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Rapid Mixing and Filter Polymer Selection for the Filtration of Alum Clarified Water

by

Christian Madsen ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the Requirements for the degree of Master of Science

in

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Date: Jan 29, 2001

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Abstract

There are two water treatment plants serving the Edmonton metropolitan area. Both utilize enhanced coagulation, using alum and an anionic polymer, followed by lime softening and filtration. Water quality is highly variable through the year with raw water turbidities ranging from 3 to 4000 NTU. Although currently, the water produced at both plants is of a higher quality than specified in the Guidelines for Canadian Drinking Water Quality, improvements to the process are continually being examined using a pilot plant at the E.L. Smith water treatment plant. In accordance with continually improving water quality, the use of online particle counters has recently been incorporated into the operation of the filters. By the end of 1999, the lime softening process was removed from both plants.

Pilot work has recently focused on the addition of a filter polymer to the clarifier effluent, foregoing the softening process in order to simulate the future full-scale operation of the plants. Initial runs, without the use of filter polymer, showed particle count removals using dual media filters were not satisfactory. Initial polymer selection was done through a series of bench top tests measuring pH, turbidity, particle counts, and zeta potential. From these results five polymers were selected to be tested on the pilot plant filters. A representative range of doses of filter aid was examined and particle count data, turbidity, headloss, and flow were measured. Particle counts were found to be a more sensitive measure

of filter performance than turbidity. Rapid mixing of the polymer was held constant. Polymer type had a significant impact on filtrate quality. A high molecular weight non-ionic polymer was found to result in the best removal of particles and turbidity. The mixing intensity and dose interaction was studied for this polymer and it was found that a minimum velocity gradient of 700 s^{-1} is required to prevent the buildup of headloss and maintain low effluent particle counts and turbidity.

To further optimize the filtrate quality, the pilot plant was run during the winter months of 1998/99 when the North Saskatchewan River is ice covered with the water quality remaining relatively stable. Under these conditions it was possible to optimize the rapid mixing and dosing of the primary coagulant to reduce clarifier effluent particle counts and produce a flocculent particle that can be easily removed by the filters. Rapid mixing intensity was found to significantly affect filter performance, with higher velocity gradients producing lower filtrate particle counts.

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1.0 Introduction

1.1 Background

The E.L. Smith water treatment plant produces on average 185 million liters per day, representing approximately half of the City of Edmonton and surrounding communities' water supply. The treatment plant is owned and operated by EPCOR Water Services Inc, and is located on the western edge of the City, upstream of the cities storm and combined sewer outfalls. With the North Saskatchewan River as a raw water source, the plant was designed to treat for highly variable turbidities (3 to 3000 NTU) and colour (1 to 60 TCU). The plant has two upflow clarifiers that run in parallel with enhanced alum coagulation, flocculation, and sedimentation followed by lime softening in a third upflow clarifier, recarbonation, chlorination, fluoridation, filtration, and the addition of post filter ammonia. Powder activated carbon is fed during spring runoff to eliminate taste and odor. E.L. Smith Water Treatment Plant (WTP) has been softening drinking water since it was built in 1976. Recently, however, it has been decided to discontinue the lime softening process in order to meet new 5 log *Giardia* removal criterion by converting the current lime clarifier into a chlorine contact basin. Aluminum reduction is also a consideration in the removal of lime, as the lower pH of the clarifier effluent without softening will aid in the precipitation and removal of $Al(OH)_3$ in the dual media anthracite/sand filters.

This has been undertaken as a target for EPCOR because of new guidelines for aluminum residual set by Health Canada.

In the spring of 1998 EPCOR began using online particle counts in combination with turbidity as criteria for filter run times as well as filter to waste during ripening. Individual filter particle counts as well as combined filter effluent is monitored continuously. A guideline was established with consultation with Alberta Environment of 50 particles (>2μm) per mL on individual filter effluent with a limit on the combined filter effluent of 30 particles/mL. This guideline contains a certain degree of flexibility, however, with an absolute limit of 100 particles/mL in instances when reservoir levels are low through the distribution system. In order to meet these new operating guidelines with the removal of softening, it has become necessary to assess the effectiveness of filter polymer to compensate for the loss of the physical removal that was occurring during the softening stage of treatment. All of the results discussed in the body of this text are site specific to the period of study and it is not intended to endorse any of the products mentioned herein.

1.2 Objectives

The purpose of this study was to select an appropriate polymer for use as a filtration aid with unsoftened, alum coagulated water at the E. L. Smith Water Treatment Plant and then optimize the dose and mixing intensity for that polymer based on particle counts, turbidities, and headloss. The major objectives of the study were:

1. Select the best performing polymer on the pilot scale using treated water from the full-scale facility;
2. Investigate the rapid mixing process of alum to improve enhanced coagulation and the filtration of the clarifier effluent; and
3. Optimize the rapid mixing and dosing of final polymer.

2.0 Literature Review

2.1 Introduction

Filtration is a unit process which physically removes suspended materials. It is typically the final or only physical barrier for the removal of pathogens from drinking water and in the United States is regulated by the U.S. EPA Surface Water Treatment Rule in terms of combined filter effluent turbidity limits based on the type of filtration system being used and the influent water quality. This review will give a general overview of filtration types used in drinking water applications and empirical filtration theories on particle transport and attachment mechanisms. Filter performance is largely impacted by the nature of the particles being filtered. In a conventional treatment plant the filter influent particles have passed through coagulation, flocculation, and sedimentation processes. The mixing in the coagulation process and of filtration aids play an important role in determining the nature of the particles going into the filter and the primary literature on this topic will be summarized. The use of polymers to improve filter performance is a relatively recent development in drinking water treatment and the major advantages and disadvantages of their use and the factors determining polymer impacts on efficiency will be discussed. Finally, an overview of zeta potential and its potential applications in filtration is also included.

2.2 Removal of Softening

Health Canada has recommended aluminum levels in drinking water should be minimized to the lowest extent possible. Although there is a provision for plants that use the lime softening process with a higher residual, 0.2 mg/L, EPCOR has chosen to meet the operational guidance value for conventional water treatment plants of 0.1 mg/L. This is a significant decision as the removal of lime softening also removes a unit process that contributes to the physical removal of particulates, potentially placing a higher burden on the filters for the removal of potential pathogens. Early pilot testing confirmed this with poor particle count and turbidity removal through the filters with alum clarified water. This led to the almost three years of filter polymer pilot testing of which this research is a part.

The lime softening process is also very physically labor intensive. In order to reduce operators working on night shifts, it is planned to have the E. L. Smith water treatment plant run remotely from the Rossdale water treatment plant in various stages with the ultimate goal of eliminating night work at the E. L. Smith plant. Operation of the slakers where the lime slurry is mixed, belt feeders and regular pigging or cleaning of the lime feed lines, as well as monitoring the softening process requires a twenty-four hour per day operator presence. Removing the lime softening unit process allows for less night shift work and the opportunity for upgrading operator skills to maintain and operate the more highly automated plant.

2.3 Filtration

2.3.1 Types of Filters in Water Treatment

There are several potential ways to classify filter types in water and wastewater treatment. Most commonly, some type of porous granular media is used to filter water, although increasingly membranes are being used, as the technology becomes more cost efficient. Granular media filters can be classified based on the type of media used. Filter media can be made of some type of sand, anthracite, granular activated carbon, garnet, or a combination of these materials. With these media types, there is a significant depth to the filter bed. Alternatively, precoat filters use a thin layer of very fine granular material such as diatomaceous earth and the filtration occurs along a very thin layer of the media. These different media types introduce a different classification of filtration based on how the filters remove materials. In cake filtration, suspended solids are removed through physical straining, along the surface of the media. This classification would include precoat filters as well as membrane filtration. Alternatively in depth filtration, solids are removed through the entire bed of granular media.

Another classification is based on the rate of filtration or the flow per unit area through the filter. This can be used to differentiate between granular media filters. Slow sand filters typically operate at less than 0.5 $m^3/m^2/h$. Rapid sand filters can operate at rates ranging from 4.0 to 24 $m^3/m^2/h$.

The final classification of filter types is based on the hydraulic arrangement of the filter. Water can be filtered using gravity or pressure. Gravity filters are employed in most large scale filtering applications. Open to the atmosphere, gravity filters can be operated either as constant rate, controlling the effluent flow with a control valve, or as declining rate, allowing the filter flow rate to decline through the filter run as the media pores become clogged with removed solids. Pressure filters are enclosed in a pressure vessel containing the filter media and water enters the vessel at a high pressure driving it through the media.

The filters at the E. L. Smith Water Treatment Plant are dual media, with 450 mm of anthracite and 300 mm of sand. They are run as declining rate filters, meaning that as the filter pores become clogged, the flow decreases through the filter and the head gradually increases across all of the filters, although typically the effluent quality improves through the duration of the filter run. If this was left to continue, however, there would be an increasing risk of turbidity or particle breakthrough, a deterioration of finished water quality. To compensate for gradually increasing head, the filter with the lowest flow or longest run time is taken offline and another clean filter is put online, keeping the head across all of the filters constant. Operating the filters as declining rate constant head filters produces consistent, high quality filter effluent, although it requires that a spare filter always be available in reserve to be put online as the filter head increases and a dirty filter is taken offline for backwashing.

2.3.2 Mechanisms of Filtration

Filtration is the final physical mechanism for particulate removal in the water treatment process. Impurities in water can be of organic or inorganic nature, dissolved or particulate material. Although the coagulation and flocculation process can remove some of the higher molecular weight dissolved organic materials, filtration primarily removes the insoluble particulate material. Early theories on the filtration of water attempted to find a link between the influent concentration of particles and the effluent concentration (Iwasaki, 1937). Particles causing turbidity within water can range in size from colloidal to 15 μm or more. The type of particulates in a filter influent stream is dependent on the raw water quality and the treatment processes upstream of the filters. Microbes adsorbed onto the surfaces of these particles, whether they be of natural origin or the result of the coagulation process, can be protected from disinfection by a coating of slime. Or the particles themselves may be protozoan cysts such as *Giardia lamblia* (5 to 15μm), *Cryptosporidium spp.* (4 to 7μm), bacteria, or viruses (Bolto, 1995). With the operation of a well-designed and efficient filtration system, it should be possible to remove 99% or more of the particles coming onto the filters (Hendricks, 1984). Most surface water treatment plants utilize some type of coagulation/flocculation process prior to filtration. Coagulation refers to the destabilization of dispersed negatively charged colloids through double layer compression, adsorption and charge neutralization. Flocculation refers to the bringing together of destabilized particles into agglomerates through transport aspects of the process i.e. adsorption, interparticle bridging, and precipitate enmeshment or sweep flocculation. The flocculation processes can be under diffusion control (perikinetic) or induced by fluid motion (orthokinetic) (Gregory, 1988). With only the use of inorganic coagulants such as alum, the primary mechanisms are charge neutralization and sweep flocculation.

Filtration is a complex process, with many interdependent variables affecting performance. Factors such as temperature can have large effects on filter performance. Generally, cold water is more difficult to filter than warm water with increased floc penetration into and through the filter for cold water (Rice, 1974). This primarily is a result of the increased viscosity of water at colder temperatures, with the viscosity increasing 44 percent from 20^0C to 0^0C. Particle size and concentration can also influence filtration, although the specific effects are dependent on the media (Yao, 1971). The removal of these suspended particles through filtration can essentially be broken down into two steps: transport and attachment (O'Melia and Stumm 1967). Transport is generally considered a physical step where the particles are brought into contact with the filter media. Transport mechanisms can include Brownian diffusion, sedimentation or gravity settling, interception, and hydrodynamics. The hydrodynamics within the filter bed are affected by factors such as media grain size, shape, and porosity, fluid temperature and density, interception rate, and the size, density, and shape of the suspended particles. Attachment of the particulates to the media or particles that have already been captured in the filter bed is controlled largely by the surface properties of the materials. Two primary attachment mechanism models are the double layer model and the bridging model (O'Melia and Stumm, 1967). The double layer model incorporates the attractive van der Waals forces, which are not affected by the composition of the aqueous phase, with the coulombic repulsive or attractive forces of the double layers. The bridging model was developed to explain the adsorption of colloids onto anionic or non-ionic polymers and incorporates mechanisms such as hydrogen bonding, ion exchange, and the formation of coordinative links and bonds. In this model, the segments adsorbed onto colloids or media are called trains and the segments extending into solution are called loops, with the ends of the polymeric chains termed tails (Ghosh et al. 1985). The loops and tails extending into solution interact and adsorb with other polymer chains, colloids, or media to form bridges. Ginn et al. (1992) incorporated the theory of particle detachment into filtration theory after using particle count data to determine that detachment is a major source of particles in filtered effluent and that in declining rate filters, when breakthrough occurs, there is a size distribution shift towards larger particles. The larger particles coming out of the filter were detached deposits that were sheared off of the filter media as a result of the increased interstitial velocity and 'avalanche effects'.

Filtration theories are somewhat limited to an interpretation of observed filter performance with specific media and water conditions. Comparisons of filtration theories has shown disagreements to such a degree that their applicability to general situations is not possible (O'Melia and Stumm, 1967). Even basic hydraulic flow through granular media does not lend itself to analytical solutions. As there is not a comprehensive, predictive theoretical model of filtration, the only means to evaluate performance is generally accepted to be through pilot or full scale testing.

2.4 Filter Performance

Filter performance can be assessed in a variety of ways. Through monitoring the effluent water quality for turbidity and or particle counts, the filter to waste time and the filter run time are determined.

A typical filter run is seen below in Figure 1. Three distinct stages are evident in this graph. As a filter comes online after backwashing filtrate turbidity and particle counts are high. This initial peak is called the ripening period and follows a similar pattern for both turbidity and particle counts. This peak of high turbidity or particle counts results from particles passing through the filter that were not removed in the backwashing process. In most filter operation, filters are put to waste for this period until the water quality reaches a certain turbidity criterion.

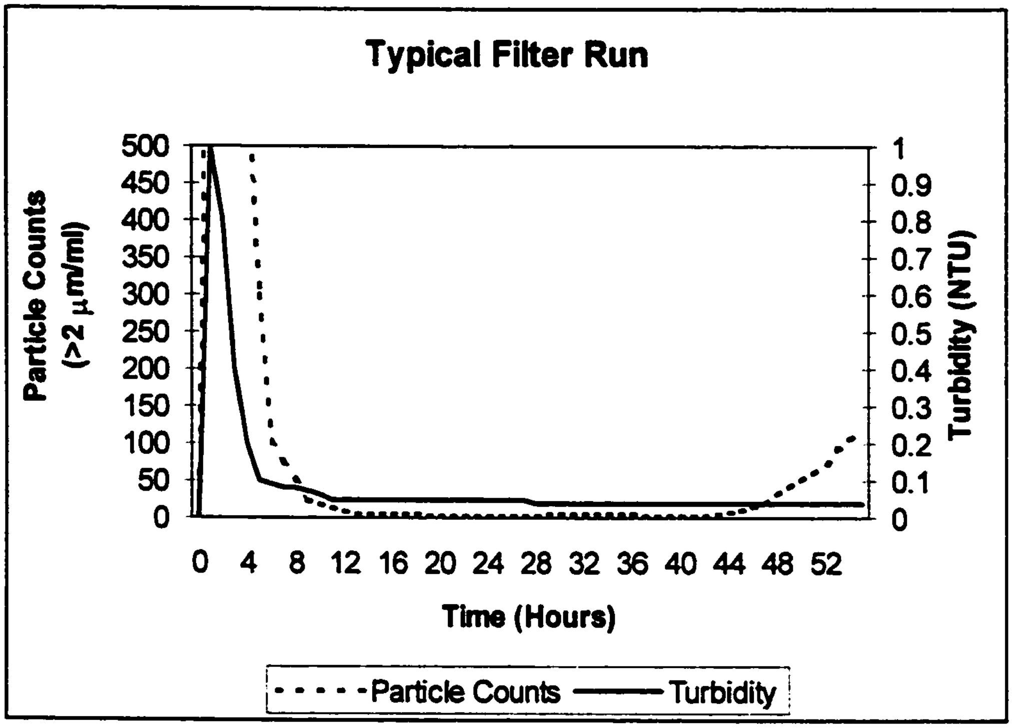

Figure 1: Typical Filter Run Particle Counts and Turbidity

Once the filter turbidity reaches the pre-determined criterion for coming online, there follows a period of relatively stable effluent quality. As the pore spaces in the filter media become clogged with particulates from the filter influent stream they become smaller, increasing interstitial velocity through the media and force the effective filtration zone deeper into the media bed. Eventually, there will not be any clean, effective media remaining in the bed or the shear forces will exceed the attachment forces and breakthrough will occur. This deterioration of filter effluent quality typically indicates the endpoint of the filter run requiring the filter to be backwashed.

The interim surface water treatment rule has produced more stringent requirements for filter effluent turbidity. Large water utilities serving 10, 000 people or more using conventional treatment must have combined filter effluent turbidity of 0.3 NTU or less 95 percent of the time, at no time exceeding 1 NTU, based on measurements taken every 4 hours over the period of a month. Continuous monitoring of individual filter turbidity is also required with explicit criteria for exception reporting. The most stringent of which requires reporting if a filter has an effluent turbidity greater than 0.5 NTU at the end of the first four hours of filter operation based on two consecutive measurements taken fifteen minutes apart.

The development of headloss, or pressure drop through the filter media, can be monitored using peizometers or differential pressure gauges. Headloss data can provide information on the particle removal through the filter, indicating when the filter becomes clogged and can potentially indicate the effectiveness of particle removal through the depth of the filter media showing differential headloss development at different points through the filter media. In declining rate filters, the effluent flow rate can also be monitored and used to assess filter performance, backwashing the filter when the flow has diminished to a level that is no longer efficient, and another clean filter could be put online.

2.5 Filter Polymer and Flocculation in Filtration

Polymers have been used in the treatment of water since the early 1950's (Leu and Ghosh, 1988). Due to many of the early studies being done with poorly characterized polymers, however, the current state of theories on polymer behavior in coagulation and flocculation is quite broad. Through the selection of an appropriate polymer and dosage for filtration, it is expected to result in increased particulate removal and better utilization of the entire depth of the filter bed. The primary function of polymers as a filter aid is to produce aggregate flocs that will be large enough to be captured and strong enough to be able to withstand shear forces within the filter bed voids (Yeh and Ghosh, 1981). Floc growth is the result of interparticle collisions created by agitation. The value in having a strong floc to aid in the filtration of water has been recognized for years (Baylis, 1949). Other benefits to the use of polymer as a filter aid can include increased filtration rates and longer filter runs (Carns and Parker, 1985). The addition of a small amount of polymer during the end of a backwash cycle has also been found to reduce the duration and turbidity peak of the ripening period when a filter first comes online after backwashing (Yapijakis, 1982). Adin and Rebhun, (1974) found that the use of filter polymer created a 'working zone' within the filter where effective particle removal occurred. This working zone moved down through the filter bed at a rate that was determined by the media grain size and the polymer concentration. The working layer was characterized by saturation with particulate deposit above it and a relatively clean layer below it. The use of filter polymer can potentially allow a more coarse media to be used, reducing the degree of headloss, and permit greater fluctuations in filtration rate without the risk of particulate breakthrough. A potential supplementary benefit can be the reduction of plant waste through lower backwash quantities, of up to fifty percent being required (Carns and Parker, 1985). There are several potential disadvantages to using polymers in water treatment including potential toxicity effects of residual monomers (Mallevialle, et al. 1984), inadequate information provision by suppliers, and potential re-stabilization of a dispersion with overdosing. Also, with the use of a filter polymer some type of surface wash or air scour system must be incorporated into the backwash procedure. This becomes necessary due to the increased floc attachment to the media that occurs with polymer usage.

Selection of polymers is based on a variety of characteristics such as molecular weight, charge density, monomer type, and the concentration of active polymer in the solution. Cationic polymers with high charge density have been found very effective in the removal of humic substances responsible for colour, lowering the potential for the formation of THMs with the use of chlorine as a primary disinfectant (Bolto, 1995). Although molecular weight was not found to be an important polymer variable in this study, the jar tests were conducted with low turbidity water with high colour. If the optimum dose is found at independent of the polymers molecular weight, charge neutralization is likely the dominant mechanism of flocculation of the particles (Ghosh, et al. 1985).

In the selection of an appropriate filter polymer, increased headloss is a major consideration. The development of headloss or pressure drop occurs when particles are removed from suspension as water moves through the filter media. Headloss development is dependent on media size and depth, flow rate through the filter, removal efficiency, and the depth of the working zone (Letterman, 1987). Terminal headloss can result from the removal of large particles blocking interstitial spaces or when particle destabilization is effective with large quantities of sub-micron particles. Habibian and O'Melia (1975), found headloss development to be inversely proportional to the size of particles removed from suspension. The optimum condition is for terminal headloss and turbidity breakthrough to occur simultaneously. A lack of penetration into the filter bed usually results in filter runs ending due to terminal headloss, although this is accompanied by excellent turbidity removal for the duration of the filter run. The use of high molecular weight polymers tends to improve particulate removal at the expense of increased head loss. This likely occurs through the restriction of the interstitial spaces between the media, especially at the top of the filter bed (Tanaka and Pirbazari, 1986), (Zhu, et al. 1996), (Habibian and O'Melia, 1975), resulting in an inefficient use of the entire depth of the filter bed. When anionic or nonionic polymers are used as a filter aid, a minimum molecular weight is required for interparticle bridging to become the dominant mechanism of removal of the negatively charged colloids or small destabilized flocs (Stump and Novak, 1979).

There are four mechanisms for the adsorption of particles to the polymer: electrostatic interactions between the charged particle surface and the charged polymer, hydrogen bonding, hydrophobic bonding, and specific adsorption (Leu and Ghosh, 1988). The polymers physical configuration may also have a significant impact on adsorption and particle removal. Tanaka and Pirbazari, (1986) proposed that highly branched or randomly coiled polymers may adsorb colloids more efficiently than linear, straight chain polymers. This information is rarely provided by polymer manufacturers, however, and is only evident after relatively intensive laboratory examinations of the polymers. Adding an organic polymer to a filter influent stream creates charge neutralization of the colloid and interparticle bridging with destabilized colloids and flocs. Typically, the polymers interact with colloidal particles surfaces and are adsorbed to the point to charge neutralization (Yeh and Ghosh, 1981) and (Leu and Ghosh, 1988). If there is too strong an electrostatic repulsion between the charged polymer loops, the polymer can form a flat configuration on the particles surface resulting in no loops extending into solution and a restabilized particle (Leu and Ghosh, 1988).

Depending on the type of polymer used the pH of the solution can affect the polymers performance. Cationic polymers have a greater variety of molecular structures than other polymers and tend to maintain their charge properties independently of pH. This is due to the quaternary ammonia groups contained in the monomers (Bolto, 1995). As pH adjustment is often not within the realm of most water treatment facilities until just before entering the distribution system, this makes the use of cationic filter polymers favorable.

Habibian and O'Melia, (1975) also discovered that glassware competes very effectively with colloids for adsorption meaning that only a fraction of the polymer added to a jar test, or likely a pilot filter is available for particle removal. The magnitude of the available polymer is determined by the ratio of the surface area of the material surrounding the suspension to the surface area of the suspended particles in solution. This implies that optimal doses found at the bench or pilot scale will likely need to be reduced full-scale.

2.6 Filter Polymer and Particle Counting

Applications of polymers to improve the water treatment process has focussed on their use in enhanced coagulation and as a flocculent aid for direct filtration (Adin and Rebhun, 1974; Carns and Parker, 1985; Yeh and Ghosh, 1981; Letterman et. al, 1979; Yapijakis, 1982). In these studies, filter performance was assessed through effluent turbidity, development of headloss, and filter run time. As the physical mechanisms of particulate removal have improved with enhanced coagulation prior to filtration, particle counting technology has begun to emerge as a more sensitive measure of filter performance. Although particle counting has been recognized as being more sensitive than turbidity since the late 1970s (Watkins et al. 1978), the technology has only recently become more widely used, as water treatment technology has become more efficient at the physical removal of particulates. The EPCOR water treatment plants had been achieving filter effluent turbidities as low as 0.02 NTU with combined filter turbidities consistently below 0.03 NTU. Turbidity has been found to be loosely related to particle counts for turbidity above 1 NTU, however, at turbidities below 0.1 NTU particle counts (>2μm/mL) particle counts can vary from 10 to 1000 (Hargeshemir and Lewis, 1995). This implies that the lower sensitivity limit for a turbidity meter is 0.1 NTU. In order to continue improving the physical removal of particulates, it was necessary to move to this more sensitive technology to determine suspended solids in filtered water. Besides being a more sensitive instrument, particle counters provide additional information, specifically the size of the particulates in solution, that is not available with turbidity meters.

There have been an increasing number of applications of particle counting being used to assess and optimize the performance of water treatment plants (Fibas, et al. 2000; Carlson and Gregory 2000; Childress et al. 1999; Adin et al. 1998). Hargeshemir et al., (1998) found filter effluent particle counts to be sensitive to very small changes in primary coagulant doses, while turbidity showed a relative unresponsiveness to the same dose changes. Similar results have been found by Lind, (1997), who demonstrated through four case studies that enhanced coagulation using polyaluminum chloride produced lower finished water particle counts than could be attained by using alum or ferric salts alone. These and other studies have used particle counters as an additional source of information along with turbidity and showed conclusively that particle counts are a more sensitive technology than standard turbidity meters. Only one study has been found that studied the relationship between filter effluent particle counts and the addition of a filter polymer. Although the Hargeshemir (1992) study found a positive impact on filter particle counts with the addition of a cationic filter polymer, only one polymer type and dose was tested, and the potential impact of rapid mixing was not investigated. A rigorous examination of potential further improvements in filter effluent particle counts with the addition of filter polymer has not yet been conducted.

2.7 Mixing in Coagulation and Filtration

The importance of mixing in the coagulation process has been thoroughly investigated in water treatment. Coagulation using an inorganic salt occurs primarily through two mechanisms. The adsorption of colloids to the hydrolysis products of the coagulant causing charge neutralization and removal by particle enmeshment (sweep coagulation) where the colloids interact with the precipitating hydroxide species. The reactions occurring for alum as a coagulant are shown below.

$$\begin{gathered} Al_2(SO_4)_3 \bullet 14.3H_2O \rightarrow Al(H_2O)_6^{+3} + SO_4^{-2} + H_2O \rightarrow \\ Al(OH)^{+2} + Al(OH)_2^{+} + Al_7(OH)_{17}^{+4} \rightarrow AL(OH)_3(s) \end{gathered}$$

The initial hydrolysis reactions causing charge neutralization occur very quickly when inorganic coagulants are combined with water. For charge neutralization to occur and destabilize the colloids, it is essential that the coagulant be dispersed effectively through the water within less than 0.1 second from its time injection (Amirthatajah and Tambo, 1991). This mechanism produces a small or pinpoint floc. The reaction producing the secondary hydrolysis products and the final, much heavier and solid form of the coagulant, important for sweep coagulation and interparticle bridging occurs much slower, within 1 to 7 seconds. The competitive nature of the two modes of coagulation implies that if charge neutralization is to occur, the dispersion of the coagulant must be done very efficiently so that the hydrolysis products can destabilize the colloids. This can be effective in lower turbidity source water where there can be transport and collisions with the colloids in suspension and the quickly forming products of the hydrolysis reactions to from a pinpoint floc suitable for flocculation. If sweep coagulation is the primary mechanism of coagulation, rapid mixing is not as important a factor as long as the resulting precipitate has opportunity to contact the colloids.

In the use of polymers as a coagulant or filter aid, the hydrolysis products formed by inorganic salts are not present. Flocculation with polymer addition must be intense enough to properly disperse the polymer, however, de-aggregation of the floc particles can occur with too intensive mixing conditions. Shear stress on the floc increases directly with the size of the particle. Floc size is dependent on polymer type, dose and the mixing intensity. Once a floc exceeds a critical diameter for a given G value, its size will be reduced through splitting into smaller flocs or through surface erosion (Ghosh, et al. 1985). This implies that the high mixing intensities required for rapid mixing should not be required for polymer dispersion (Amirthatajah and Tambo, 1991). Slower, flocculent mixing has been found to have an important role not only in the dispersion of the polymer to make contact with and adsorb the colloids, but also to rearrange the polymer on the surface of the particles so that it becomes suitable for flocculation (Ghosh, et al. 1985). This has implications that there is not only an optimum mixing intensity, but also an optimum t for all values of G (Yeh and Ghosh, 1981), (Stump and Novak, 1979), (Leu and Ghosh, 1988). This has also been found using polymers in coagulation. Morrow (1974), used a cationic polymer as a primary coagulant, it was found that optimum flocculation occurred in less than two minutes of mixing at a G of 400 s^{-1}, with degrading performance as the mixing time deviated from this optimum. Other investigators have examined the time it takes for filter polymer flocculation reactions to occur through flocculation monitoring and found that the time required for significant polymer adsorption can be several minutes from the time of polymer addition (Lee and Gregory, 1991). Rapid mixing should not be prolonged for too long of periods as it may result in shearing of the polymer segments and impair the flocculating capability of the polymer. For low to medium molecular weight polymers (10 000 to 100 000) it is thus essential to have a vigorous rapid mixing to ensure an optimum Gt ($300 < G > 650$) (Yeh and Ghosh, 1981).

Typically there is an optimum polymer dose required to flocculate the colloidal suspension and this optimum dose decreases as the mixing intensity increases (Amirthatajah and Tambo, 1991). To maintain the same effluent quality with a higher mixing intensity required a reduction in the detention time, i.e. a constant Gt as well as a reduced polymer dose. When the detention time was not reduced with higher mixing intensities floc shearing occurred. Stump and Novak, (1979) examined the effects of mixing intensities with direct filtration. Across the range of cationic polymers molecular weight an optimum range for G of 300 s^{-1} of 600 s^{-1} with a constant t of 120s was found for optimum turbidity removal. The specific mixing intensity optimal for each polymer was dependent on the molecular weight and raw water quality. This interdependence on mixing intensity and molecular weight has been found by other investigators. Cationic polymers with high molecular weights were found to perform better with respect to turbidity removal, headloss, filter run time, and volume of filtered water at higher velocity gradients (600 to 1000 s^{-1}); lower molecular weight polymers were found to perform better at lower mixing intensities (300 s^{-1}) (Stump and Novak, 1979). As mentioned earlier, the impacts of rapid mixing of filter polymer on filter effluent particle counts has not yet been investigated.

Mixing characteristics can also determine how a filter run terminates. Letterman, et al. (1979) looked at the effects of different mixing intensities, filtration rates, and polymer concentrations with the resulting changes in zeta potential. It was found that the only factor which influenced effluent turbidity was the cationic filter polymer concentration. Mixing intensities of 700 s^{-1} and 25 s^{-1} were combined with a constant detention time of 240 s. At the higher Gt (168

000) values turbidity breakthrough occurred, while at a Gt of 6000, filter runs continued until the headloss reached a terminal level.

2.8 Zeta Potential

Zeta potential provides a rough estimate of electrostatic interactions and can potentially be used for clarifier or filtration performance optimization as it provides information on coagulation, flocculation, and filterability. The surface charge potential of colloids is an important parameter influencing colloid stability and adsorption behaviors with the best removals of turbidity and colour occurring when the zeta potential is close to zero (Bolto, 1995). Determining optimum polymer dosing based on zeta potential contains a certain degree of uncertainty, however. Most solutions contain particles with both positive and negative charges making the zeta potentials close to the charge neutralization region difficult to determine with any accuracy or reproducibility (Chang, et al. 1997).

Polymers of all potential charges react with colloidal suspensions to change the zeta potential of the particles (Welday and Baumann, 1979). The magnitude with which each polymer will affect the colloids is dependent on the specific polymer and the aqueous solution with each polymer having a unique zeta potential curve with cationic polymers typically increasing the zeta potential and anionic or non-ionic polymers having less predictable results. Using a cationic polymer, (Chang, et al. 1997) found zeta potentials to increase from negative to positive with increasing polymer dose. With a non-ionic polymer, the effect on zeta potential would be expected to be negligible with interparticle bridging being the primary mechanism for removal. (Letterman, et al. 1979) used a cationic polymer and found the dosage could be optimized by bringing the zeta potential to zero. The filtration efficiency or solids deposition within the filter media was improved using the movement of the clogging front or filtration zone as a performance measure. Ghosh, et al. (1985) found similar results optimizing flocculation in bringing the zeta potential close to zero in a bentonite suspension.

The zeta potentials of aggregate flocs are strongly dependent on pH (Chang, et al. 1997), with it being suggested that the proton concentration affects the floc charge density through the hydrolysis reaction. With a cationic polymer in acidic conditions, it was found that there was increased repulsion between the polymer segments and decreased repulsion in the aggregate promoting destabilization and removal. Welday and Baumann, (1979) found a variety of pH – zeta potential curves without any consistency shown between polymers. Without detailed information on polymer structure, which is often unavailable, the causes of the pH dependent changes remain unknown. As information on polymer and monomer structure is often unavailable, this means that without empirical observation, it is difficult to determine whether changes in pH will affect the zeta potential of polymers towards more positive, negative, or leave it unchanged.

3.0 Materials and Methods

3.1 Overview

The experimental work for this thesis was done in three separate stages. Initially, five different filter polymers selected from prior bench tests were tested on pilot scale filters using full-scale alum clarified water. A range of filter polymer doses for each polymer was tested to choose the best performing polymer in terms of particle counts, turbidity, and headloss to study in further detail. Even the best performing polymer did not give consistent results that would be acceptable full-scale, however. This led to the investigation of the rapid mixing of alum on the pilot scale to determine whether improving the clarification process would result in better filter performance. Finally, the best performing polymer selected from the initial experiments was tested across a range of doses and mixing intensities to determine the impact of mixing on filter polymer and optimize filter performance. A description of the pilot facilities where the work was conducted is included below.

3.1.1 Pilot Plant

The main pilot plant at the E. L. Smith WTP takes in raw water from the North Saskatchewan River and treats it using coagulation/flocculation, sedimentation, and filtration. Due to space restrictions, however, a separate set of pilot filters has also been built in order to accommodate for peizometers to measure headloss as well as a polymer rapid mixing and delivery systems. All of the pilot scale filters are of 150 mm diameter, a size that has been found representative of full-scale filters with similar media in terms of headloss development, turbidity, and particle counts (Lang, et al. 1993) and give reproducible results. For the purposes of this study, the two pilot plants will be referred to as the main pilot plant and filter pilot plant, respectively. The initial part of this experiment was the screening of five filter polymers at a constant velocity gradient at the filter pilot plant. Photographs of the pilot facilities used in these experiments are included in Appendix D. A Schematic showing the chemical injection points and instrumentation of the filter pilot plant is shown below in Figure 2.

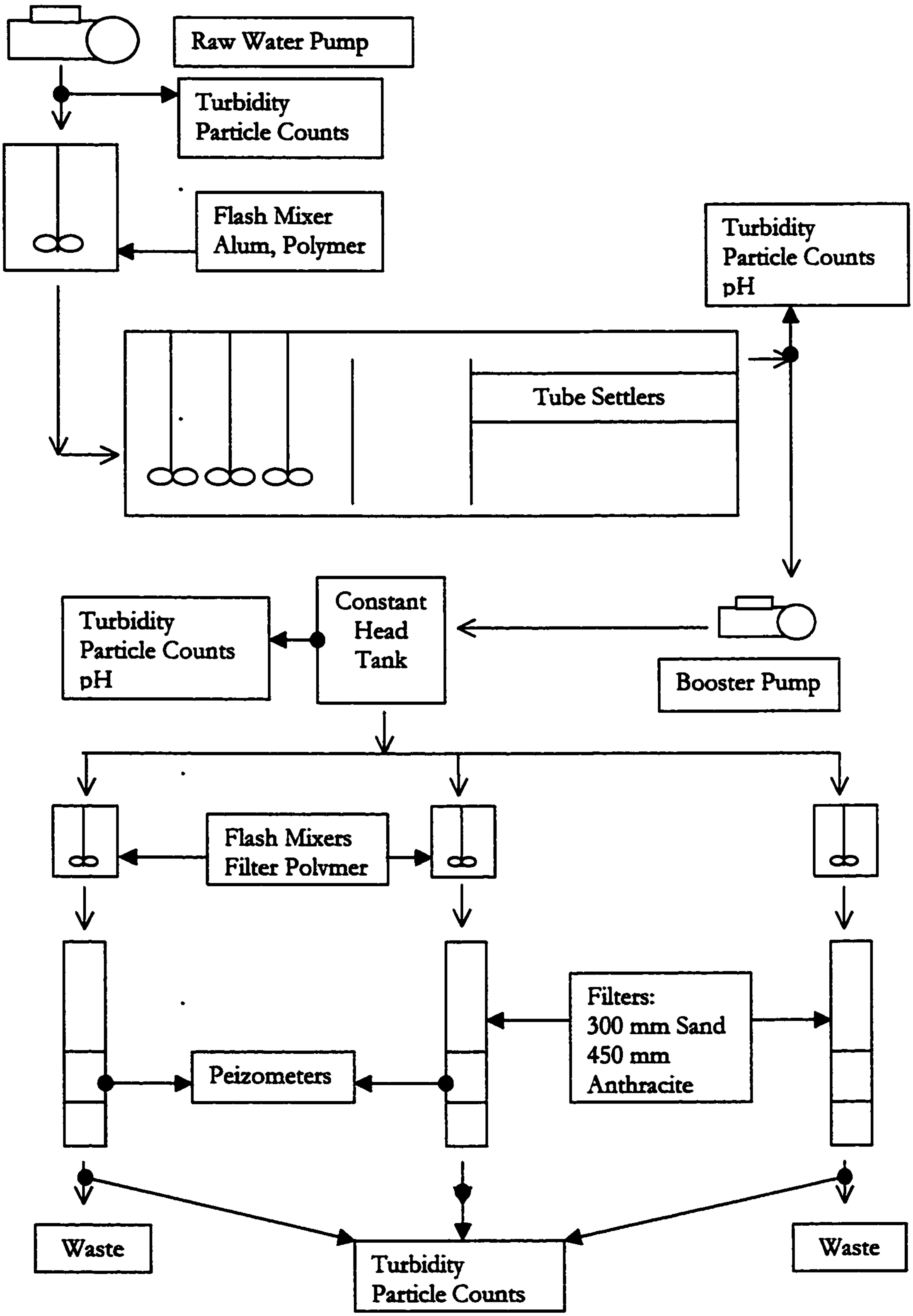

Figure 2: Pilot Plant Schematic

3.1.2 Filter Pilot Plant

Several modifications to the existing filter pilot plant were required for this study. In order to more accurately represent the full-scale filters at E.L. Smith, which are dual media sand (300 mm) / anthracite (450 mm), media had to be added to each of the 3 pilot scale filters. Filter one, the control filter required 40 mm of anthracite, filter two required 30 mm of anthracite, and filter three required 25 mm of anthracite. As prior work on the filter polymer pilot plant had used softened water, the filters were also washed with concentrated 10 molar HCl to remove any calcium carbonate that may have bound to the media. In addition, an online pH meter was installed after the constant head tank into the filter influent feed line. A direct line with a pump was installed to deliver water directly from the full-scale upflow continuous bed clarifiers to the three pilot scale filters to allow for the testing of unsoftened water produced on the full-scale with filter polymer. Another line was installed to pump water from the main pilot plant to the filter polymer pilot plant to allow for changes in the process upstream of filtration. The turbidity meters used (Hach 1720C) were all calibrated in the range of zero to twenty NTU using a 20 NTU polystyrene bead standard and an ultra pure zero NTU standard, both provided by EPCOR. The sealed solutions were used once and discarded. This was done following the same procedure used at the full-scale E.L. Smith facility and as recommended in the Hach 1720C maintenance and operations manual. The flow through the filter influent and effluent turbidity meters was also calibrated to 750 mL/min as per instrument specifications. Met One particle counters were installed to measure filter influent and filter effluent. All particles greater than 2 micrometers in diameter were counted and sized based on the same bin sizes currently being used on the full-scale (>2μm, 2 to 5 μm, 5 to 7 μm, 7 to 10 μm, 10 to 15 μm, and >15 μm). The turbidity, particle count, and pH data was all logged using the Water Quality Software Vista v.1 supplied with the particle counters. Calibration of the particle counters is done at manufacturer facilities prior to shipping. As of the time of this writing the software and standard sized solutions used to calibrate the particle counters is not available for on-site calibrations. In order for the particle counters to be accurate, the flow through the particle counters must be constant at 100 mL/min. Any deviation in this flow rate would represent a directly proportional difference in the actual number of particle counts in relation to the number recorded and displayed. If the total number of particles >2μm shown on the display is 100 and the flow through the particle counter is 90 mL/min, the actual number of particles >2μm would be 90/mL. The flow through the particle counters is set to a constant 100 mL/min using a water weir flow controller, and the height was adjusted appropriately using a 100 mL graduated cylinder and stopwatch.

The flow of water through the main pilot plant is measured at various points of the process. At the main pilot plant, magnetic flow meters measure the raw water flow, the flow into the rapid mix tank, and the flow onto the filters. The filter polymer pilot plant has rotameters on the influent into the rapid mix tank for each filter and the filter effluent. Each of these flow meters was calibrated using a 2000 mL graduated cylinder and a stopwatch. The time to fill the graduated cylinder was measured in 0.5 L increments from 1.0 to 7.0 LPM, the range of possible flow. Calibration curves were developed comparing the flow reading shown and the actual flow to confirm the accuracy of the meters.

As the performance of polymers as a filter aid has been shown dependent on the amount of mixing, it is critical to determine the velocity gradient for the polymer rapid mix tanks. The mixing intensities tested were somewhat restricted by the existing equipment at the pilot plants. The velocity gradient is determined by the equation:

$$G = \left(\frac{P}{\mu v} \right)^{\frac{1}{2}}$$

Where:

G = Velocity Gradient (1/sec)

P = Power Input (W)

μ = Dynamic Viscosity (N-sec/m^2)

v = Volume of mixing chamber (m^3)

It is possible to determine the power input through the formula:

$P = T * \omega$

Where:

P = Power Input (W)

T = Torque (Nm)

ω = Angular Velocity (rad/sec)

Torque was measured using a torque meter attached to a portable mount. Measurements were taken with the torque meter attached to the flash mixer motors with and without water in the mixing chamber at a range of mixing speeds. The difference in torque between these values is the energy that is applied to mixing the water in the flash mixer. Replicate readings were taken for each setting of mixing speed and the mean value was used for the calculations. Angular velocity was calculated by taking rpm measurements across the range of mixing speeds using a digital tachometer. A directly proportional linear relationship was found between the velocity gradient and percent mixing speed. Calibration curves for the velocity gradients of the flash mixers are found in Appendix A.

Full-scale filter runs at E.L. Smith can typically run for up to72 hours and it was intended initially to be able to have pilot filter runs of this duration as well. It was found in preliminary control runs, however, that the headloss development over this period with unsoftened water was too great for the filter effluent to flow through the particle counters by gravity. To ensure that 100 mL/min was available to flow through the particle counters, it was necessary to install an overflow chamber after the filter clearwell. From this overflow tank, water was pumped, using a centrifugal pump, to the particle counters weir. As it was uncertain how the centrifugal pumps would affect the particle counts, several one-day filter runs were done comparing the particle counts with and without the pumps. Although initial ripening peaks were larger and took slightly longer to decline with the pumps, within 30 minutes, the two sets of particle counts were similar. Once all modifications to the filter were completed at the plant, a control run was done to ensure that all three filters were performing similarly under identical conditions.

The existing polymer delivery system was also slightly modified so that the polymer solution from the day storage container could be delivered directly under the impeller to improve mixing. Several preliminary trials were done to determine an appropriately sized peristaltic pump and tubing size for the polymer doses being considered. Once selected, the pumps were calibrated for the effective dose delivered at a range of rpm settings. As the viscosity of the fluid can have an impact on the flow rate through peristaltic pumps, the polymer solutions to be used in the experimental runs were used to calibrate the pumps.

3.1.2.1 Instrument Error

Instrument error can be expressed as an absolute value, a percentage of the current value, or a proportion of the instrument range. EPCOR has developed a quality assurance / quality control program to ensure all online instrumentation is producing as accurate measurements as possible, with the standard for assessing instrument error varying with the type and operational function of the instrument. All online analyzers are compared regularly with bench top analyzers to ensure accuracy and adjust the analyzers when necessary.

Filter effluent turbidity meters are ranged from 0 to 10 NTU. The limit of accuracy for these instruments is 0.1 NTU when performing a benchtop quality assurance test. The clarifier effluent and pilot plant raw water turbidity meters are ranged from 0 to 20 NTU with accuracy of within 10% for turbidities above 10 NTU; within 20% for turbidities between 3 and 10 NTU; and within 30% for turbidities below 3 NTU. The online pH meter is accurate to within 0.2 pH as compared with a grab sample test. All particle counters in the process prior to filtration are accurate to within 10% of the current value as compared with grab samples analyzed with a bench top particle counter. Post filter particle counts are accurate to with 10 absolute counts, again as compared with a grab sample comparison with a bench top particle counter. EPCOR has developed these unique standardized operational criteria specific to the applications as at this time there is not any industry wide concentration standards to assess the accuracy of particle counters. Particle counters come from the factory standardized for measuring a distribution of sizes of particles, and only very recently have these known particle size standardized solutions come available for performing quality assurance on the instruments. As has been pointed out by Van Gelder et al. 1999, there is still not a known concentration standard available to test that the particle counters are actually counting the accurate number of particles. As particle counting technology becomes more widely used throughout the water treatment industry it is likely that these quality assurance standards will become available. Other than sensor or software issues, particle counters accuracy is also very dependent on the flow rate through the sensor. The particle counters sensor is calibrated for a particular flow rate through the sensor and deviations from this flow rate can impact the particle counts and sizing (Hargesgeimer et. al, 1992). Higher than calibration flow rates results in under sizing of the particles and a lower number of counts than what is actually in the sample. Conversely, lower than calibration flow rates result in particle counts higher than what is actually in the sample.

To eliminate error being generated in the data being collected for analysis across all of the online instrumentation, the instrument scaling, PLC scaling, and SCADA scaling were consistent through the chain.

3.1.2.2 Filter Pilot Plant Operation

At the beginning of each filter polymer run, the following procedure was used to clean the filter media.

Backwash Protocol:

- Turn off influent flow
- Close all peizometers
- Drain filter to a height of 300 mm above the filter media
- Pressurize air scour line to a constant 200 kPa
- Slowly turn on backwash flow to slightly fluidize filter bed
- Turn on air scour
- Turn off backwash flow
- Turn on influent flow to 1 LPM (note – this is necessary to prevent clogging in the overflow elbow with anthracite)
- Air scour media at 200 kPa for 3 minutes
- Slowly turn on backwash flow and turn off air scour over a 30 second period
- Backwash filter for 15 minutes at a flow rate of 24 LPM
- Slowly turn off backwash over a period of 30 seconds
- Allow media to settle
- Increase influent flow to 6 LPM (in order to completely clear overflow elbow)

- Tap down media with rubber mallet until the top of the media is just below the top of the influent overflow
- Turn off the influent flow
- Repeat for all filters
- Drain peizometer lines of water from the end of prior runs
- Purge air scour line of all air to prevent inadvertent leakage of air

Turning off the backwash flow slowly was used in the procedure as it has been found that closing the valve quickly results in increased loose-bed porosity (Lang et al. 1993). Due to the hydraulics in the pilot filter column and the necessity of having to tap down the media, it is not likely that any benefit was gained from this procedure. The larger porosity at the point of union of the filter media with the filter column wall relative to the media bed is the source of wall effects. This media bridging was described by (Lang et al. 1993), who suspected that the higher loose bed porosity's would adversely affect pilot filter performance relative to full scale tests, although it was not conclusively proven in that study.

3.1.3 Polymer Selection

3.1.3.1 Primary Selection: Initial Five Polymers

Prior to this study, 23 polymers were screened and five were chosen for further testing on the pilot scale (Tun, 1998). The initial polymers were selected based on a range of physical properties including molecular weight, charge,

charge density, and monomer type. A modification of the paper filter test (Dentel, 1987) was used, recording filtration time, particle counts, turbidity, pH, and zeta potential. Although this procedure is recommended as a valid qualitative method of screening the effectiveness of filtration aids, it has several known limitations, and only trends in performance may be duplicated on both pilot and full scale with fine-tuning required. The primary mechanism involved in this method is straining which is known not to be the principle method of deep bed filtration. Additionally, as only 10% of the filter paper area contains pores, not all of the particles of critical size will pass through the filter. For these reasons, the test fails to be useful for predicting exact turbidities or particle counts as they occur full-scale and does not produce results which are reproducible.

3.1.3.2 Preliminary Selection: Testing the Five Polymers

The best performing five polymers were then tested further on a pilot scale at E. L. Smith. Appropriate dose ranges were determined based on the polymer type and the manufacturers recommendations for use in water treatment. Dosage with polymer does not primarily refer to the concentration of active ingredients concentration, i.e. take into account percent activity. Dosage was calculated on a mass basis, with relative performance being measured and compared. This was necessary due to the limited amount of information that was available from the polymer suppliers on the percent activities in their liquids and emulsions. The physical characteristics of each polymer as well as the dose range tested in the initial portion of this study are shown below in Table 1. Once the highest and lowest doses were selected, a midpoint was chosen for testing and the trials were randomized.

Table 1: Polymer Characteristics and Dose Ranges

Polymer Name	Characteristics	Dose Range Tested (mg/L)
Catfloc CL	Low molecular weight, Very high charge density, Cationic, polyDADMAC	0.05 to 0.25
Nalcolyte 8100	Cationic, polyamine	0.05 to 1.0
Percol LT-24	Medium molecular weight, low charge density, Cationic, polyacrylamide	0.001 to 0.01
Percol LT-7996	Low molecular weight, high charge density, Cationic, polyDADMAC	0.05 to 0.25
POL-E-Z 652	High molecular weight, Non-ionic, polyacrylamide	0.004 to 0.04

The characterization of polymers molecular weights is somewhat arbitrary. A guideline established by (Mangravite, 1983) gives estimates of 1 x 10^4 to 1 x 10^5 for low molecular weight, 1 x 10^5 to 1 x 10^6 for medium, 1 x 10^6 to 5 x 10^6 for high, and greater than 5 x 10^6 for very high molecular weight.

3.1.4 Initial Polymer Selection Experimental Design

Two experimental conditions were run at a time with one filter being used as the control. Table 2, below, shows the order in which the runs were conducted.

Table 2: Initial Polymer Selection Experimental Design

Randomized Trial Number	Polymer	Dose (mg/L)
1	Catfloc CL	0.1
2	LT 7996	0.25
3	Catfloc CL	0.25
4	Pol E-Z 652	0.004
5	Nalcolyte 8100	0.1
6	Catfloc CL	0.15
7	Pol E-Z 652	0.02
8	Nalcolyte 8100	0.05
9	Percol LT 24	0.001
10	Catfloc CL	0.05
11	Percol LT 24	0.01
12	Percol LT 24	0.005
13	Nalcolyte 8100	1.0
14	LT 7996	0.15
15	Pol E-Z 652	0.04
16	LT 7996	0.05

Approximate duration of each filter run was three days, with new polymer solutions being prepared daily. The underdrain flow rate was set initially at 7.5 m/h, and the filters were run as declining rate, constant head filters to model the full-scale as closely as possible. Operating the twelve full-scale filters in this manner reduces the problems of sharp rises in water level that accompany backwashing filters. Data on particle counts, turbidity, and pH, for the influent water and filtrate was collected and stored every two minutes in a database within the WQS Vista software. Additional data on temperature, flow, and headloss was taken at the beginning of the run and at twenty-four hour intervals for the length of the filter run. This information was recorded manually on data template sheets, an example is shown in Appendix B. The velocity gradient was kept constant at the value of 700 G (1/s), the value that was found to achieve the best filtration performance in the prior study at this pilot plant (Zhu et al. 1996).

Although it is know that charge density of certain filter polymers can be significantly affected by the pH of solution (Ghosh et al. 1985), it was decided not to control for this factor, leaving the pH determined primarily by the alum dose. This will model the pH of the full-scale plant when softening is eliminated.

The source water for the filter influent stream was the full-scale clarifiers treated with alum and polymer and of a relatively consistent quality. Temperature ranged from 0 to 5 degrees Celsius, with raw turbidity from 2 to 40 NTU. Alum dose to the clarifiers ranged from 25 to 35 mg/L and the primary anionic polymer in the clarifiers ranged from 0.25 to 0.45 mg/L. The clarifier effluent had a mean pH of 7.4 with turbidities of 0.5 to 3 NTU and particle counts ranging from 900 to 11000 (>2 μm/mL).

3.2 Alum Dose and Rapid Mixing

3.2.1 Main Pilot Plant

The second stage of this study was done at the main pilot plant. These facilities can model the entire water treatment process as it occurs at both the E. L. Smith water treatment plant (upflow, continuous bed clarifiers) as well as

Rossdale (crossflow clarifiers with tapered flocculation), Edmonton's other water treatment plant. There are two sets of crossflow clarifiers and two upflow clarifiers allowing several different experimental conditions to be run at once. For these experiments, the two sets or trains of crossflow clarifiers were run taking common raw water from the North Saskatchewan River. The only modifications required at the main pilot plant were the installation of the particle counters. Each train of the pilot plant was run separately under identical conditions to determine if the filters were performing similarly. Particle counters were installed to measure the particle counts of the clarifier effluent, on the combined filtrate for each train, and on an individual filter on each train. The individual filters were selected by connecting a particle counter to each filter on each train and running the filters with common source water for twenty-four hours. It was found that train one filter two and train two filter two were performing the most similarly. Although filter turbidity was continuously monitored and recorded, the clarifier effluent turbidity was collected by grab samples and measured on a bench top Hach turbidity meter every eight hours.

