summarized in Table 4.20.

Table 4.20. Summary of DAFT Trials for Dedicated BAF Backwash Thickening

Parameter	Trial 1	Trial 2	Trial 3	Average
Influent turbidity (a) (NTU)				400
Influent TSS (a) (mg/L)				640
Influent $CBOD_5$ (a) (mg/L)				40
Subnatant turbidity (NTU)	43.5	35.3	39.1	39.3
Subnatant TSS (mg/L)	59.8	55.0	54.4	56.4
Subnatant $CBOD_5$ (mg/L)	20.4	19.1	18.9	19.5
Sludge TS content (percent by weight)	3.66	NS (b)	3.54	3.60
Sludge VS content (percent of TS)	73.5	NS (b)	71.4	72.5
Approximate solids removal efficiency (percent)	90.7	91.4	91.5	91.2

(a) The influent BAF backwash for each trial was taken from the same sample
(b) NS = Not sampled

These results indicate the following:

- The sludge removal efficiency was typical for DAFT systems (90 – 95 percent).
- Sludge TS content obtained in the three trials was substantially lower than the 5.6 percent required to avoid construction of new digesters at PLWTP.
- To achieve a combined primary and BAF sludge TS content of 5.6 percent, the primary sludge would need to be thickened to 7.1 percent prior to mixing with the DAFT-thickened solids.
- More analysis is required to either confirm or rule out the feasibility of dedicated DAFT thickening of BAF backwash for PLWTP.

Co-thickening of the Blended Primary Sludge and BAF Backwash Water. For the co-thickening experiment, a mixture of BAF backwash with primary sludge obtained from the existing CEPT was prepared. The primary sludge and BAF backwash were blended at the ratio expected for a full-scale system. This was estimated to be 2.6 pounds primary solids per pound of BAF solids. Jar testing for polymer dosage and preliminary trials to determine the recycle ratio were repeated as described above. The selected polymer dose was 3.0 mg/L as active polymer. The selected recycle ratio was 1.5 based on the minimum A/S ratio of 0.04. Jar test trial data are provided in Appendix G. Photographs of the bench-scale DAFT unit with the thickened co-thickened solids is shown in Figure 4.25

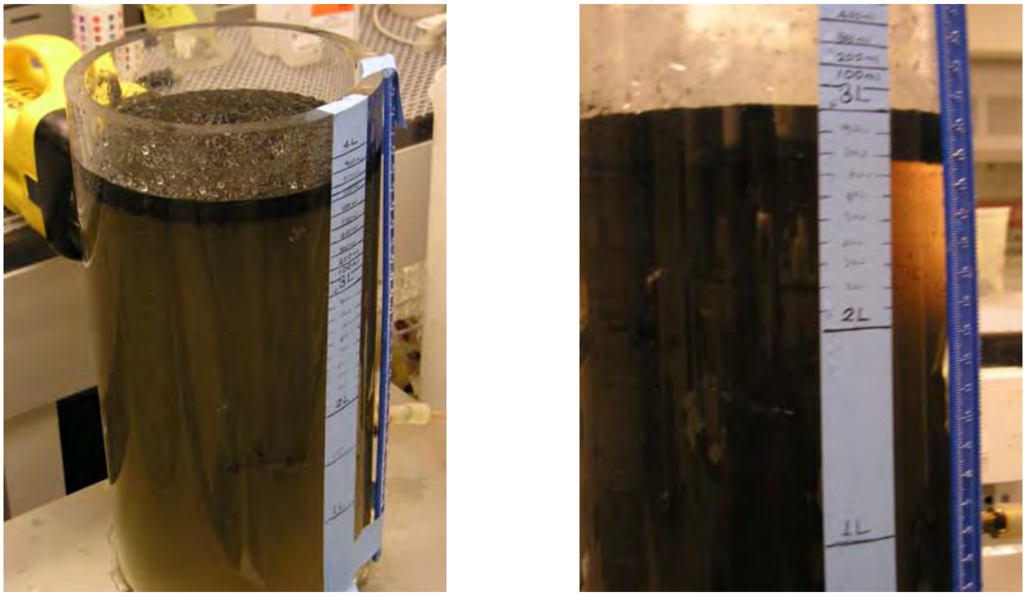


Figure 4.25. DAFT Bench-scale Unit BAF Backwash/Primary Sludge Mixture

Three DAFT trials were run at the polymer dose and recycle ratio stated above. In each case the sludge rise rate was estimated to approximately 0.5 inches per second for each trial. The same parameters as listed above for the dedicated BAF backwash thickening experiment were determined for the co-thickening experiment. The results are summarized in Table 4.21.

Table 4.21. Summary of DAFT Trials for Co-Thickening of BAF Backwash and CEPT Sludge

Parameter	Trial 1	Trial 2	Trial 3	Average
Influent turbidity (a) (NTU)				>999
Influent TSS (a) (mg/L)				1790
Influent CBOD$_5$ (a) (mg/L)				ND(b)
Subnatant turbidity (NTU)	99.1	104	95.1	99.4
Subnatant TSS (mg/L)	114	122	102	113
Subnatant CBOD$_5$ (mg/L)	32.6	<60	36.7	ND(b)
Sludge TS content (percent by weight)	5.46	5.94	5.30	5.56
Sludge VS content (percent of TS)	77.9	76.6	78.4	77.6
Approximate solids removal efficiency (percent)	93.6	93.2	94.3	93.7

(a) The influent BAF backwash for each trial was taken from the same sample
(b) ND = Not determined

These results indicate the following:

- The sludge removal efficiency was typical for DAFT systems (90 – 95 percent).
- Sludge TS content obtained in the three trials was marginally in the range needed (i.e., 5.6 percent on average) to avoid construction of new digesters at PLWTP.

A major consideration for full-scale application of DAFT or some other type of thickening process is the clarified stream that is produced. This consideration is explored below.

Thickening Process Recycle Stream Management. In a full scale BAF system, it may be possible to manage the recycle stream from the solids thickening operation by commingling it with effluent for ocean disposal. The regulatory status of this scheme is uncertain; it would require an evaluation and interpretation by the EPA as it relates to the permit standards. If the recycle stream cannot be blended according to the EPA, it would need to be recycled back to the PLWTP CEPT influent tunnel downstream of the existing headworks and grit removal facilities. Otherwise, the recycle stream can be discharged directly to the ocean along with the BAF effluent, thus reducing the hydraulic impact to the clarification and BAF system.

The characteristics of the underflow from the DAFT experiments were used to approximate the results of commingling the recycle stream with the BAF effluent. Table 4.22 shows results for the dedicated BAF thickening option described above. In this case, the effluent TSS and $CBOD_5$ of the underflow were below the 30-day average permit limits for these parameters, but the combined Biostyr effluent quality was very close to the TSS limit.

Table 4.22. Assessment of Thickening Process Recycle Stream Management Assuming Dedicated BAF Backwash Thickening

BAF Unit	Effluent Quality Before Thickening Process Recycle Stream Addition (mg/L)	Effluent Quality After Thickening Process Recycle Stream Addition (mg/L)	Effluent 30-d Discharge Limits (mg/L)
Biostyr	$CBOD_5$= 10 TSS= 23	$CBOD_5$= 12 TSS= 29	$CBOD_5$= 25 TSS= 30
Biofor-C	$CBOD_5$= 7.5 TSS= 13	$CBOD_5$= 9 TSS= 17	

Table 4.23 shows the anticipated results of commingling the thickening recycle stream with BAF effluent assuming the co-thickening option described above is used for combined primary and BAF solids thickening.

Table 4.23. Assessment of Thickening Process Recycle Stream Management Assuming Co-Thickening of BAF Backwash and PLWTP CEPT Sludge

BAF Unit	Effluent Quality Before Thickening Process Recycle Stream Addition (mg/L)	Effluent Quality After Thickening Process Recycle Stream Addition (mg/L)	Effluent 30-d Discharge Limits (mg/L)
Biostyr	$CBOD_5$= 10 TSS= 23	$CBOD_5$= 15 TSS= 39	$CBOD_5$= 25 TSS= 30
Biofor-C	$CBOD_5$= 7.5 TSS= 13	$CBOD_5$= 11 TSS= 24	

The mass balance results shown in Table 4.23 show the following:

- Biostyr effluent quality is not adequate to absorb the recycle stream solids and reliably meet anticipated TSS effluent limit.
- Although it might be possible to manage the recycle stream from co-thickening by commingling with secondary effluent for ocean discharge, the margin of error is greater than was seen with the dedicated thickening experiment. This will likely mean that thickener underflow will have to be redirected to the plant influent for reprocessing.
- High rate filters can be used to remove solids from the recycle stream to improve the feasibility of adding the recycle stream to the BAF effluent for direct discharge to the ocean.

BAF Oxygen Transfer Efficiency (OTE), Aeration and Power Requirements

In mid-December 2004, off-gas testing of the two BAF pilot columns was conducted by Dr. Michael Stenstrom of UCLA to determine the OTE of each column under a variety of influent and air flows. The resulting off-gas test report by Dr. Stenstrom is provided in Appendix F. The off-gas testing data from the December 13 and 14 testing were analyzed to evaluate differences in oxygen transfer efficiency for each of the BAF pilot units and to estimate aeration air requirements for a full-scale installation. These data include nine runs at three different airflow rates in the Biofor-C pilot unit and 18 runs at four different airflow rates in the Biostyr unit. Standardized techniques have been developed to analyze clean water and process water oxygen transfer with fine-pore aeration systems in well-mixed aeration tanks (ASCE Standard: Measurement of Oxygen Transfer Efficiency in Clean Water, ANSI/ASCE 2-91; ASCE Standard: Standard Guidelines for In-Process Oxygen Transfer Testing, ASCE 18-96). However, these analytical techniques could not be used for the off-gas testing data because of differences between a well-mixed aeration tank that is part of an activated sludge system and a BAF. The process oxygen demand (i.e., oxygen uptake rate) is relatively constant throughout the aeration tank depth for an activated sludge process while it varies with depth throughout a BAF as a result of the difference in hydraulic regime between the two systems (relatively completely mixed for the activated sludge process versus plug flow for the BAF).

OTE. Differences in OTE between the two pilot units were evaluated by normalizing the off-gas testing data to account for airflow rate and pilot unit column diameter, temperature, and effluent DO concentration. The airflow rate (scfm) for each run was divided by the appropriate pilot unit cross sectional area (ft^2) to calculate a specific airflow rate ($scfm/ft^2$). The measured OTE for each run was adjusted by temperature and effluent DO concentration to calculate a "normalized" OTE that could be compared against those from the other runs. The measured OTE was normalized to 20 degrees C using the following relationship:

$$\text{Temperature factor} = \theta^{(T-20)}$$

where = 1.024 and T = test temperature (degrees C).

The measured OTE was normalized to a DO concentration of 0.0 mg/L using the following relationship:

$$\text{DO gradient factor} = \frac{\left(\beta C^* - DO\right)}{C^*}$$

$$C^* = C^*_{20} \cdot \frac{51.6}{\left(31.6 + T\right)}$$

where = 0.95; C^* = DO saturation concentration at test temperature, T; DO = test effluent DO concentration; and C^*_{20} = DO saturation concentration at 20 degrees C, 9.07 mg/L.

A normalized OTE was calculated from the measured OTE using the following relationship:

Normalized OTE = OTE/(Temperature factor * DO gradient factor).

Note that the normalized OTE is not the same as standard oxygen transfer efficiency (SOTE) that is defined for well-mixed aeration tanks, but represents a basis for relative comparison of the measured off-gas test data.

The normalized OTE for each of the 27 runs is plotted as a function of specific airflow in Figure 4.26. This figure shows that the normalized OTEs are equivalent for the two pilot units for specific airflows between 0.4 and 1.1 $scfm/ft^2$. (Five runs were conducted using the Biofor-C pilot unit at a specific airflow of 2.3 $scfm/ft^2$. However, the specific airflow rate for these runs appears to be beyond the typical operating range and the results are not included in this analysis.) A curve was fit to the data to describe normalized OTE as a function of specific airflow.

