## ABSTRACT

KATHRYN L. MALLON. The Release of Particles From GAC Filter-Adsorbers and Their Effect on Disinfection. (Under the Direction of Dr. FRANCIS A. DIGIANO)

Granular Activated Carbon (GAC) filter-adsorbers can be an effective process for the removal of organic compounds in the treatment of drinking water. They have also been shown to provide a favorable environment for microbial activity. A consequence of the attachment of microorganisms to the GAC surface is the release of particle-attached organisms into the product water of the filter-adsorbers. Previous research has shown that attachment of organisms to surfaces can provide a mode for microbial survival during disinfection.

A pilot plant consisting of three GAC filter-adsorbers was constructed to examine the impact of GAC filtration, and its associated microbial growth, on product water quality. Of primary interest was the disinfection efficiency of microorganisms attached to particles released from the filter-adsorbers.

The results indicated that the GAC filter-adsorbers produced extremely high quality water as measured by turbidity and gravimetric analysis. The filter-adsorbers shed a significant concentration of microorganisms (10,000 HPC/mL); however only a very small percentage of these organisms were found to be attached to particles (0.01 to 0.05%). In addition, organisms attached to particles were found to be effectively disinfected at chlorine dosages common to water treatment plants. Resistance to disinfection of attached organisms was only noticed in experiments conducted in solutions of particle concentrations unrealisitic of an actual drinking water treatment plant (> 1 mg/L particles).

## ACKNOWLEDGEMENTS

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# CHAPTER ONE

# INTRODUCTION

## Introduction

Activated carbon has long been used in drinking water treatment plants for the removal of organic contaminants, mainly those causing taste and odor. However, the application of activated carbon has increased significantly due to its ability to remove many of the synthetic organic chemicals regulated by the 1986 amendments to the Safe Drinking Water Act.

Granular activated carbon (GAC) can be employed as adsorbent media in either a filter-adsorber or post-filter-adsorber. In a filter-adsorber, the GAC is used as a filtration media for the physical-chemical removal of particles as well as for adsorption of organics. Conventional filters (sand and anthracite media) can be converted to GAC filter-adsorbers by replacing several feet of filter media with GAC. Many new plants and expansions of old plants incorporate filter-adsorbers. (An excellent review of the design, operation, and performance of GAC filter-adsorbers is provided by Graese et al., 1987.) In some instances where SOC control is needed, a GAC bed is placed after conventional filtration, this being referred to as post-filter-adsorbers.

GAC filter-adsorbers and post-filter-adsorbers have been found to provide an excellent environment for microbial proliferation (AWWA Committee Report, 1981, Sontheimer et al., 1978, van der Kooij, 1976). Microorganisms attached to the surface of GAC filter media can provide both potential advantages and disadvantages in the treatment of drinking water. Advantages include the ability of the microorganisms to remove adsorbable and non-adsorbable organic contaminants thus extending the adsorptive capacity of the GAC filter. Removal of biodegradable organics by microorganisms within the treatment plant also reduces the opportunity for biological regrowth in the distribution system and reduce the disinfection demand.

Despite the advantages offered by microbial activity, it may also be a potential hazard in the treatment of drinking water. Microbial activity can substantially increase the number of microorganisms released during filtration thus serving as a source for regrowth in the distribution system. Microbially-active, GAC filters can potentially provide an environment for pathogens and opportunistic pathogens to survive and be released into the finished water. Endotoxins produced during the endogenous decay of gram-negative organisms can be released from microbially active filters (AWWA Committee Report, 1981, Stewart et al., 1990). Finally, and most relevant to this research, the potential exists for

release of carbon particles having attached growth or sheared clumps of bacteria (Camper et al., 1987). These attached or "clumped" organisms can compromise the disinfection process due to the physiological advantages attachment provides for microbial survival (Fletcher, 1980).

The release of attached bacteria from GAC filters has received considerable attention in recent research. Studies have repeatedly shown that bacteria attached to surfaces can be significantly resistant to disinfection (LeChevallier et al., 1988b). Viable microorganisms have been found in chlorinated distribution systems, indicating that attachment of microorganisms to surfaces is a mode of survival (Ridgeway and Olson, 1982). Several researchers have reported the presence of particle attached microorganisms in the product waters of GAC filters (LeChevallier et al., 1984, Camper et al., 1987, Stewart et al., 1990). These findings suggest that GAC filters can introduce chlorine resistant, attached bacteria into the finished water.

**Research Objectives**

The American Water Works Association Research Foundation (AWWARF) recently sponsored a project at the University of North Carolina to assess the impact of microbial activity in GAC filter-adsorbers on product water quality (DiGiano, et al., 1991). A pilot plant was constructed at the Franklin

Water Treatment Plant in Charlotte, North Carolina. The study was conducted over a two-year period and included five experimental runs. Run No. 1 examined the effect of application rate on microbial activity both in the filter-adsorber and the product water, while Run No. 2 focused on the effect of backwash strategy. The results of the first two Runs can be found in Cobb, 1990 and DiGiano et al., 1991.

The results of Run Nos. 3, 4 and 5 will be reported here. The focus of these runs was to quantify the release of particles from new, old, and reactivated GAC and subsequent disinfection of particles. The specific objectives were:

1. to quantify the concentration of particles, particularly carbon particles, in the product water,
2) to quantify the number of microorganisms attached to these particles, and
3) to study the resistance of particle attached microorganisms to disinfection with chlorine.

Included in the study were solids concentration measurements; microscopic particle counting; scanning electron microscopy (SEM) analysis; disinfection of product water samples; and disinfection of concentrated solutions of particles released from the filters. In addition, bench scale carbon columns were set-up in the laboratory to quantify the release of carbon fines during GAC filtration in a more controlled environment.

# CHAPTER TWO

# LITERATURE REVIEW

## Explanation for Microbial Proliferation in GAC Filters

Researchers have postulated the following explanations for the proliferation of microorganisms in GAC filters: the availability of sorbed oxygen at the carbon surface; the availability of sorbed substrate at the carbon surface; the ability of carbon to reduce disinfectants; the shielded environment from shear forces provided by the jagged surface; the presence of various functional groups on the carbon surface; and the ability of carbon to adsorb and thus remove compounds considered toxic to microorganisms (AWWA Committee Report, 1981, Stewart, 1990).

## Enumeration of Microorganisms Associated with GAC Filters

Filtration of water through a biologically-active, GAC filter results in a significant release of microorganisms in the product water (van der Kooij, 1976, Sontheimer, 1978). Literature reports reveal concentrations of approximately $10^8$ Heterotrophic Plate Counts (HPC) per gram of carbon in GAC filters (Werner et al., 1979, Cobb, 1990). As a result of attached growth within the GAC filter, concentrations of

microorganisms in filter product water range from 10 to 100,000 HPC/mL (McElhaney and McKeon, 1978, Fiore and Babineau, 1977, Stewart et al., 1990)

**Identification of Microorganisms in GAC Filters**

Since GAC filtration results in a significant release of microorganisms, it is important to identify species which commonly proliferate GAC filters. The typical species identified in the product water of GAC filters vary greatly due to differences in raw water sources. However, dominant species include *Acinetobacter, Alcaligenes, Moraxella, Azomonas, Bacillus, Flavobacterium, Aeromonas, Chromobacterium* and *Pseudomonas* (Werner et al., 1979, McElhaney and McKeon, 1978, Parsons et al., 1980, Stewart et al., 1990). All are heterotrophic organisms common to natural organic-laden waters and none is a known pathogen. Some, however, have been labeled "opportunistic" pathogens affecting only weakened hosts. In general, species found in the raw water are also found in the GAC product water. However, the product water microorganisms tend to be less diversified. This suggests that a selection process occurs in GAC filters (Werner et al., 1979, van der Kooij, 1976).

Coliforms have been isolated in GAC filter product water (Camper et al., 1986, Camper et al., 1985, LeChevallier et al., 1984); however, it is more frequently reported that

coliforms do not survive or proliferate in GAC filters (van der Kooij, 1976, Cairo et al., 1979, Sontheimer et al., 1978). Researchers have found that undesirable microorganisms do not compete well with the autochthonous population found in GAC beds. Rollinger and Dott (1987) showed that *Escherichi a coli* (*E. coli*) was able to colonize a sterilized bench-scale GAC filter. However, when inoculated into a mature GAC filter containing autochthonous organisms, *E. coli* counts decreased below detection levels within 10 days. Camper et al. (1985) examined the ability of three enteric pathogens (*Yersinia enterocolitica, Salmonella typhimurium, and Escherichia coli*) to colonize GAC filters. Once again, the results showed that pathogens were able to colonize sterile columns. However, when the pathogens were mixed with HPC microorganisms and then added to a mature column, the pathogens colonized at a lower level and decreased at a more rapid rate.

The following explanations have been offered for the inability of pathogens to compete in microbially active GAC filters: typical species found in GAC filters such as *Bacillus*, *Pseudomonas*, and *Actinomycetes*, are antagonistic to toward some pathogenic organisms (Rollinger and Dott, 1987) and the naturally occurring GAC filter community is better adapted to the low nutrient supply common to raw water sources (LeChevallier and McFeters, 1985).

**Attachment or Aggregation as a Mode of Disinfection Survival**

Attachment to surfaces provides a survival mechanism for many microorganisms in aquatic ecosystems (Marshall & Bitton, 1980). Upon attaching to a surface, the cells often grow and colonize the site, simultaneously excreting exopolymers. This action creates multilayer colonies, or biofilms. These biofilms can provide protection for the organisms from outside perturbations or toxic compounds (Fletcher, 1984). For instance, biofilm formation in a water treatment plant can aid in survival of microorganisms during disinfection. Several mechanisms which may aid in microbial survival of attached or aggregated organisms include: decrease in cell surface area exposed to the disinfectant (LeChevallier, et al., 1988); competing demand for disinfectant caused by sorbed organic material at the liquid solid interface; and, protection provided by the extracellular polymer or slime layers which limit disinfectant penetration (Ridgeway and Olson, 1982).

Several studies have examined the impact of microbial attachment to solid surfaces on disinfection. LeChevallier, (1988) examined the disinfection efficiency of *K. pneumoniae* attached to sterile glass microscope slides. Results showed that attached organisms were approximately 75 times more resistant to disinfection with hypochlorous acid than similar unattached cells. LeChevallier et al. (1988a) also found that even relatively thin films of sparsely populated organisms

were still hundreds of times more resistant to disinfection with chlorine than dispersed organisms. Disinfection of attached cells with monochloramine, however, revealed different results. No difference was found in disinfection efficiency of attached or unattached organisms. The authors suggest that monochloramine is a less reactive oxidant and hence, able to penetrate deeper into the biofilm than the hypochlorous acid.

Cell aggregation has also been shown to enhance the survival of microorganisms during disinfection. This is because aggregation can offer the same physiological advantages to survival as attachment to inert surfaces. Olson and Stewart (1987) showed that aggregation of *Acinetobacter*, a bacteria commonly found in GAC filters, increased its resistance to chlorine over 100-fold that of dispersed cells. This has important relevance to GAC filtration since microscopic evidence of sloughed organisms in GAC product water is well documented (Parsons et al., 1980, Ridgeway and Olson, 1982).

The disinfection efficiency of dispersed microorganisms was compared to that of attached or aggregated microorganisms in a study by Ridgeway and Olson (1982). The water was obtained from the distribution system of a non-chlorinated groundwater source. Attached and aggregated cells were collected by passage of the water sample through a 2.0 um

filter whereas dispersed microorganisms were assumed to be collected on a 0.2 um filter. Scanning electron microscopy analysis of the material captured on the 2.0 um filter showed approximately 1% of the captured particles to have attached microorganisms. The number of attached bacteria per particle ranged from five to several hundred and particles with attached growth were usually larger than 10 um in diameter. Results of disinfection studies conducted on the material collected on the 2.0 um filter were then compared to those conducted on material collected on a 0.2 um filter. Microorganisms retained on the 2.0 um filter were over 10-fold more resistant to disinfection with free chlorine (10 mg/L) than the microorganisms retained on the 0.2 um filter. The greater resistance of attached bacteria was explained as being due to extracellular polymers excreted by the attached and agglomerated species that offered protection from chlorine penetration.

Particles were collected from the distribution system of a conventional treatment plant (Herson et al., 1987). The captured particles were composed primarily of iron and manganese and lacked attached organisms. The particles were inoculated with *Enterobacter cloacae*, allowing 18 hours for attachment. The sample was chlorinated with 0.8 mg/L free chlorine for one hour, dechlorinated, and then plated for bacterial enumeration. Prior to chlorination, the particle

solution contained approximately 50% attached and 50% unattached bacteria. After chlorination, the attached bacteria comprised 87% of the total bacteria. Thus the attached bacteria were found to be more resistant to disinfection. However, a significant kill of attached bacteria also occurred; on average, 99.5% of the dispersed bacteria were killed as compared to 98% of the attached bacteria. Therefore, while the attached bacteria were more resistant to disinfection, they were still significantly reduced.

The same researchers also found that increasing the chlorine dose had a greater impact on the dispersed bacteria then the attached bacteria (Herson et al., 1987). Thus simply increasing the disinfection dose in a water treatment plant may not eliminate attached microorganisms in the distribution system.

Turbidity has often been implicated in poor disinfection. This is not only because high turbidity is an indication of poor treatment, but also because turbidity particles can serve as host to attached bacteria. In a study by LeChevallier et al. (1981), the relationship between turbidity and disinfection efficiency of autochthonous coliforms was examined. Water samples from a surface water source were diluted to various turbidity values using sediment collected from the lake bottom. These samples were exposed to various

concentrations of free chlorine for one hour at 10C. The results showed that as turbidity increased, resistance to chlorine disinfection increased. A 99.5% reduction in coliform was achieved at a chlorine dose of 1.0 mg/L in a solution containing 1.5 NTU. When turbidity was increased to 8 NTU the disinfection efficiency was reduced to 90%. Increasing turbidity even further (13 NTU), caused the disinfection efficiency to drop to only 70%. Increasing the turbidity also increased the chlorine demand of the solutions; however, it did not fully explain the decrease in disinfection efficiency. Therefore, attachment of organisms to turbid particles was the proposed mechanism of bacterial survival.

**Release of Attached Microorganisms During GAC Filtration**

Microbial growth and the subsequent release of microorganisms is an unavoidable consequence of GAC filtration. Furthermore, attached or aggregated organisms released from GAC filters may exhibit resistance to disinfection. Small carbon particles with attached growth can break-off from the GAC media during filtration and enter the finished water. In addition, clumps of microorganisms can be sheared from the carbon surface and enter the product water. These attached and aggregated microorganisms can compromise the disinfection process.

The disinfection efficiency of microorganisms attached to GAC particles was compared to that of dispersed microorganisms (LeChevallier et al., 1984). GAC media was removed from a biologically mature bed in a full scale facility and dosed with 2.0 mg/L chlorine. After one hour contact time, (1.7 mg/L residual) there was no significant decrease in HPC attached to the GAC particles. A sample of dispersed microorganisms was collected by desorption from the surface of the GAC particles. The dispersed microorganisms were disinfected under similar conditions to those for attached. A much greater extent of disinfection was achieved. Plate counts decreased by over 5 log units within 5 minutes contact time as compared to no reduction in one hour for attached microorganisms.

LeChevallier et al. (1984) also examined scanning electron micrographs of the chlorinated GAC particles. Bacterial growth was evident in cracks and crevices of the carbon. The organisms were also found to be coated with a layer of extracellular polymers. Survival of attached microorganisms was thus attributed to the inability of the chlorine to penetrate the slime layer. However, an alternative explanation is offered by chemical reduction of chlorine by the GAC which can create a thin film of chlorine-free water at the carbon surface. This would restrict contact between the microorganisms and the disinfectant.

The disinfection efficiency of a human pathogen attached to GAC particles has also been examined (LeChevallier et al., 1984). Virgin GAC particles were inoculated with *E. coli* and the bacteria were permitted to attach for 20 minutes. The attachment period was brief to prevent the formation of a biofilm. Samples of GAC media were withdrawn from a biologically active bed and disinfected with 2.0 mg/L free chlorine for one hour (1.4-1.7 mg/L residual). No significant decrease in viable cells was observed. However, unattached bacteria were reduced by 2.5 logs after only 10 minutes contact.

The results of LeChevallier et al (1984) suggest that both heterotrophic and potentially pathogenic organisms attached to GAC particles are highly resistant to chlorine disinfection. However, disinfection studies conducted on large GAC particles may not be relevant to the disinfection of particles which escape the filter. First, chlorine penetration may be faster and thus more effective in the smaller particles which escape. Second, GAC filtration can be viewed as a fixed film process where biofilm formation is substantial. This may not be true of very small particles which escape the filter.