3.2.1.1 Rapid Mixing

The entire water treatment process determines the nature of the particles going onto the filters. One potential improvement that is being considered at E.L. Smith is to replace the rapid mixer for alum and polymer going into the upflow clarifier. A prior study, (Curtis, 1997), determined the velocity gradients for the rapid mixing tanks at the main pilot plant. These calculations were confirmed using the original data, and this information was used for the purposes of this study with modifications made for the volume of the mixing chamber.

3.2.1.2 Chemical Delivery

The alum and polymer chemical pumps are diaphragm pumps, with stroke and percent speed adjustments that must be made manually for calibration. Keeping the stroke constant and using a stopwatch and graduated cylinder, the volume delivered at a range of percent speeds was determined. A stroke was chosen that would be able to deliver the entire range of chemical doses through the duration of the experimental run, modifying only percent speed. The intercept and slope of the resulting calibration curves were then entered into the Intellution FIX 32 v.6.15 software which adjusts the percent speed accordingly to deliver a specified dose. Alum was fed at a concentration of 48.5%, the same as is used full scale at the E. L. Smith water treatment plant. Enhanced coagulation is used full scale and this was modeled at the pilot plant. The anionic polymer Percol LT 27a was fed at a constant dose of 0.25 mg/L just after the alum injection prior to entering the tapered flocculation. This was the similar dose of 0.3 mg/L being fed full scale during the duration of these tests. A lower dose was selected due to the slightly different clarifiers being used i.e. crossflow pilot clarifiers versus upflow full-scale clarifiers. Historically, the crossflow clarifiers have required a lower polymer dose than the upflow clarifiers. Full-scale alum dose remained unchanged at 30 mg/L for the length of the pilot testing. Raw water quality remained relatively constant for the duration of the filter testing with turbidity ranging from 1.8 to 2.8 NTU as the river was covered in ice.

3.2.1.3 Zeta Potential

To gain further information on the nature of the colloids that are present and how chemical dosing could be optimized through the water treatment process the zeta potential of colloids at various stages of the treatment process was measured. Zeta potential was measured using a Zeta-Meter System 3.0 from Zeta-Meter, Inc. Prior to the second stage of experimental trials, a series of jar tests was done comparing a range of alum doses and the resulting zeta potential. This was done to ensure that it would be possible to destabilize the colloidal suspensions so that the effects of rapid mixing could be investigated. The following linear relationship was found.

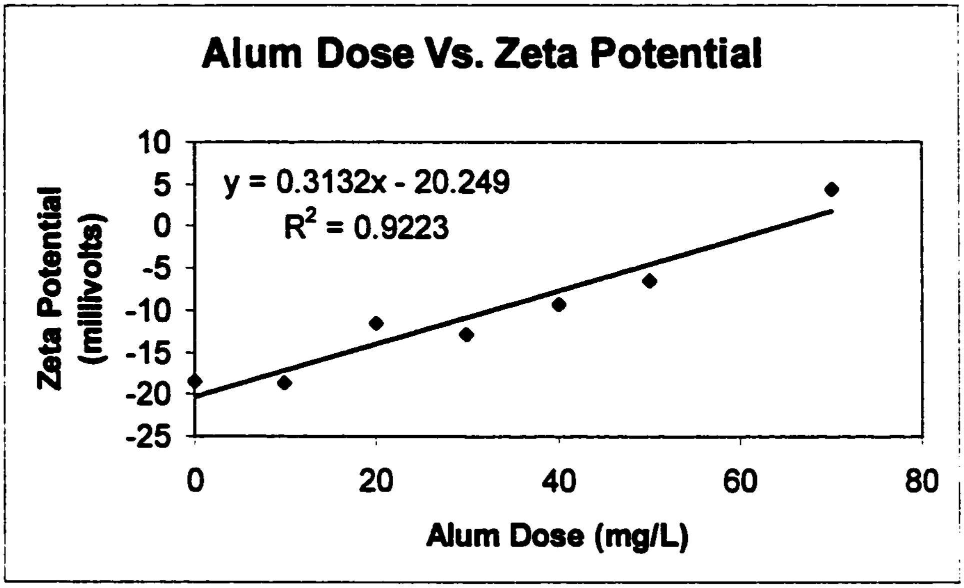

Figure 3: Alum Dose versus Zeta Potential

For the purposes of this experiment, the filter influent and effluent zeta potential was measured for each train. Once the sample was collected, they were stored at a temperature consistent with the water temperature, until the zeta potential could be measured. A continuous flow sampler was used with the zeta meter. This method has several advantages over batch sampling such as minimizing sedimentation problems within the sample cell and reducing thermal overturn, the continuous increase in sample temperature from the frictional heat generated by moving particles causes them to move in a spiral rather than linear motion. Samples were taken from the filter influent and effluent for each train at the end of the filter run. Initially, sampling was done at the beginning and end of the filter run to determine if there was a change in the nature of the particles through the duration of the filter run, however, there was not a noticeable difference, so the sampling frequency was reduced to once per run. Twenty zeta potential measurements were taken for each sample and the zeta-meter recorded the mean value as well as the standard deviation.

3.2.2 Main Pilot Plant Alum Dose and Rapid Mix Experimental Design

A range of alum doses and velocity gradients were tested. Each combination of alum dose and mixing was replicated on a separate train. As it had been determined that the two trains were performing similarly during initial control runs, the replicates were not run concurrently. The experimental design for these trials is seen below in Table 3. Doses were selected in a range around current full-scale use. The selection of velocity gradients was limited by the design of the available flash mixer, however, the range selected (10 to 500 G) was expected to be sufficient to determine whether rapid mixing would be an important factor. The flow of water was cut to 2.0 m^3/min, approximately one third of the plants design flowrate to increase the Gt. This resulted in a 6.0 second detention time in the flash mixer.

Table 3: Rapid Mixing Vs. Alum Experimental Design

Randomized Trial Number	Train 1		Train 2	
	Alum Dose (mg/L)	Mean Velocity Gradient G (1/s)	Alum Dose (mg/L)	Mean Velocity Gradient G (1/s)
1	25	500	10	500
2	10	10	45	500
3	45	500	45	350
4	25	10	10	350
5	45	10	25	500
6	10	350	25	10
7	10	500	45	10
8	25	350	10	10
9	45	350	25	350

To ensure that the pilot plant clarifiers were stable after dose and mixing intensity changes all filter runs commenced twenty-four hours after process changes were made.

3.3 Filter Polymer Dose and Rapid Mix

The third stage of the experiment used the best overall-performing polymer from the initial experiments to test filter performance of full-scale clarifier effluent water. It was decided to use the full-scale alum clarified water as this is a very stable filter influent source and would introduce less error over the eighteen one day runs than trying to match the pilot plants clarifiers to perform similarly.

3.3.1 Experimental Design

Using only the polymer Pol E-Z 652, a range of doses and velocity gradients in the polymer flash mixer were investigated. Three doses and three mixing intensities were tested and replicated; the experimental design is shown below in Table 4.

Table 4: Pol E-Z Dosing and Rapid Mixing Experimental Design

Randomized Trial Number	Pol E-Z 652 Dose (mg/L)	Velocity Gradient G (1/s)
1	0.04	1100
2	0.04	400
3	0.03	400
4	0.03	400
5	0.02	1100
6	0.04	700
7	0.02	700
8	0.03	1100
9	0.03	700
R1	0.04	1100
R2	0.04	400
R3	0.03	400
R4	0.02	400
R5	0.02	1100
R6	0.04	700
R7	0.02	700
R8	0.03	1100
R9	0.03	700

For the period of these filter runs the raw temperature ranged from 10 to 15 degrees Celsius, with raw turbidities of 5 to 57 NTU. Alum dosing ranged from 55 to 70 mg/L and the primary polymer was quite constant at 0.25 mg/L.

This alum dose resulted in a stable 7.1 to 7.3 pH range for the pilot filter influent. During this time the full-scale clarifier effluent or pilot filter influent water was very stable at 1 NTU with particle counts (>2μm/mL) ranging from 1500 to 2000.

4.0 Results and Discussion

With the broad range of variables examined and the massive amounts of data collected, it becomes impossible to analyze all theoretical combinations and variable correlations, so trends were examined showing the critical parameters.

4.1 Initial Polymer Testing

The primary criterion for determining the polymers performance was the use of particle count, flow, headloss, and turbidity data. Only the best-performing filter run summaries for each of the five tested polymers will be shown in this section. The remaining data is in Appendix C.

4.1.1 Nalco 8100 1.0 mg/L

Very little information was provided on the characteristics of the Nalco polymer. However, the high dose range suggested by the manufacturer suggests a low molecular weight. Alternatively the polymer itself may have a high molecular weight and the emulsion supplied by the manufacturer may have a very low percent activity. The Nalcolyte 8100 performed the better in terms of particle count removal and filter effluent turbidity with increasing doses. At the highest dose tested of 1.0 mg/L some of the best particle counts of the entire experiment were observed, however, the run ended due to terminal headloss in just less than 40 hours. Total filtrate particles dropped to below fifty within less than three hours of starting the filter run and remained low for the duration of the run. The turbidity trend followed total particle counts very closely as can be seen by comparing Figure 4 and Figure 5. This was true for both the control and polymer results. Turbidity quickly dropped to 0.05 NTU and slowly dropped over the rest of the filter run to 0.03 NTU.

Comparing the headloss profiles for the Nalco run and the control it can be seen that the headloss development occurred almost entirely in the anthracite layer with the Nalco. As the headloss profile for the control filter runs did not significantly differ through the course of these experiments, the polymer runs will all be compared to a representative Figure 7. This indicates the formation of a floc that was not passing easily through the pore spaces of the anthracite layer and the mechanism of removal was essentially straining at the upper layer of the media. This hypothesis is further supported by the relatively linear headloss curves above the boundary with a sharp increase at the boundary. This same pattern is evident in the control filter although to a lesser extent, with most of the removal occurring at the upper layer of the media. The headloss profile shown for the Nalco is consistent with a high molecular weight polymer (Stump and Novak 1979).

The flow rate through the filter dropped off sharply after the first day, losing one third of the flow after only one day and eighty percent of the flow after forty-five hours. This massive reduction is well outside the potential margin of error and is significant, not being considered acceptable in terms of full-scale performance.

The lower doses of Nalcolyte tested, 0.05mg/L and 0.1 mg/L were almost completely ineffectual in turbidity and particle removal, in fact performing worse than control with little development of headloss or reduction in filtration rate greater than the control.

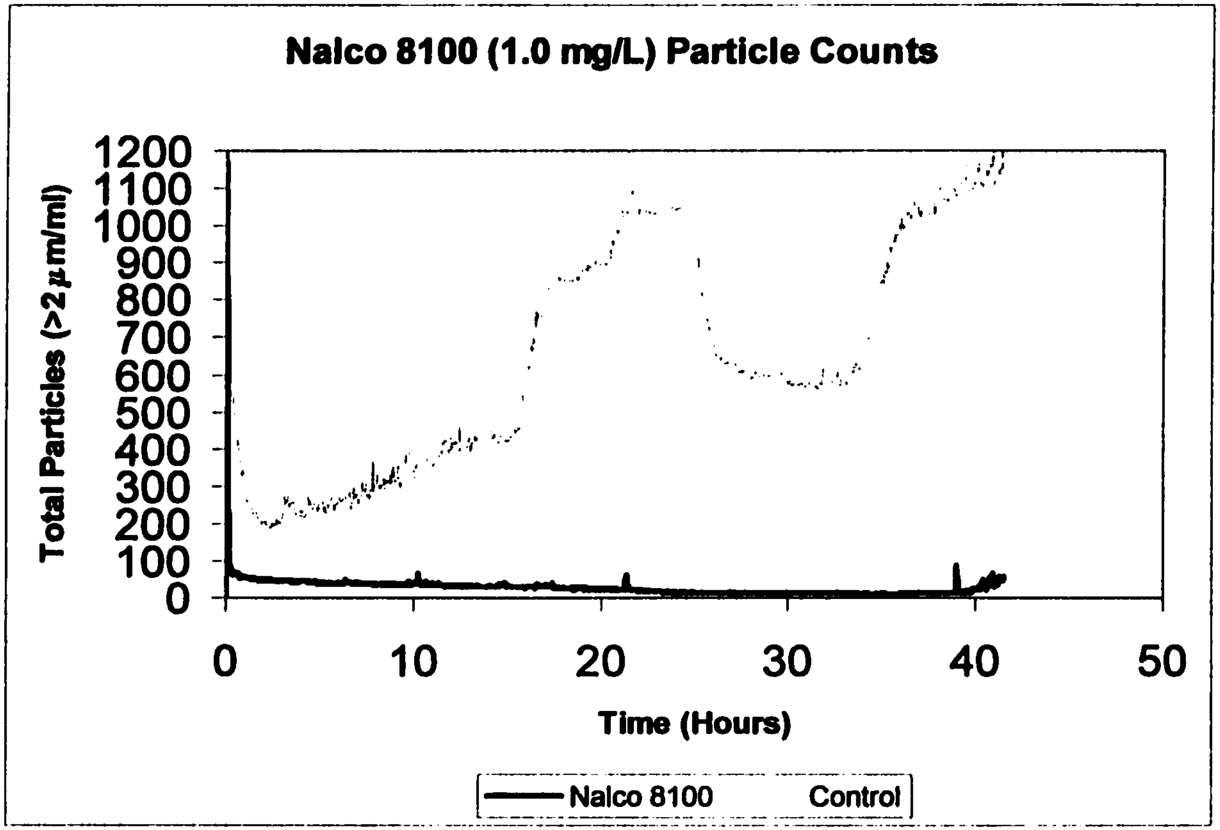

Figure 4: Nalco 8100 (1.0 mg/L) Particle Counts

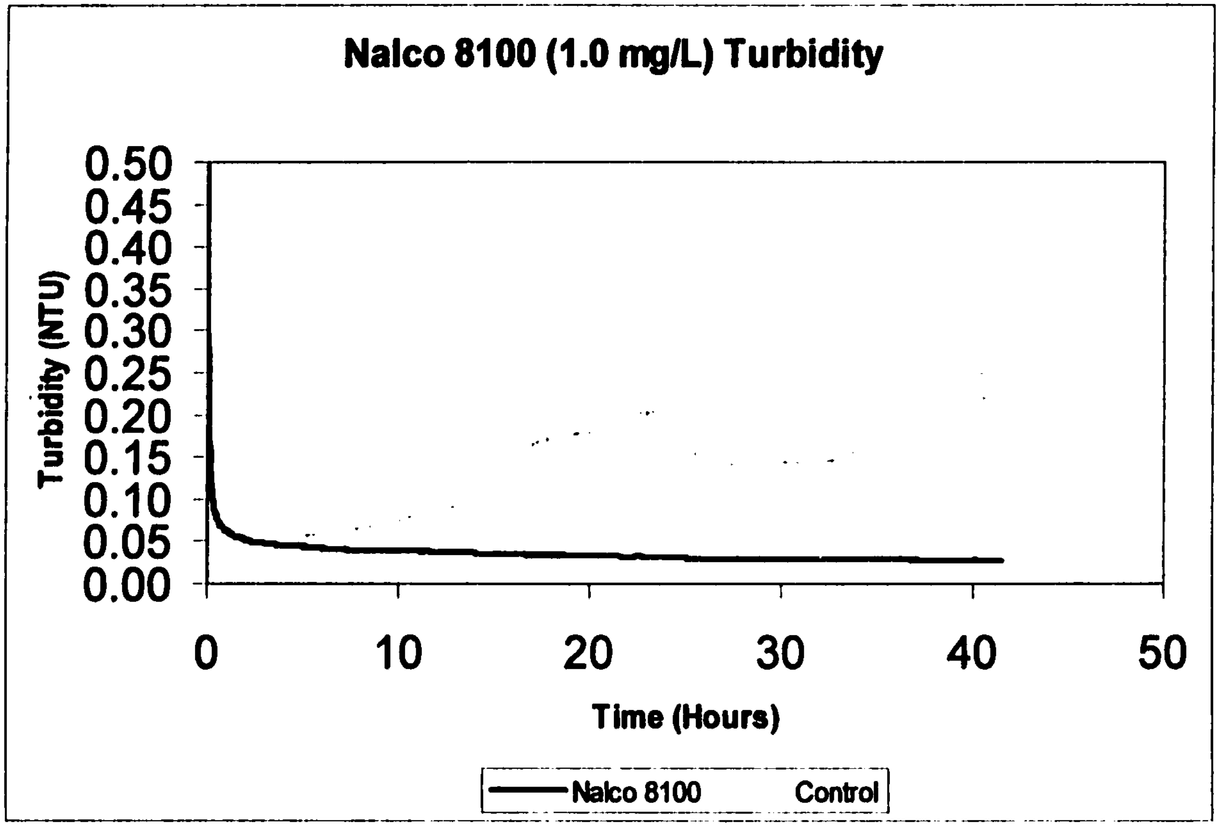

Figure 5: Nalco 8100 (1.0 mg/L) Turbidity

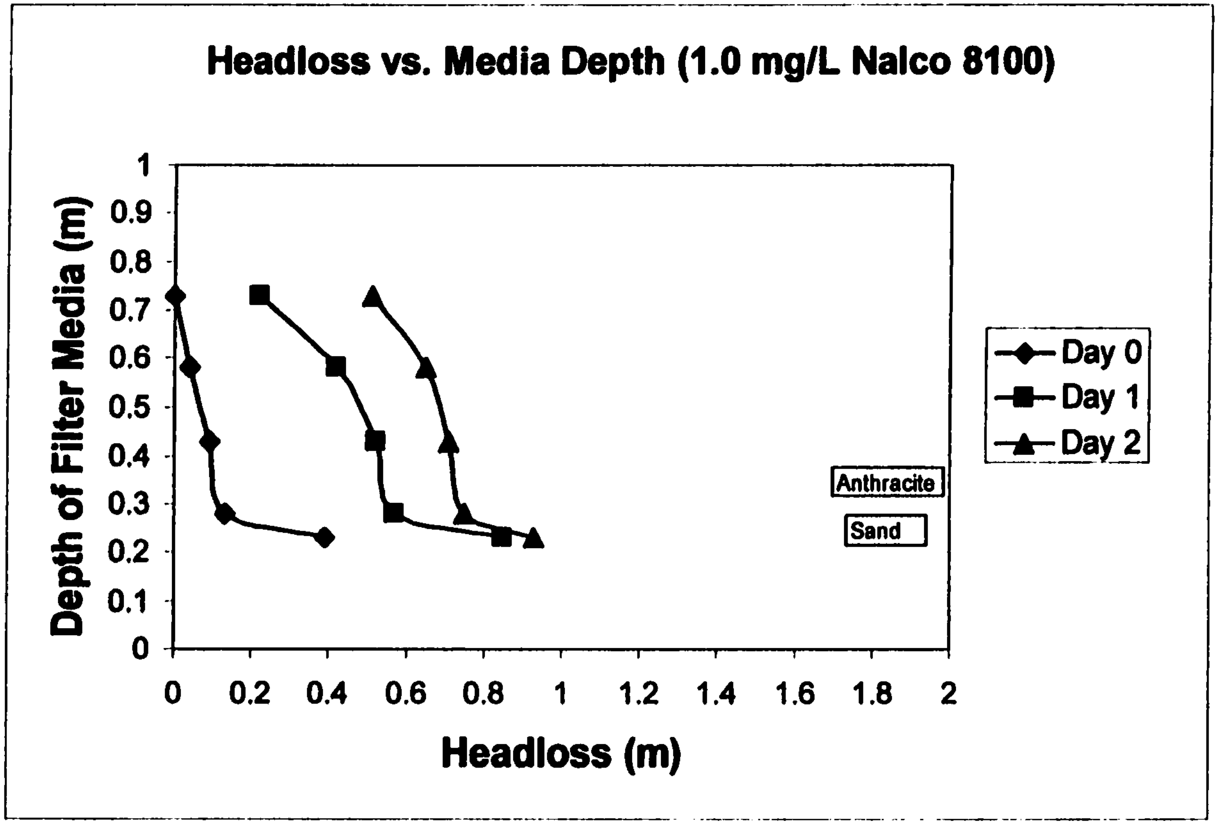

Figure 6: Nalco 8100 (1.0 mg/L) Headloss

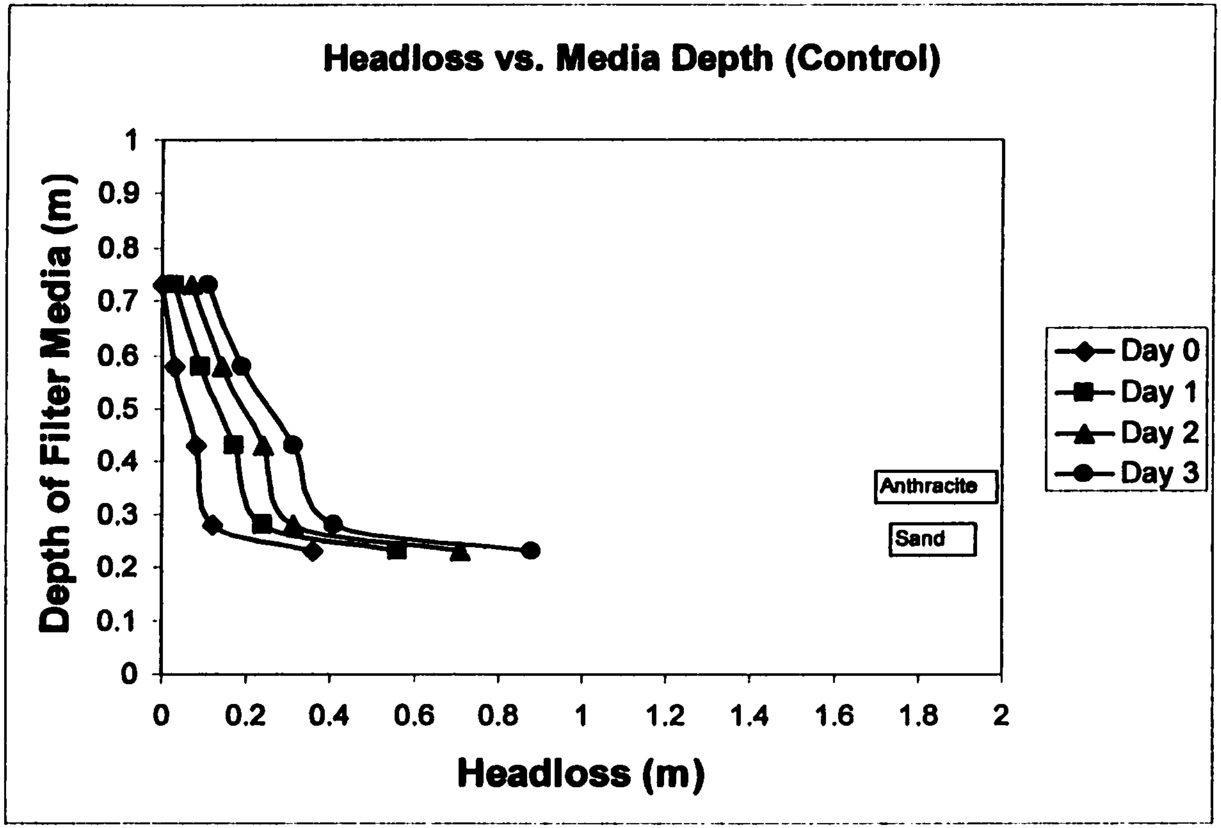

Figure 7: Control Filter Headloss

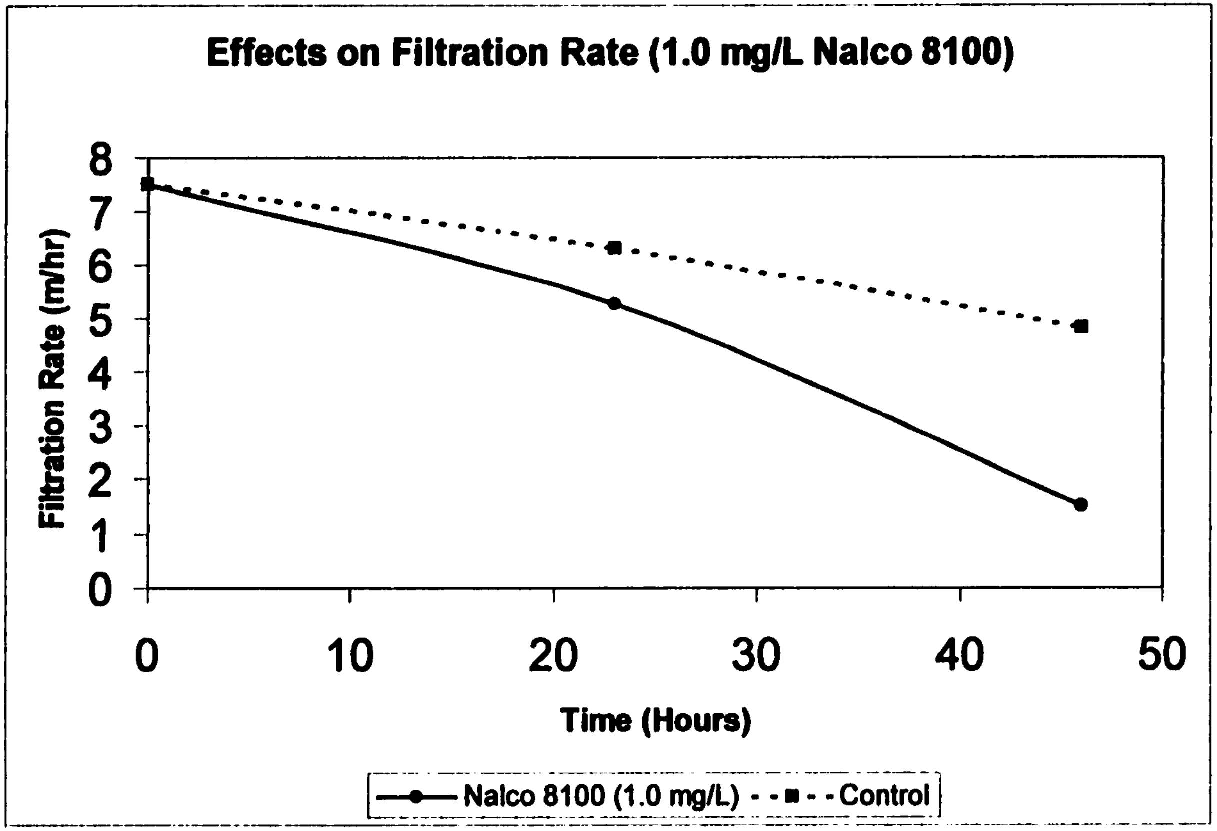

Figure 8: Nalco 8100 (1.0 mg/L) Filtration Rate

4.1.2 Pol E-Z 652 0.02 mg/L

The Pol E-Z performed consistently well as compared with the other polymers tested. At a dose of 0.02 mg/L filtrate particle counts dropped to the 100 particles per mL almost immediately and decreasing steadily through the rest of the run reaching 35 after three days. Turbidity similarly performed well, quickly dropping to 0.05 NTU and decreasing similarly with particle counts over the filter run to 0.03 NTU, near the limits of detection and accuracy of the meter. This pattern of turbidity is identical for the Pol E-Z 0.04 mg/L run and the two day Nalco run and demonstrates how additional information on filter performance can be provided by the collection of particle count information. Although lower particle counts were seen with the higher dose of Pol E-Z (down to 30/mL at the end), this run terminated at fifty hours due to headloss.

As this polymer is non-ionic, the likely mechanism of attachment is interparticle bridging. Despite being high molecular weight, as described by the manufacturer, the headloss development was quite consistently distributed through the depth of the filter as seen in Figure 11. This suggests that the entire depth of the media was being used in the removal of suspended particles relatively evenly. The filtration rate was maintained with only a twenty percent loss after twenty-four hours and thirty five percent after forty-eight hours. By the end of the filter run, however, this had increased to almost seventy-five percent with the control filter losing only twenty five percent by the end of the run.

With the higher dose tested, the headloss in the upper layers of the media was substantially increased and the filtration rate had dropped to a third of the initial flow after two days. This, accompanied with the lower particle count results is consistent with the use of high molecular weight polymers being used as a filtration aid (Zhu et al. 1996) where only turbidity was monitored with headloss. It should also be noted that the mixing intensity chosen to test all of the polymers, $G = 700$, the optimum found in the Zhu et al. study was chosen for a low molecular weight polymer. As Pol E-Z is a high molecular weight polymer, it is likely that the optimal mixing intensity would be higher, up to 1000 s^{-1} (Stump and Novak, 1979).

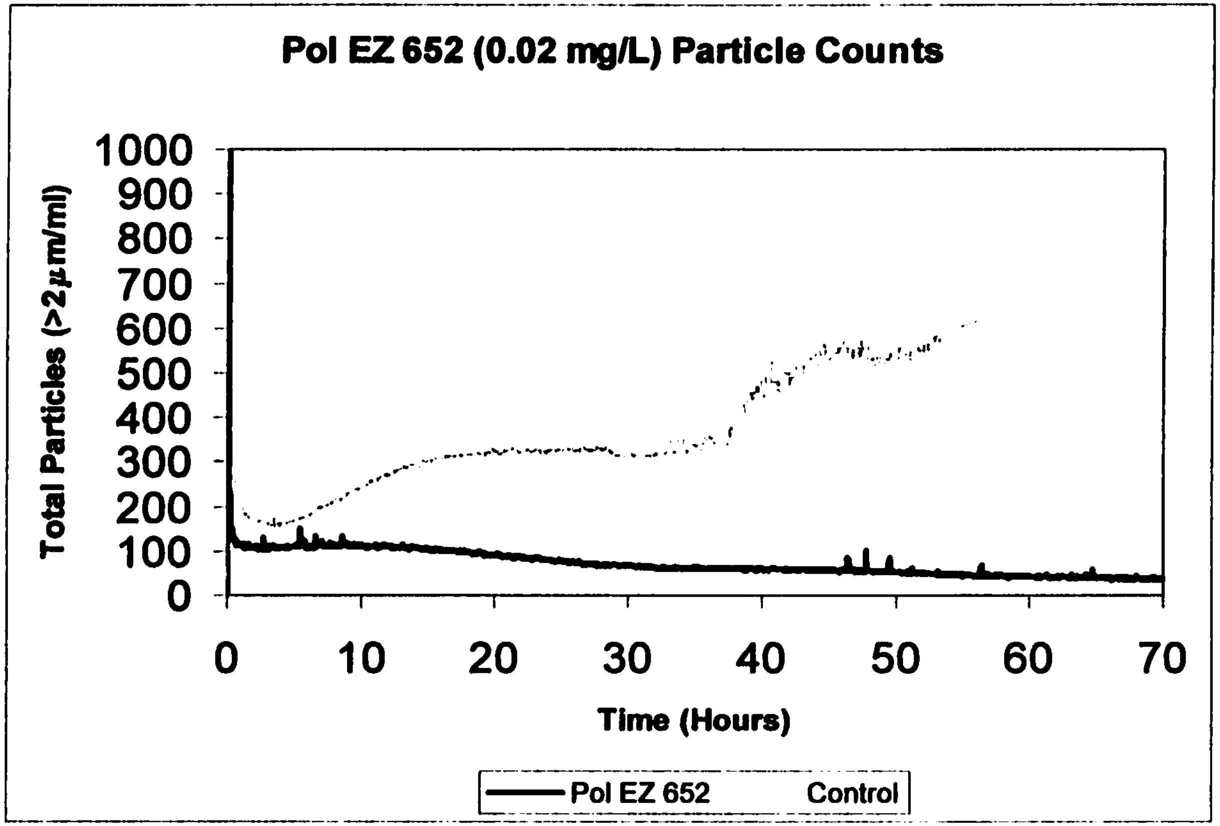

Figure 9: Pol E-Z 652 (0.02 mg/L) Particle Counts

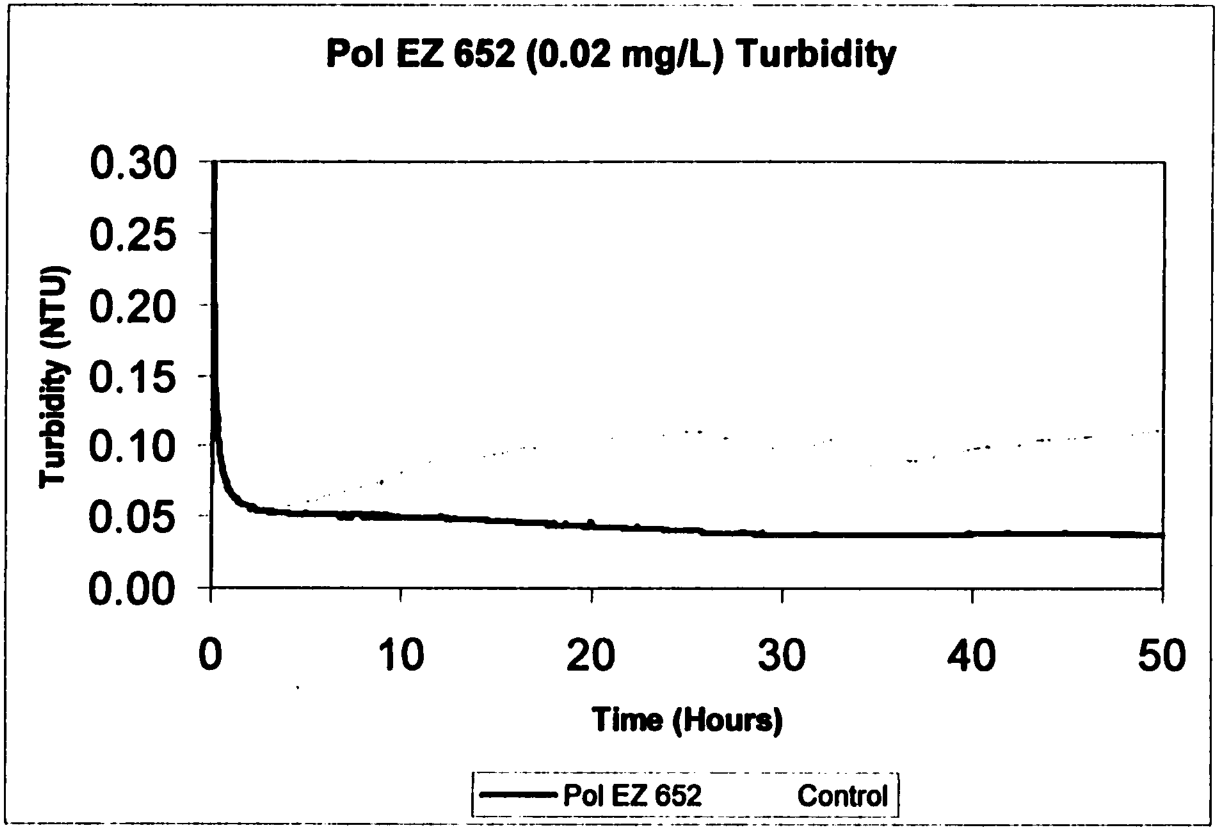

Figure 10: Pol E-Z 652 (0.02 mg/L) Turbidity

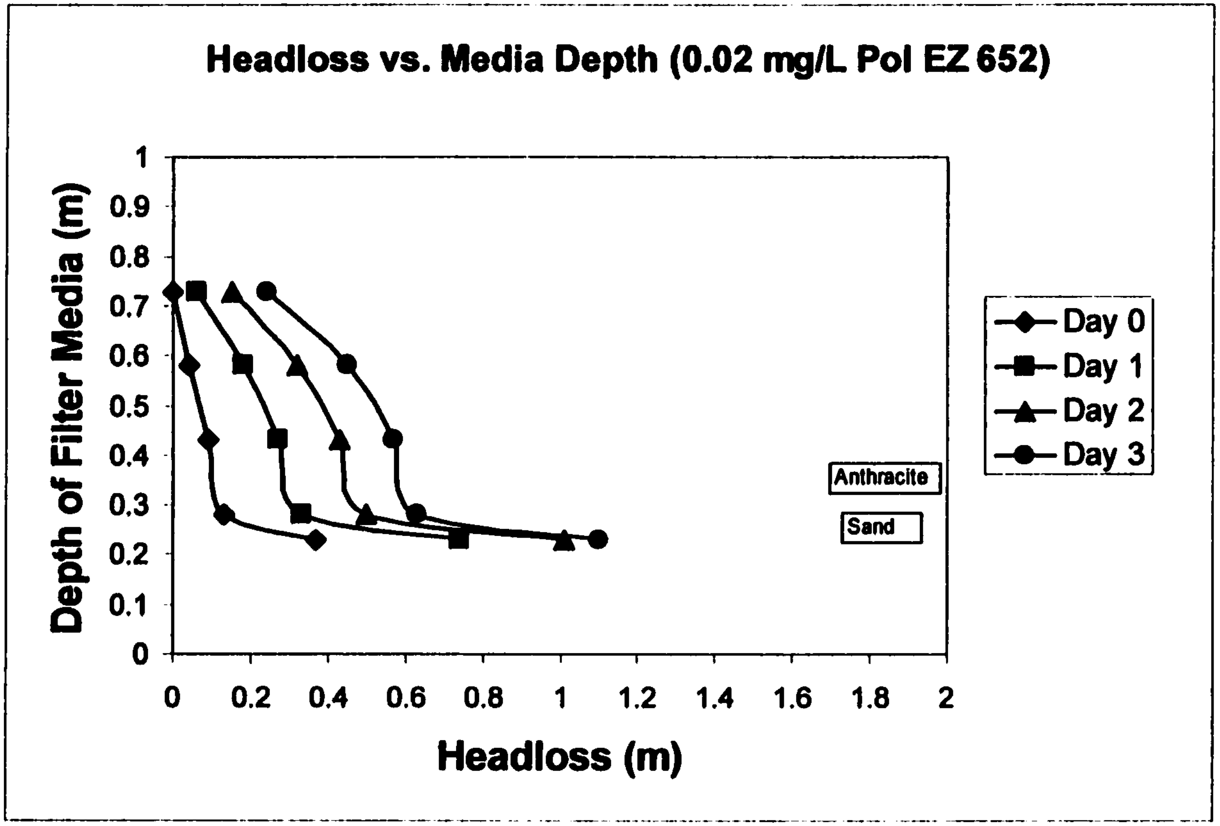

Figure 11: Pol E-Z 652 (0.02 mg/L) Headloss

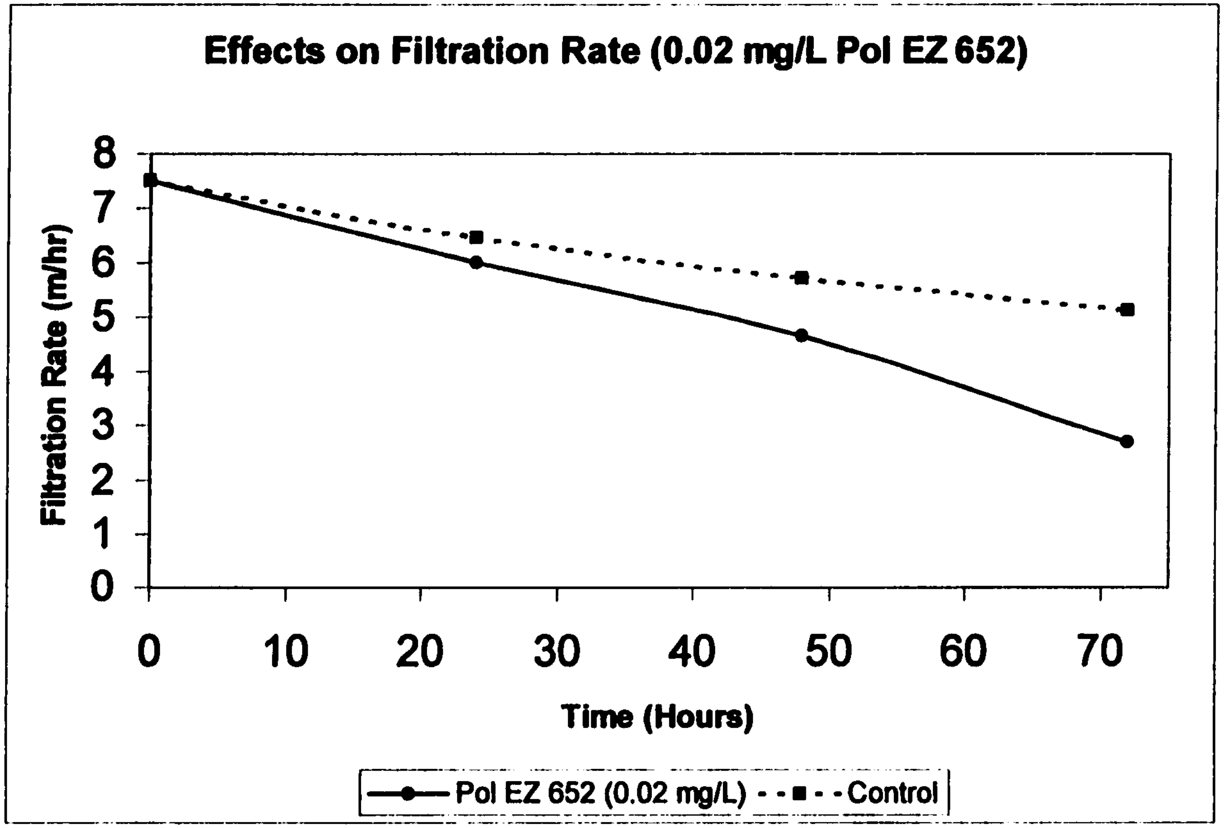

Figure 12: Pol E-Z 652 (0.02 mg/L) Filtration Rate

4.1.3 Catfloc CL 0.25 mg/L

The Catfloc CL did not perform well in terms of particle or turbidity removal. This finding is contrary to the prior pilot study done at this plant using lime softened water measuring filter performance by turbidity and headloss (Zhu et al. 1996). There it was found that a similar polymer with a low molecular weight and high cationic charge with high charge density produced the best quality filtrate. At the optimum doses found in that study, 0.01 mg/L no difference could be seen between control and polymer tests in preliminary runs.

The best results with Catfloc CL in this study were found at a dose of 0.25 mg/L. At this dose, particle counts reached a minimum of 160/mL after one day, stabilized and deteriorated over the rest of the three-day filter run. Filtrate turbidity stabilized quickly at 0.05 NTU, however, began to increase after forty-eight hours breaking through 0.1 NTU at fifty-five hours.

The reduction in filtration rate with the Catfloc was very small even at the end of the run, with only a 15% difference between the control filter and the Catfloc filter. Headloss development was uniform through the media similar to the control run, with only slightly higher values. This may potentially indicate an even higher dose would be required to get the target particle performance results, as there is some additional room for reduced filtration rates.

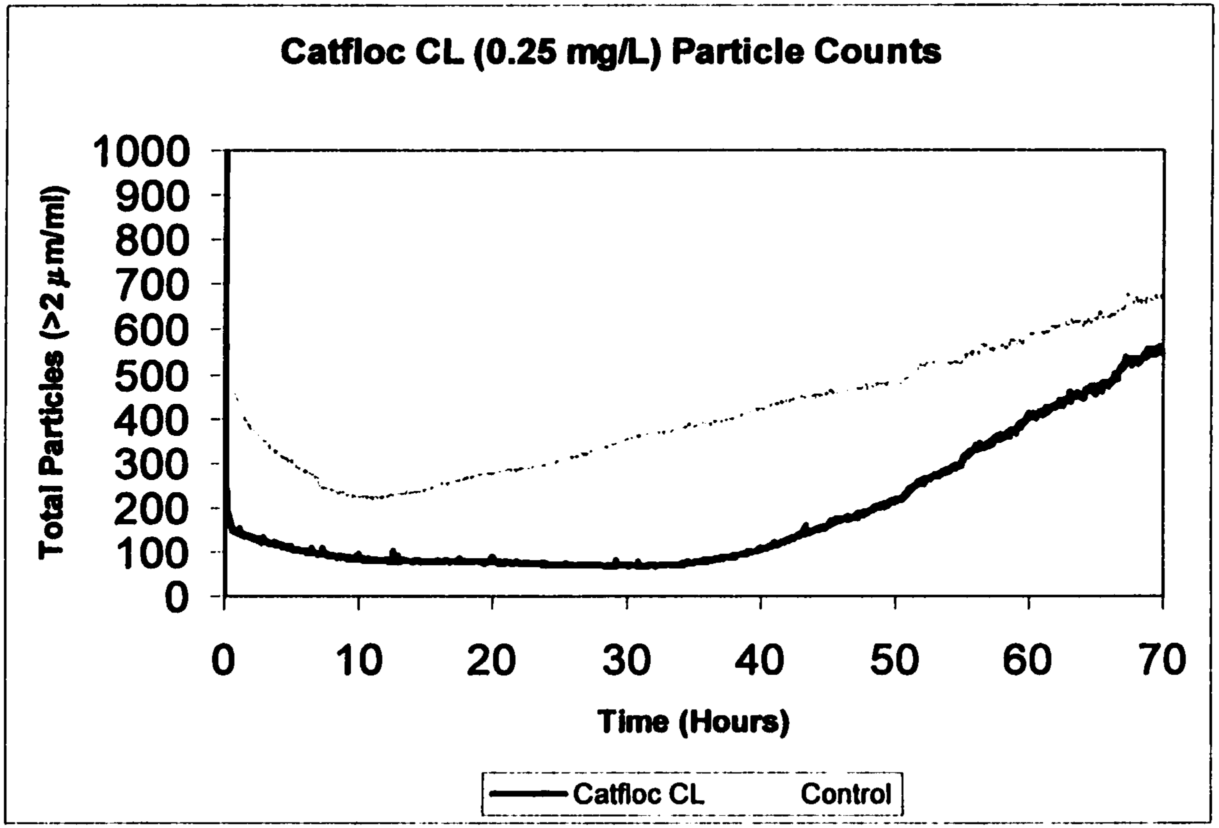

Figure 13: Catfloc CL (0.25 mg/L) Particle Counts

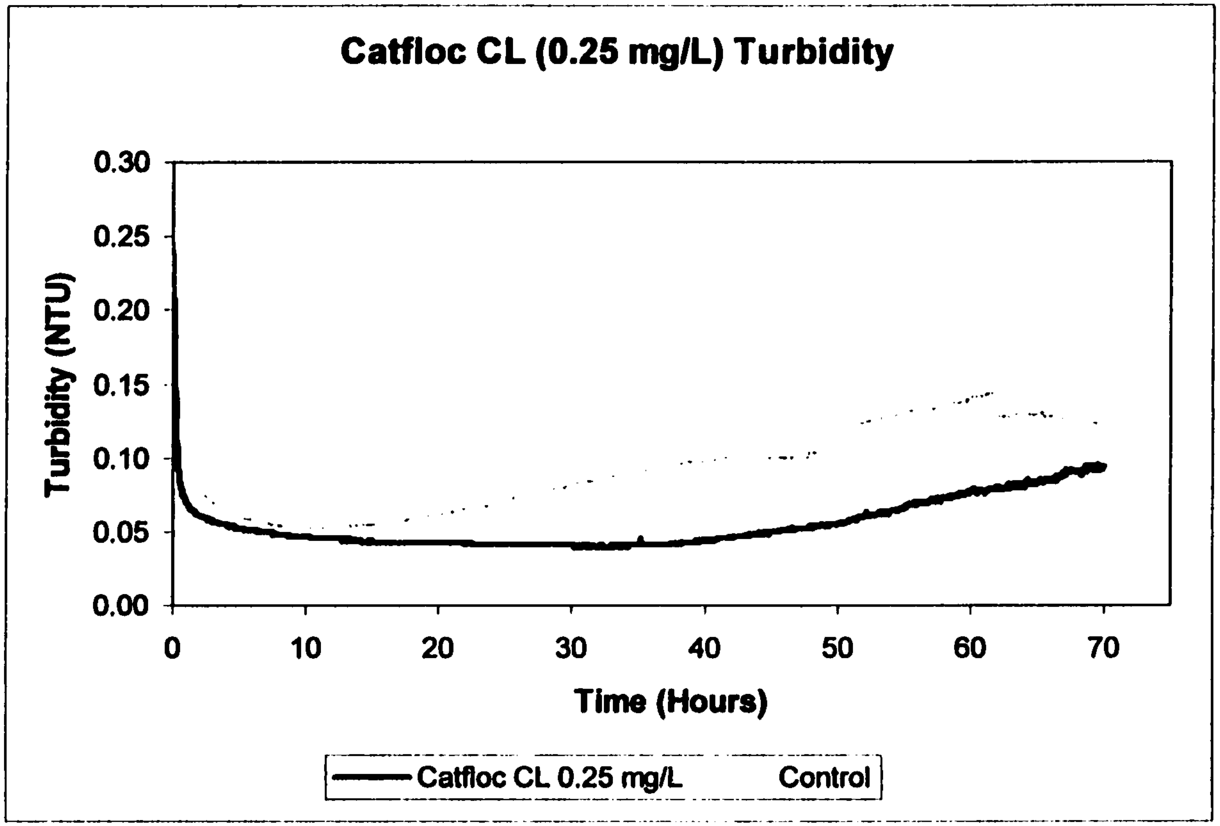

Figure 14: Catfloc CL (0.25mg/L) Turbidity

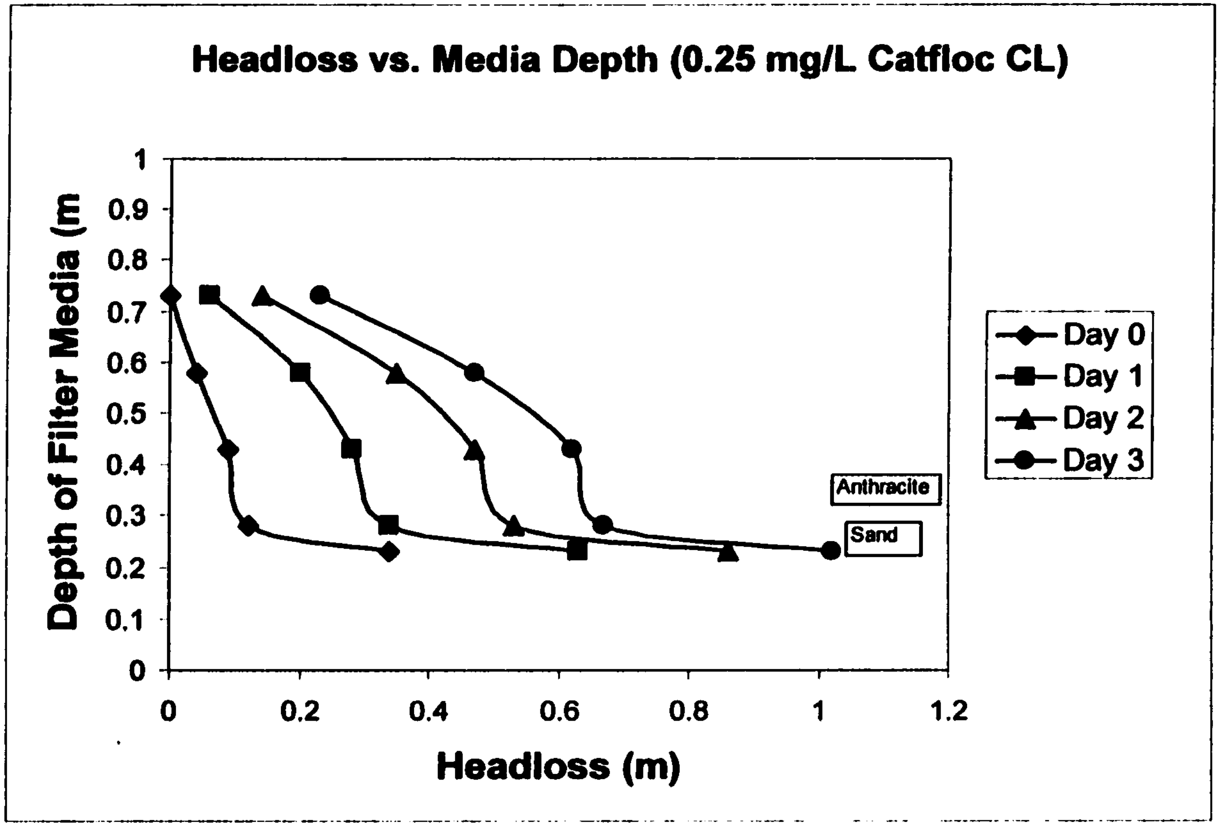

Figure 15: Catfloc CL (0.25 mg/L) Headloss

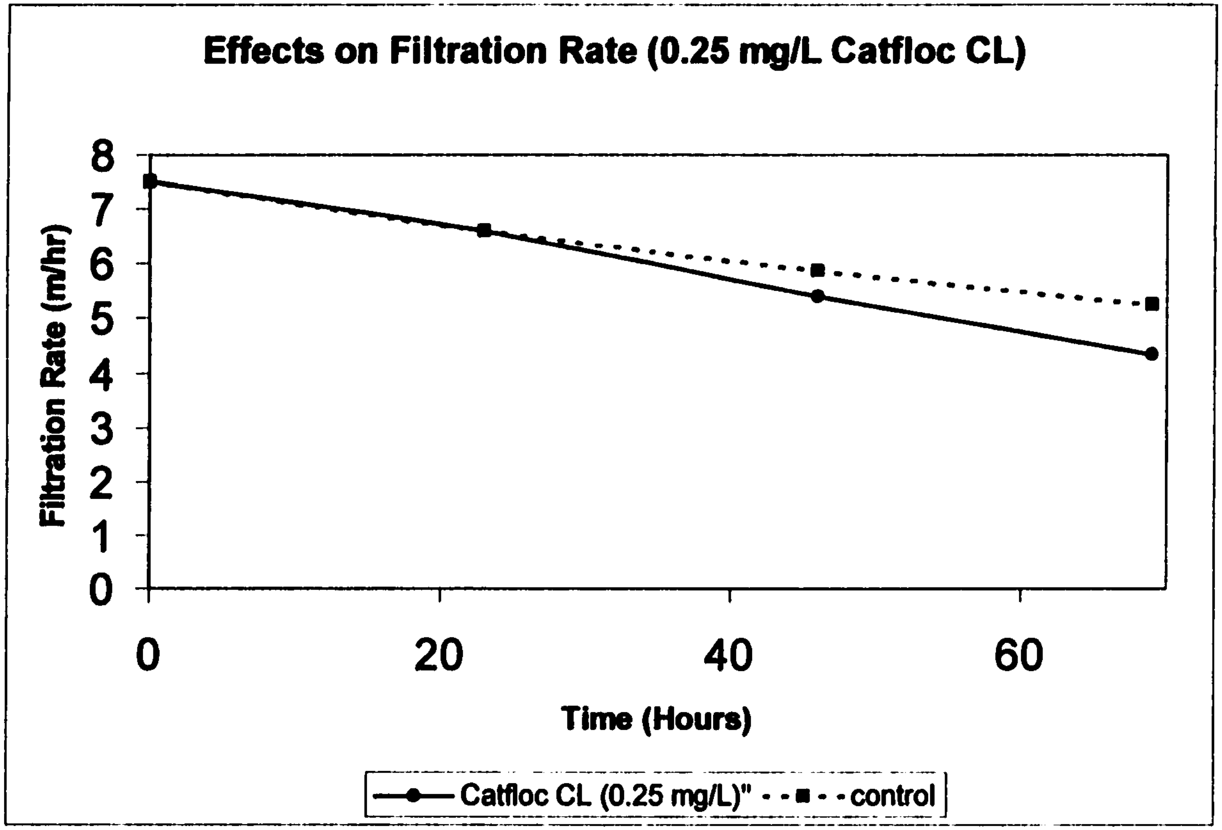

Figure 16: Catfloc CL (0.25 mg/L) Filtration Rate

4.1.4 LT 7996 0.25 mg/L

The best-performing filter run with LT 7996 was at a dose of 0.25 mg/L. The particle counts quickly dropped to 200 per mL and there was a decreasing trend across the filter run with the counts reaching a low of 130 at the end. Turbidity followed a similar trend dropping below 0.1 NTU within two and a half hours and reaching 0.06 NTU by the end of the run. The LT 7996 has very similar characteristics to the Catfloc CL with low molecular weight, cationic, and having high charge density with the same DADMAC monomer. The purpose in testing two such similar polymers was to compare the differences in manufacturer and their polymer descriptions. Calgon makes Catfloc, while the LT 7996 is made by Allied Colloid. There appears to be consistent results between the two polymers. At the lower doses of LT 7996 tested, 0.15 mg/L and 0.05 mg/L the polymer addition resulted in worse performance than the control for both particle counts and turbidity, with the two measurements trending closely.

