

ABSTRACT

JAMES WORK MOORE. Operational Evaluation of Pilot GAC Filter Adsorbers (Under the Direction of DR. FRANCIS A. DIGIANO)

Granular activated carbon (GAC) filter-adsorbers are becoming widely used in the United States for control of taste and odor and synthetic organic compounds (SOCs). While filter-adsorbers are relatively inexpensive to install, especially as retrofits to existing filter beds, their limited empty bed contact times (EBCTs) and frequent backwashing may hamper control of organics.

A pilot plant consisting of three filter-adsorbers was installed at the Franklin WTP in Charlotte, N.C. Although the focus of this investigation was on the microbial quality of the product water, other data were collected to assess the operational characteristics of GAC as a filter and an adsorber of natural organic matter (NOM).

The GAC filter-adsorbers reduced turbidity as least as well as the full-scale dual media filters at application rates of 2, 4, and 6 gpm/ft² and backwash frequencies of one and two days. Similarly, headloss accumulations in the filter-adsorbers were comparable to that in the full-scale dual media filters. The filter-adsorbers did not effectively remove TOC, as 50% breakthrough was observed in less than 1 month for the lowest application rate in current practice (2 gpm/ft²). This poor performance was attributed to mass transfer limitations due to limited EBCT. Steady state removal of TOC was statistically significant at application rates of 2 and 4

gpm/ft², but was observed to be no more than 0.5 mg/L. Some steady-state removal of THMFP was also noted; however, the significance of this removal is dependent upon the new maximum contaminant levels.

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CHAPTER 1. INTRODUCTION

Granular activated carbon (GAC) filter-adsorbers are becoming widely used for control of taste and odor and synthetic organic compounds (SOCs). While filter-adsorbers are relatively inexpensive to install, especially as retrofits to existing filter beds, their limited empty bed contact times (EBCTs) and frequent backwashing may hamper control of organics.

The water utilities industry in the United States is interested in the problems associated with retrofitting beds with GAC. The American Water Works Association Research Foundation (AWWARF) sponsored a pilot plant study of GAC filter-adsorbers at the Franklin Water Treatment Plant in Charlotte, North Carolina. The primary focus of this investigation was on the microbial quality of product water and generation of carbon fines.

The scope of work for this project was divided into the following three aspects:

1. General operations of filter-adsorbers including total organic carbon (TOC) removal, turbidity removal, and headloss accumulation.
2. Microbial activity on GAC.
3. Generation of carbon fines.

Previous reports by Cobb (1990) and Mallon (1991) discussed microbial activity and carbon fines. This report provides practical information on the operational aspects of GAC as a filter and as an adsorber of natural organic matter (NOM).

Proper operation of the pilot plant is a necessary first step in the overall study. Additionally, this report analyzes the breakthrough and steady state removal of NOM. Limited adsorptive capacity renders GAC filter-sorbers economically infeasible as a method of reduction for most NOM and SOC's. However, microbial biodegradation may allow steady state removal over significant periods of time. This would allow utilities to implement GAC filter-adsorbers to the new MCLs as set forth by amendments to the SDWA. The results presented in this paper both support and complement the scope of the AWWARF project.

The specific objectives of the studies described in this report were:

1. Construct AWWARF filter-adsorber pilot plant at the Franklin WTP in Charlotte, North Carolina and develop operational procedure.
2. Evaluate performance of pilot filter-adsorbers as a filter.
3. Evaluate performance of pilot filter-adsorbers for adsorption and biodegradation of organic matter.

CHAPTER 2. BACKGROUND

Granular activated carbon (GAC) is currently being used in over 150 water treatment plants in the United States (Schuliger, 1988). The primary use for GAC in water treatment is the removal of tastes and odors, which have been effectively removed with bed lives of 1-5 years (Graese et. al., 1987). In some cases, (e.g. Jefferson Parish, LA; Cincinnati, OH) GAC is employed to remove trihalomethane formation potential (THMFP). However, the short bed life for removal of these compounds is cost intensive, and thus application is not very widespread.

Across Europe, GAC is placed in post-filter adsorbers for removal of THMFP or other specific SOC's. In the United States, GAC is commonly used in place of granular media in conventional rapid filters (GAC filter-adsorbers) for both turbidity and organics removal (Graese et. al., 1987). Experience has shown GAC to be as effective as sand for turbidity removal (Hyde et. al., 1987).

The question of whether filter-adsorbers can be used to meet future maximum contaminant levels (MCLs) for specific compounds is important because of lower capital cost compared to post-filter adsorbers. Although effective for removal of taste and odor, use of filter-adsorbers for THMFP and other weakly-adsorbed compounds is limited. One reason for this is the limited EBCTs available due to restraints imposed by existing filter structures in sand-replacement filters. Shortened EBCTs require more rapid regeneration of GAC, resulting in higher costs.

Another issue related to filter-adsorbers is frequency of

backwash. Solids loading on filter-adsorbers requires more frequent backwashing, which causes a redistribution of particles within the bed, elongation of the mass transfer zone (MTZ), and faster breakthrough of the contaminant(s) (Cairo et. al., 1979). It is not yet fully understood if post-filter adsorbers are advantageous to filter-adsorbers with respect to backwash frequency. Experience shows that post-filter adsorbers must be backwashed eventually, although certainly not as often as filter-adsorbers. Research has shown no noticeable difference in performance of GAC backwashed every day versus GAC backwashed every thirty days (Weisner et. al., 1987).

Design and operation of GAC processes are influenced by their placement in the treatment scheme. Two important considerations for design of filter-adsorbers are media size and EBCT. Media selection for filter-adsorbers must accommodate both filtration and adsorption requirements. GAC media characteristics influence headloss development, filter run length, backwash requirements, and filtered water quality. A survey of several treatment plants in the United States shows filter-adsorbers to average 15 to 30 inches of 12x40 mesh (0.55-0.65 mm) or 8x30 mesh GAC (0.80-0.90) over two to twelve inches of sand (Graese et. al., 1987). These sizes of GAC provide the proper combination of effective size and uniformity coefficient to promote adsorption while allowing for longer filter runs and better cleaning.

The selected EBCT directly impacts the performance of the carbon for removing organic compounds (Westerhoff and Miller,

1986). In addition, as EBCT increases, the ratio of MTZ to EBCT decreases, and the specific volume of water treated increases (Hand et. al., 1989). A survey of filter-adsorbers in used show an average EBCT of 8.6 minutes with a range of 3.2 to 24.8 minutes. These filter-adsorbers produced an average effluent turbidity of 0.3 NTU with an average filter run length of 55 hours when fed at an application rate of 1 to 4 gpm/ft² (Graese et. al., 1987).

Much of current research is focused on microbial activity in GAC beds. Bioactivity on GAC is encouraged in several Western European countries, e.g. Germany, France, and the Netherlands. Microbes existing on GAC biodegrade organic compounds leading to increased steady state removal and longer bed life. Research has shown biodegradation to remove 8.5% - 16% of influent TOC (Maloney, 1984). This removal may be further enhanced by pre-ozonation (Maloney et. al., 1986).

In U.S. water treatment plants, however, practice is often to impair or preclude development of biological activity by pre-chlorination, rigorous scouring of filter media, and frequent backwashing (Bouwer, 1988). This is largely due to concern over the possible release of microbially-populated carbon fines into the distribution system. Populated GAC filter fines have been found in drinking water from numerous properly operated treatment facilities (McFeters, 1987). Bacteria on GAC has been found to be resistant to 2.0 mg/L chlorine for up to one hour of exposure (McFeters, 1987). This trade-off of enhanced organic removal versus the threat of microbial contamination of water systems is the impetus

for this project.

CHAPTER 3. METHODS AND MATERIALS

3.1 Treatment Plant Description

The 72 MGD Walter M. Franklin Water Treatment Plant (WTP), built in 1958 and upgraded in 1967, 1981, and 1990, currently produces three-fourths of the water used by customers in the Charlotte Mecklenburg Utility District (CMUD). A schematic of the Franklin WTP process train is shown in Figure 3-1. The water is treated by coagulation, flocculation, sedimentation, filtration, and disinfection.

The raw water is supplied from Mountain Island Lake which is fed from Lake Norman, an impoundment on the Catawba River. Water from Mountain Island Lake is pumped to a 250 million gallon reservoir located next to the plant for temporary storage prior to treatment. Characteristics of the water are given below:

Plant flowrate: 35-40 MGD
Turbidity: 3-25 NTU, avg= 8 NTU
Threshold Odor Number: 7-9, avg= 8
Alkalinity: 10-15 mg/L as calcium carbonate

Powdered activated carbon (1-2 mg/L) and chlorine (2-2.5 mg/L) are added to the water in the flash mixer feed lines for taste and odor control and disinfection. In the flash mixers, 9-11 mg/L of aluminum sulfate is added for destabilization of colloids that cause turbidity. After flocculation, water flows through the sedimentation basins, over a weir and onto the filters. Fluorine (0.9-1.2 mg/L), chlorine (0.1-1.0 mg/L), and lime (10-12

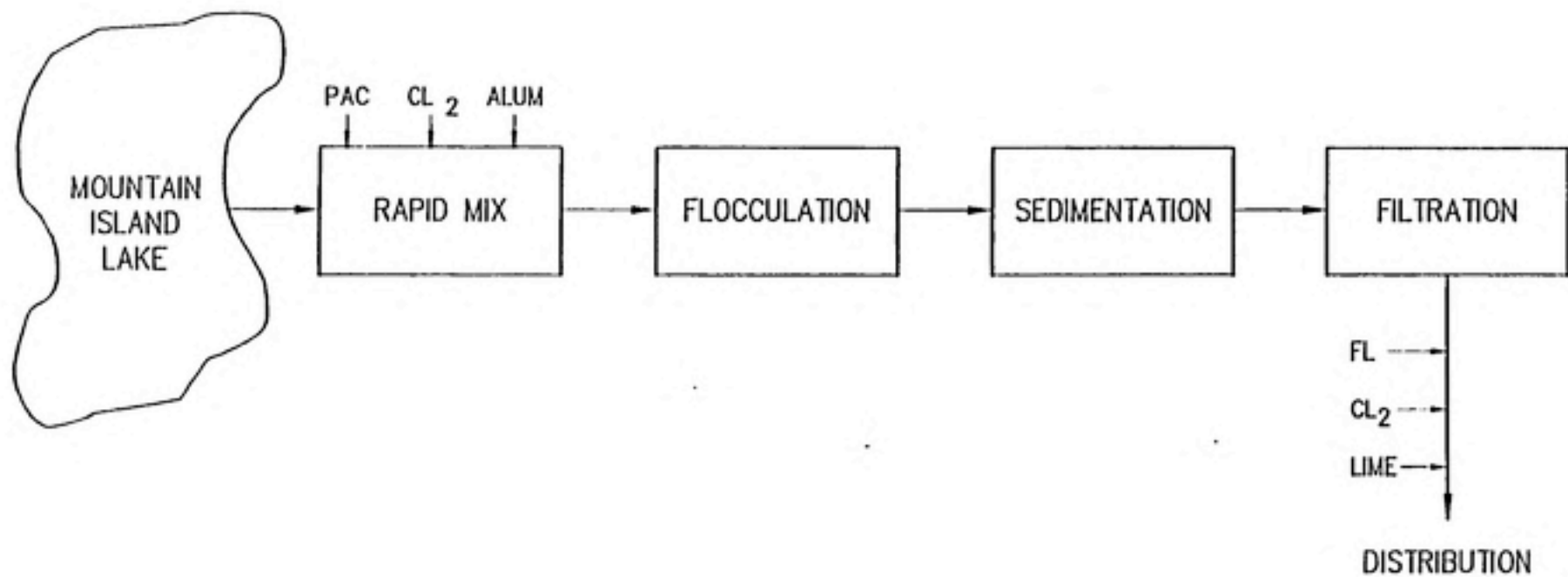


FIGURE-3.1 FRANKLIN WTP FLOW DIAGRAM

mg/L) are added to the filtered water prior to release into the distribution system.

3.2 Pilot Plant Description

The pilot plant was located in the basement of the filter building at the Franklin WTP. Settled water from the Franklin WTP was used as feed for the pilot plant, eliminating the need for simulation of coagulation, flocculation, and sedimentation processes.

The pilot plant consisted of three polyvinyl chloride filter housings having a height of 130 in. and a diameter of 4 in. A diagram of a typical pilot filter-adsorber is shown in Figure 3-2. These contained 30 in. of GAC over 12 in. of sand. A valved feed line near the top of the housing delivered water from the Franklin WTP sedimentation basin. Also near the top of the housing were the filter overflow and backwash exit lines, both connected to the drain. The location of the filter-adsorber overflow allowed for 6 ft of water on top of the media and 9.5 ft of total available head through the media. The columns were equipped with Camp nozzle underdrains that connected to three valved lines for filtered water effluent, backwash feed, and air scour. Sample ports were located at GAC depths of 2, 15, and 30 in. to allow for collection of water and media. In addition, other sample ports throughout the media were connected to manometer tubes to allow for headloss

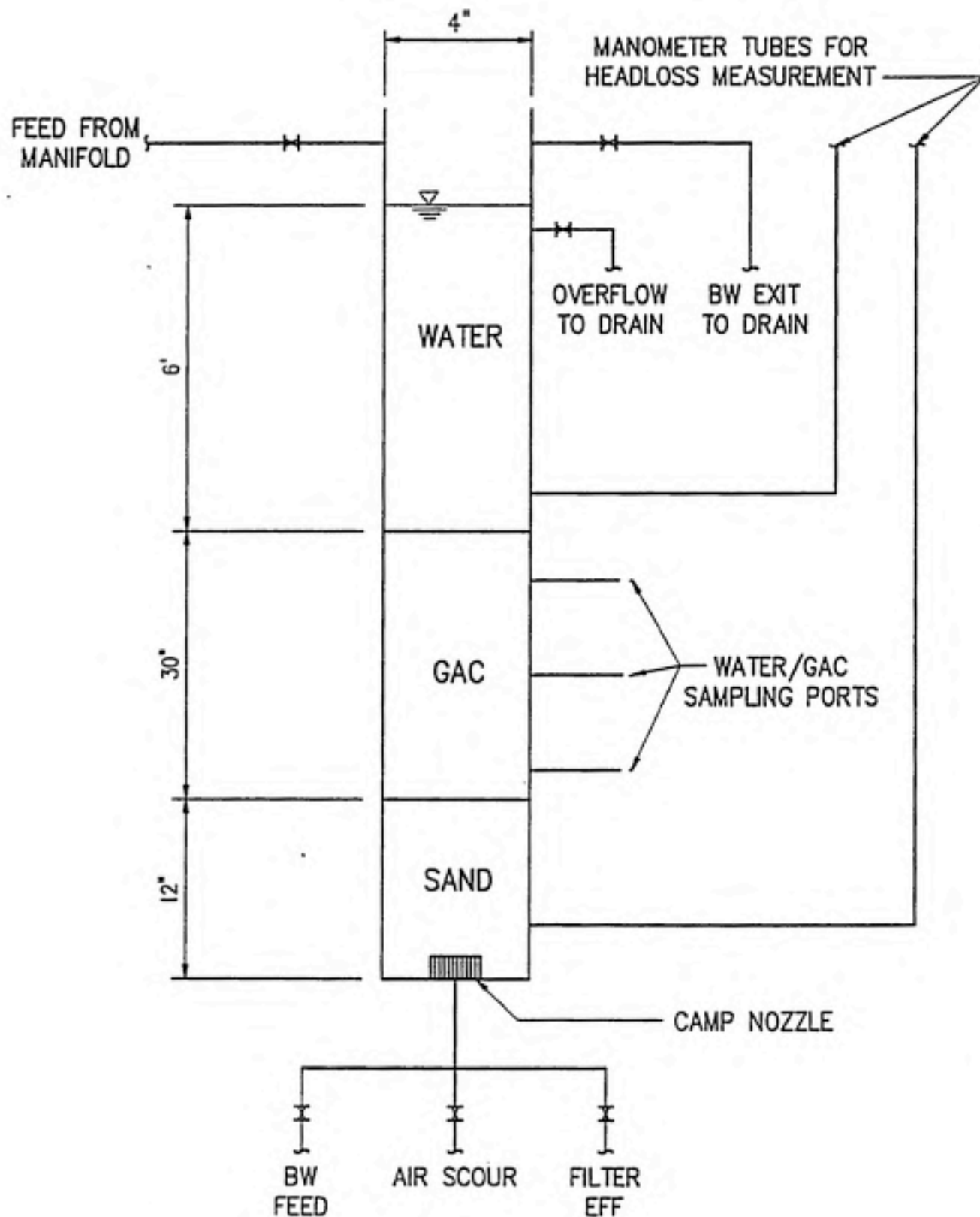


FIGURE-3.2 SCHEMATIC OF PILOT FILTER-ADSORBER

measurement.

The flow diagram for the pilot plant is given in Figure 3-3. Water was taken from a position in sedimentation basin at the Franklin Plant that was approximately 3 ft below the surface and directly below the overflow weir. The water was gravity-fed to the pilot plant feed manifold, which consisted of ball valves to distribute flow to the filters. Water from the manifold flowed in excess to the top of the filters. Variable-speed centrifugal pumps, connected to the filter underdrains, controlled the flow through the filters. Any excess water from the manifold drained through the filter overflows. Feed water and filtered water samples were collected at taps located at the manifold and pump suction, respectively.

Filtered water was pumped into 55 gallon clearwells. Overflow taps at the top of the clear wells drained excess flow while keeping the wells full at all times. The clearwells served as reservoirs for backwash water. Pilot plant valving allowed for the variable-speed centrifugal pumps to also be used as backwash pumps. During backwashing, filtered water was pumped from the clearwells, back through the filters and out the backwash drain at the top of the filter. Backwashing was augmented with air scour.