Full-scale design OTE values for Biofor-C and Biostyr were calculated based on maximum month design conditions and information from the December 12, 2003 IDI and November 21, 2003 Krüger proposals. The minimum design temperature of 21.8 degrees C was used to calculate the temperature factor and C values. The target effluent DO concentrations for Biofor-C and Biostyr were not specified in the proposals, so the average effluent DO concentration of 4.7 mg/L measured during the 27 runs was used to calculate the DO gradient factor. The full-scale OTE was calculated as a function of specific airflow and is shown in Figure 4.27.

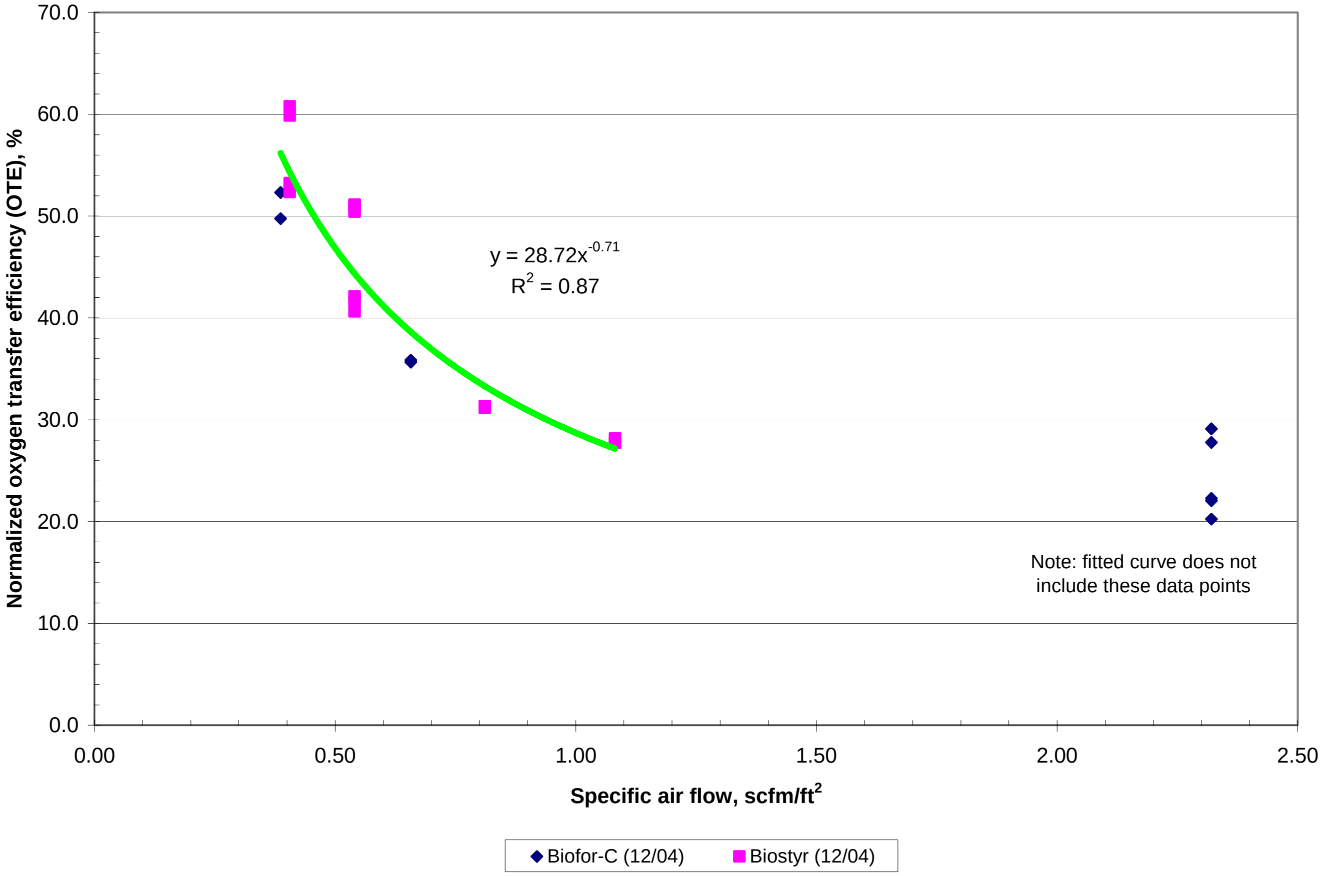


Figure 4.26. Normalized Off-Gas Testing Data

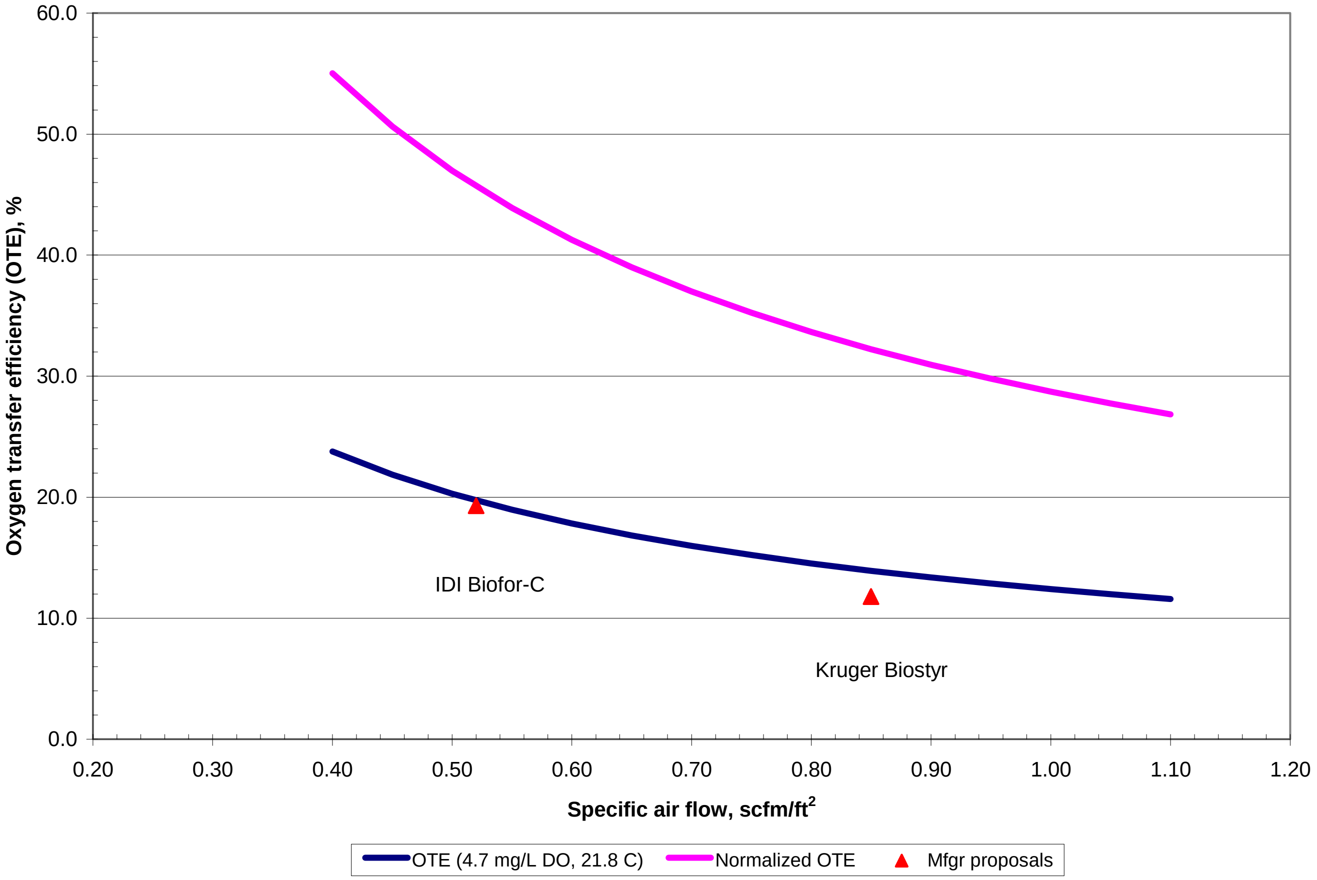


Figure 4.27. Design Oxygen Transfer Efficiency

The full-scale design OTE curve shown in Figure 4.27 agrees with OTE values calculated using information from the IDI and Krüger proposals. OTE values for each manufacturer were calculated using the proposed full-scale aeration airflow, proposed BAF surface area, and the maximum month $TBOD_5$ loading of 255,400 lb/d. An oxygen demand of 1.0 lb oxygen/lb $TBOD_5$ was assumed to calculate the full-scale OTE value. Figure 4.27 shows that the calculated OTE values for the full-scale Biofor-C and Biostyr units agree with the OTE curve calculated from the off-gas tests. This indicates that the full-scale aeration airflow reported in each proposal are reasonable for maximum month requirements, but maximum day and maximum hour requirements will need to be evaluated during preliminary design. The estimation of full-scale aeration and power requirements is described below.

Estimation of Full-Scale Aeration and Power Requirements. The design oxygen transfer efficiencies estimated (based on off-gas test results and described above) were then used to re-evaluate the aeration requirements for the proposed Biostyr and Biofor- full-scale BAF facilities. Calculations used to re-evaluate the aeration requirements are provided in Appendix H. The design conditions used were the same as in the respective proposals (See Appendix B). These design assumptions are summarized as follows:

- Biofor-C specific process air flow = 0.52 $scfm/ft^2$ (estimated based on proposal design information in Appendix B)
- Biostyr specific process air flow = 0.85 $scfm/ft^2$ (estimated based on proposal design information in Appendix B)
- Flow = 264 mgd
- BAF Influent $TBOD_5$ concentration = 116 mg/L
- Temperature = 22 ^{O}C (71.6 ^{O}F)
- Diffuser submergence depth = 20 ft. (note this was not given in either proposal and was assumed)
- Inlet filter pressure loss = 0.3 psi.
- Maximum month peaking factor for oxygen demand = 0.3 (based on the ratio of peak month to average organic loading)
- Cost of power = 11¢ per kWh

The resultant aeration requirements and power costs and a comparison with those proposed by the BAF manufacturers are provided in Table 4.24. The results confirm the aeration estimates by the manufacturers. Also presented in Table 4.24 is the annual power cost for backwash air requirement, and power cost for total air requirement. The design assumptions for backwash air requirement are summarized as follows:

- Biofor-C specific backwash air flow = 0.94 scfm/ft^2 (average of field measurements listed in Table 4.12)
- Biostyr specific backwash air flow = 5.15 scfm/ft^2 (average of field measurements listed in Table 4.12)
- Biostyr air scour blower capacity = 2427 scfm (10 units per blower)
- Biofor-C air scour blower capacity = 8307 scfm (8 units per blower)
- Biostyr air scour run time per backwash =4 min
- Biofor-C air scour run per backwash =15 min
- Backwash frequency is once every 24-hrs
- Cost of power = 11¢ per kWh

Table 4.24. Comparison of Pilot-Study-Based Aeration Requirements with those Proposed by the Manufacturers

Aeration Parameter	Value based on manufacturers proposal		Value based on pilot study off-gas testing and field measurements	
	Biostyr	Biofor-C	Biostyr	Biofor-C
Maximum-month aeration requirement (scfm)	88,000	53,600	74,600	52,500
Maximum-month power cost ($/month)	$267,000	$163,000	$227,000	$160,000
Average annual power cost for process air supply ($/year)	$2,475,000	$1,507,000	$2,101,000	$1,474,000
Average annual power cost for backwash air supply ($/year)	NA	NA	$10,500	$211,000
Annual power cost for total air supply ($/year)	NA	NA	$2,111,500	$1,685,000

BAF Stress Testing

The purpose of the BAF stress testing was to determine the hydraulic loading conditions that could cause process failure or limit capacity due to increased backwash frequency. For the latter, it is reasonable to expect the process to be able to tolerate occasional high loading. However, the plant capacity can be fatally limited if an increased number of units concurrently undergo a backwash. In discussing the basis of stress testing with the City, it was reasoned that hydraulic loadings during the stress test could be selected by varying the percentage of the full-scale plant that would be out of service for backwashing. The hypothetical out-of-service scenarios and corresponding target hydraulic loading rates were shown in Table 3.6 of Section 3. The three-part trial was extensively described in Section 3; a more detailed discussion on the actual events is provided here. For convenience the HLRs selected for the stress test are repeated in Table 4.25. A discussion on the selection of the HLRs selected is provided in the protocol in Appendix I.