Particles released from operating GAC filters at nine drinking water treatment plants were examined in a study by Camper et al. (1986). Gauze filters were attached to sampling

ports of GAC filters to trap particles released during filtration. These particles were then subject to scanning electron microscopy, size analysis, and enumeration of attached microorganisms. Scanning electron microscopy analysis of the collected particles showed microcolonies of bacteria coated with extracellular polymers in the cracks and crevices of the carbon surfaces. Image analysis was done on black particles (presumably escaped GAC particles) and showed their diameters to range from 1.0 to 3.5 x $10^3$ um.

To ensure that only attached microorganisms were enumerated, Camper et al. (1985) devised a disinfection procedure to eliminate dispersed organisms. Solutions containing captured particles (presumably activated carbon) were first dosed with 2 mg/L chlorine for 30 minutes. This was followed by dechlorination after which the microorganisms were detached from the particles for enumeration. According to the authors' definition, all of these attached bacteria had survived chlorination with 2 mg/L chlorine for 30 minutes. Surviving attached bacteria were found in 41.4% of the samples and 17% of these samples contained particles colonized with coliforms. The authors state that microorganisms were attached specifically to escaped carbon particles. However, this can not be substantiated by their research since not all the captured particles were GAC. Rather, the particles were

more likely a heterogeneous mixture consisting of activated carbon, chemical floc, etc.

The release of particles from a GAC post-filter-adsorber was thoroughly studied through operation of a pilot plant by Stewart et al. (1990). The concentration and size distribution of escaped particles were measured. In addition, attached organisms were enumerated and disinfection studies on GAC particles removed from the filter were conducted.

Microscopic examination of captured particles showed that an average of 36 with a range of 10 to 62 GAC particles per liter were released into the product water. The particles ranged in size from 2 to 40 um in diameter with a mean of 5.4 um. Large volumes of product water (approximately 1000 L) were filtered through a 10 um polycarbonate filter to capture particles and enumerate attached microorganisms. Highly concentrated solutions of captured particles were then subjected to the procedure developed by Camper et al. (1986) to identify "attached" microorganisms (i.e., "attached" was defined as those that survive 20 minutes chlorine contact time). The release of attached microorganisms was estimated to be between 0 to 434 per liter of product water. Based on the observed concentration of GAC particles in the product water, the authors estimate that each GAC particle contained 0 to 7 attached organisms. Like Camper et al. (1985), the assumption was made that all microorganisms were attached

specifically to GAC particles. This may be reasonable for post-filter-adsorbers. Furthermore, SEM analysis of released GAC particles showed 85% to have less than 50 attached cells while 8% had several hundred to several thousand attached cells.

Finally, Stewart et al. (1991) reported on disinfection of GAC media removed from the post-filter-adsorber. Their results were similar to those of LeChevallier et al. (1984) in that very little reduction in HPC was observed. This was true using either chlorine or chloramine as the disinfectant (1.5 mg/L residual) and 40 minutes of contact time. While such disinfection results suggest that activated carbon can protect microorganisms during disinfection, the results may not be relevant to disinfection of organisms attached to smaller particles which escape into the product water.

**Summary**

Microbial growth is an unavoidable consequence of GAC filtration. As a result, product water from carbon filters usually contains from 10 to 100,000 HPC/mL, while the carbon media itself has on the order of $10^8$ HPC/gram of attached bacteria. The vast majority of species isolated in GAC product water have no known pathogenic significance; however, some opportunistic pathogens have been isolated. Species of

importance to human health do not compete as effectively as the autochthonous populations found in GAC filters.

Recent research has identified attachment of organisms to surfaces to be a mode of survival during disinfection. Studies examining bacterial survival in chlorinated distribution systems have implicated attachment of bacteria to inert surfaces as an important survival mechanism. Laboratory studies on the disinfection of bacteria attached to surfaces have confirmed these field observations.

Bacteria attached to both GAC media taken from an operating bed and from particles collected in product water have been shown to be highly resistant to disinfection. However, some caution is needed in interpreting disinfection results when experiments are conducted with concentrations of particles that are orders of magnitude greater than actually observed in product water and on particles that may be much greater in diameter. SEM analysis of particles released from GAC filters has shown them to contain a considerable amount of attached growth. In perspective, however, the number of attached bacteria has been found to comprise a very small percentage of the total bacteria released from GAC filters.

# CHAPTER THREE

# DESCRIPTION OF PILOT PLANT FILTER-ADSORBERS

## Location of Pilot Plant

The pilot plant filter-adsorbers were constructed at the Franklin Water Treatment Plant (WTP) in Charlotte, North Carolina. The WTP receives its raw water from Lake Norman, a high quality surface water. The plant uses a conventional treatment train consisting of rapid mix, flocculation, sedimentation and dual media (sand and anthracite) filtration processes. Free chlorine (0.8 to 1.2 mg/L) and PAC (1 to 2 mg/L) are added during rapid mix.

## Description of the Pilot Plant Filter-Adsorbers

Figure 3-1 is a schematic of the pilot plant filter-adsorbers. The filter-adsorbers, provided by Camp, Dresser and McKee, Inc. were assembled in the filter gallery at the Franklin Water Treatment Plant. Settled water from the Franklin WTP sedimentation basin flowed by gravity to a manifold which distributed the water to three filter-adsorbers. The filter-adsorbers were housed in Plexiglas columns approximately 11 ft in height and 4-inches in

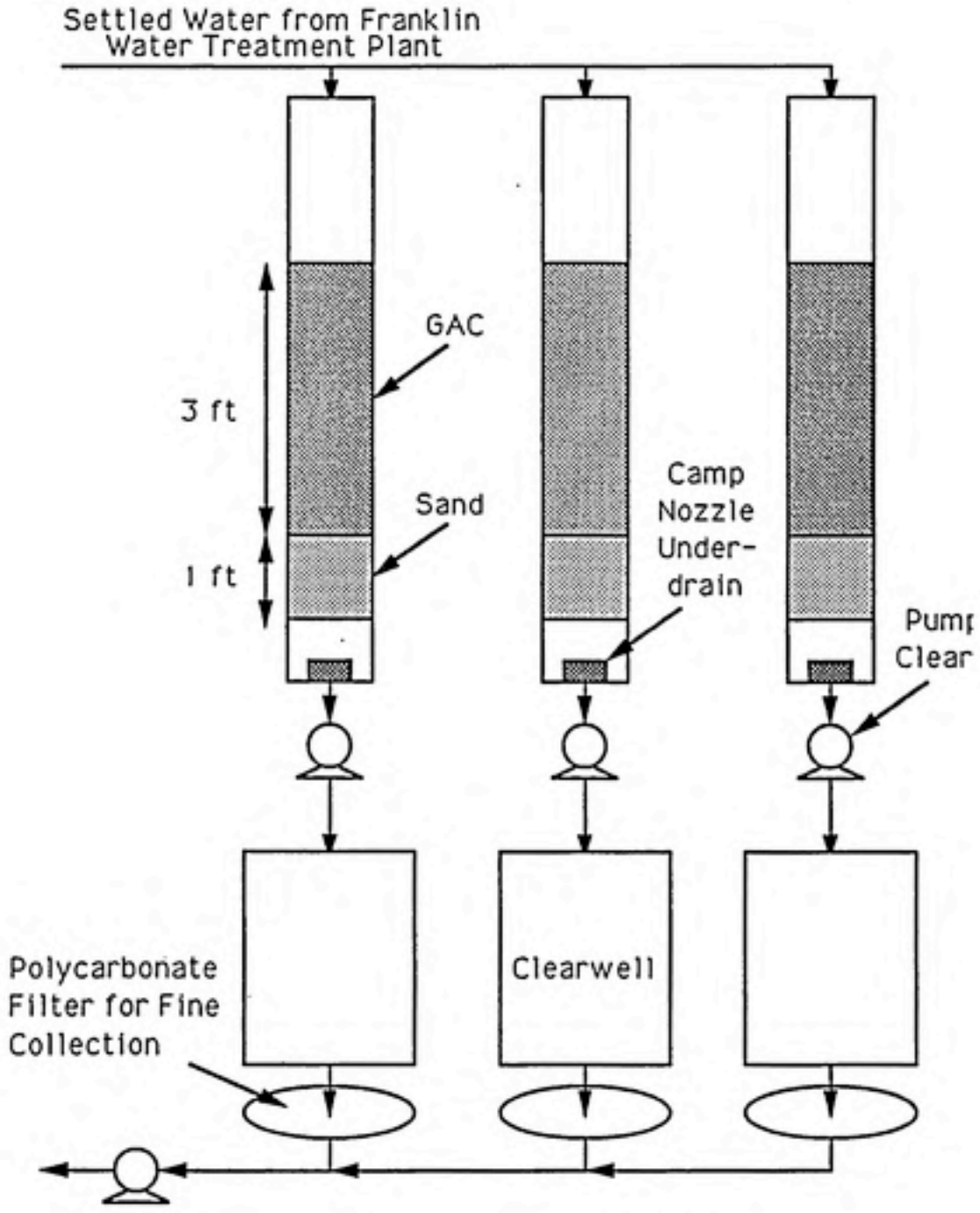



Figure 3-1. Schematic of pilot plant at Franklin WTP.

diameter. The underdrain consisted of a single, Camp nozzle which is constructed of stainless steel and has very fine vertical slits that prevent the passage of large solids.

Flow rates through the filters were maintained by three, variable-rate centrifugal pumps. The application rate for Run Nos. 3 to 5 to be presented in this report, was set at 4 gallons per minute per square foot (gpm/sf). The product water was discharged into a 55 gallon drum which acted as a clearwell. The detention time in each clearwell was approximately 140 minutes. A stainless steel, Millipore filter-holder was attached to each clearwell. The filter holders housed a polycarbonate membrane filter used to capture particles in the product water of the filter-adsorbers. The polycarbonate filter was 247 mm in diameter with 5-um nominal pore diameters.

Each filter was backwashed once per day. During backwashing, the flow of water to the columns was shut-off while the pumps continued to drain the filters to a level of 6 in. above the filter media. At this point, the filter pumps were turned-off and the valving was altered to reverse the direction of flow. Water was then pumped from the clearwells, which contained filter product water, back into the filters. The filters were backwashed for 10 minutes at an application rate of 15 gpm/sf. Air scouring accompanied the first two minutes of backwashing.

**Media Used in Filter-Adsorbers**

The filter media used in this study consisted of: sand, old GAC, reactivated GAC, and new GAC. The different types of GAC were chosen to examine the effect of age and reactivation on biological activity in the filter-adsorbers. The sand media was provided by the Franklin WTP and was similar to that used in the plant filters. The old GAC (Calgon F300) was obtained from the Lynchburg WTP in Lynchburg, Virginia and had previously been in service for two years. The reactivated GAC (mixture of Calgon F300 and CECA) was sent to the University of North Carolina (UNC) from the Buffalo Pound WTP in Regina, Canada. It had been reactivated and then returned to service for approximately 7 months, prior to shipment to UNC. The new GAC sample (Calgon F300) was shipped to the Franklin WTP direct from Calgon Carbon, Inc. All GAC samples were thoroughly rinsed, dried, and then sieved to a uniform distribution (8 x 30 U.S. Standard sieve) before being placed in the filter-adsorbers. Pre-sieving was required since the GAC samples which had previously been in service (old and reactivated) had significantly smaller particle size distributions than the new GAC sample. This was presumed to be a result of obtaining the used GAC samples from the upper layer of the full-scale filters where the media size tend to be significantly smaller.

The depth of media was not constant throughout all runs. A total filter depth of 2 ft was used when sand alone was the media. In contrast, the filter-adsorbers contained 3 ft of GAC over 1 ft of sand. The difference in heights was necessary to permit the same backwashing frequency in each of the filters. Originally, 3 ft of sand was used in the sand filter; however, headloss developed quickly and backwashing was required more frequently than once per day. The interval between backwashing could be extended to one day by removing 1 ft of sand from the filter.

# CHAPTER FOUR

# EXPERIMENTAL METHODS

## ROUTINE MEASUREMENTS

The experimental methods described below were used on a routine basis throughout the course of the study. Because the pilot plant was located in Charlotte, NC, it was necessary to rely on the staff of the Franklin WTP to collect these data.

### Product Water Turbidity

Turbidity was measured by a continuous flow turbidimeter (Hach) connected to the product water line of each of the pilot filter-adsorbers. Occasionally, the instrument was calibrated by a member of the Franklin WTP staff. The turbidity reading was recorded every four hours and the data were converted into frequency distribution graphs for analysis.

### Heterotrophic Plate Counts (HPC) in Product Water

Samples from the influent to the pilot plant and the product water of each of the filter-adsorbers were collected on alternate days for HPC determination. Colonies were grown at room temperature (spread plate technique) using R2A agar.

The incubation period was seven days. Previous studies have shown that the R2A agar can enhance the enumeration of bacteria in drinking water samples owing to its low nutrient content which parallels many drinking water sources (Reasoner and Geldreich, 1985). In addition, the seven day incubation period has been found to be optimal for plating drinking water samples since microorganisms in drinking water sources tend to be slow growers (Werner et al., 1978).

**Coliforms in Product Water**

Samples from the influent to the pilot plant and the product water of the filter adsorber were collected once per week for total coliform enumeration. The membrane filtration technique (Method 9222B, APHA, 1989) and later, the presence/absence test (Method 9221E, APHA,1989) was used for coliform detection. Sample volumes used in the analysis were 100 mL.

**NON-ROUTINE MEASUREMENTS**

The remaining methods describe procedures conducted non-routinely. Samples required for these procedures were collected during periodic visits to the Franklin WTP by the graduate research assistants working on this project.

**Measurements of Particle Concentrations**

Several different methods were used in this study to measure the concentration of particles released from the filter-adsorbers. Sampling techniques were altered over the course of the study as problems with sample volume measurements and bacterial contamination were revealed.

The initial technique used a pump attached to an automatic timer. At 2 hr intervals, the pump filtered 60 gallons of water from the 55 gallon clearwell (at 10 gpm) through the 5 um polycarbonate filter. After passage through the membrane filter, the water recirculated back into the clearwell. Since the hydraulic residence time of the clearwells was 140 minutes, and the pump filtered the entire volume of the clearwell every 120 minutes, it was assumed that all the product water passed through the membrane filter. Thus all the particles released from the filter-adsorbers had been captured on the polycarbonate filters. The polycarbonate filters were aseptically removed from their holder and returned to the UNC laboratory approximately every two weeks.

The polycarbonate filter was placed in an autoclaved glass bottle (250 mL) containing 100 mL of distilled water. The filter was chopped into fine pieces using sterilized scissors. The jar was then agitated to dislodge the particles from the polycarbonate filter surface. Visual inspection of the polycarbonate filter pieces was used to ensure that the

majority of the particles had been removed. The solution of polycarbonate filter pieces and dislodged particles was poured through an autoclaved strainer to retain the polycarbonate filter while permitting the particles to pass into a sample bottle. Approximately 10 mL of this solution was removed, filtered, and oven-dried for particle concentration measurements. The remainder of the solution was used for enumerating attached bacteria and disinfection studies.

The following problems arose using this initial sampling technique to collect particles in the product water:

1. During the two week sampling period, the polycarbonate filters became progressively clogged. This resulted in a decrease in the pumping rate through the filters. Thus with time, the pump was no longer sampling 60 gallons at a time.

2. Recirculation of the filtrate back into the clearwell caused mixing in the clearwell volume. Therefore, the clearwell did not behave as an ideal plug-flow reactor. This disqualified the assumption that all the particles could be captured as long as the entire clearwell volume was pumped within one detention time (140 min).

3. Very few particles were released by the filter-adsorbers. Since the collected particles had to be used for both particle concentration measurements and disinfection studies, only a small aliquot of solution could be removed for concentration measurements. The remainder of the solution was needed for the disinfection studies. This placed a large margin of error on the solids concentration data, which only used 10 mL of the concentrated fines solution.

4. The polycarbonate filters were collected once approximately every 2 weeks. Therefore, extensive microbial growth may have occurred on the polycarbonate

filter during the sampling period. This growth could have artificially enhanced the number of microorganisms attached to the particles as the particles left the filter-adsorber.