3.3 Pilot Plant Operation

Prior to each run, the filters were charged with 12 in. of

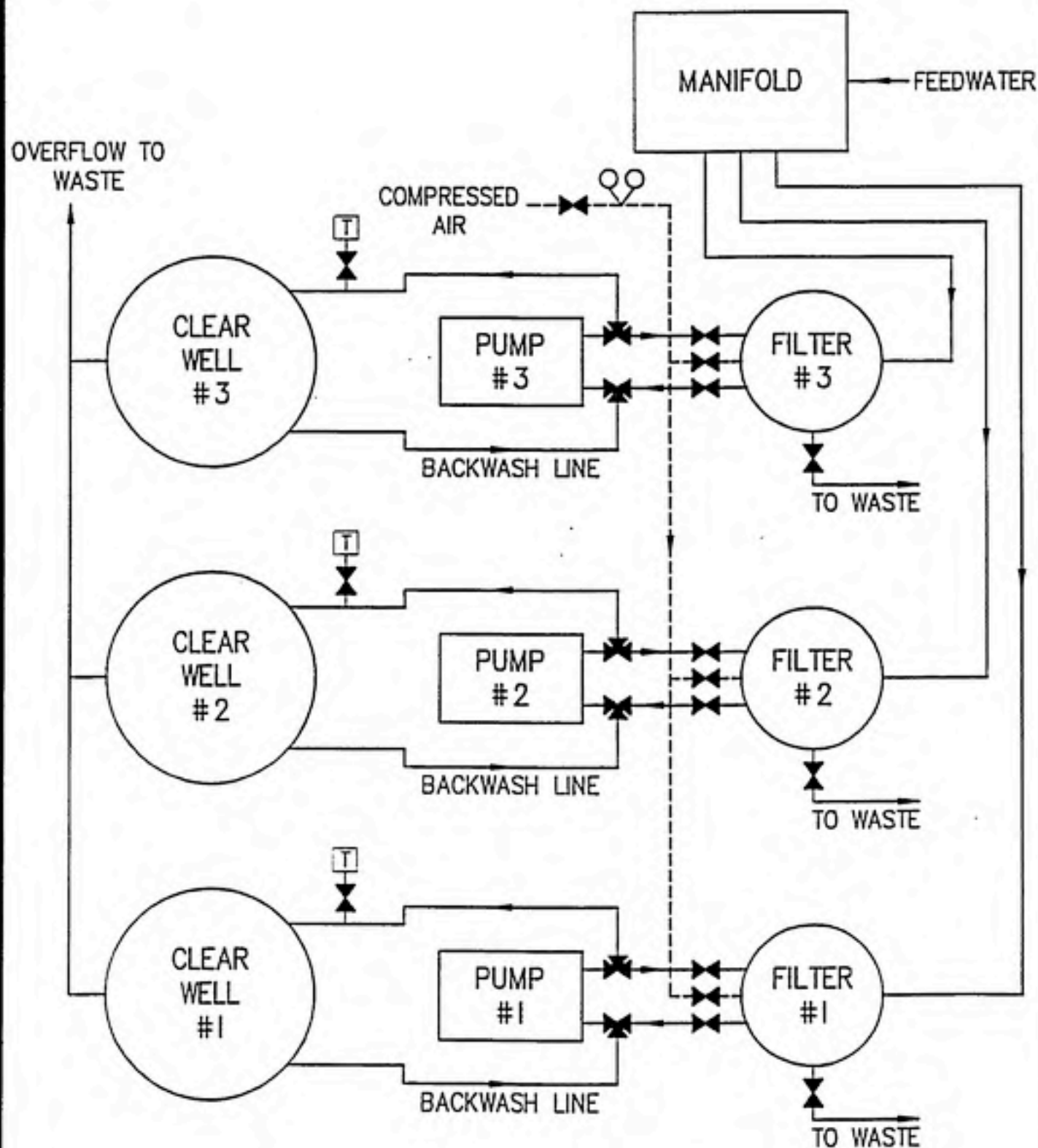


FIGURE-3.3 SCHEMATIC OF PILOT PLANT

Franklin WTP sand and 30 in. of fresh 8x30 GAC (Calgon Filtrasorb 300). The specific characteristics of the media are listed in Table 3-1.

Table 3-1: Pilot Plant Media Characteristics

<u>Media</u>	<u>Depth</u>	<u>Effective Size</u>	<u>Uniformity Coefficient</u>
GAC	30 in.	0.8-0.9 mm	1.9-2.4
sand	12 in.	0.5 mm	

The characteristics of 8x30 GAC closely resemble anthracite; this GAC is widely used in filter-adsorbers (Graese et. al., 1987). The sand provided an extra barrier against turbidity breakthrough. The filters were backwashed with filtered plant water several times after charging to assure initial carbon fine removal and bed stratification. Feedwater supplied to the pilot plant for Runs One and Two was Franklin Plant settled water. Characteristics of the feedwater for both runs are given below in Table 3-2.

Table 3-2: Pilot Plant Feedwater Characteristics

<u>Parameter</u>	<u>Run 1</u>	<u>Run 2</u>
pH	6.1-7.0	6.0-6.8
Average Turbidity, NTU	1.1	0.7
Average Color	9	9
Alkalinity, mg/L as CaCO ₃	15	15

3.3.1 Pilot Plant Runs

The operating condition for the two pilot plant runs discussed

in this report are summarized in Table 3.3 below:

Table 3.3 Pilot Plant Runs

<u>Run</u>	<u>Filter</u>	<u>Operating Conditions</u>		
		<u>App. Rate</u> <u>(gpm/ft²)</u>	<u>EBCT</u> <u>(min)</u>	<u>Backwash</u> <u>Frequency</u>
1	1	2	8.2	72 hr
	2	6	2.7	24 hr
	3	4	4.1	48 hr
2	1	4	4.1	48 hr*
	2	4	4.1	24 hr
	3	4	4.1	48 hr

* backwash water was chlorinated to 2 mg/L

3.3.1.1 Run One: Effect of Application Rate on Performance

The purpose of Run One (December 16, 1988 - April 8, 1989) was to determine the effect of settled water application rate and corresponding EBCT on filter-adsorber performance. Feed rates were set by the variable-speed centrifugal filter pumps and measured by Wheaton rotameters located on the discharge side of the pumps. Filter 1 was set at 2 gpm/ft², Filter 2 at 6 gpm/ft² and Filter 3 at 4 gpm/ft².

Operating three filters at different application rates with the same feed water produced three different rates of headloss accumulation. During Run One, Filter 1 (2 gpm/ft²) was backwashed every 72 hr, Filter 3 (4 gpm/ft²) every 48 hr, and Filter 2 (6 gpm/ft²) every 24 hr. Backwashing at a given time rather than at

a designated headloss assured adequate plant staff availability in case of breakdown and minimized operator oversight. The standard backwash procedure used for all filter-adsorbers during Run One is discussed in Section 3.3.2 of this report.

Operators monitored the pilot plant every four hours, checking and recording application rates, and filter effluent turbidities, and filter headlosses. Turbidity and headloss measurements are discussed later in Section 3.4 and 3.5 of this report.

3.3.1.2 Run Two: Effect of Backwashing Strategy on Performance

The purpose of Run Two (May 17-August 7, 1989) was to determine the effect of backwash strategy on filter-adsorber performance. During Run Two, all filters were run at an application rate of 4 GPM/ft². Filters 1 and 3 were backwashed every 24 hr, and Filter 2 every 48 hr. Filter 1 washwater was chlorinated to 2 mg/L by adding approximately 40 mL of chlorine bleach to Clearwell 1 prior to backwashing. Actual backwashing procedure and pilot plant monitoring were continued as in Run One.

3.3.2 Procedure for Backwashing of Filter-Adsorber

The standard backwashing procedure used during Runs One and Two was developed in accordance with recommendations from the literature (Graese, 1987). Table 3.4 presents the backwash

Table 3.4 Operator Instructions for Backwashing of Filter-Adsorbers

PILOT FILTERS BACKWASH PROCEDURES

1. Shut off source water for unit
2. Allow water level to reach 6" above top of filter media
3. Turn off pump
4. Shut off valve on bottom of unit that feeds pump
5. Open valve on bottom of unit for backwashing
6. Open compressed air valve and set to - 2.5 psi
7. Open air scour valve on bottom of unit (visually adjust rate to slow boil)
8. Reverse 2 valves at pump to draw from barrel and feed to backwash filter.
9. Switch pump on and adjust to 0.5 GPM (make sure pump isn't air-locked)
10. When water level reaches 6" below waste line, turn off air scour.
(NOTE: As water level is rising, the air pressure might have to be increased to counter increase in head and maintain slow boil)
11. Increase pump rate to 1.4 GPM
12. Backwash at this rate for 5.5 minutes
13. Shut off backwash pump
14. Reverse 2 valves at pump to original settings (pumping to drums)
15. Open valve at bottom of unit that feeds pump
16. Close backwash valve at bottom of unit.
17. Switch pump on and adjust to normal setting.
18. Open source water valve to unit
19. Shut off compressed air valve on the wall
20. Do a final check to see that water is coming into the unit and being pumped out to the drum at the desired rate.

procedure in the form of operator's instructions. The initial backwash rate was 5 gpm/ft² and included air scour. After approximately 2 minutes, the air scour was ceased, and the backwash rate was increased to 14 gpm/ft² for 5.5 minutes.

3.4 Measurement of Turbidity

Hach Low-Range Process Turbidimeters sampled water from the discharge lines of the filter pumps. Turbidity measurements were recorded every four hours by the plant operators during routine inspection. The turbidimeters were calibrated according to manufacturer's specifications by the Franklin plant instrument staff prior to the start of each run.

3.5 Measurement of Headloss

Filter headlosses were measured by tygon manometer tubes that were inserted into ports located along the depth of the filters. The tubes were attached to a board which was marked-off in 0.25 ft increments. The total headloss across the filter was the difference in water levels of manometer tubes connected to ports located at points in the filter freeboard and underdrain. Operators recorded total headloss every four hours during routine inspection of the pilot plant.

3.6 Measurement of Total Organic Carbon

Total organic carbon (TOC) samples were analyzed with an O. I. Corporation Model 700 TOC Analyzer. Samples introduced into the OI 700 were automatically acidified with 5% phosphoric acid, purged to remove inorganic carbon, and analyzed to measure inorganic carbon. After the purging step, sodium persulfate (100 g/L) was introduced to the sample in a 100°C reactor to oxidize the organics to carbon dioxide. The carbon dioxide was subsequently purged to an IR detector and measured against a linear KHP calibration to yield TOC (actually non-purgeable organic carbon). The specifications for this instrument indicate $\pm 2\%$ of full scale error as a result of the linear assumption and $\pm 2\%$ of full scale error of repeatability for sample concentrations greater than 0.002 mg/L (Harrington, 1987).

TOC samples were collected daily in 40 ml septum vials. The samples were dosed with concentrated nitric acid to inhibit biological activity, refrigerated, and analyzed within two weeks of collection.

3.7 Measurement of Trihalomethane Formation Potential (THMFP)

Samples analyzed for THMFP were buffered with a phosphate buffer solution and chlorinated to 20 mg/L with a stock solution of sodium hypochlorite. After a five day incubation period in the

dark, the samples were analyzed for remaining chlorine residual, and THMs were extracted using a liquid/liquid technique. The solvent used was n-pentane with carbon tetrachloride as an internal standard. After extraction, THMs were chromatographed on SP-1000 using a GC equipped with a ^{63}Ni electron capture detector. For a more detailed description of THMFP analytical procedures, refer to Reckhow (1984).

3.8 Determination of GAC Adsorption Isotherm

The equilibrium adsorption of TOC in plant settled water was determined using the bottle point method as described by Randtke and Snoeyink (1983). GAC (Filtrisorb 300) was prepared by washing with distilled-deionized water, drying at 110°C and grinding to 200 x 325 U.S. Standard mesh size. After preparation, different dosages of activated carbon were added to 16 bottles, each containing 100 mL of settled water from the Franklin WTP with a known TOC concentration of 1.47 mg/L. Activated carbon doses ranged from 2 to 240 mg/L; one bottle contained no activated carbon. Phosphate buffer (3 mg/L) and sodium azide (5 mg/L) were added to the sample bottles to maintain pH and inhibit biological degradation of TOC, respectively. The bottles were then placed on a tumbler and equilibrated for 7 days at room temperature.

After equilibration, the samples were filtered with 0.45 μm membrane filters to remove the activated carbon. The filters had

been pre-soaked to remove any residual TOC. The TOC of the samples was measured after filtration.

CHAPTER 4. RESULTS AND DISCUSSION

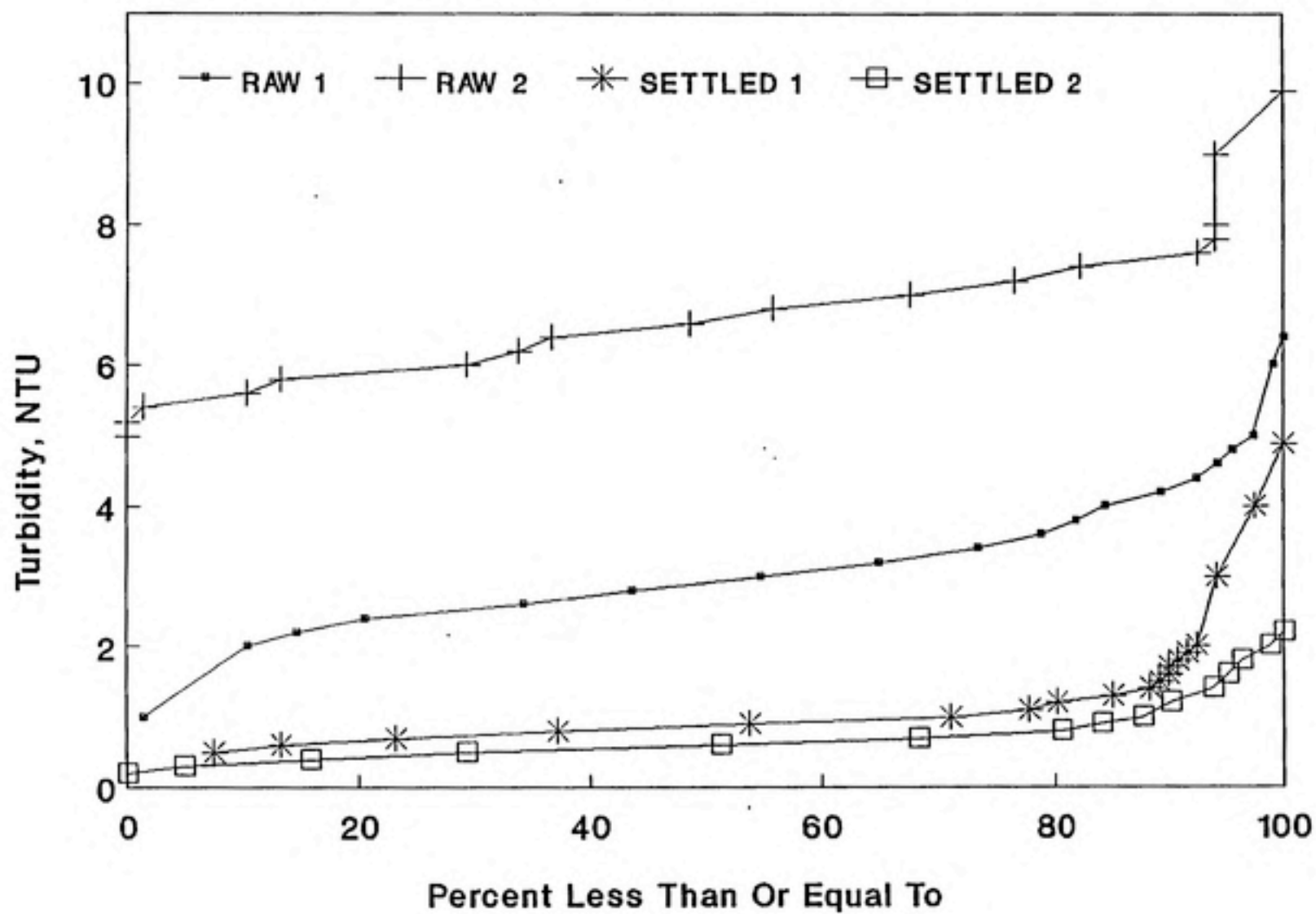
4.1 Turbidity Removal

4.1.1 Raw and Settled Water Turbidity During Pilot Plant Studies

Results of turbidity measurements made during this study are presented in the form of frequency plots in Figures 4-1. Inspection of these data shows that 95% of the time the raw water turbidity during Run One was less than 4.8 NTU and 50% of the time the NTU was less than 2.7. During Run Two, 95% of the time the raw water turbidities were less than 9.2 NTU and 50% of the time less than 6.7 NTU.

The higher raw water turbidity found in Run Two than Run One was attributed to seasonal lake dynamics. Changes in temperature cause lakes to turn over during the spring and fall. Associated with these turnovers is increased turbidity as murky water near the bottom of the lake is cycled to the surface. Run Two occurred May 17-August 7 and included water from the spring turnover. Run One, on the other hand, occurred December 16-April 8, between the fall and spring turnovers. The difference in raw water turbidities between Runs One and Two, however, is not reflected in the settled water turbidity data. This shows that Franklin plant maintained effective coagulation, flocculation, and sedimentation throughout both runs.