Table 4.25. Stress Test Target Hydraulic Loading Rates

Stress Test Trial No.	Hydraulic Loading Rate (gpm/ft^2)	
	Biostyr	Biofor
1	3.2	3.2
2	3.8	3.7
3	4.3	4.3
4	5.1	5.0

The backwash controls for each BAF system differed. The Biofor-C initiated its backwashing based on a preset timer value. Column pressure was measured and a maximum value of 10.5 psi was selected as the trigger for initiating normal backwash. Using readings taken during the day, the backwash timer was set based on linear projection of the pressure data. On the other hand, the Biostyr initiated a backwash automatically, based on both time of day and column headloss. Note that a backwash was initiated if the preset column headloss limit was reached, regardless of the time of day. In a 24-hour period, the Biofor-C would initiate one normal backwash whereas the Biostyr might have multiple mini-backwashes followed by a single normal backwash at the 24-hour mark.

These differences lead to deviations in HLR from the target loadings of both units, particularly with the Biofor-C. When the average hydraulic loadings over the individual filter runs were calculated for the Biofor-C, the actual average HLR was less than for the Biostyr. On the average, the Biostyr was loaded at a 16 percent higher rate than the Biofor-C throughout the stress testing. Table 4.26 shows the actual average HLR calculated for each of the BAF units based on the measured filter run times and volumes of treated wastewater.

Table 4.26. Stress Test Actual Hydraulic Loading Rates

Stress Test Trial No.	Hydraulic Loading Rate (gpm/ft^2)	
	Biostyr	Biofor
1	3.7	3.1
2	4.4	3.6
3	5.0	4.1
4	5.4	4.7

The main reason for the discrepancy between target and actual HLRs was that the Biofor-C filter runs were substantially shorter due to the method of backwash initiation. This meant that the influence of the ramping up period over the filter run was more pronounced for the Biofor-C.

Since the durations and backwash volumes of normal and min-backwashes differ, this ruled out the validity of a comparison strictly based on number of backwashes. In addition, the volumes and durations differed between normal backwashes of the Biofor-C and Biostyr systems as well. Therefore, the following accounting was used:

- Biostyr filter cycle time was essentially constant at 22-hours (1320 minutes) with only minor variations.

- For each trial, the Biostyr backwash duration and volume varied depending on number of intermediate "mini-backwashes. Time for mini-backwashes was approximately 10-minutes and normal backwashes approximately 20-minutes.

- Biofor-C backwash duration was essentially constant at 68 minutes; volume of normal backwash was essentially constant at 780 gallons.

- Biofor-C filter cycle time varied depending on column pressure buildup and projected timer setting.

Three conditions were evaluated:

- Affect of hydraulic stress loading on treatment capacity.

- The backwash volume as a percentage of the treated wastewater.

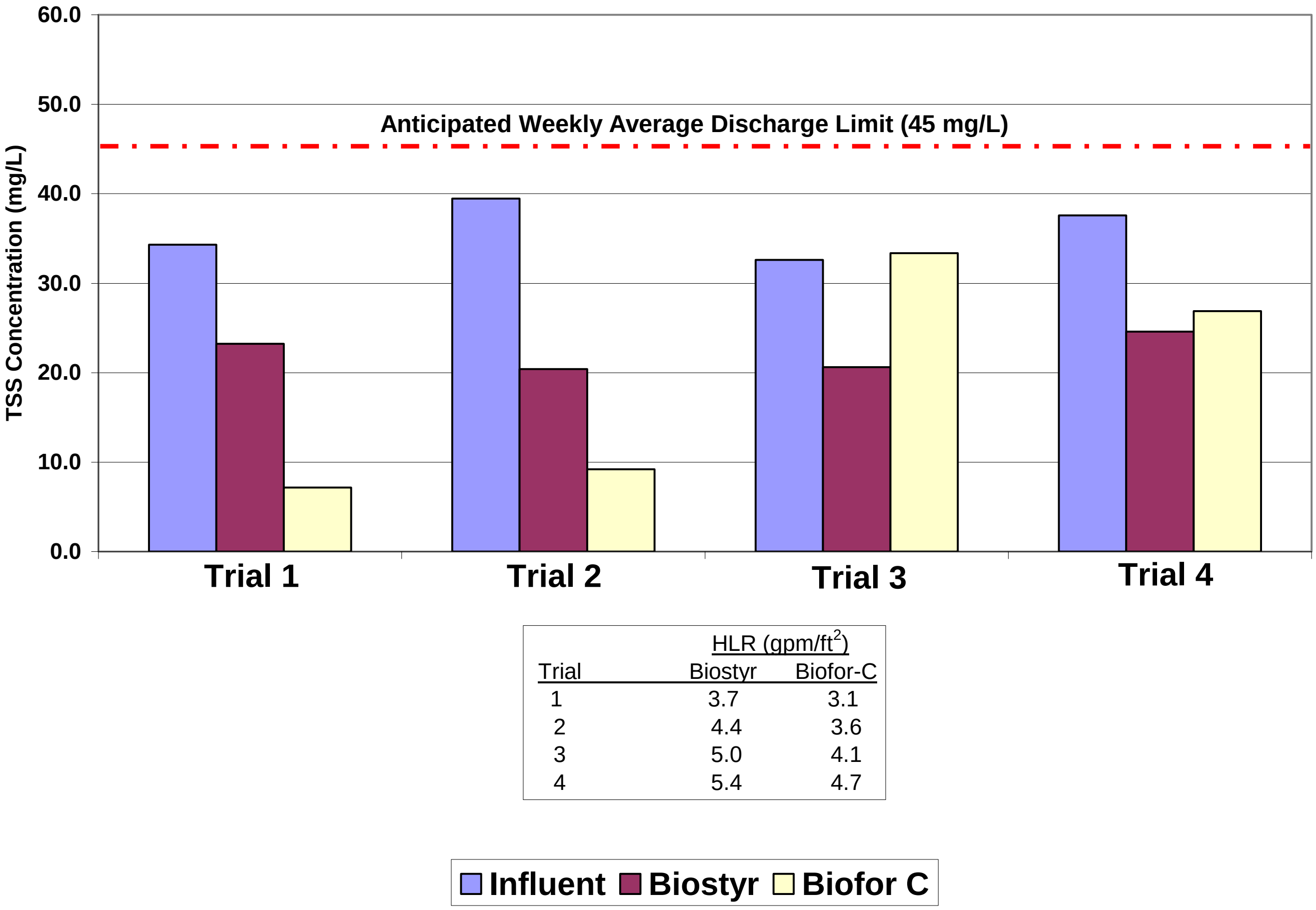
- The percentage of the filter cells that must be in backwash mode under average conditions.

These results are discussed below.

Affect of Hydraulic Stress on Treatment Capacity. The results of the stress testing are shown in Figures 4.28 through 4.32. These graphs show the BAF influent and effluent concentrations of the three anticipated permit parameters (i.e., TSS, $TBOD_5$, and $CBOD_5$). These results indicate that the BAF process was able to adjust quickly to the increases in hydraulic loading beyond the design peak hydraulic loading recommended by the BAF manufacturers of 3 gpm/ft^2. In all but one instance, both BAF pilot units were able to produce treated effluent with concentrations lower than the anticipated weekly average permit limit (strictly used for comparison purposes only).

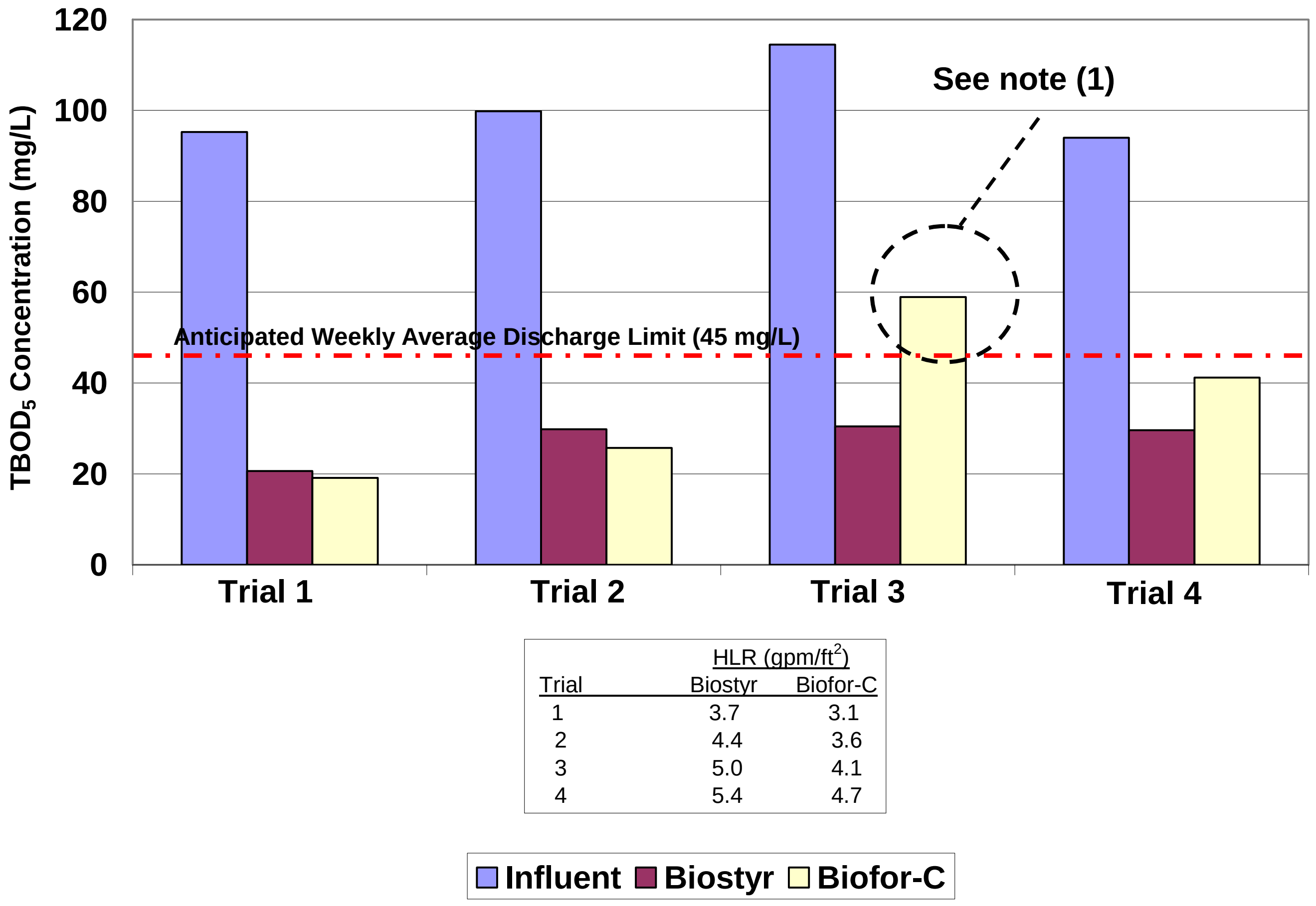
Given the relatively short duration of the trials (~22 hours) as compared to the duration associated with the permit limit (i.e., one week), the results indicate that both BAF units provided adequate treatment capacity under the conditions and durations tested. The Biofor-C effluent $TBOD_5$ spiked upward on one occasion (see Figure 4.28), possibly due to the TSS breakthrough (shown in Figure 4.31) that resulted from a process control error rather than from the process itself. This is supported by the temporary nature of the spike and subsequent return of the effluent quality to a normal range during Trial 4, despite the higher hydraulic loading condition. An automated backwash system based on column headloss, turbidity, and/or particle count may have prevented such excursion, thereby highlighting the importance of automated process control in maintaining effluent quality with the BAF process.

The accidental breakthrough of TSS in Trial 3 also illustrates the sensitivity of the 5-day BOD test to increased TSS in fixed film secondary treatment systems such as the BAF. Fixed film processes are partly nitrifying in temperate climates such as San Diego. Nitrifying bacteria are likely to be present in the BAF solids and in the BOD bottle, thereby increasing the NOD_5 fraction of the measured $TBOD_5$. As noted earlier, NOD_5 is linearly proportional to increases in effluent TSS. To illustrate this phenomenon, the NOD_5 for each of the Biofor-C trials results were calculated by subtracting the effluent $CBOD_5$ results from the $TBOD_5$ results. The effluent TSS concentration was then plotted against the calculated effluent NOD_5 concentration, as shown on Figure 4.32. The plot shows that the NOD_5 increases as the TSS increases, the same outcome of the NOD_5 testing described earlier.