The headloss and filtration rate curves for the LT7996 are also very similar to the Catfloc CL with relatively uniform distribution of headloss through the depth of the filter media and little reduction in filtration rate as compared to control.

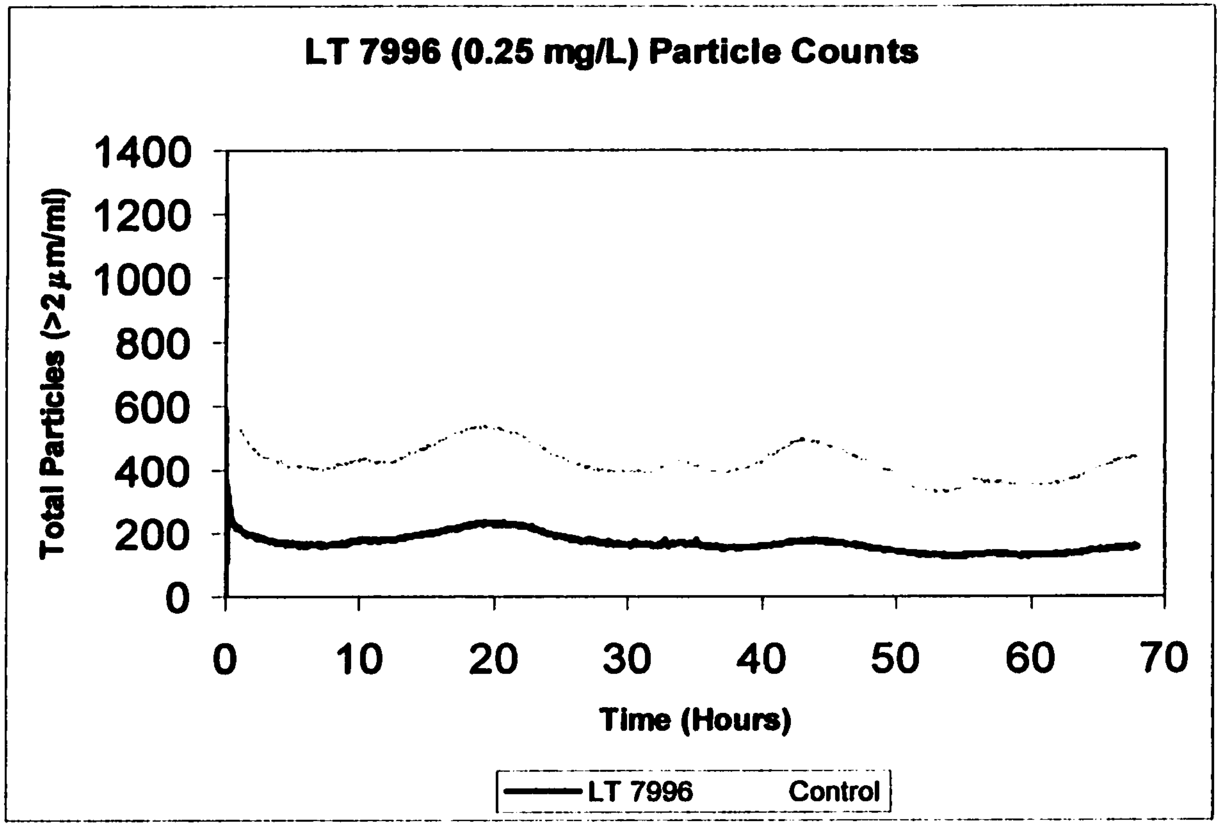

Figure 17: LT 7996 (0.25 mg/L) Particle Counts

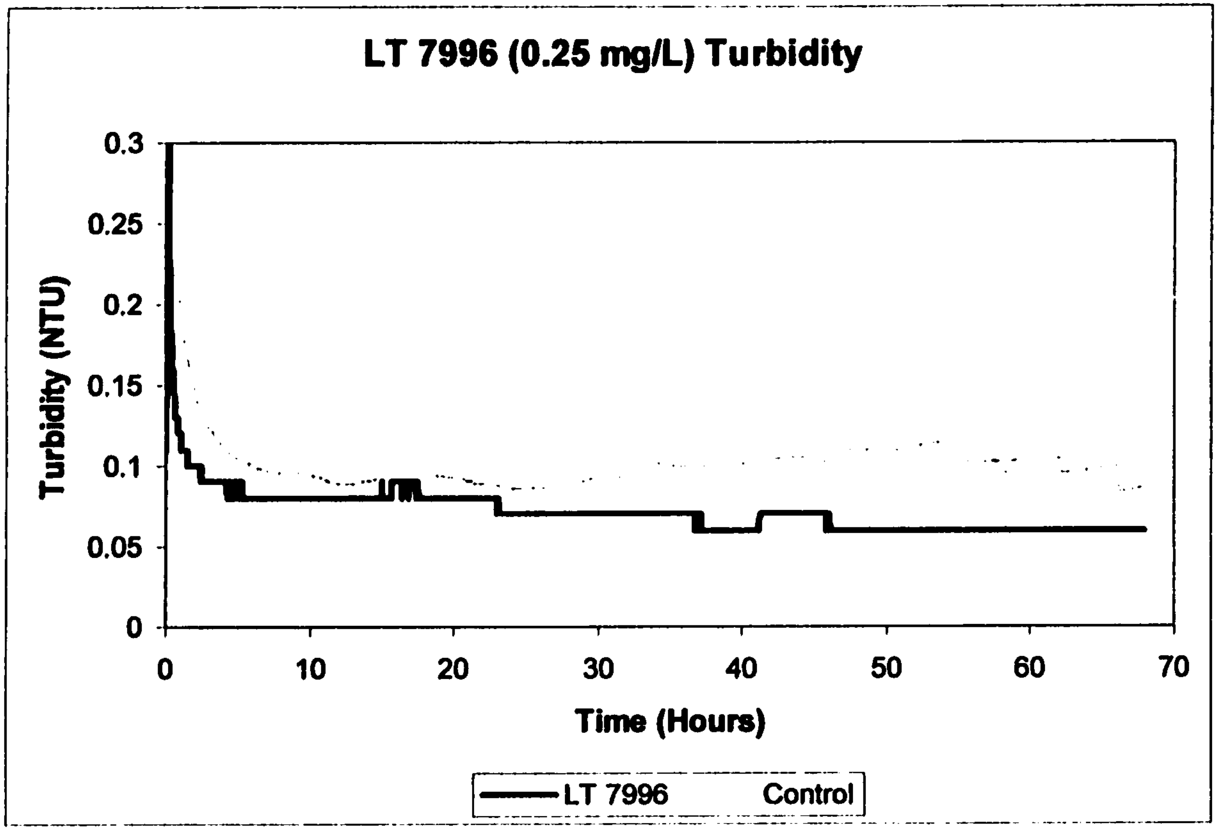

Figure 18: LT 7996 (0.25 mg/L) Turbidity

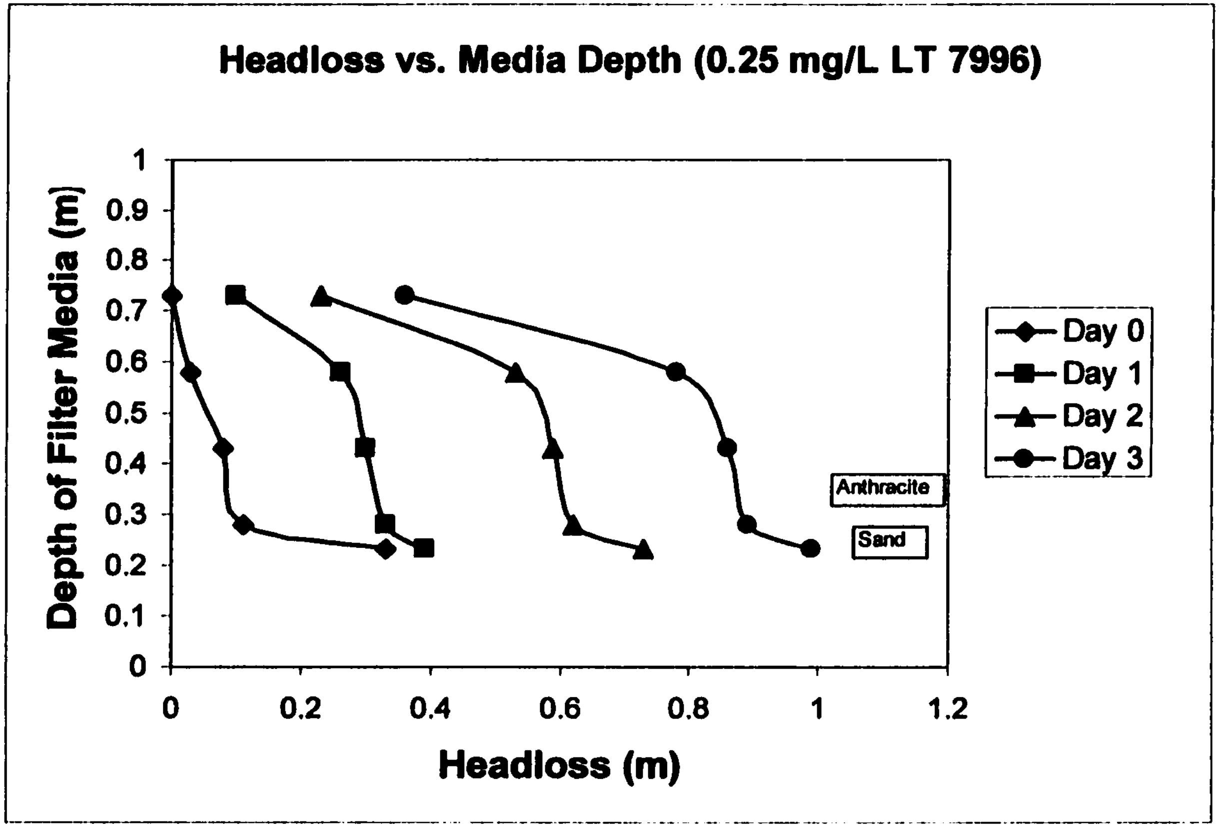

Figure 19: LT 7996 (0.25 mg/L) Headloss

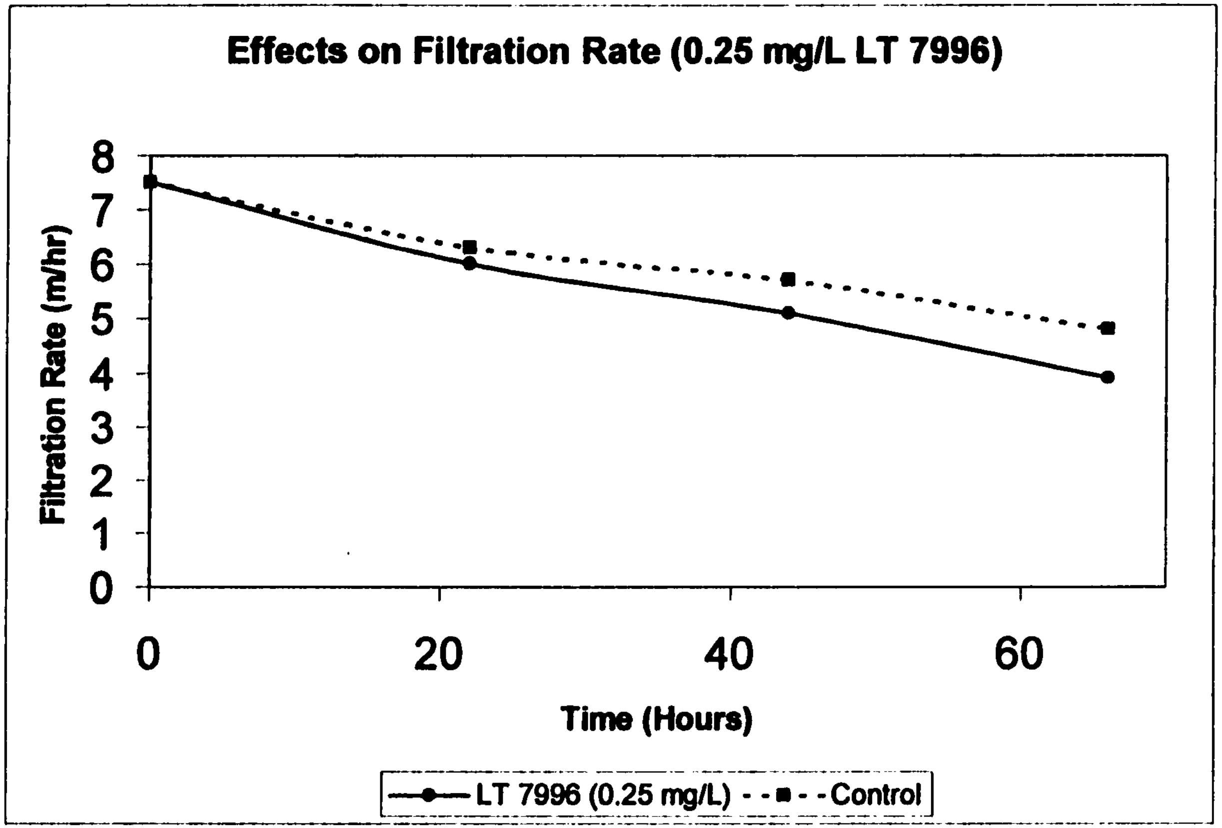

Figure 20: LT 7996 (0.25 mg/L) Filtration Rate

4.1.5 Percol LT 24 0.01 mg/L

At the lowest tested doses of LT 24, the filter polymer runs were either not significantly different from or were significantly worse than the control runs. Although the particle counts initially dropped to 85, by the ten hour point they had begun to increase and were at around 800 for the duration of the filter run as can be seen in Figure 21. Once again turbidity followed a similar pattern initially ripening to 0.05 NTU and then increasing at the 10 hour mark to stabilize at 0.10. There was a turbidity breakthrough at 55 hours (see Figure 22) that was not seen on the particle count data.

The headloss data, Figure 23, shows that the majority of headloss was occurring through at the top of the anthracite layer accompanied by a significant reduction in the filtration rate of fifty five percent after forty eight hours. The loss in flow is considered significant in terms of the high degree of accuracy of the flow meters and the large relative difference between the control and filter polymer filters.

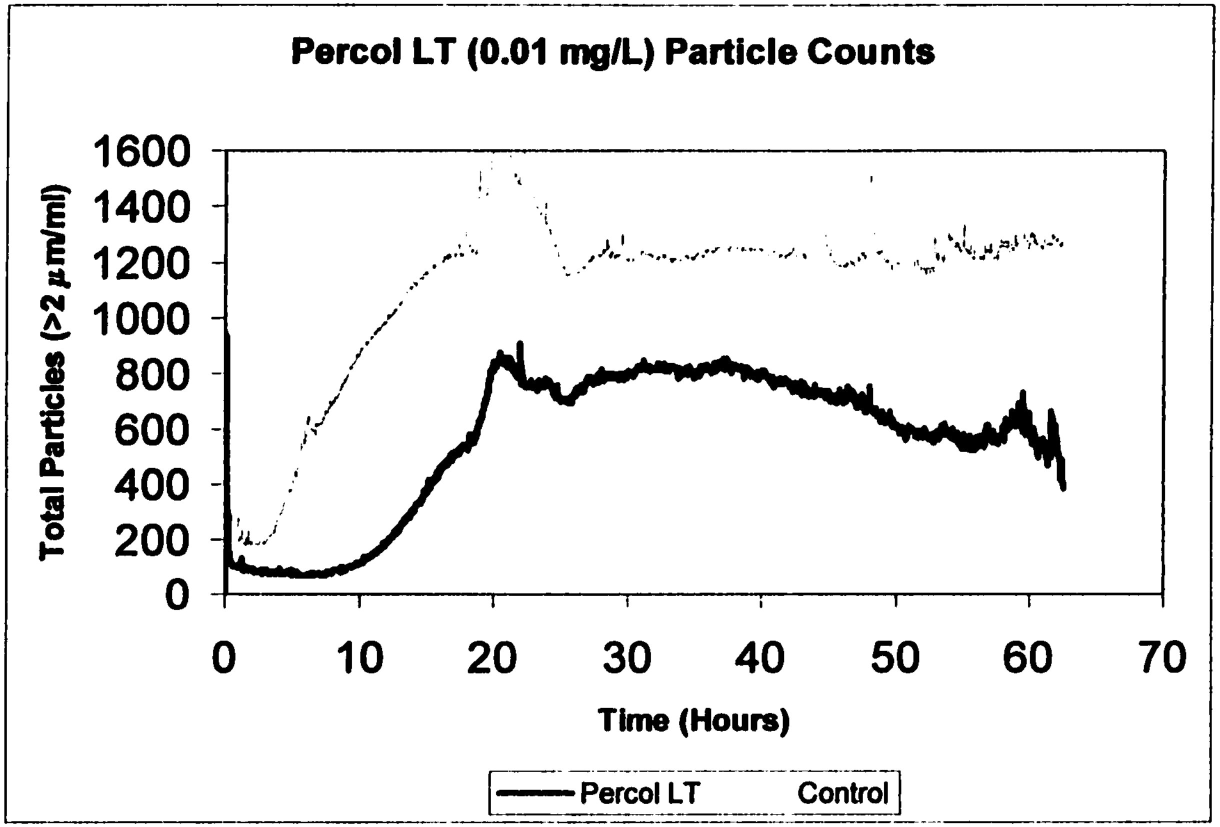

Figure 21: Percol LT 24 (0.01 mg/L) Particle Counts

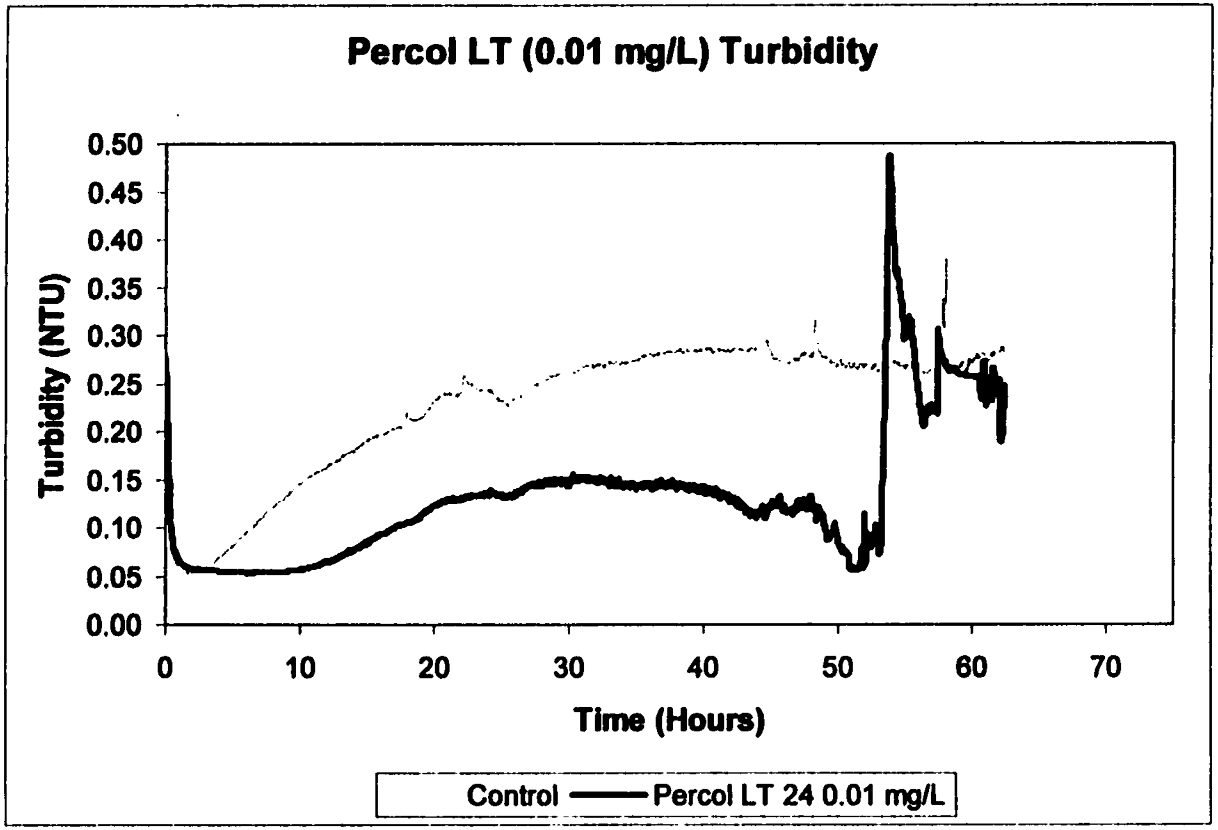

Figure 22: Percol LT 24 (0.01 mg/L) Turbidity

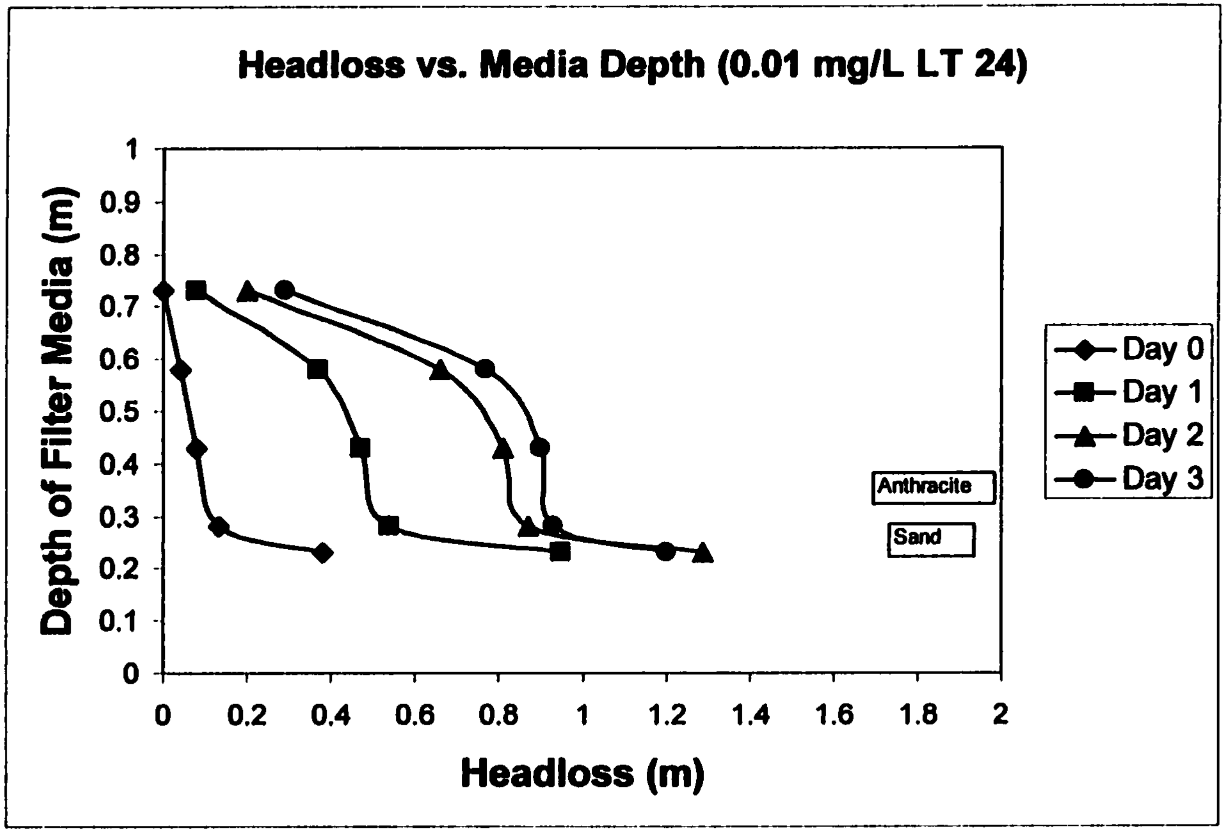

Figure 23: Percol LT 24 (0.01 mg/L) Headloss

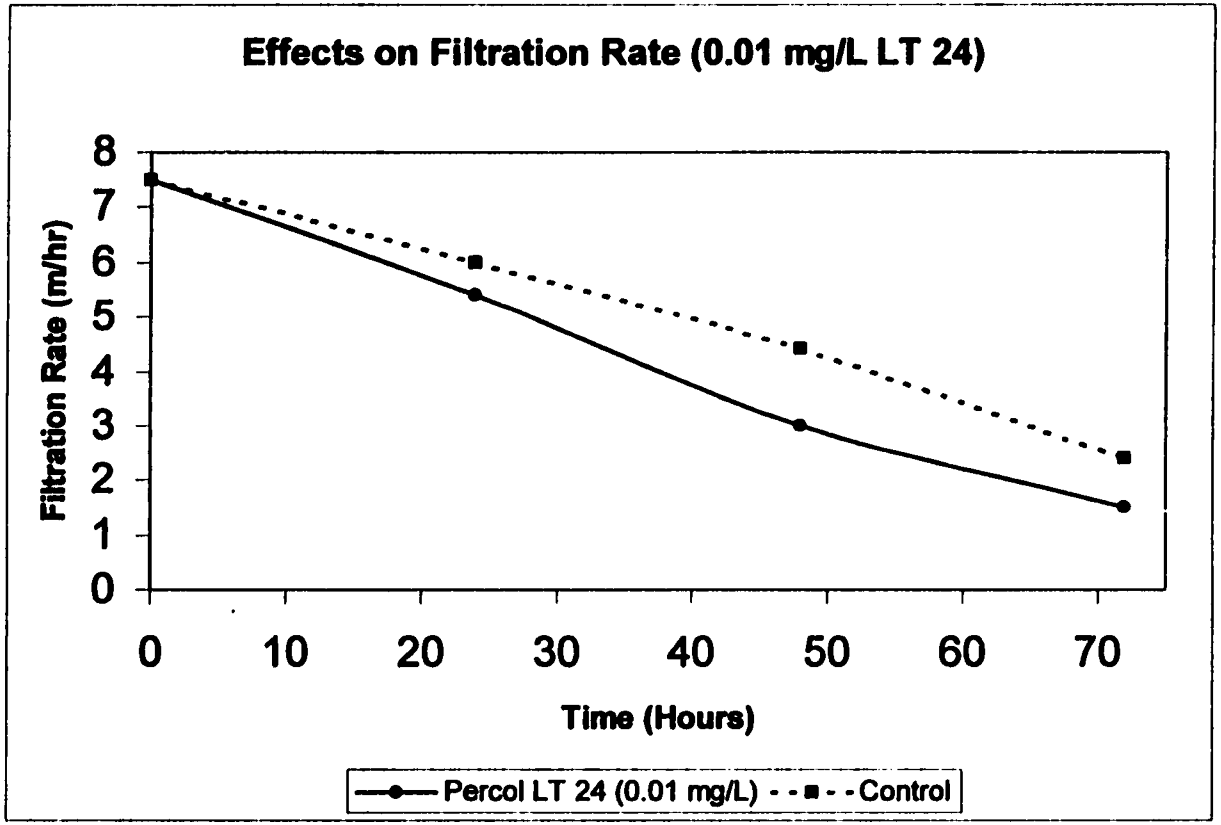

Figure 24: Percol LT 24 (0.01 mg/L) Filtration Rate

4.2 Initial Polymer Testing Summary

It could be seen in almost all of the polymer runs that the particle count data provided additional sensitivity when measuring filter performance. Filters that were performing similarly with respect to turbidity, such as the Pol E-Z and Nalco displayed significant differences in terms of particle counts. Additionally, as the filter polymer runs would often stabilize at the absolute low limit of the turbidity meters range, it becomes difficult to measure relative changes in performance without particle count data. It is likely that particle counters will provide additional quality control in optimizing filters rather than replacing turbidity as a drinking water standard, however, as it is possible to have a turbidity breakthrough without seeing the impact on particle counts as was seen in the LT 24 filter polymer run. This result has important implications for water treatment as most previous studies on filter polymer and effluent quality have been based on turbidity.

The best overall performing polymer from these results was found to be the Pol E-Z 652. Particle count and turbidity data for the filter effluent was consistently low without substantial impairment of the filtration rate over the length of the filter run. It appears as though the major polymer particle interaction is interparticle bridging with polymer loops extending into solution.

Non-ionic polymers may contain both positive and negative charged groups resulting in a net zero charge on the polymer. As the Pol E-Z is a non-ionic polymer, the dominance of this mechanism would be consistent with the literature if the clarifier carryover onto the filters is a destabilized floc (Stump and Novak, 1979). Essentially the destabilized particles flocculate together with the addition of the filter polymer to form a larger, filterable particle. A summary figure showing the results for the lowest filter effluent particles for the different polymers studied in this section is shown below in Figure 25. From this figure it is immediately obvious that filter polymer is an effective means of reducing filter effluent particle counts by up to an order of magnitude as compared with the control. Theses values are the minimums stable counts shown over the best filter run with a particular polymer. The accompanying comparative Table 5 shows the minimum, estimated average values, and maximum values for those runs.

Table 5: Polymer Comparison

Polymer Name (Dose)	Estimated Mean Particle Counts	Maximum Particle Counts	Minimum Particle Counts
Catfloc CL (0.25 mg/L)	180	540	70
Nalcolyte 8100 (1.0 mg/L)	25	85	10
Percol LT-24 (0.01 mg/L)	600	900	70
Percol LT-7996 (0.25 mg/L)	165	230	125
POL-E-Z 652 (0.02 mg/L)	70	85	35
Control (no polymer)	640	1200	280

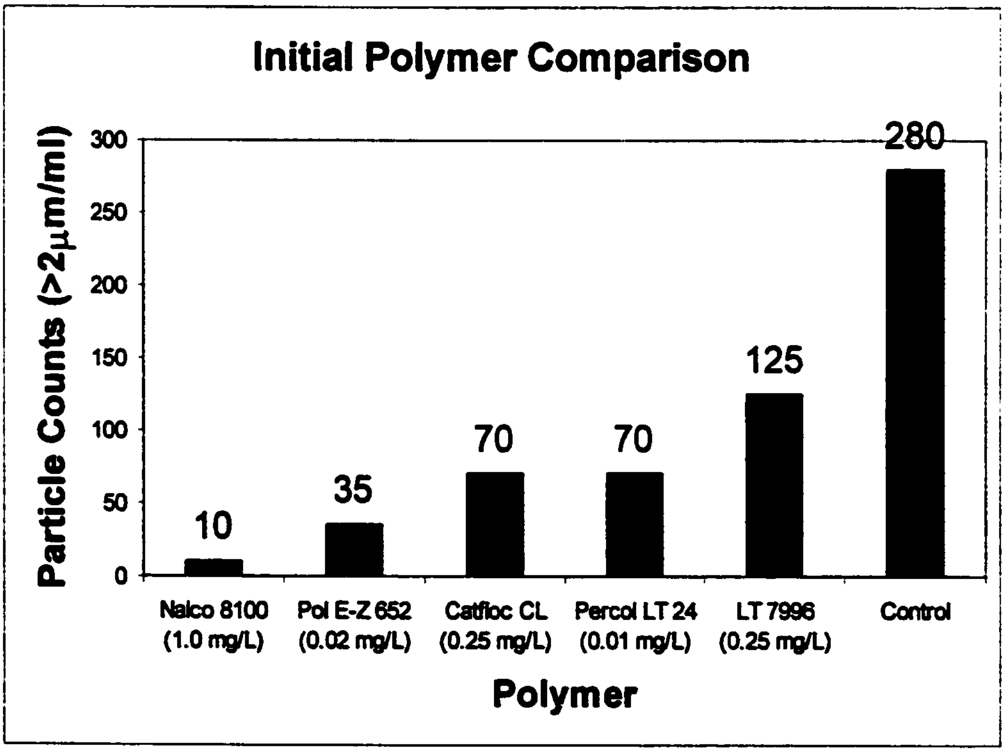

Figure 25: Estimated Mean Particle Count Comparison

Based on the results in this section and the findings of the (Zhu et al. 1996) study, it was decided to investigate the processes upstream in the water treatment process to attempt to consistently achieve filter effluent particle counts below 50 without achieving terminal headloss. In the Zhu paper, excellent particle removal was found with lime softened water using a low molecular weight, high charge density cationic polymer. This was determined to work because the majority of particles coming onto the filters had a net surface charge close to zero. In this study, it was hypothesized that interparticle bridging was suspected to be the dominant mechanism of attachment and charge neutralization was insignificant. Although this interaction between colloids and polymers is usually dominant with high molecular weight polymers (Tanaka and Pirbazari 1986), it has also been found applicable for low molecular weight polymers (Yeh and Ghosh 1981). To attempt to replicate these successful results with only alum clarified water it was decided to investigate the relationships between alum dosing and rapid mixing intensity and the resulting impact on the charges on particles to improve the filter performance.

4.3 Main Pilot Plant Results : Alum Dose & Rapid Mixing

As it was not possible to add filter polymer to the main pilot plant filters, the relative filter performance across the different changes in mixing intensity and alum dose were compared using clarifier effluent without any further chemical addition. Only one day filter runs were performed as it is possible to see the relative results between the runs during this period as well as developing a trend of how the particle counts and turbidity are performing. Although on control runs, the two trains performed similarly in terms of particle counts, during the one day experimental runs comparisons between the two trains was difficult as the runs did not replicate well. This is possibly due to minor changes in raw water quality in the times between the replications and sub optimal dosing of the alum. Clarifier turbidity and particle counts on both trains were consistently higher than the raw water during the pilot runs although this is not unusual for winter time operation of the full-scale plants.

4.3.1 Effects of Rapid Mixing

A summary of the rapid mixing and alum dosing results is shown below in Table 6. The figures which are the source of this data can be referred to in Appendix E. The average values mentioned in the following tables refer to estimated arithmetic means. As mentioned before, the entire water treatment process determines the nature of the particles going onto the filters. When the different mixing intensities were tested at a range of plausible alum doses, it was found that the best results in terms of particle counts and turbidity of the filtrate occurred at the higher velocity gradients. Of the best five filter run average effluent particle counts and turbidity, four were at the highest mixing intensity, G = 500 s^{-1}, and the fifth was at a mixing intensity of 350 s^{-1}. This result is independent of the alum dose. The best performing runs in terms of turbidity were not consistently the best performing runs as measured by particle counts. The overall best result was found at the highest alum dose tested of 45 mg/L and mixing intensity of 500 s^{-1}. A relatively stable filtrate with only 65 particles >2µm/mL resulted with the highest filter influent particle counts (18100). It is interesting to note that the filter influent turbidity was only 4.1 NTU, putting it in the best third of the runs for clarifier performance. This was also the best-performing run in terms of turbidity reaching 0.02 NTU. Both particle counts and turbidity dropped quickly, although the ripening peak was somewhat extended for turbidity, taking five hours to reach 0.02 NTU. Total particle counts reached a minimum of 45/mL three hours into the run and fluctuated around the mean for the duration.

The next best filter run in terms of particle counts occurred at a dose of only 10 mg/L and G of 500 s^{-1}. This dose was substantially below the 30 mg/L being fed full-scale. Although the particle counts were stable at 90 for the duration of the run, filtrate turbidity remained high at 0.10 NTU.

The low mixing conditions at a G of only 60 s^{-1} were generally poor. If the filtrate particle counts did stabilize, they did so at a very high absolute number. In all cases within the trains and across doses, the highest mixing intensity produced lower filter effluent particle counts and were more stable, that is likely to maintain that level of performance. This trend was not as universal for the turbidity, remaining consistent with the particle count trend only at the higher doses of 25 mg/L and 45 mg/L.

The concentration of particles in the filter influent stream does not seem to be directly related to the filter performance. The trend, especially in terms of particle counts is actually that there is an inverse relationship. That is, independent of the alum dose, with the highest mixing intensity, there are higher clarifier effluent particle counts than with the lowest mixing intensity.

The importance shown in these filter runs of the rapid mixing process implicates charge neutralization as a key mechanism of destabilization in the coagulation process for this source water. Quick dispersion of the alum is essential for charge neutralization to occur due to the short life span of the hydrolysis products of the dissociation of alum. This finding is consistent with the literature on the rapid mixing process (Amirthatajah, 1991; Montgomery, 1985). The relatively low rapid mixing intensities tested were a limitation inherent in the pilot plant and it is expected that achieving higher velocity gradients would lead to improved charge neutralization and coagulation.

Table 6: Rapid Mix/Alum Run Summary

Pilot Train	Alum Dose (mg/L)	G (1/sec)	Average Filter Influent Particle Counts (>2um/ml)	Average Filter Influent Turbidity	Average Filter Effluent Turbidity	Average Filter Effluent Particle Counts (>2um/ml)	Filter Effluent Particle Count Trend
Train 1	10	10	14700	4.7	0.03	400	Stable
Train 1	10	350	15000	6.6	0.10	1600	Increasing
Train 1	10	500	12100	10.7	0.08	250	Stable
Train 2	10	10	10000	1.6	0.06	323	Increasing
Train 2	10	350	8350	3.3	0.13	110	Stable
Train 2	10	500	12750	5.6	0.10	90	Stable
Train 1	25	10	6400	3.2	0.07	550	Stable
Train 1	25	350	9600	3.9	0.06	680	Stable
Train 1	25	500	11600	5.3	0.04	270	Stable
Train 2	25	10	13700	5.8	0.12	1700	Increasing
Train 2	25	350	8450	6.1	0.07	910	Increasing
Train 2	25	500	14900	4.9	0.11	1100	Increasing
Train 1	45	10	13000	5.5	0.19	3020	Increasing
Train 1	45	350	14500	6.5	0.06	1350	Increasing
Train 1	45	500	15250	8.2	0.05	1700	Stable
Train 2	45	10	12700	9.4	0.24	1200	Stable
Train 2	45	350	16900	8.2	0.04	380	Increasing
Train 2	45	500	18100	4.1	0.02	65	Stable

4.3.2 Alum Dose and Zeta Potential

The lack of any conclusive findings regarding the zeta potential measurements taking is worth mentioning here. Increasing Alum dose seemed to have little impact on zeta potential of clarifier effluent at the pilot plant, contrary to jar test results. The zeta potential on average in the raw water over the filter runs was – 17.5. Although there tended to be a slight increase in the zeta potential with the addition of alum, a trend in the zeta potential of the clarifier effluent could not be determined based on the alum dose. Following this, filter performance could not be correlated with an absolute zeta potential or relative change. This may have been a result of testing too small a range of alum doses. That is, much higher alum doses than 45 mg/L would be required to significantly increase the zeta potential.

4.4 Pol E-Z 652 Effects of Dose and Mixing Intensity

Rather than take the best performing results from the rapid mixing portion of the study and use water from the main pilot plant to determine the effects of mixing intensity with different doses of Pol E-Z, it was decided to use clarifier effluent from the full-scale plant. This was done as the main pilot results did not replicate well between trains, and without continual monitoring, it is difficult to maintain a stable filter influent stream with even small changes in raw water conditions. Alternatively, the upflow clarifiers with the continuous sludge blanket at the full-scale plant produces a very stable effluent in terms of particle counts and turbidity, more suitable for isolating and testing the effects of dosing and mixing.

The different polymer doses and mixing intensities were tested in a series of one-day filter runs.

4.4.1 Pol E-Z 652 (0.02 mg/L)

The effects of mixing intensity on particle counts and turbidity with the addition of 0.02 mg/L of pre-filter Pol E-Z 652 are show in Table 7. Looking at the filtrate turbidity it is difficult to see any significant change when varying the mixing intensity, with all polymer trials either stable at 0.05 NTU or decreasing slightly. It can be seen that there is a substantial improvement over the control filters that all had effluent turbidities over 0.2 and were showing a trend to increase. The particle count data shows two distinct trends. There is always a trend of decreasing or stable filter effluent particle counts and a trend of slightly increasing counts with higher mixing intensities at the dose of 0.02 mg/L. The average total particle counts >2µm/mL at a G of 400 s^{-1} is 72.5. This increases slightly to 100 at a G of 700 s^{-1}, and to 102 at a G of 1100 s^{-1}.

At the lowest mixing intensity tested, however, the average flow reduction through the filter after twenty-four hours was significantly higher at 55% than the control filters at 20%. This data is shown in Table 8. Here it can be seen that with increasing mixing intensity, there is a significant improvement in the flow reduction. This finding is consistent with the use of high molecular weight polymers in filtration. Comparing the two tables, it can be seen that there is a large improvement in filtration rate between a G of 700 s^{-1} to 1100 s^{-1}. There is only an additional 7.5% flow reduction over the control at the highest mixing intensity, however at the midrange this reduction in flow is 15% greater than control. This improvement in filtration rate with higher mixing is not accompanied with any increase in particle counts or turbidity over the mixing intensity of 700 s^{-1}.

Table 7: Pol E-Z 652 (0.02 mg/L) Effects of Mixing Intensity on Particle Counts and Turbidity

Pol EZ 652 Dose (mg/L)	Filter Poly Mixing Intensity (G)	Average FilterInfluent Turbidity	Average Filter Influent Particle Counts (>2μm/ml)	Average Filter Effluent Particle Counts (>2μm/ml)	Filter Effluent Particle Count Trend	Average Filter Effluent Turbidity	Filter Effluent Turbidity Trend
0.02	400	2.5	11700	60	Decreasing	0.05	Stable
Control	400	2.5	11700	1250	Increasing	0.25	Increasing
0.02	400	3.1	13050	85	Stable	0.05	Stable
Control	400	3.1	13050	1350	Stable	0.23	Stable
0.02	700	2.95	12500	55	Decreasing	0.04	Stable
Control	700	2.95	12500	1300	Increasing	0.28	Increasing
0.02	700	3.25	12550	145	Decreasing	0.06	Stable
Control	700	3.25	12550	1500	Increasing	0.26	Increasing
0.02	1100	2.5	11700	70	Decreasing	0.05	Decreasing
Control	1100	2.5	11700	1250	Increasing	0.25	Increasing
0.02	1100	3.62	14150	135	Decreasing	0.06	Stable
Control	1100	3.62	14150	1650	Increasing	0.27	Increasing

Table 8: Pol E-Z 652 (0.02 mg/L) Effects of Mixing Intensity on Filtration Performance

Pol EZ 652 Dose (mg/L)	Filter Poly Mixing Intensity (G)	Percent Particle Removal	Percent Turbidity Removal	Percent Flow reduction after 24 hours
0.02	400	99.5	98.0	60
Control	400	89.3	90.0	20
0.02	400	99.3	98.4	50
Control	400	89.7	92.6	20
0.02	700	99.6	98.6	40
Control	700	89.6	90.5	20
0.02	700	98.8	98.2	30
Control	700	88.0	92.0	20
0.02	1100	99.4	98.0	25
Control	1100	89.3	90.0	20
0.02	1100	99.0	98.3	30
Control	1100	88.3	92.5	20

4.4.2 Pol E-Z 652 (0.03 mg/L)

The results seen at a dose of 0.02 mg/L display similar trends at a dose of 0.03 mg/L. It can be seen in Table 9 that the particle counts show an increasing trend with higher mixing intensities. The difference in particle counts between a G of 700 s^{-1} and 1100 s^{-1} was relatively unchanged. Turbidity showed a slightly increasing trend averaging 0.045 NTU at the lowest mixing intensity and increasing to 0.06 NTU at the highest mixing intensity.

At the velocity gradient of 400 s^{-1}, there was substantial flow reduction at a dose of 0.03 mg/L as can be seen in Table 10. Both filter runs tested at this dose and velocity gradient reached terminal headloss prior to the end of the twenty-four hour run. At the G of 700 s^{-1} there was an average 52% flow reduction by the end of the run. This value is comparable to the reduction in flow at a dose of 0.02 mg/L at a G of 400 s^{-1}. Similarly, the reduction in filtration rate of 35 % at 0.03 mg/L with a G of 1100 s^{-1} is comparable to the flow reduction at 0.02 mg/L with a G of 700 s^{-1}. That is, at a higher dose of the filter polymer, a higher velocity gradient is required to achieve the same result. This general trend was also seen in the filtrate particle count data, where the results at 0.03 mg/L and G of 1100 s^{-1} are similar to the dose at 0.02 mg/L and G of 700 s^{-1}. This finding is consistent with the general theories of polymer dosing and mixing intensity as described by (Stump and Novak, 1979) and (Amirthatajah, 1991). Although the turbidity data shows the same general trend, it appears less sensitive to the effects of dosing and mixing, with average changes within doses of only 0.015, making it's use difficult to support the conclusions.

Table 9: Pol E-Z 652 (0.03 mg/L) Effects of Mixing Intensity on Particle Counts and Turbidity

Pol EZ 652 Dose (mg/L)	Filter Poly Mixing Intensity (G)	Average FilterInfluent Turbidity	Average Filter Influent Particle Counts (>2μm/ml)	Average Filter Effluent Particle Counts (>2μm/ml)	Filter Effluent Particle Count Trend	Average Filter Effluent Turbidity	Filter Effluent Turbidity Trend
0.03	400	3.02	12900	55	Decreasing	0.04	Stable
Control	400	3.02	12900	1500	Increasing	0.26	Increasing
0.03	400	3.1	13050	80	Decreasing	0.05	Stable
Control	400	3.1	13050	1350	Stable	0.23	Stable
0.03	700	2.85	11450	55	Decreasing	0.04	Stable
Control	700	2.85	11450	1250	Increasing	0.25	Increasing
0.03	700	2.77	11100	165	Decreasing	0.07	Stable
Control	700	2.77	11100	1650	Increasing	0.27	Increasing
0.03	1100	2.85	11450	65	Stable	0.05	Stable
Control	1100	2.85	11450	1250	Increasing	0.25	Increasing
0.03	1100	3.25	12550	145	Decreasing	0.07	Stable
Control	1100	3.25	12550	1500	Increasing	0.26	Increasing

Table 10: Pol E-Z 652 (0.03 mg/L) Effects of Mixing Intensity on Filtration Performance

Pol EZ 652 Dose (mg/L)	Filter Poly Mixing Intensity (G)	Percent Particle Removal	Percent Turbidity Removal	Percent Flow reduction after 24 hours
0.03	400	99.6	98.7	100 @ 12.5 hrs
Control	400	88.4	91.4	20
0.03	400	99.4	98.4	100 @ 18 hrs.
Control	400	89.7	92.6	20
0.03	700	99.5	98.6	65
Control	700	89.1	91.2	20
0.03	700	98.5	97.5	40
Control	700	85.1	90.3	20
0.03	1100	99.4	98.2	40
Control	1100	89.1	91.2	20
0.03	1100	98.8	97.8	30
Control	1100	88.0	92.0	20

4.4.3 Pol E-Z 652 (0.04 mg/L)

Consistent with the use of high molecular weight polymer as a filter aid, the higher dose tested resulted in improved particle removal at the cost of reduced filtration rate. Both filter runs at the lowest mixing intensity terminated at 19 hours due to the flow rate dropping to zero, see Table 12. At a velocity gradient of 700 s^{-1}, the average flow reduction was 85% as compared to only 20% for the control filters. Again, it can be seen at the highest mixing intensity of 1100 s^{-1} that the results in terms of flow reduction (52.5% on average) and particle counts (~100) are comparable to the dose of 0.03 mg/L at a velocity gradient of 700 s^{-1}.

Table 11: Pol E-Z 652 (0.04 mg/L) Effects of Mixing Intensity on Particle Counts and Turbidity

Pol EZ 652 Dose (mg/L)	Filter Poly Mixing Intensity (G)	Average FilterInfluent Turbidity	Average Filter Influent Particle Counts (>2µm/ml)	Average Filter Effluent Particle Counts (>2µm/ml)	Filter Effluent Particle Count Trend	Average Filter Effluent Turbidity	Filter Effluent Turbidity Trend
0.04	400	3.02	12900	50	Decreasing	0.05	Stable
Control	400	3.02	12900	1500	Increasing	0.26	Increasing
0.04	400	2.76	11950	90	Decreasing	0.05	Stable
Control	400	2.76	11950	1650	Increasing	0.27	Stable
0.04	700	2.95	12500	55	Decreasing	0.05	Stable
Control	700	2.95	12500	1300	Increasing	0.28	Increasing
0.04	700	3.62	14150	110	Decreasing	0.06	Decreasing
Control	700	3.62	14150	1650	Increasing	0.27	Increasing
0.04	1100	2.82	12150	85	Decreasing	0.05	Stable
Control	1100	2.82	12150	1150	Increasing	0.25	Increasing
0.04	1100	2.76	11950	95	Decreasing	0.05	Stable
Control	1100	2.76	11950	1650	Increasing	0.27	Stable

Table 12: Pol E-Z 652 (0.04 mg/L) Effects of Mixing Intensity on Filtration Performance

Pol EZ 652 Dose (mg/L)	Filter Poly Mixing Intensity (G)	Percent Particle Removal	Percent Turbidity Removal	Percent Flow reduction after 24 hours
0.04	400	99.6	98.3	100 @ 19 hrs
Control	400	88.4	91.4	20
0.04	400	99.2	98.2	100 @ 19 hrs
Control	400	86.2	90.2	20
0.04	700	99.6	98.3	100 @ 19.5 hrs
Control	700	89.6	90.5	20
0.04	700	99.2	98.3	70
Control	700	88.3	92.5	20
0.04	1100	99.3	98.2	55
Control	1100	90.5	91.1	20
0.04	1100	99.2	98.2	50
Control	1100	86.2	90.2	20

4.5 Pol E-Z 652 Dosing and Mixing Intensity Summary

Pol E-Z filter polymer doses in the range of 0.02 mg/L to 0.04 mg/L were tested at mixing intensities (G) of 400 $^{s-1}$, 700 $^{s-1}$, and 1100 $^{s-1}$. Across these tests, the average total filtrate particle counts (>2µm/mL) ranged from 50 to 165 over the twenty-four hour filter runs with turbidity ranging from 0.04 – 0.06. The control filter runs had particle counts averaging 1400 and turbidities of 0.26. Addition of filter polymer gives an additional average 10% improved removal of the influent particle counts and turbidity as compared to the controls. The results from these filter runs, showing the average filter effluent particle counts for each dose-velocity ,gradient condition are shown below in Figure 26. This figure shows a significant impact of the filter polymer mixing intensity on the effluent particle counts, with lower counts at the lowest mixing intensity of 400 $^{s-1}$. Overall there is a trend to higher particle counts at mixing intensities over this value with less absolute difference between the 700 $^{s-1}$ and 1100 $^{s-1}$ mixing intensities.