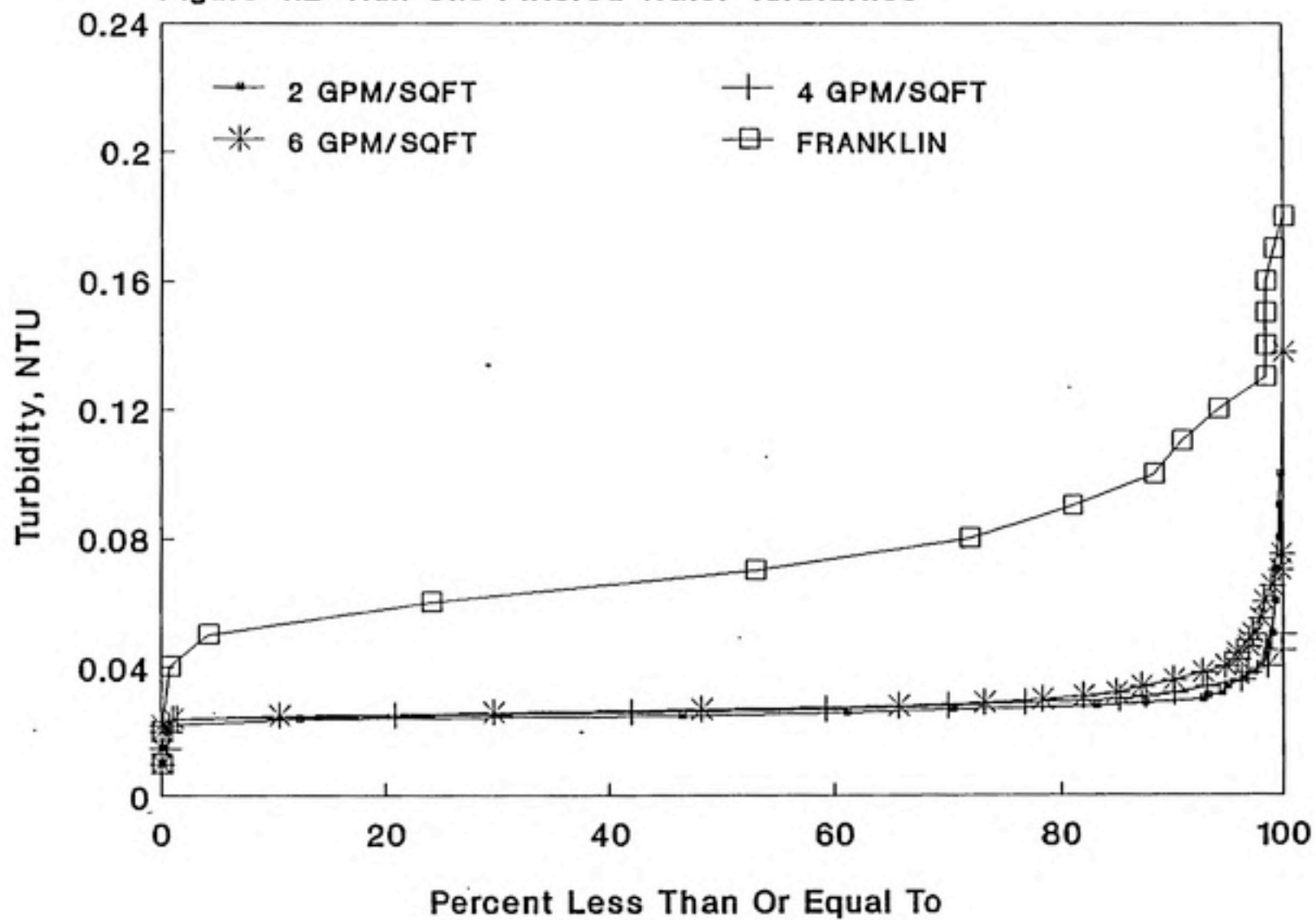
Figure 4.1 Franklin WTP Turbidities



4.1.2 Effect of Application Rate on Turbidity Removal (Run One)

Filtered water turbidity data from Run One is presented in Figure 4-2. Because a common manifold was used to deliver settled water to all three filters, it was assumed that the feed water was of the same turbidity. The data in Figure 4-2 show that the same product water turbidity was obtained regardless of application rate. Although 4 gpm/ft² is widely considered standard practice for a filter application rate, Lykins and Adams (1989) give several examples of comparable filter performance at application rates to 6 gpm/ft². Further, Graese et. al. (1987) reports successful turbidity removal by 8x30 GAC and sand filters at filter application rates ranging from 1 to 3.5 gpm/ft². In addition, it would appear that the GAC pilot filter-sorbers were more effective at turbidity removal than the Franklin dual media sand-anthracite filters: 90% of filtered water turbidity values from the pilot filter-adsorbers were less than 0.02 NTU as compared to 90% of the values from the Franklin dual media filters being 0.10 NTU. While GAC has been shown to be better than anthracite for turbidity removal due to increased surface angularity (Hyde, 1987), the inaccuracy of the turbidimeters at turbidities this low (less than 0.1 NTU) prevent drawing a definite conclusion.

Figure 4.2 Run One Filtered Water Turbidities



4.1.3 Effect of Backwashing on Turbidity Removal (Run Two)

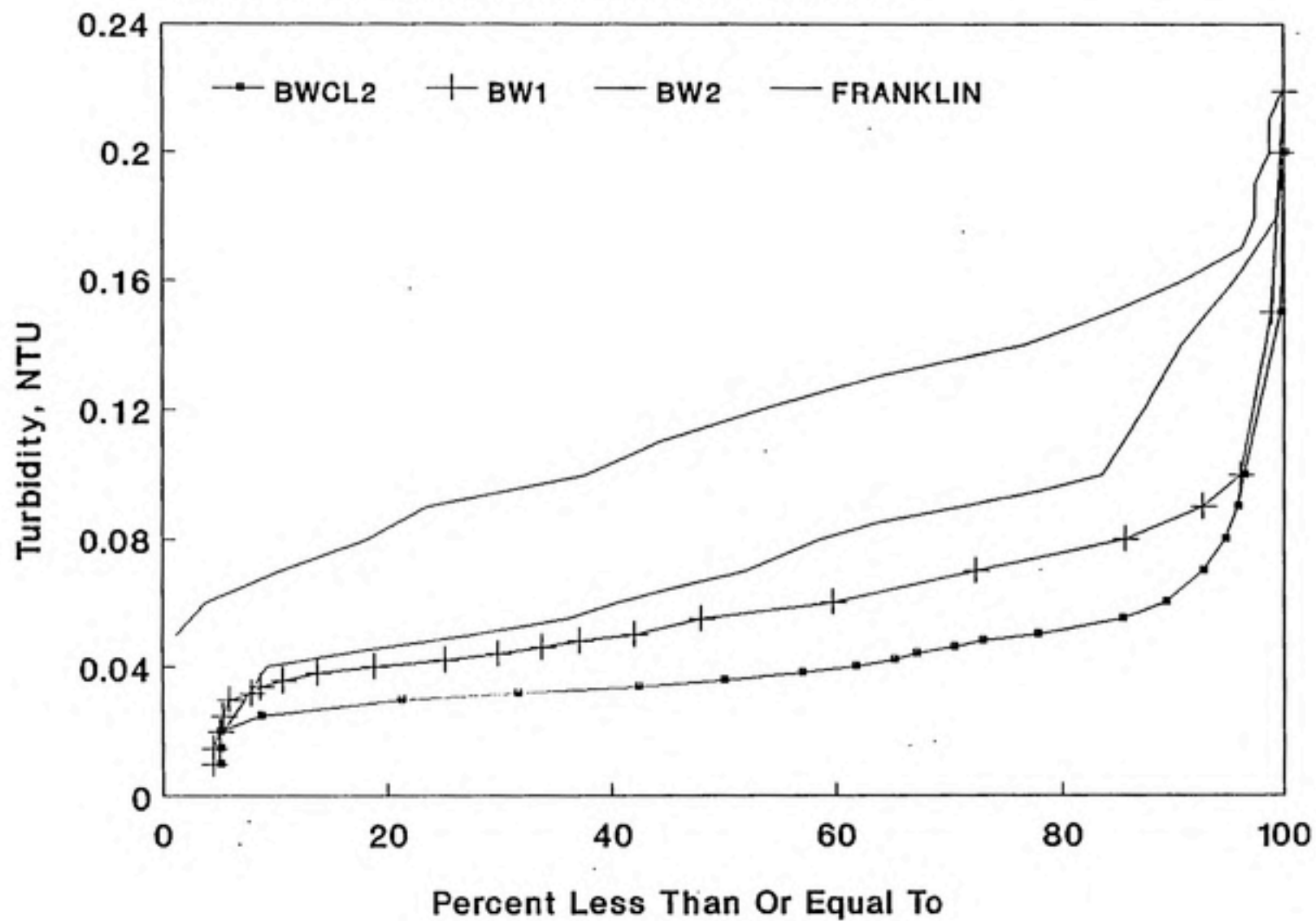
Figure 4-3 represents filtered water turbidity data from Run Two. As in Run One, considering the precision of the turbidimeter, there is no discernible difference amongst the pilot filters or between the pilot filters and the Franklin plant filters. This is not unexpected since the backwash strategies employed during Run Two were not expected to alter turbidity removal.

4.1.4 Conclusions on Turbidity Removal

Overall, these turbidity data suggests GAC filter-adsorbers were as effective in removing turbidity as sand-anthracite filters. In addition, performance was not affected by application rate or the different backwash strategies employed. As shown in Figures 4-2 and 4-3, 90% of the time the filtered water turbidities for the filter-adsorbers were below 0.2 NTU. The few high turbidity values beyond this range may be explained by readings recorded soon after backwashing, i.e., during the ripening stage of filtration. However, overall the turbidity values were very low and suggest that performance met the current MCL of 1 NTU and the proposed NTU of 0.5 without difficulty.

Removal of turbidity by the filter-adsorbers during Runs One and Two was undoubtedly aided by the 12 in. sand layer placed below the GAC. While sand is an effective barrier against turbidity

Figure 4.3 Run Two Filtered Water Turbidities

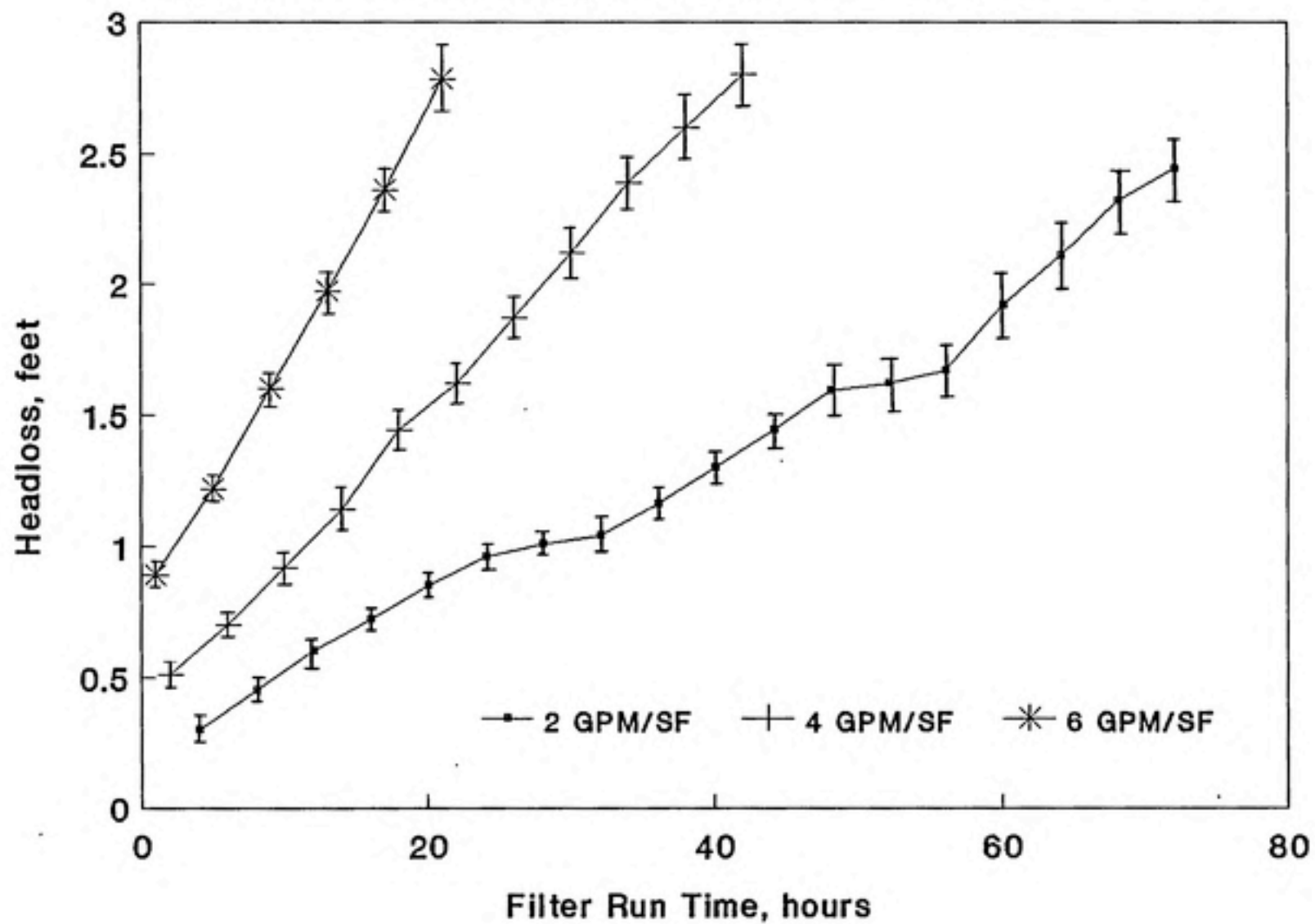


breakthrough, it also reduces the adsorptive capacity of the filter-adsorber by taking up filter-box volume that would otherwise be occupied by additional GAC. The occupation of filter-box volume by sand can be even more problematic for existing filter boxes that are relatively shallow. The Coliform Rule, as part of amendments to the Safe Drinking Water Act, sets a maximum level for turbidity at 0.5 NTU. The filtered water turbidities were much lower than this goal, and suggests less sand could have been used. Further investigations should address the proper depth of sand layer to maintain compliance with the Coliform Rule while maximizing the adsorption capacity of the filter-adsorber.

4.2 Headloss Accumulation

Each filter run generated a series of headloss data. Headloss readings were then organized with respect of time into each filter run. All of these individual filter runs were averaged over the entire pilot run (two to three months of data) in order to generate representative curves for headloss accumulation. Included with the curves are confidence intervals with a coefficient $(1 - \alpha) = 0.95$. Both filter run time and volume of water filtered to a given filter run time were of interest.

Figure 4.4 Run One Average Headloss Accumulations



4.2.1 Effect of Application Rate on Headloss Accumulation

Figure 4-4 shows the average headloss accumulations as a function of filter run time in Run One. The order of increasing headloss was for application rates of 2, 4, and 6 gpm/ft². Assuming consistent settled water quality between the filter-adsorbers and comparable filtered water turbidities, each of the three filter-adsorbers removed the same amount of turbidity per unit volume of water treated. Thus, it was reasonable to expect headloss to accumulate faster as application rate (and volume applied per unit time) increased.

The effect of application rate on headloss accumulation was normalized by plotting headloss as a function of bed volumes filtered (BVF). $BVF = Qt/V_b$, where Q is flow rate, t is the time of saturation, and V_b is the volume of the filter bed. The results are given in Figure 4-5. The headloss accumulations with BVF are fairly parallel for each application rate. A higher initial headloss with higher application rate is expected based on filter hydraulics.

Calculating the slopes of headloss accumulation vs. BVF data produces the average headloss accumulation rate for each filter-sorber during Run One. Table 4-1 lists these rates in addition to accumulation rates for Franklin plant filters during the same time.

Figure 4.5 Run One Average Headloss Accumulations

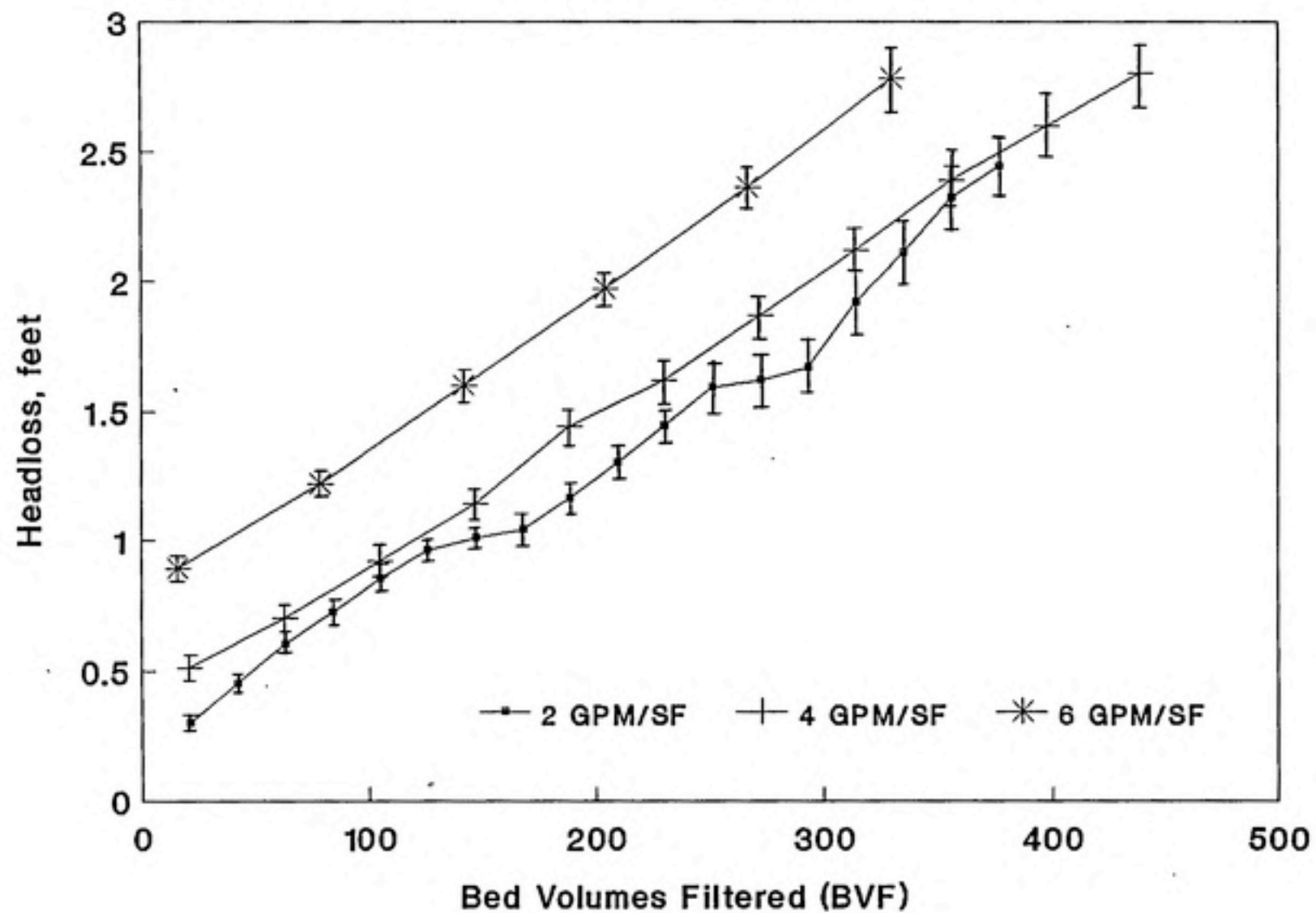


Table 4-1: Average Headloss Accumulation Rates During Run One

<u>Application Rate</u>	<u>Pilot</u>	<u>Franklin WTP</u>
2 gpm/ft ²	0.072 in./BVF	-----
4 gpm/ft ²	0.066 in./BVF	0.043 in./BVF
6 gpm/ft ²	0.072 in./BVF	0.059 in./BVF

A comparison of headloss accumulation rates between the filter-adsorbers shows application rate to have no discernible effect on filter headloss accumulation. In addition, these rates are similar to those in the full-scale filters at the Franklin plant.