	HLR (gpm/ft^2)	
Trial	Biostyr	Biofor-C
1	3.7	3.1
2	4.4	3.6
3	5.0	4.1
4	5.4	4.7

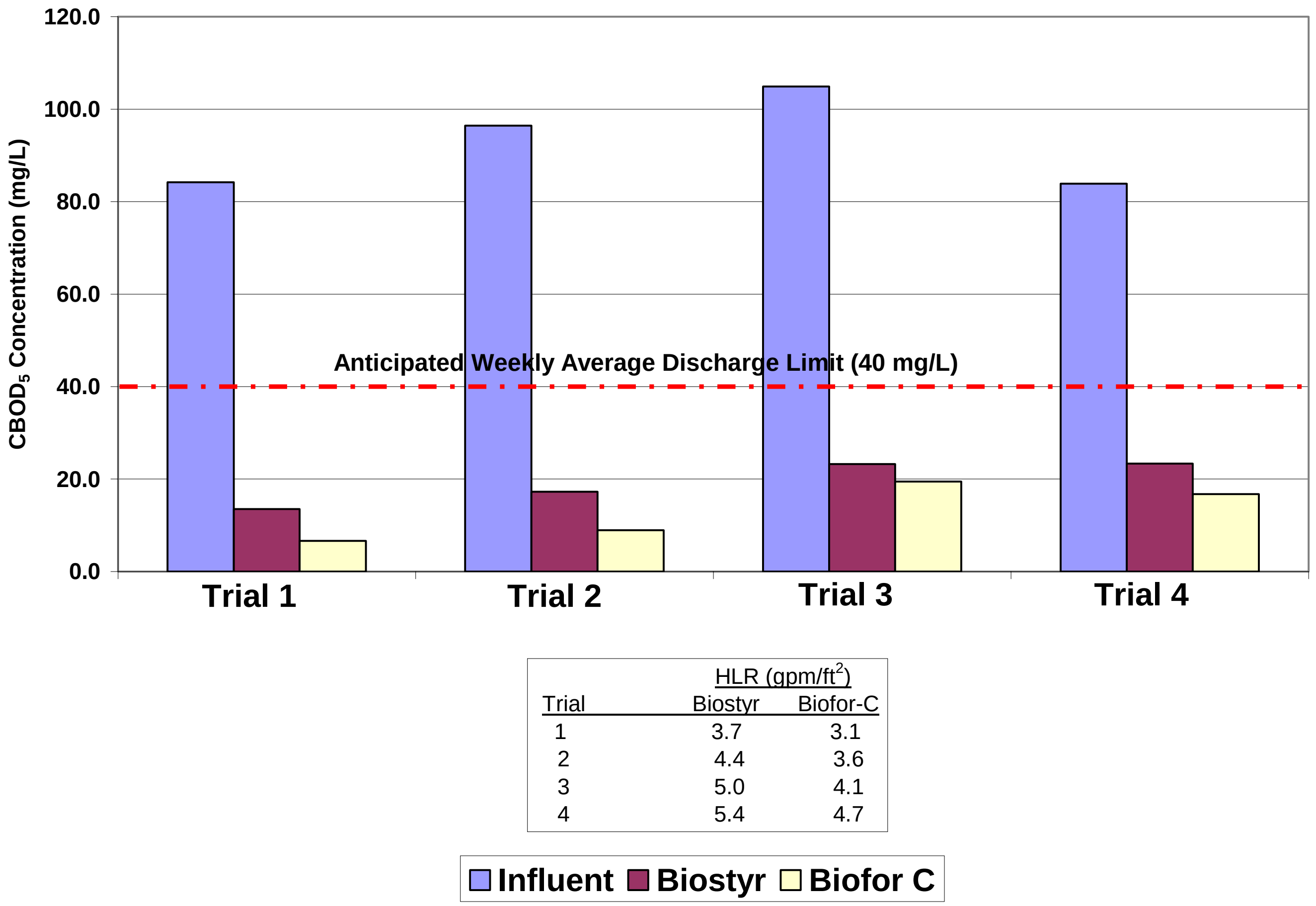
Figure 4.28. BAF Stress Testing TSS Results



	HLR (gpm/ft^2)	
Trial	Biostyr	Biofor-C
1	3.7	3.1
2	4.4	3.6
3	5.0	4.1
4	5.4	4.7

Figure 4.29. BAF Stress Testing $TBOD_5$ Results

Note (1): $TBOD_5$ exceedance probably due to process control error that caused solids breakthrough and seeding of BOD bottle with nitrifying bacteria. The additional oxygen demand was the resultant 5-day nitrogenous oxygen demand (NOD_5). The relationship between effluent TSS and NOD_5 illustrated in Figure 4.32



	HLR (gpm/ft^2)	
Trial	Biostyr	Biofor-C
1	3.7	3.1
2	4.4	3.6
3	5.0	4.1
4	5.4	4.7

Figure 4.30. BAF Stress Testing CBOD$_5$ Results

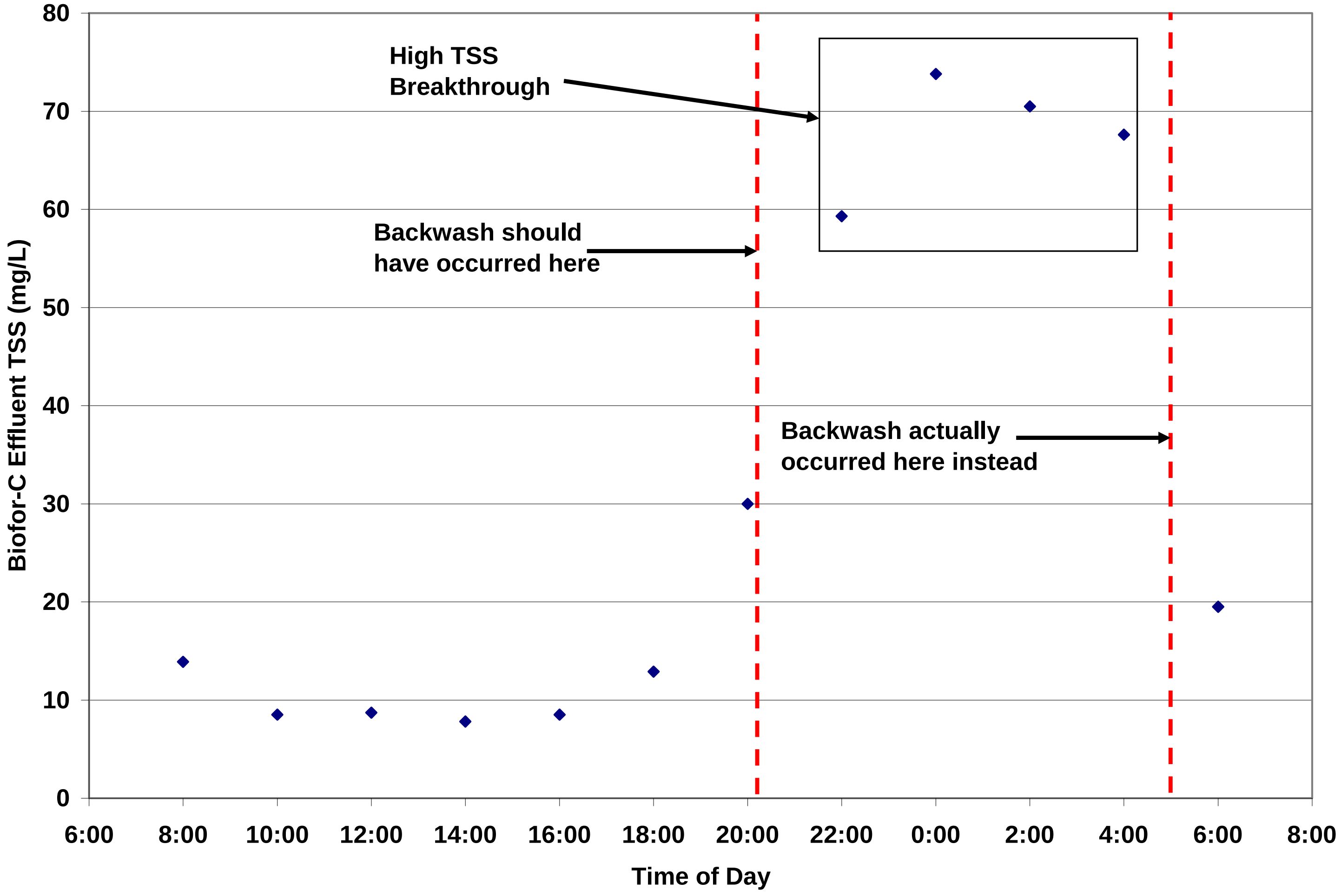


Figure 4.31. Time Plot of Biofor-C Effluent TSS During Trial 3 Showing TSS Breakthrough Due to Process Control Error

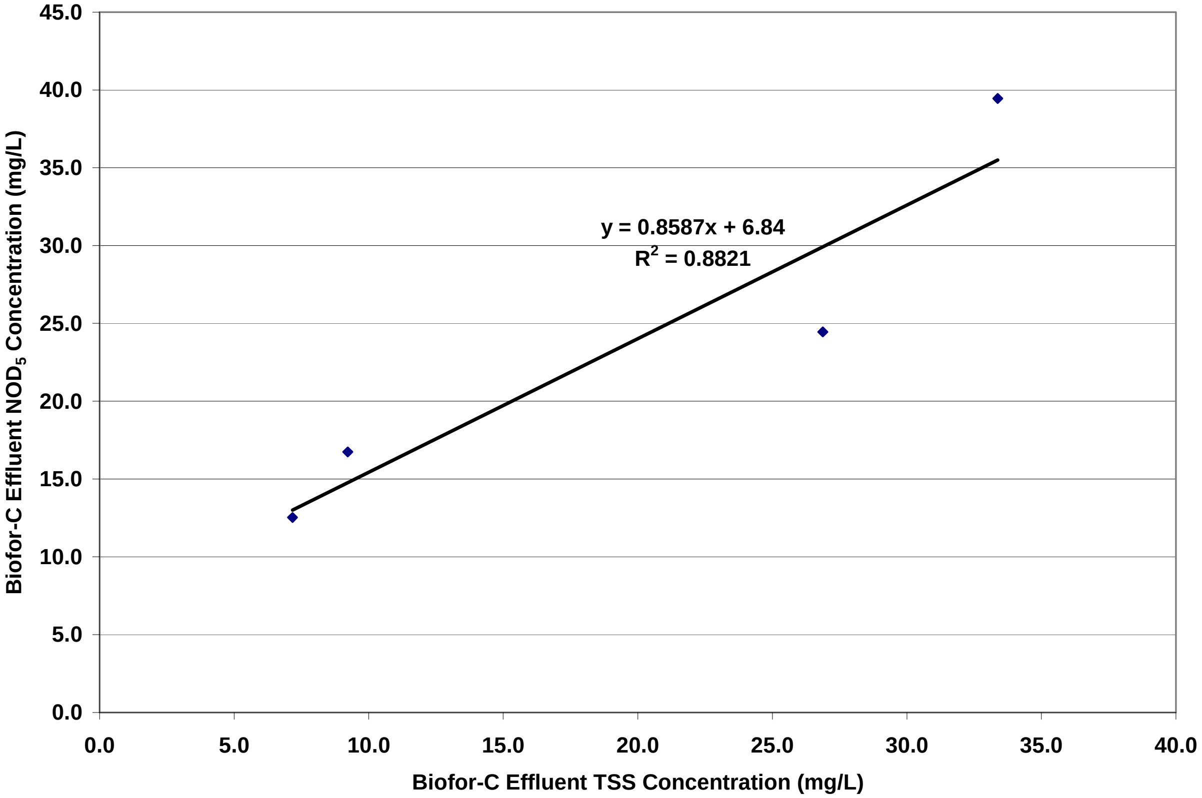


Figure 4.32. Biofor-C Effluent TSS versus NOD$_5$ Concentrations During Stress Testing

Backwash Volume as a Percentage of the Treated Wastewater. The backwash volume as a percentage of the treated wastewater for each pilot BAF were measured and compared.