To correct these deficiencies, the following changes were made to the sampling procedure:

1. A batch method for collecting particles was used instead of the two week, automated sampling technique Water was pumped from the clearwell and into a graduated drum. This ensured that a known volume of product water had been sampled and also reduced the time that the particles spent on the polycarbonate filter. This curtailed the opportunity for regrowth of microorganisms on the filters.

2. Two collections of particles, one immediately following the other, were made where one sample was used for gravimetric analysis and the other for disinfection studies. The technique for preparing the solution of particles for disinfection experiments remained the same. The polycarbonate filter was placed in a small tub and particles were rinsed off with distilled water. This solution was filtered and dried at 105 C for gravimetric analysis.

**Particle Size Distributions**

Samples (40 mL) of product water and concentrated particle solutions from each of the three filter-adsorbers (reactivated, old and new GAC) were sent to Dr. Appiah Amirthirajah, Depart. of Civil Engineering at the Georgia Institute of Technology for particle size distribution analysis. The analysis was conducted on a Brinkman Particle Size Analyzer. The instrument measured the distribution of particles ranging from 0.5 to 60 um in diameter. Additional

information on the particle concentration and mean particle diameter was also provided. This procedure was conducted once during the course of this research.

**Particle Counting of Carbon Fines Released into Product Water**

Microscopic particle counting of black particles was used to isolate the concentration of GAC particles in the product water. Grab samples (4 L) of influent water and product water from each of the three filter-adsorbers were collected by a staff member at the Franklin WTP every other day for approximately one month. The samples were returned periodically to the University of North Carolina for particle counting. An appropriate volume of water (50 mL to 300 mL) was withdrawn and vacuum filtered through a gridded filter. The specific volume was chosen to produce particle counts ranging from approximately 30 to 300 particles per filter. Particle counting was done on a light microscope at 30X magnification and only black particles were counted. This procedure was performed in triplicate on each of the 4 L samples.

**Scanning Electron Microscopy Analysis**

Scanning Electron Microscopy (SEM) analysis was performed on grab samples of particles released from the filter-

adsorbers. The SEM work was done in the Pathology Department at UNC by graduate assistant William Stringfellow.

A small piece of the polycarbonate membrane filter used to capture particles at the pilot plant was cut and rinsed three times with deionized water. The filter was dehydrated with a series of ethanol/water mixtures (50, 70, and 95% each for 5 minutes and then 100% twice for five minutes each), placed in a solution of Freon 113 (twenty minutes), followed by critical point drying (Balzer CPD 020). The sample was then mounted on aluminum stubs with colloidal silver paste, and coated with Au/Pd alloy (Denton vacuum evaporator).

**Disinfection of Microorganisms Attached to Particles Released in Product Water**

The effect of particle concentration and chlorine concentration on the rate of disinfection of particle attached microorganisms was examined. Concentrated solutions of particles (collected as described in "Measurements of Particle Concentrations") were diluted with distilled water (phosphate buffered to pH 6.5) into three samples of varying particle concentrations. A single dose of free chlorine (HOCl) was applied to each of the samples. Small aliquots (5 mL) were transferred periodically to a dilution bottle and dechlorinated with thiosulfate. The microorganisms were then detached from the surface of the particles by vigorously

shaking the bottle for several minutes. This procedure was found to be as effective as methods incorporating extraction solutions (zwitterionic detergent, polyvinyl propylene, etc.) or mechanical agitation devices [homogenizer, centrifuge, etc.,(DiGiano, et al., 1991)]. The sample was then plated for HPC determination. The experiment was conducted twice during this research.

The effect of chlorine concentration on the rate of disinfection was examined. A concentrated solution of particles was divided into three separate solutions of equal particle concentrations and dosed with chlorine concentrations of 0.5, 1.0, and 2.0 mg/L free chlorine. Samples were periodically withdrawn and dechlorinated and microorganisms detached and plated. The experiment was conducted twice during this research.

**Bench-Scale GAC Filter**

A bench-scale GAC filter (Figure 4-1) was used to quantify the release of carbon fines from GAC filters under controlled conditions that were not possible in the pilot plant at the Franklin WTP. The old, new and reactivated GAC from the pilot plant was also used in the bench-scale filters. Samples of GAC were sieved to 14 x 16 U.S. Standard mesh in order to maintain a uniform distribution of GAC. The GAC was

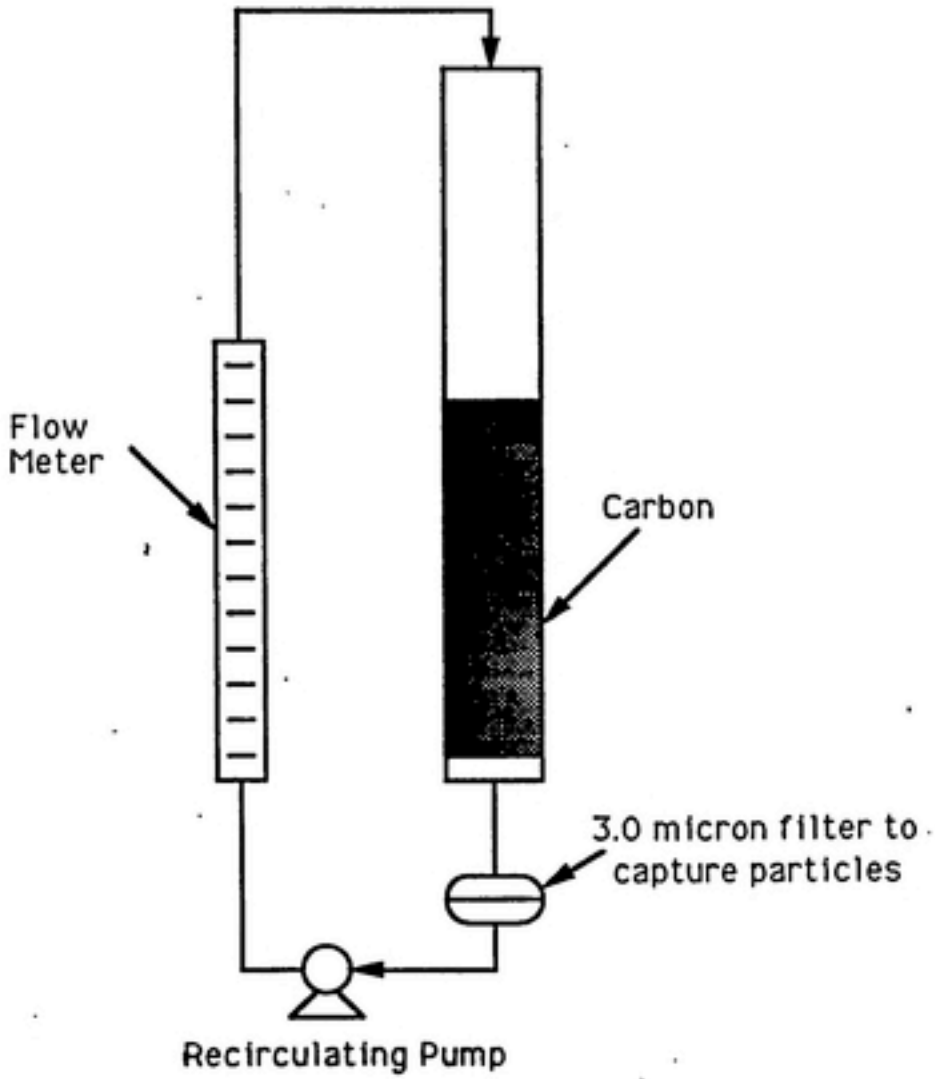



Figure 4-1. Schematic of bench-scale GAC filter.

then rinsed (approximately 30 minutes) with tap water in the 16 mesh sieve to remove smaller particles.

An 18 in depth of GAC was placed in a plexiglass column having a height of 4 ft and diameter of 2 in. Initially, the column was backwashed for 30 minutes (12 or 15 gpm/sf) to remove any pre-exisitng particles before beginning a run. The two remaining backwashings for a given sample run were only 15 minutes in duration. Distilled water was passed through the filter column with a peristaltic pump and recirculated back to the influent of the filter. The surficial loading rate was maintained at 3 gpm/sf. A 3.0-um polycarbonate filter, housed in a 47 mm diameter filter holder, was placed on the effluent line of the column to capture particles. The polycarbonate filter was removed periodically and captured particles were microscopically counted at 30X magnification. After approximately 48 hours of filter run time, the filters were backwashed (15 minutes) and the procedure for capturing particles was repeated. For each run, the filter was backwashed three times and average particle concentrations were plotted versus filter run time.

The type of GAC (old, new, and reactivated) was compared to determine whether age or reactivation had any effect on the attrition of GAC particles during backwashing and filtration. In addition, two different backwashing rates (12 and 15 gpm/sf) were used to determine its effect on particle attrition.

# CHAPTER FIVE

# RESULTS AND DISCUSSION

## Previous Findings of Research Project

This report discusses research conducted during the second year of a two year project. The entire project consisted of 5 experimental runs in which Run Nos. 1 and 2 were conducted in the first year while Run Nos. 3 to 5 were conducted in the second. A summary of the dates of operation and objectives of each of the five experimental runs conducted in this research is shown in Table 5-1. In addition, a brief summary of the findings of Run Nos. 1 and 2 is given below.

## Run Nos. 1 and 2

Run Nos. 1 and 2 were conducted during the first year of pilot plant operation (Cobb, 1990). Run No. 1 began on 12-14-88 and ended 04-14-89 (122 days). The objective of this Run was to examine the effect of the application rate on microbial activity in the filter-adsorbers. Application rates of 2, 4, and 6 gpm/sf were used in the three filter-adsorbers. Microbial activity was evaluated based on HPCs in the product water and HPCs attached to the filter media in the bed. The

Table 5-1. Operational variables selected in each pilot plant run.

| Run No. | Dates | Operational Variable |
|---|---|---|
| 1 | 12-14-88 to 04-14-89 | Application Rate: 2, 4, and 6 gpm/sf |
| 2 | 05-16-89 to 08-07-89 | Backwashing Strategy: once per day, once every two days, once per day w/ $Cl_2$ |
| 3 | 01-22-90 to 04-02-90 | Media Type: new GAC over sand and sand only |
| 4 | 04-11-90 to 07-18-90 | Media Type: new GAC over sand, old GAC over sand, and sand only |
| 5 | 07-21-90 to 11-15-90 | Media Type: new GAC over sand, old GAC over sand, and reactivated GAC over sand |

concentration of HPCs in the product water and attached to the GAC media was found to decrease with increasing application rate. It was assumed that lower application rates permitted greater biodegradation of substrate and thus produced more growth.

In Run No. 2, conducted from 05-16-89 to 08-07-89_ (83 days), the effect of backwash strategy on microbial activity was examined. The application rate in each filter-adsorber was maintained at 4 gpm/sf; however, backwashing protocol was

varied as follows: backwashing once every 24 hours, once every 48 hours, and once every 48 hours with chlorinated backwash water (2 mg/L HOCl). Results showed backwashing with chlorine to have the most significant impact on microbial activity reducing HPCs in both the product water and attached to the GAC media. More frequent backwashing was also found to reduce HPCs, however, this effect was less pronounced than the effect of chlorine addition.

**Run Nos. 3, 4 and 5**

The major objective in Run Nos. 3 to 5 was to examine the release of particles from the filter-adsorbers and furthermore, to assess the effect of particle-attached microorganisms in the product water on disinfection. Comparisons were made based on the type of media installed in the pilot filters during each run. Run No. 3 compared sand and new GAC media; Run No. 4, compared sand, old GAC, and new GAC; and Run No. 5 compared reactivated GAC, old GAC, and new GAC.

**Product Water Turbidity**

The distributions of product water turbidity values from Runs Nos. 3, 4, and 5, are shown in Figures 5-1, 5-2, and 5-3, respectively. The turbidity of the product water from each of

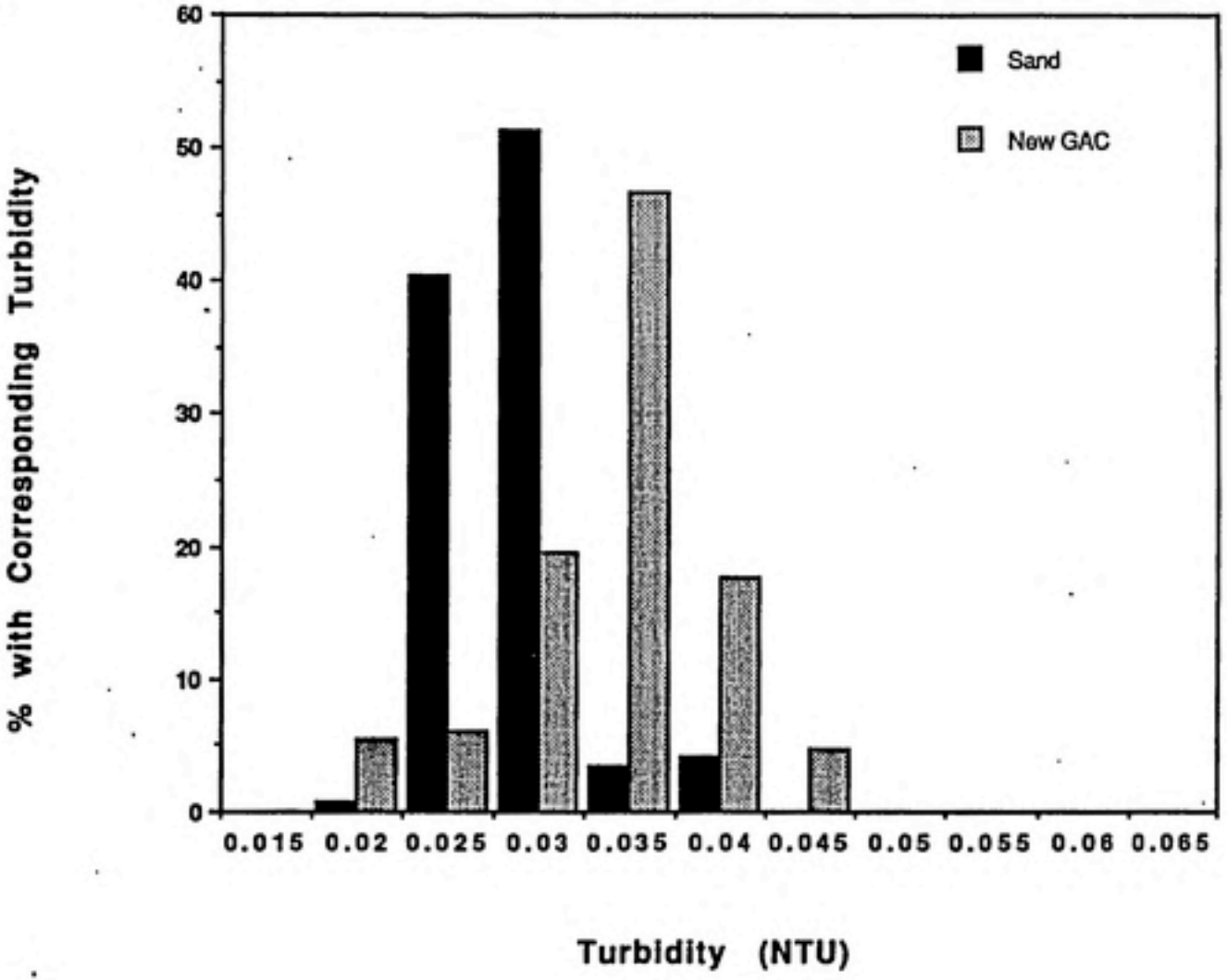



Figure 5-1. Distribution of product water turbidity values for Run No. 3 comparing a sand filter to a new GAC over sand filter-adsorber.