4.2.2 Effect of Backwashing on Headloss Accumulation (Run Two)

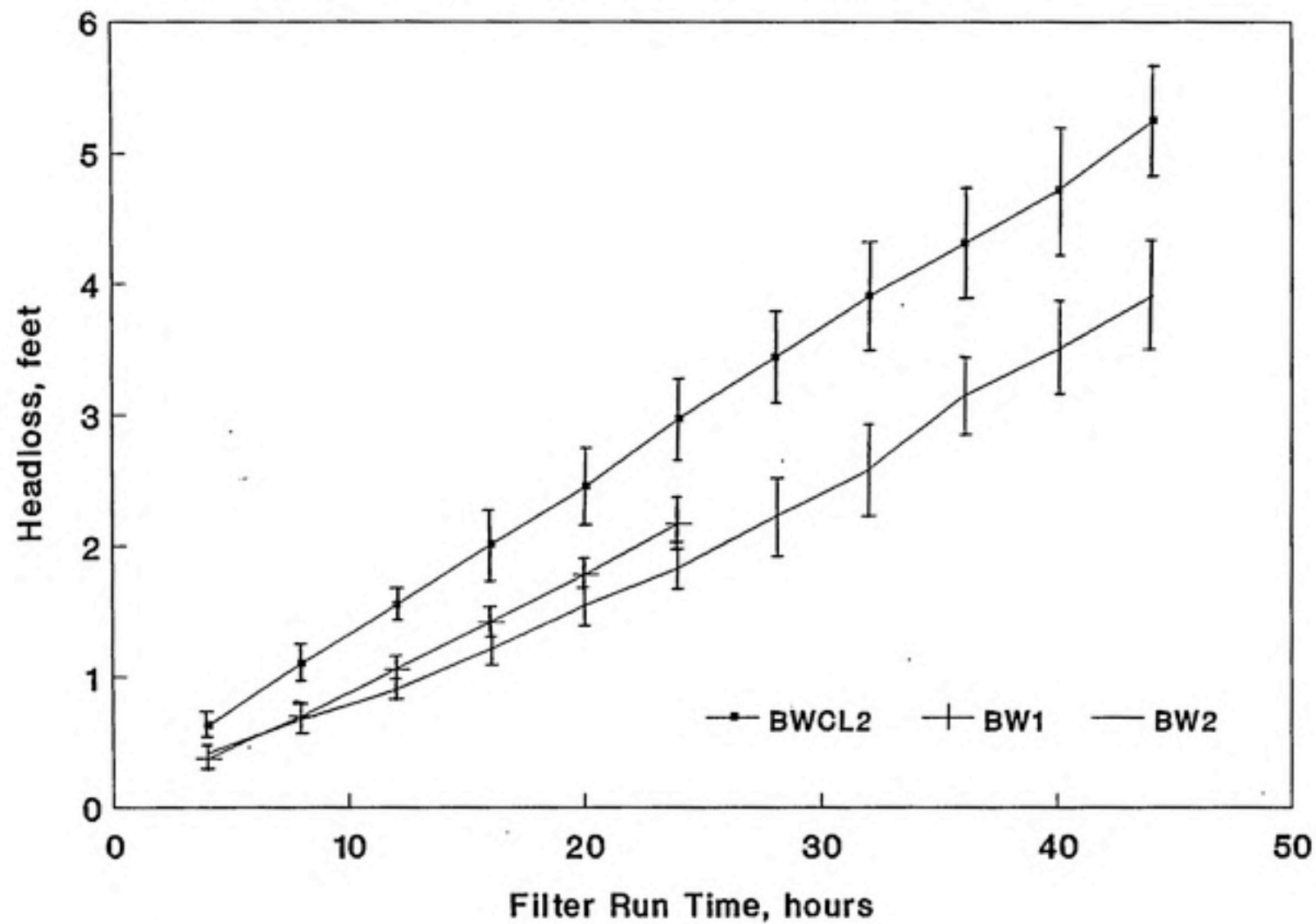
Average headloss accumulation curves for Run Two are shown in Figure 4-6. Normalization of application rate by BVF is not necessary for these data since all of the filter-sorbers were operated at the same application rate of 4 gpm/ft². Corresponding headloss accumulation rates (from the slopes of the data in Figure 4-6) for the filter-adsorbers are calculated in Table 4-2.

Table 4-2: Average Headloss Accumulation Rates During Run Two

<u>Backwash Strategy</u>	<u>Headloss Accumulation Rate</u>
daily	1.06 in./hr (0.101 in./BVF)
every two days	1.03 in./hr (0.098 in./BVF)
chlorinated, every two days	1.37 in./hr (0.130 in./BVF)

The data in Table 4-2 show that backwash frequency had no

Figure 4.6 Run Two Average Headloss Accumulations



effect on headloss accumulation rate. However, the filter-adsorber backwashed with chlorinated water exhibited a much higher rate. This is not easily explained. It is possible that chlorine had a brittling effect on the GAC; however, at 2 mg/L, only 0.076 grams of mass chlorine were added to this filter-adsorber during backwashing. This is small compared to the 5.2 grams of chlorine received by all of the filter-adsorbers from the feed water during every filter run.

Over time, the shape and/or size of the media could have been changed due to numerous backwashings. However, filter runs during the first 5 days of Run Two averaged headloss accumulations of 1.32 in./hr while filter runs during the last 5 days average 1.35 in./hr. It is evident that time was not a factor. This would also rule out any biological explanation considering the filter-adsorbers would become more populated with time.

Another possible explanation is operator error in measuring headloss. A comparison of headloss data between the two runs shows larger confidence intervals in Run Two. This suggests the data were not as consistent throughout this run. It is possible the manometer tubes became fouled with activated carbon dust and more difficult to read over time. Assessing the confidence intervals in Figure 4.6, it is difficult to determine if the difference in the slopes of the curves is real or the result of error in measurement.

Expressing headloss accumulation rates as in./BVF allows comparison of results from Runs One and Two. The operation of the

filter-adsorber backwashed every other day during Run Two is identical to the operation of the filter-adsorber with an application rate of 4 gpm/ft² during Run One. While similar headloss accumulation rates would have been expected, that in Run Two was much higher. One possible explanation is a change in settled water quality between the two, pilot-plant runs. Section 3.1 of this report described differences in raw and settled water turbidity in the two pilot runs. Raw water turbidity was higher in Run Two than in Run One but settled water turbidity remained about the same. Nevertheless, the higher raw water turbidity meant an increase in floc in the sedimentation basins. The intake for the pilot plant was located approximately 3 ft. below the surface of the sedimentation basins. Thus, the settled water turbidity measured by plant personnel is not necessarily the actual turbidity entering the pilot plant. It is possible that the increased amount of floc in the sedimentation basins resulted in a higher concentration of floc (and thus higher turbidity) to the pilot filter-adsorbers during Run Two. This would explain the higher headloss accumulation rates.

4.2.3 Conclusions on Headloss Accumulation

Overall, the performance of the filter-adsorbers was comparable to conventional filters over a range of application rates and backwash conditions. The explanation for increased rate

of headloss in the chlorinated-backwash filter-adsorber remains unclear. Perhaps the additional floc in the feedwater to the pilot plant during Run Two was not evenly distributed by the manifold, and this particular filter received a heavier load. Alternatively, errors in reading the manometer tubes could have occurred. As noted in Section 3.1, sand used in the filter-adsorbers may not be necessary to prevent turbidity breakthrough. Eliminating the sand layer may lessen the rate of headloss accumulation.

4.3 TOC Removal

4.3.1 TOC Removal-- Run One

The effect of application rate on TOC adsorption was investigated in Run One. As application rate increased, the adsorbate loading rate (mass/time) increases and the EBCT of the filter-adsorber decreases. According to the simple equilibrium adsorption model, loading rate increases and the time to reach exhaustion of adsorbent capacity should decrease. As EBCT decreased, the ratio of the MTZ to EBCT increases thereby causing the MTZ to comprise a larger portion of the length of the filter-adsorber. If the MTZ is large (due to slow mass transfer characteristics), as is the case for NOM, more adsorbate escapes into the product water and less of the total adsorptive capacity is

Figure 4.7 Run One TOC Breakthrough Curves

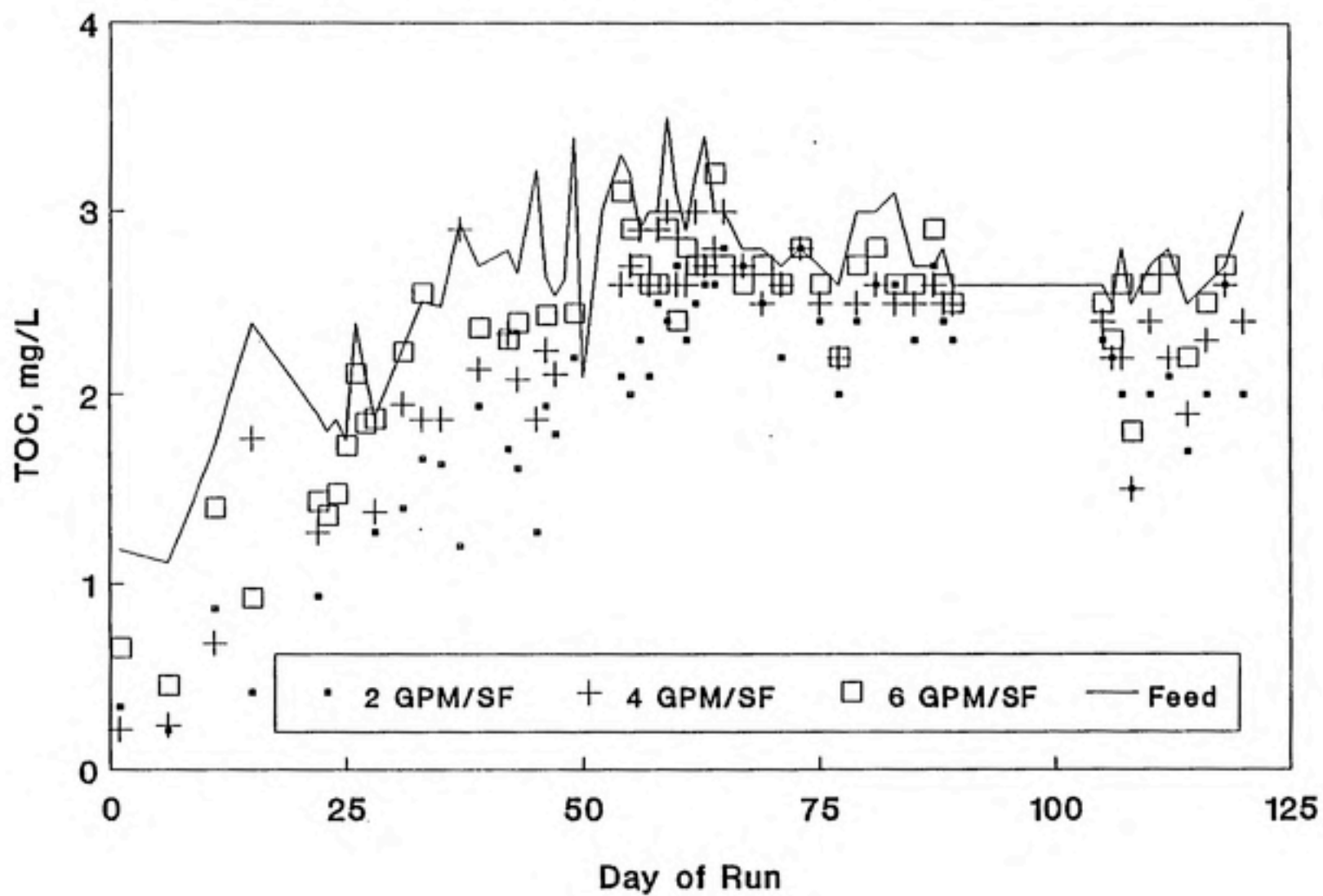
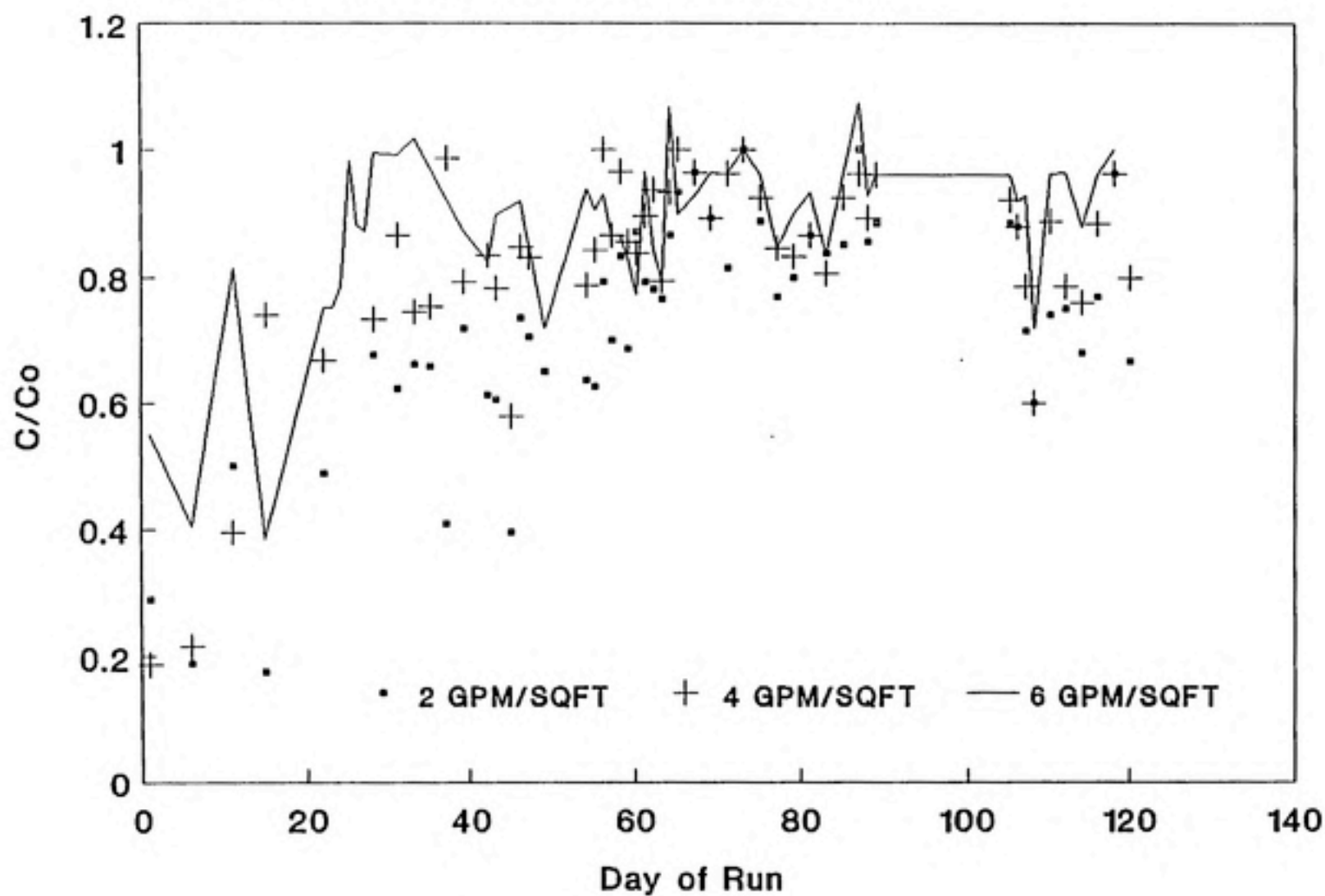


Figure 4.8 Run One TOC Breakthrough Curves



utilized.

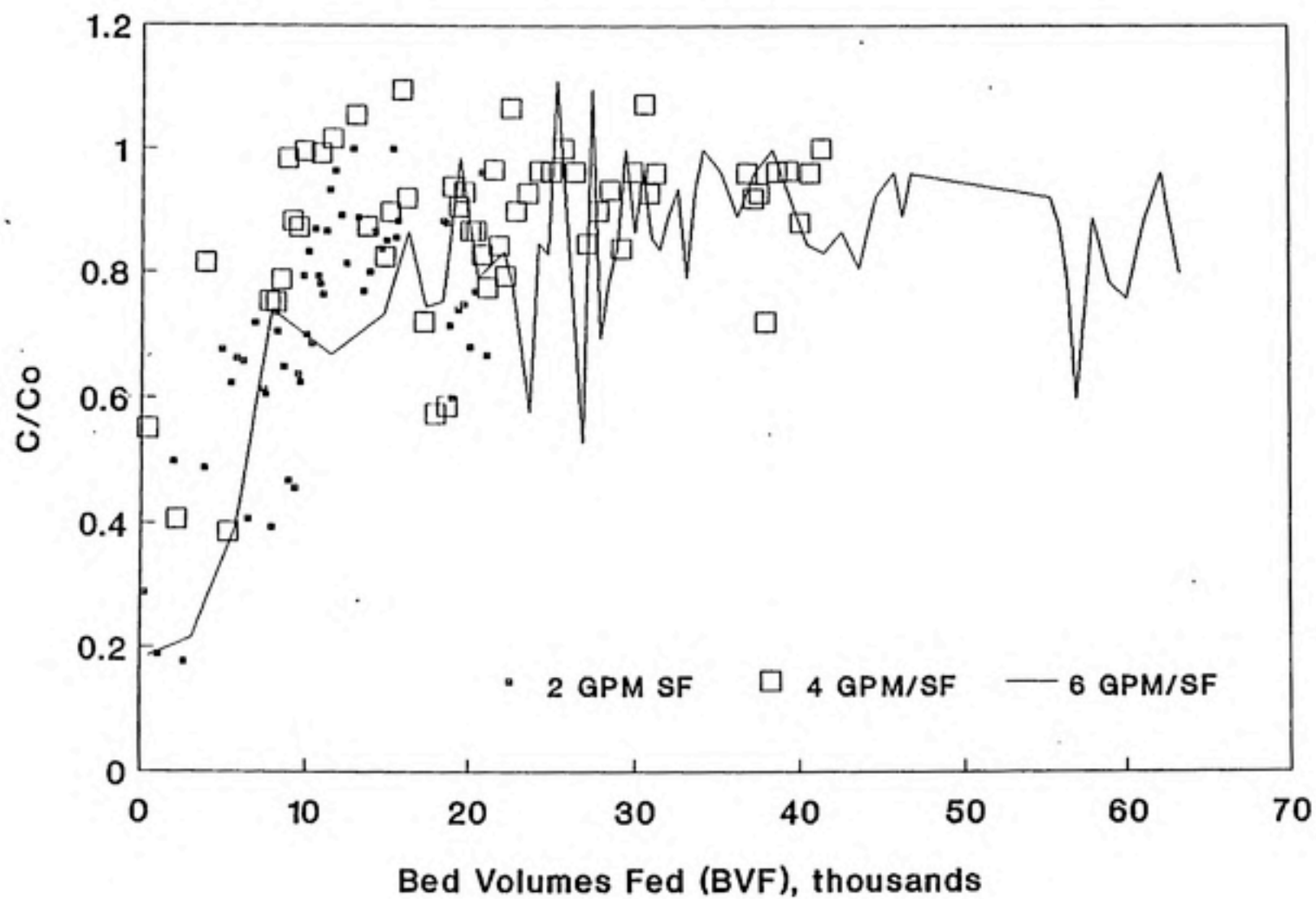
Figure 4-7 presents TOC breakthrough data from Run One. Samples for Day 1 were collected immediately after start-up of the filter-adsorbers. Presence of TOC in these samples suggest either a non-adsorbable fraction of TOC or severe mass transfer limitations caused by insubstantial EBCT.