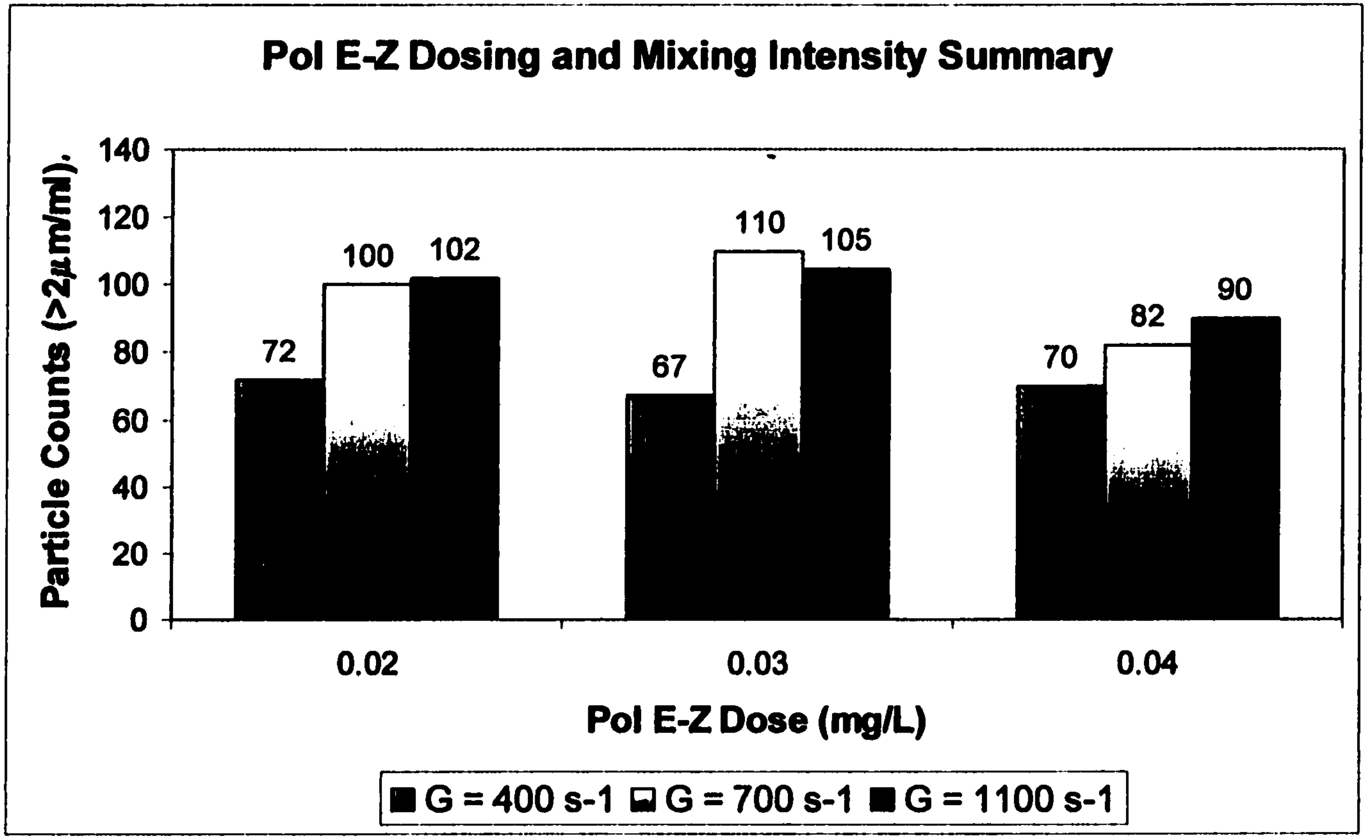

Figure 26: Pol E-Z Dosing and Mixing Intensity Effects on Particle Counts

Particle counts alone cannot provide enough information to make an appropriate selection, however. Even with the lowest polymer doses tested, a minimum polymer mixing intensity of 700 $^{s-1}$ is required to optimize overall filter performance. At mixing intensities less than this, flow is significantly reduced within 24 hours. An average 55% flow reduction was seen at a dose of 0.02 mg/L and this increased to 100% at 0.03 mg/L with a mixing intensity of 400 $^{s-1}$. Filter run times will definitely be reduced from their current lengths with the use of filter polymer based on the filtration rates.

Higher mixing leads to substantially reduced flow reduction independent of dose with only slightly reduced particle removal efficiency. It would likely be better to design for a higher mixing intensity (~1100 $^{s-1}$) rather than risk under mixing full-scale, and choking off flow to the filters.

5.0 Conclusions And Recommendations for Further Work

The addition of a polymer into the filter influent stream can have a significant impact in terms of lower and more stable filtrate particle counts and turbidity. Polymer type and dose significantly determine filter performance.

The rapid mixing of alum at a high velocity gradient is important for producing a filterable floc. Charge neutralization is very important in this case. Dosing should have less of an impact than quick dispersion or high mixing intensities. A higher velocity gradient essentially gives a higher effective dose of the hydrolysis products required for charge neutralization.

Improvements could be made to the alum rapid mixer at the main pilot plant such as a static mixer or the addition of baffles into the mixer to prevent short-circuiting and ensure maximum mixing intensity. Relocating the alum injection point closer to the most intensive mixing would also be recommended.

With the removal of softening, improvements are required at the full-scale water treatment plant over the current inline mixer.

Although scale-up issues exist in pilot testing of filters, there is a lack of formal work done on wall effects in pilot scale filters and scale-up studies. Full-scale testing, likely with lower doses should be done with best performing polymer or two.

It may be worthwhile increasing the flow through the filters and studying the Nalco 8100 with different mixing intensities. Different media testing at E.L. Smith may also be a consideration.

Prior to this work, the coagulation process will need to be further improved, possibly through pilot plant trials using a range of primary polymers in addition to the rapid mix improvements currently under way

To aid in charge neutralization, which has been shown effective in producing a filterable floc, the consideration of a cationic polymer to add with the alum for enhanced coagulation may be considered. The current polymer being used is anionic and has been shown to create a sweep floc, removing particulates through particle enmeshment. This polymer was selected for optimization with the softening process, however, where the stable colloids passing through the clarification process could be removed through softening.

5.1 Full Scale Implications

Following the experimental work done here, there have been several full scale capital projects completed at both the E. L. Smith and Rossdale Water Treatment Plants based, in part, on these results. A liquid filter polymer system was installed prior to stopping softening, and since the removal of softening from the process, has become a critical component of the water treatment process for maintaining low filtered water particle counts and turbidity. At the Rossdale plant, each filter has its own individual mixer equipped with a VFD, and it is planned to install a filter polymer mixing system at E. L. Smith in 2001. Currently the filter polymer at E. L. Smith is mixed at a weir, and tends to average slightly higher particle counts than the Rossdale plant. The rapid mixing of alum was improved in the Summer of 2000 by relocating the alum injection point from the raw water line, where the alum was mixed with an inline mixer to the low lift pumps. Using the impeller of the low lift pumps to mix the alum, the improvement in overall plant performance was immediate. Colour in the clarifiers dropped fifty percent and although the clarifier turbidity and particle counts remained relatively constant, filter effluent particle counts dropped approximately twenty-five percent on average.

6.0 References

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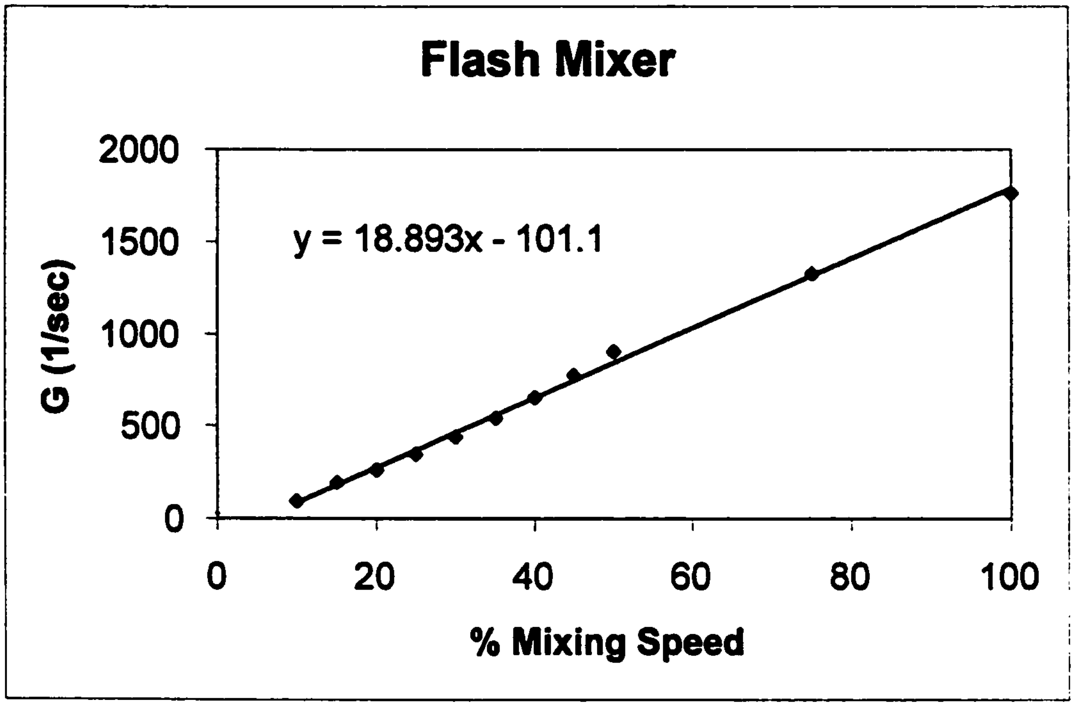
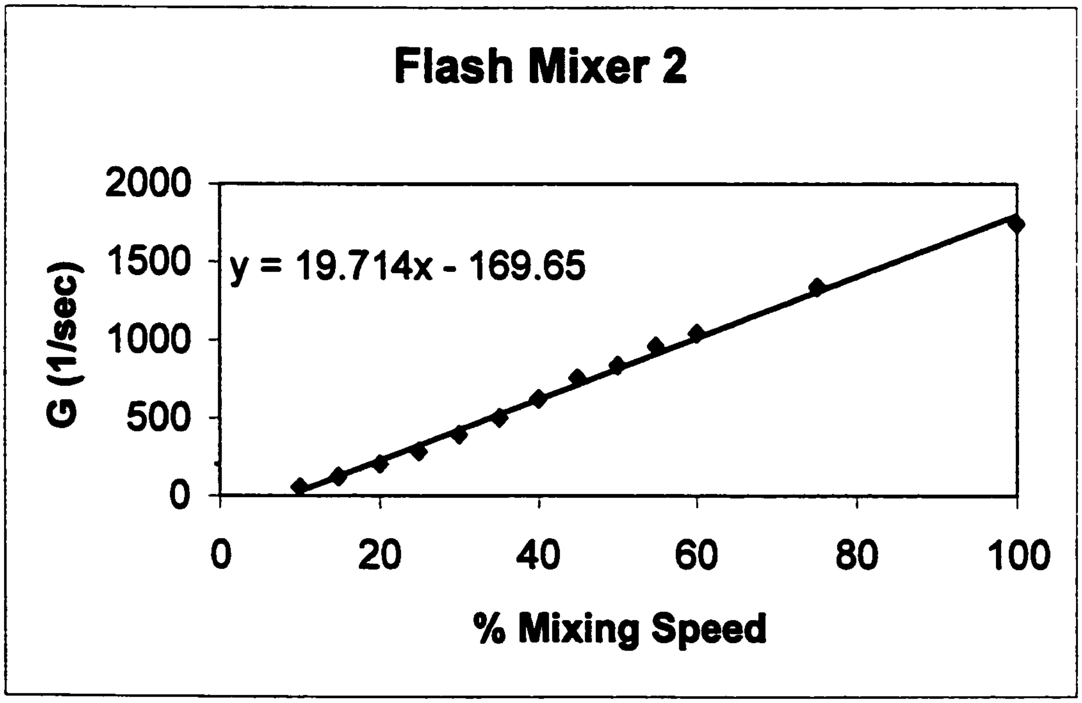
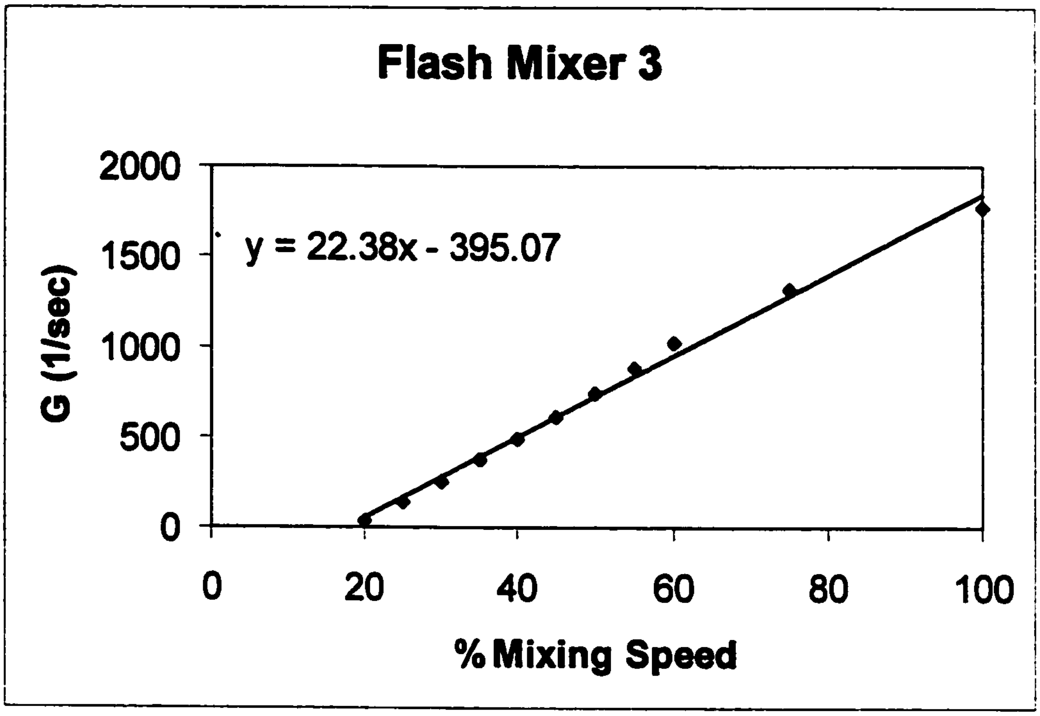
Appendix A: Filter Polymer Velocity Gradient Calibration Curves


Flash Mixer
y = 18.893x - 101.1
G (1/sec)
2000
1500
1000
500
0
0
20
40
60
80
100
% Mixing Speed


Flash Mixer 2
y = 19.714x - 169.65
G (1/sec)
2000
1500
1000
500
0
0
20
40
60
80
100
% Mixing Speed


Flash Mixer 3
2000
1500
1000
500
0
G (1/sec)
y = 22.38x - 395.07
0
20
40
60
80
100
% Mixing Speed

Appendix B: Data Collection Template

Run I.D. ____________

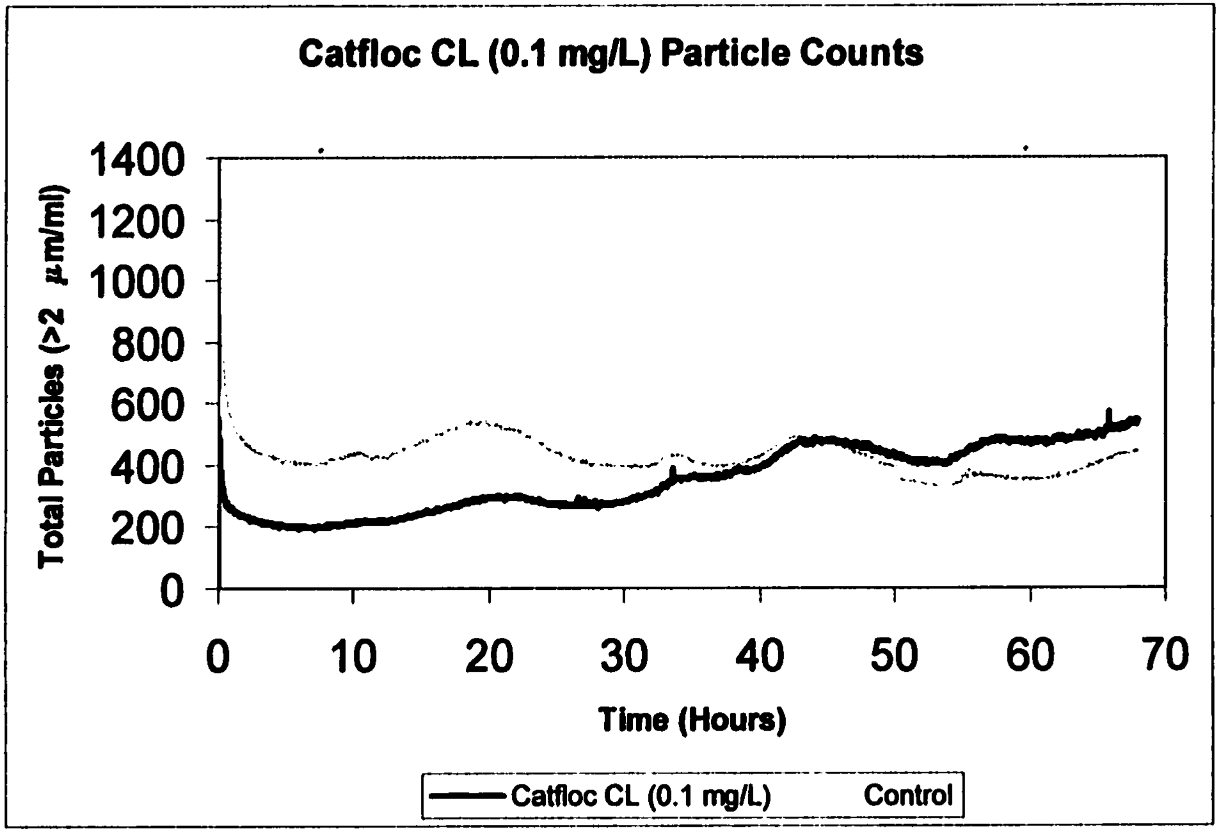
Start Time: ____________

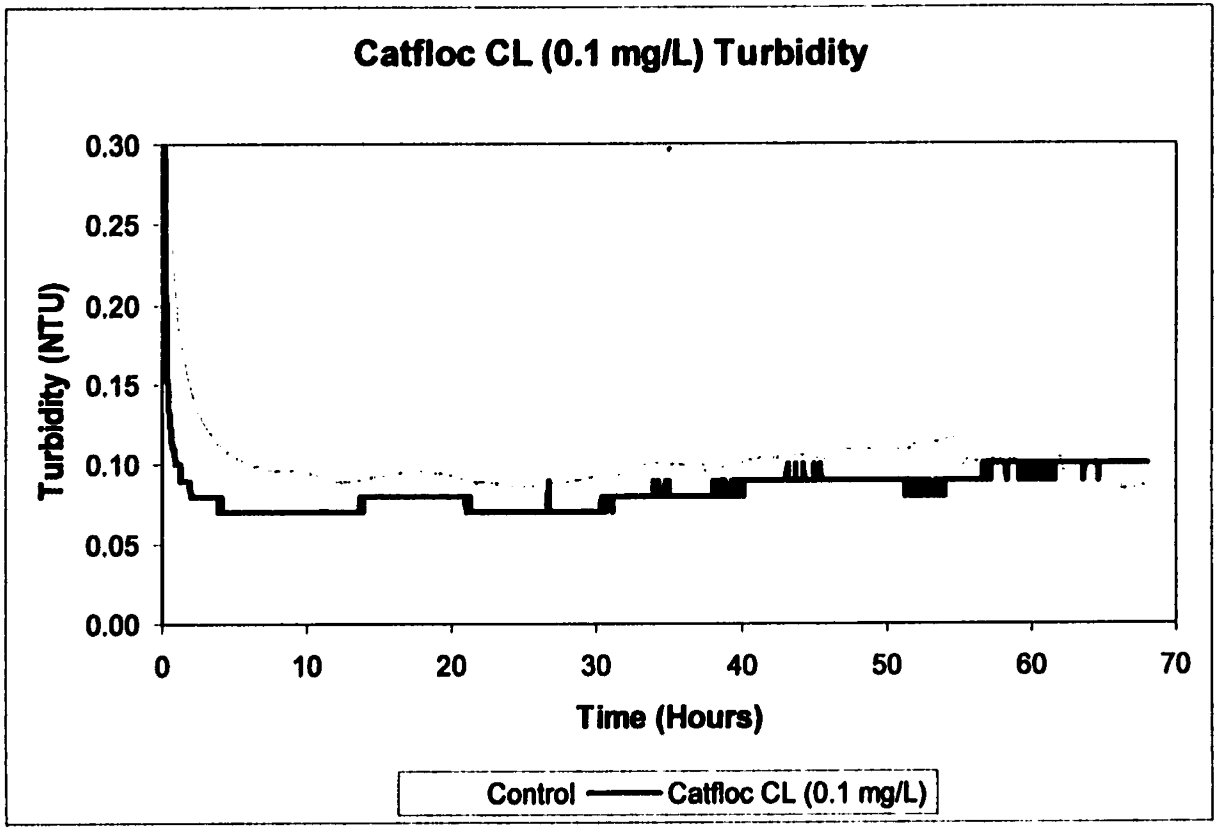
Finish Time: ____________

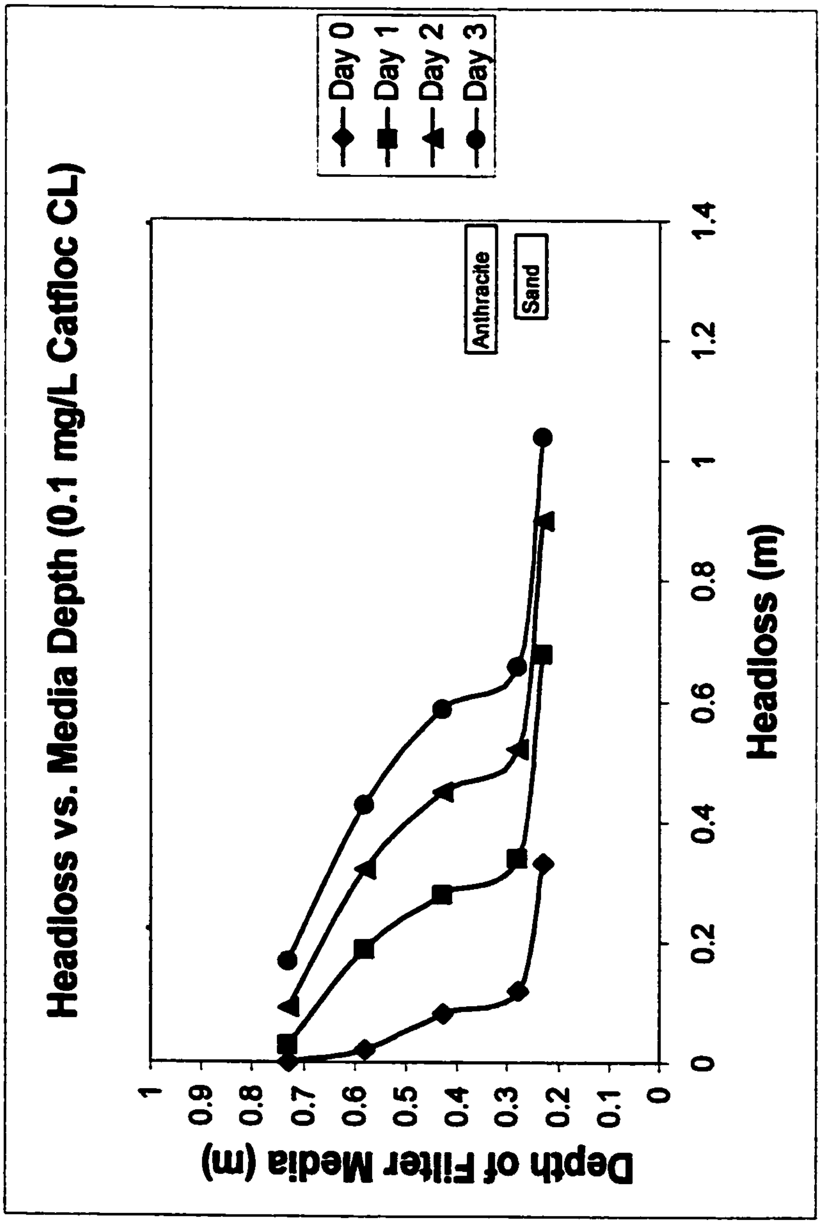
	Start	Day 1	Day 2	Day 3
Temperature				
CO_2 Flow				
Zeta Potential				
Filter 1				
Flow rate (Lpm)				
Head (2 cm)				
Head (17 cm)				
Head (32 cm)				
Head (47 cm)				
Head (52 cm)				
Filter 2				
Flow rate (Lpm)				
Head (2 cm)				
Head (17 cm)				
Head (32 cm)				
Head (47 cm)				
Head (52 cm)				
Polymer Stock Solution Concentration				
mass %				
mg/L				
Feed Flow Rate				
ml/min				
rpm				
Tubing				
Actual Flow				
Actual Dose				
Filter 3				
Flow rate (Lpm)				
Head (2 cm)				
Head (17 cm)				
Head (32 cm)				
Head (47 cm)				
Head (52 cm)				
Polymer Stock Solution Concentration				
mass %				
mg/L				
Feed Flow Rate				
ml/min				
rpm				
Tubing				
Actual Flow				
Actual Dose				

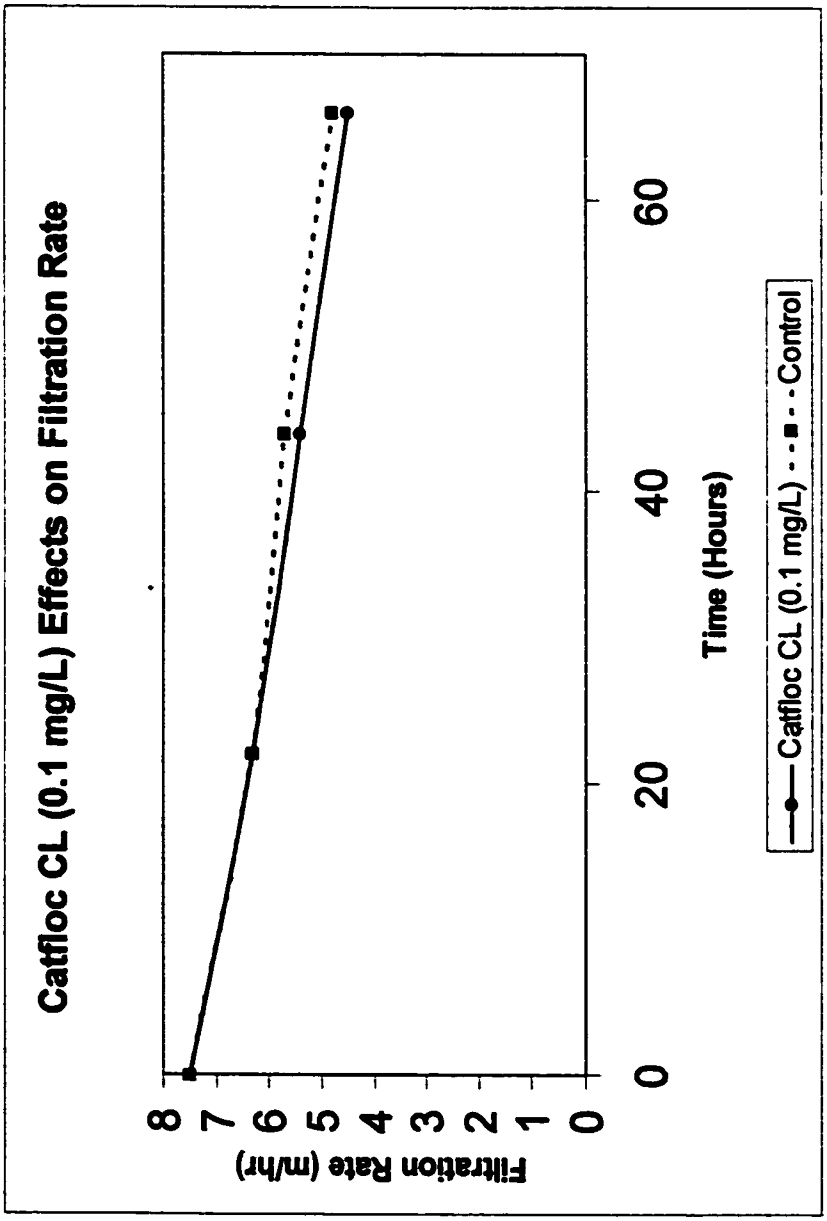
Notes/Calculations

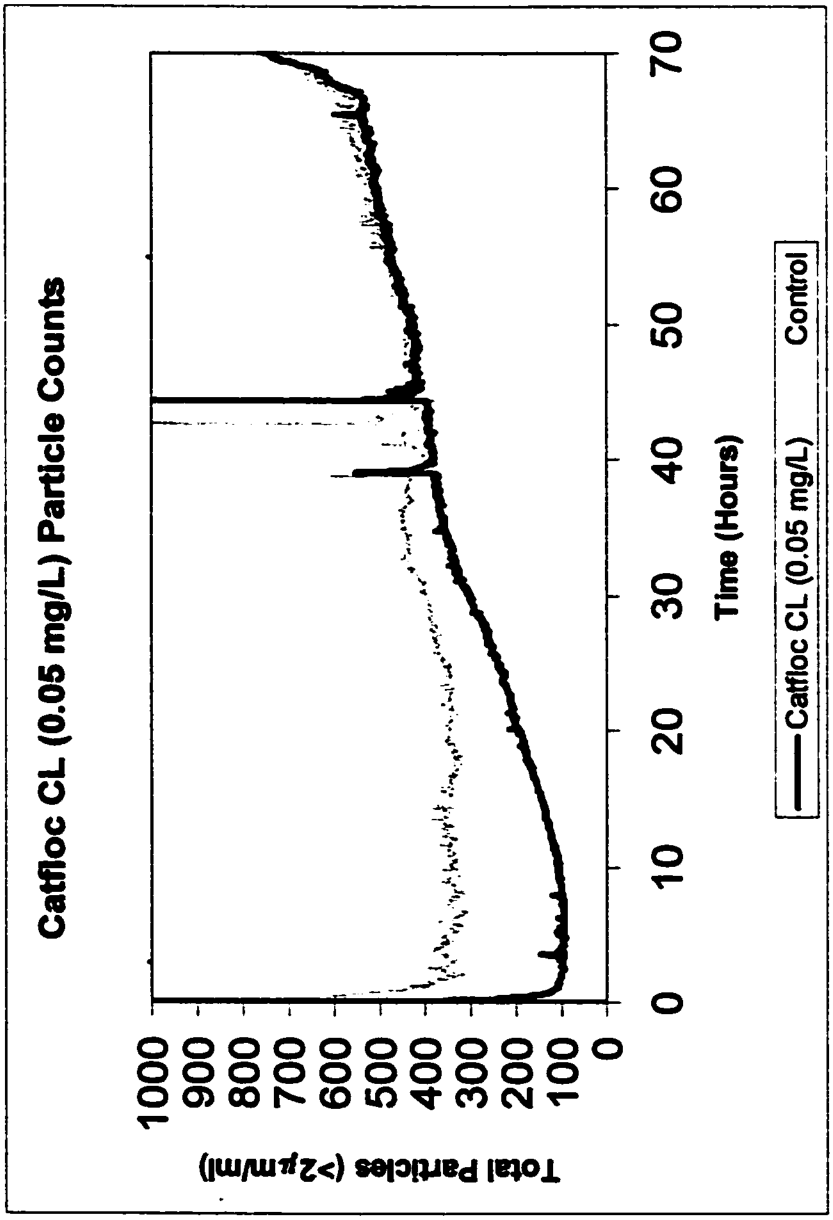
Appendix C: Initial Filter Polymer Selection Graphs

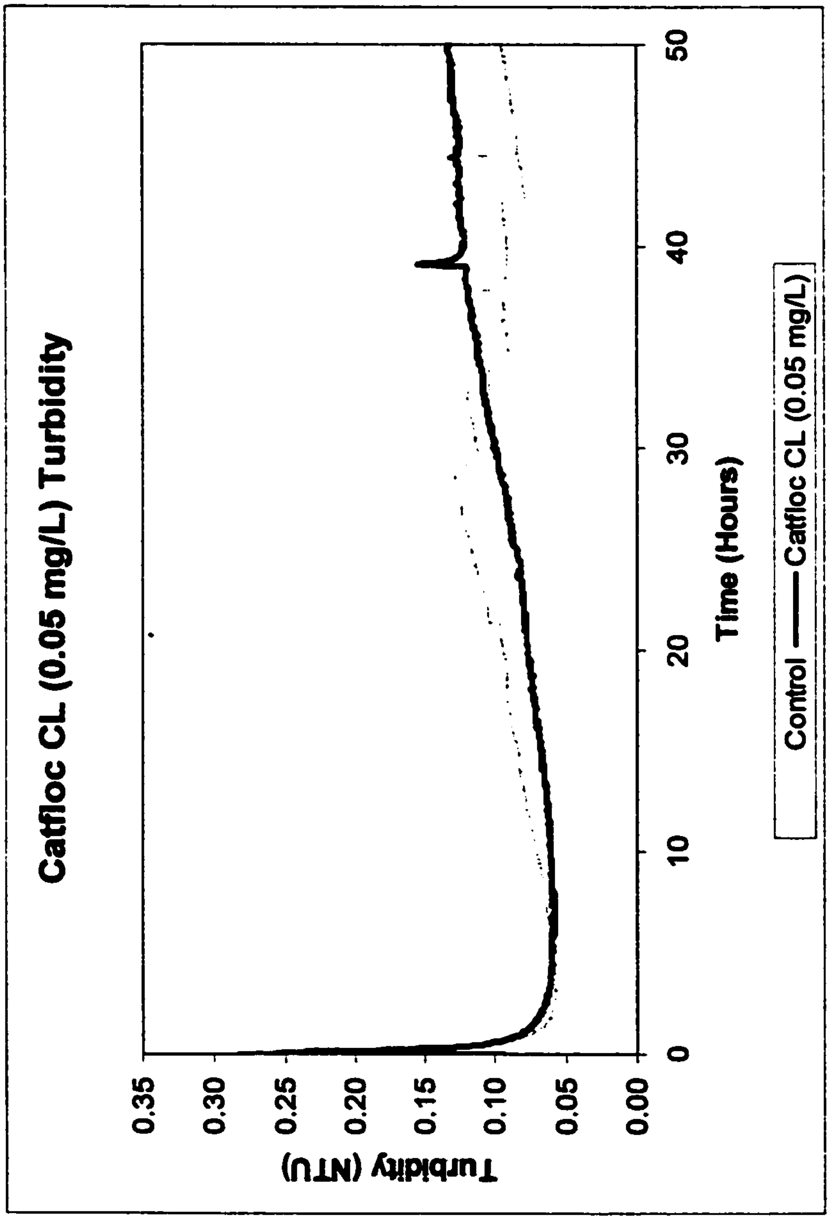

Catfloc CL (0.1 mg/L) Particle Counts
Total Particles (>2 µm/ml)
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
Time (Hours)
Catfloc CL (0.1 mg/L)
Control

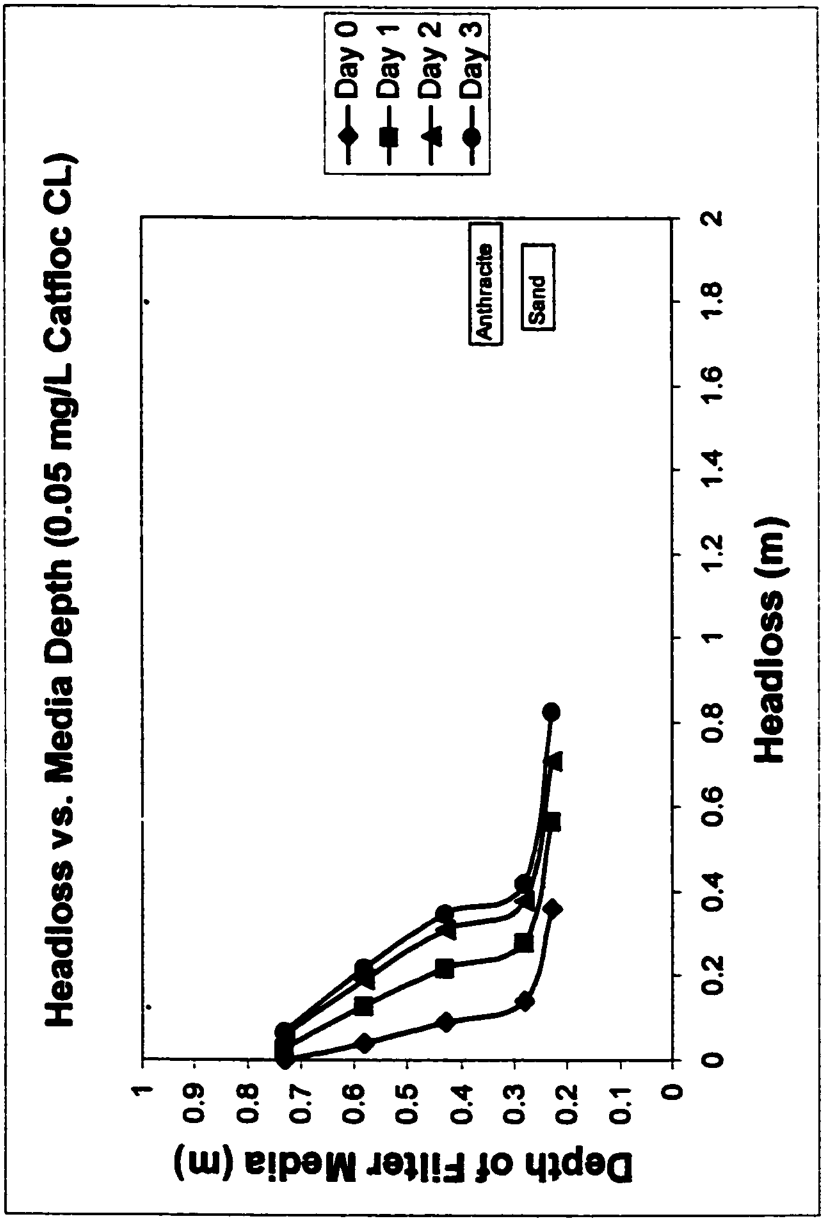

Catfloc CL (0.1 mg/L) Turbidity
Turbidity (NTU)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
Time (Hours)
Control
Catfloc CL (0.1 mg/L)

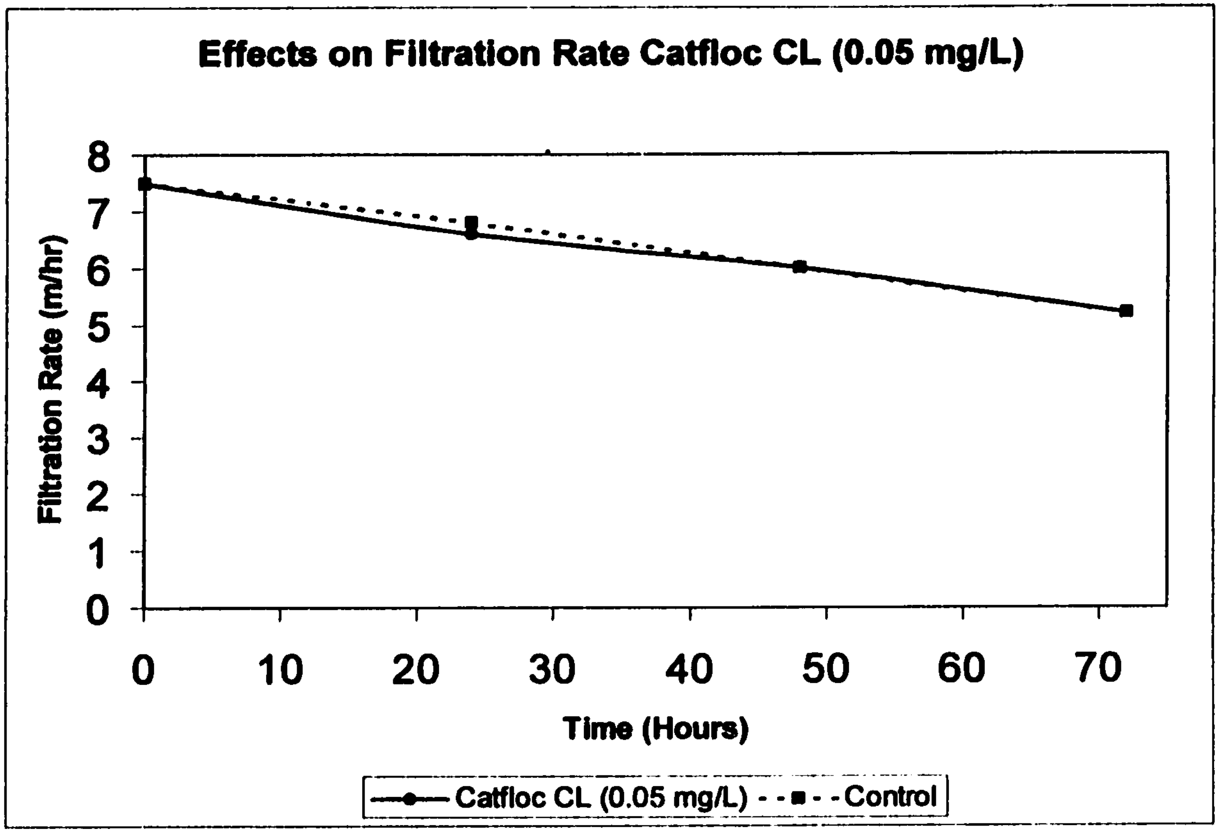

Headloss vs. Media Depth (0.1 mg/L Catfloc CL)
Depth of Filter Media (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Headloss (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Anthracite
Sand
Day 0
Day 1
Day 2
Day 3


Catfloc CL (0.1 mg/L) Effects on Filtration Rate
Filtration Rate (m/hr)
8
7
6
5
4
3
2
1
0
0
20
40
60
Time (Hours)
Catfloc CL (0.1 mg/L)
Control

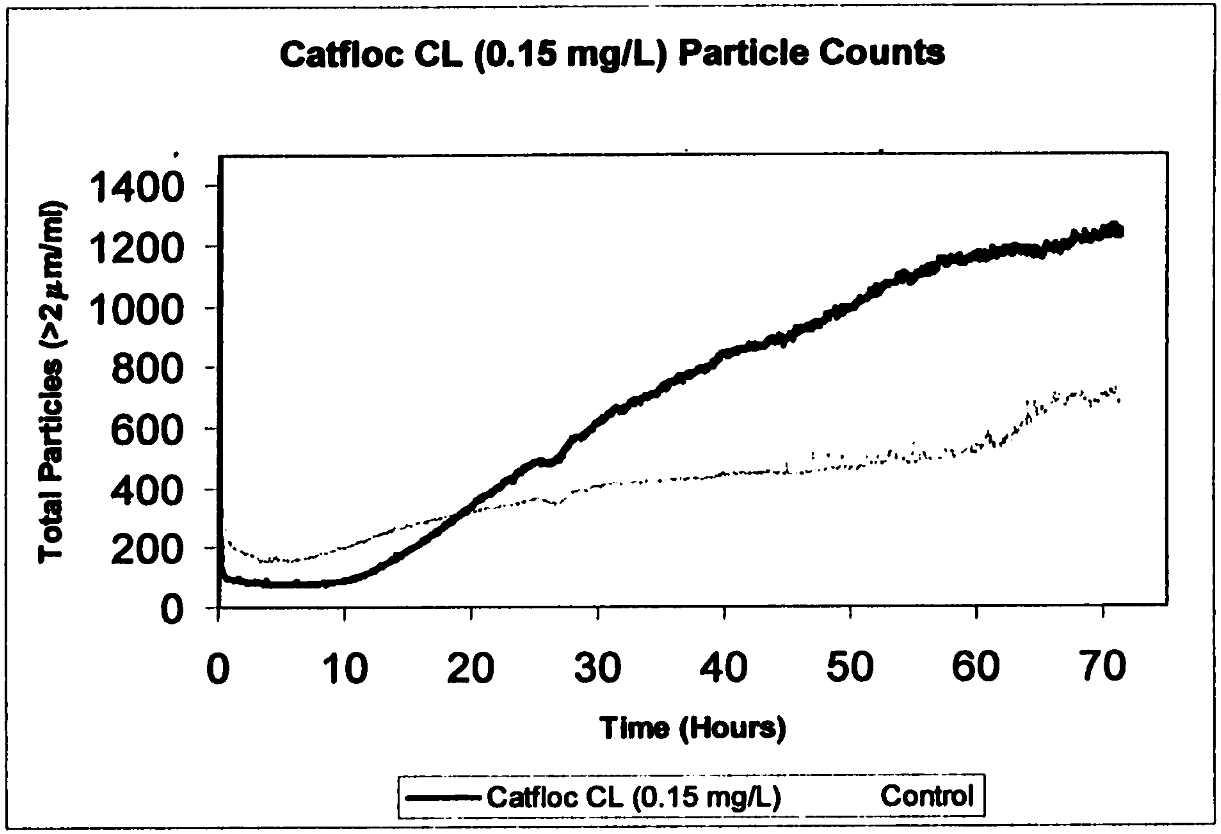

Catfloc CL (0.05 mg/L) Particle Counts
Total Particles (>2µm/ml)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
Time (Hours)
Catfloc CL (0.05 mg/L)
Control

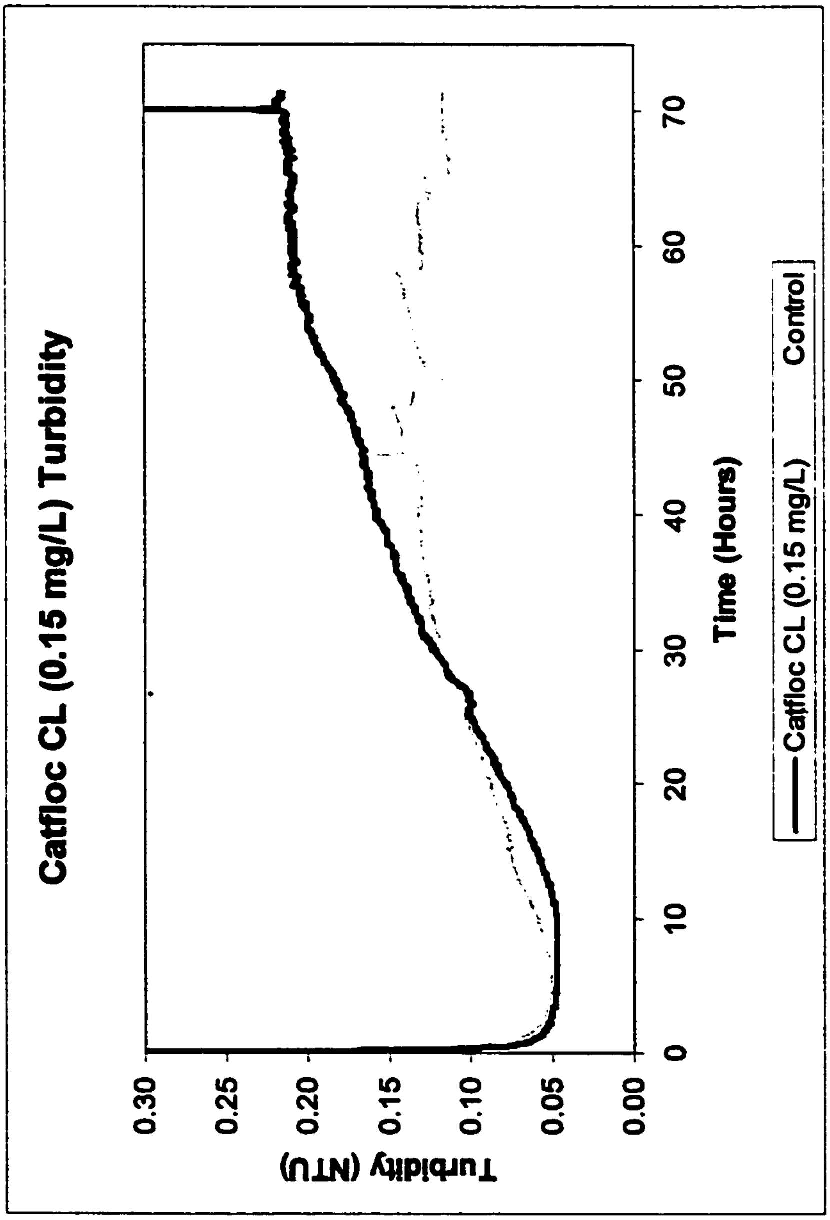

Catfloc CL (0.05 mg/L) Turbidity
Turbidity (NTU)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
Time (Hours)
Control
Catfloc CL (0.05 mg/L)

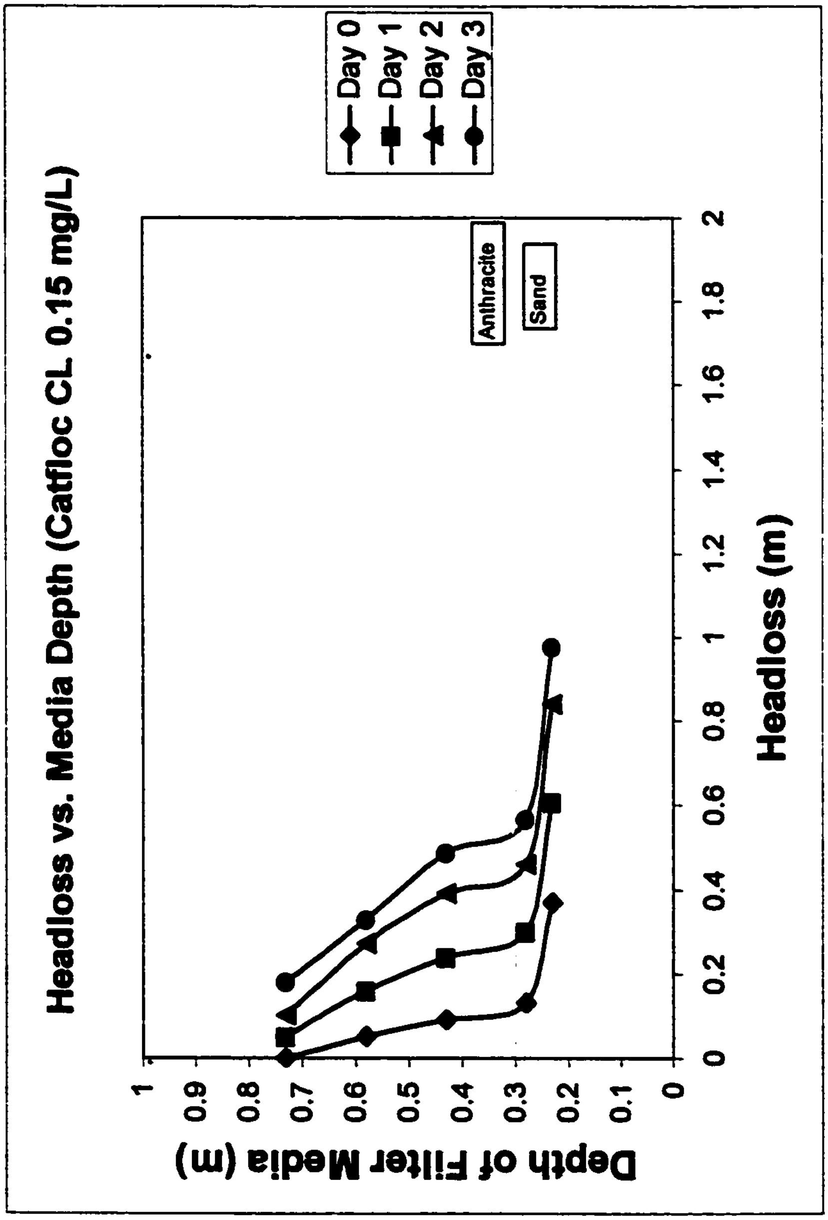

Headloss vs. Media Depth (0.05 mg/L Catfloc CL)
Depth of Filter Media (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Headloss (m)
Anthracite
Sand
Day 0
Day 1
Day 2
Day 3