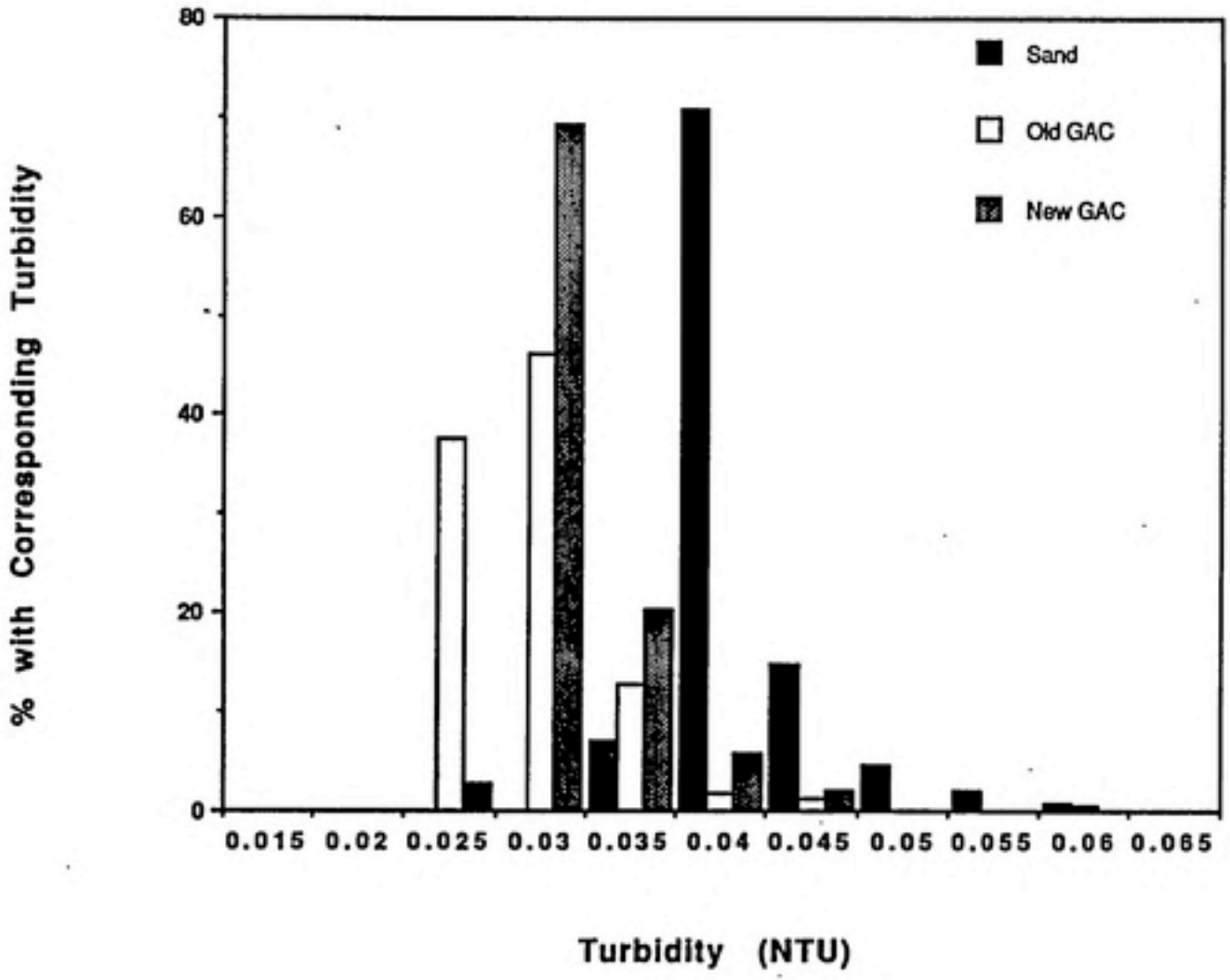



Figure 5-2. Distribution of product water turbidity values for Run No. 4 comparing a sand filter, old GAC filter-adsorber and new GAC filter-adsorber.

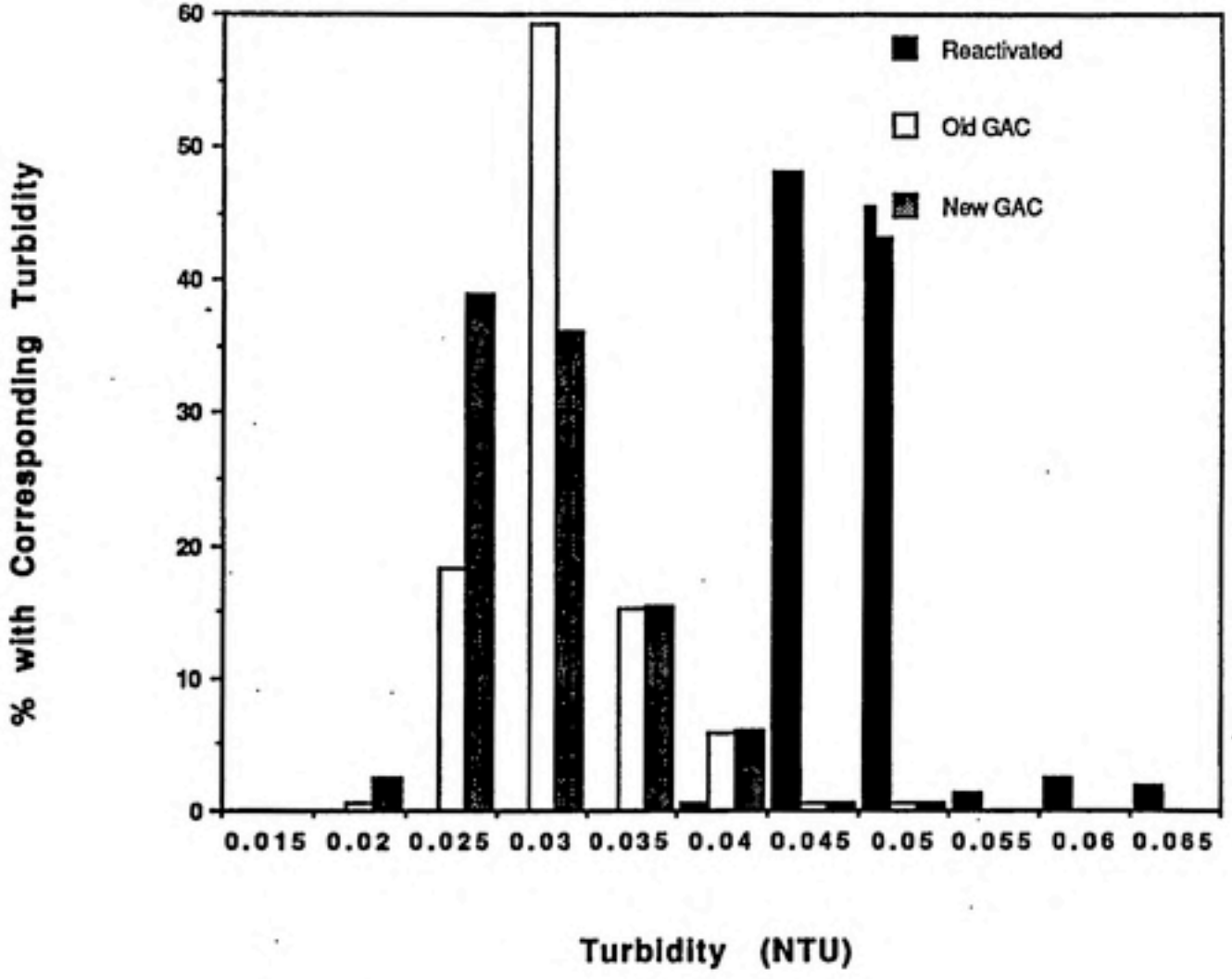



Figure 5-3. Distribution of product water turbidity values for Run No. 5 comparing Reactivated, Old, and New GAC filter-adsorbers.

the filters was extremely low. In Run Nos. 3 and 4 (Figures 5-1 and 5-2), in which GAC over sand and sand alone were used as the test media, the GAC filter-adsorbers were as effective as the sand filters for turbidity removal. In Run No. 3, the mean turbidity value of the sand filter was approximately 0.03 NTU while the new GAC filter was 0.035 NTU. In Run No. 4, the sand column mean turbidity value was approximately 0.04 NTU while both the new and old GAC filter-adsorbers was 0.03 NTU. A GAC sample which had previously been in service for approximately two years was used during Runs Nos. 4 and 5 (Figure 5-2 and 5-3) to examine the effect of GAC age on turbidity removal. In both Runs, turbidity removal in the old GAC and new GAC filter-adsorbers were similar (mean turbidity of 0.03 NTU). This suggests that turbidity removal in GAC filter-adsorbers is independent of the age of the GAC. Finally, the effect of reactivation on the ability of GAC to remove turbidity was examined (Run No. 5, Figure 5-3). In this Run, the reactivated GAC filter-adsorber produced higher turbidity values then either the new or old GAC filters (mean of 0.045 NTU versus 0.03 NTU). While the old and new GAC filters had lower distributions of turbidity values the average difference (0.015 - 0.02 NTU) is fairly insignificant as compared to the EPA finished water standard of 1 NTU.

**Penetration of Chlorine**

The ability of the GAC filter-adsorbers to chemically reduce chlorine (added at the head of the Franklin WTP) was measured. Chlorine concentrations at three different depths in the old, new, and reactivated GAC filter-adsorbers were measured several times during Run No. 5. As shown in Table 5-2, the chlorine profiles in all three GAC filter-adsorbers are similar. Most of the chlorine has been reduced at a depth of 1.5 ft and no chlorine was present at 2.5 ft. Thus, prechlorination at the Franklin WTP provided little deterrence to microbial growth in the filter-adsorbers. Even the old GAC filter, which had previously been in service for two years at a WTP that prechlorinates, was able to reduce the chlorine as well as the new GAC filter. It is well known that GAC has a large capacity to reduce chlorine (Suidan et al., 1977), therefore, chlorine added prior to GAC filtration will likely be reduced by the GAC limiting its ability to control microbial growth.

Table 5-2. Chlorine penetration profile in Reactivated, Old and New GAC filter-adsorbers.

| Filter Depth (Ft) | Average Chlorine Concentration (mg/L) Reactivated | Old | New |
|---|---|---|---|
| 0.5 | 0.65 | 0.64 | 0.65 |
| 1.5 | 0.03 | 0.09 | 0.10 |
| 2.5 | 0.00 | 0.00 | 0.00 |

**Release of Microorganisms into Product Water**

HPC were routinely measured to assess microbial colonization in each of the pilot filters. Comparisons of product water HPC were made based on media type (sand, old GAC, new GAC, and reactivated GAC) The average and standard deviation of HPC in the influent to the pilot plant and the filter product waters during Run Nos. 3, 4, and 5 are shown in Table 5-3. The HPC entering the pilot plant were very low in all the runs due to prechlorination at the Franklin WTP. Passage through the sand filter (Run Nos. 3 and 4) resulted in an insignificant increase in HPC in the product water during Run No. 3 and an order of magnitude increase during Run No. 4. The difference in results was probably due to seasonal differences during the runs. Run No. 3 was conducted during the winter months while Run No. 4 occurred during the Spring. Warmer water temperatures often times result in increased microbial growth. Nonetheless, the product water concentrations in both runs were quite low ($5 \pm 9$ and $320 \pm 700$, respectively). Low HPC in the product water of the sand filter was attributed to the ability of chlorine to penetrate the column thus restricting growth.

In contrast, filtration through the GAC filter-adsorbers resulted in increases in HPC of several orders of magnitude. For example, during Run No. 3, product water from the sand column released an average of 5 HPC/mL, whereas the new GAC

Table 5-3. HPC/mL in Influent and Product Water of Pilot Plant Filters.

**RUN NO. 3**

| Filter Type | Number of Samples | Average Bacteria (HPC/mL) | Standard Deviation (HPC/mL) |
|---|---|---|---|
| Settled Water | 82 | 3 | 5 |
| Product Water from: | | | |
| Sand Filter | 29 | 5 | 9 |
| New GAC Filter | 43 | 5,180 | 7,090 |

**RUN NO. 4**

| | | | |
|---|---|---|---|
| Settled Water | 84 | 11 | 30 |
| Product Water from: | | | |
| Sand Filter | 59 | 320 | 700 |
| Old GAC Filter | 52 | 6,310 | 6,670 |
| New GAC Filter | 56 | 11,780 | 8,080 |

**RUN NO. 5**

| | | | |
|---|---|---|---|
| Settled Water | 68 | 13 | 45 |
| Product Water from: | | | |
| Reactivated GAC Filter | 20 | 12,500 | 11,210 |
| Old GAC Filter | 41 | 8,490 | 8,050 |
| New GAC Filter | 33 | 9,440 | 8,560 |

filter-adsorber released approximately 5,180 HPC/mL. This difference in HPC was primarily due to the chemical reduction of chlorine in the upper layer of the GAC filter-adsorber. (See Table 5-2) Unrestrained microbial growth was permitted throughout most of the GAC filter. Similar values of HPC in product water from GAC filters are reported in the literature (Cobb, 1990, Werner et al., 1979, McElhaney et al., 1978).

The data for Run Nos. 4 and 5 in Table 5-3 show the effect of different types of GAC media on HPC in product water. No statistically significant difference was found between the old and new GAC in Run Nos. 4 and 5. This is true despite the HPC from the new GAC filter in Run No. 4 being almost twice that of the old GAC filter; the difference was nevertheless, statistically insignificant ($p<0.001$) due to the high standard deviation in the samples. Similarly, in Run No. 5, the difference between HPC in the product water from the reactivated GAC filter and either the old or new GAC filter was not statistically significant. Thus any changes in the surface properties of GAC as a result of reactivation or age, seemed to have little effect on the growth and subsequent release of microorganisms from the filter-adsorbers.

The release of microorganisms with time of filter-adsorber operation was also examined. The pattern suggested in Figure 5-4 is typical of bacterial growth. The HPC concentration in the product water was low during the first

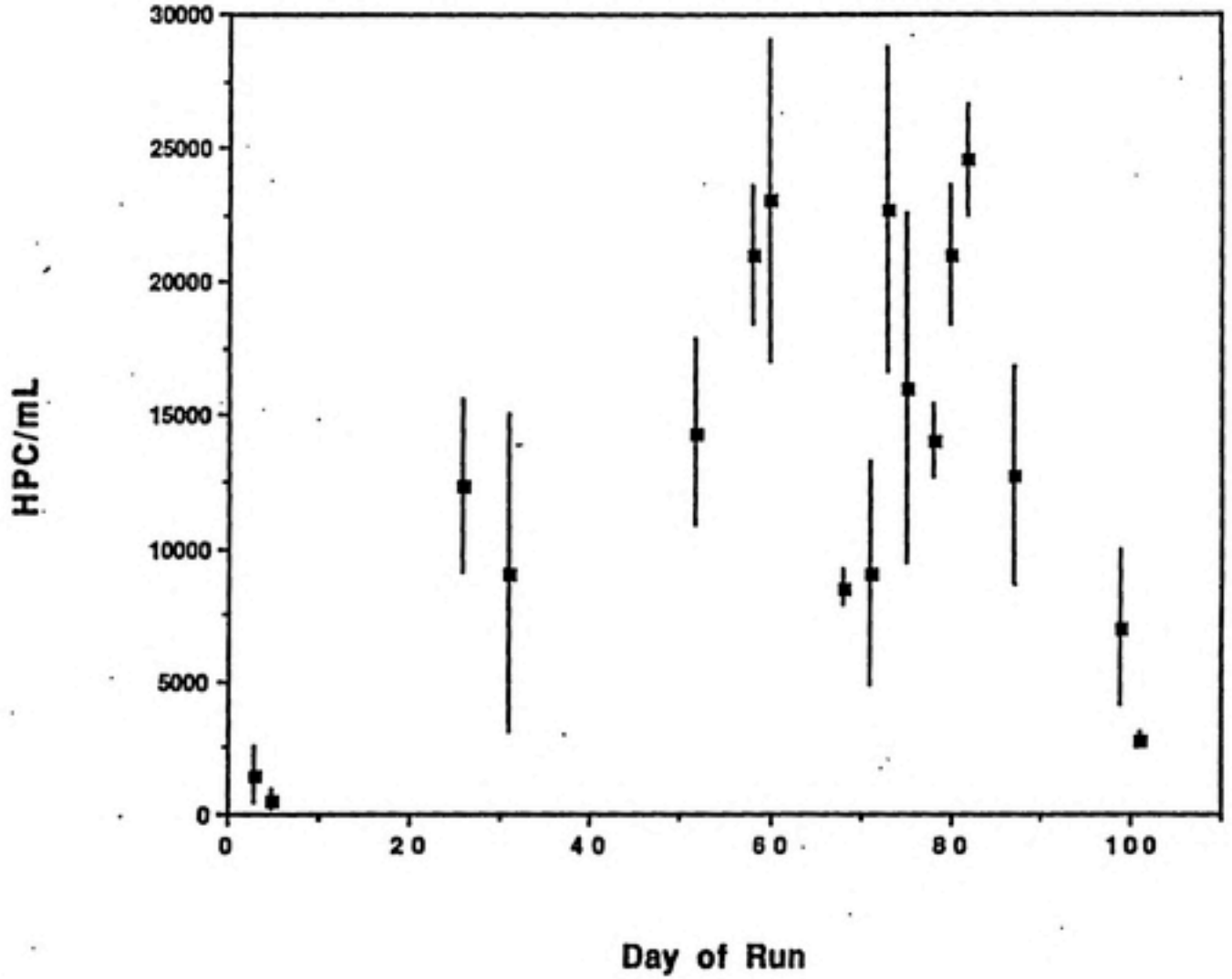



Figure 5-4. Typical growth curve of HPC released in product water of new GAC filter-adsorber. Error bars represent ± 1 standard deviation.

few weeks of operation presumably due to a required acclimation period, (Stewart, et al., 1990, van der Kooij, 1976). The low HPC could also be attributed to an initial period of attachment to the GAC surface with minimal shearing of microorganisms. Following the start-up period, it was assumed that the system would approach steady-state where attachment and shearing of microorganisms occurred at a similar rate. However, it is difficult to claim that steady-state existed owing to the large degree of variability in the data. Not only is there large variability from sample to sample, but also in individual samples as revealed by the error bars (± one standard deviation) shown in the figure. Variability in microbiological data collected from GAC filters is common to other studies as well (Parsons et al., 1980, McElhaney and McKeon, 1978). Therefore, it appears from the data that the microbiological community within the filter-adsorbers is a highly dynamic and unpredictable system.