A comparison of fractional TOC breakthrough curves is presented in Figure 4-8 by normalizing the product water TOC data by the average feed TOC. The general trend (although the data show considerable scatter) is for TOC breakthrough to occur later as application rate decreased. For example, 50% breakthrough occurs almost immediately for the application rate of 6 gpm/ft², whereas it occurs between Day 11 and Day 15 for 4 gpm/ft² and between Day 22 and Day 28 for 2 gpm/ft².

The effect of application rate on mass loading rate of TOC can be normalized by plotting TOC breakthrough as a function of BVF rather than time. As shown in Figure 4-9, it is difficult to determine one common shape for the initial pattern of the breakthrough. This suggests that the effect of mass loading rate alone may not explain differences with application rate.

The effect of increasing the ratio of MTZ to EBCT as application rate is increased can also be examined. The amount of TOC adsorbed to some target TOC in the product water is calculated for each filter-adsorber by subtracting the area under the filter-adsorber breakthrough curve (Figure 4-7) from the area under the

Figure 4.9 Run One TOC Breakthrough Curves



feed water TOC curve. This area is calculated up to the time when 1 mg/L of TOC appears in the product water, or Days 9, 12, and 23 for the 6, 4, and 2 gpm/ft² filter-adsorbers, respectively. Using the trapezoidal rule for area calculations, TOC removed at each application was 29 grams at 2 gpm/ft², 24 grams at 4 gpm/ft², and 16 grams at 6 gpm/ft². The decrease in TOC removal with increasing application rate suggests that the effect of MTZ/EBCT ratio is important.

4.3.2 Approach to Steady State Removal-- Run One

After adsorption capacity is exhausted, removal of adsorbate can continue to be realized through biodegradation. Data shown after Day 100 in Figure 4-8 suggest that steady state removal of TOC may be occurring, though scatter in the data prevents drawing a definite conclusion. T-tests analyses were performed to determine at what level the differences between the average feedwater TOC concentration after Day 100 (u_f) and the average filtered water TOC concentrations after Day 100 (u_2 , u_4 , u_6) were statistically significant. Results from these analyses, summarized in Table 4-3, show removal of TOC to be statistically significant at a confidence level greater than 99% for application rates of 2 gpm/ft² and 4 gpm/ft². Removal for the application rate of 6 gpm/ft² was shown to be at a much lower confidence level, as was the difference between the 2 and 4 gpm/ft² removals.

Table 4-3: T-test Analyses on Significance of Run One Steady-State TOC Removal

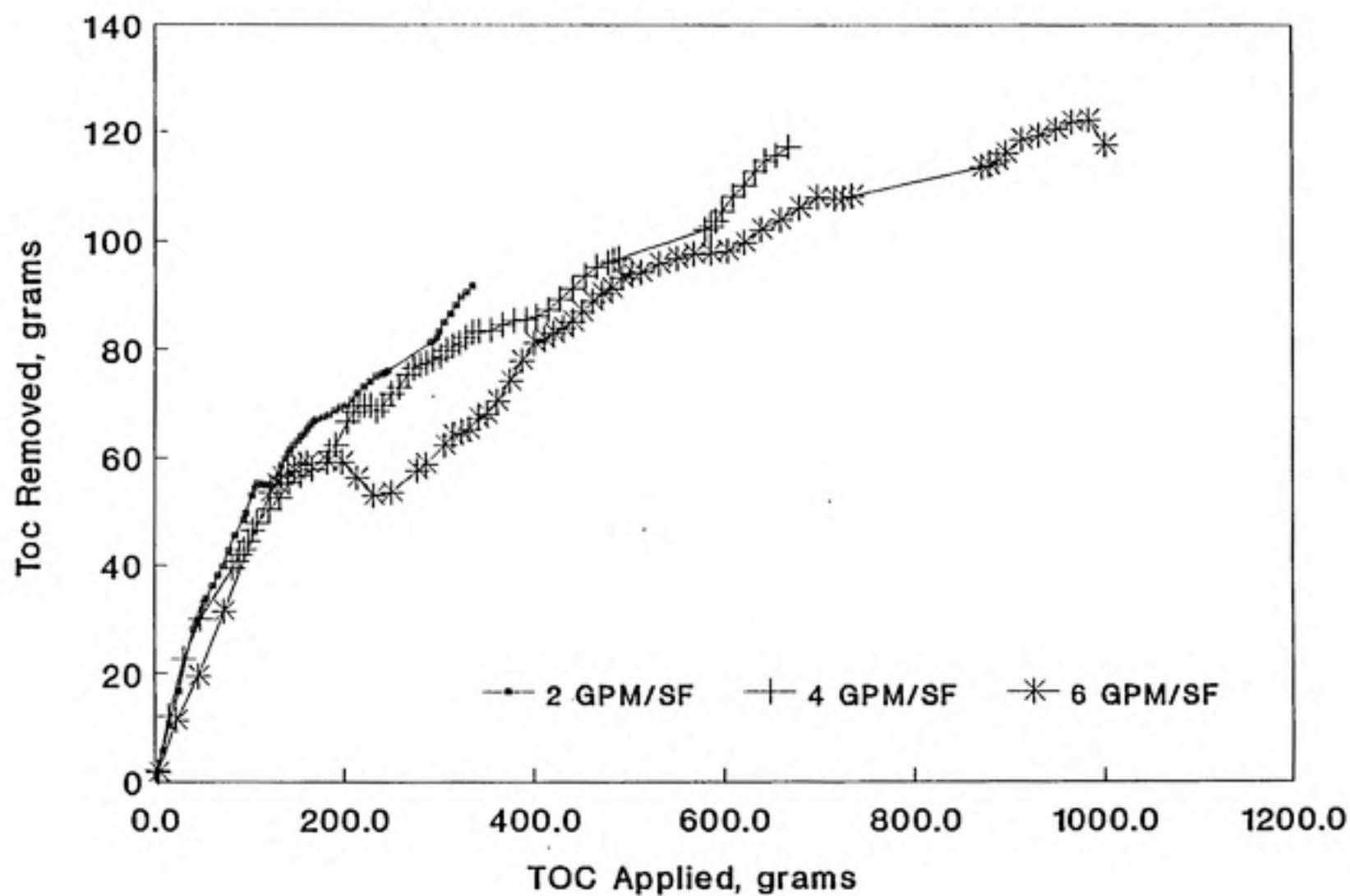
Sample	TOC mg/L Mean, $\bar{u}$	Std. Dev.	Samples
Feed	2.63	0.12	9
2 GPM/ft ²	2.04	0.32	9
4 GPM/ft ²	2.19	0.32	9
6 GPM/ft ²	2.43	0.29	9

Null Hypothesis	T-value	p-value
$(u_f - u_2) = 0$	5.23	< 0.01
$(u_f - u_4) = 0$	3.90	< 0.01
$(u_f - u_6) = 0$	1.93	0.05 < p < 0.10
$(u_4 - u_2) = 0$	1.00	> 0.20

To further evaluate the attainment of TOC steady-state removal, the mass of TOC removed for each filter-adsorber was plotted with respect to mass of TOC applied in Figure 4.10. These data were obtained by using the areas under feed and breakthrough curves in Figure 4-7 as explained in Section 4.3.1.

During the initial stage of filter-adsorber operation, the mass of TOC removed per mass of TOC applied (i.e., the slope of Figure 4.10) is considerably larger than the later stage. Other investigators (Maloney et. al., 1984) have interpreted the shift in removal rate to an exhaustion of adsorption capacity and an attainment of some constant removal rate due to biodegradation. If adsorption alone were occurring, the rate of TOC removal would

Figure 4.10 Run One TOC Removal vs. TOC Applied



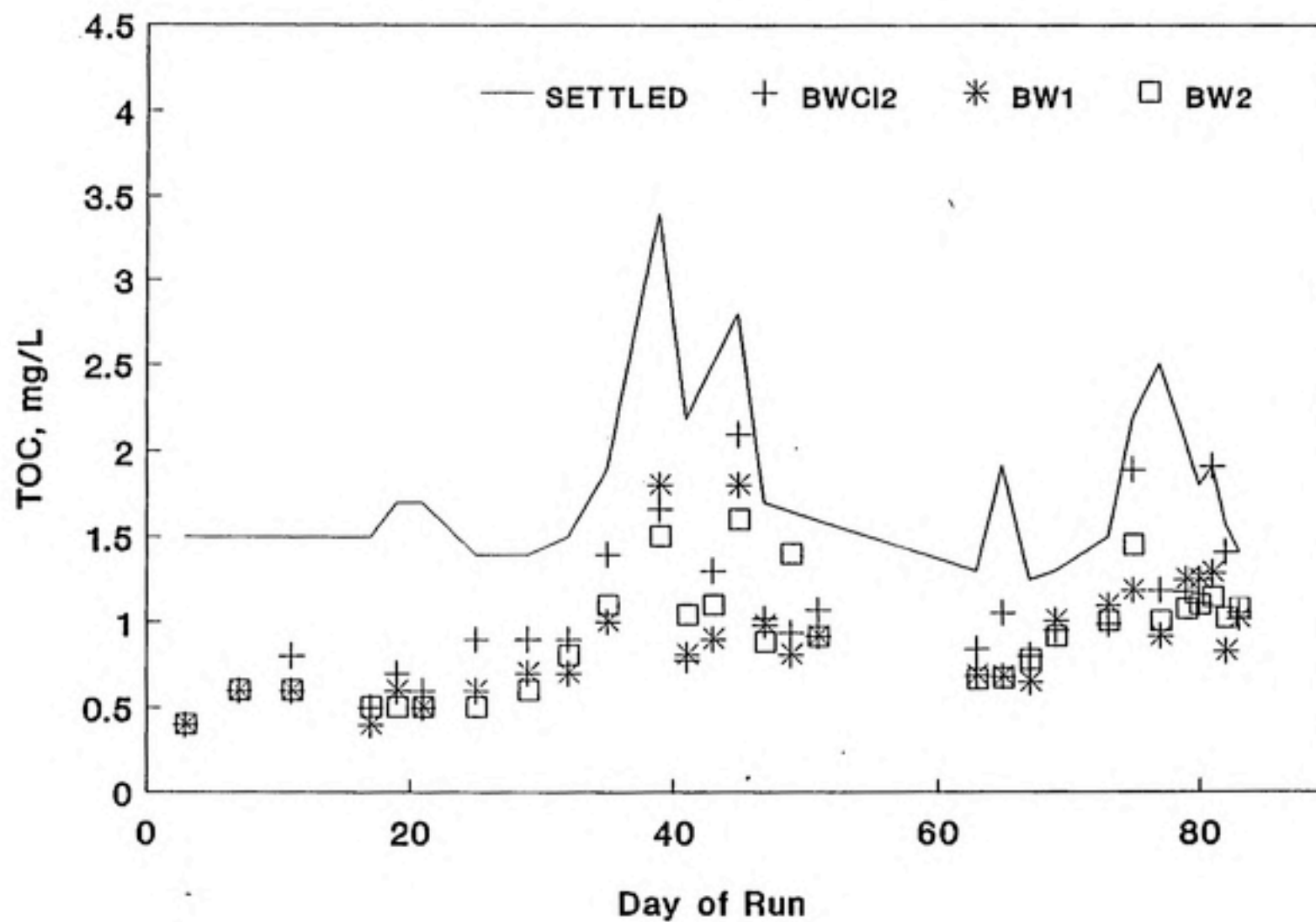
slowly decrease and the slope in Figure 4-10 would reach zero. Alternatively, biodegradation would lead to a steady-state removal, or constant slope. Although the data during the later stage of filter-adsorber do not describe a perfectly linear relationship, there is reasonable evidence for a steady state condition. The steady-state removal is not clearly shown to increase with decreasing application rate as may be expected if a large EBCT was important for achieving biodegradation.

4.3.3 TOC Removal-- Run Two

Backwashing is known to redistribute media, even in beds with high uniformity coefficients. Redistribution of GAC in an adsorption column results in elongation of the mass transfer zone and faster breakthrough of TOC (Hand et. al., 1989). Other researchers (Graese et. al., 1987) also report decreases in time of breakthrough due to backwashing. However, in another report, Wiesner et. al. (1987) concludes that while backwashing reduced the time of breakthrough, there was little difference in breakthrough of filter-adsorbers backwashed daily versus filter-adsorbers backwashed monthly.

Figure 4-11 shows the feed TOC and the TOC breakthrough curves for three different backwash strategies used in Run Two. All three filter-adsorbers were operated at the same application rate (4 gpm/ft²) and therefore the breakthrough curves should be expected

Figure 4.11 Run Two TOC Breakthrough Curves



to be the same if backwashing strategy had no effect. These suggest this to be true. A similar conclusion is reached from Figure 4-12, in which the breakthrough curves have been normalized by the average feed concentration of TOC. Thus, TOC breakthrough was not noticeably altered by increasing the backwash frequency by a factor of two (once every day compared to once every two days) nor by addition of chlorine to the backwash water.

4.3.4 Approach to Steady State Removal-- Run 2

TOC removed during Run Two is plotted against TOC applied in Figure 4-13. For comparison, the corresponding data for the application rate of 4 gpm/ft² from Run One (backwashing once every two days) are also shown. While TOC removal rate was initially the same for all three filter-adsorbers in Run Two, the rate at later stages was measurably lower for the filter-adsorber backwashed with chlorine than those backwashed without chlorine. This could be an indication of less microbial activity in the bed. In earlier reported work at this pilot plant, Cobb (1990) found that the filter-adsorber backwashed with chlorine released statistically less heterotrophic plate count; this is also an indication of less microbial activity. All of the removal rates in Run Two were higher than that in Run One (at the same application rate). The only difference between the two runs is temporal: Run One was conducted in late winter and early spring whereas Run Two was