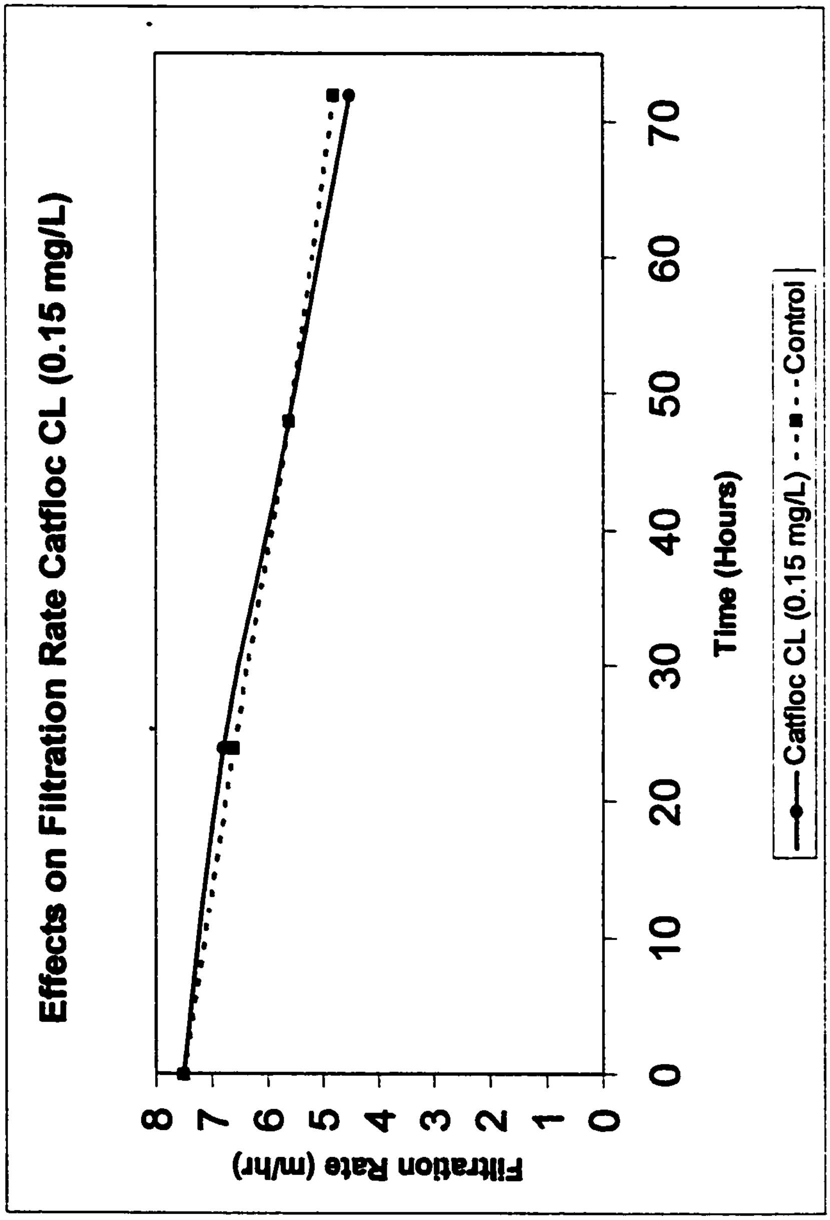


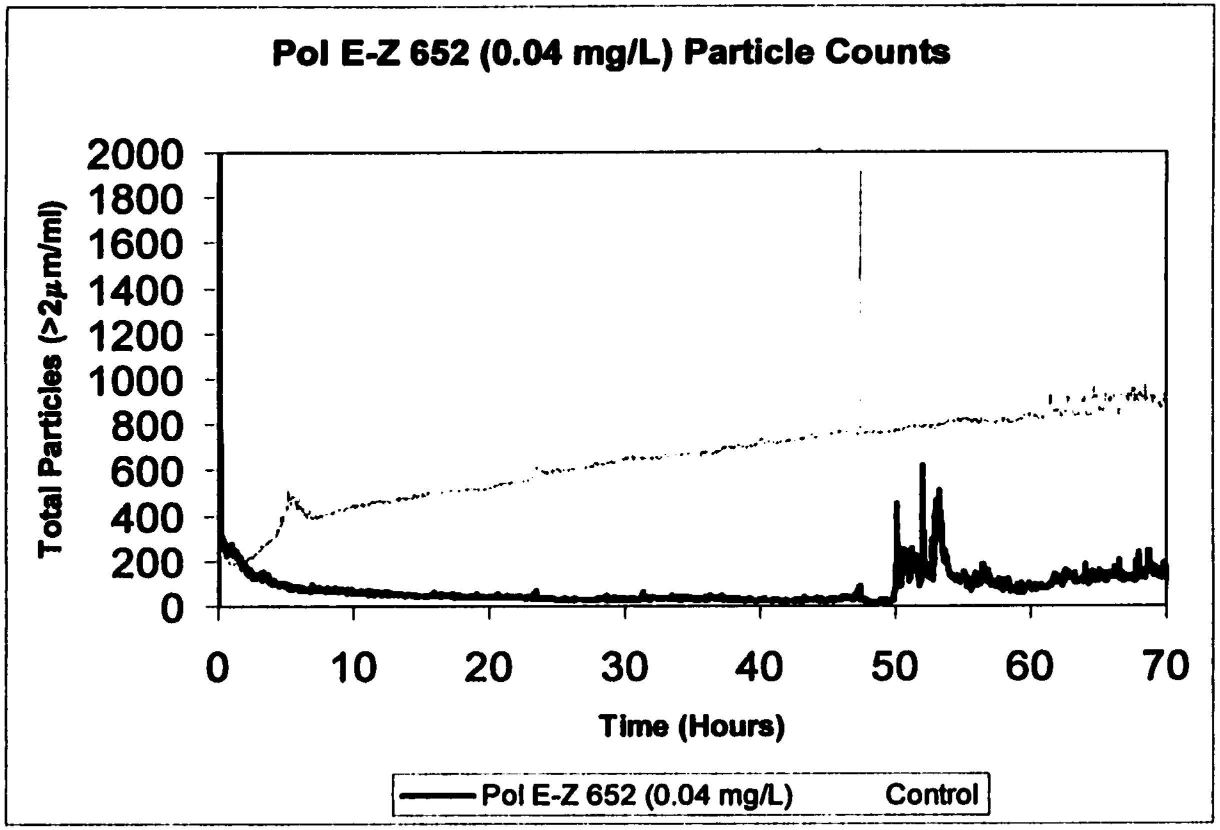
Effects on Filtration Rate Catfloc CL (0.05 mg/L)

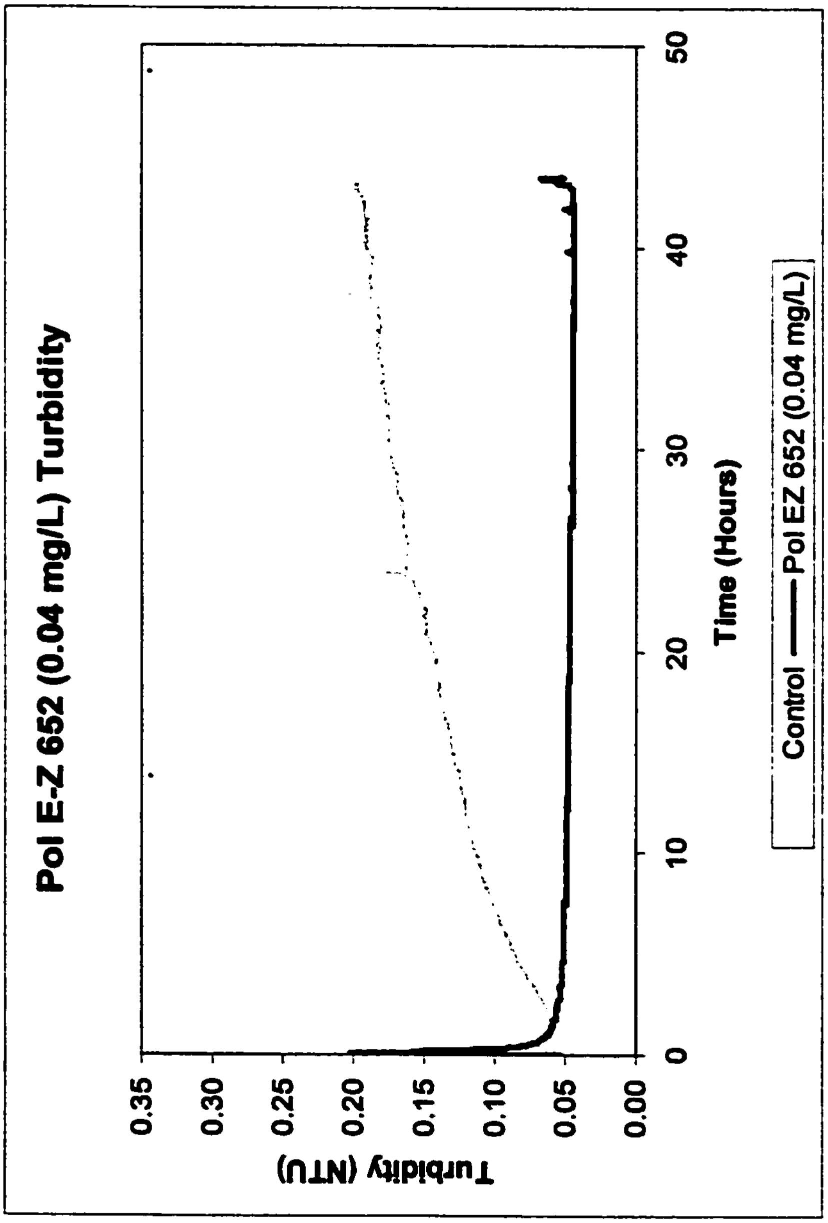

Catfloc CL (0.15 mg/L) Particle Counts
Total Particles (>2 µm/ml)
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
Time (Hours)
Catfloc CL (0.15 mg/L)
Control

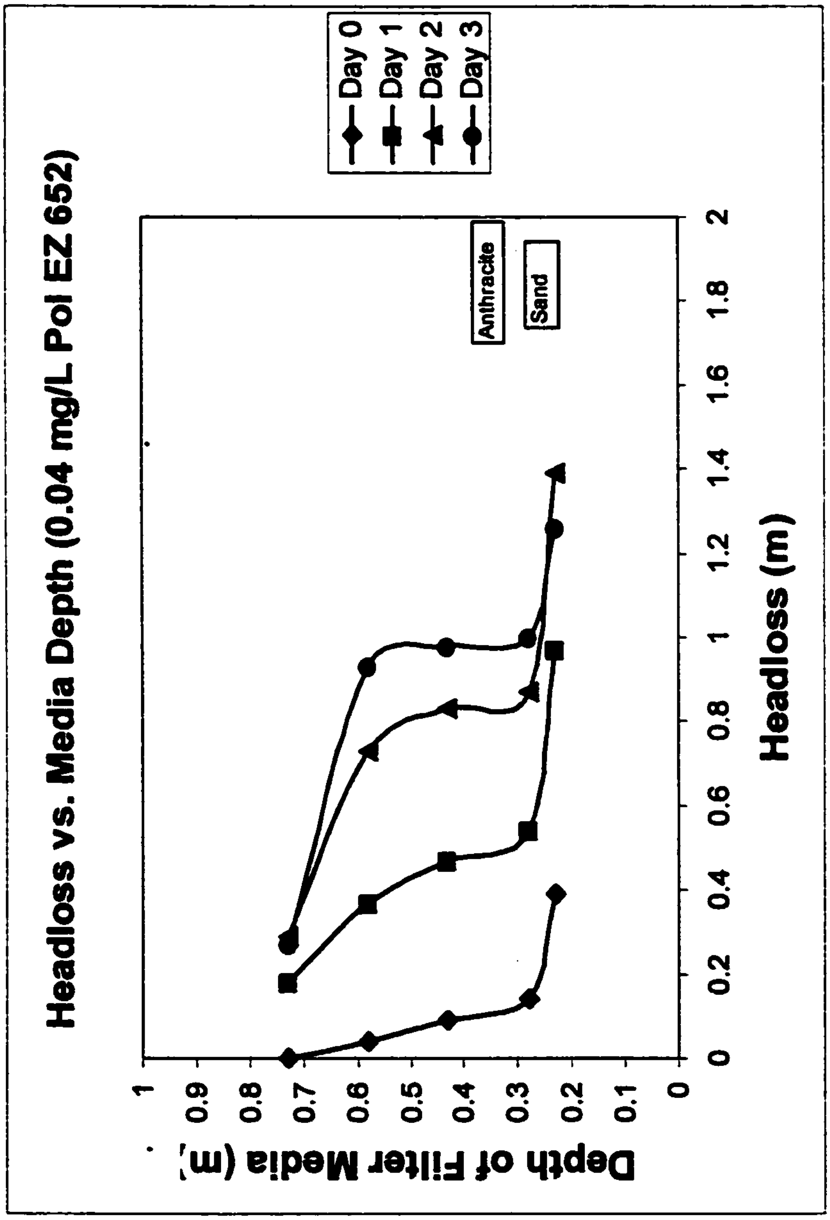

Catfloc CL (0.15 mg/L) Turbidity
Turbidity (NTU)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
Time (Hours)
Catfloc CL (0.15 mg/L)
Control

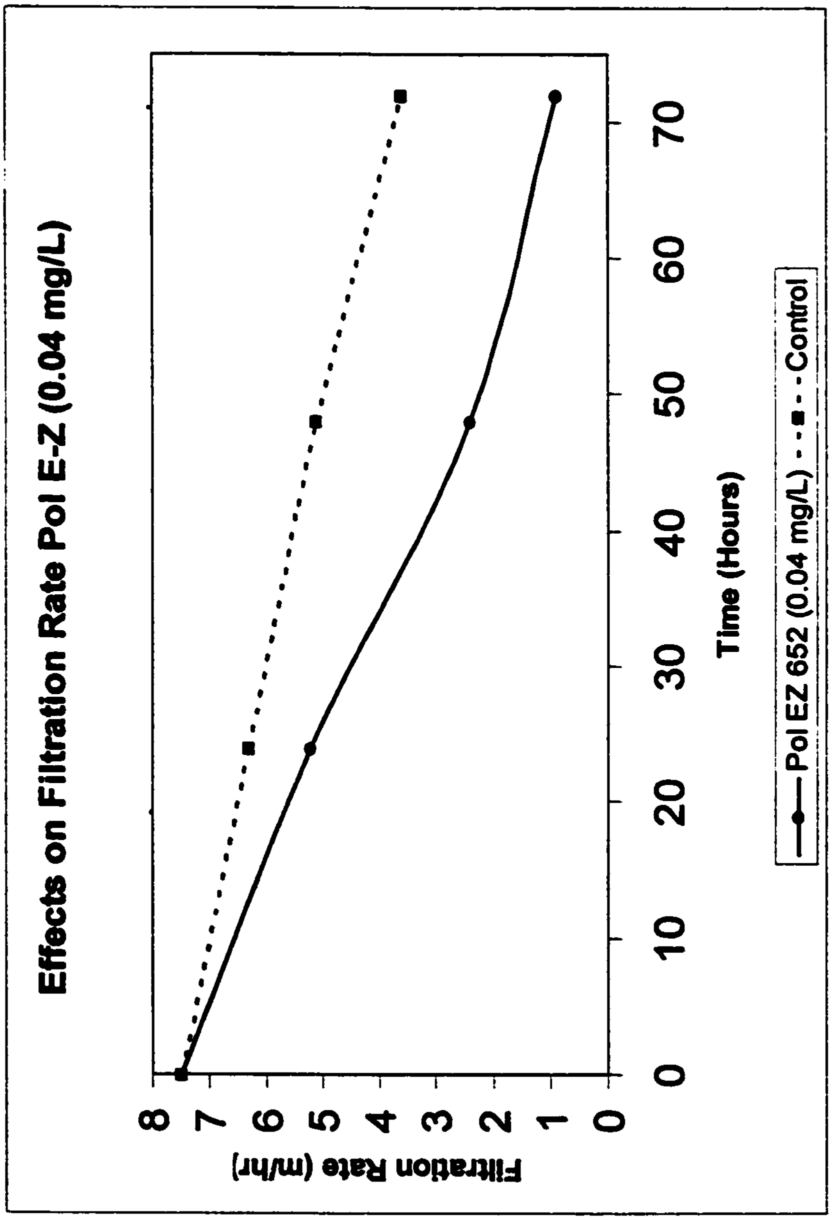

Headloss vs. Media Depth (Catfloc CL 0.15 mg/L)
Depth of Filter Media (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Headloss (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Anthracite
Sand
Day 0
Day 1
Day 2
Day 3

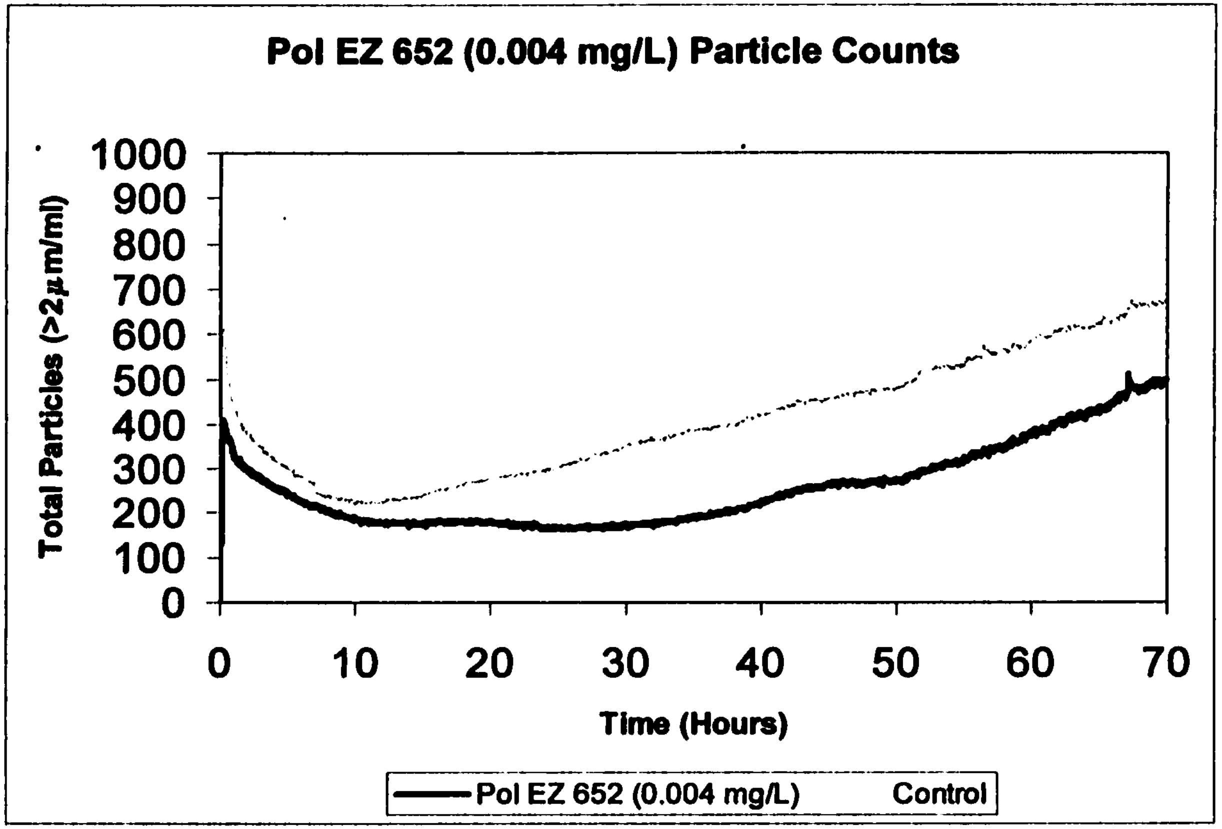

Effects on Filtration Rate Catfloc CL (0.15 mg/L)
Filtration Rate (m/hr)
0
1
2
3
4
5
6
7
8
Time (Hours)
0
10
20
30
40
50
60
70
Catfloc CL (0.15 mg/L)
Control

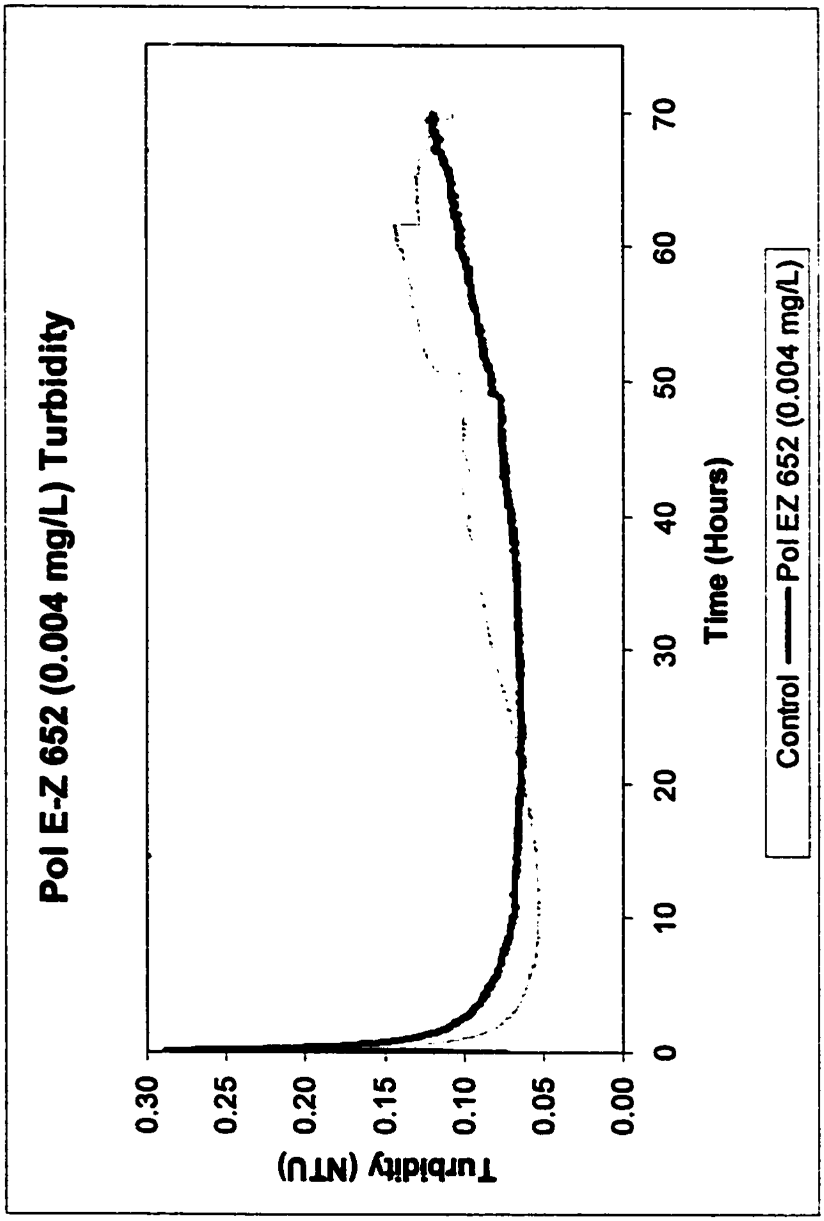

Pol E-Z 652 (0.04 mg/L) Particle Counts
Total Particles (>2µm/ml)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
Time (Hours)
Pol E-Z 652 (0.04 mg/L)
Control


Pol E-Z 652 (0.04 mg/L) Turbidity
Turbidity (NTU)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
Time (Hours)
Control
Pol EZ 652 (0.04 mg/L)

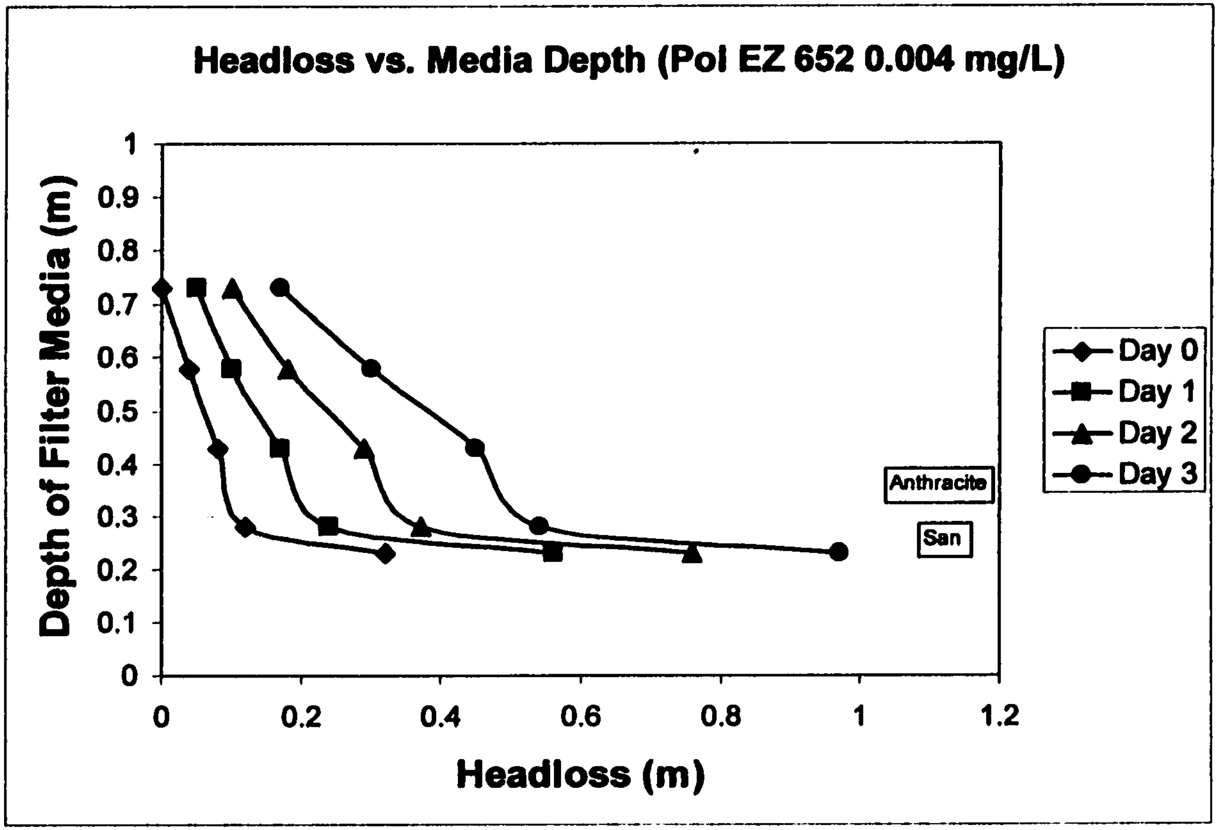

Headloss vs. Media Depth (0.04 mg/L Pol EZ 652)
Depth of Filter Media (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Headloss (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Anthracite
Sand
Day 0
Day 1
Day 2
Day 3


Effects on Filtration Rate Pol E-Z (0.04 mg/L)
Filtration Rate (m/hr)
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Time (Hours)
Pol EZ 652 (0.04 mg/L)
Control

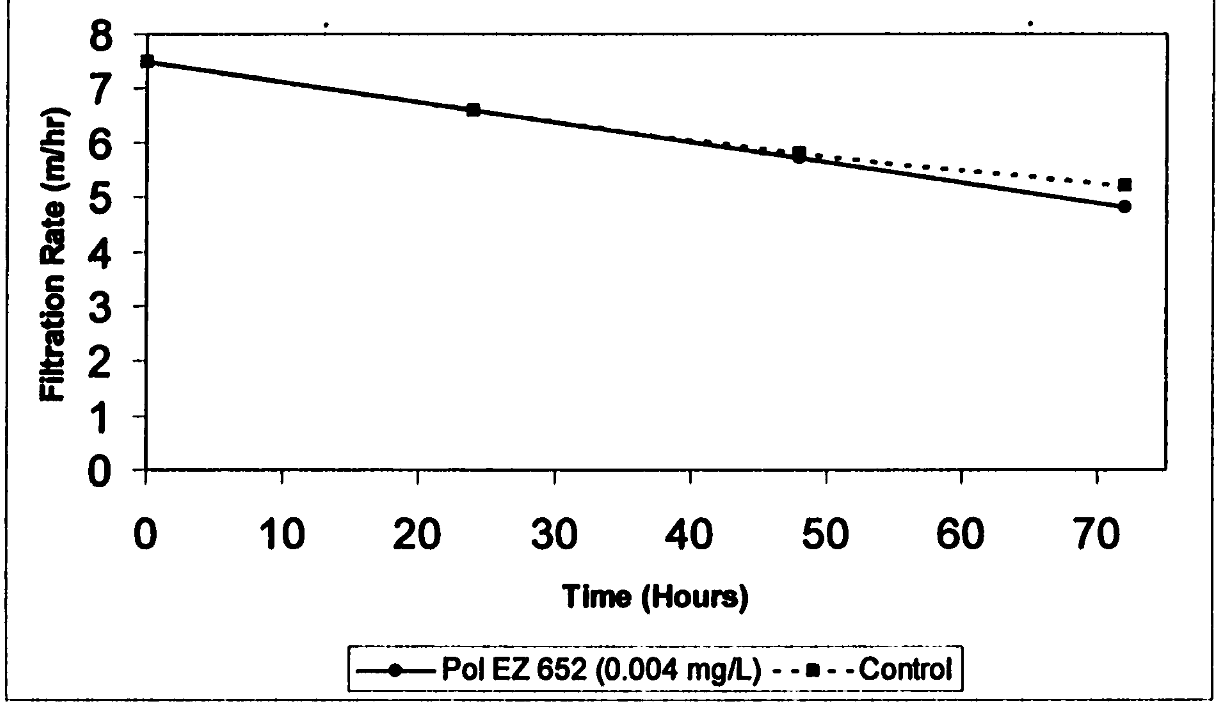

Pol EZ 652 (0.004 mg/L) Particle Counts
Total Particles (>2μm/ml)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
Time (Hours)
Pol EZ 652 (0.004 mg/L)
Control

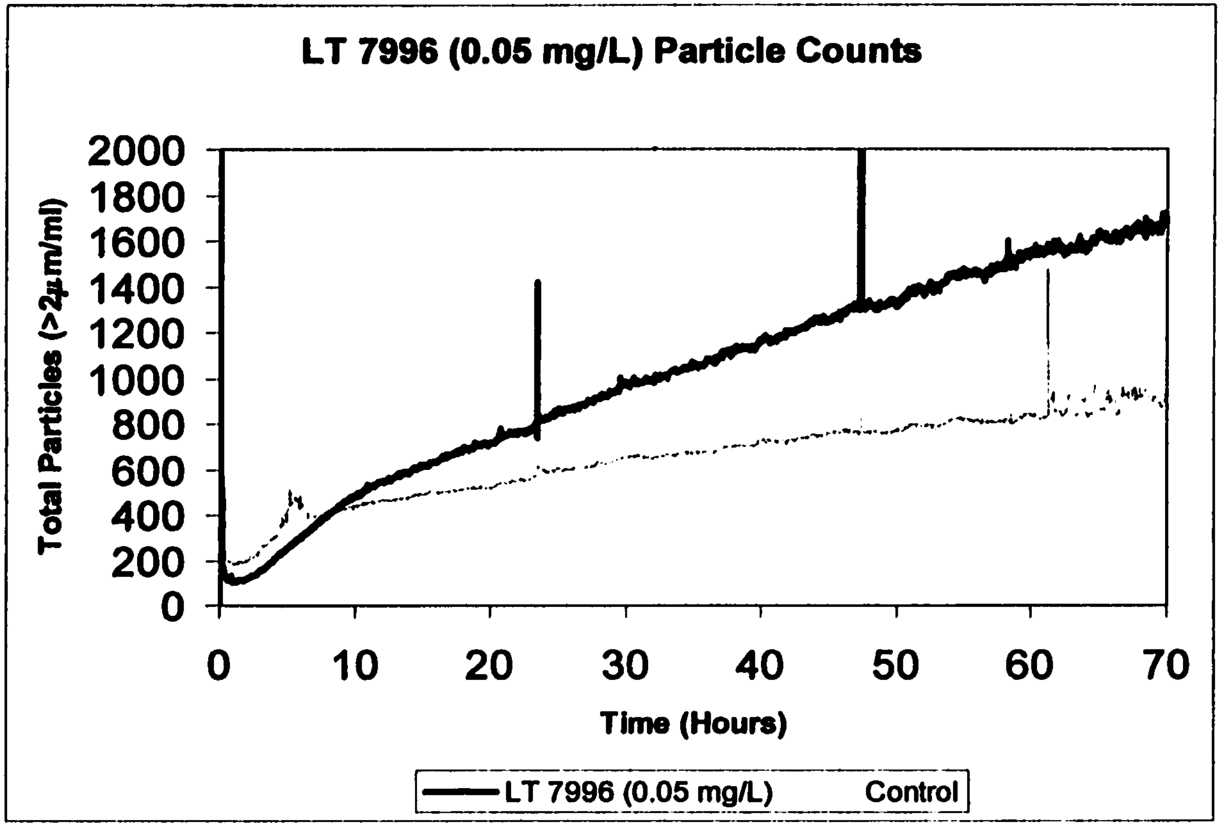


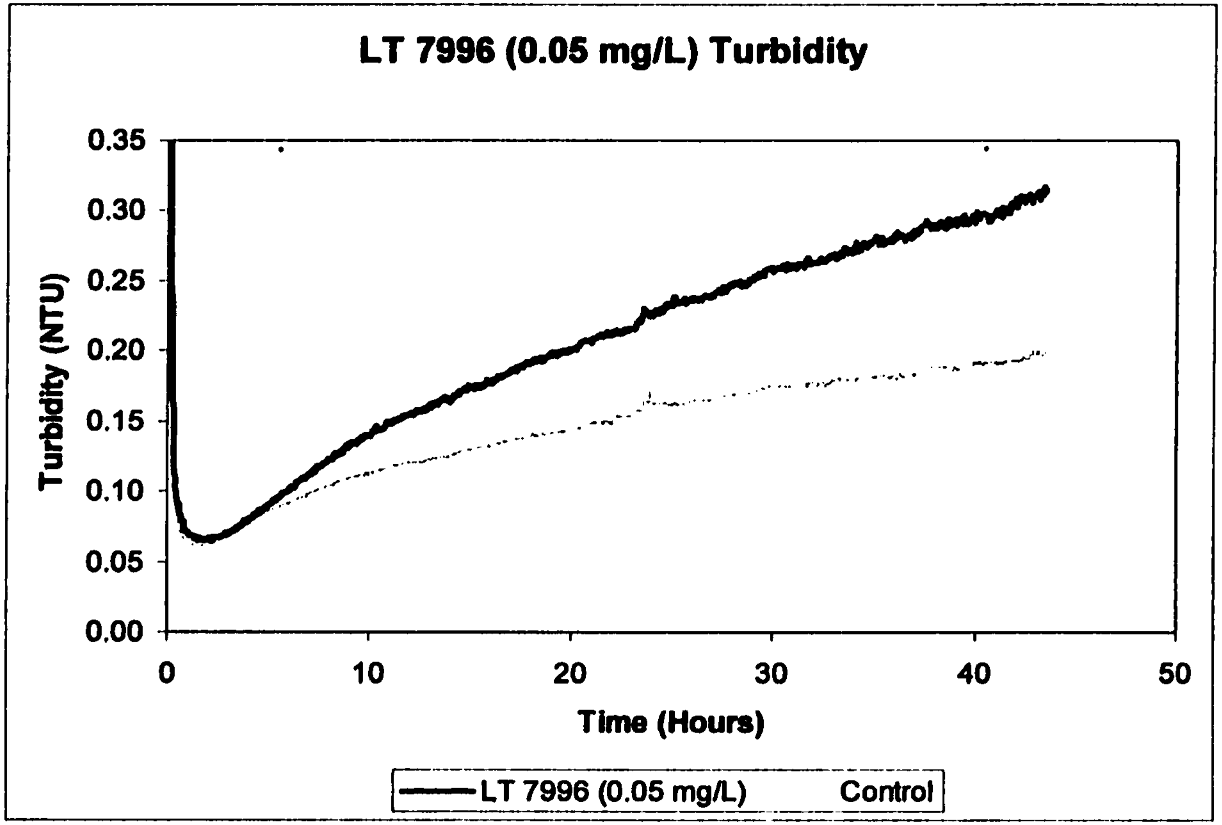
Pol E-Z 652 (0.004 mg/L) Turbidity
Turbidity (NTU)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
Time (Hours)
Control
Pol EZ 652 (0.004 mg/L)

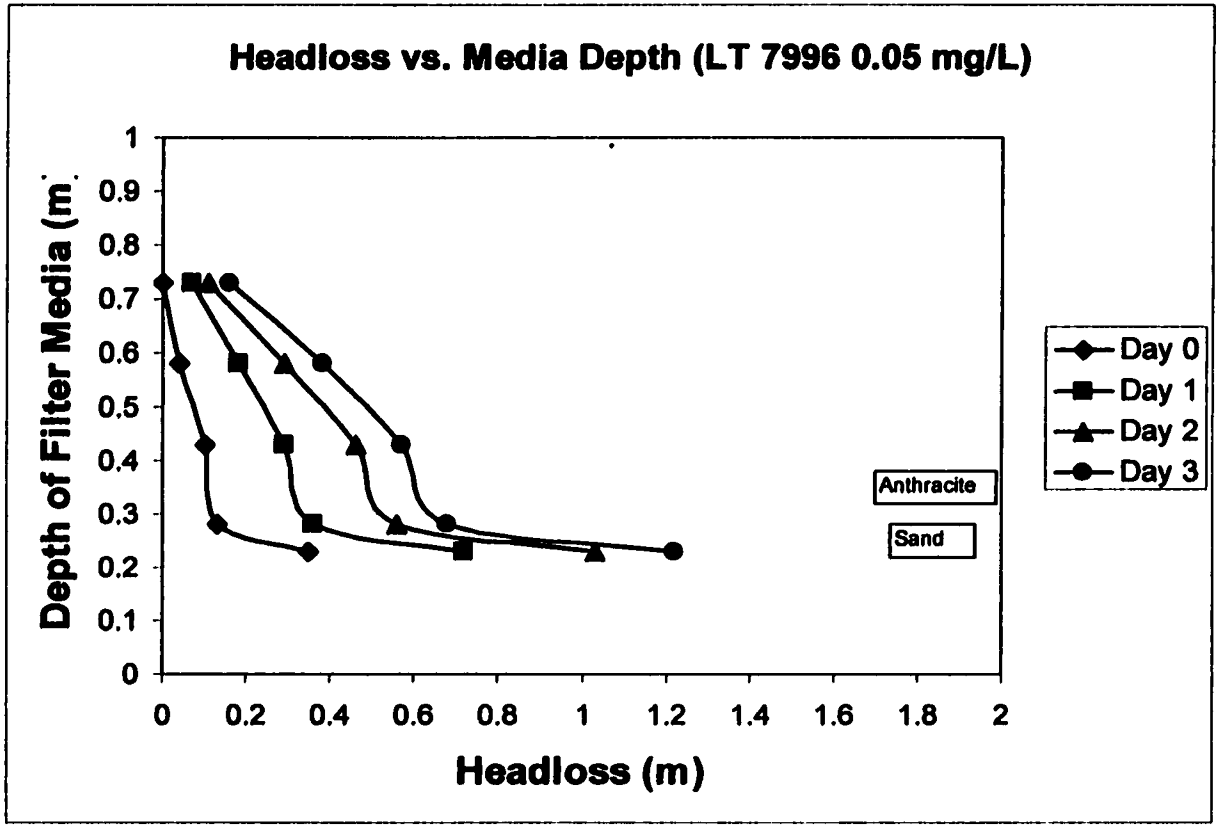

Headloss vs. Media Depth (Pol EZ 652 0.004 mg/L)
Depth of Filter Media (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
Headloss (m)
Anthracite
San
Day 0
Day 1
Day 2
Day 3

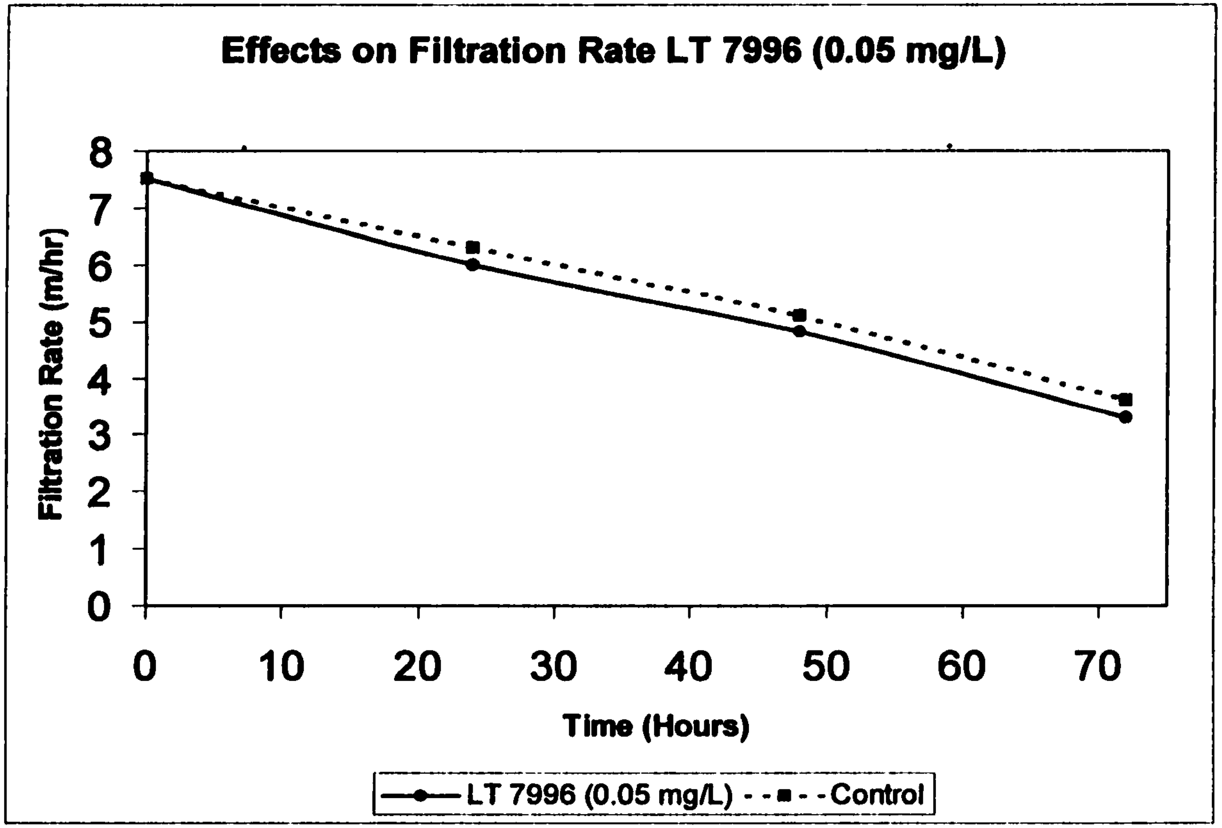
Pol E-Z 652 (0.004 mg/L) Effects on Filtration Rate

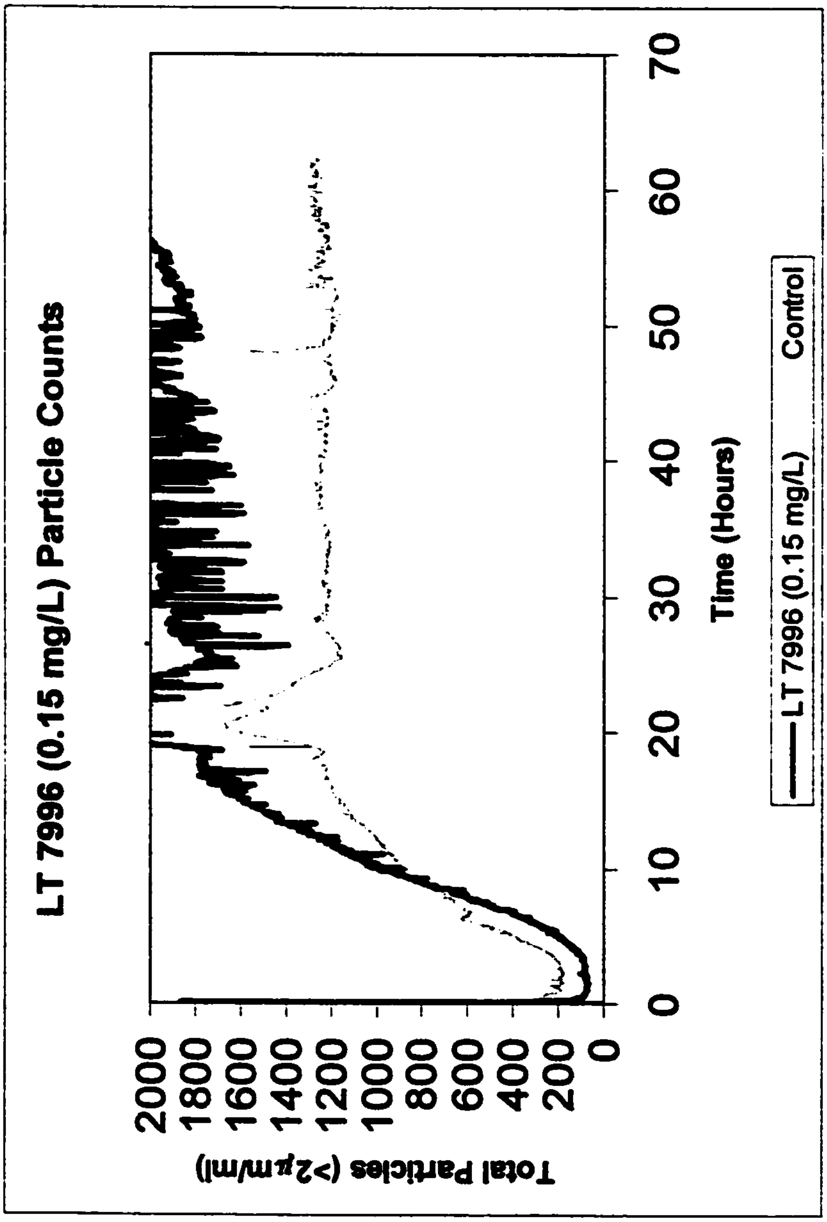


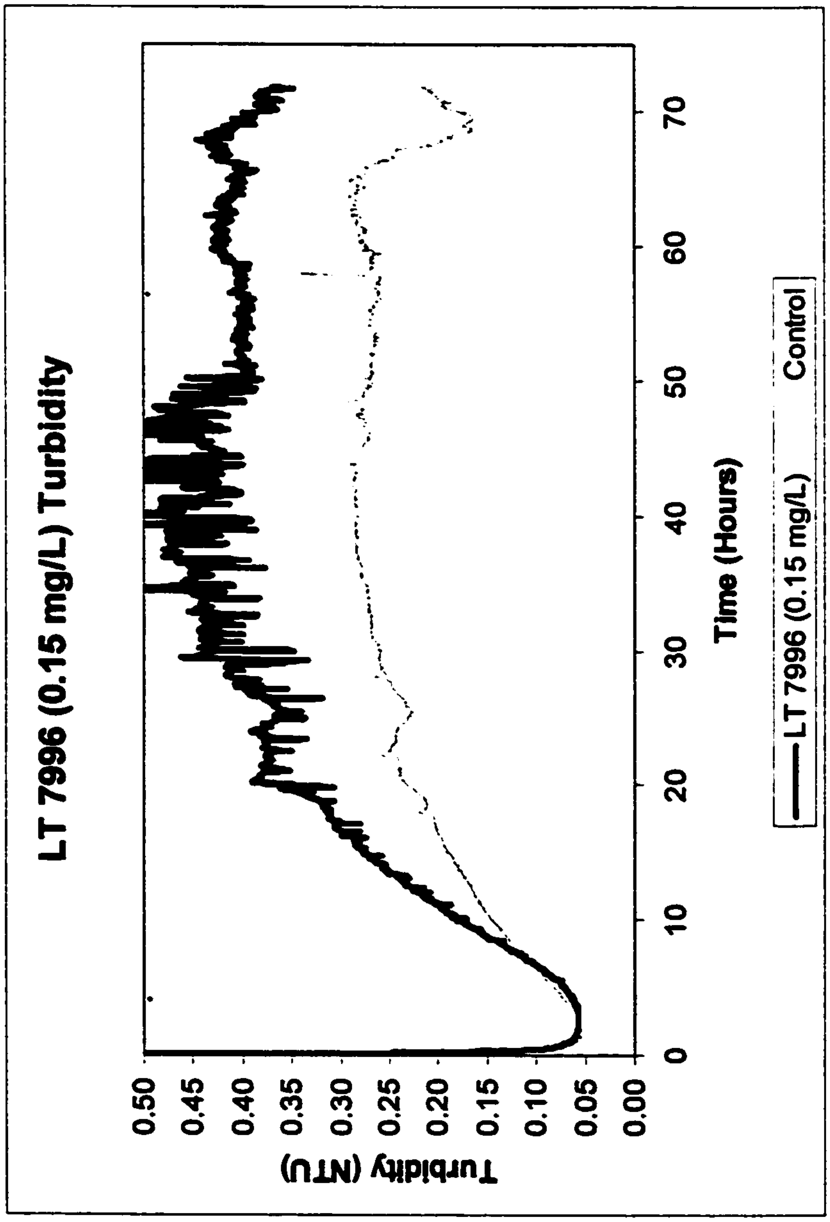

LT 7996 (0.05 mg/L) Particle Counts
Total Particles (>2μm/ml)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
Time (Hours)
LT 7996 (0.05 mg/L)
Control

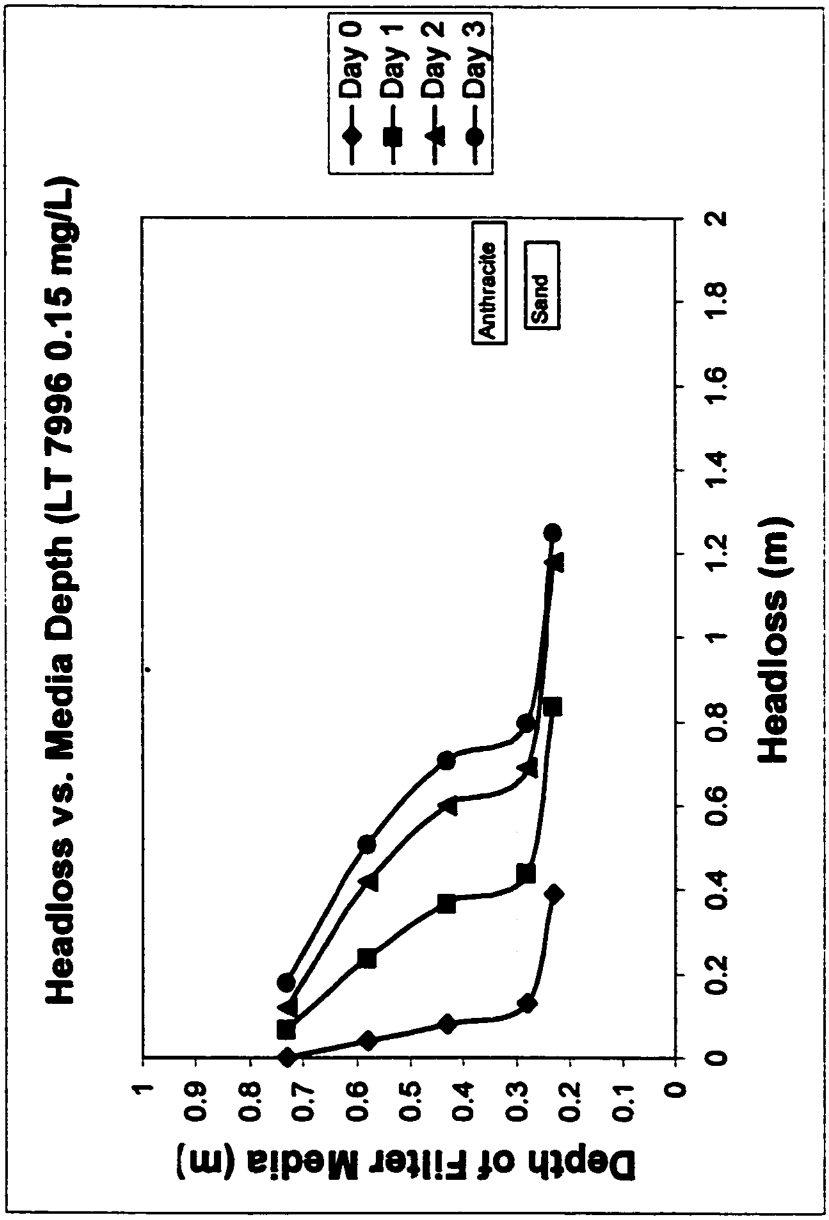

LT 7996 (0.05 mg/L) Turbidity
Turbidity (NTU)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
Time (Hours)
LT 7996 (0.05 mg/L)
Control