Table 4.27 shows the estimated volumes of treated wastewater, backwash water, and the ratio of the two resulting from each pilot unit during each of the stress test trials. The results show that the amount of backwash water produced as a percentage of the wastewater treated was substantially higher for the Biostyr compared to the Biofor-C. This result is consistent with the results over both phases of BAF testing.

Table 4.27. Stress Test Treated Wastewater and Spent Backwash Volumes

Pilot Unit	Parameter	Trial 1	Trial 2	Trial 3	Trial 4
Biostyr (1)	Treated Wastewater Volume, gallon	15120	18536	20861	23393
	Volume Backwash Produced, gallon	1974	2444	3979	3775.5
	BW volume as a percent of volume treated	**13%**	**13%**	**19%**	**16%**
Biofor-C (2)	Treated Wastewater Volume, gallon	9639	9955	8826	11363
	Volume Backwash Produced, gallon	783	783	783	783
	BW volume as a percent of volume treated	**8%**	**8%**	**9%**	**7%**

(1) *Biostyr volume of wastewater treated included the treated wastewater for the entire trial minus time for mini-backwashing. The backwash volume included the final backwash plus all intermediate backwashes.*

(2) *Biofor-C volume of wastewater treated included treated water until normal backwash was initiated. The backwash volume was the volume of one normal backwash.*

The estimated OLR for each trial is presented in Table 4.28. Comparing the data in Tables 4.27 and 4.28, note that the highest OLR and the largest backwash:treated wastewater volumetric ratio occurred at the same time, i.e., during Trial 3. It is difficult to draw any conclusions given the relatively short duration of each trial (~22 hours).

Table 4.28. Summary of Organic Loading Rates During Stress Testing

Trial No	Estimated OLR (lb/day-1000 ft^3)			
	Biostyr		Biofor-C	
	TBOD$_5$	CBOD$_5$	TBOD$_5$	CBOD$_5$
1	363	321	297	263
2	446	431	353	341
3	581	533	463	424
4	525	469	441	394

The results of the stress testing indicate that the BAF process can withstand substantial increase in hydraulic loading without exceeding anticipated effluent limits. The main affect of hydraulic (and consequent organic) stress would appear to be an increase in backwash frequency. This leads to the concern regarding having adequate number of cells in service to treat the incoming wastewater during the backwashing cycle. The percent of units that would need to be in backwash mode on a daily average basis were calculated by dividing the backwash duration by the filter cycle time. The results were plotted against OLR as pounds of TBOD$_5$/day-1000ft^3. The results are presented in Figure 4.33.

Figure 4.33 is a two part graph showing the correlation between OLR (as lb CBOD$_5$/day-1000 ft^3) and percent of total filter area that must be backwashing (i.e., unavailable for treatment) at any particular time (on an average basis). In general, the percent of filters that must be in backwash mode at any particular time increases with increasing OLR. Surprisingly, it occurs over a relatively short time (i.e., ~22-hours), indicating that the rate of biomass accumulation responds quickly with increasing OLR. A second general observation is that the Biofor-C process requires a larger portion of the filter area to be backwashing at any particular time. This may be because the backwashing cycle time for the Biofor-C is substantially higher than the Biostyr—the Biostyr normal backwash takes approximately 20-minutes while the Biofor-C normal backwash takes 68 minutes. Two explanations for why the Biofor-C requires more time to backwash can be considered:

1. Biofilm adheres more firmly to the clay media and thus requires longer backwash time to dislodge old biofilm for optimum process control.

2. Styrofoam media requires less agitation energy due to its relatively low specific gravity.

Figure 4.33 part (a) shows that a strong correlation exists for the Biofor-C, but not for the Biostyr. However, by inspection it can be seen that three of the Biostyr data in part (a) appear to fall on a best fit parabola described while one datum lies far above this line. The apparent outlier is for trial 4. When the trial 4 datum is suppressed, as shown in part (b), a strong correlation for the Biostyr can be seen.

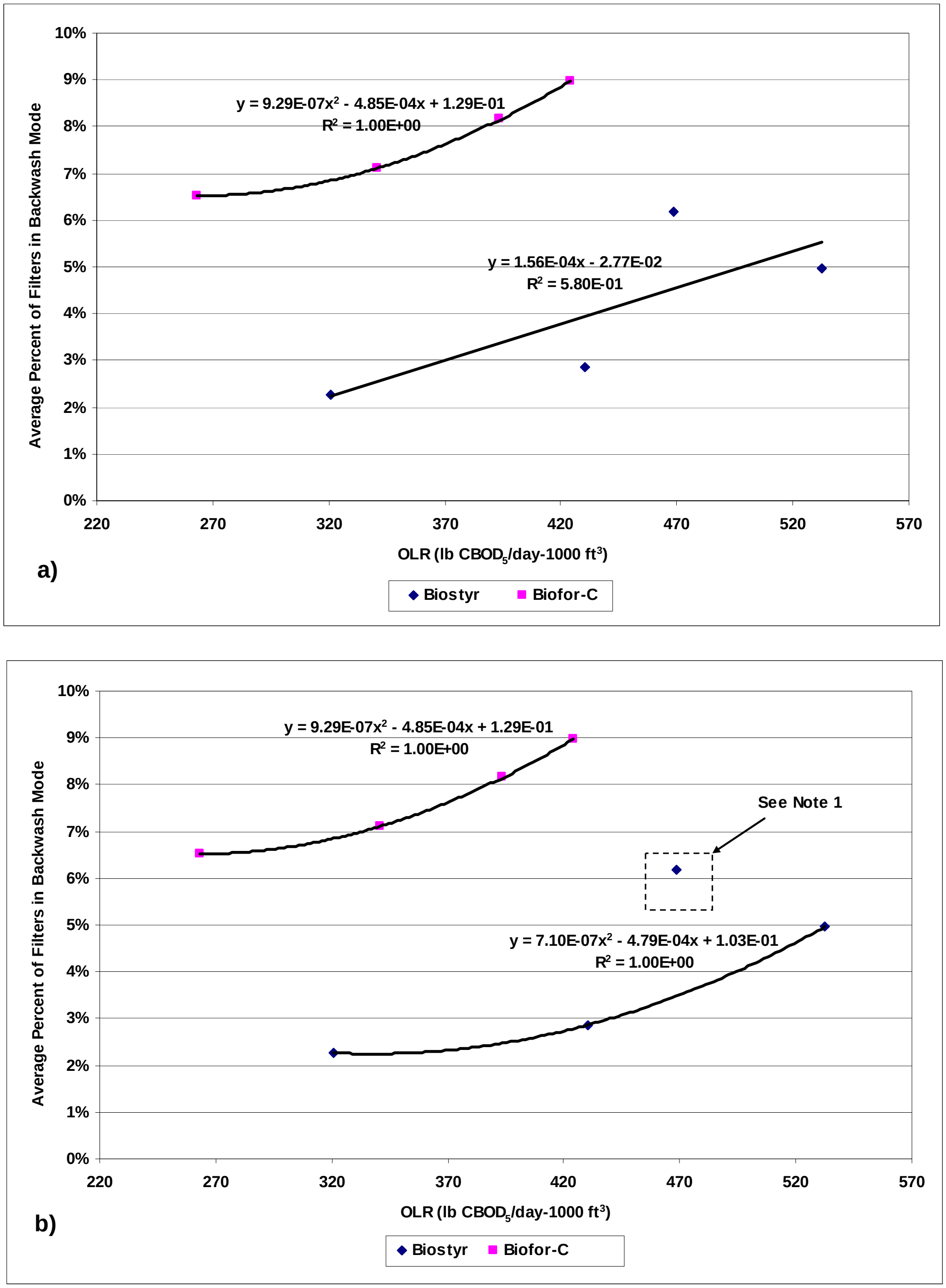


Figure 4.33. Average Percent of Cells That Must Be in Backwash Mode as a Function of Organic Loading Rate

Note 1: Biostyr datum from Trial 4 reflects result that might be artificially high due to operator induced normal backwash during trial. This increased the amount of time that counted toward backwashing and lessened the filter run time.

An explanation why the Trial 4 datum might be problematic is that during Trial 4, there were problems with a mini-backwash that led staff to manually initiate a normal backwash in the middle of the filter run. This added substantial amount of backwash time to the calculated percent-of-filters-in-backwash-mode value. As explained above, this value is the ratio of backwash time to the sum of filter-run plus backwash-time.

To check if filter plugging due to increased solids loading to the BAFs might also explain the increase in backwash frequency, the solids loading rates (SLRs) for each trial were also plotted against average-percent-filters-in-backwash-mode. The resulting 2-part plot is shown in Figure 4.34. Part (a) shows no correlation in the case of Biofor-C and an weak correlation in the case of Biostyr. Part (b) of the Figure 4.34 plot shows that removal of some seemingly anomalous data from the plotted data set does not improve the correlation; rather, it made it worse. Therefore, the data indicate that SLR is not correlated to backwash frequency over the range of SLRs tested.

The implications of Figures 4.33 and 4.34 are reasonable from a basic biological process approach. Consider that the organic loading rate (expressed in here terms of $CBOD_5$) will take into account the influent soluble organics that will be converted to biological solids and the influent particulate $CBOD_5$ that may or may not be converted to more biological solids. Therefore, as the OLR increases, higher solids production occurs, causing blockage of the pores at a faster rate than at lower OLRs. This, in turn, will invoke a need for backwashing at an earlier time, thereby increasing the frequency of backwashing. Interpreting the increased BW rate as a result of increased solids loading rate is confounded by the conversion of soluble $CBOD_5$ to solids that are not taken into account in the solids loading rate measure.

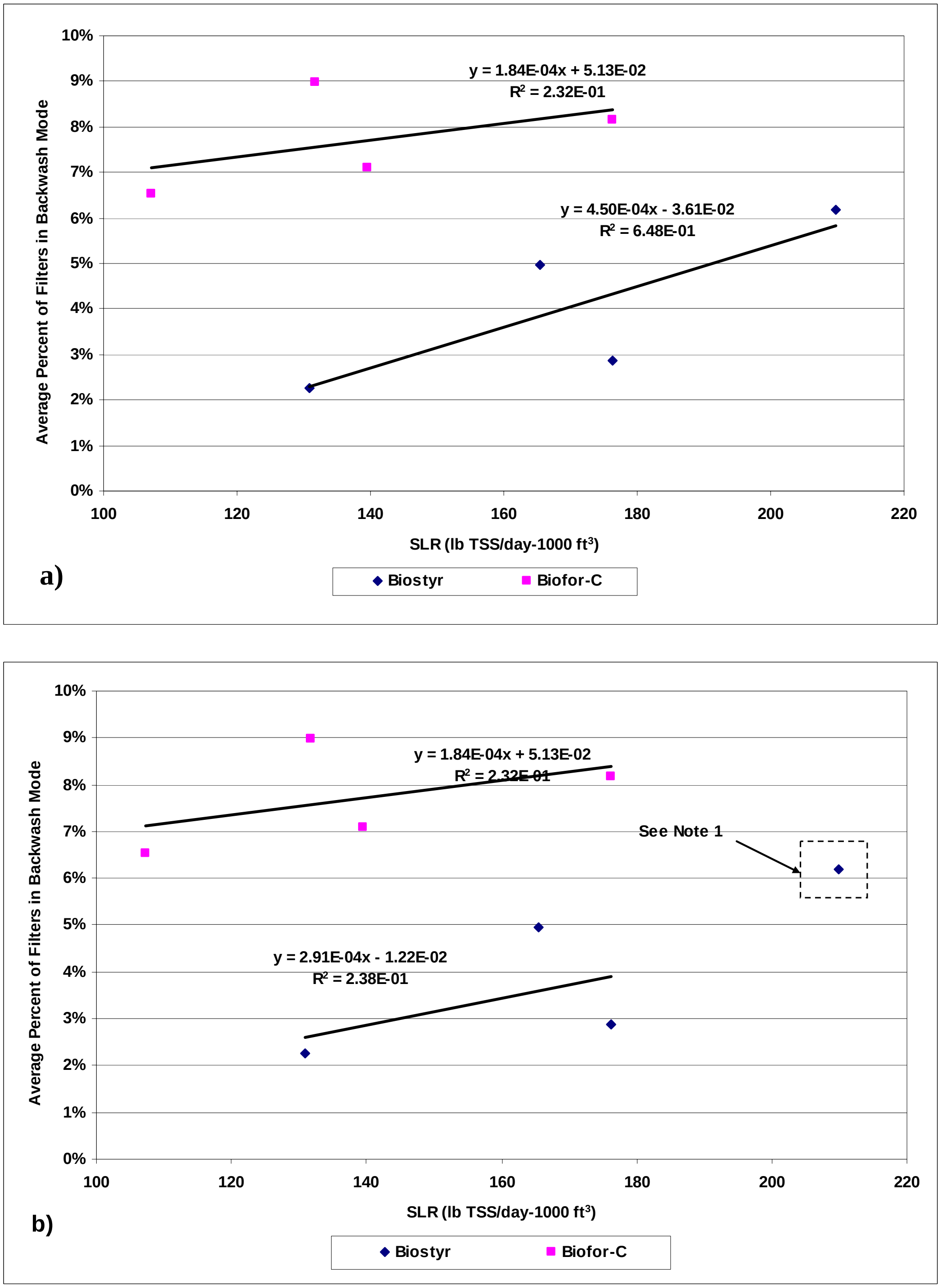


Figure 4.34. Average Percent of Cells That Must Be in Backwash Mode as a Function of Solids Loading Rate

Note 1: Biostyr datum from Trial 4 reflects result that might be artificially high due to operator induced normal backwash during trial. This increased the amount of time that counted toward backwashing and lessened the filter run time.