Figure 4.12 Run Two TOC Breakthrough Curves

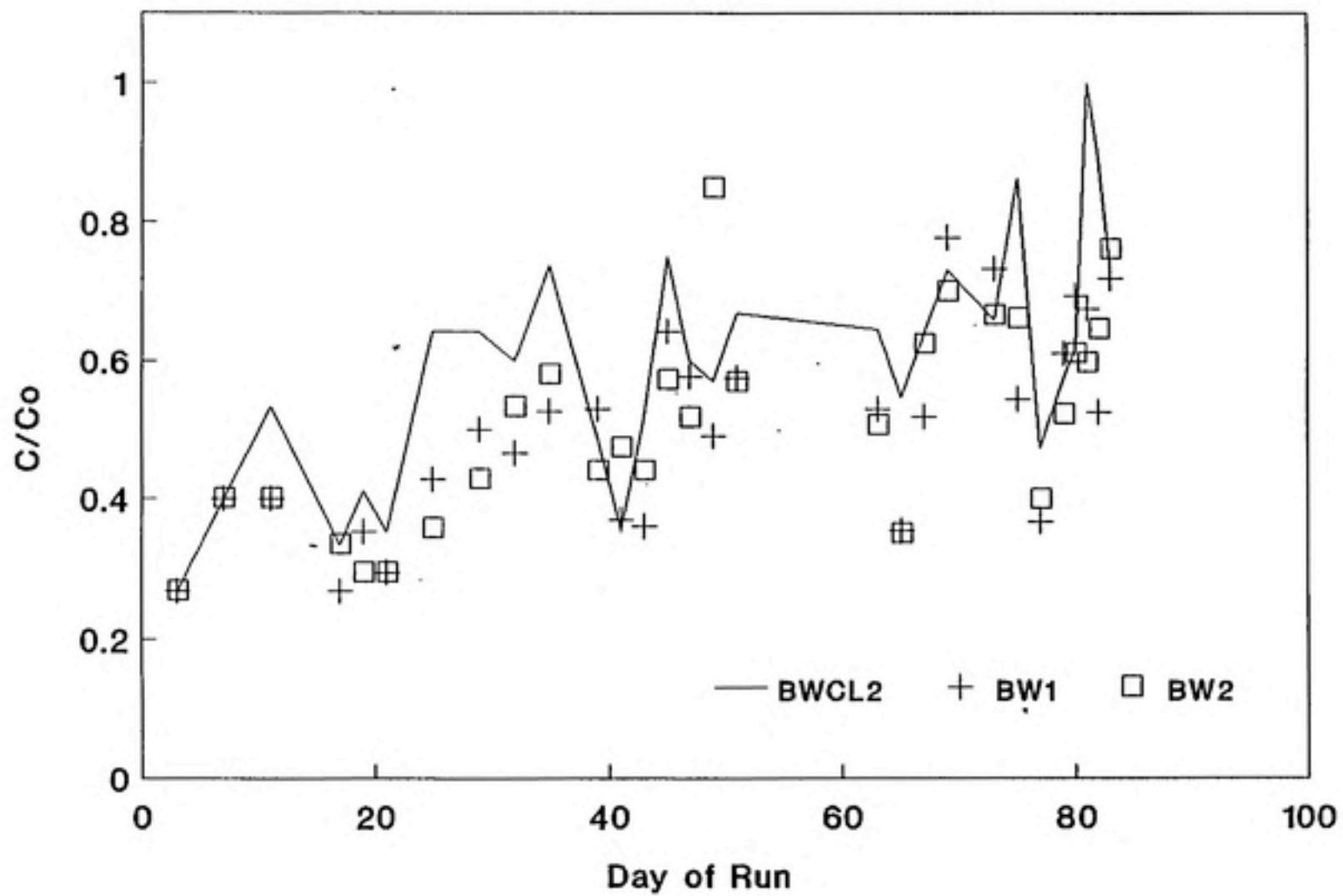
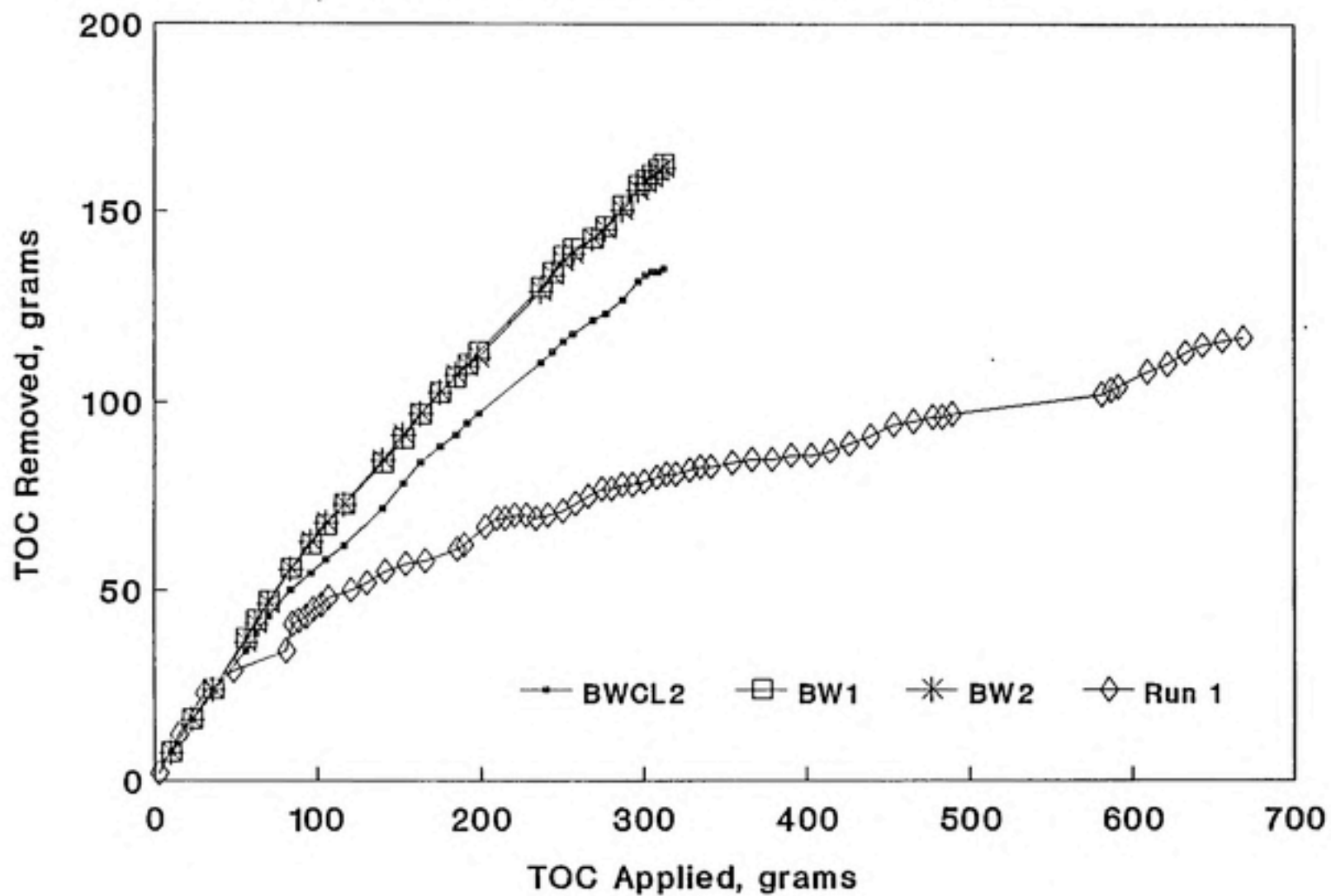


Figure 4.13 Run Two TOC Removal vs. TOC Applied



conducted in late spring and summer. Both higher water temperature and different TOC character could explain the higher removal rate toward the end of Run Two if biodegradation was the dominant effect. Alternative explanations are possible having to do with changes in adsorbability of TOC but no conclusions are possible because the adsorption isotherm was determined only once in this study (during Run Two).

4.3.5 TOC Profiles in Filter-adsorbers

Water samples were withdrawn at various depths in the filter-adsorbers on Day 107 of Run One and Day 21 of Run Two. The TOC profile on Day 107 should correspond to that for steady-state removal. As indicated in Figure 4-14, TOC did not decrease very much with depth as may be expected if significant biodegradation was occurring. Also shown is the TOC concentration for Franklin WTP filtered water on Day 107 of Run One. This level indicates the full-scale dual media filters were not removing TOC. The filter-adsorber TOC data can be plotted against EBCT at each depth for each application rate as shown in Figure 4-15. Aside from the slight increase in TOC noted at the top of the filter-adsorbers, the overall trend is of a decrease in TOC with an increase in EBCT. This observation is consistent with previous findings in this chapter indicating adsorption and biodegradation to be dependent of EBCT. A simple linear removal rate of 0.06 mg/L/min EBCT was

Figure 4.14 Run One TOC Profile-- Day 107

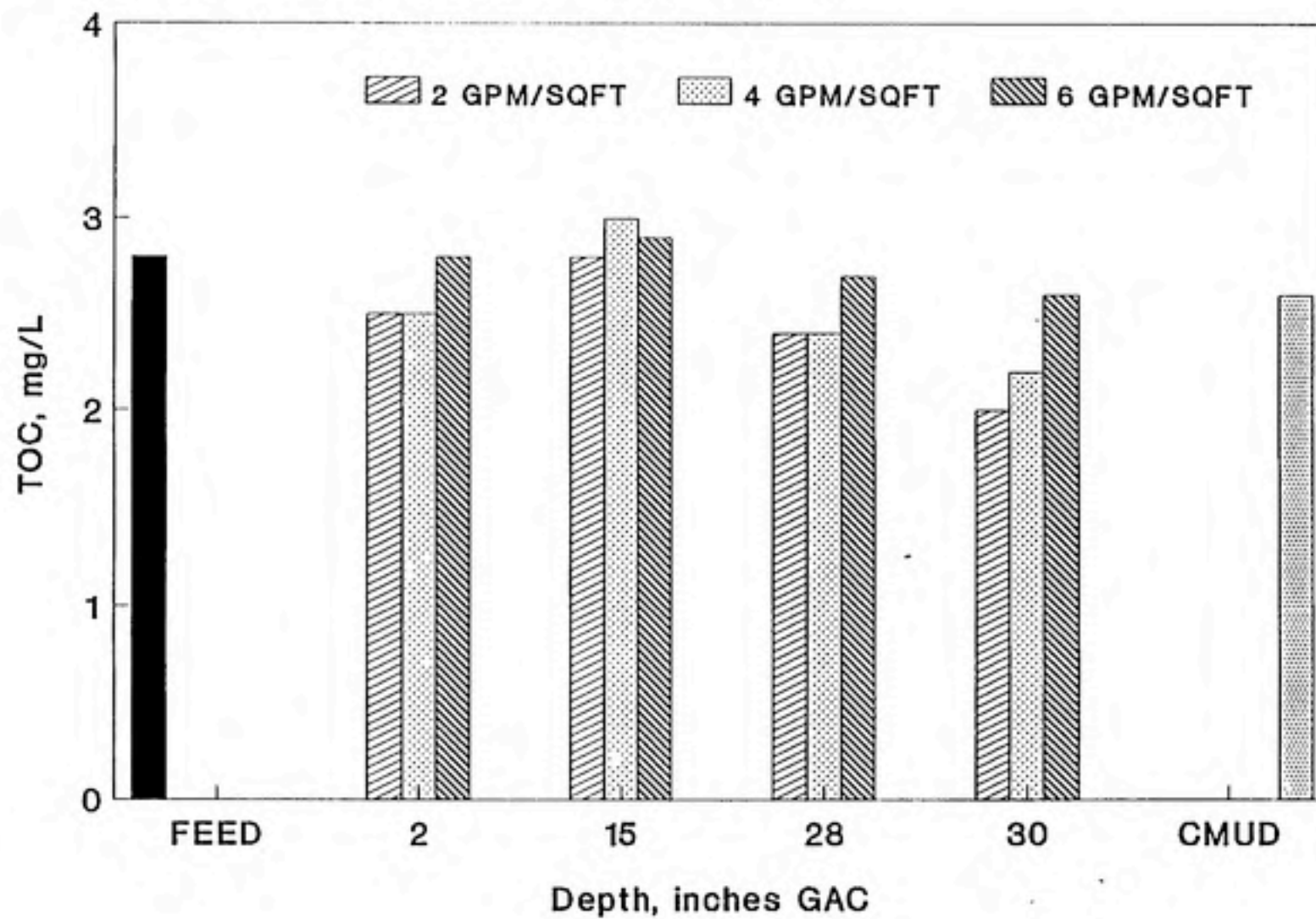
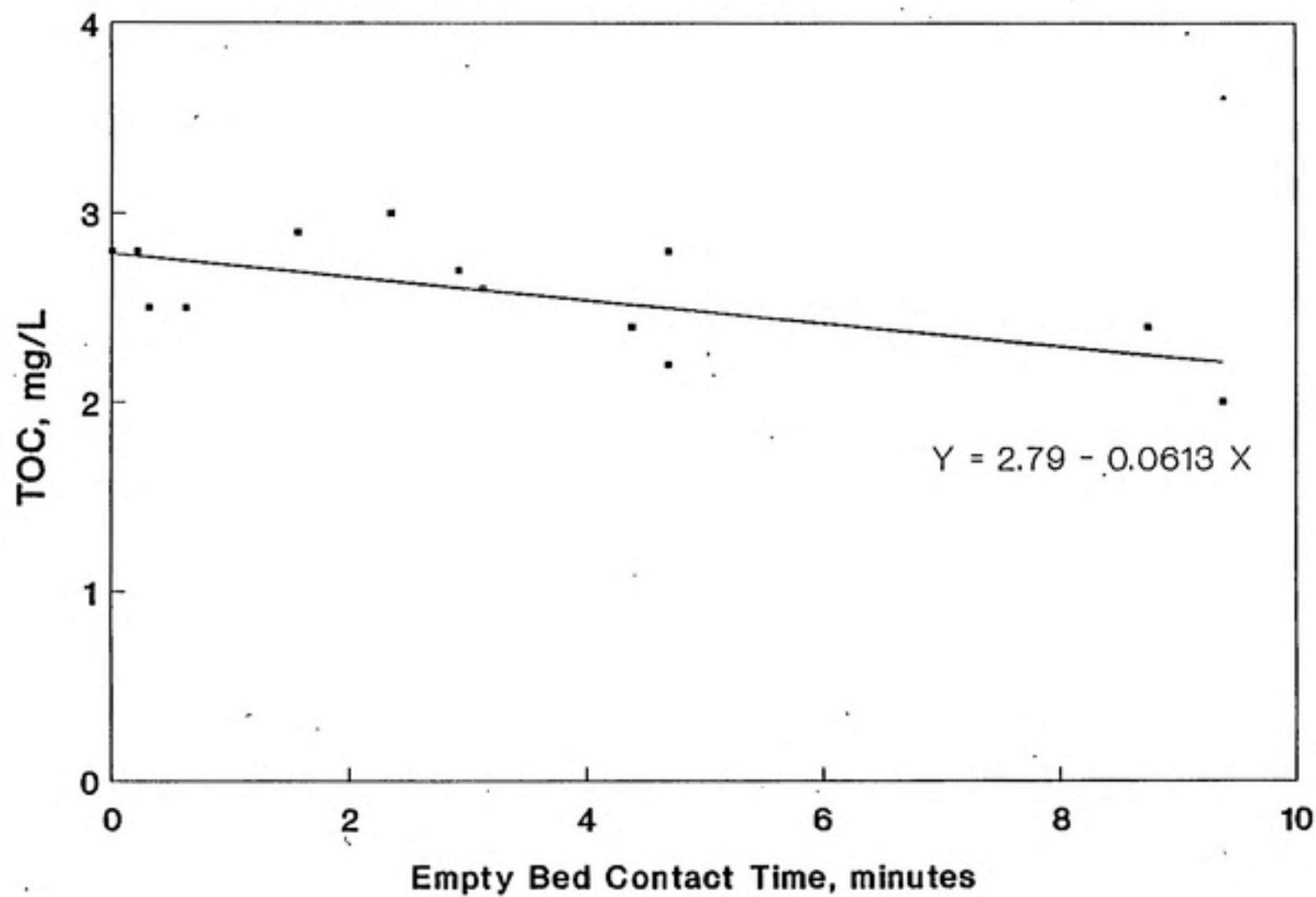


Figure 4.15 Run One TOC Removal vs. EBCT-- Day 107



calculated from Figure 4-15. This rate becomes an important design parameter to determine if adequate steady state removal of TOC is possible in a filter-adsorber. As an example, an EBCT of 25 minutes would be required to realize 50% removal of 3 mg/L TOC.

In contrast to the TOC profile on Day 107, that on Day 21 of Run 2 should reveal the presence of an adsorption front because adsorptive capacity had not yet been exhausted. The resulting TOC profile given in Figure 4-16 shows that 50% of the TOC was removed in the first 2 in. of GAC. TOC removal occurred to a much less extent deeper in the bed. This suggests a long MTZ as is expected for natural organic matter. Moreover, TOC at the bottom of the filter-adsorber is higher than the refractory concentration (0.2 mg/L) found in the adsorption isotherm (Figure 4.7). This is consistent with the idea that the MTZ was not contained, and thus the EBCT (4.1 min) was too short to provide the most effective adsorption.

4.3.6 TOC Adsorption Modelling

Results from an isotherm performed on Franklin WTP settled water using pulverized Filtrasorb 300 are listed in Table 4.4. The fraction of non-adsorbable TOC can be estimated by noting the amount of TOC that remains at high dosages of activate carbon. The values in the last 5 rows of Column 3 indicate this non-adsorbable fraction to be approximately 0.2 mg/L. After subtracting the non-