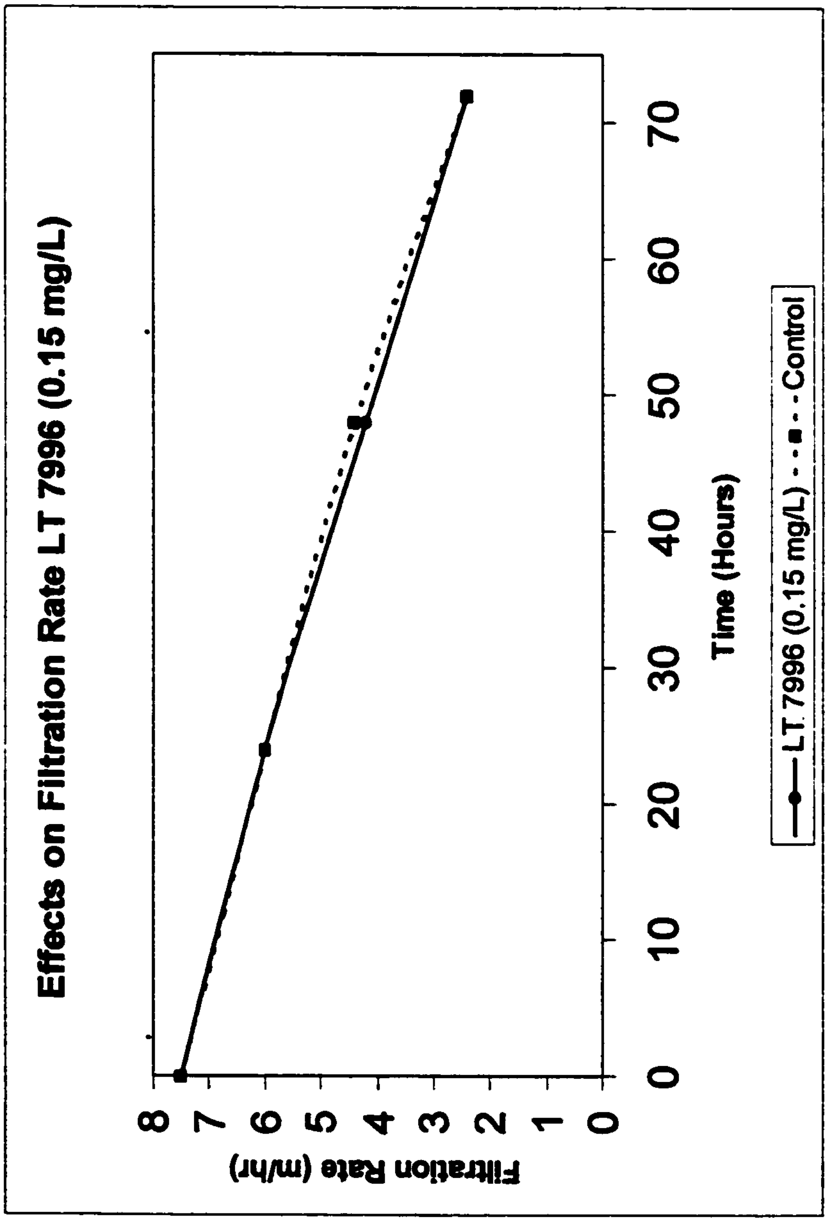

Headloss vs. Media Depth (LT 7996 0.05 mg/L)
Depth of Filter Media (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Headloss (m)
Anthracite
Sand
Day 0
Day 1
Day 2
Day 3

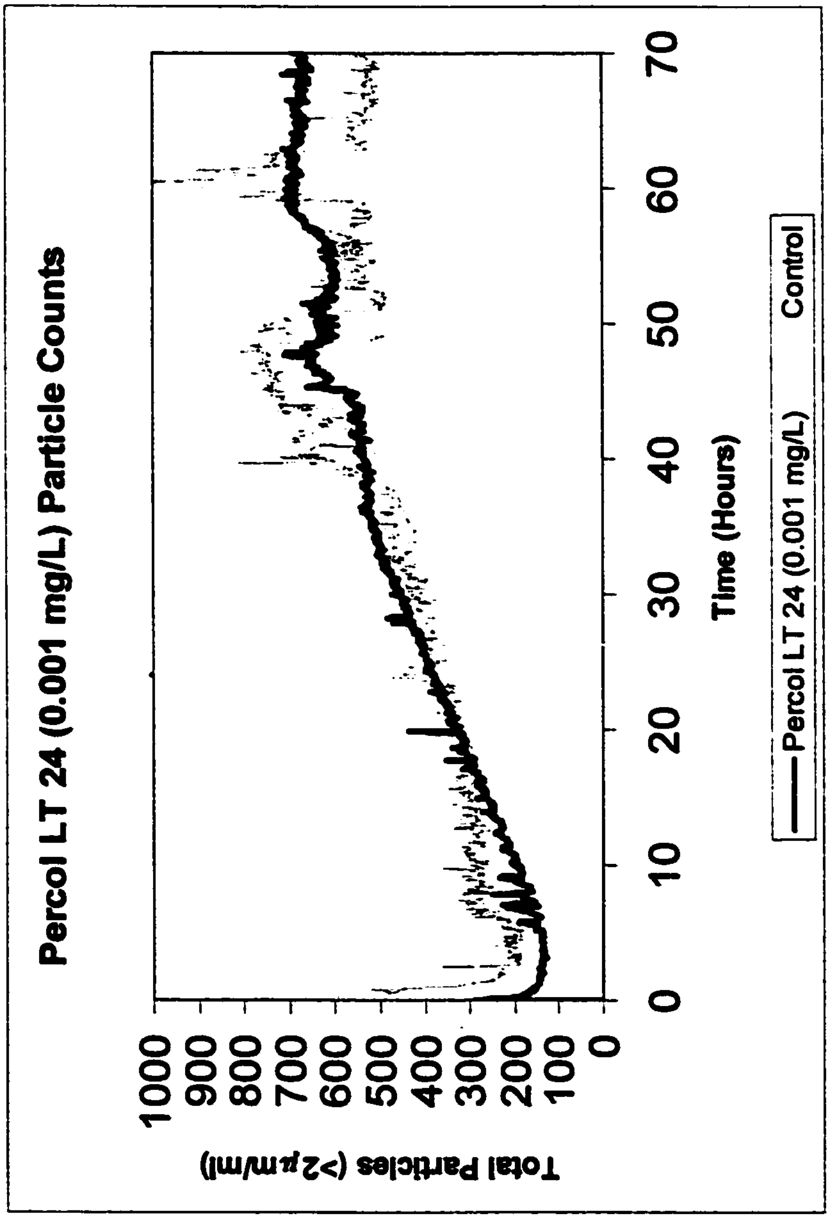

Effects on Filtration Rate LT 7996 (0.05 mg/L)
Filtration Rate (m/hr)
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Time (Hours)
LT 7996 (0.05 mg/L)
Control

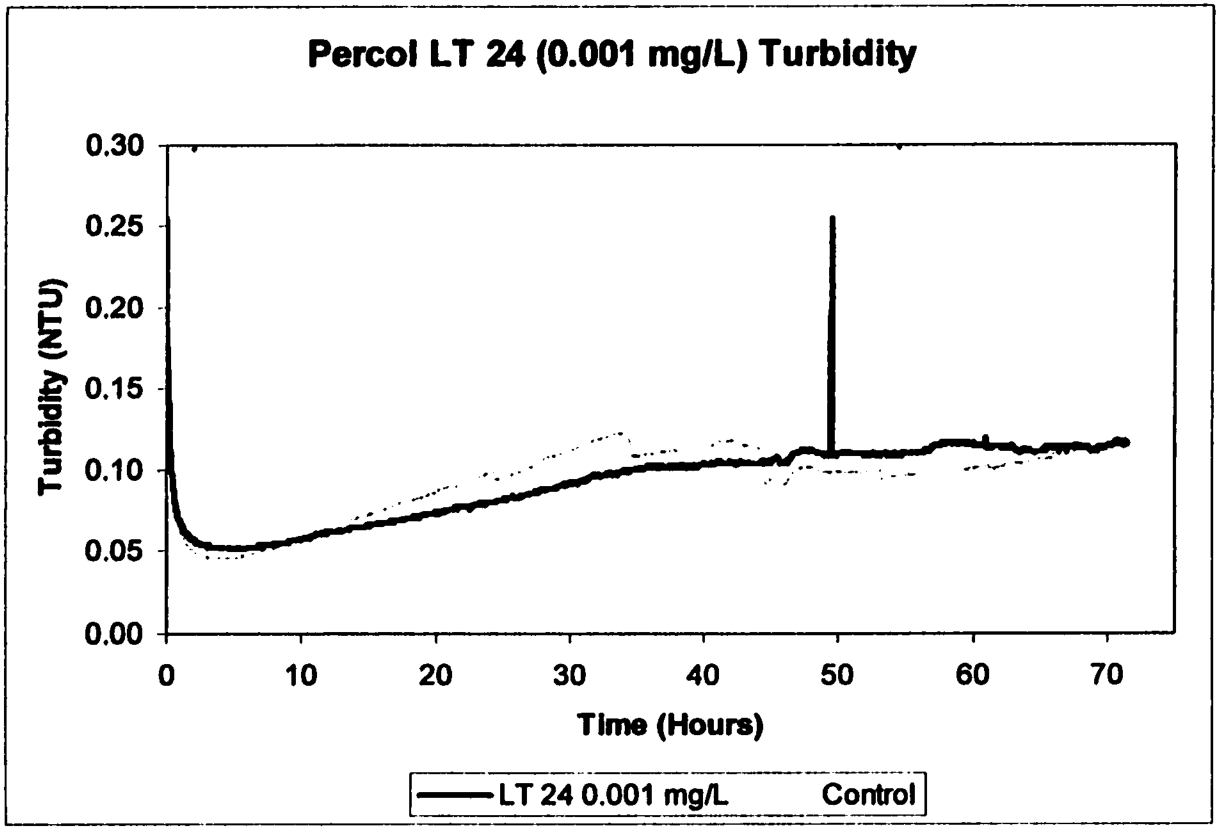

LT 7996 (0.15 mg/L) Particle Counts
Total Particles (>2µm/ml)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
Time (Hours)
LT 7996 (0.15 mg/L)
Control

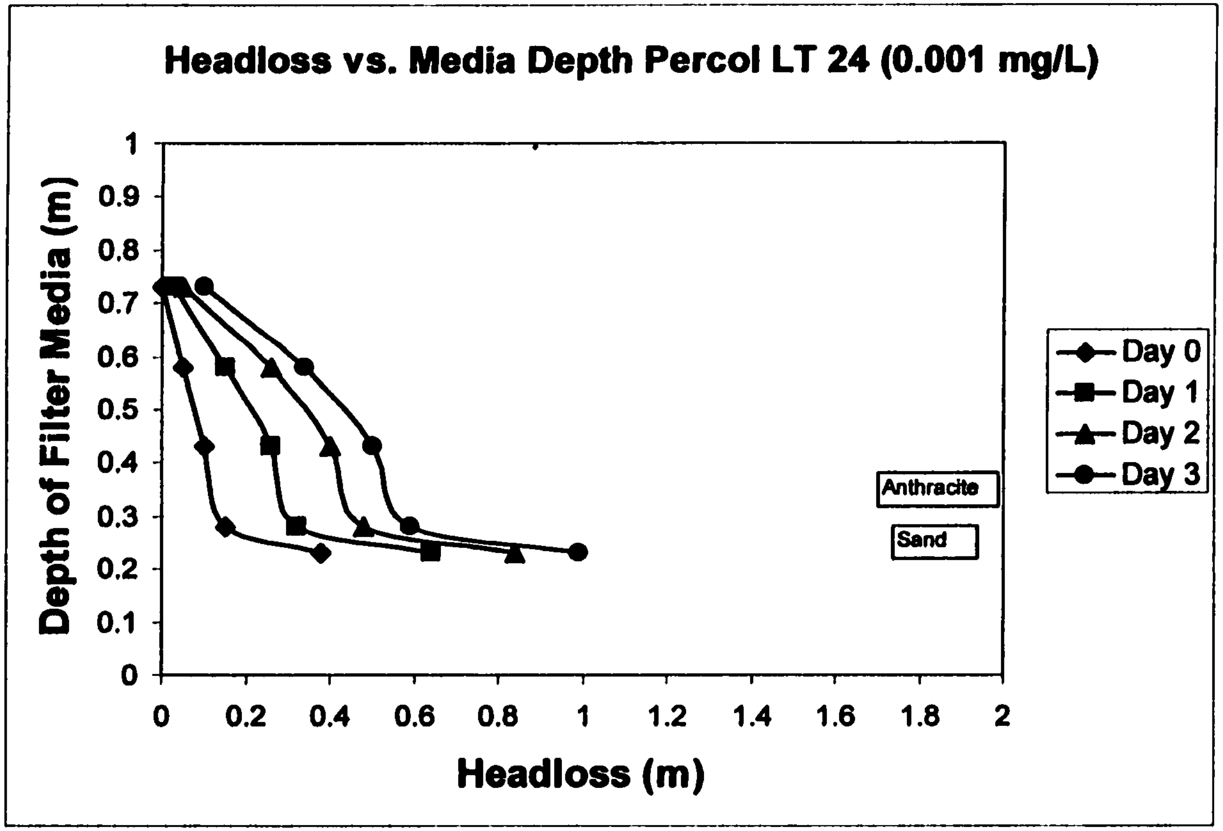

LT 7996 (0.15 mg/L) Turbidity
Turbidity (NTU)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
Time (Hours)
LT 7996 (0.15 mg/L)
Control

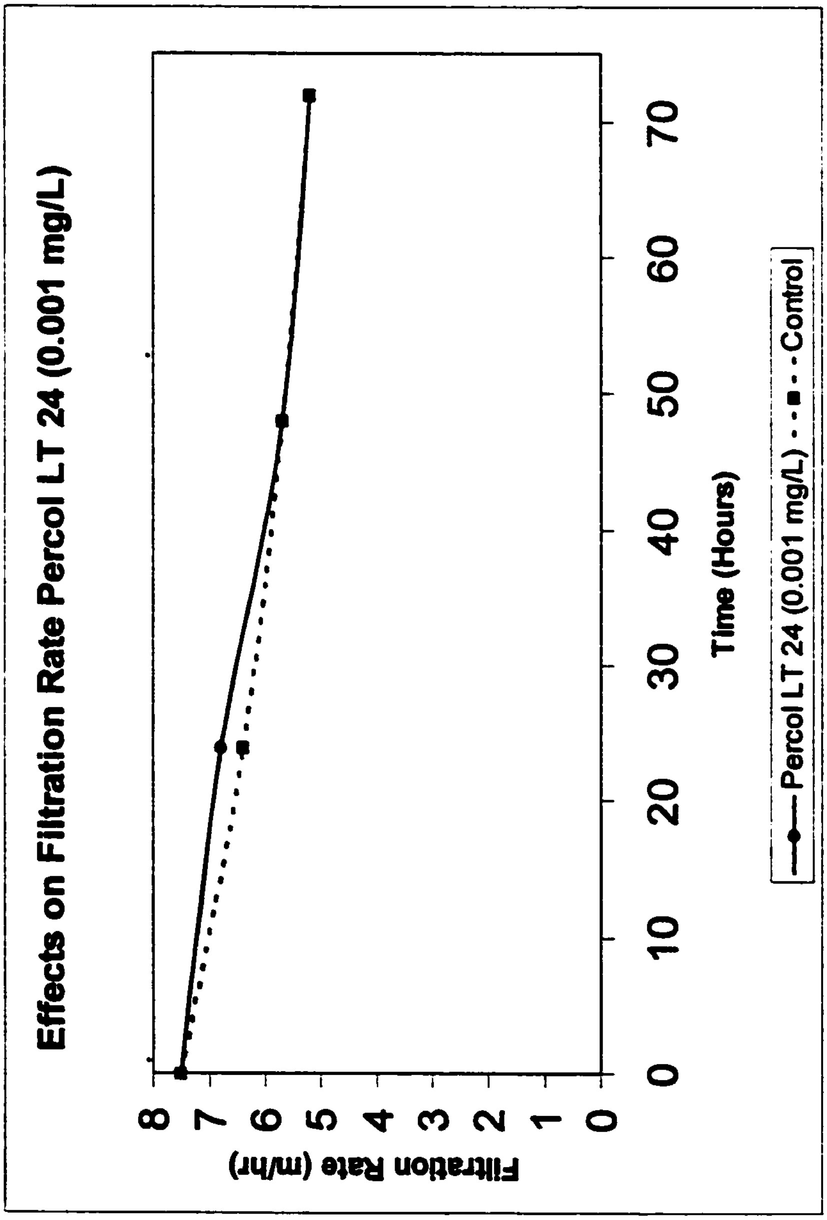

Headloss vs. Media Depth (LT 7996 0.15 mg/L)
Depth of Filter Media (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Headloss (m)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Anthracite
Sand
Day 0
Day 1
Day 2
Day 3

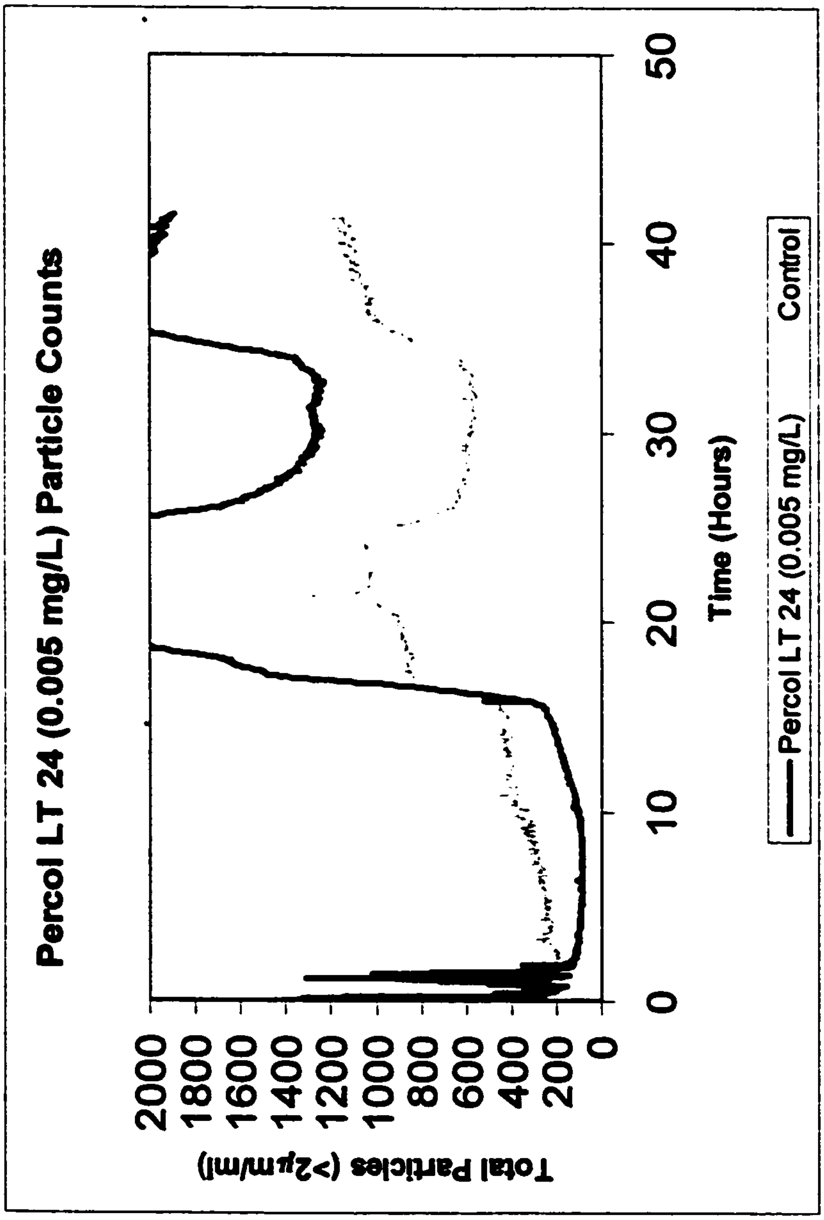

Effects on Filtration Rate LT 7996 (0.15 mg/L)
Filtration Rate (m/hr)
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Time (Hours)
LT 7996 (0.15 mg/L)
Control

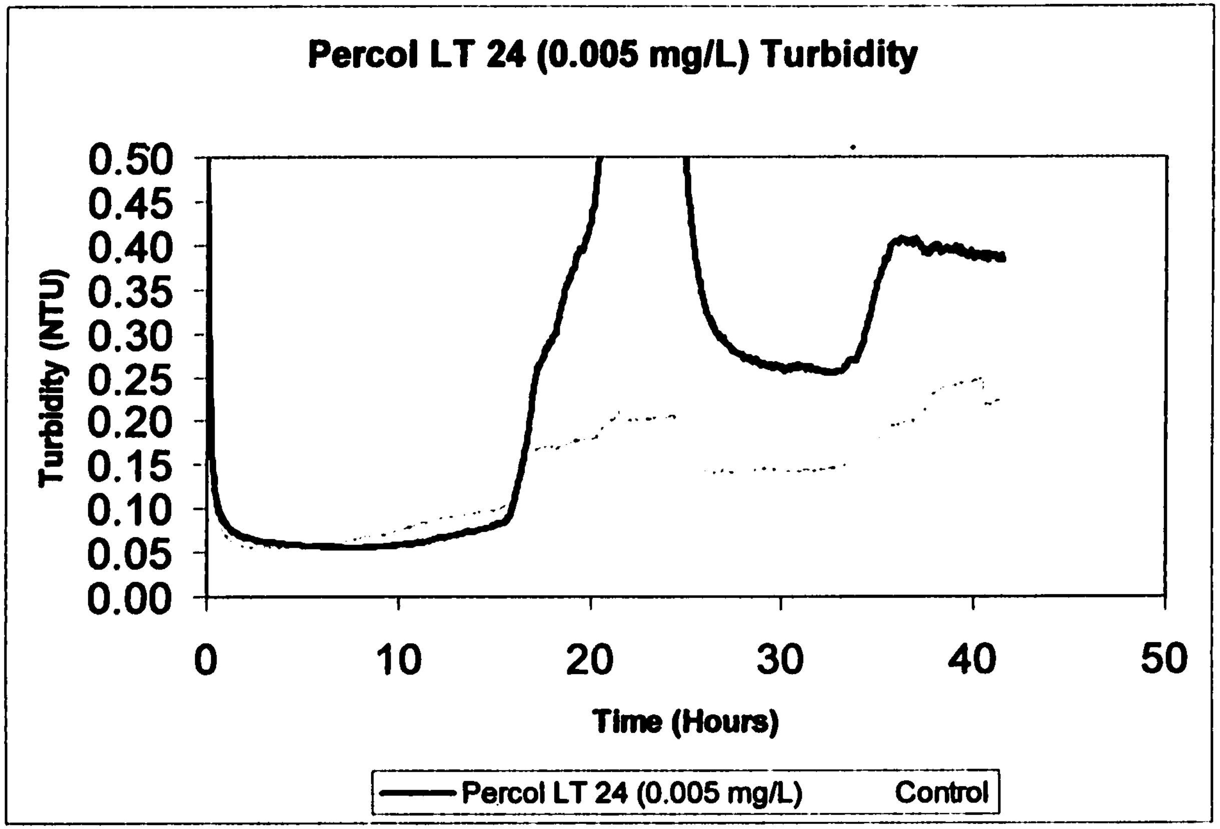

Percol LT 24 (0.001 mg/L) Particle Counts
Total Particles (>2µm/ml)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
Time (Hours)
Percol LT 24 (0.001 mg/L)
Control


Percol LT 24 (0.001 mg/L) Turbidity
Turbidity (NTU)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
Time (Hours)
LT 24 0.001 mg/L
Control

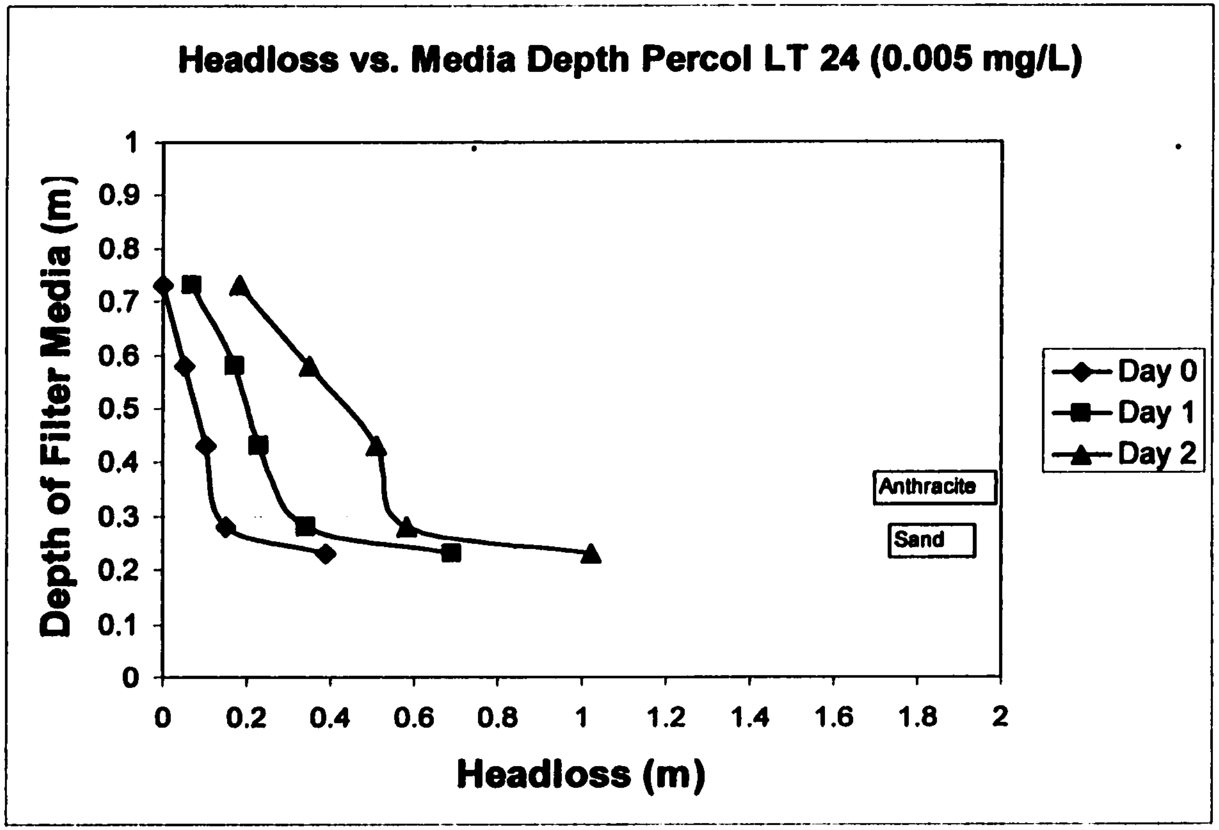

Headloss vs. Media Depth Percol LT 24 (0.001 mg/L)
Depth of Filter Media (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Headloss (m)
Anthracite
Sand
Day 0
Day 1
Day 2
Day 3


Effects on Filtration Rate Percol LT 24 (0.001 mg/L)
Filtration Rate (m/hr)
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Time (Hours)
Percol LT 24 (0.001 mg/L)
Control

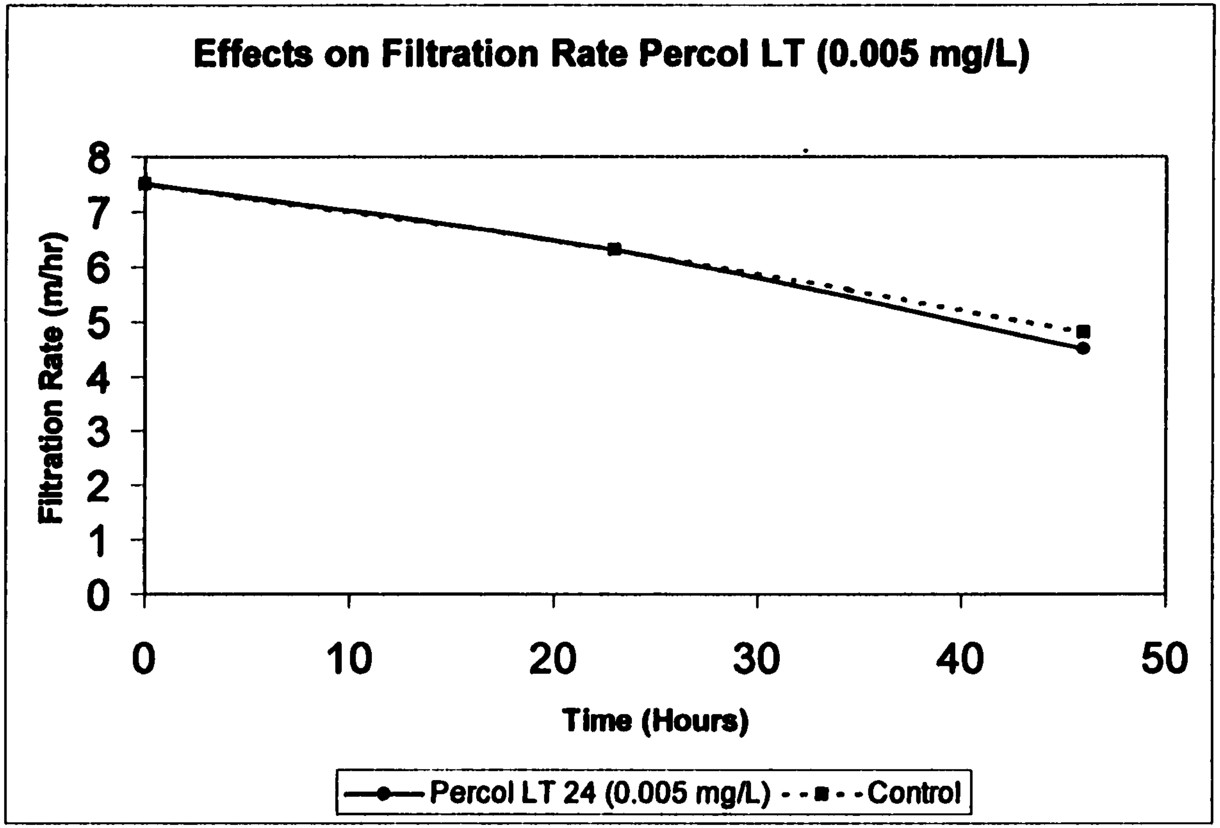

Percol LT 24 (0.005 mg/L) Particle Counts
Total Particles (>2µm/ml)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
10
20
30
40
50
Time (Hours)
Percol LT 24 (0.005 mg/L)
Control

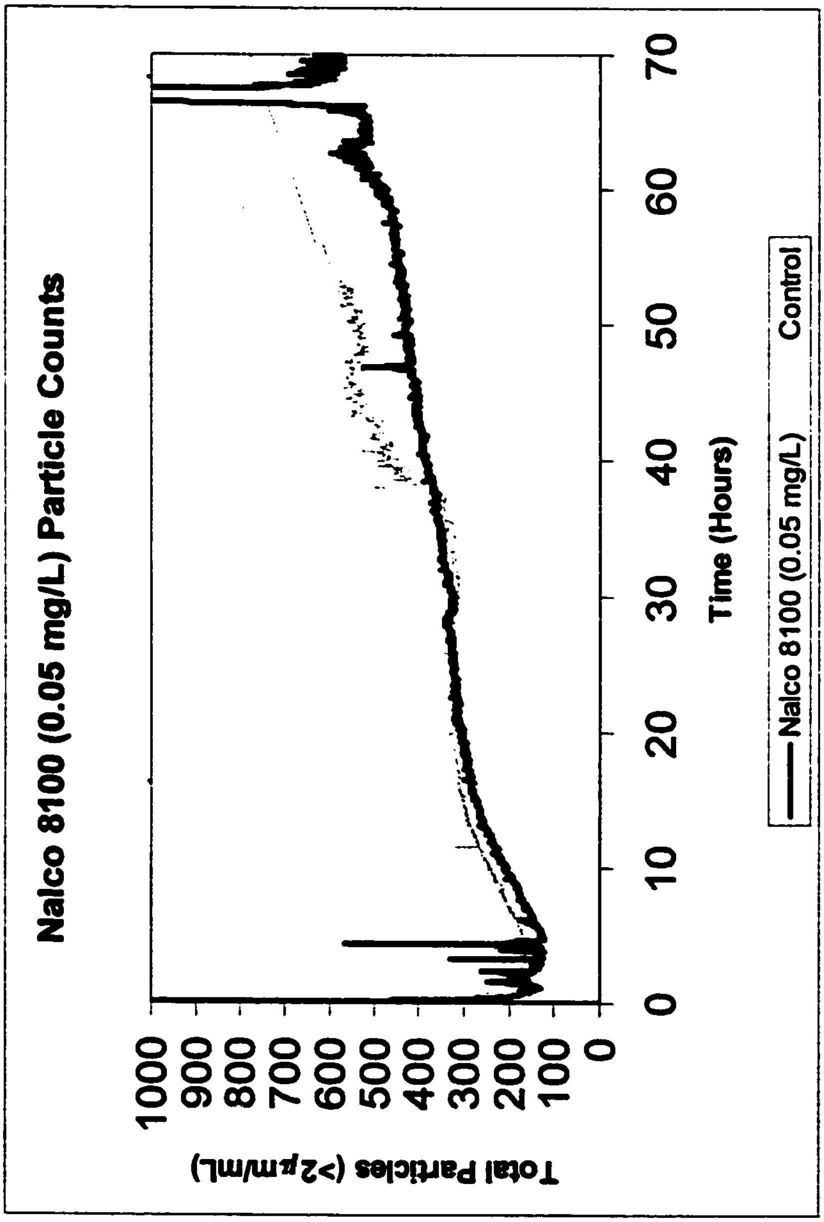


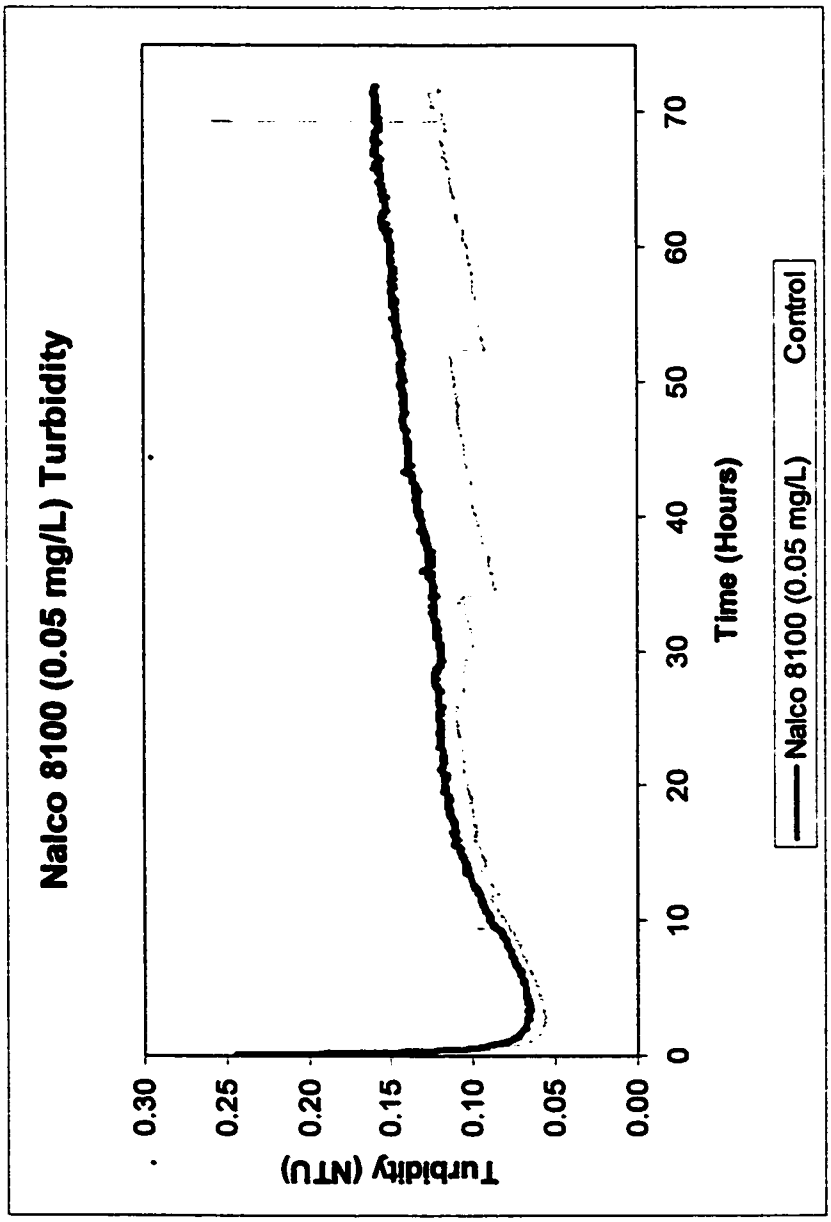
Percol LT 24 (0.005 mg/L) Turbidity
Turbidity (NTU)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
Time (Hours)
Percol LT 24 (0.005 mg/L)
Control

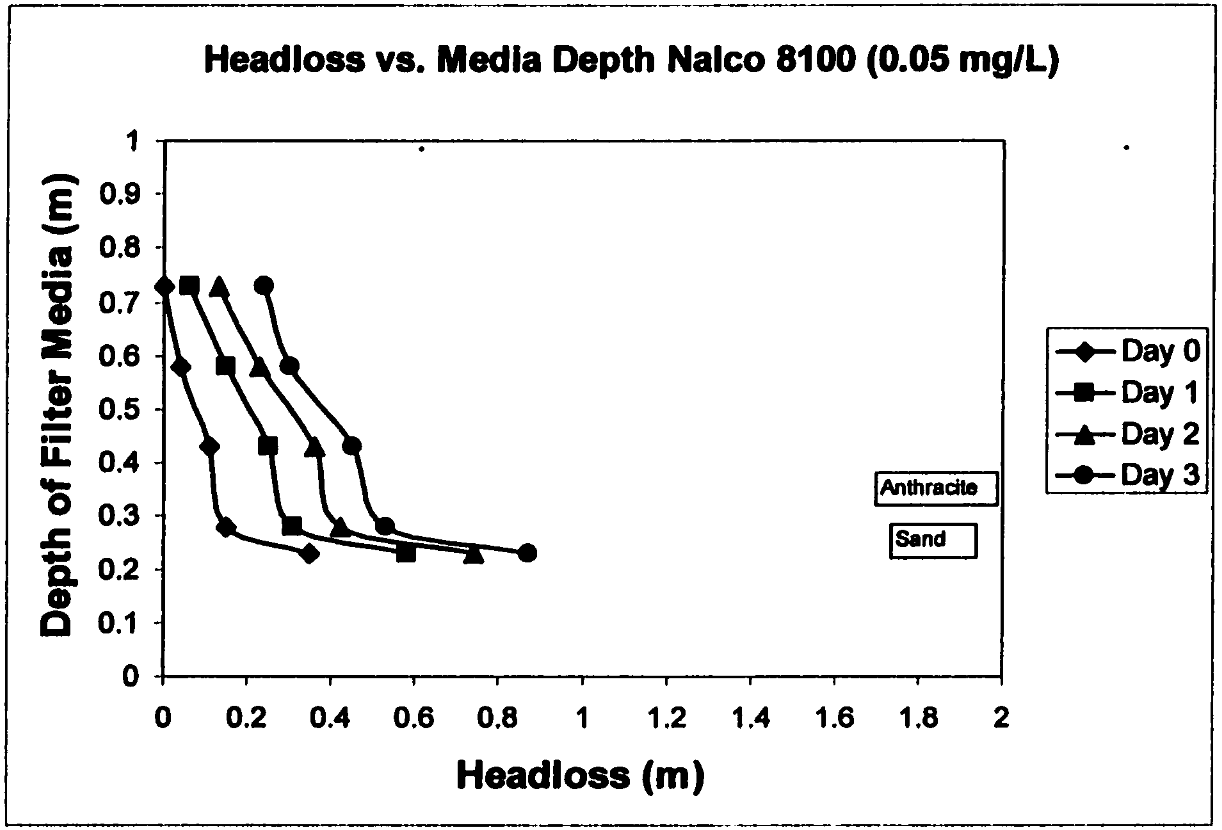


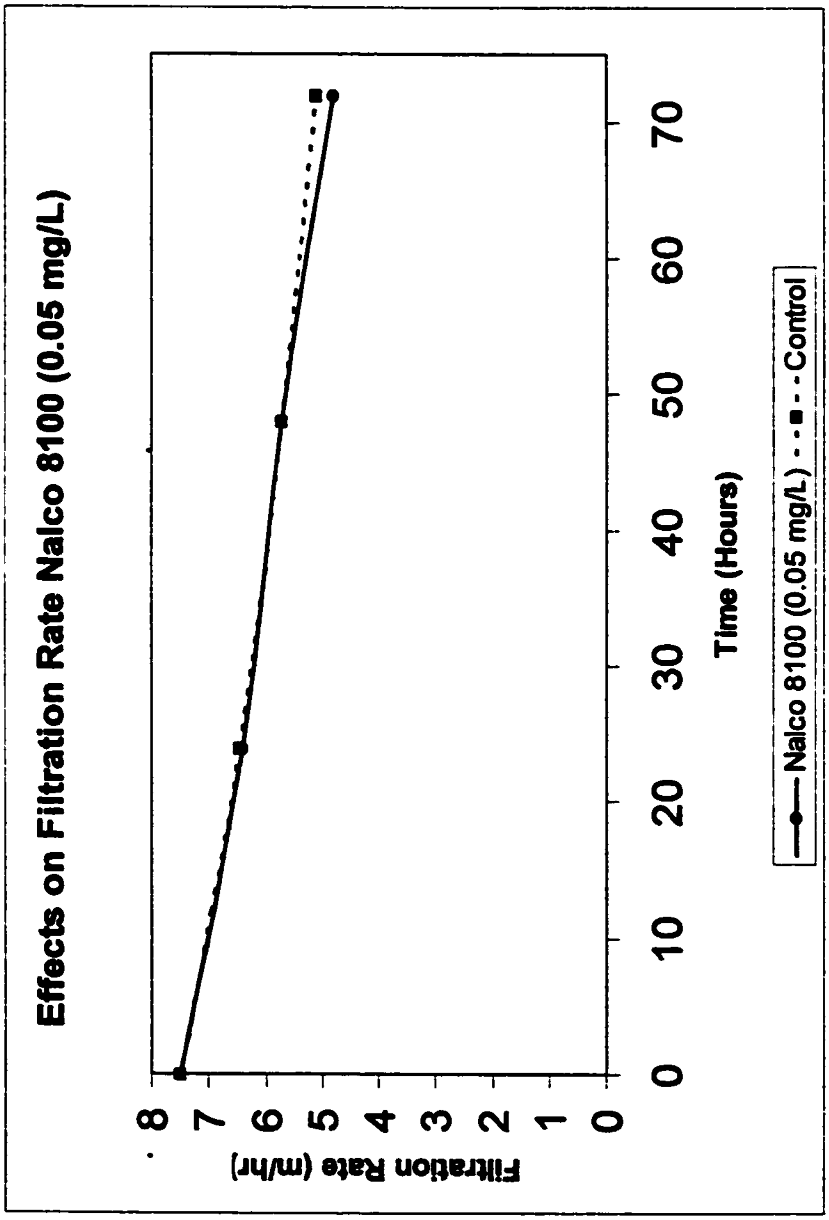
Headloss vs. Media Depth Percol LT 24 (0.005 mg/L)

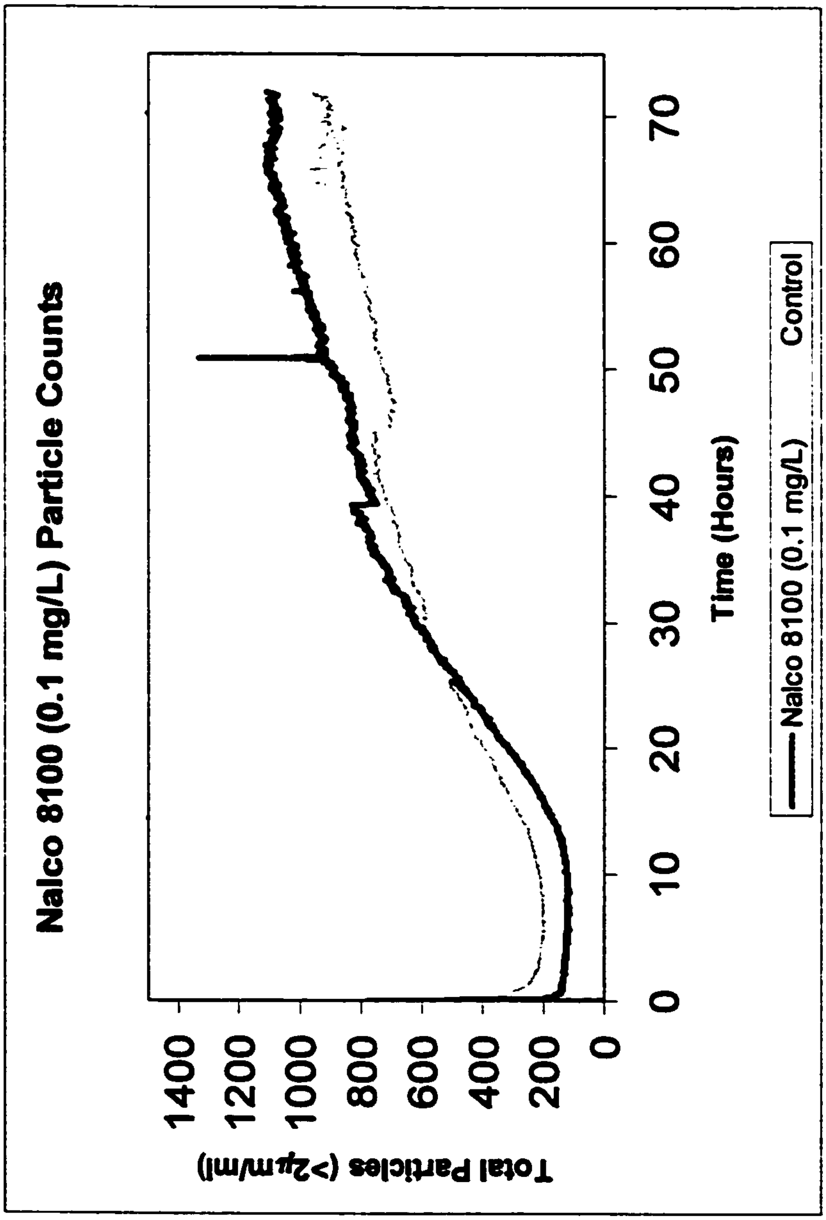

Effects on Filtration Rate Percol LT (0.005 mg/L)
Filtration Rate (m/hr)
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
Time (Hours)
Percol LT 24 (0.005 mg/L)
Control

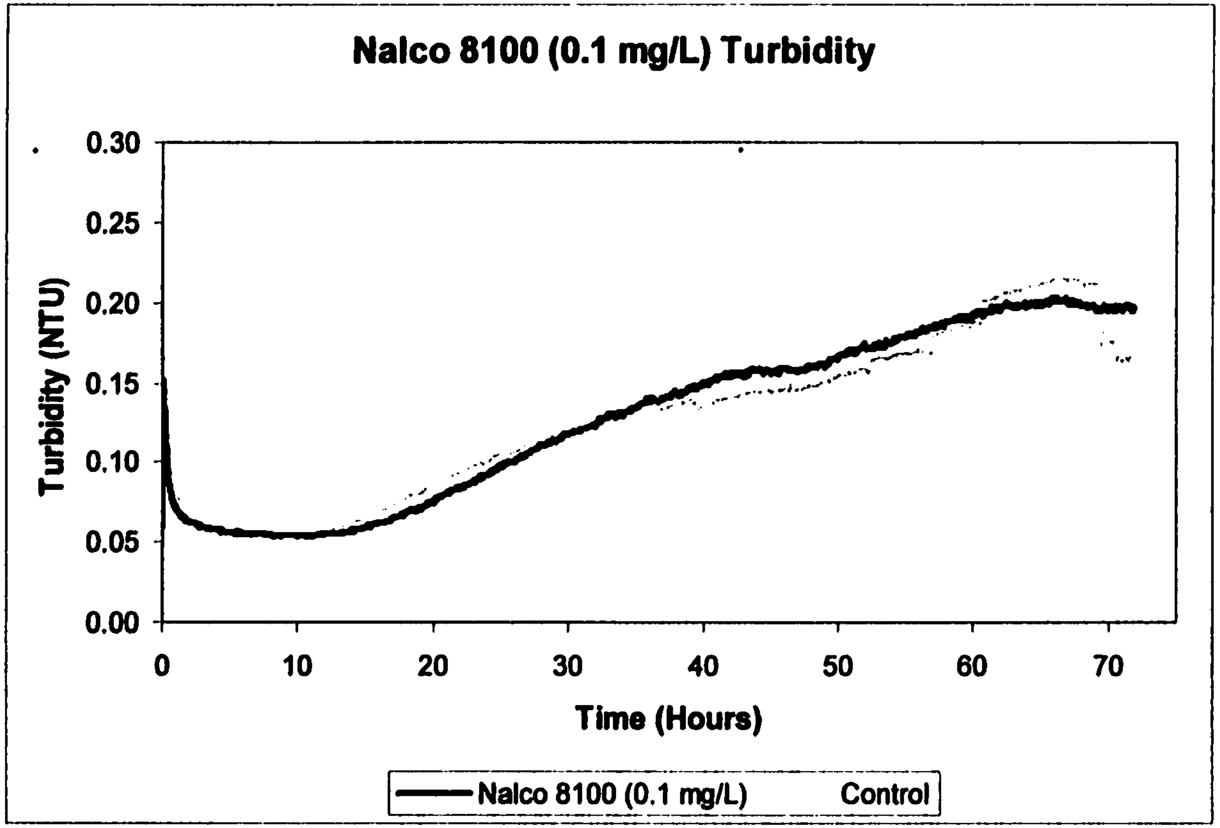

Nalco 8100 (0.05 mg/L) Particle Counts
Total Particles (>2µm/mL)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
Time (Hours)
Nalco 8100 (0.05 mg/L)
Control

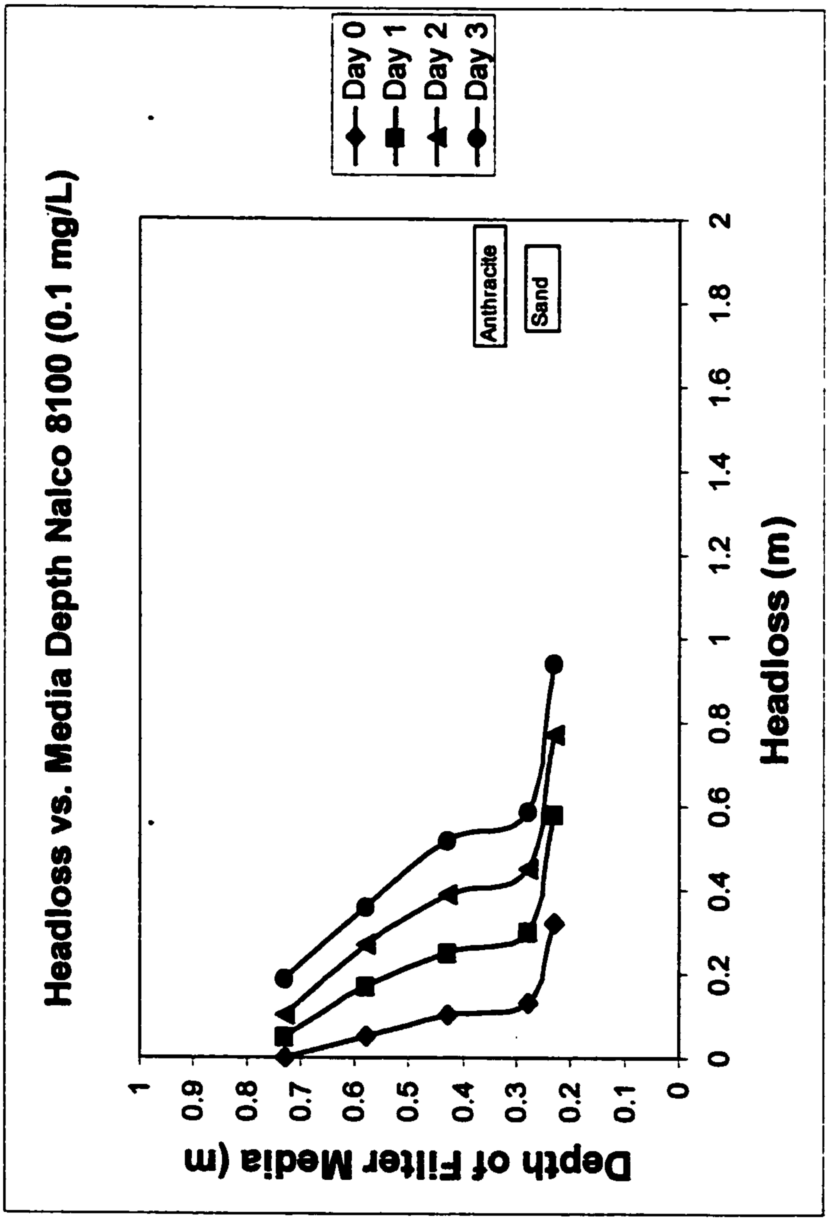

Nalco 8100 (0.05 mg/L) Turbidity
Turbidity (NTU)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
Time (Hours)
Nalco 8100 (0.05 mg/L)
Control