The settled water entering the pilot plant contained a total organic carbon (TOC) concentration ranging from 1.5 to 3 mg/L (Cobb, 1990). Despite the fairly low concentration of substrate, there was still a significant level of microbial growth in the filter-adsorbers. This suggests that very little biodegradable organic carbon is required to produce a substantial amount of microbial growth.

Product water samples from the filter-adsorbers were also tested for total coliforms. While high HPC were released, coliforms were never detected in any of the product water samples. This is a reflection of the high quality of Lake Norman and possibly the inability of coliforms to survive in the autochthonous filter population (Rollinger and Dott, 1987 and LeChevallier and McFeters, 1985).

**Particle Concentrations in Product Water**

Gravimetric measurements of particles captured on the 5.0-um polycarbonate filters were used to calculate solids concentration in product water from the pilot plant. The gravimetric analysis was used to evaluate the potential for the release of particle-associated microorganisms. Results from Run Nos. 4 and 5 are shown in Table 5-4. Little difference was noted in solids concentrations in Run No. 4, where sand, old GAC over sand, and new GAC over sand filters were compared. The old GAC filter released slightly higher concentrations of solids then the sand or new GAC filters. Visual inspection of the captured particles from the old GAC filter revealed an orange coloration different from both the sand and new GAC particles (brownish). It was suspected that the orange coloring and higher concentrations were a result of iron retained by the old GAC and subsequently leaching from the surface. The raw water concentration of iron at the

Table 5-4. Solids Concentrations in Product Water of Pilot Filters

**RUN NO. 4**

| Filter Type | Solids Concentration (ug/L) | Average Concentration (ug/L) |
|---|---|---|
| Sand | 10.1<br>17.9 | 14.0 |
| Old GAC | 27.3<br>21.8 | 24.6 |
| New GAC | 19.4<br>13.2 | 16.3 |

**RUN NO.5**

| | | |
|---|---|---|
| Reactivated GAC | 9.1<br>8.1 | 8.6 |
| Old GAC | 14.5<br>3.8<br>11.1<br>6.4<br>2.7 | 7.7 |
| New GAC | 0.6<br>5.2<br>4.7<br>10.3<br>3.7 | 4.9 |

Lynchburg WTP (where the GAC was obtained) was approximately 0.4 mg/L. Regardless, more samples would be required to make statistically significant comparisons.

Particles in product water from filter-adsorbers containing reactivated, old, and new GAC were compared in Run No. 5 (Table 5-4). The results show little difference between the three types of GAC. The reactivated and old GAC filters had slightly higher solids concentrations which suggests that age or reactivation may have an effect on GAC particle attrition. However, again, more samples would be required to make any statistically supported conclusions.

The concentration of particles released from each of the filter-adsorbers in both Run Nos. 4 and 5 was extremely low, ranging from 0.6 to 27.3 ug/L. These results are also reflected in the low values of product water turbidity reported previously. It suggests that interference to disinfection from turbidity should be minimal. In addition, low particle concentrations implies little surface area available for the attachment of microorganisms.

**Attached HPC in Product Water**

Microorganisms were detached from captured particles to estimate the concentration of attached HPC in the product water of the pilot filters. The results for Run Nos. 4 and 5 are shown in Table 5-5. The attached HPC is also expressed as

Table 5-5. Concentration of Attached HPCs in Pilot Filter Product Water.

**RUN NO. 4**

| Filter Type | Number of Samples | Attached HPCs (HPC/L) | Ave. Total HPC (HPC/L) | % Attached |
|---|---|---|---|---|
| Sand | 2 | 75 | $3.20 \times 10^5$ | 0.02 |
| Old GAC | 2 | 2930 | $6.31 \times 10^6$ | 0.05 |
| New GAC | 2 | 2740 | $1.18 \times 10^7$ | 0.02 |

**RUN NO. 5**

| | | | | |
|---|---|---|---|---|
| Reactivated GAC | 2 | 2810 | $1.25 \times 10^7$ | 0.02 |
| Old GAC | 5 | 1940 | $8.49 \times 10^6$ | 0.02 |
| New GAC | 5 | 1060 | $9.44 \times 10^6$ | 0.01 |

a percentage of the total HPC in the product water (Table 5-5, column 5). These data show that attached (or aggregated) organisms are released into the product water; however, they comprise a very small percentage of the total organisms (less than 0.05%). Thus the vast majority of HPC are unattached, dispersed organisms. Similar results were reported by Stewart

et al., (1990), who found attached microorganisms to comprise from 0 to 0.04% of the total HPC.

**Particle Size Distribution Analysis Product Water**

Product water samples from filter-adsorbers containing old, new and reactivated GAC were taken for particle size distribution (PSD) analysis. Each sample revealed similar PSDs. A typical distribution is shown in Figure 5-5. The average concentration of particles released from the filter-adsorbers based on twelve samples (four replicates of product water from each of the three filter-adsorbers) was 28,500/mL. The laser PSD analysis includes microorganisms in the particle counting. Since the GAC filters released a considerable number of microorganisms into the product water (the viable microorganisms alone comprised approximately 10,000 HPC/mL as shown in Table 5-3), the PSD is highly skewed toward particles of this size range (0.5 to 2.0 um in diameter). As the figure shows, the majority of released particles were less than 2.0 um in diameter. The majority of particles in this size range can be accounted for by microorganisms as revealed by the previously reported HPC concentrations. Particles shown in the distribution which are larger than 2.0 um in diameter are probably not microorganisms (unless clumped) and thus could provide surfaces for attachment of microorganisms. However, Olson et al. (1987) used SEM to examine particles in a

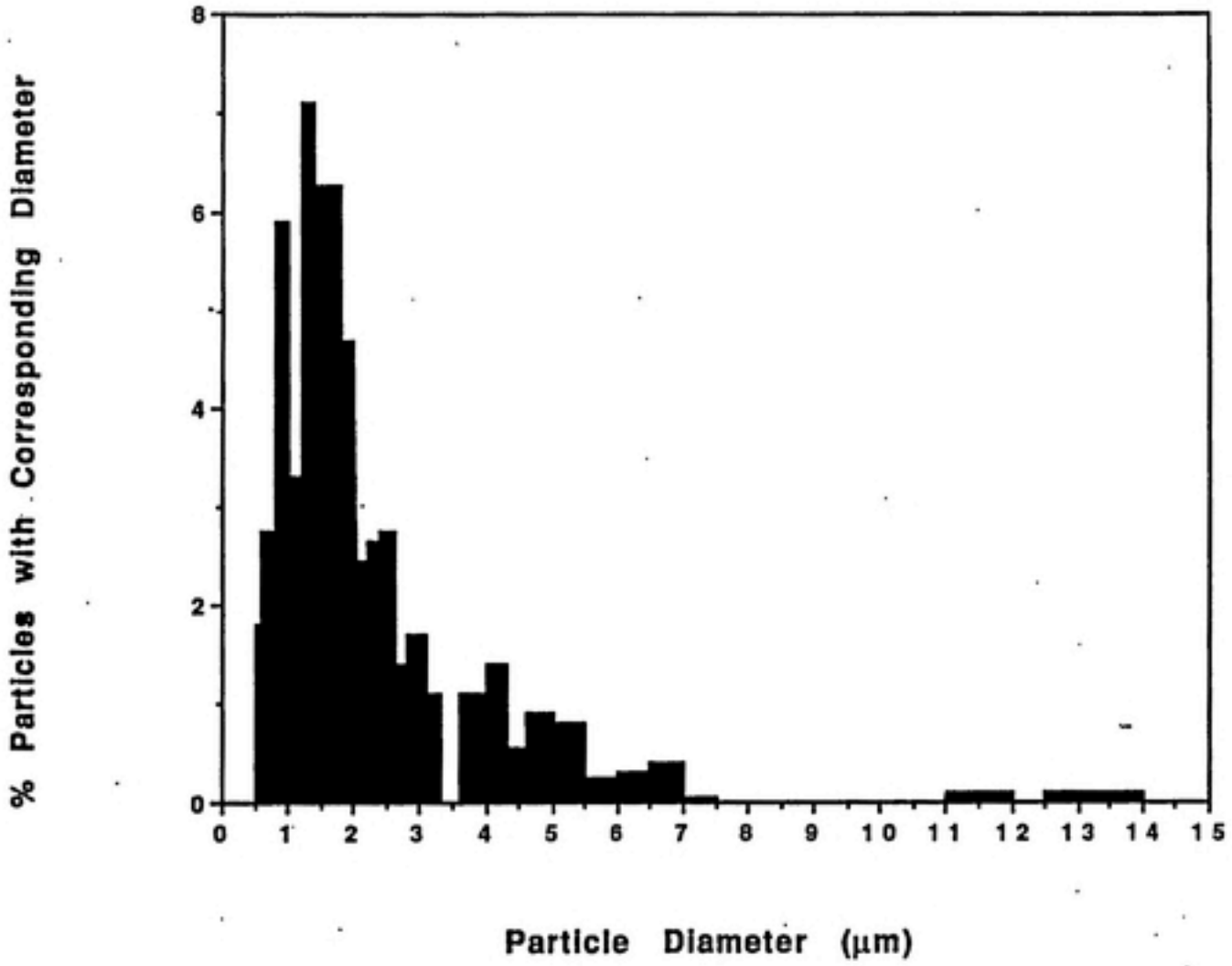



Figure 5-5. Typical particle size distribution of product water from GAC filter-adsorber.

chlorinated distribution system and found that attached microorganisms grew predominantly on particles having diameters much larger than 2 um (about 10 um). The PSD from the filter-adsorbers showed that the product water contained very few particles in the range of 10 um diameter. Thus very few attached microorganisms may be expected in the product water. The extremely low percentage of attached microorganisms in the product water as reported in Table 5-5 (from 0.01 to 0.05%) support this hypothesis.

## Activated Carbon Particles in Product Water

### Microscopic Particle Counting

Microscopic analysis of black particles was used to isolate GAC particles in the pilot filter product water. The initial assumption was that black particles originated from the shearing of the GAC media in the filter-adsorbers. However, it was quickly realized that PAC addition at the Franklin WTP was adding to the number of black particles in the product water samples. Initial attempts to count black particles in the product water revealed extremely high concentrations (approximately 3000 particles/L) in the influent to the pilot plant (settled water from the Franklin WTP). Moreover, similar concentrations of black particles were found in both the sand and GAC filters. Neither of these

two observations is consistent with the postulation that black particles originated from GAC media. Instead, penetration of PAC is implied even though used in very low dosages (1 to 2 mg/L) at the head of the Franklin WTP.

The interference of PAC on particle counting made it impossible to quantify GAC attrition in the filter-adsorbers. In response, staff at the Franklin WTP agreed to halt PAC addition temporarily during Run No. 3 (comparing sand, old, and new GAC filters). The effect of the shut-down and resumption of the PAC feed on the concentration of black particles in the settled water entering the pilot filters is shown in Figure 5-6. Initially, particle concentrations ranged from 100 to 1000/L (days 7 to 16). However, particle counts rose sharply when the PAC addition was resumed on day 18. The concentration peaked at approximately 8,000/L and then dropped to a steady level of about 4,000/L. The increase in black particles in the pilot plant influent was attributed to the carry-over of PAC which had not been effectively removed during sedimentation at the Franklin WTP.

The effect of PAC addition on the concentration of black particles in the product water of the pilot filters is given in Figure 5-7. Initially, the concentration of particles was stable and low (20 to 200/L) when PAC was not being added at the Franklin WTP. However, the concentration rose sharply in both the sand and old GAC filters after the PAC feed was

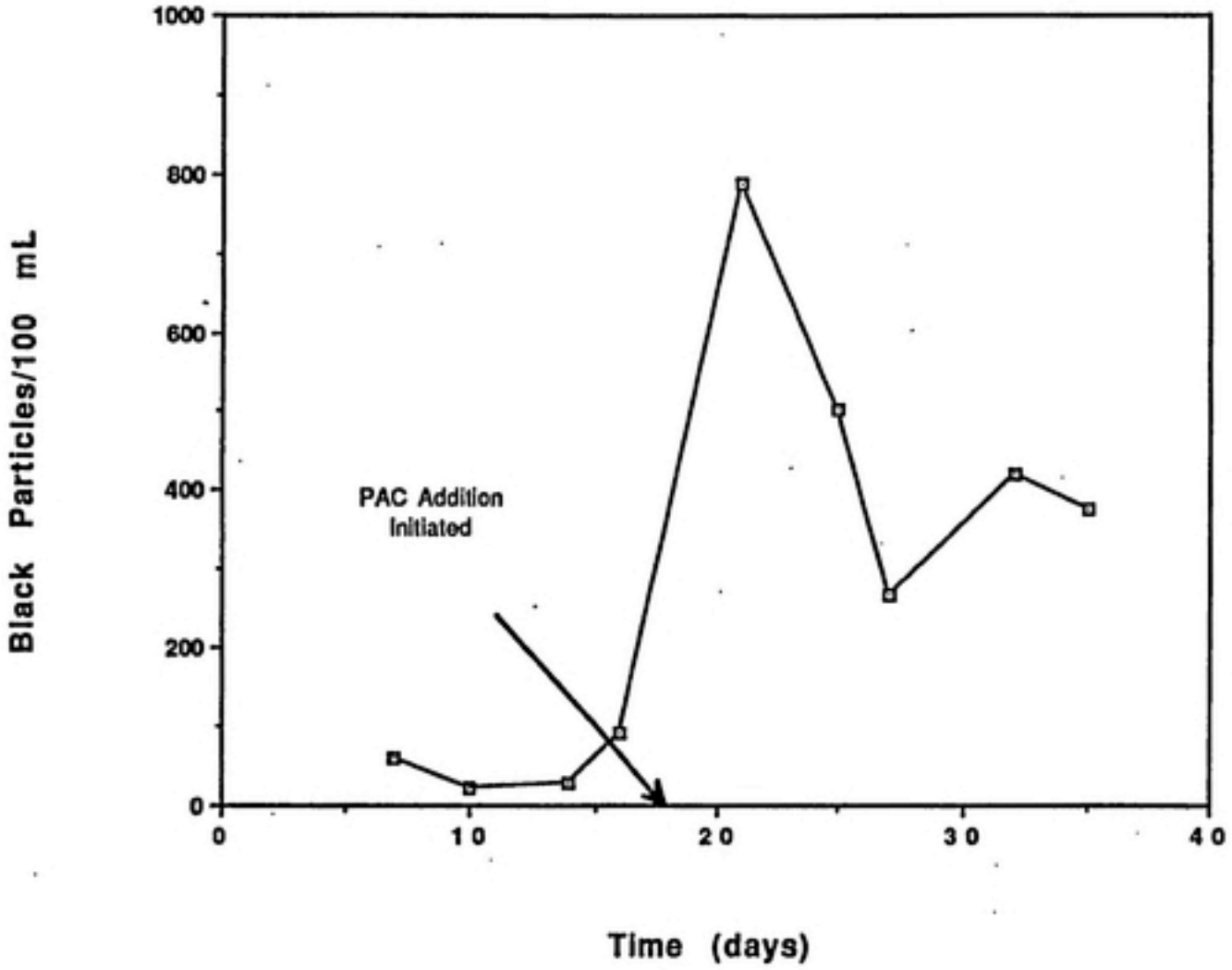



Figure 5-6. Concentration of black particles in settled water entering the pilot plant.