In summary, the BAF stress testing indicates the following:

- Both Biofor-C and Biostyr processes are robust and able to tolerate shock loading in excess of the design peak-hour HLR.
- Although target HLR were selected to simulate various scenarios of units out of service, the actual HLR varied from those selected. The result was that the HLR to the Biostyr was about 15 percent higher on average than the Biostyr. The Biostyr did appear to perform well despite the higher loading.
- During the trial, a missed backwash for the Biofor-C led to breakthrough of TSS in the effluent. This did not occur with the Biostyr because the Biostyr is programmed to backwash the unit automatically when the column headloss reaches a preset target value. This highlights the importance of automated backwashing controls regardless of which BAF process ultimately selected.
- Biostyr required more backwash water as a percent of the influent flow than the Biofor-C. The higher backwash water required (over a comparatively short duration) implies that higher velocities are required to backwash the Styrofoam media. This could be necessary to free trapped material with specific gravities close to that of the Styrofoam, which presumably could be carried over from the primary clarifiers into the BAF columns. In addition, Krüger staff indicated that the Biostyr process driver for the intermediate mini-backwashes is to clear accumulations of primary solids that tend to form relatively quickly on the bottom of the media column. This material would otherwise cause excessive headloss over the first few inches of column. This indicates that in general, primary solids do not penetrate substantially into the Biostyr media bed. Analogous conditions for the Biofor-C have not been identified.
- Despite the higher backwash volume and velocity requirements of the Biostyr, the time required for backwashing the Biostyr was less than for the Biofor-C meaning that in a full-scale facility, a smaller percentage of the total Biostyr filter area will need to be in backwash-mode than would be for the Biofor-C under similar organic loading conditions.
- The amount of filter area that must be in backwash mode (as a percentage of the total filter area) at any time on average was shown to be greater for the Biofor-C than for the Biostyr. This is because the Biofor-C (clay media) normally requires more time to backwash than the Biostyr.

Headloss Development Along the BAF Column

As explained previously, the BAF units must be backwashed on a regular interval to release accumulated biomass and primary solids trapped in the pore voids in the media bed. In Phase I and for most of Phase II, the backwash interval used for both Biofor and Biostyr pilot units was 24 hours. It was only during the stress testing when the backwash interval was shortened.

Each BAF pilot unit was equipped with pressure sensors along the length of the media column, as shown on Figure 4.35, to observe the pressure development along the height of the column. The collected data provided an insight on the ability of each backwash event to cleanse the columns and revert back to its original condition in terms of pressure.

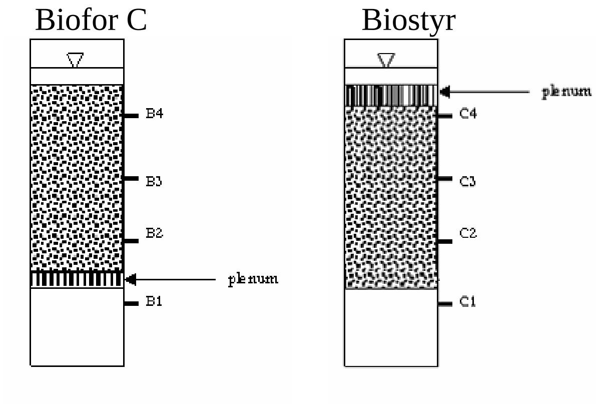


Figure 4.35. Pressure Sensor Locations along the Biofor-C and Biostyr Columns

Conditions inside the filter are in a non-steady state between backwash events, mainly characterized by increasing column pressure. Figure 4.36 demonstrates a typical differential pressure buildup patterns for Biofor-C and Biostyr (complete pressure data are provided in Appendix D). As seen in the pattern, the differential pressure increases steadily throughout the entire filter run. This pattern indicates that the normal backwash frequency provides sufficient bed cleaning to restore sufficient solids-handling capacity for the whole filter run.

In addition, as seen from Figure 4.36, most of the pressure buildup occurs at the lower levels of both Biostyr and Biofor-C columns, possibly due to trapped solids. The pressure builds up from 150 to 220 inches (70 inches total) for Biofor-C and from 200 to 290 inches (90 inches total) for the Biostyr between backwash cycles.

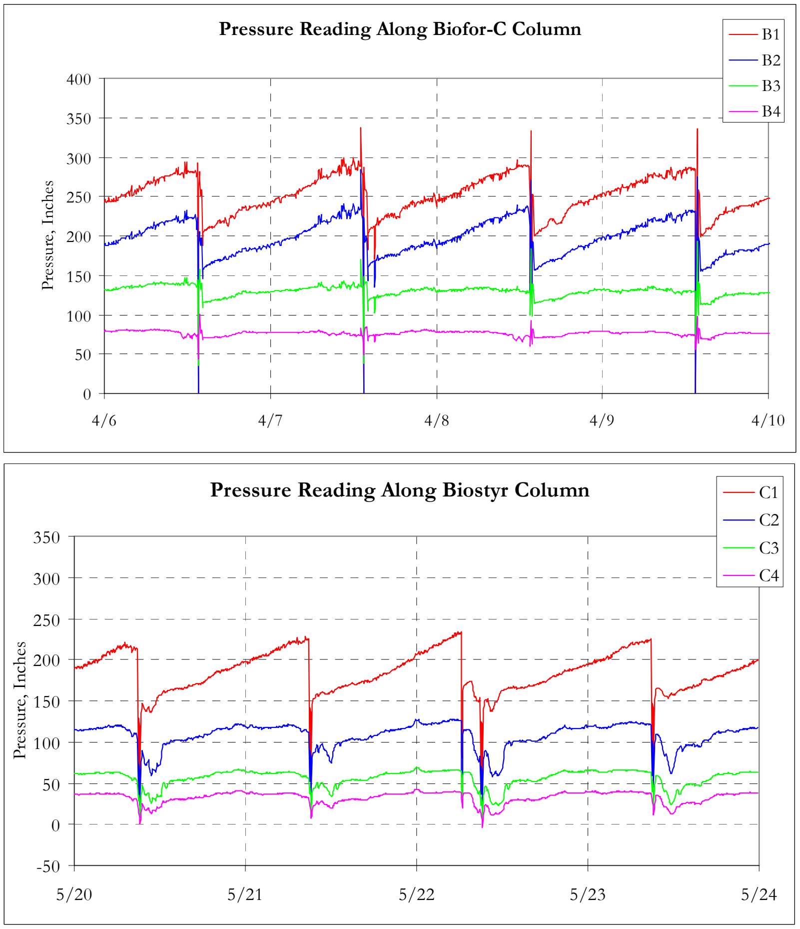


Figure 4.36. Normal Pressure Readings along the Biofor-C and Biostyr Columns

In the early stages of Phase II, the

Densadeg operated poorly due to reasons previously described. Both BAF pilot units were subjected to excessive solids. The fully automated Biostyr unit reacted to the excessive solids loading by going through several minibackwashes, as observed in Figure 4.37, between the regularly scheduled backwashes every 24 hours. While this automation preserves the integrity of the column and prevents compression of the floating Biostyrene beads, it results in a large volume of backwash water that must be treated. This additional volume must be considered when sizing the backwash basin for the full scale application.

The less automated Biofor-C column did not fare favorably during the Densadeg upsets. As shown in Figure 4.37, the pressure in the column increased rapidly causing the process blowers to fail several times. In addition, the columns needed to be backwashed aggressively between the normal 24-hour cycle to rid the column of the trapped solids. IDI has indicated that the full scale system backwash system will be automated such that a backwash will be initiated before the blowers can be severely impacted.

Pressure taps are not customarily provided in pilot units or full scale systems. However, the choice to insert pressure sensors along the column has proven to be an invaluable diagnostic tool. Inclusion of this type of monitoring instrumentation is recommended for the full scale system.

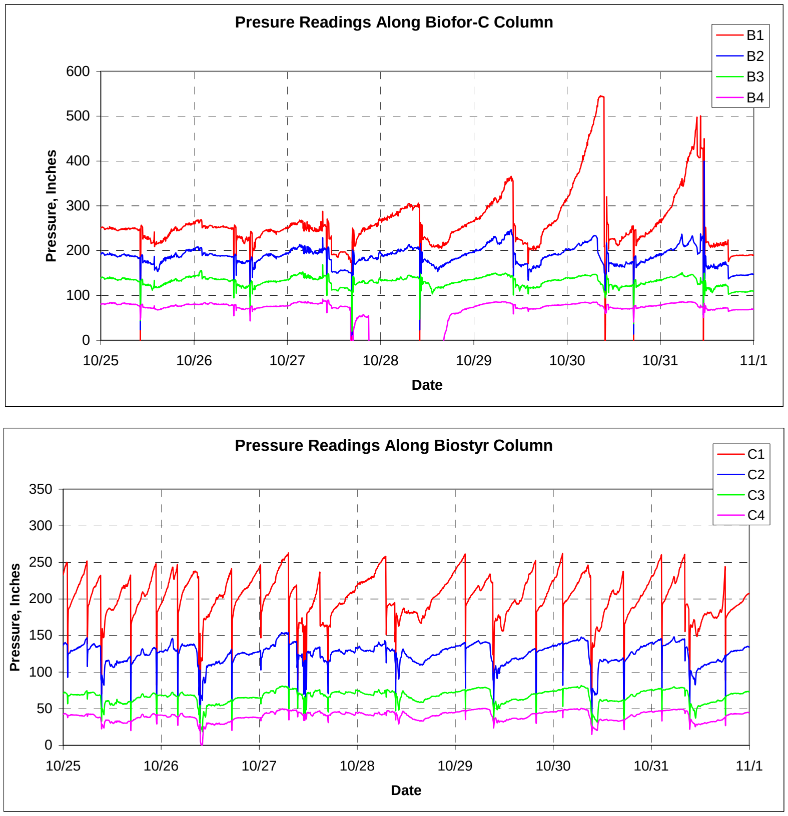


Figure 4.37. Pressure Readings along the Biofor-C and Biostyr Columns Experiencing High Solids Loading

Fate of Phosphorus Compounds in BAF Column

Ferric chloride is used to enhance primary clarification at the PLWTP; it coagulates non-settleable colloidal material in the plant influent creating flocculent particles that will settle, increasing TSS removal efficiency to about 85 percent. This technology is used in other plants to control effluent phosphorus. However, phosphorus is used as a nutrient by biological processes to support $TBOD_5$ oxidation. The practice of chemically enhanced primary clarification with ferric chloride could result in the inadvertent precipitation of phosphorus, and a concomitant nutrient deficiency in downstream biological processes.

Analysis of BAF influent showed that the average $TBOD_5$ concentration was typically <100 mg/L. Stabilization of this level of $TBOD_5$ requires approximately 1 mg/L phosphorus. The average primary effluent (BAF influent) TP concentration during Phase I was 2-3 mg/L, indicating that there should have been sufficient phosphorus nutrient present in the BAF influent flow.