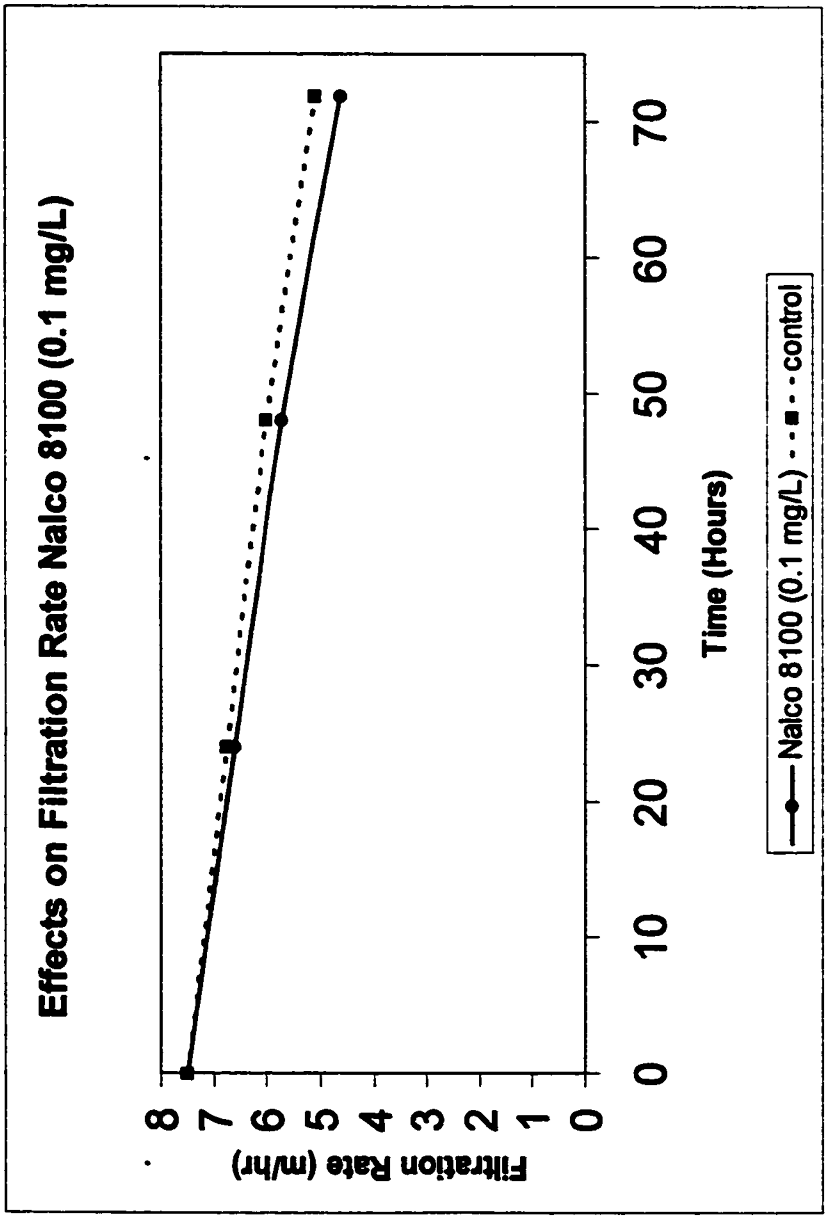

Headloss vs. Media Depth Nalco 8100 (0.05 mg/L)
Depth of Filter Media (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Headloss (m)
Anthracite
Sand
Day 0
Day 1
Day 2
Day 3


Effects on Filtration Rate Nalco 8100 (0.05 mg/L)
Filtration Rate (m/hr)
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Time (Hours)
Nalco 8100 (0.05 mg/L)
Control


Nalco 8100 (0.1 mg/L) Particle Counts
Total Particles (>2µm/ml)
0
200
400
600
800
1000
1200
1400
0
10
20
30
40
50
60
70
Time (Hours)
Nalco 8100 (0.1 mg/L)
Control


Nalco 8100 (0.1 mg/L) Turbidity
Turbidity (NTU)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
Time (Hours)
Nalco 8100 (0.1 mg/L)
Control


Headloss vs. Media Depth Nalco 8100 (0.1 mg/L)
Depth of Filter Media (m
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Headloss (m)
Anthracite
Sand
Day 0
Day 1
Day 2
Day 3


Effects on Filtration Rate Nalco 8100 (0.1 mg/L)
Filtration Rate (m/hr)
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Time (Hours)
Nalco 8100 (0.1 mg/L)
control

Appendix D: Pilot Plant Facilities

Plate 1: Filter Pilot Plant

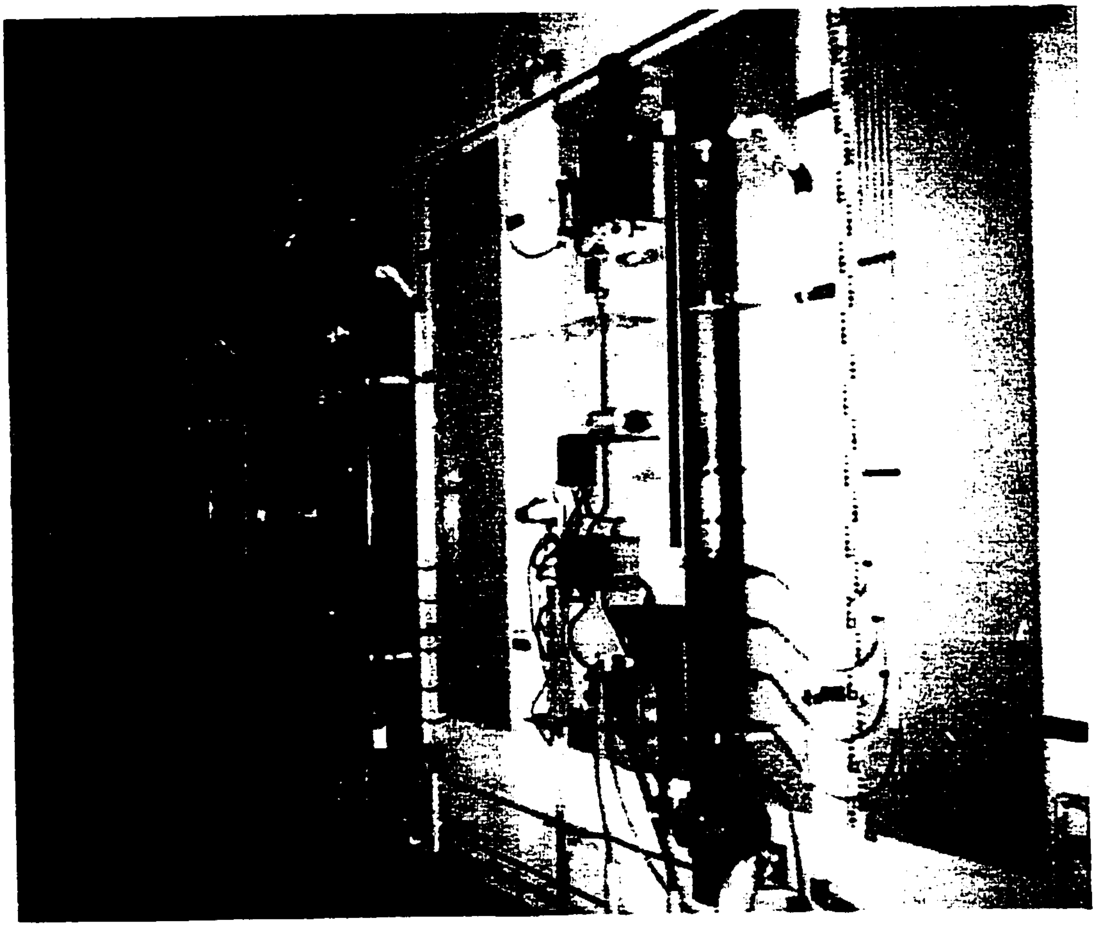


Plate 2: Filter Polymer Delivery System

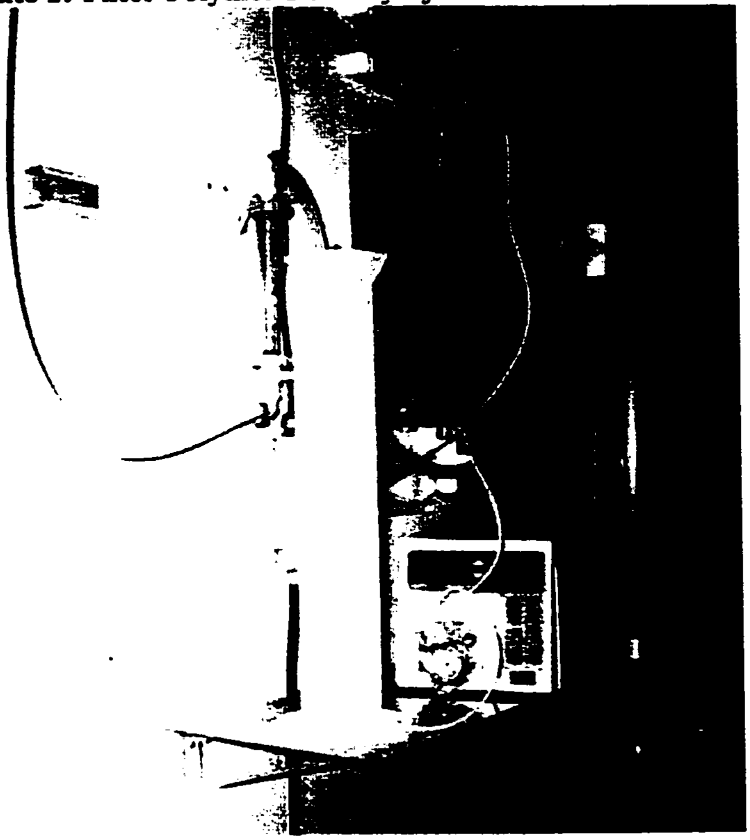


Plate 3: Main Pilot Plant Flash Mixer

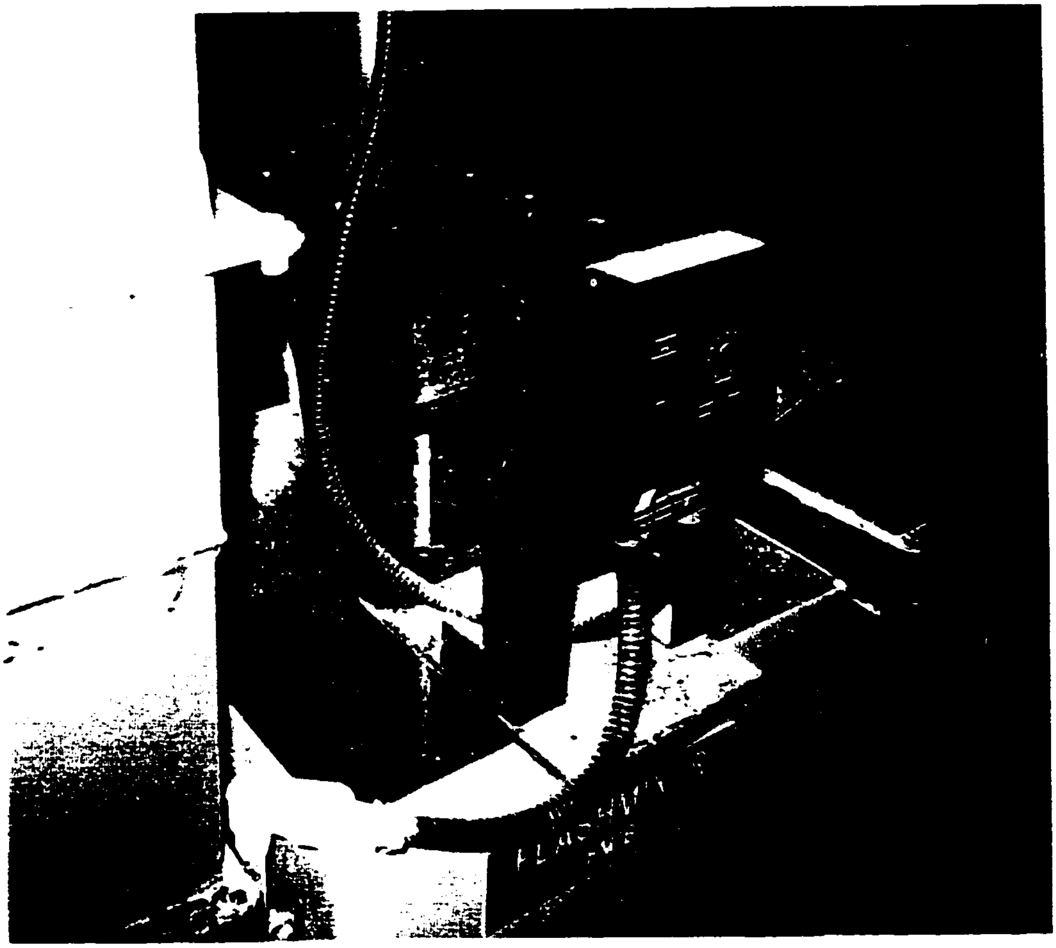


Plate 4: Main Pilot Plant Crossflow Clarifier

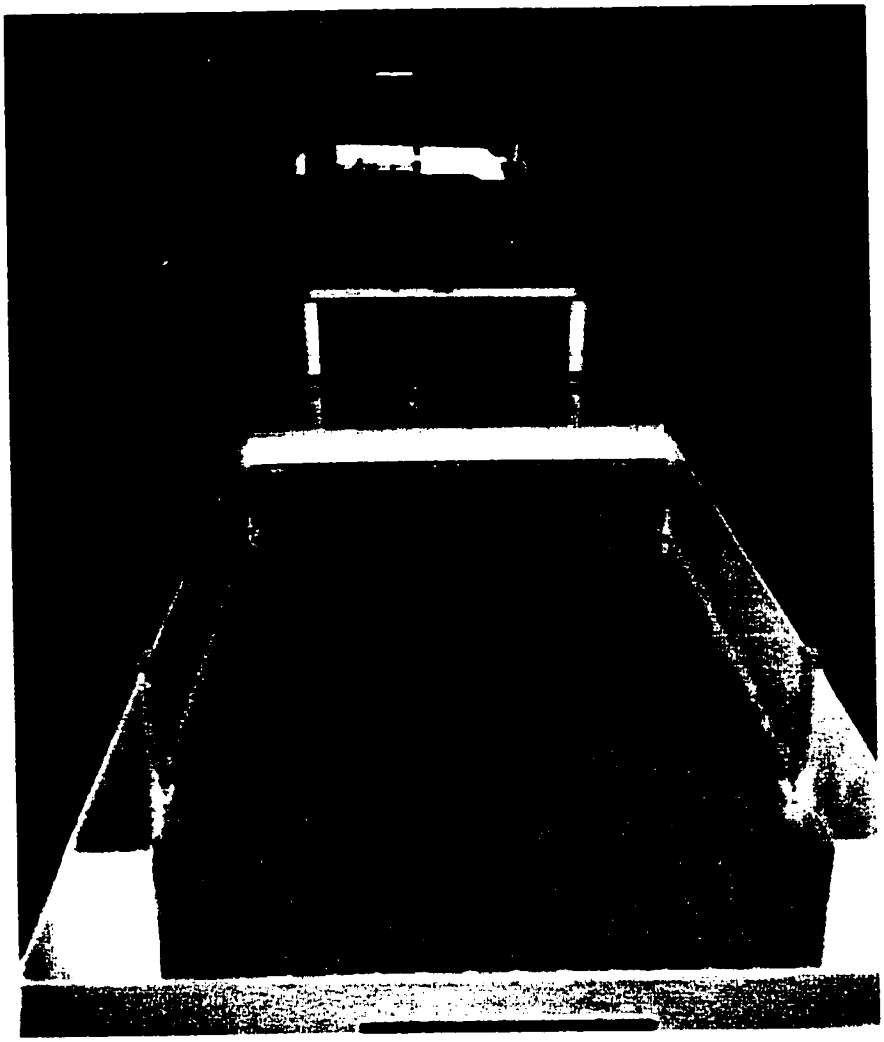


Plate 5: Main Pilot Plant Filters

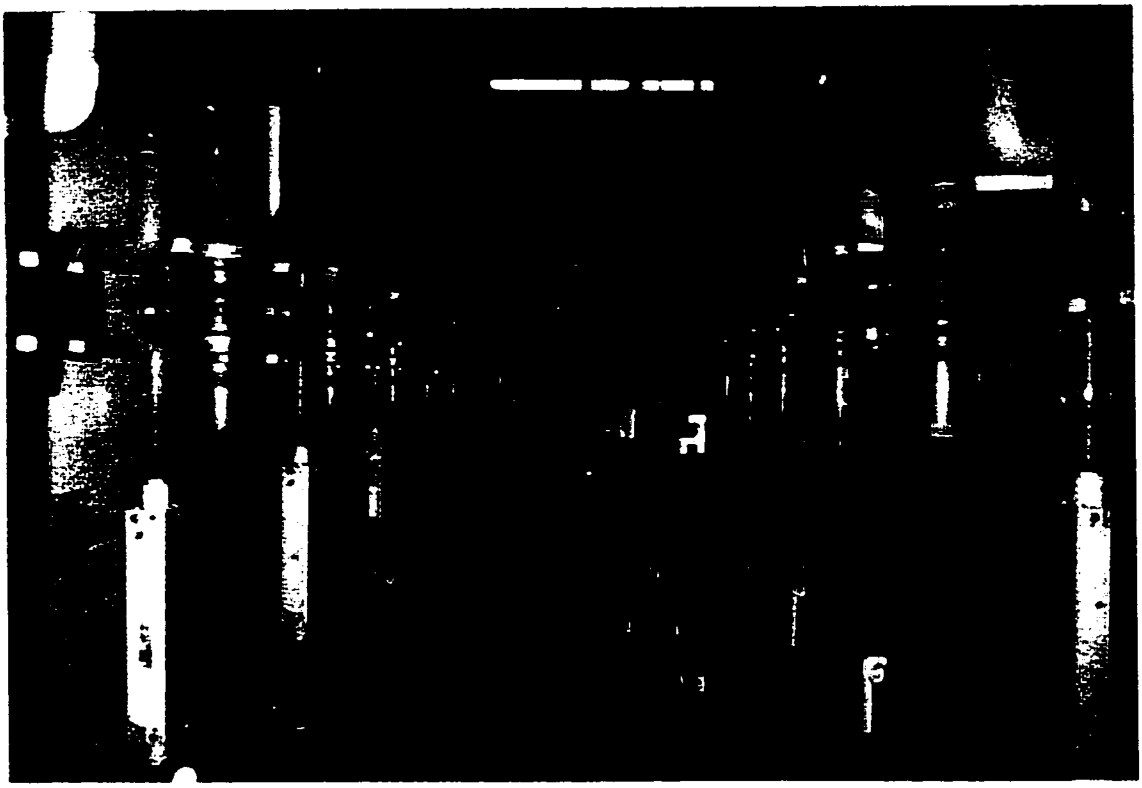


Plate 6: Zeta Meter

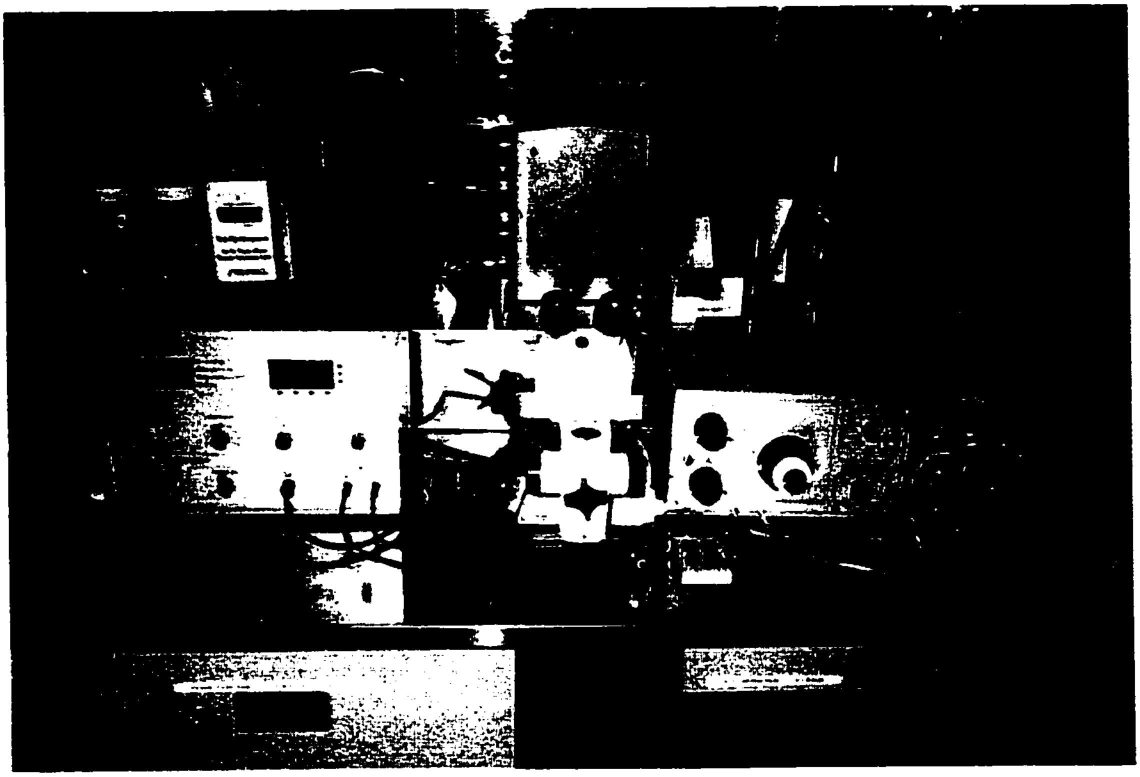
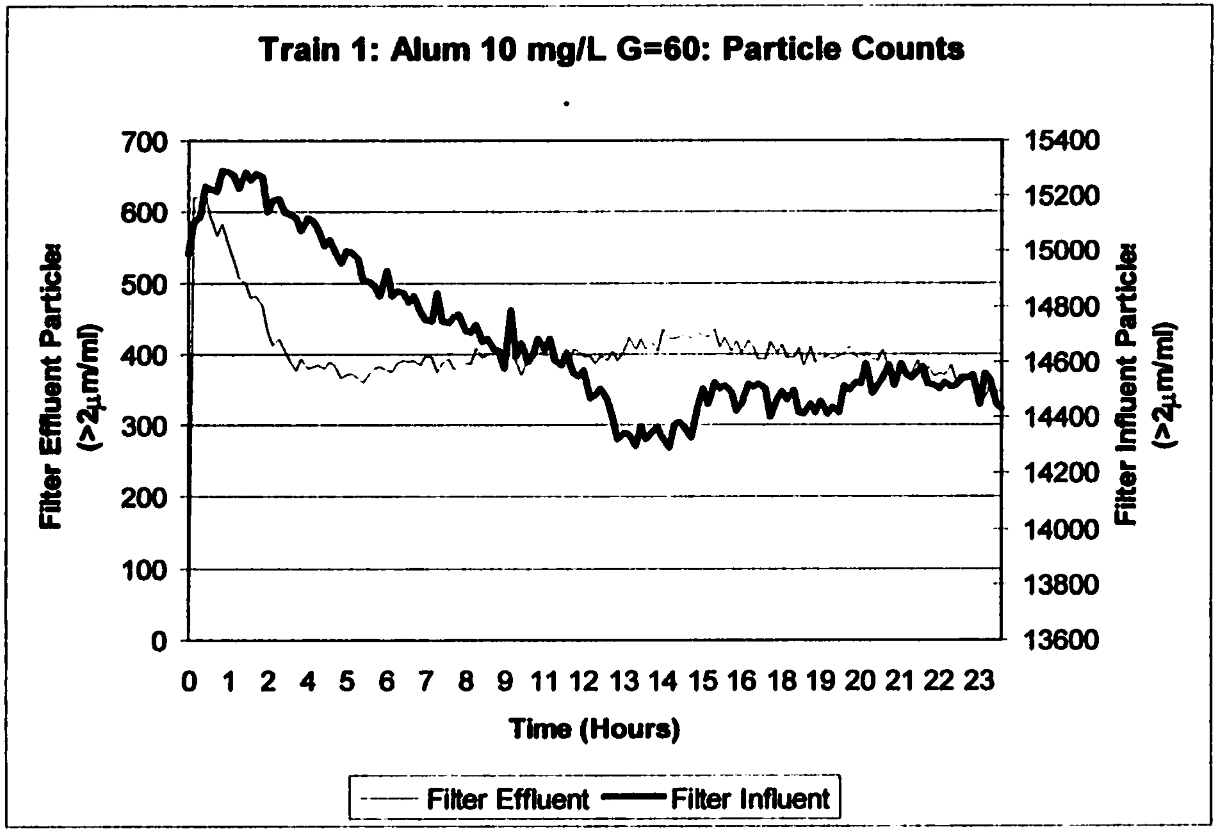
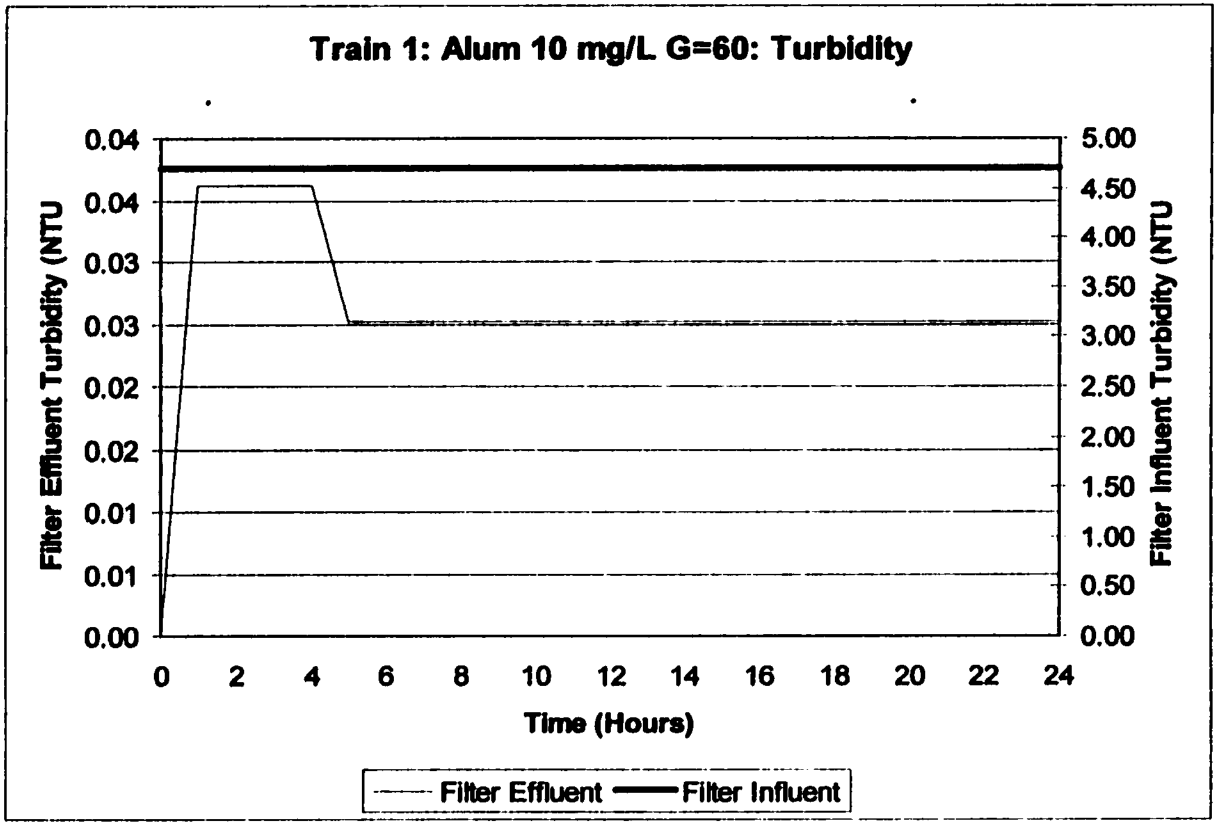
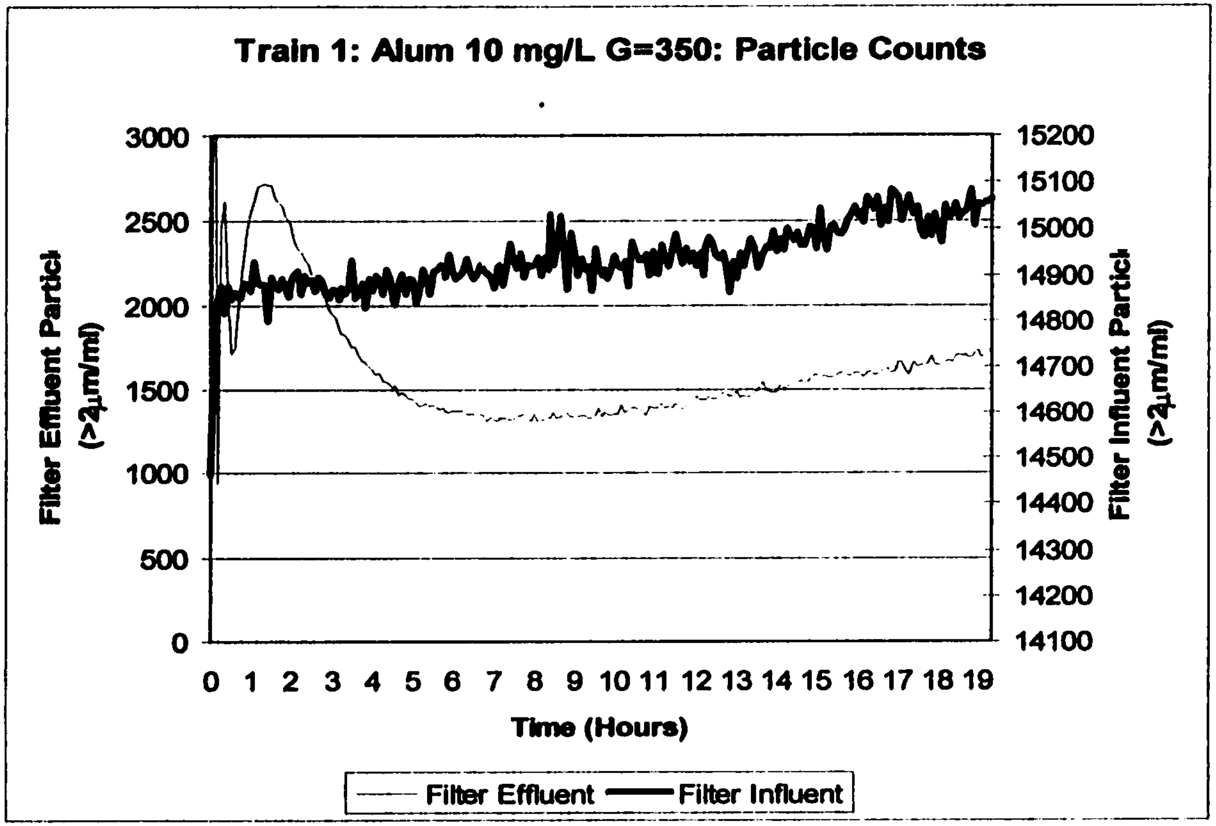


Plate 7: Data Collection System

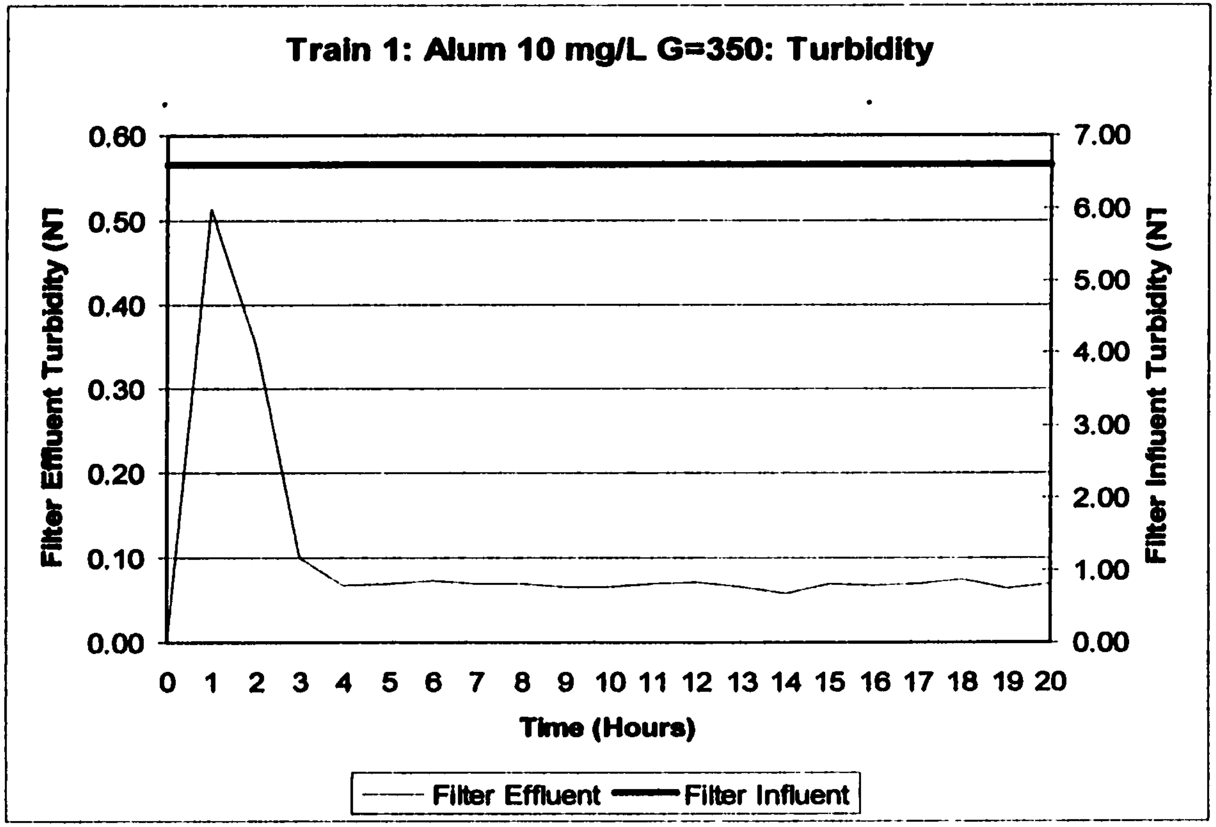
Appendix E: Alum Dose and Rapid Mixing – Filtrate Particle Counts and Turbidity

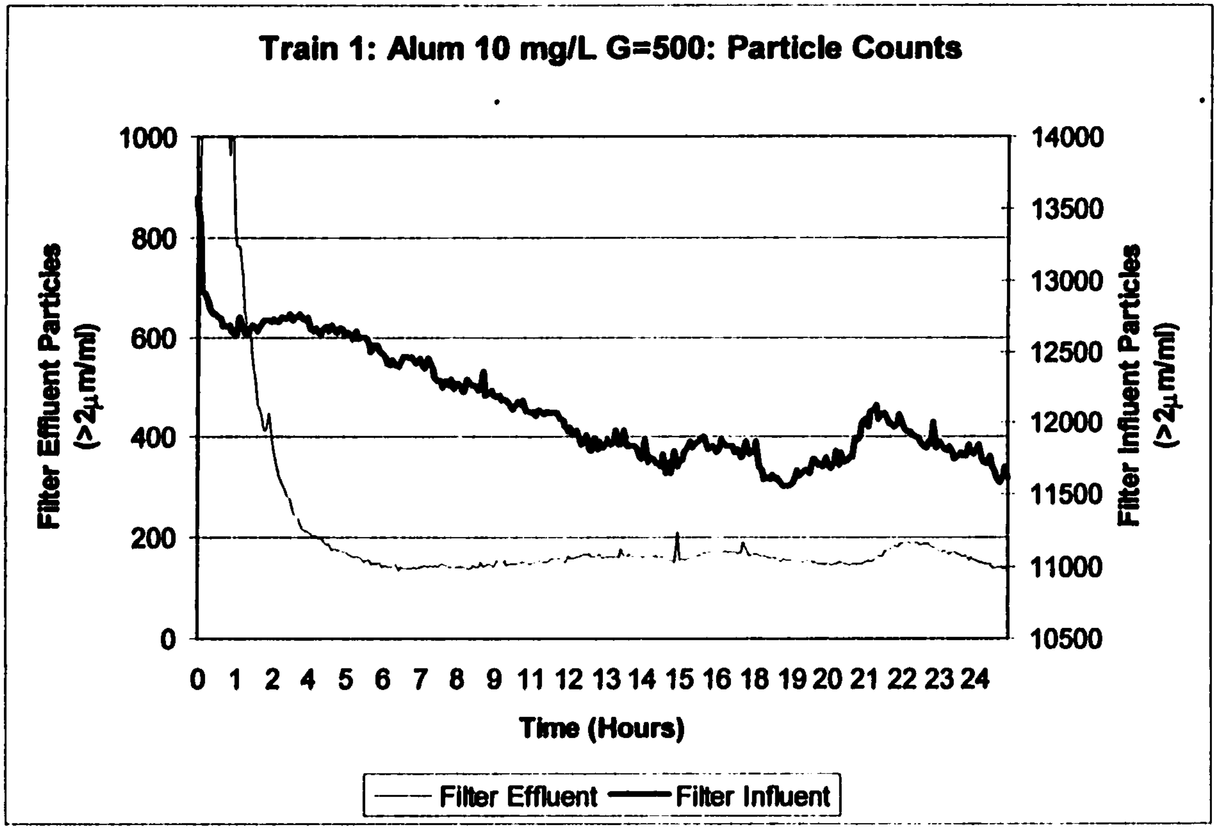

Train 1: Alum 10 mg/L G=60: Particle Counts
Filter Effluent Particles (>2µm/ml)
700
600
500
400
300
200
100
0
Filter Influent Particles (>2µm/ml)
15400
15200
15000
14800
14600
14400
14200
14000
13800
13600
0 1 2 4 5 6 7 8 9 11 12 13 14 15 16 18 19 20 21 22 23
Time (Hours)
Filter Effluent
Filter Influent

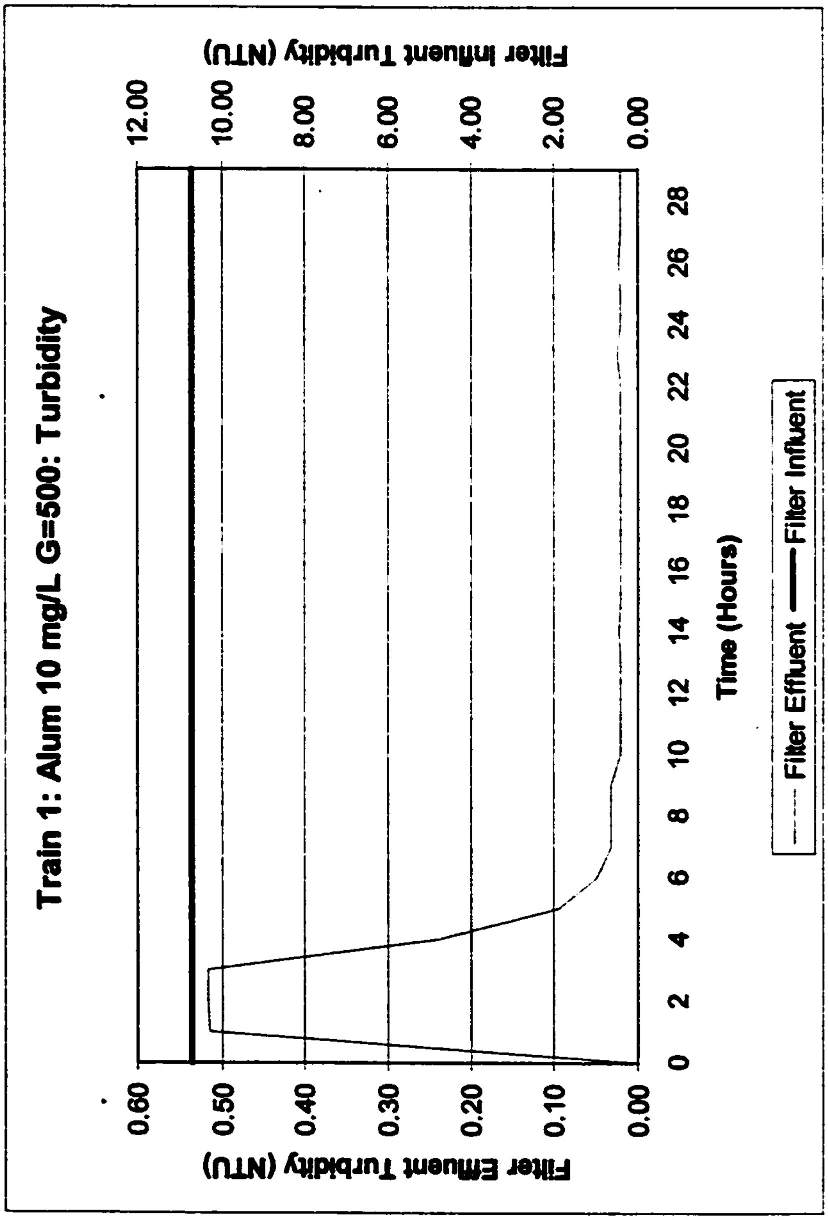

Train 1: Alum 10 mg/L G=60: Turbidity
Filter Effluent Turbidity (NTU
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
Filter Influent Turbidity (NTU
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (Hours)
Filter Effluent
Filter Influent

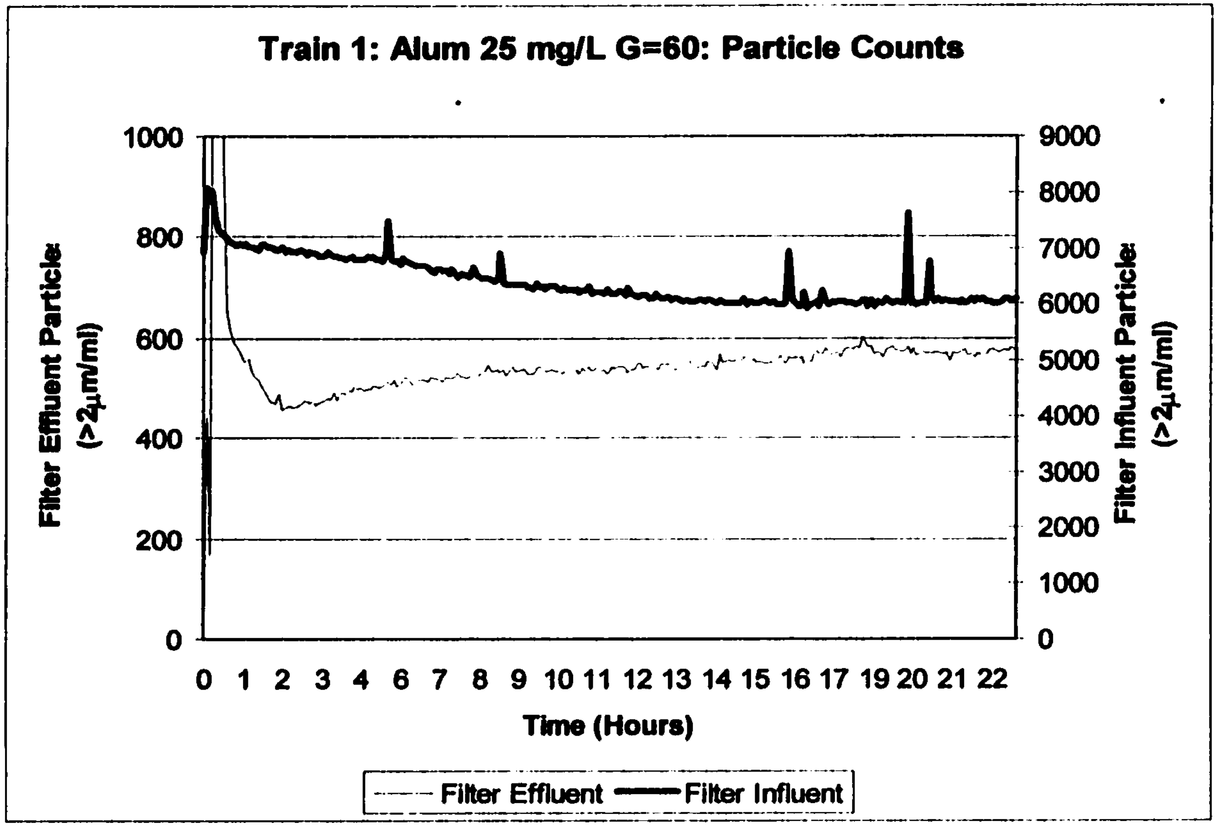


Train 1: Alum 10 mg/L G=350: Particle Counts

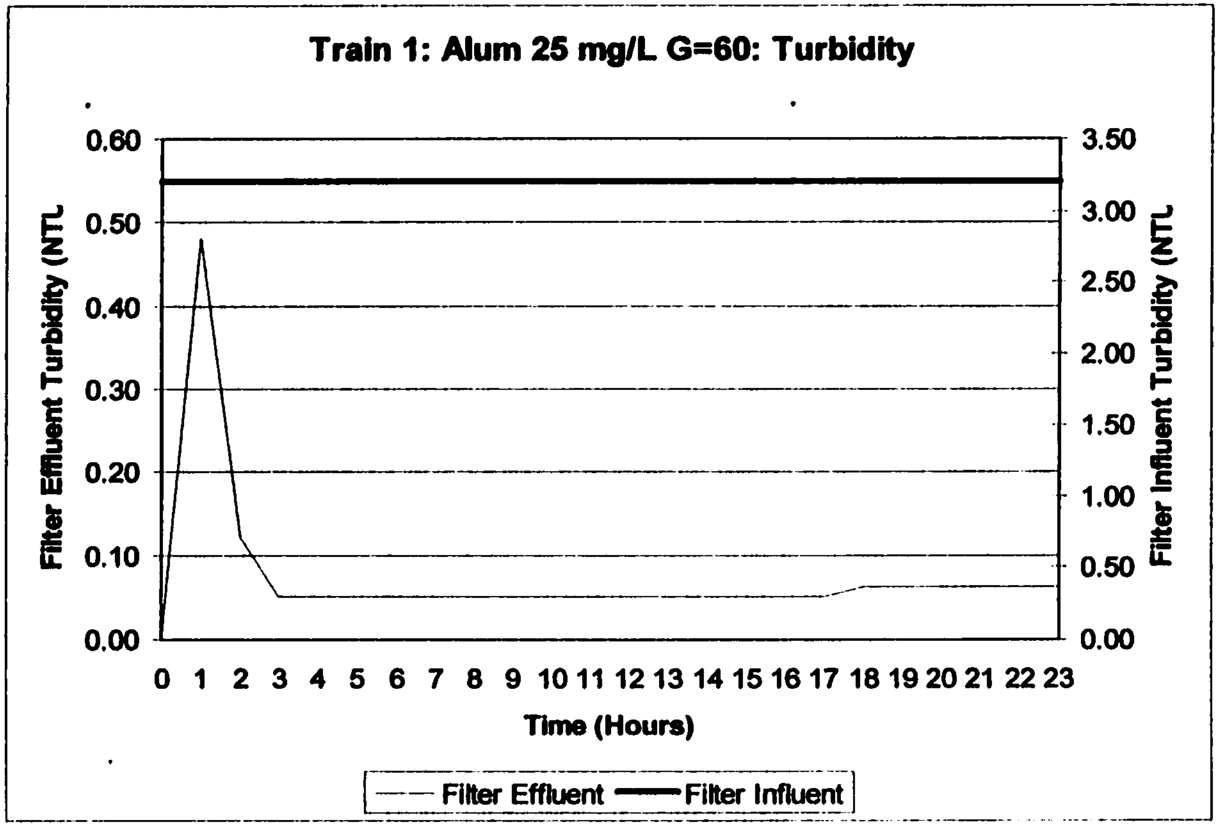

Train 1: Alum 10 mg/L G=350: Turbidity
Filter Effluent Turbidity (NT
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Filter Influent Turbidity (NT
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Time (Hours)
Filter Effluent
Filter Influent

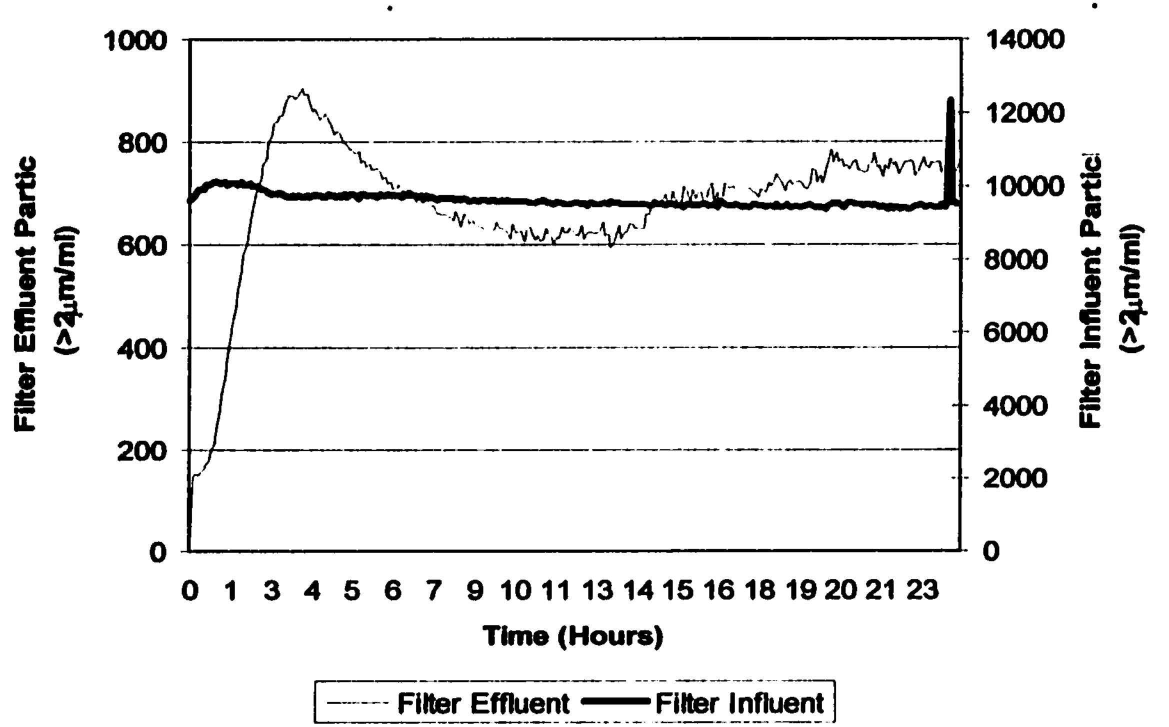

Train 1: Alum 10 mg/L G=500: Particle Counts
1000
800
600
400
200
0
Filter Effluent Particles
(>2μm/ml)
14000
13500
13000
12500
12000
11500
11000
10500
Filter Influent Particles
(>2μm/ml)
0 1 2 4 5 6 7 8 9 11 12 13 14 15 16 18 19 20 21 22 23 24
Time (Hours)
Filter Effluent
Filter Influent


Train 1: Alum 10 mg/L G=500: Turbidity
Filter Effluent Turbidity (NTU)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
Filter Influent Turbidity (NTU)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
Time (Hours)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Filter Effluent
Filter Influent