Figure 4.16 Run Two TOC Profiles-- Day 21

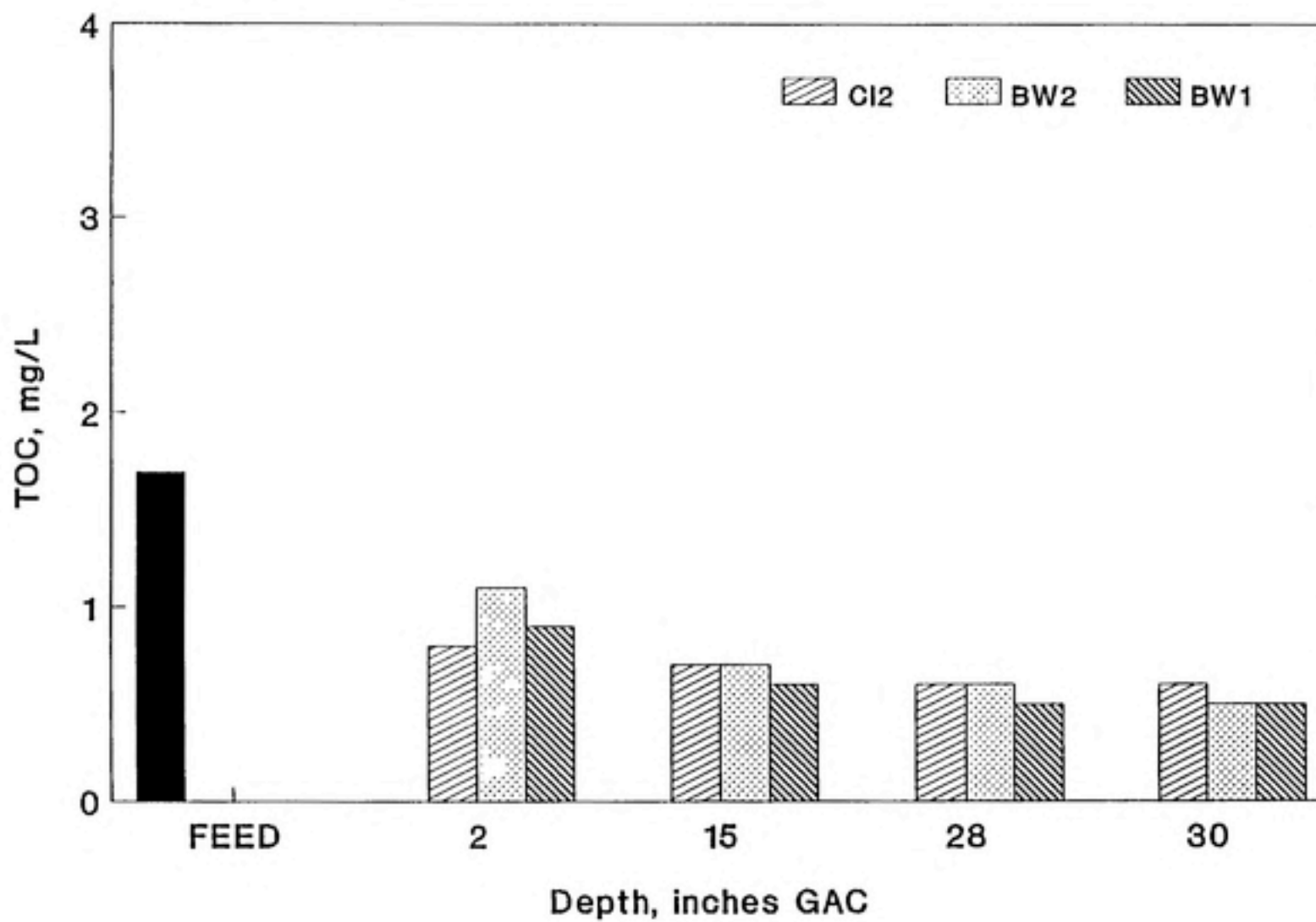


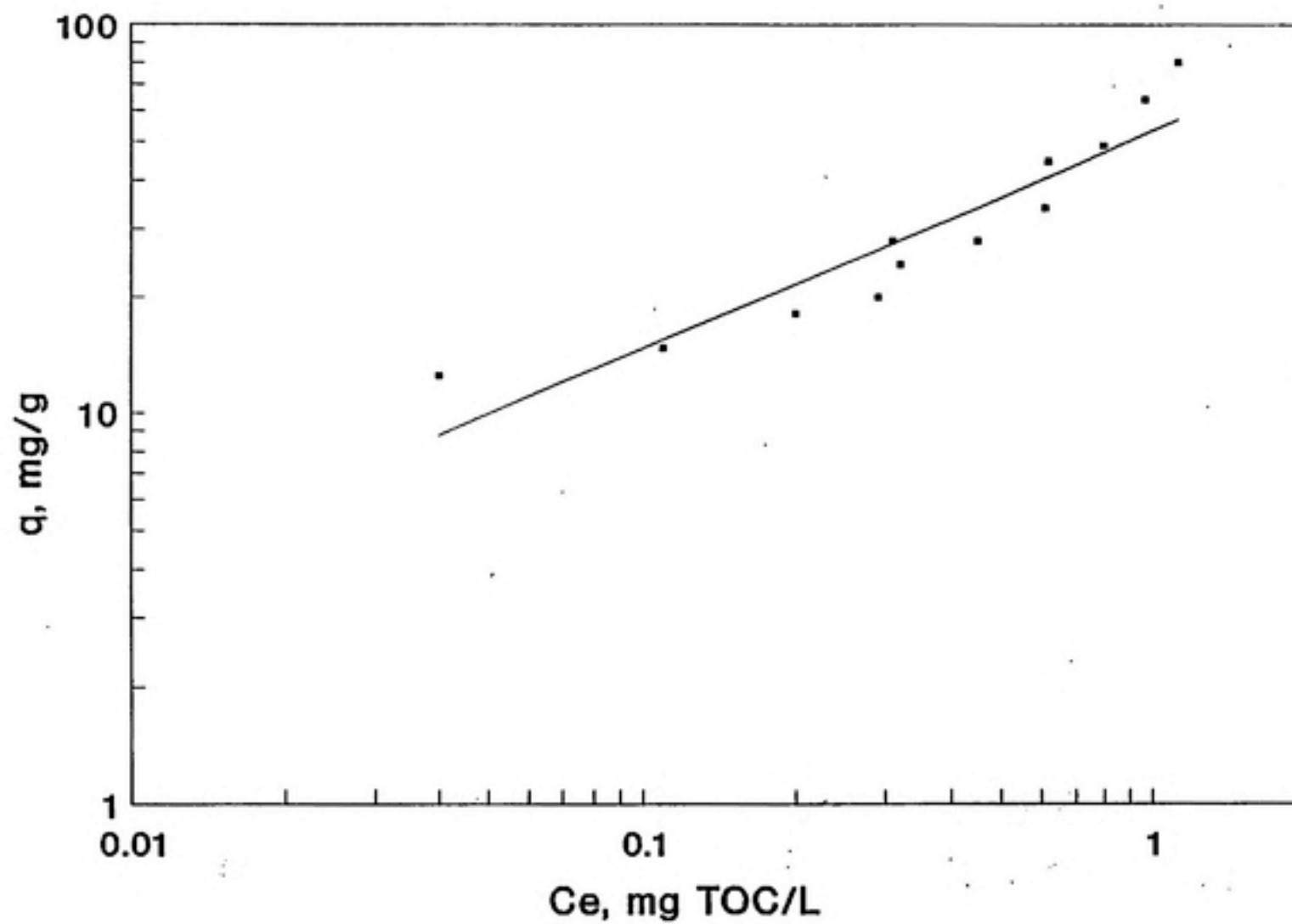
Table 4.4 GAC Isotherm Data

(1)	(2)	(3)	(4)	(5)
M (g/L)	Co (mg/L)	Ce (mg/L)	Corr. Ce (mg/L)	q (mg/g)
0.002	1.47	1.31	1.13	80.0000
0.005	1.47	1.15	0.97	64.0000
0.010	1.47	0.98	0.8	49.0000
0.015	1.47	0.80	0.62	44.6667
0.020	1.47	0.79	0.61	34.0000
0.030	1.47	0.63	0.45	28.0000
0.035	1.47	0.49	0.31	28.0000
0.040	1.47	0.50	0.32	24.2500
0.050	1.47	0.47	0.29	20.0000
0.060	1.47	0.38	0.2	18.1667
0.080	1.47	0.29	0.11	14.7500
0.100	1.47	0.22	0.04	12.5000
0.120	1.47	0.19	0.01	10.6667
0.140	1.47	0.18	0	9.2143
0.160	1.47	0.18	0	8.0625
0.200	1.47	0.18	0	6.4500
0.240	1.47	0.18	0	5.3750

Regression Output:

Constant	1.72670635 = log k
Std Err of Y Est	0.09657122
R Squared	0.86605649
No. of Observations	12
Degrees of Freedom	10
X Coefficient(s)	0.560 = 1/n
Std Err of Coef.	0.070
t-calc	8.041

Figure 4.17 Calgon Filtrasorb 300 8X30 GAC Isotherm



adsorbable fraction, the data were fitted to a Freundlich isotherm model: $q = k C^{1/n}$, where $k = 53.29$ and $1/n = 0.56$. The correlation of this fit was 0.87 and the calculated T-value was 8.04. Figure 4-17 is a plot of the corrected isotherm data along with the corresponding Freundlich fit.

A rough estimate of time for TOC breakthrough can be calculated by assuming that adsorption is not rate limited using the following equilibrium adsorption model:

$$t_b = (k * C_o^{1/n} * W) / (Q * C_o)$$

where,

t_b = time of TOC breakthrough
 $k, 1/n$ = Freundlich parameters
 C_o = settled water TOC concentration = 1.5 mg/L
 W = mass of GAC in filter-sorber = 3000 g
 Q = volumetric flowrate

This model uses the isotherm data and mass of GAC to calculate the TOC adsorption capacity of the filter-adsorber, and then estimates time of breakthrough using the amount of TOC applied daily. The equilibrium adsorption model predicts complete breakthrough for application rates of 2, 4, and 6 gpm/ft² can be to occur at 139, 70, and 46 days, respectively. These are conservative estimates of service time because mass transfer limitations cause some fraction of sorbate to escape adsorption and appear in the product water earlier than the equilibrium model predicts (JMM, 1985).

To account for some of the mass transfer limitations and gain a better prediction of TOC adsorption, a simplified version of the homogeneous surface diffusion model (HSDM) was employed. Using the

isotherm data corrected for non-adsorbable TOC and a volumetric flowrate of 4 gpm/ft², the HSDM model calculated an immediate TOC breakthrough of 35%, 50% breakthrough in 42 days, and 95% breakthrough in 349 days. The entire predicted breakthrough curve is presented in Figure 4-18. The model calculations used for generating this breakthrough curve are presented in Appendix A. For a complete description of the simplified HSDM model, refer to Hand et. al. (1984).

Equilibrium and HSDM model predictions are plotted with actual Run Two TOC breakthrough curves in Figure 4-19. The comparison of the HSDM model and the actual data to the equilibrium model gives an indication of the mass transfer limitations imposed by the restricted EBCT at the given application rates.

4.4 Removal of Trihalomethane Formation Potential

The removal of TOC by filter-adsorbers also implies removal of precursors of THMs. Thus, this study included measurements of THMFP. Due to limited laboratory equipment availability, testing during Run One was limited to three days during the last three weeks of the run. However, these data are still useful for assessment of THMFP removal at steady state. In Run Two, THMFP tests were conducted on five days throughout the entire length of the run.

The THMFP of feed and product water on three days toward the

Figure 4.18 HSDM Predicted TOC Breakthrough

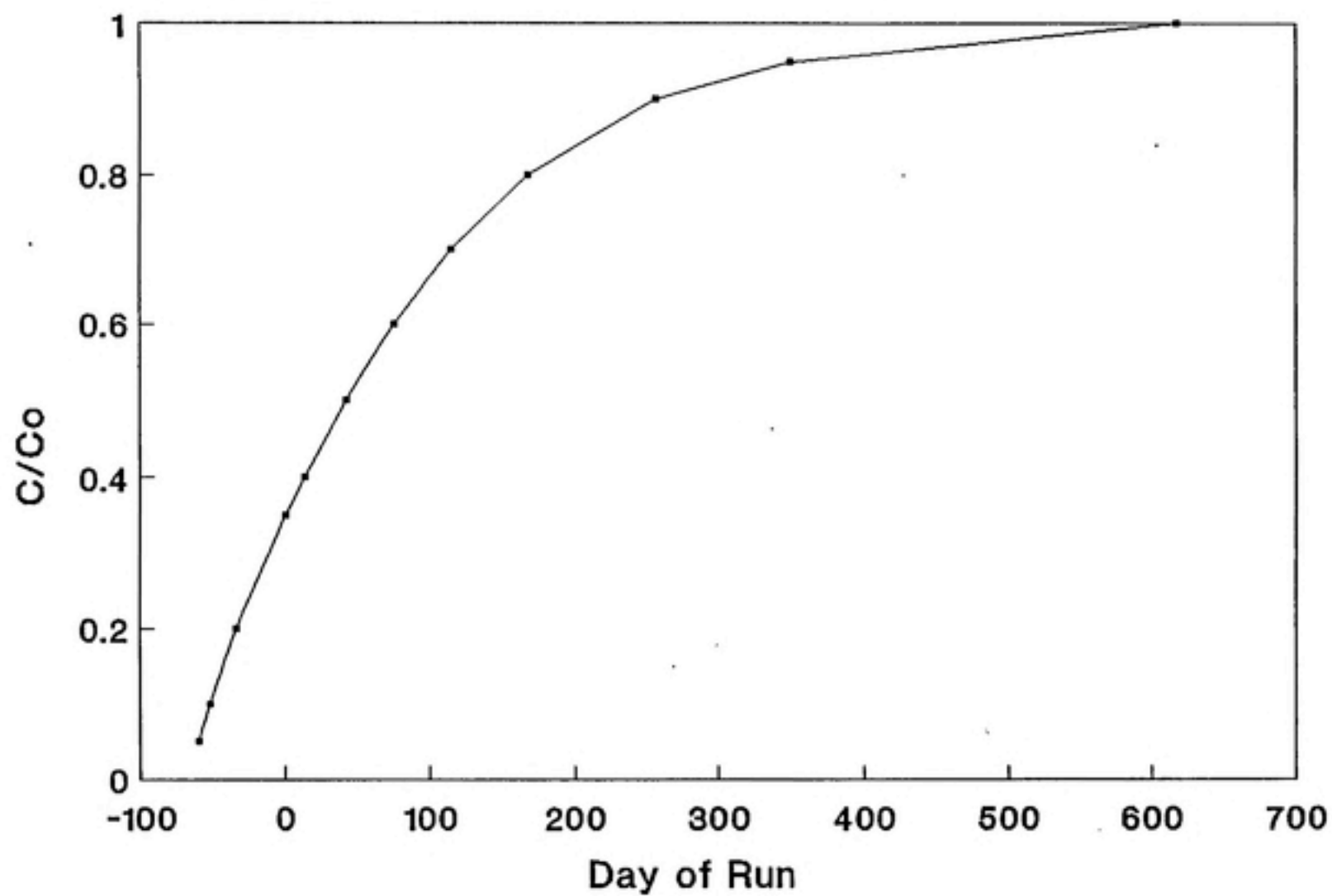


Figure 4.19 Comparison of Predictive Models to Run 2 TOC Breakthrough

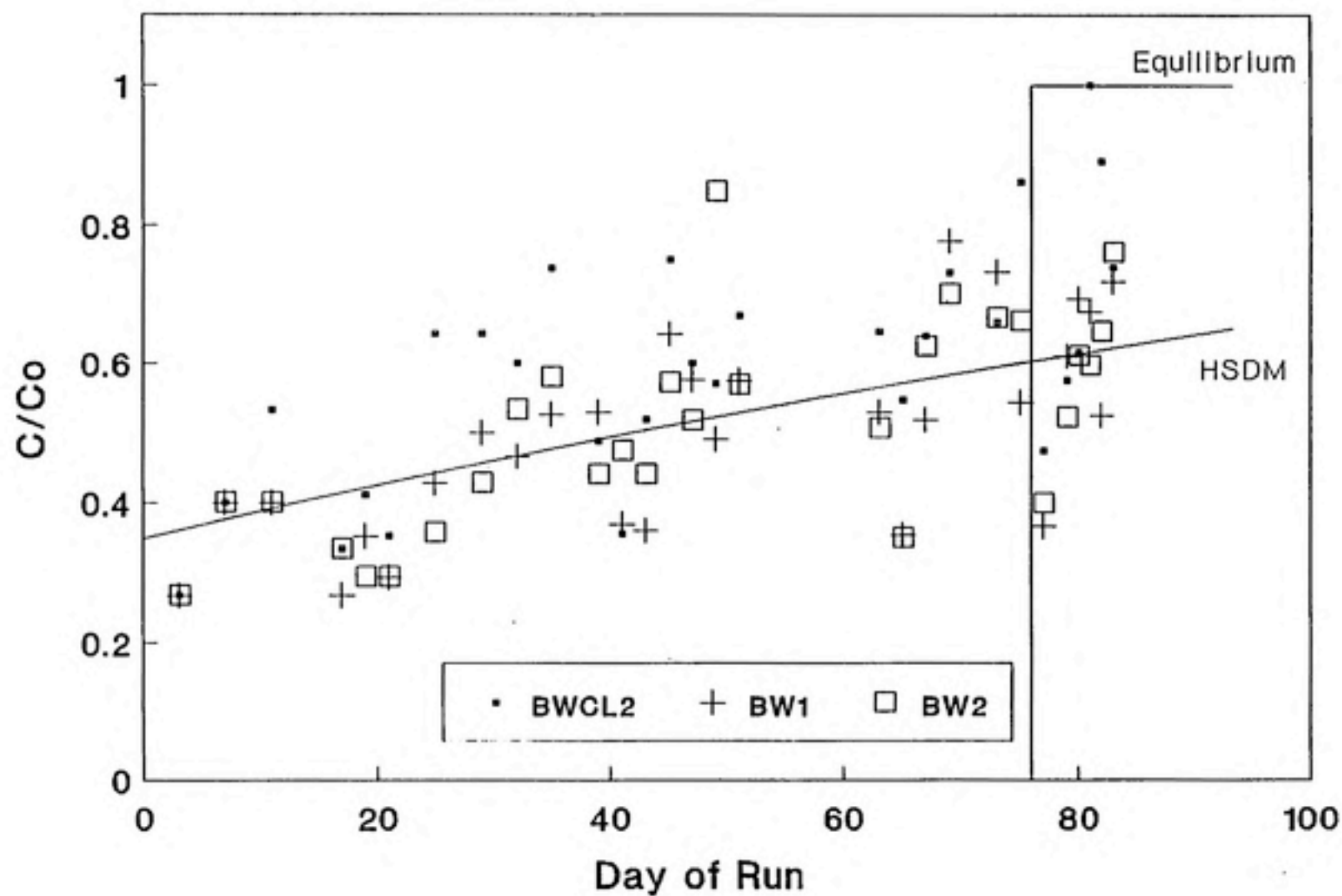
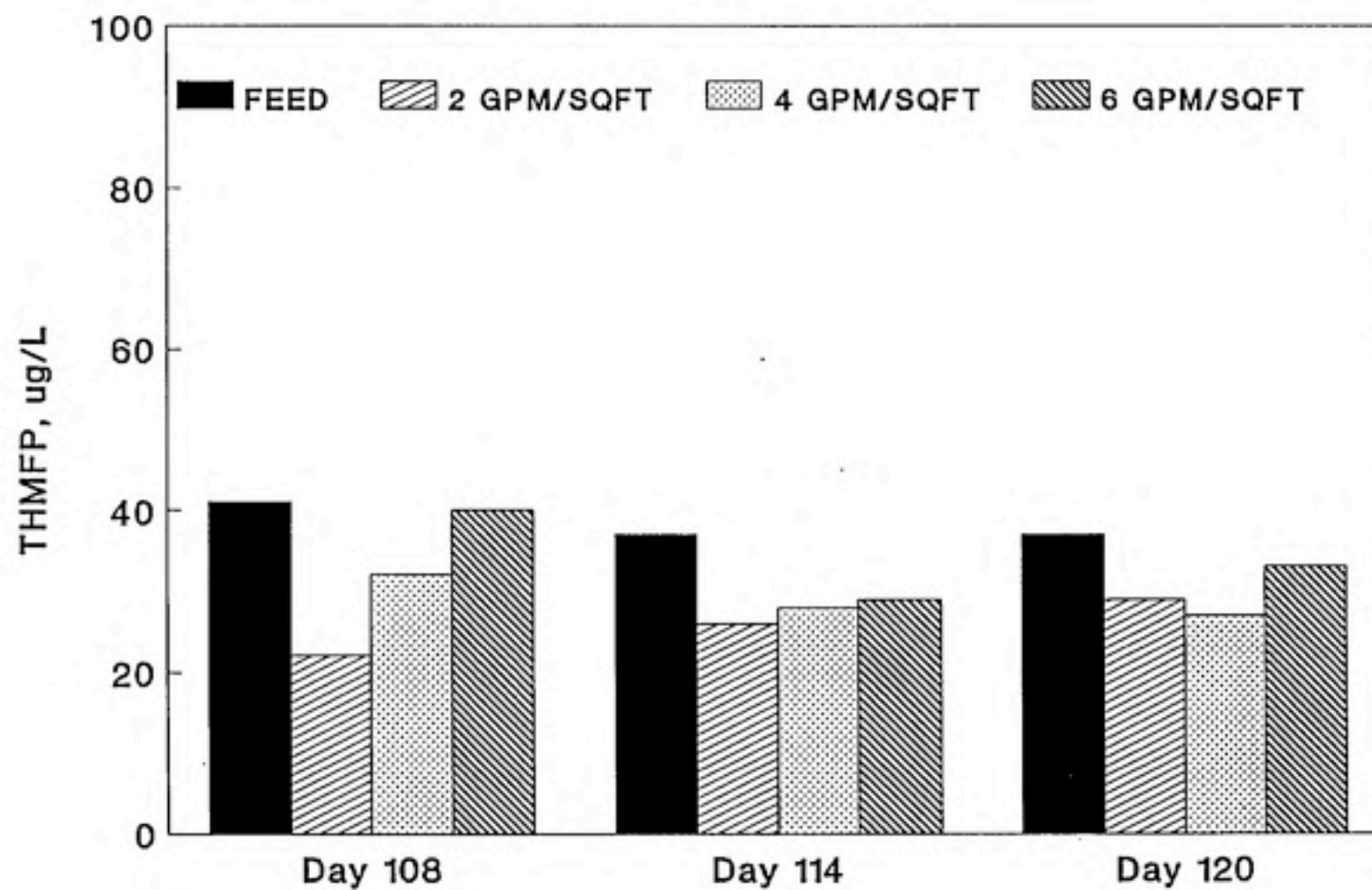