Phosphorus occurs typically in soluble and particulate forms in raw sewage. The soluble form—orthophosphate—is readily assimilated by microorganisms. The particulate form requires that the microorganisms hydrolyze it so as to render it biologically available. The average influent soluble orthophosphate concentration was <0.4 mg/L during Phase I (and <0.2 mg/L during the earlier rainy period). The concern was whether this low level of soluble orthophosphate concentration was inhibiting biomass growth.

Limited data collected during the study showed that the raw influent total phosphorus concentration was on the order of 6-7 mg/L compared to the 2-3 mg/L found in the BAF influent, suggesting that two thirds of the influent phosphorus may have been precipitated in the primary clarifiers. Relatively low dissolved oxygen concentrations measured in the lower reaches of the BAFs suggested that the biofilm may have had pockets of anaerobic activity. Observations of black deposits in the biofilm also indicate anaerobic activity. Biological phosphorus release can be expected to occur in anaerobic environments. It is possible that this mechanism may have contributed sufficient orthophosphate to prevent phosphorus nutrient deficiency from occurring. It is important to note that in a full scale system, plant operators would have the option of reducing ferric dose to limit precipitation of phosphorus in the CEPT basins. This, of course, would have implications for the solids removal efficiency of the CEPT. An integrated approach to designing and operating the entire system including primary and secondary treatment systems would need to strike a balance in this regard.

Although time and resource availability prevented detailed analysis of the fate of phosphorus during pilot study, this issue it is perhaps worth studying prior to preliminary design.

Pathogen Removal

Discharge requirements for the PLWTP are issued by the SDRWQCB and the USEPA. These requirements are specified in the plant's NPDES Permit No. CA0107409 and the Permit's subsequent Addendum No.1. The permit specifies the terms and conditions that allow treated effluent to be discharged to the Pacific Ocean via the Point Loma Ocean Outfall (PLOO) and is designed to meet the standards defined in the California Ocean Plan (COP). The permit also defines the requirements for monitoring the receiving waters surrounding the PLOO, including sampling plan, compliance criteria, laboratory analysis, statistical analysis, and reporting guidelines.

The bacterial requirements of the plants NPDES permit are designed to ensure public safety by setting limits on bacterial density at nearby "water contact" zones. The permit defines water contact zones to be the shoreline areas north and south of the PLOO and the associated offshore kelp beds. Samples are taken at these water contact zones five times per month and bacteria levels are tested.

Samples collected at the kelp beds have been 100 percent compliant with the bacterial density requirements specified in the permit since 1993 when the PLOO was extended from 2.4 miles to 4.5 miles. Samples collected at the shoreline stations are also compliant the vast majority of the time. Exceptions to this occur after periods of heavy rainfall when storm water runoff causes the shoreline areas to be out of compliance.

The BAF study included periodic virus, total coliform and fecal coliform, and *Enterococcus* testing. The purpose of the testing was to evaluate the ability of the BAF and units to remove bacteria and viruses from incoming wastewater. Samples were collected and shipped to the laboratory for testing three times per week during both Phase I and Phase II. All samples were collected at 08:00.

Results of Bacteria and Virus Testing. Results of the bacteria and virus sampling for Phases I and Phase II are summarized in Tables 4.29. and 4.30, respectively. The tables present geometric mean values of influent and effluent total coliform, fecal coliform, *Enterococcus*, and the coliphage virus as well as Log_{10}-removal through the BAF units. Also shown is the range of each data set. See Appendix J for the full set of bacteria and virus data.

The results indicate that the BAF pilot units provided between a 0.48 and 2.55 Log_{10}-removal of bacteria and between a 0.21 and 0.82 Log_{10}-removal of the coliphage virus. During Phase I the Biostyr system outperformed Biofor C by providing on the average a 2.55 Log_{10}-removal of total coliform as compared to the 0.96 Log_{10}-removal achieved by Biofor C. During Phase II, however, the Biofor C system performed best. Results of Phase II data show that on the average the Biofor C system provided a 1.70 Log_{10}-removal of total coliform as compared to the 1.15 Log_{10}-removal achieved by Biostyr. The data and operational records were carefully reviewed in an effort to ascertain the cause for the reversal. No clear reasons were found.

As noted earlier, bacterial samples have been 100% compliant with the requirements of the plant's NPDES permit ever since 1993 with the exception of periods after heavy rainfall when storm water runoff causes the shoreline areas to be out of compliance. Results of sampling the BAF pilot's effluent indicate that the addition of BAF treatment at the PLWTP would further reduce effluent bacteria levels by between 0.48 and 2.55 Log_{10}.

Table 4.29. Phase I Bacteria and Virus Removals in BAF Units

		Magnitude			
Sample ID	**Based on**	**Total Coliform CFU/100mL**	**Fecal Coliform CFU/100 mL**	**Enterococcus CFU/100mL**	**Coliphage PFU/100mL**
Plant Effluent	Geo. Mean	43,395,300	4,334,140	88,170	15,430
	Range	(25,000,000-74,000,000)	(2,000,000-12,000,000)	(26,000-190,000)	(3,900-90,000)
Biofor-C Effluent	Geo. Mean	4,708,450	621,400	29,300	7,700
	Range	(460,000-27,000,000)	(70,000-3,800,000)	(4,900-120,000)	(2,100-33,000)
Biostyr Effluent	Geo. Mean	120,990	20,090	780	2,340
	Range	(10,000-4,000,000)	(1,800-530,000)	(200-9,000)	(600-35,000)

		Log Removal			
Sample ID	**Based on**	**Total Coliform**	**Fecal Coliform**	**Enterococcus**	**Coliphage**
Biofor-C Effluent	Geo. Mean	0.96	0.84	0.48	0.30
Biostyr Effluent	Geo. Mean	2.55	2.33	2.05	0.82

Table 4.30. Phase II Bacteria and Virus Removals in BAF Units

Sample ID	Based on	Magnitude			
		Total Coliform CFU/100mL	Fecal Coliform CFU/100 mL	Enterococcus CFU/100mL	Coliphage PFU/100mL
Raw Wastewater	Geo. Mean	100,945,000	9,761,000	373,000	108,700
	Range	(15,000,000-280,000,000)	(5,000,000-23,000,000)	(100,000-2,000,000)	(24,000-430,000)
Densadeg Effluent	Geo. Mean	35,922,000	3,884,000	10,500	21,000
	Range	(7,700,000-84,000,000)	(610,000-13,000,000)	(1,000-140,000)	(2,000-170,000)
Biofor-C Effluent	Geo. Mean	724,000	117,000	2,400	12,800
	Range	(41,000-4,000,000)	(6,000-1,300,000)	(150-23,000)	(300-90,000)
Biostyr Effluent	Geo. Mean	2,522,000	316,000	17,000	12,000
	Range	(630,000-20,000,000)	(71,000-3,700,000)	(5,000-140,000)	(1,700-80,000)

Sample ID	Based on	Log Removal			
		Total Coliform	Fecal Coliform	Enterococcus	Coliphage
Densadeg Effluent	Geo. Mean	0.45	0.40	1.55	1.72
Biofor-C Effluent	Geo. Mean	1.70	1.52	0.64	0.21
Biostyr Effluent	Geo. Mean	1.15	1.09	-0.21	0.23

Effluent Toxicity

Toxicity samples were taken from the BAF effluents three to five times during both Phase I and Phase II. Kelp Germination and Mysidopsis bahia LC_{50} results are given in Tables 4.31 and 4.32, respectively. Results indicate that toxicity for both Biostyr and Biofor-C effluents were below PLWTP NPDES permit limits.

Table 4.31. Chronic Bioassay Results

Week	Comp Sample Start Date	Giant Kelp (Macrocystis pyrifera) Germination & Growth					
		Biostyr Effluent		Biofor-C Effluent		Biofor-N Effluent	
		Germination(%)	Growth (%)	Germination (%)	Growth (%)	Germination (%)	Growth (%)
4	15-Mar-04	sample not available		0.88	0.88	0.88	0.49
6	4-Apr-04	0.88	0.88	0.88	0.88	sample not available	
12	10-May-04	0.88	0.88	0.88	0.88	0.88	
29	7-Sep-04	0.88	0.88	sample not available			
33	5-Oct-04	0.88	0.88	0.88	0.88		
37	5-Nov-04	sample not available		sample not available			
42	7-Dec-04	0.88	0.88	0.88	0.88		

Table 4.32. Acute Bioassay (LC_{50}) Results

Week	Comp Sample Start Date	Mysidopsis bahia 96-h Survival		
		Biostyr Effluent	Biofor-C Effluent	Biofor-N Effluent
4	21-Mar-04	sample not available	>31	>31
6	11-Apr-04	>31	>31	>31
9	25-Apr-04	>31	>31	>31
10	2-May-04	>31	>31	sample not available
12	16-May-04	>31	>31	>31
17	20-Jun-04	>31	>31	---
29	12-Sep-04	>31	sample not available	---
31	26-Sep-04	sample not available	>31	---
33	10-Oct-04	>31	>31	---
35	24-Oct-04	>31	>31	---
38	14-Nov-04	>31	>31	---

Evaluation of the Biomass

Biomass sampling was attempted during the course of the pilot study as a means of anticipating biological changes in the media bed and assessing the health of the biomass. Two types of assessments were considered. First, BC made numerous attempts to collect media samples from discrete depths within each pilot column. Second, a microscopic analysis of biomass contained in the spent backwash water was performed.

Initially, the emphasis was on the collection and analysis the media samples because more could be determined this way regarding the health and characteristics of various regions in the vertical media column. By contrast, analysis of the spent backwash solids could only yield a gross estimate of overall condition but would not allow for a more defined characterization of the biomass at different depths. Therefore, many unsuccessful attempts were made to collect media samples before it was decided that microscopic analysis of the backwash should be performed. Samples of spent backwash solids were collected on December 21st and 22nd and these were assessed under the microscope. The microscopic assessment revealed the presence living higher life-forms (e.g., protozoa) in both Biofor-C and Biostyr samples. In general, this is seen as evidence that aerobic conditions prevailed in at least portions of the media beds of these units, although it was likely anaerobic conditions also existed in portions of the units. Photos of the spent backwash microorganisms are shown in Figures 4.38 and 4.39 for the Biofor-C and Biostyr, respectively.