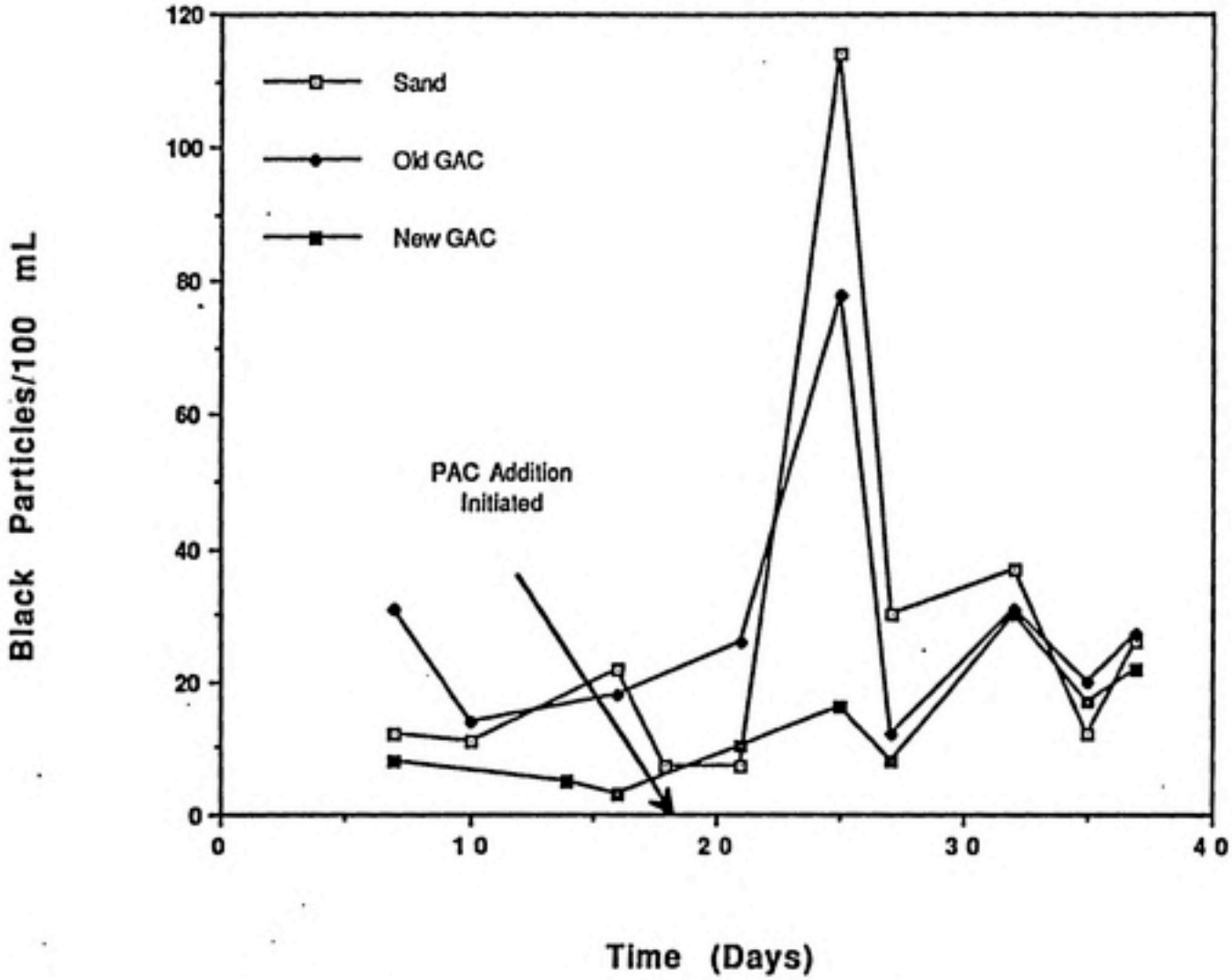



Figure 5-7. Concentration of black particles in product water of pilot plant filters during Run No. 4.

resumed (over 1000/L in the sand filter and 800/L in the old GAC filter). Concentrations then reduced to a level of 80 to 300/L in each of the filters shortly after the PAC feed was resumed. Penetration of PAC through the filter-adsorber was the most reasonable explanation for the increase in the number of black particles in the product water. Also of interest in Figure 5-7 is the similar concentration of black particles released in the sand filter as compared to the filter-adsorbers: in-situ production of GAC particles in the filter-adsorber is therefore not a significant contributor to the total number of black particles in the product water.

A simple calculation for estimating the number concentration of PAC particles per mg PAC reveals approximately 320,000 particles per mg PAC (density = 0.75 g/mL and diameter = 10 um). Therefore, particle concentrations found in the settled water (ranging between 4,000 and 8,000/L) correspond to greater than 97% removal of PAC particles added during rapid mix at the Franklin WTP (1 mg/L or 320,000/L). This suggests that despite effective flocculation and sedimentation of PAC particles in a WTP, PAC particles will enter the filters in considerable concentration. In addition comparing particle concentrations in the settled and filtered waters of the pilot plant (4,000-8,000 L and 80 -300/L, respectively), it can be estimated that filtration removed approximately 90 to 99% of the PAC

particles entering the columns. This suggests that PAC particles can serve as a substantial source of particles in the product water of filters.

**Residence Time Distribution of PAC Particles**

Since PAC particles were found to penetrate into the product water, an experiment was designed in Run No. 4 to measure their residence time in the filters. The postulation was that if the detention time of PAC particles in the filter was long enough, these particles could serve as hosts to attached microorganisms. A pulse input of PAC (5 g) was added to the settled water ahead of the sand filter and new GAC filter-adsorber in the pilot plant. Product water samples were taken every hour and subjected to microscopic counting. The intent was to construct a residence time distribution (RTD) curve from these data.

No increase in the concentration of black particles in the product water was found after 24 hours for either the sand or new GAC filter-adsorber. A visual inspection of the sand filter showed a thick layer of PAC still remaining on the upper surface of the media with some PAC penetration to a depth of approximately 6 in. The experiment was concluded after 24 hours without observing breakthrough of PAC that was introduced as a pulse. The results suggest that PAC particles can spend a considerable amount of time in the filters

(greater than 24 hours) and thus can serve as hosts for attached microorganisms. Further studies into bacterial attachment of microorganisms to particles transported through filters is needed to assess their effect on disinfection.

**Scanning Electron Microscopy (SEM) Analysis**

The attachment of microorganisms to particles in the product water of the GAC filter-adsorbers was examined by SEM. A comparison of particles captured on a 0.2 um versus 2.0 um filter is shown in Figure 5-8 a and b. The micrograph of particles captured on the 2.0 um filter showed very few dispersed or unattached microorganisms. However, the vast majority of particles captured on the 0.2 um filter were dispersed microorganisms. The micrographs of particles captured on the 0.2 um filter confirmed that the majority of microorganisms in the product water of the GAC filter-adsorbers are dispersed, unattached organisms. In contrast, very few dispersed or unattached microorganisms were captured on the 2 um filter. Thus, the majority of microorganisms captured on the 5.0 um polycarbonate filter used to collect particles from the product water were attached to particles.

A typical SEM micrograph of particles collected over a period of several weeks (Figure 5-9a) exhibited substantially higher numbers of attached bacteria then a typical microograph of particles captured over a single day (Figure 5-9b). As the

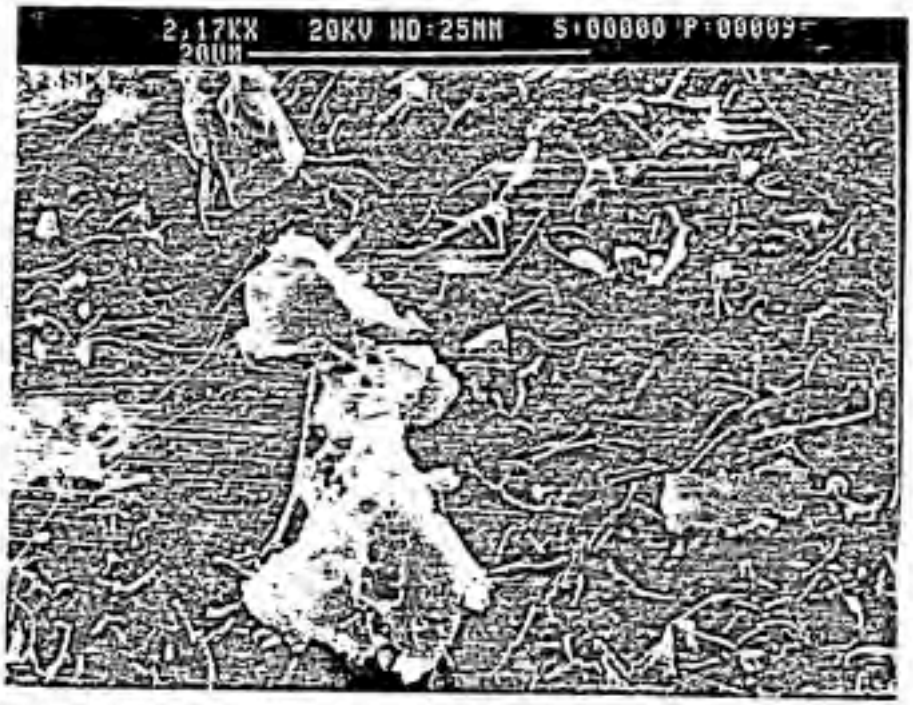
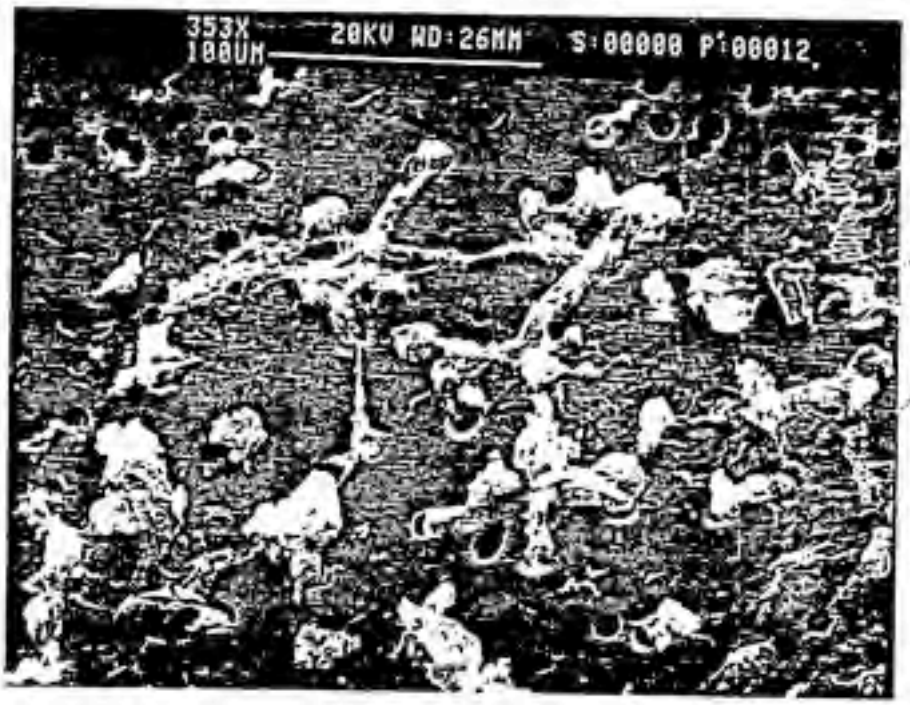
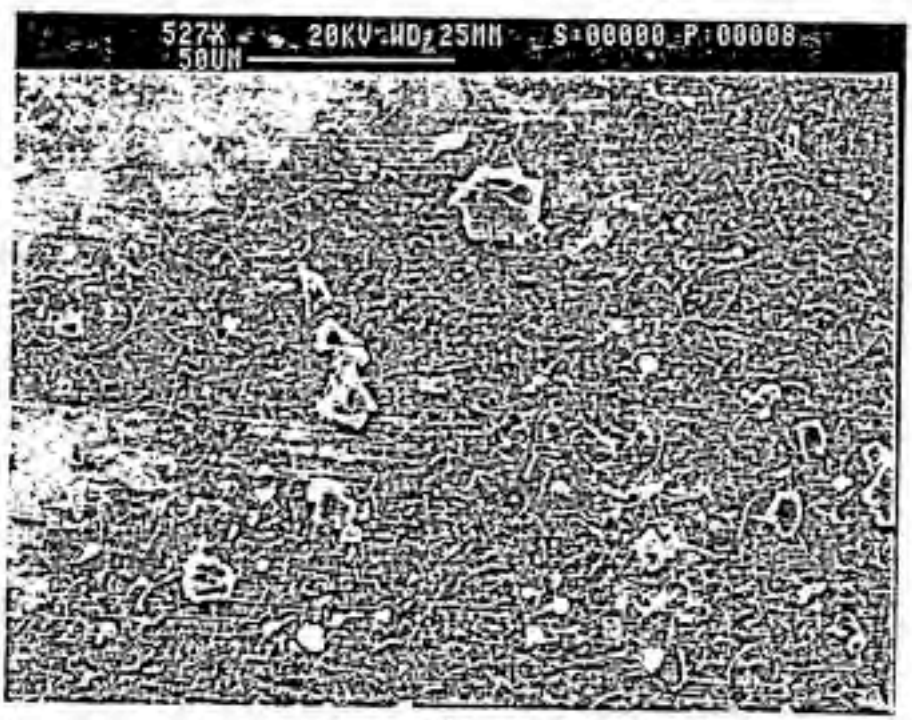



Figure 5-8a SEM of grab sample of product water from new GAC filter-adsorber after membrane filtration (0.2 uM) showing both dispersed and fines


Figure 5-8b SEM of grab sample of product water from new GAC filter-adsorber after membrane filtration (2.0 uM) showing fines only




(a)




(b)

Figure 5-9 a&b. SEM of fines collected over several weeks (a) versus fines collected over a single day (b).

figure shows, the vast majority of fresh particles (Figure 5-9b), have no attached microorganisms while the older sample shows extensive growth. Microorganisms attached to particles left on the filter for extended periods of time also showed evidence of excreted extracellular material. In contrast, SEM microographs of particle associated microorganisms captured over one day showed no evidence of extracellular material (Figure 5-9b). These observations indicate that the sampling period must be kept to a minimum in order to prevent further growth of microorganisms after leaving the GAC filter-adsorber. Additionally, physiological changes which occur to microorganisms with time may influence the results of disinfection studies. For instance, disinfection kinetics can be slowed by the presence of extracellular material protecting the microorganisms. These observations about methodology for collecting particles should be carefully considered when designing experiments to measure the impact of attached microorganisms released during GAC filtration.

In addition to understanding the state and origin of microbial attachment, SEM was used in determining the nature of the particles. A selection of typical micrographs of particles collected from the product water is shown in Figure 5-10. The particles do not display the craggily, porous texture, typical of GAC. Thus, shearing of GAC particles to produce fines was not clearly shown.