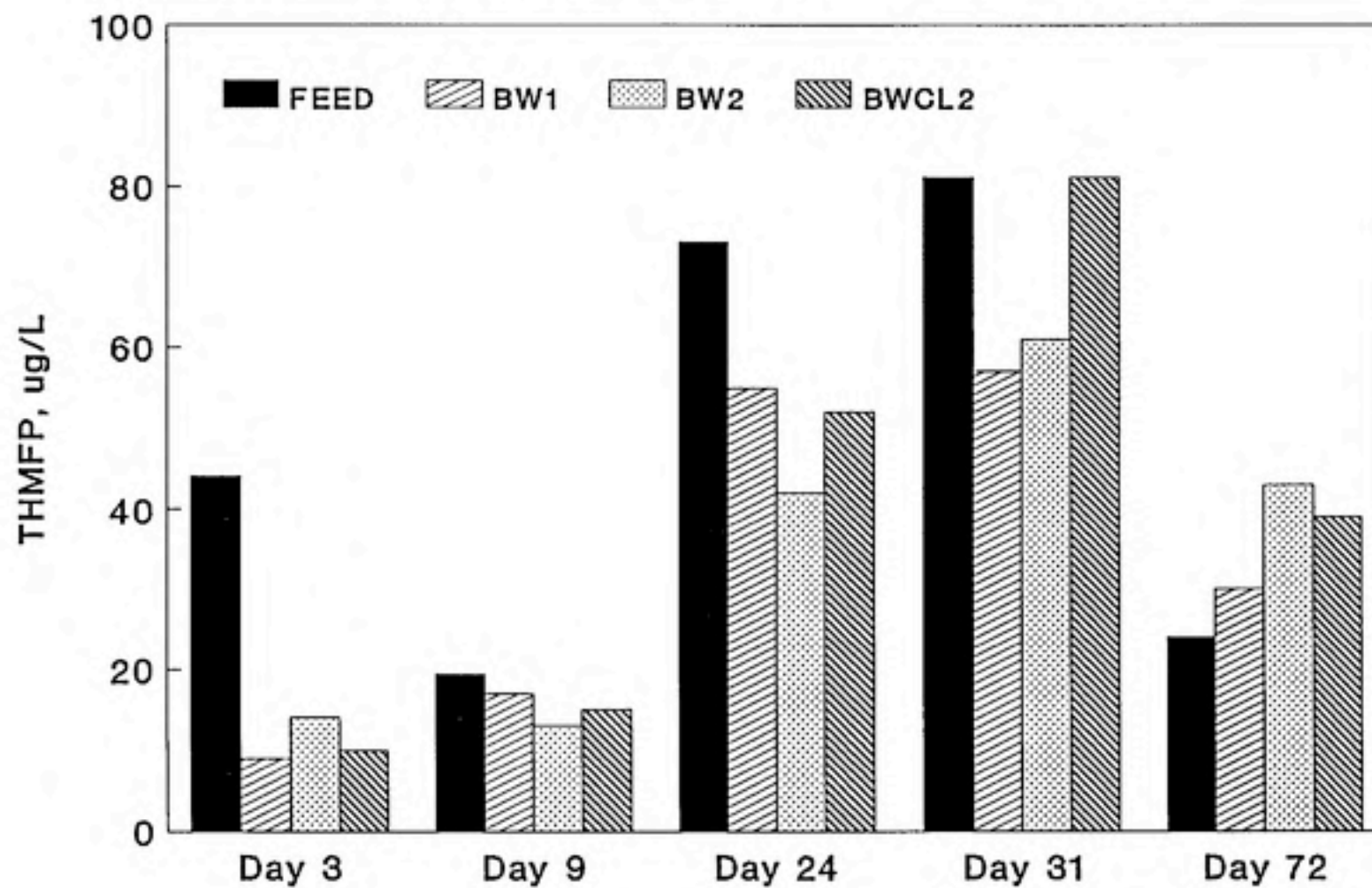
Figure 4.20 Run One THMFP Removal



end of Run One are shown in Figure 4-20. The TOC breakthrough curves and adsorption model predictions (Section 4.3.5) imply that adsorption capacity was exhausted during this time period and any removal was most likely due to biodegradation. Data in Figure 4-20 reveals THMFP removal ranged from 5-20 ug/L with greater removals being realized at lower application rates (higher EBCTs). While these reductions may not be meaningful based on effluent goals anticipated from EPA, it is possible that further increases in EBCT could yield more THMFP removal. The data also suggest that THMFP removal, like TOC removal, had reached a steady state.

The THMFP data from Run Two are presented in Figure 4-21. Much greater THMFP removal was obtained on Days 3 and 9 than later in the run. However, some breakthrough of THMFP (10-20 ug/L) was noted. This implies that a fraction of NOM responsible for formation of THMs is not adsorbable. This is an important consideration for assessing the effectiveness of GAC for eliminating precursors to THM formation. Removal of 25-40 ug/L THMFP was still occurring approximately one month into Run Two. However, the THMFP had increased to 40 ug/L. The THMFP data from Day 72 suggest that feedwater concentration dropped precipitously and that THMFP exceeded the feedwater concentration, possibly as a result of desorption. However, the corresponding feed TOC concentration on Day 72 was not appreciably lower than previous (see Figure 4-11). This raises some concern about the accuracy of the THMFP data (THMFP should roughly correlate to TOC) and suggests

Figure 4.21 Run Two THMFP Removal



caution in interpreting desorption as an explanation for higher THMFP in the product water from the feed water. Finally, no difference was found in THMFP removal with backwashing strategy, i.e., all three filter-adsorbers produced about the same THMFP. This is consistent with observations made on TOC removal in Section 4.3.3.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

The GAC filter-adsorbers, consisting of 30 in. of 8x30 Filtrasorb 300 over 12 in. of sand, were shown to reduce turbidity at least as well as the full-scale dual media filters at application rates of 2, 4, and 6 gpm/ft² and backwash frequencies of one and two days.

Headloss accumulation in the filter-adsorbers were comparable to that in the full-scale dual media filters. The rate of headloss accumulation (with respect to bed volumes of water filtered) was about the same regardless of application rate. Similarly, headloss accumulation rate did not depend on backwash frequency (once per day versus once every two days). However, headloss accumulation rate was about 30% higher when backwashing with chlorinated washwater; no explanation for a higher rate could be found.

Overall, the pilot filter-adsorbers performed adequately as filters. They produced water of acceptable turbidity without excessive accumulation of headloss over a range of practical application rates and backwash frequencies. The GAC used in this application (Filtrasorb 300) has a small effective size and large uniformity coefficient which facilitates longer filter runs and better cleaning of the filter bed. In addition, the GAC was followed with 12 in. of sand which acted as a final barrier to

penetration of turbidity.

The breakthrough of TOC occurred earlier as application rate increased. Using 50% TOC breakthrough for illustration, breakthrough was immediate at 6 gpm/ft², at between Days 11 and 15 for 4 gpm/ft², and between Days 22 and 28 for 2 gpm/ft². The data showed very little potential for control of TOC unless EBCT could be extended greatly. Earlier breakthrough of TOC with higher application rate is due to two effects: (1) higher sorbate loading rate and (2) shorter EBCT relative to MTZ. The latter effect was shown by measuring the amount of TOC adsorbed up to a selected TOC concentration in the product water (1 mg/L). The mass of TOC adsorbed decreased as application rate increased. Steady state removal of TOC was found to be statistically significant (T-test) at a confidence level greater than 99% for the application rates of 2 and 4 gpm/ft². Nonetheless, the amount was only about 0.5 mg/L. Steady-state removal at 6 GPM/ft² was statistically insignificant at a much lower confidence level as was the difference between 2 and 4 GPM/ft². The data suggested some small amount of removal was due to biodegradation at steady state.

Backwash frequency and chlorination of backwash water had no effect on the initial pattern of TOC breakthrough. However, backwashing with chlorinated washwater appeared to decrease steady state removal. This could imply that chlorination limited microbial activity to some extent. Steady-state removal of TOC was

greater in Run Two than Run One. One possible explanation is more biodegradation in Run Two due to higher water temperature and/or changes in TOC composition.

A depth profile of TOC in the filter-adsorbers during the early stages of Run Two showed the presence of an adsorption zone. However, profiles measured during the later stages of Run One showed a more linear decrease in TOC with depth, as may be expected if biodegradation was important. The steady-state removal rate was calculated to be 0.06 mg TOC/L/min EBCT.

A small, steady-state removal of THMFP (5-20 ug/L) was obtained in Run One, with removal increasing as application rate decreased. More data were collected in Run Two covering the entire time of filter-adsorber operation. These data showed a refractory THMFP of 10-20 ug/L. Removal of THMFP was found to be 25-40 ug/L up to five weeks into the run. Again the importance of these numbers is dependent upon the new maximum contaminant levels.

Overall, data from this study suggest filter-adsorbers are not an effective means for removal of TOC. Data showed 50% breakthrough in less than 1 month for the lowest filter application rate in current practice (2 gpm/ft²). Bed lives of this length would require frequent regeneration or replacement of GAC, with the resulting high maintenance costs negating the capital costs saved.

One technology not studied was ozonation of the settled water prior to application. Ozone has been shown to oxidize NOM to forms that are more readily biodegradable. European practice calls for

preozonation to increase microbial activity and lengthen bed life. The following recommendations are made for future studies on GAC filter-adsorbers:

1. Vary the depth of sand below the GAC to determine minimum amount necessary to meet turbidity standards and give good overall performance while maximizing EBCT of GAC.
2. Determine if enough EBCT can be established to facilitate adequate steady-state removal of NOM to control disinfection byproducts.
3. Determine if preozonation enhances steady-state removal of NOM by biodegradation in filter-adsorbers.

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APPENDIX A

HSDM MODEL CALCULATIONS

Assumptions and calculations used to derive the theoretical breakthrough curve based on the homogeneous surface diffusion model (HSDM) are listed below. For further explanation of the model, refer to Hand et. al. (1984).

Assumptions:

- k_f = film transfer coefficient = 0.00145 cm/s
- p_s = bulk density of GAC = 0.49 g/cm³
- e = bed void fraction = 0.4
- D_l = liquid diffusivity coefficient
= 2.3×10^{-6} cm²/s (Harrington, 1986)
- e_p = particle void fraction = 0.75
- k = Freundlich parameter = 53.29
- $1/n$ = Freundlich parameter = 0.56
- C_o = feedwater TOC concentration = 1.3 mg/L
- R = adsorbent particle radius = 0.0625 cm
- EBCT = EBCT of actual GAC bed = 4.675 min

Equations:

1. Adsorbent phase equilibrium concentration, q_e

$$q_e = k C_o^{1/n} \quad (1)$$

$$q_e = 61.72 \text{ mg/g}$$

2. Partition coefficient, D_s

$$D_s = (p_s \times q_e) / (e \times C_o) \quad (2)$$

$$D_s = 58,163$$

3. Surface Diffusion Coefficient, D_s

$$D_s = (D_L \times e_p \times Co \times n) / (T_p \times q \times p_s) \quad (3)$$

$$D_s = 2.2 \times 10^{-11} \text{ cm}^2/\text{s}$$

4. Biot Number, Bi

$$Bi = [k_f \times R \times (1-e)] / (D_s \times D_g) \quad (4)$$

$$Bi = 42.5$$

5. Minimum Stanton Number for constant pattern, St_{min}

$$St_{min} = (A_0 \times Bi) + A_1 \quad (5)$$

From Table 1 (Hand et. al., 1984):

$$Bi = 42.5, 1/n = 0.56 \quad A_0 = 1.22 \quad A_1 = 0$$

$$St_{min} = 51.86$$

6. Minimum EBCT for constant pattern, $EBCT_{min}$

$$EBCT_{min} = (St_{min} \times R) / [k_f \times (1-e)] \quad (6)$$

$$EBCT_{min} = 62.09 \text{ min}$$

7. Elapsed time corresponding to $EBCT_{min}$, t_{min}

$$t_{min} = (EBCT_{min} \times e) (D_g + 1) T \quad (7)$$

$$t_{min} = 1003.1 \text{ days } T$$

8. Single solute mass throughput, T

$$T = A_0 + [A_1 \times (C/Co)^{A_2}] + [A_3 / (1.01 - (C/Co)^{A_4})] \quad (8)$$

From Table 2 (Hand et. al., 1984)

$$\begin{aligned} \text{Bi} = 50, 1/n = 0.6 : \quad & A_0 = 0.85 \\ & A_1 = 0.216 \\ & A_2 = 1.343 \\ & A_3 = 0.00473 \\ & A_4 = 0.224 \end{aligned}$$

9. Elapsed or real time, t

$$t = t_{\min} + (\text{EBCT} - \text{EBCT}_{\min})(D_0 + 1)$$

$$t = (1003.1 T - 927.62) \text{ days}$$

Combining equations (8) and (9) yields the breakthrough curve.

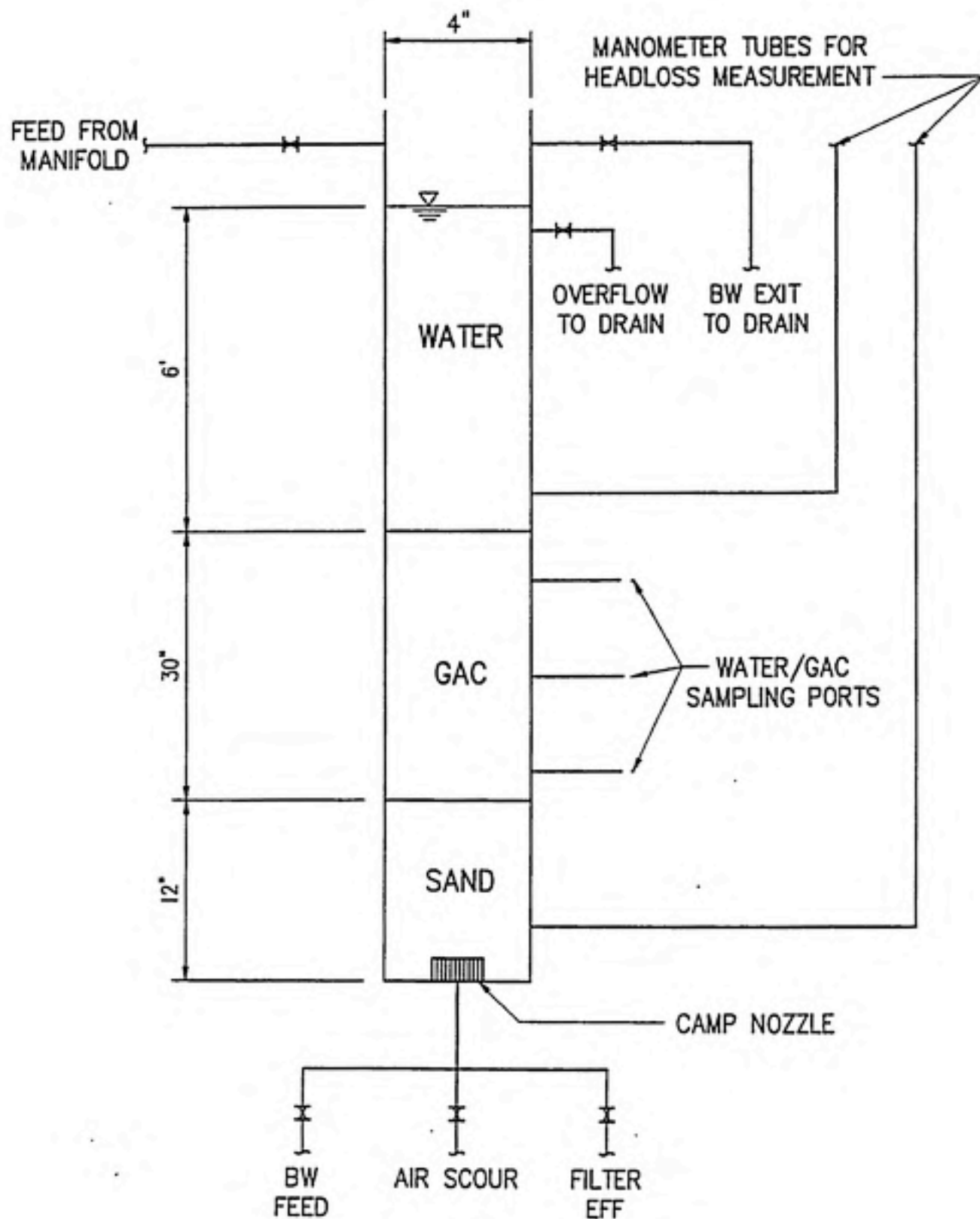


FIGURE-3.2 SCHEMATIC OF PILOT FILTER-ADSORBER