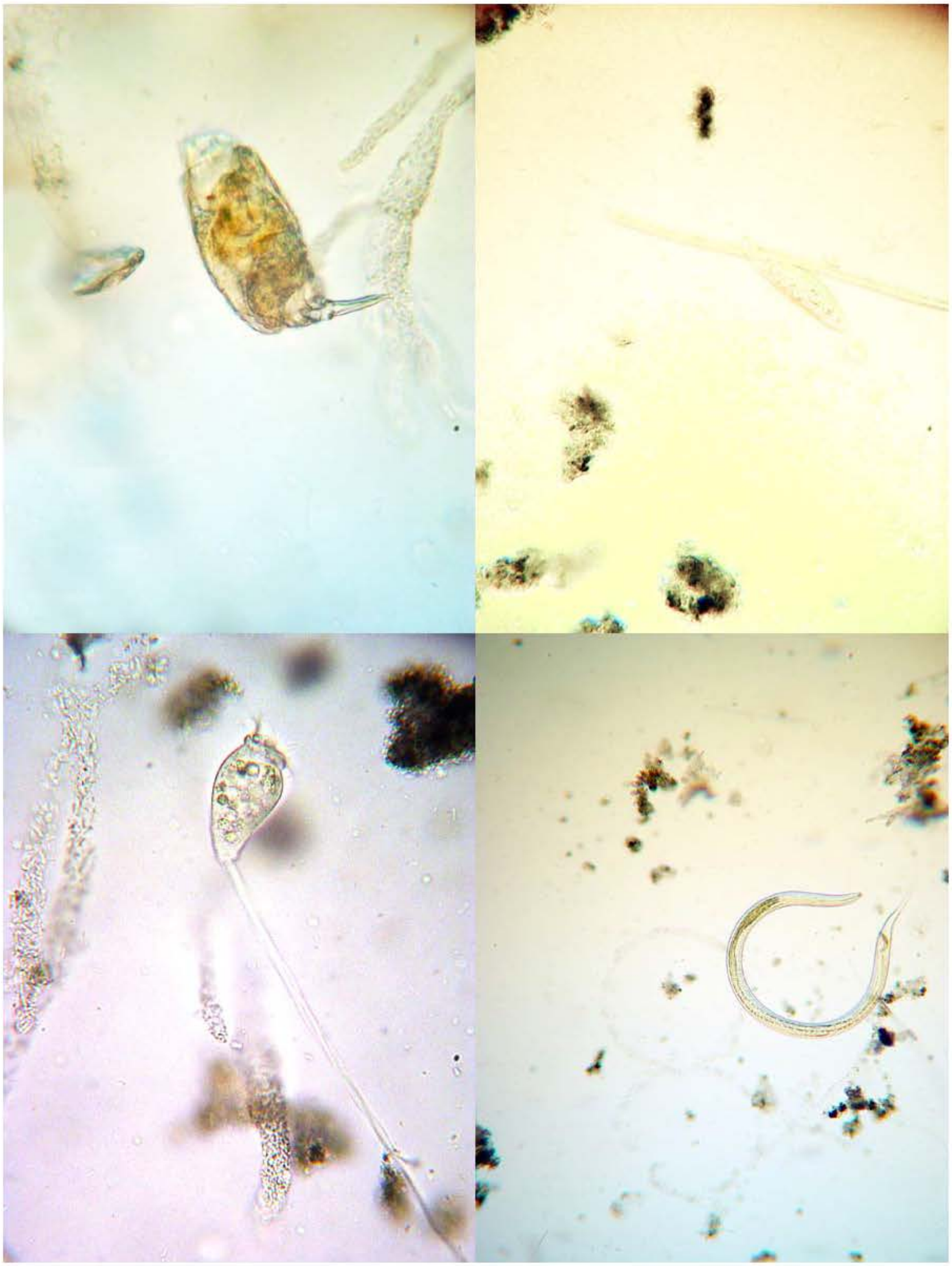


Figure 4.38. Biostyr Microscopic Photos Showing Live Higher Forms in Backwash Sample

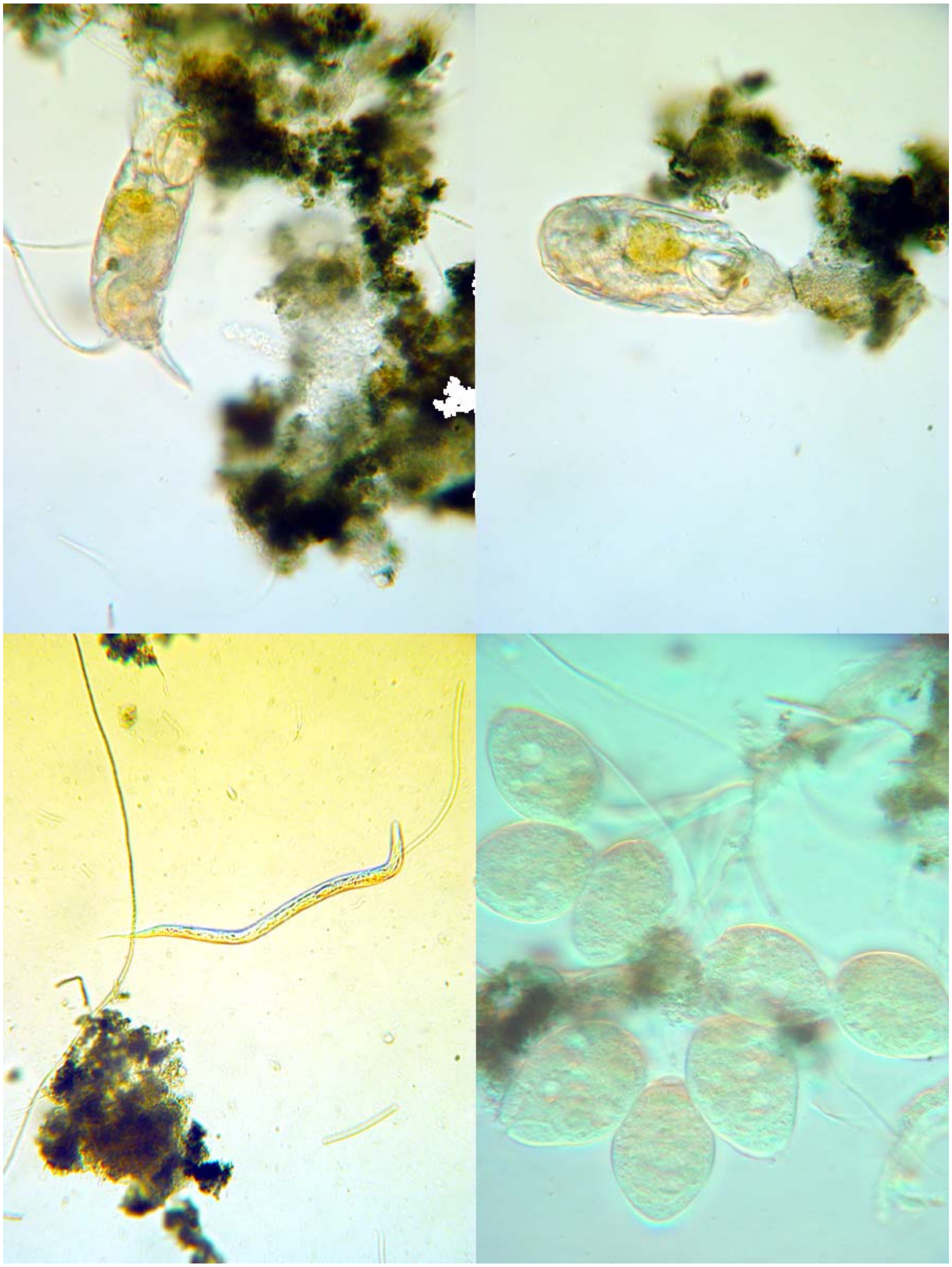


Figure 4.39. Biofor-C Microscopic Photos Showing Live Higher Forms in Backwash Sample

The task of obtaining relatively undisturbed samples at discrete depths from each of the pilot columns proved to be difficult. Various sampler designs were considered and all but one failed to produce results. BC went through six of these before arriving at one that appeared to work. Even so, this was late in the study. Moreover, the media samples were only obtainable from the Biostyr pilot unit and not from the Biofor-C. Apparently, the lighter, spherical, and relatively smooth Styrofoam media beads were easier to draw up into the sampler than the clay media; which was angular, non-uniform, heavy, and abrasive by comparison. A photograph of the sampling device used to collect these samples is shown in Figure 4.40.

As shown in Figure 4.40, the sampler consisted of two main parts. The smaller pipe consisted of four syringe-like chambers separated at 2-½ foot intervals. The syringes were actuated by a handle at the top. The entire small-pipe assembly fit inside the larger pipe. Each pipe had four inlet holes through which the discrete samples could be drawn into the sampler. The inner pipe could be rotated such that its holes lined up with the holes in the larger pipe. The sampler was operated as follows:

- Prior to plunging the sampler into the media, the holes were off-set to avoid cross-contamination of the discrete samples.
- When the sampler reached the desired depth, the inner pipe was rotated relative to the outer pipe such that the holes in the two pipes lined up.
- The syringes were then drawn upward by pulling on the handle.
- Once the samples were sucked into the sampler chambers, the smaller pipe was rotated 180-degrees to off-set the holes in the two pipes thereby preventing cross-contamination.
- The sampler apparatus was then withdrawn from the media column and disassembled to obtain the four discrete samples.

Figure 4.41 shows a photo of the samples obtained in the manner described. The numbers associated with each sample refer to the depth of the sample below the Biostyr nozzle deck (i.e., the top of the media column). The black coloration of the media taken from the 10-foot depth (i.e., the bottom of the media column) is indicative of anaerobic conditions. This tends to confirm earlier observations of partially anaerobic zones in the lower part of the Biostyr media column.

Figure 4.41 also shows that the proportion of redish to blackish grains appears to decrease as one moves down the media column (i.e., left to right in the photo). The change is most dramatic between the 7.5 and 10-foot samples. The reddish staining is probably due to iron hydroxides salt deposition. The black staining is likely to be due to ferrous sulfide deposition.

Biofilm systems in carbonaceous duty (unlike activated sludge) should be expected, theoretically, to develop anaerobic zones—this is established in the literature and confirmed by practical experience. It happens because substrate penetrates deeper than oxygen and the biofilm keeps working. If there is sufficient oxygen, the ferrous sulfide particles (black) will be converted to ferric hydroxide (red).

The persistence of black media at the bottom and portions throughout is indicative that there is insufficient oxygen to make the conversion and that that zone contains biofilm that is at least partly anaerobic. The oxygen demand is greater than the supply, sustaining the anaerobic zones.

Figure 4.40. Photo of Media Sampler Used to Collect Biostyr Media at Discrete Depths

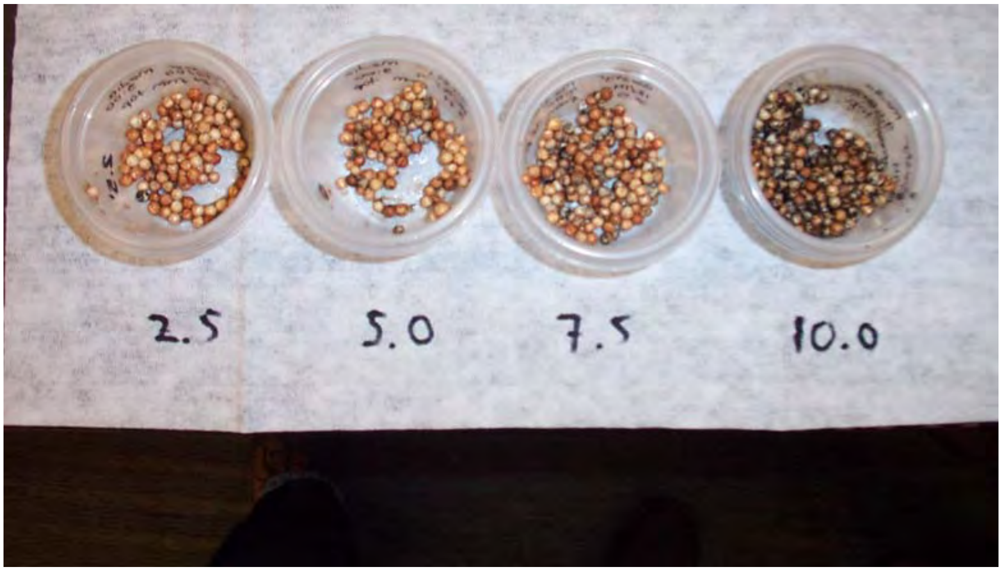


Figure 4.41. Photo of Media Sample Taken with Sampler Shown in Figure 4.40.

The prospect of collecting these depth-discrete media samples was exciting because it could provide a glimpse inside the column and into the character and health of the biomass at different depths. In addition, by running solids analysis on the sample material, one could potentially develop a depth-integrated biomass inventory for each of the columns. This could allow tracking of the solids retention times and food-to-mass-ratios as they relate to backwashing frequency and organic loading for process control and design reasons.

In order to characterize the biomass, a protocol for separating the biofilm, loosely attached biomass, interstitial biomass, and the inert media was needed. No such procedure was available in the literature and, likewise, the manufacturers were not able to provide such a protocol when asked. Therefore, BC developed a protocol specifically for the pilot testing. The complete media solids measurement protocol is provided in Appendix K. It should be noted that problems with the seals on the sampling device meant that the interstitial fluid and associated suspensions were not retained in the sampler. Thus characterization of the interstitial biomass was not possible and only the firmly attached biofilm could be measured.

Because media samples were only collected at the end of the study, these samples were stored in a refrigerator at 4°C for 7 days then batch processed for analysis. Therefore, the complete protocol was only attempted once. This meant that there was no opportunity to improve laboratory technique or for optimization that comes only with trial and error. Unfortunately, the first (and only) batch of solids analyses of media samples produced results that appeared to be in error. In general, the results indicated that columns had greater biofilm solids inventories after the units were backwashed than they did before the backwash. Since this is not likely to be the case, these results were regarded as erroneous. Unfortunately, the pilot study ended before the additional attempts could be made. It would be desirable to resume this effort if the City decides to resume additional BAF pilot testing in the future.