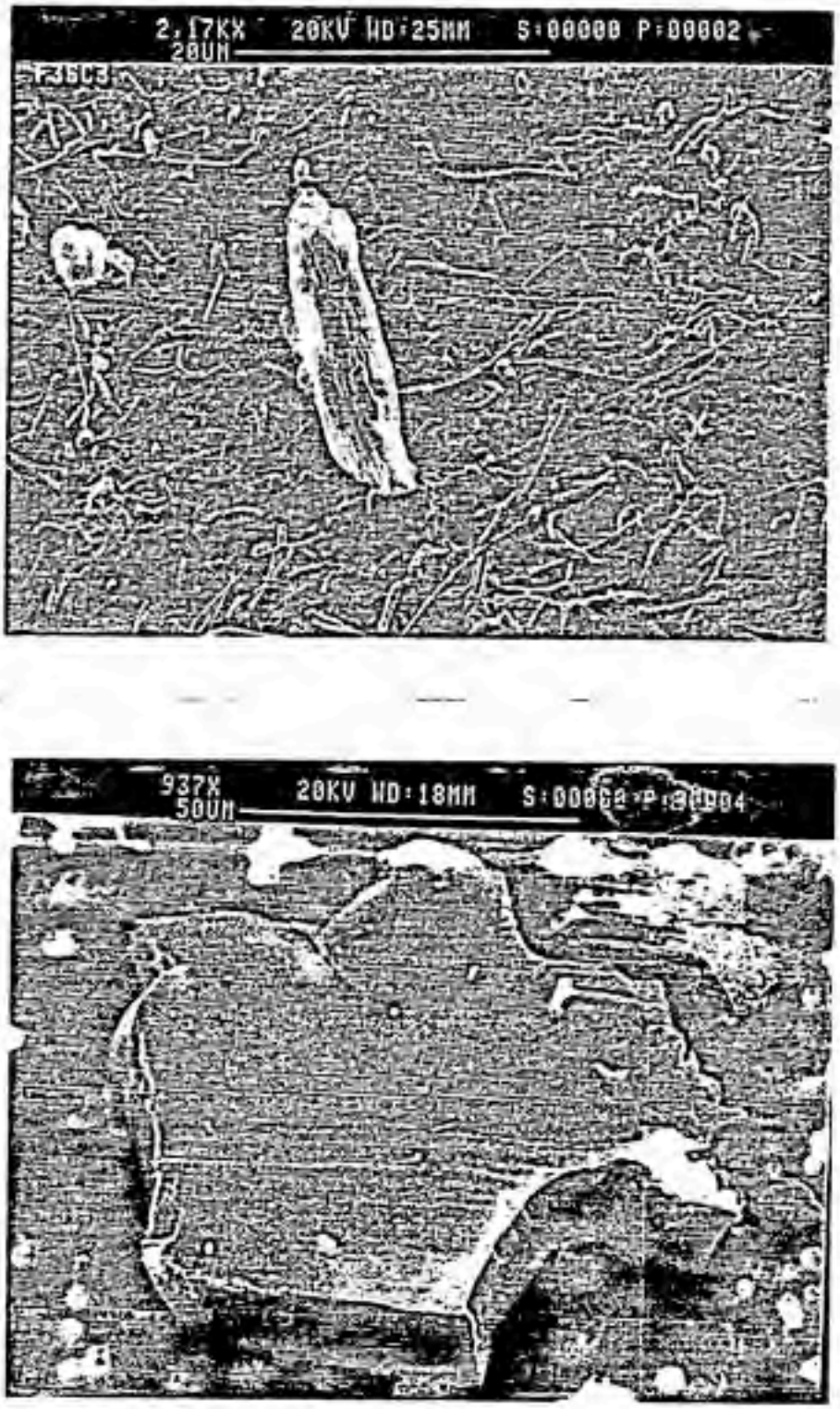



Figure 10. Selection of typical micrographs of particles released from GAC filter-adsorbers.

**Disinfection of Attached Microorganisms in Product Water**

Concentrated solutions of particles captured on the 5.0 um polycarbonate filter from the product water of the filter-adsorbers were subjected to disinfection with chlorine. Two dilutions of concentrated particles were prepared resulting in particle concentrations of 4 and 40 mg/L. Both of these concentrations are orders of magnitude larger than the actual particle concentrations measured (Table 5-4). The rate of disinfection of these two solutions was compared to that of a product water sample (14 ug/L). Each sample received an applied chlorine dose of 0.5 mg/L and experiments were conducted at room temperature. The results of this experiment are shown in Figure 5-11. The product water sample was readily disinfected, achieving a 2-log reduction in HPC in 1 minute (no further counts were measured). The solutions of concentrated particles, however, showed reduced disinfection efficiency. A 0.5-log reduction in HPC in 2 minutes of contact time was achieved for a particle concentration of 40 mg/L. However, the chlorine was depleted after 2 minutes and no further reduction in HPC was measured. Slightly faster disinfection was observed (1-log reduction in 2 minutes) at a particle concentration of 4 mg/L, but again, chlorine residual was depleted before effective disinfection was achieved.

The above experiment was flawed due to the consumption of chlorine. It was impossible to determine if the attached HPC

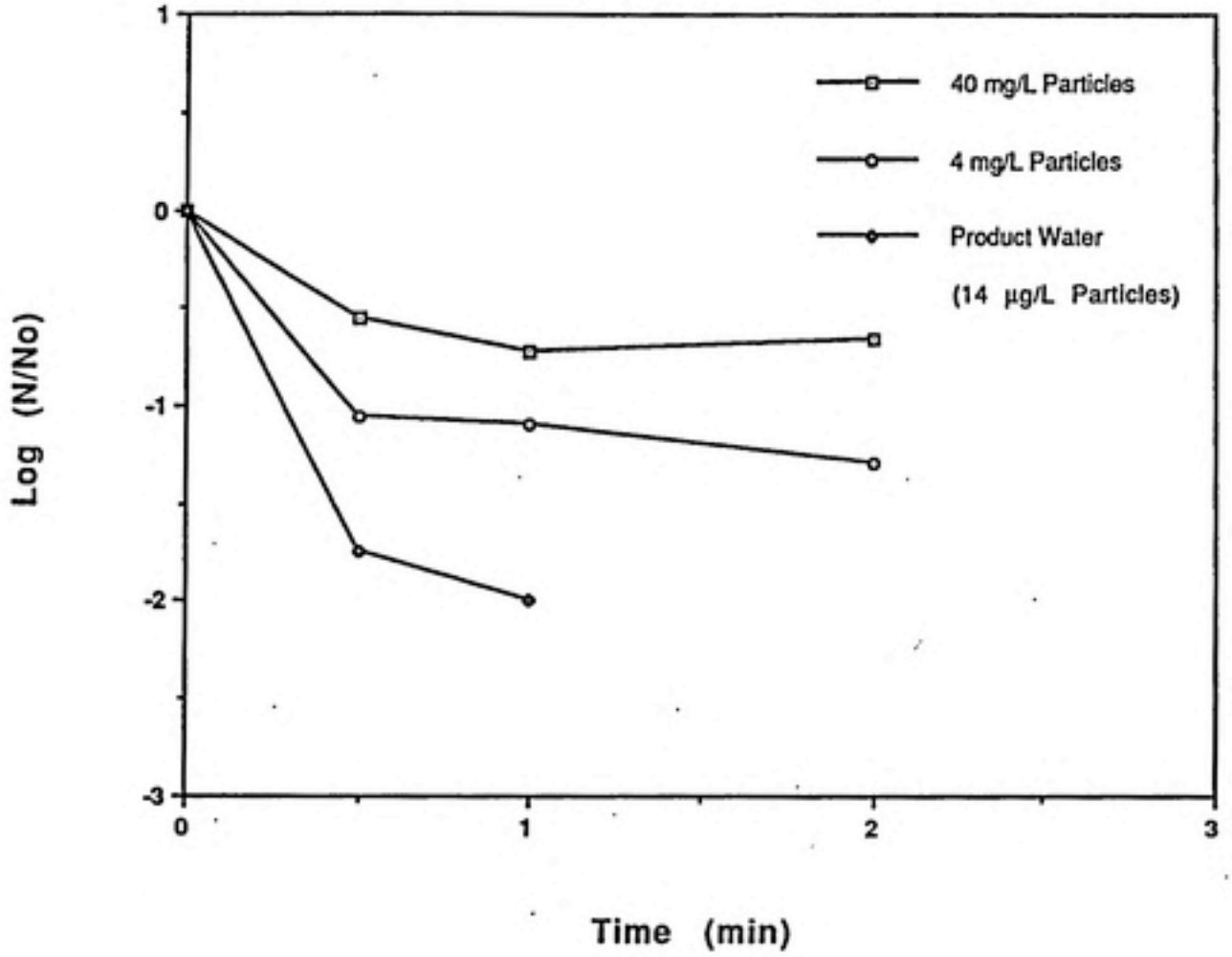



Figure 5-11. Log reduction of attached bacteria in solutions containg 4 and 40 mg/L particles compared to unattached bacteria in product water sample. (Chlorine = 0.5 mg/L, 25C, and pH = 6.6)

were resistant to chlorine disinfection or if the highly concentrated solutions of particles had exhausted the chlorine demand before disinfection could be achieved. Furthermore, these particle concentrations (4 mg/L and 40 mg/L solutions) are from 300 to 3000 times that of the product water. Thus faster disinfection of attached microorganisms at the particle concentration actually released from the filter-adsorbers may be likely.

The experiment was repeated with lower concentrations of particles and a higher chlorine dose to overcome the deficiencies of the first experimental design. Particle concentrations of 1.8, 0.18, and 0.018 mg/L were used and the applied chlorine dose was increased to 2.0 mg/L. The results are shown in Figure 5-12. Disinfection of the solution containing 0.018 mg/L of particles (approximately four times the particle concentration of product water) showed a 2.5-log reduction in HPC in 2 minutes, after which no further plate counts were observed. A 2.5-log reduction was also achieved in the sample containing 0.18 mg/L of particles (40 times greater than product water); however, 5 minutes of contact was required before no further plate counts were observed. Finally, in the sample containing 1.8 mg/L of particles (400 times that of product water), the rate of disinfection was significantly slower than with lower particle concentrations and HPC were reduced by only one log after two minutes contact

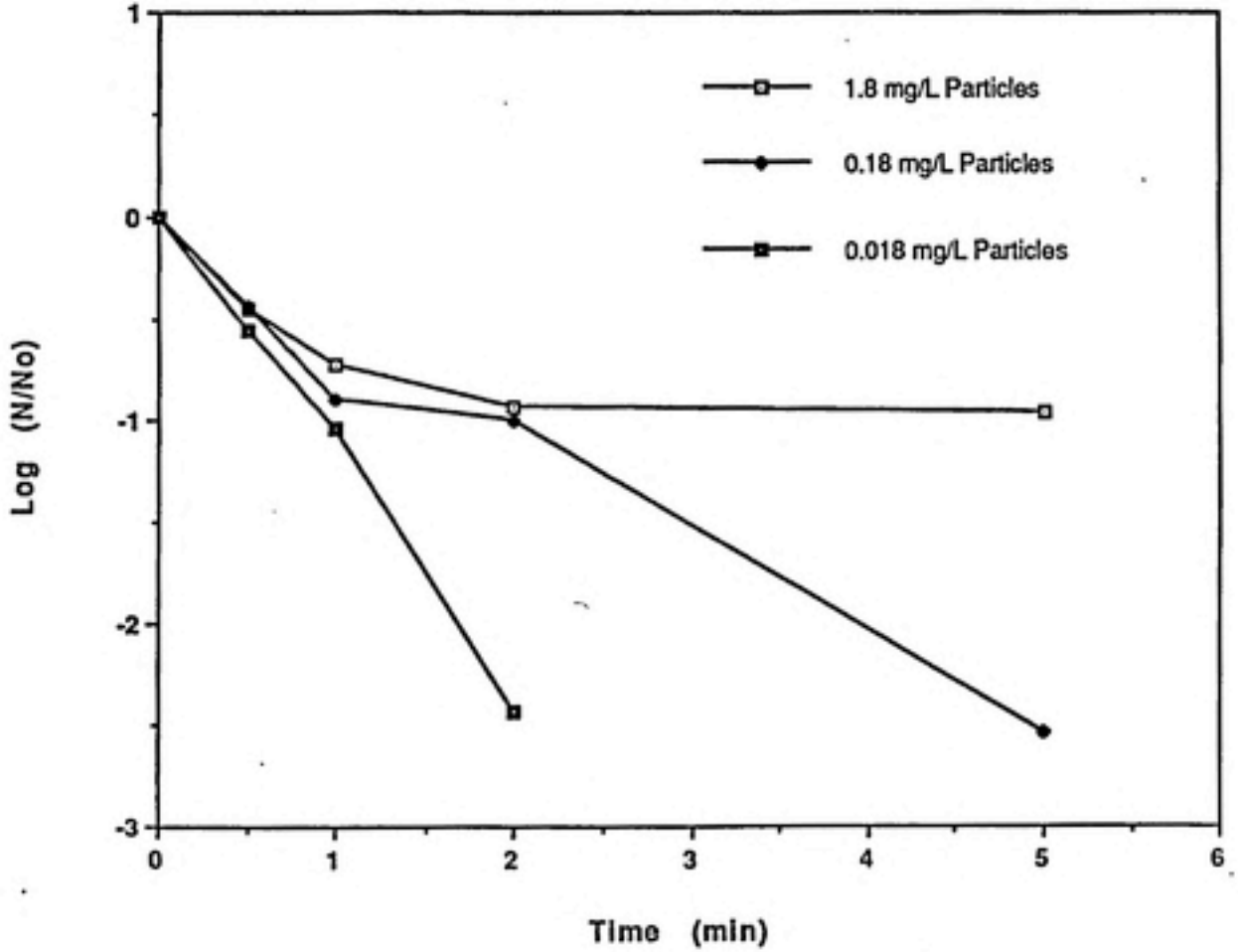



Figure 5-12. Log reduction of attached bacteria in solutions containing 1.8, 0.18, and 0.018 mg/L particles. (Chlorine dose = 2 mg/L, 10C, and pH = 6.6)

time with no further reduction after five minutes despite the presence of residual chlorine (approximately 1 mg/L).

The results showed that microorganisms attached to particles could be effectively disinfected provided that the particle concentration was not unrealistic for product water. Very high disinfection efficiencies were achieved at particle concentrations of 0.18 and 0.018 mg/L of particles under disinfection conditions similar to an actual water treatment plant (2 mg/L chlorine and 5 minutes of contact time). However, resistance to disinfection became apparent as the concentration of particles was increased. In the first experiment (Figure 5-11), resistance to disinfection was observed in samples containing particle concentrations greater than 4 mg/L (300 times product water). In the second experiment (Figure 5-12), resistance to disinfection was observed in the solution containing 1.8 mg/L (400 times product water) of particles. Resistance to disinfection in the first experiment could be explained by the depletion of chlorine by the particles. However, in the second experiment, efficiency was limited despite the presence of residual chlorine. Thus, the chlorine demand exerted by the particles in this solution could not solely explain the inability to achieve effective disinfection efficiency. One possible conclusion is that attached microorganisms can be resistant to disinfection. An alternative conclusion is that elevated

concentrations of particles (increased turbidity) can coat and shelter microorganisms, providing physical protection from chlorine penetration. At lower particle concentrations ($\leq$ 0.18 mg/L), corresponding to lower turbidity values, effective disinfection was achieved. As the particle concentration increased, and therefore turbidity increased, disinfection efficiency was reduced.

The final experiment examined the effect of chlorine dose on the disinfection efficiency of attached HPC. Particles were concentrated to 26 mg/L and dosed with 0.5, 1.0, and 2.0 mg/L of chlorine. As shown in Figure 5-13, the rate of disinfection and disinfection efficiency increased as the applied chlorine dose was increased. Resistance to disinfection was observed in the solutions dose with 0.5 and 1.0 mg/L chlorine. However, 2.0 mg/L chlorine was adequate to achieve effective disinfection despite the highly concentrated solution of particles. This is not consistent, however, with the results in which effective disinfection could not be achieved in solutions with particle concentrations in the same range (i.e., greater than 1.8 mg/L). While no explanation can be offered, further research into the correlation between particle concentrations (and turbidity) and disinfection efficiency is warranted.

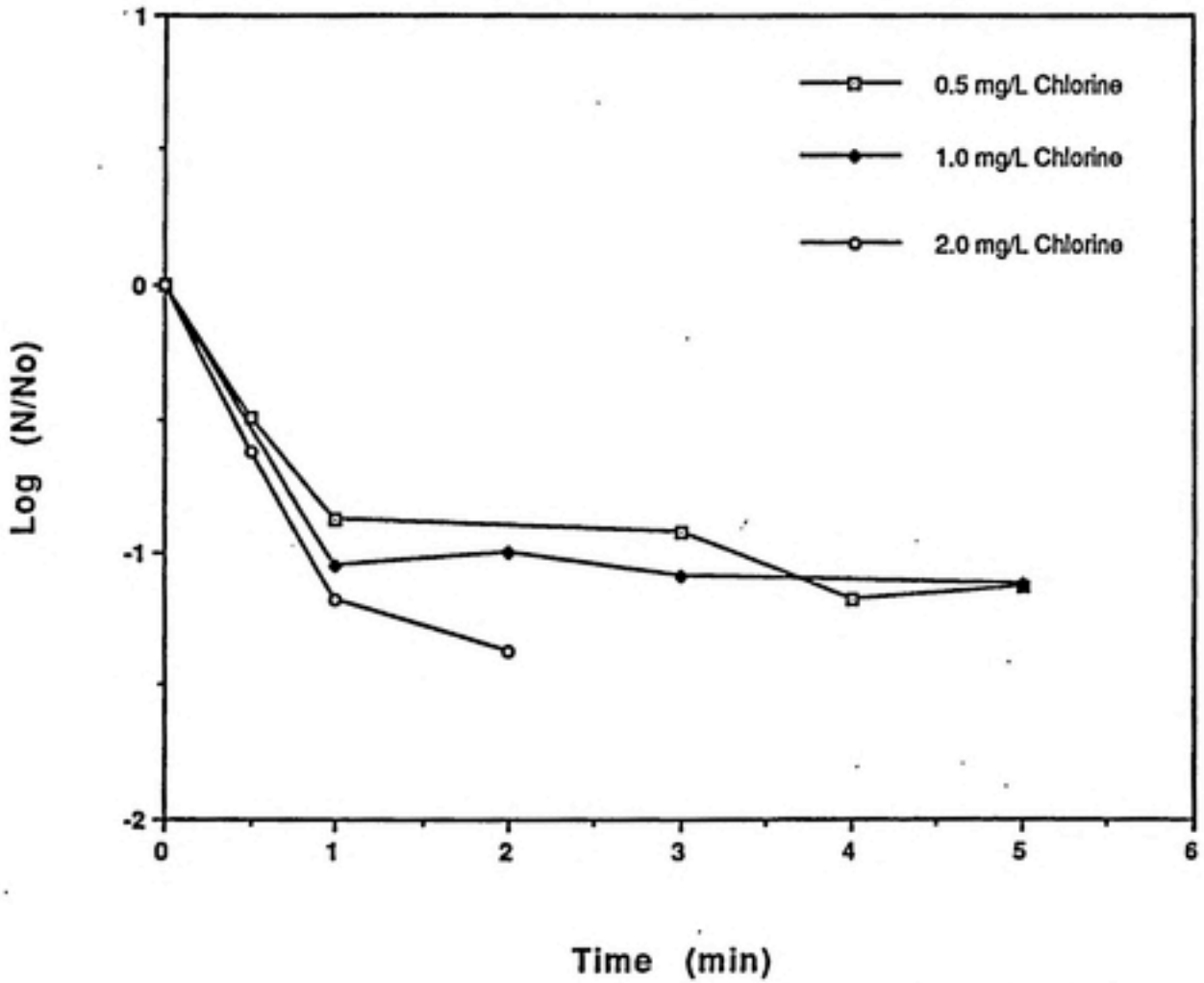



Figure 5-13. Log reduction in attached bacteria in solution containg 26 mg/L particles at various chlorine doses. (10C and pH = 6.6)

**Comparisons to Previous Research Cited in Literature Review**

As discussed in the literature review, turbidity was found to interfere with the disinfection efficiency of coliforms in a study by LeChevallier, et al., (1981). They found no interference to disinfection of coliforms grown in solutions of low turbidity (1.5 NTU) but, only 20% disinfection was achieved in more turbid water (13 NTU). They concluded that microbial attachment to turbidity particles permitted greater survival in the more turbid samples. Logically then, microorganisms attached to the turbid particles in the solutions containing lower turbidity values should also have been resistant, while these authors never suggested that the turbidity itself interfered with the mass transfer of chlorine to the microorganisms, further research is needed.

Previous studies examining disinfection efficiency of attached microorganisms released from GAC filters (Stewart et al., 1990 and Camper et al., 1986), have found attached microorganisms to be difficult to disinfect. In each of these studies, experimental samples contained extremely concentrated solutions of particles. Stewart et al. placed particles captured from approximately 1,000 L of product water into a 50 mL solution for disinfection studies. Camper et al. (1986) filtered 18,600 L of product water, concentrating the captured particles into 25 mL solutions. These experimental samples

correspond to particle concentrations 744,000 and 20,000_ times, respectively, that of the filter product water. The high turbidity values found in these solutions may have interfered with the disinfection process. Had the solutions not been so highly concentrated with particles, better disinfection efficiency would be expected according to the results of this research.

**Generation of Fines from GAC Filters in Bench Scale Experiments**

PAC addition at the Franklin WTP prevented estimation of the in-situ generation and release of fines from GAC particles. Therefore, laboratory experiments were used to examine GAC particle attrition under controlled conditions. The effect of backwash rate on fine concentration was examined in the first experiment and the results are shown in Figure 5-14. The bench-scale column was loaded with new GAC (Calgon F300) and backwashed at rates of 12 gpm/sf and 15 gpm/sf. As shown in the figure, release of fines was similar at both backwash rates, although a greater number of particles were released at the higher application rate. Initially, fines in the product water were extremely high (100 to 1000/L), but these decreased rapidly during the first hour of filtration and reached 10 to 100/L. Concentrations continued to decrease at a slower rate during the next several hours, finally

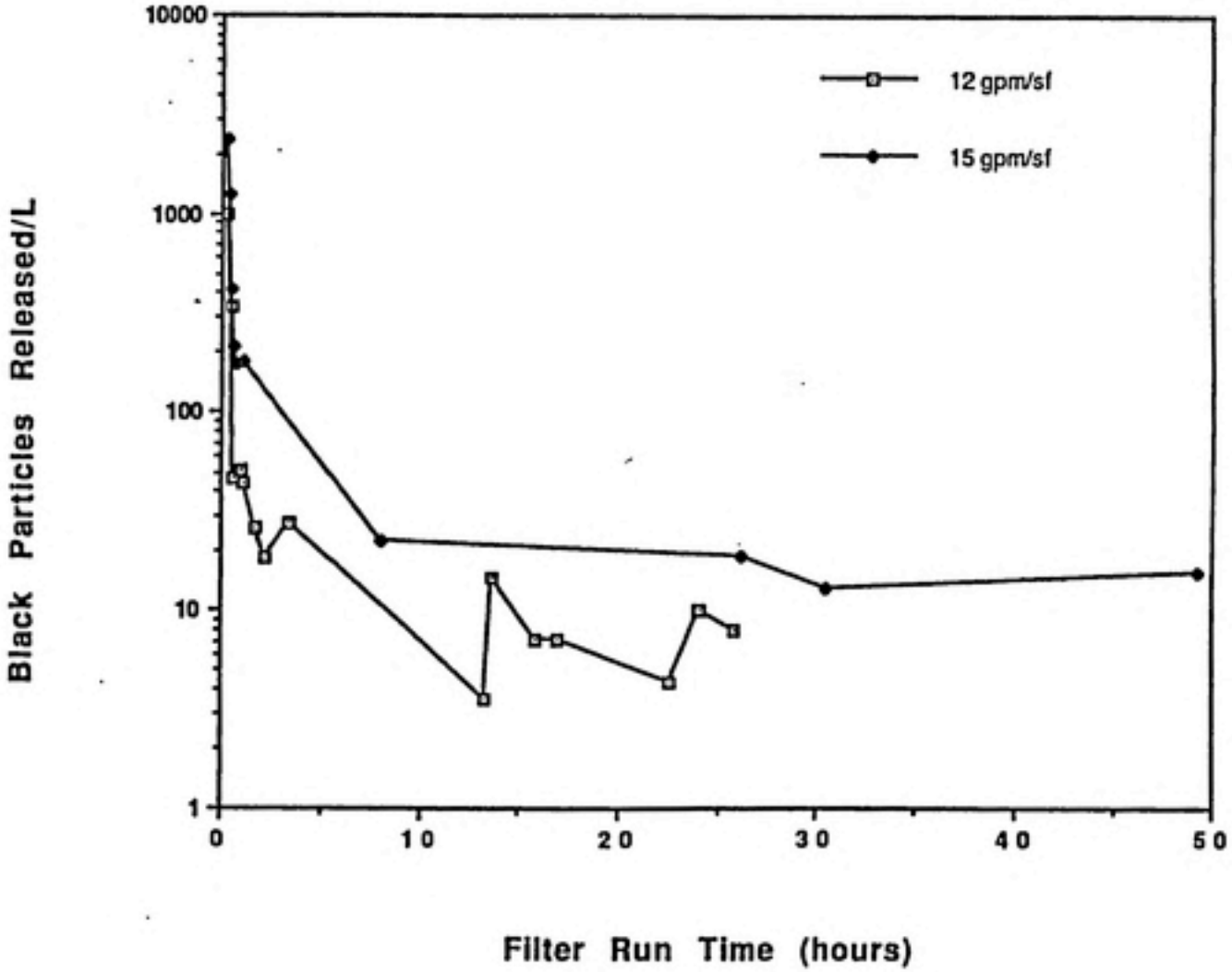



Figure 5-14. Concentration of carbon fines released from bench-scale filter backwashed at 12 and 15 gpm/sq ft. (surficial loading rate = 4 gpm/sq ft)

reaching a steady state of 5 to 20/L after approximately 5 hours.

Backwashing at a rate of 15 gpm/sf appeared to produce a greater number of fines than backwashing at 12 gpm/sf. A possible explanation is the higher level of agitation at the higher backwash rate created a greater quantity of sheared particles. The release of a high concentration of fines immediately after backwashing is then followed by a slow decline to steady-state release. Fines released during steady state may include fines created during backwashing, as well as fines sheared during filtration.

A comparison of fine generation from old, new, and reactivated GAC was made at a fixed backwash of 12 gpm/sf. The objective was to examine if age or reactivation weakened the GAC surface causing a greater amount of particle shearing. As is indicated in Figure 5-15, the fine release was similar to that in Figure 5-14. The old and new GAC filters produced similar concentrations of fines but the reactivated GAC filter released a higher concentration. The data are all rather limited to make firm conclusions. Certainly, a comparison study of fine generation over months of operation would provide the evidence needed. However, these results imply that weakening of GAC was more related to reactivation than to age.

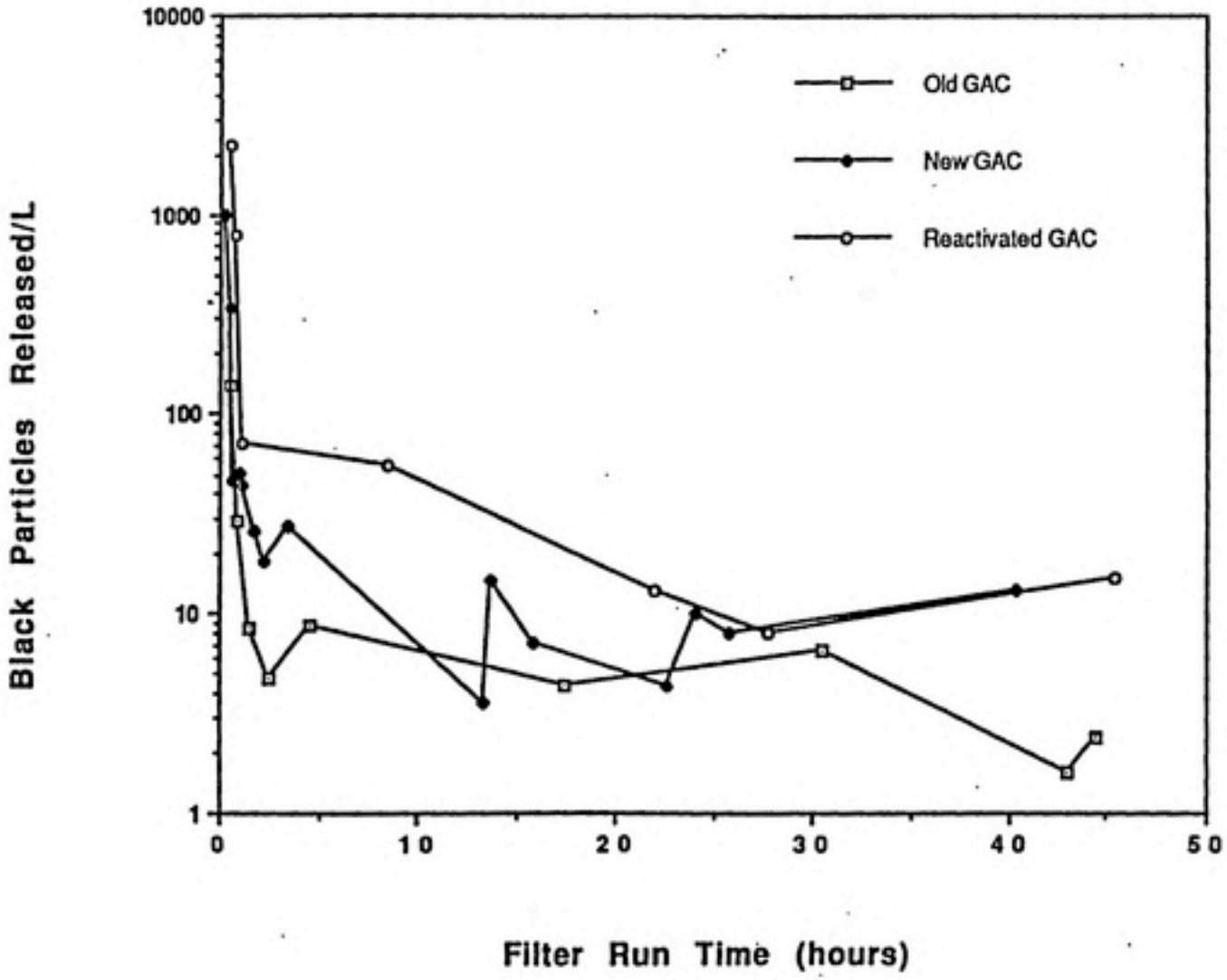



Figure 5-15. Concentration of carbon fines released from bench-scale filter using three types of GAC.

The steady-state concentration of fines in the product water of the bench-scale filters ranged between 5 and 20 particles/L. Higher concentrations would be expected in an actual treatment plant since these experiments were conducted with distilled and not coagulated water. Coagulation and the ensuing production of floc material ripens the filter media by making it more "sticky". This process enhances particle capture in the filter. For this reason, it is likely that the concentration of particles released in the bench scale experiments is lower than would be expected in a full scale plant.

# CHAPTER SIX

# CONCLUSIONS

The removal and inactivation of microorganisms is a primary objective of a drinking water treatment plant. Exposure to pathogenic organisms transmitted through drinking water has lead to outbreaks of many diseases. Since GAC filtration has been shown to shed a considerable number of microorganisms into the product water, it is a very important research objective to identify modes of microbial survival during disinfection. The following is a list of the major findings and conclusions of this research project which examined the ability of attached organisms released from GAC filter-adsorbers to survive disinfection:

1. Product water quality as measured by turbidity and gravimetric analysis was extremely high in all the GAC filter-adsorbers (new, old, and reactivated). No significant difference in turbidity or suspended solids measurements was found in the product water from the three filter-adsorbers.

2. HPC increased significantly following passage through the GAC filter-adsorbers. Product water HPC were on the order of $10^4$ HPC/mL. Despite the high HPC, no coliforms were detected in the product water.

3. Organisms attached to particles comprised a very small percentage (0.01 to 0.05%) of the HPC in the product water.

4. PAC added at the Franklin WTP penetrated the filter-adsorbers and interfered with the quantification of the in-situ generation of GAC fines.

5. SEM analysis of particles in the product water of the filter-adsorbers showed very few particles to have attached growth. SEM analysis also confirmed the results from the detachment experiments showing only a small portion of the HPC released were attached to particles. Finally, SEM analysis revealed that the majority of released particles did not appear to be GAC.

6) Attached microorganisms released into product water were shown to be effectively disinfected given an adequate chlorine dose and that turbidity did not interfere with the mass transfer of chlorine to the particle surface.

7) Bench-scale studies of the release of fines from GAC media showed that the agitation incurred by backwashing caused GAC particles to shear from the surface and subsequently be released into the product water.

# CHAPTER SEVEN

## RECOMMENDATIONS

This research has attempted to examine the effects of attached organisms released from GAC filter-adsorbers on disinfection. While some conclusions could be reached from the results, many research questions remained unanswered. The following is a list of recommended research objectives which should be addressed to better evaluate the impact of microbial growth in GAC filters:

1) Examine the potential for microbial growth on PAC particles penetrating GAC filter-adsorbers.

2) Identify the size and type of particles to which microorganisms preferentially attach. Assess the impact size or type of particle has on the ability to disinfect attached organisms.

3) Examine the impact of the reduction reaction of chlorine and GAC on the mass transfer of chlorine to the carbon surface.

4) Further examine the effects of turbidity on the disinfection of attached microorganisms.

5) Compare different disinfectants for their ability to eliminate attached microorganisms.

6) Further research into characterizing the composition of particles released from GAC filter-adsorbers.

7) Better identify operational variables which effect microbial growth in GAC filters.

8) Develop methods for reducing or eliminating microbial growth in GAC filters.

9) Identify the effects of various operational variables on the release of particles from GAC filters.

10) Examine whether prechlorination prior to GAC filtration aids in the selection for chlorine resistant microorganisms in GAC filters.

11) Assess the effect of GAC filtration on the microbial flora within the distribution system.

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