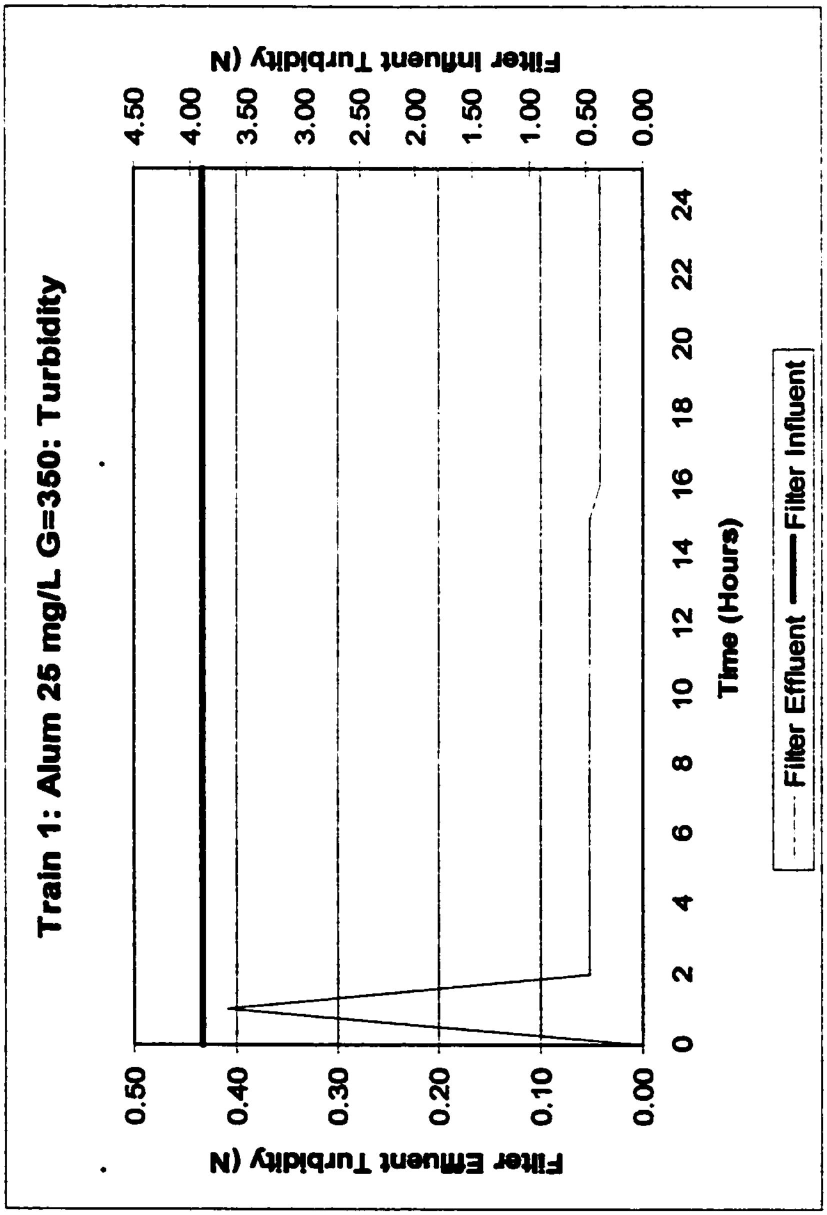


Train 1: Alum 25 mg/L G=60: Particle Counts

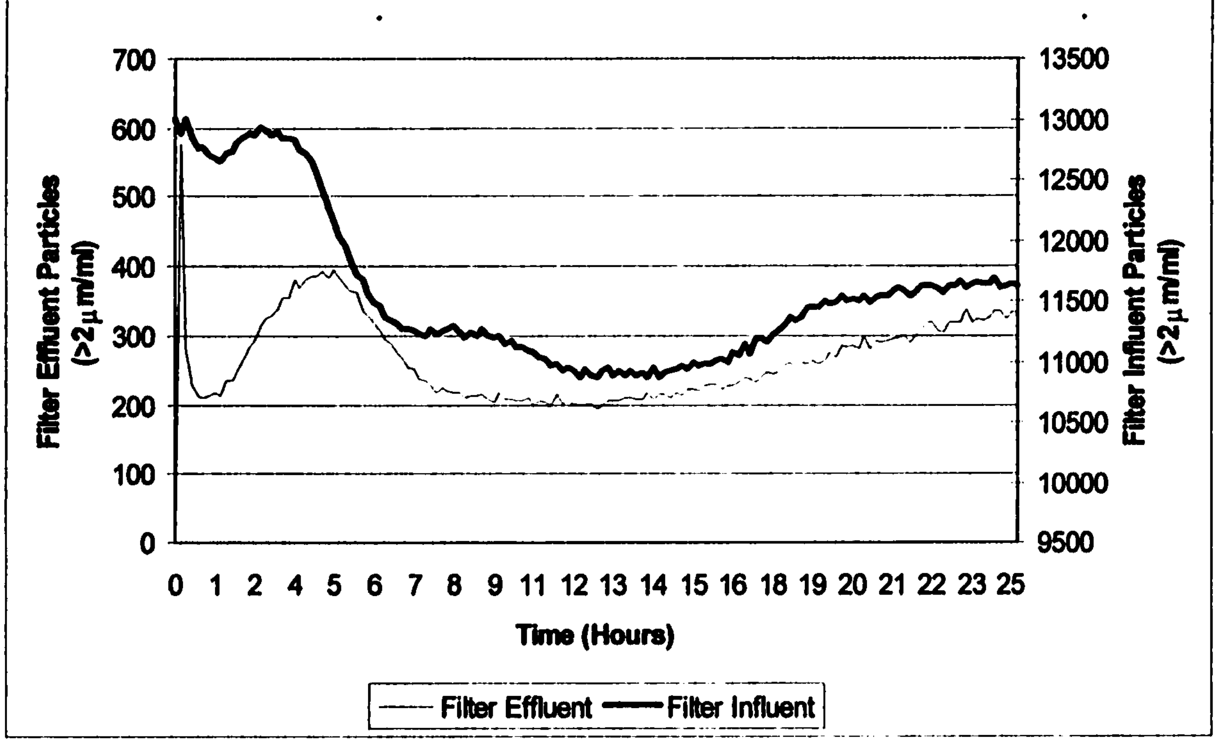

Train 1: Alum 25 mg/L G=60: Turbidity
Filter Effluent Turbidity (NTL
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Filter Influent Turbidity (NTL
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time (Hours)
Filter Effluent
Filter Influent

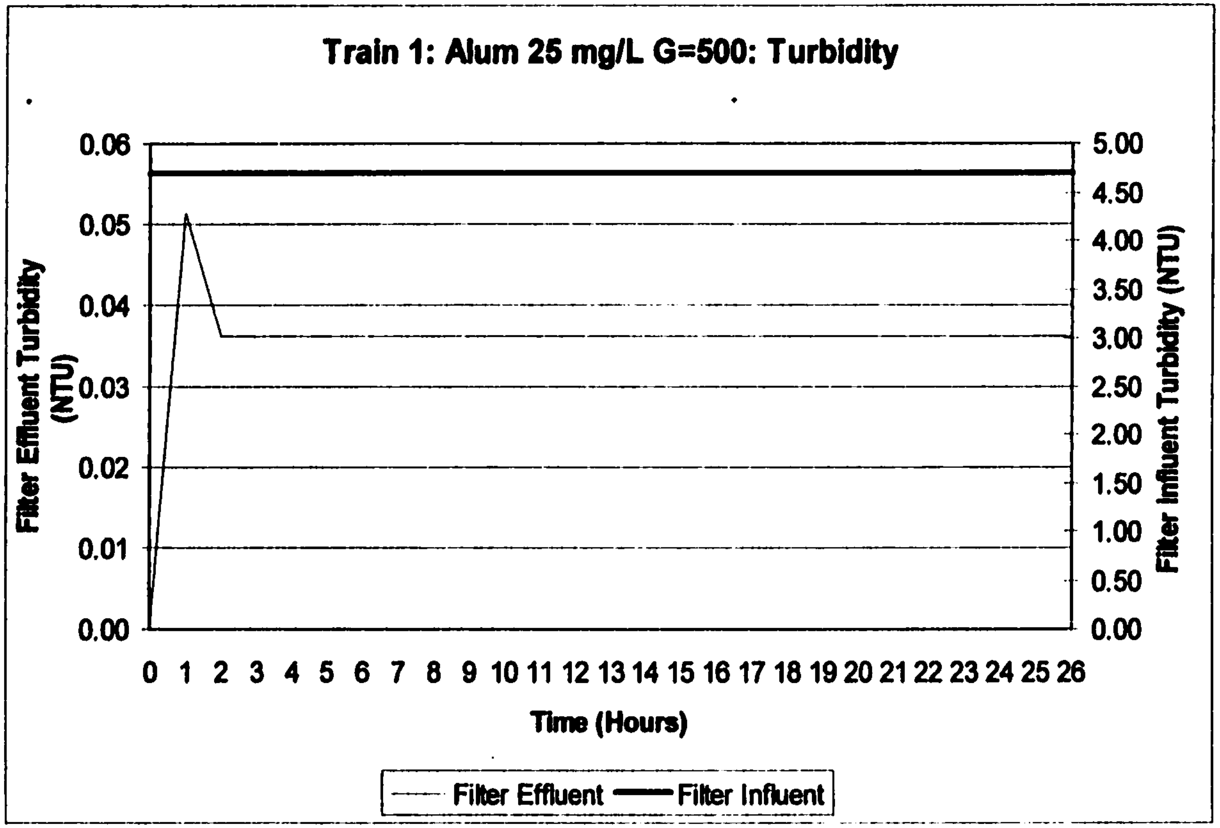


Train 1: Alum 25 mg/L G=350: Particle Counts

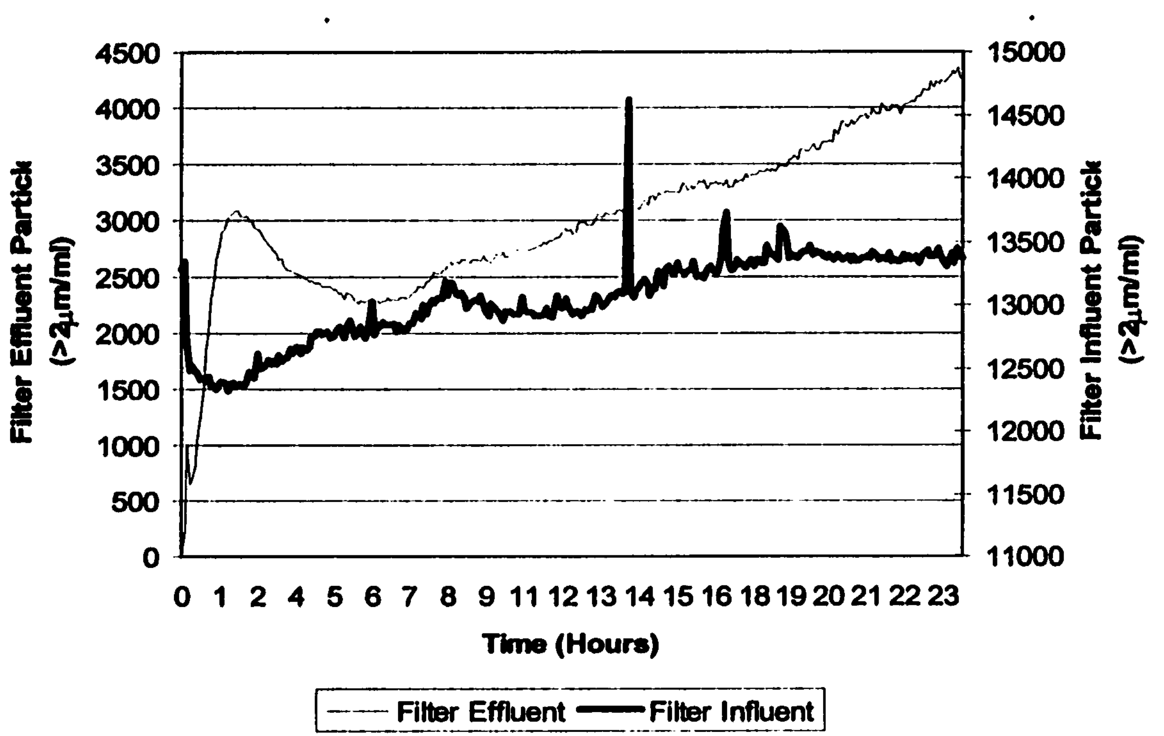

Train 1: Alum 25 mg/L G=350: Turbidity
Filter Effluent Turbidity (N
0.50
0.40
0.30
0.20
0.10
0.00
Filter Influent Turbidity (N
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (Hours)
Filter Effluent
Filter Influent

Train 1: Alum 25 mg/L G=500: Particle Counts

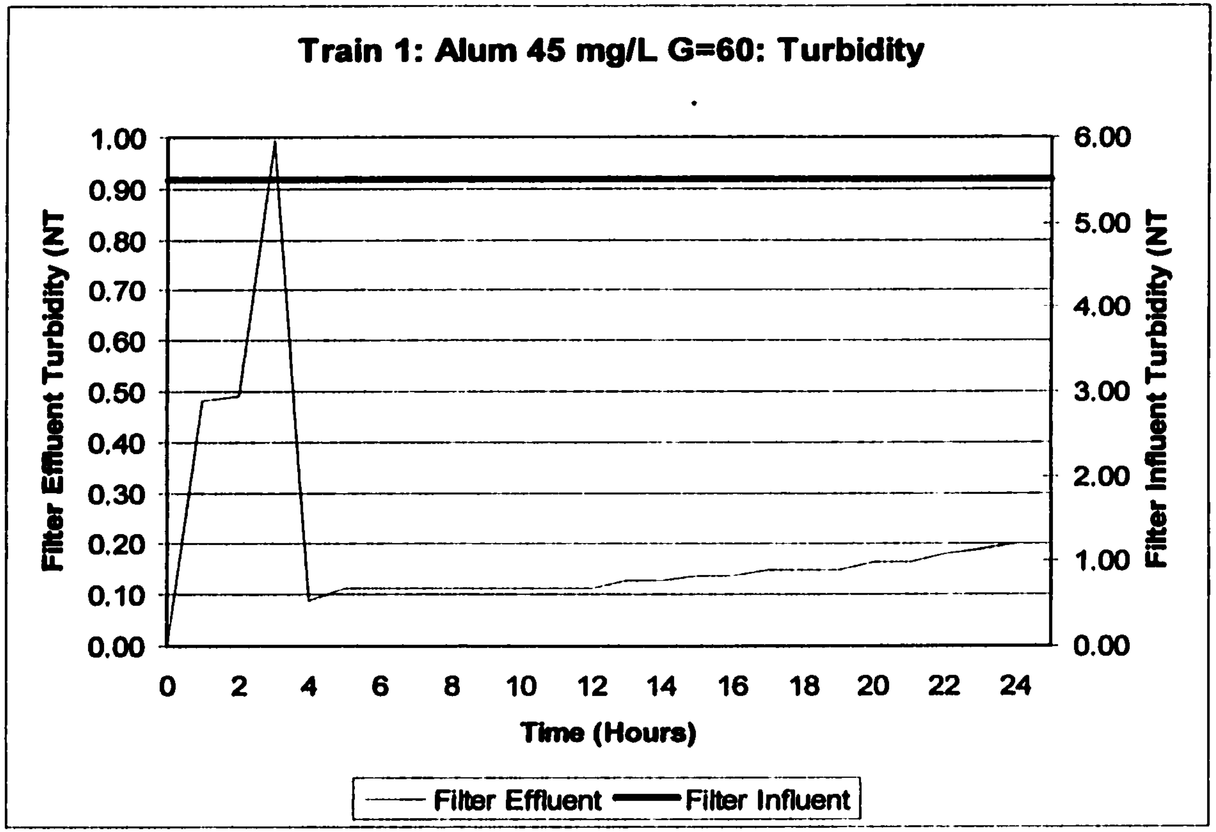


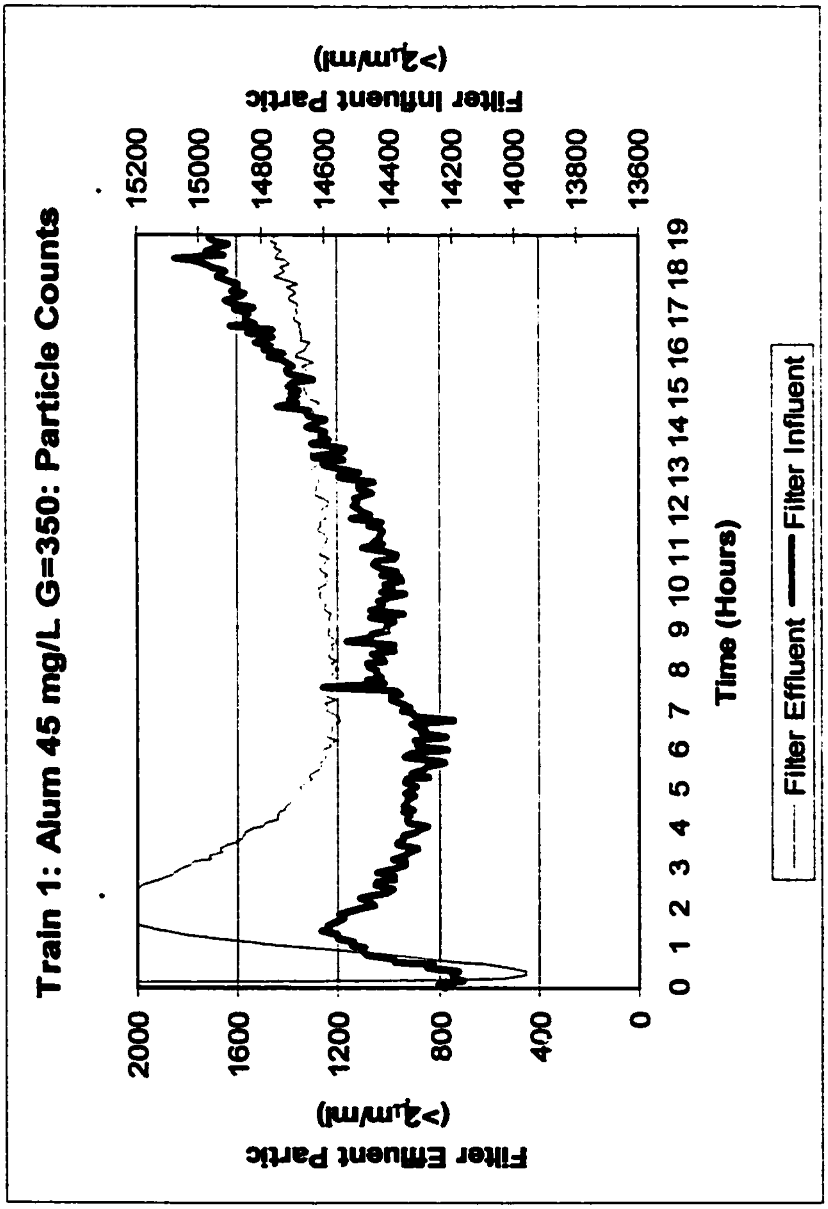


Train 1: Alum 25 mg/L G=500: Turbidity

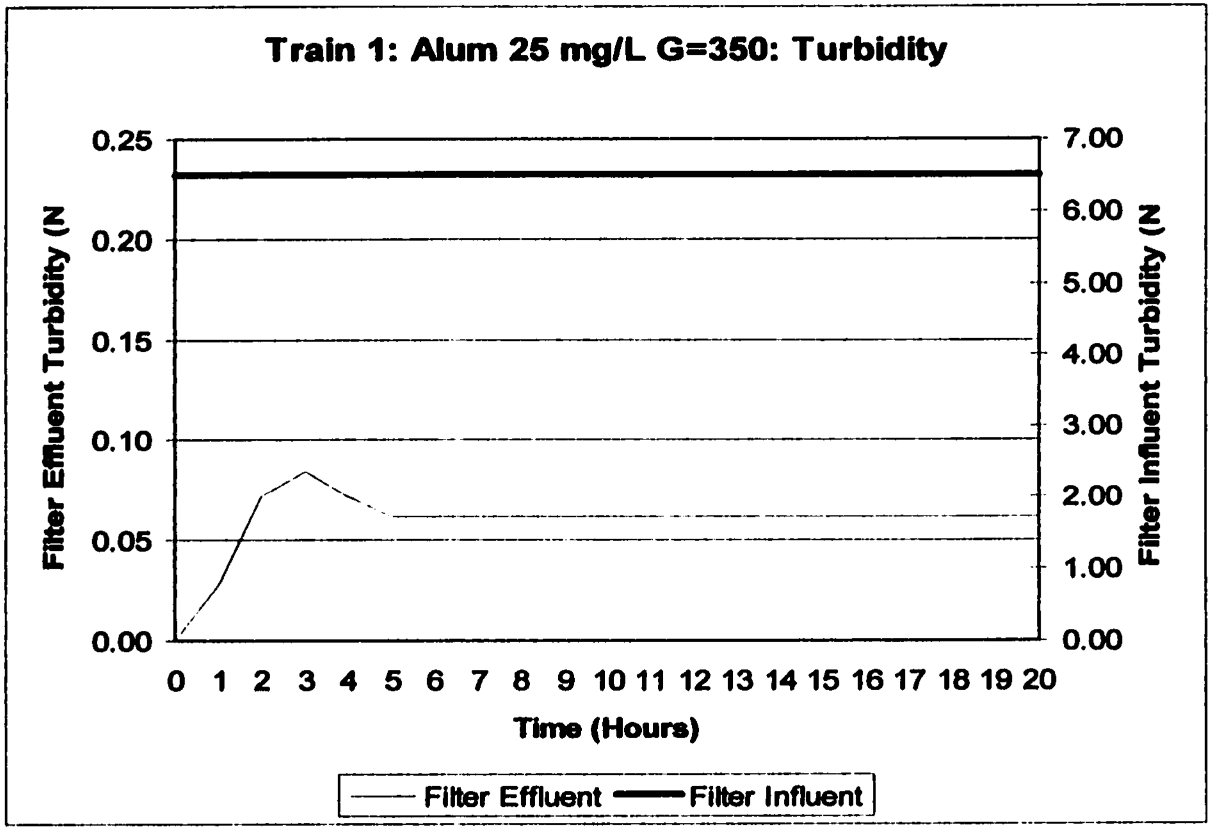


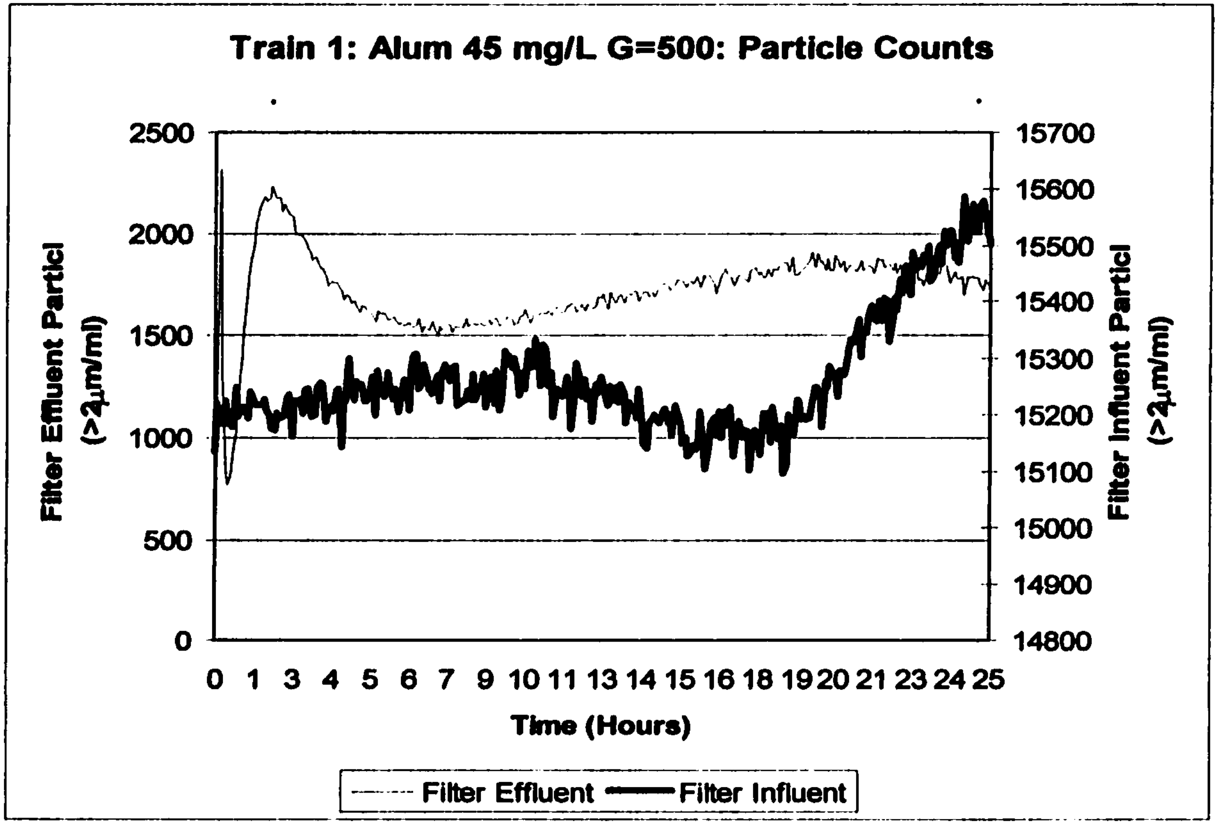
Train 1: Alum 45 mg/L G=60: Particle Counts

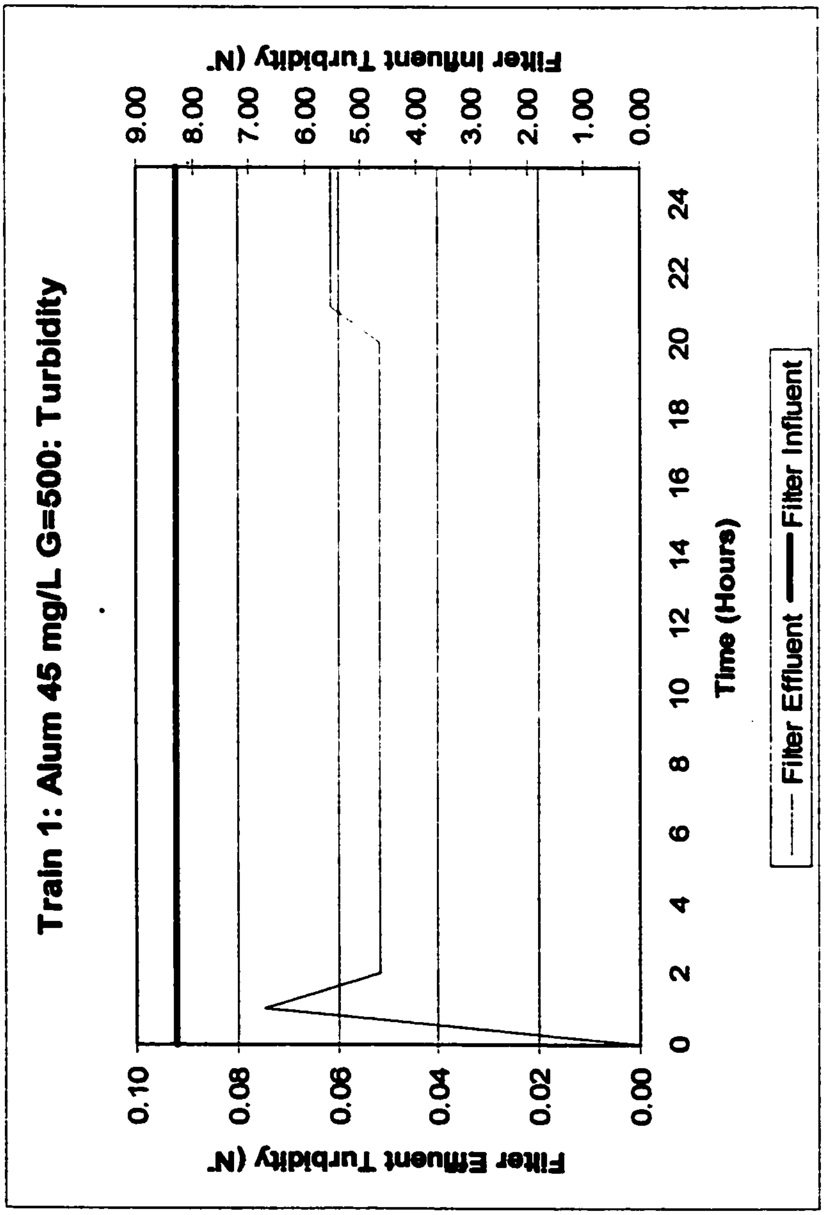

Train 1: Alum 45 mg/L G=60: Turbidity
Filter Effluent Turbidity (NT
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Filter Influent Turbidity (NT
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (Hours)
Filter Effluent
Filter Influent

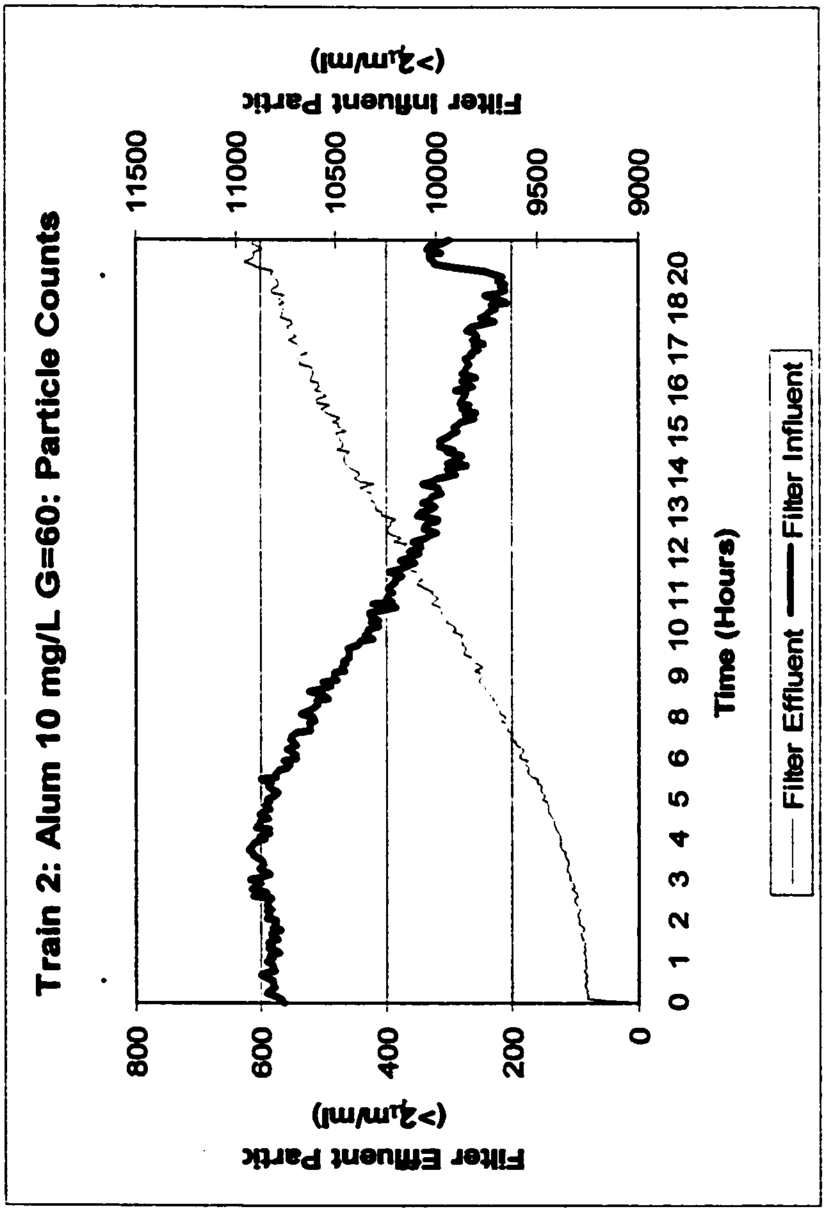


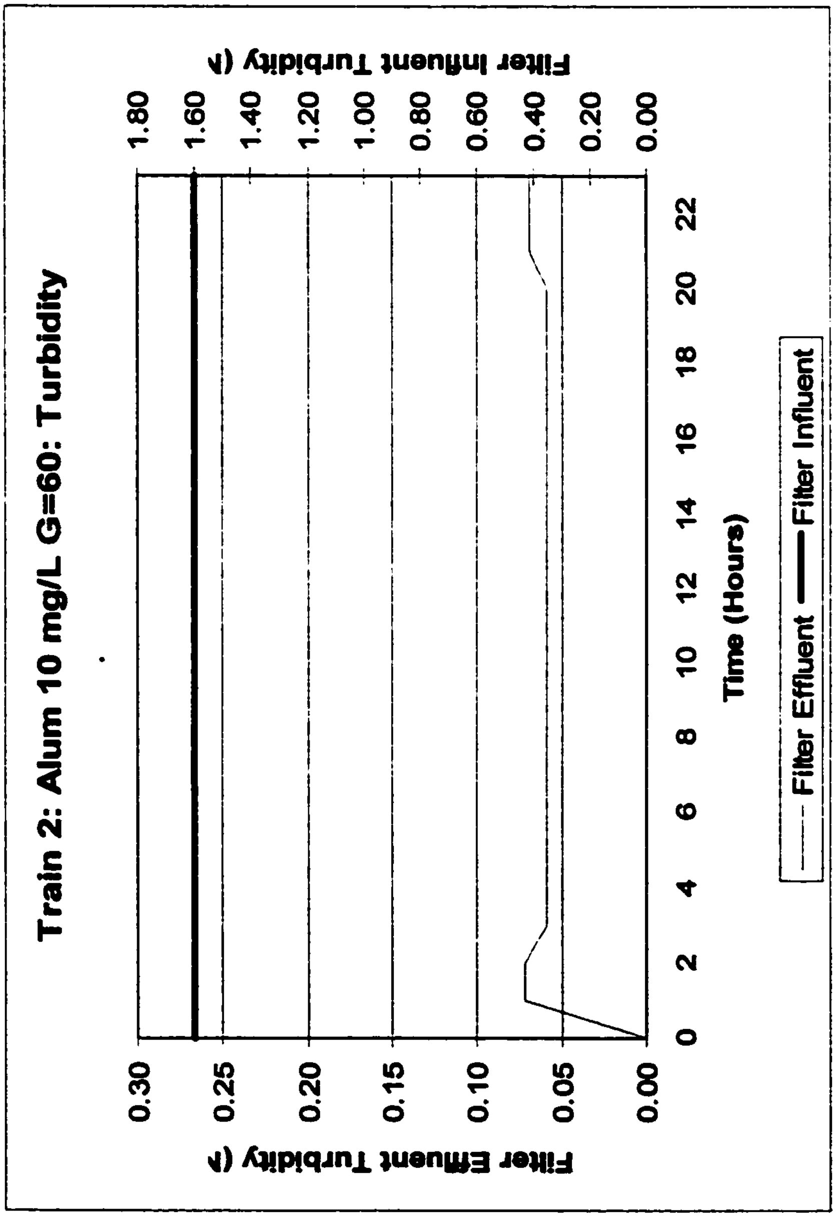
Train 1: Alum 45 mg/L G=350: Particle Counts

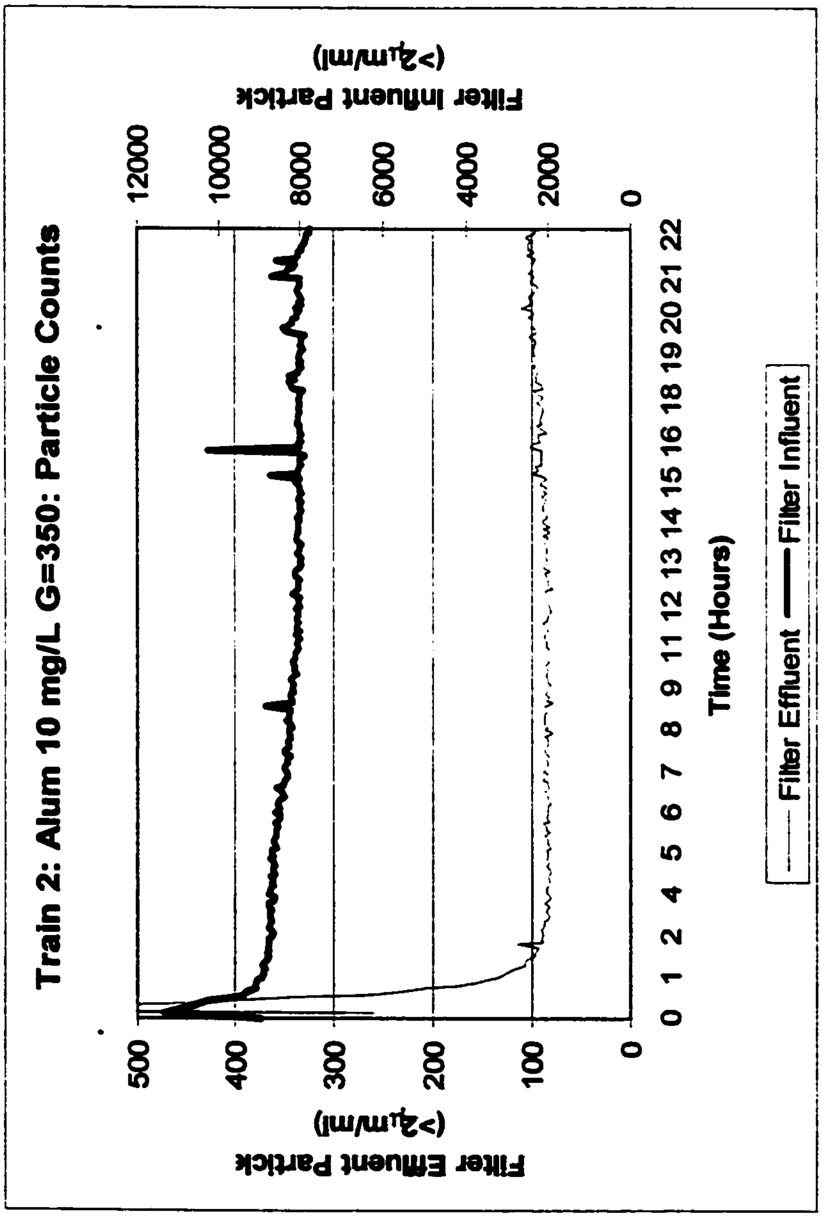

Train 1: Alum 25 mg/L G=350: Turbidity


Train 1: Alum 45 mg/L G=500: Particle Counts
Filter Effluent Particl (>2μm/ml)
2500
2000
1500
1000
500
0
Filter Influent Particl (>2μm/ml)
15700
15600
15500
15400
15300
15200
15100
15000
14900
14800
0 1 3 4 5 6 7 9 10 11 13 14 15 16 18 19 20 21 23 24 25
Time (Hours)
Filter Effluent
Filter Influent

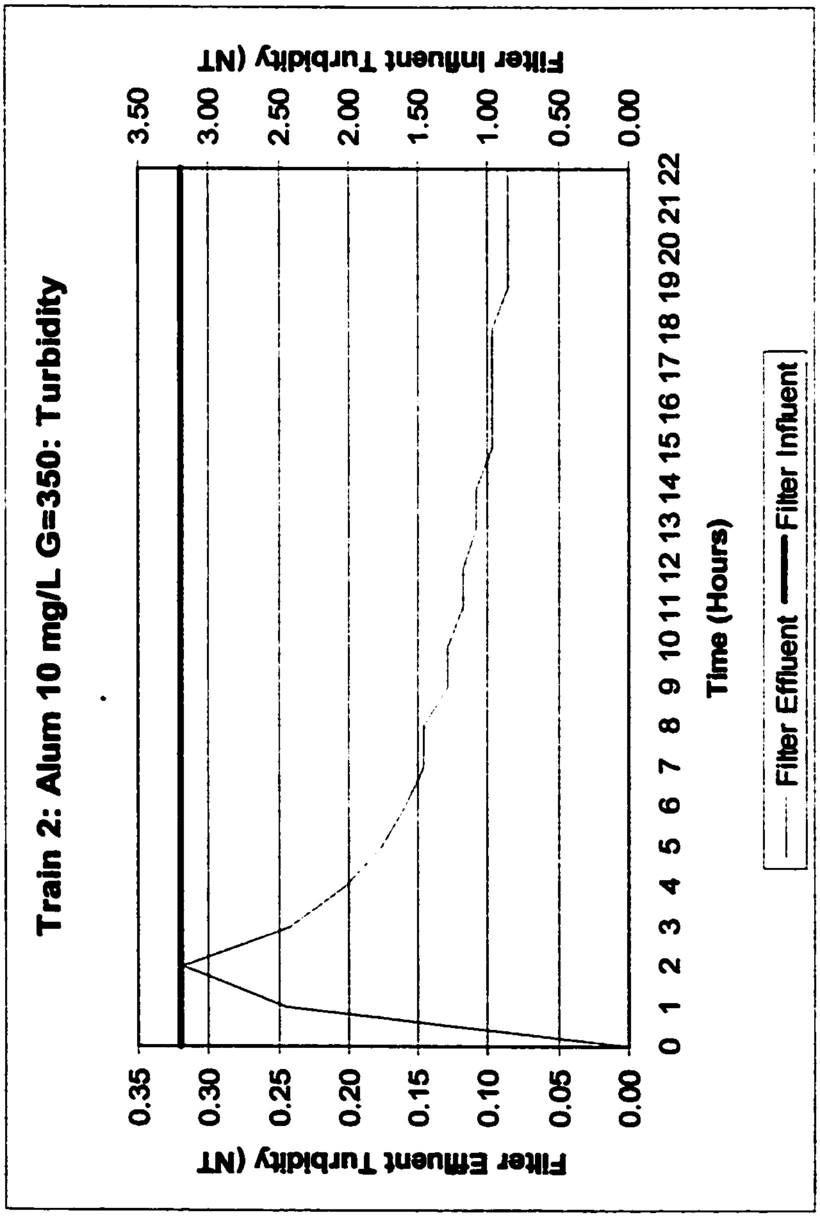

Train 1: Alum 45 mg/L G=500: Turbidity
Filter Effluent Turbidity (N
0.10
0.08
0.06
0.04
0.02
0.00
Filter Influent Turbidity (N
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (Hours)
Filter Effluent
Filter Influent

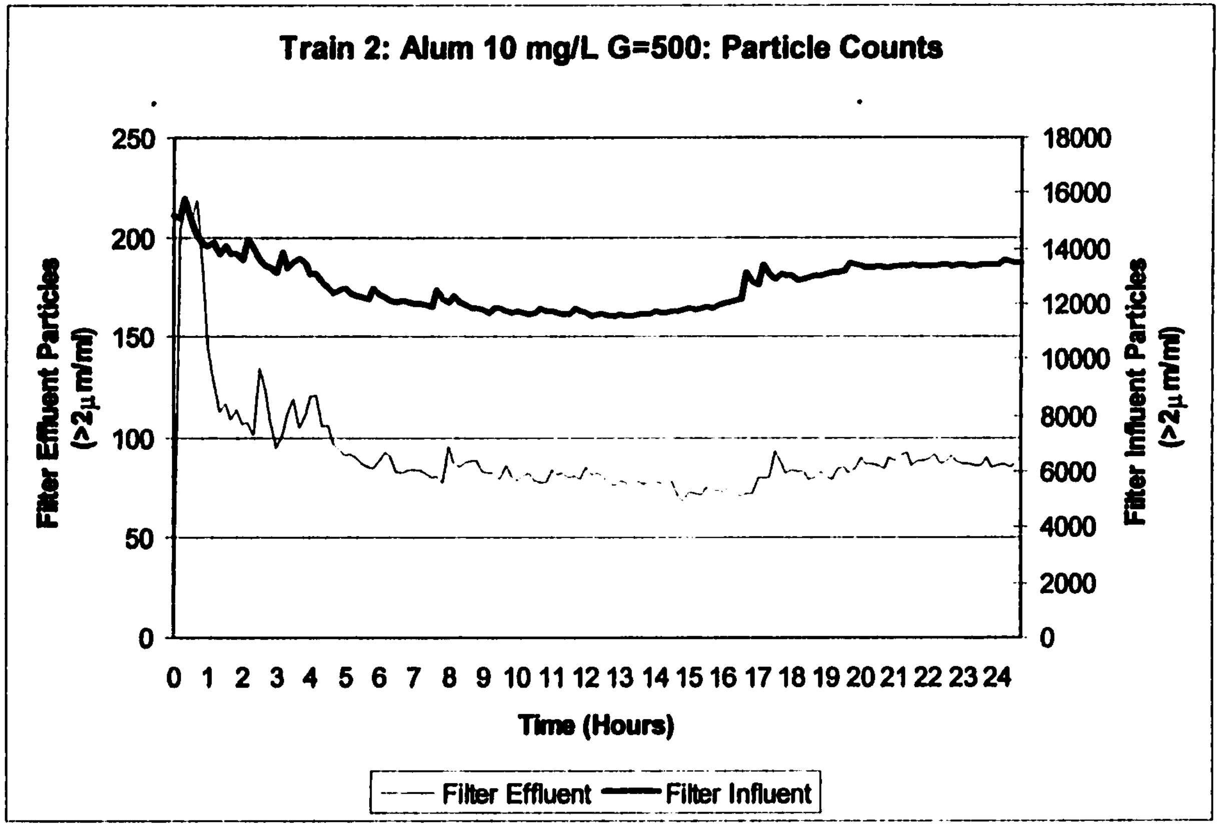

Train 2: Alum 10 mg/L G=60: Particle Counts
Filter Effluent Partic (>2μm/ml)
800
600
400
200
0
Filter Influent Partic (>2μm/ml)
11500
11000
10500
10000
9500
9000
0 1 2 3 4 5 6 8 9 10 11 12 13 14 15 16 17 18 20
Time (Hours)
Filter Effluent
Filter Influent


Train 2: Alum 10 mg/L G=60: Turbidity
Filter Effluent Turbidity (N
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Filter Influent Turbidity (N
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
2
4
6
8
10
12
14
16
18
20
22
Time (Hours)
Filter Effluent
Filter Influent

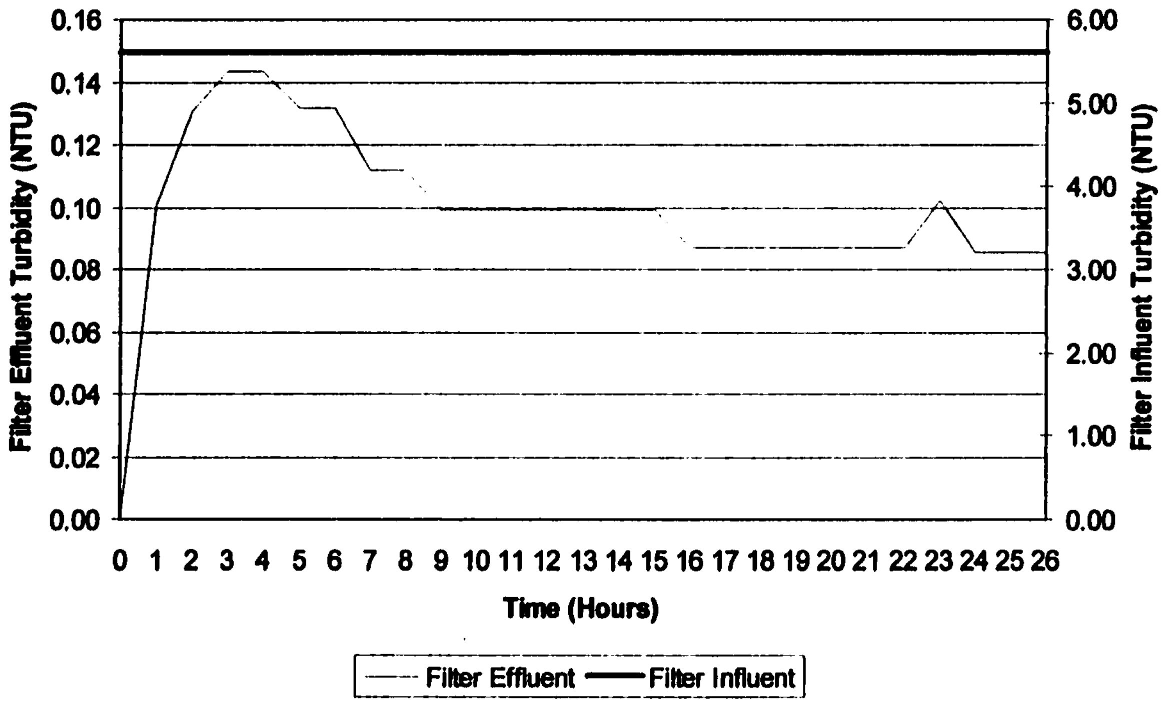


Train 2: Alum 10 mg/L G=350: Particle Counts

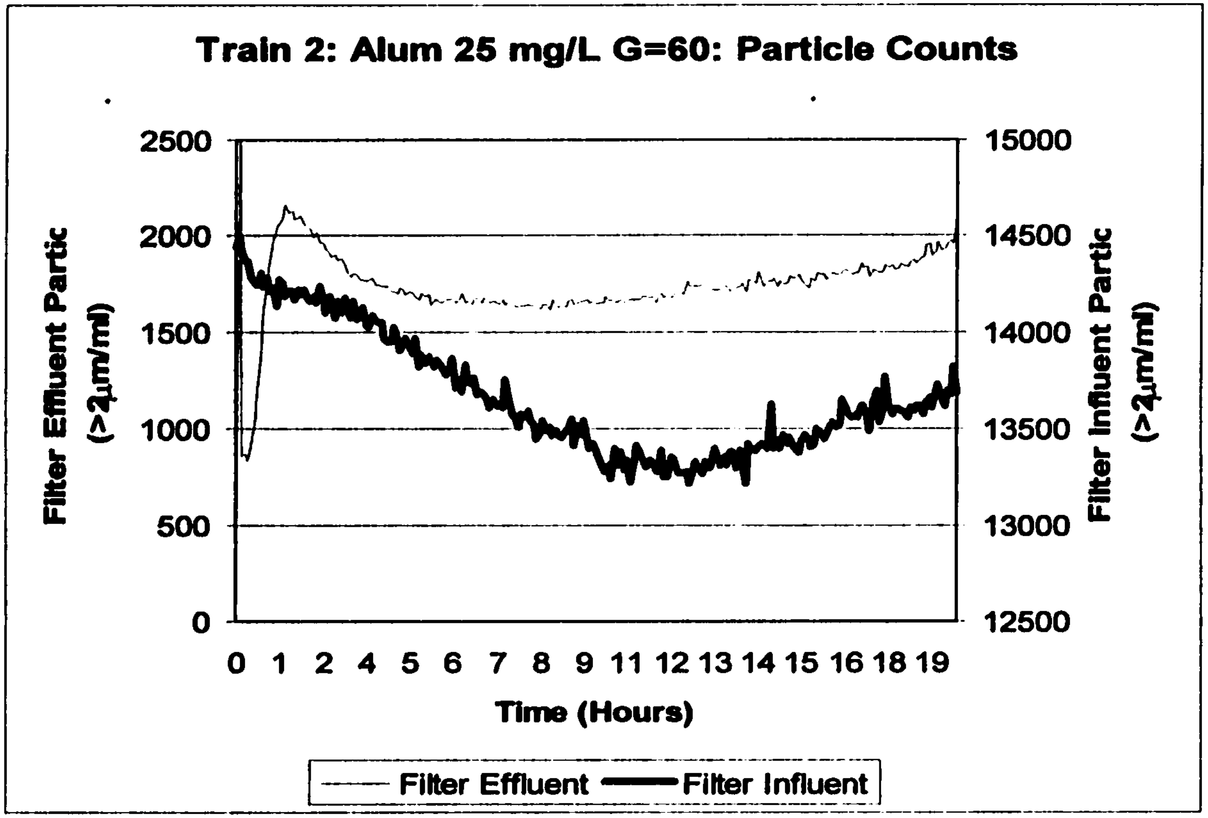

Train 2: Alum 10 mg/L G=350: Turbidity
Filter Effluent Turbidity (NT
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Filter Influent Turbidity (NT
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Time (Hours)
Filter Effluent
Filter Influent

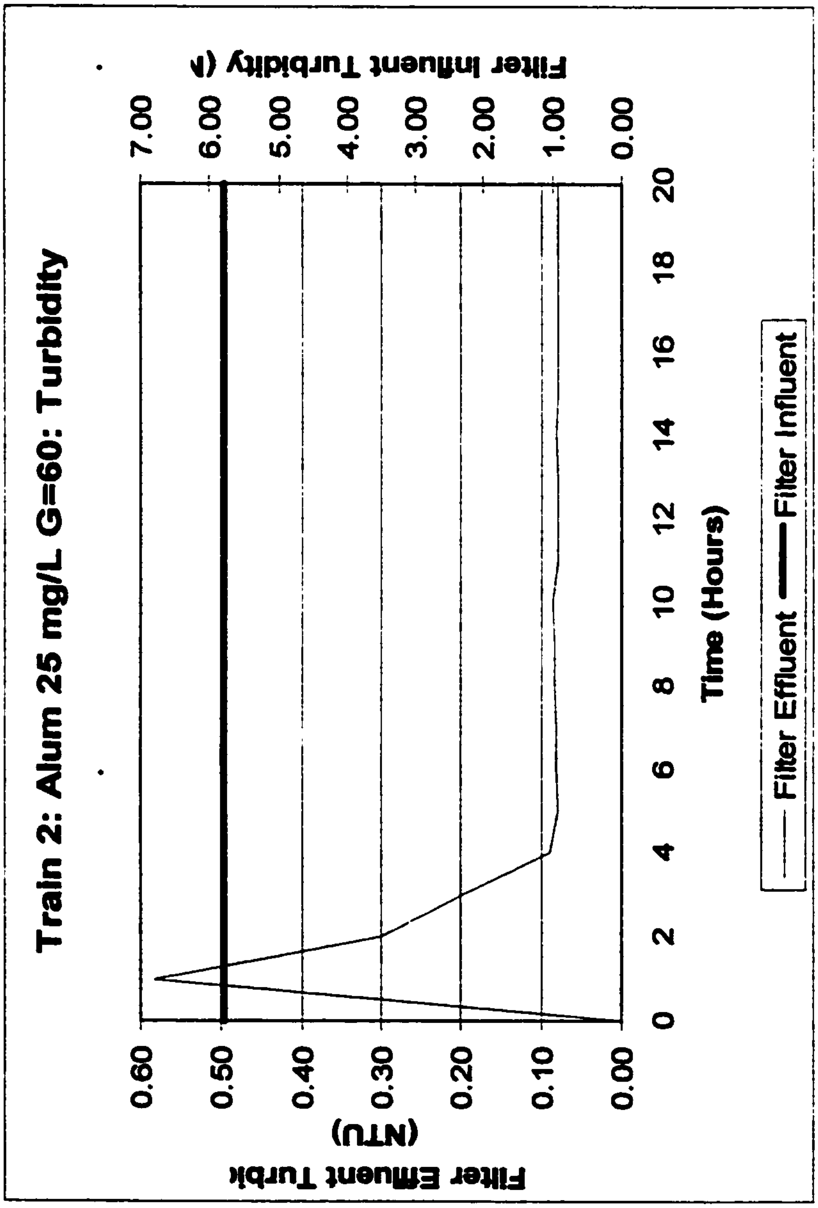


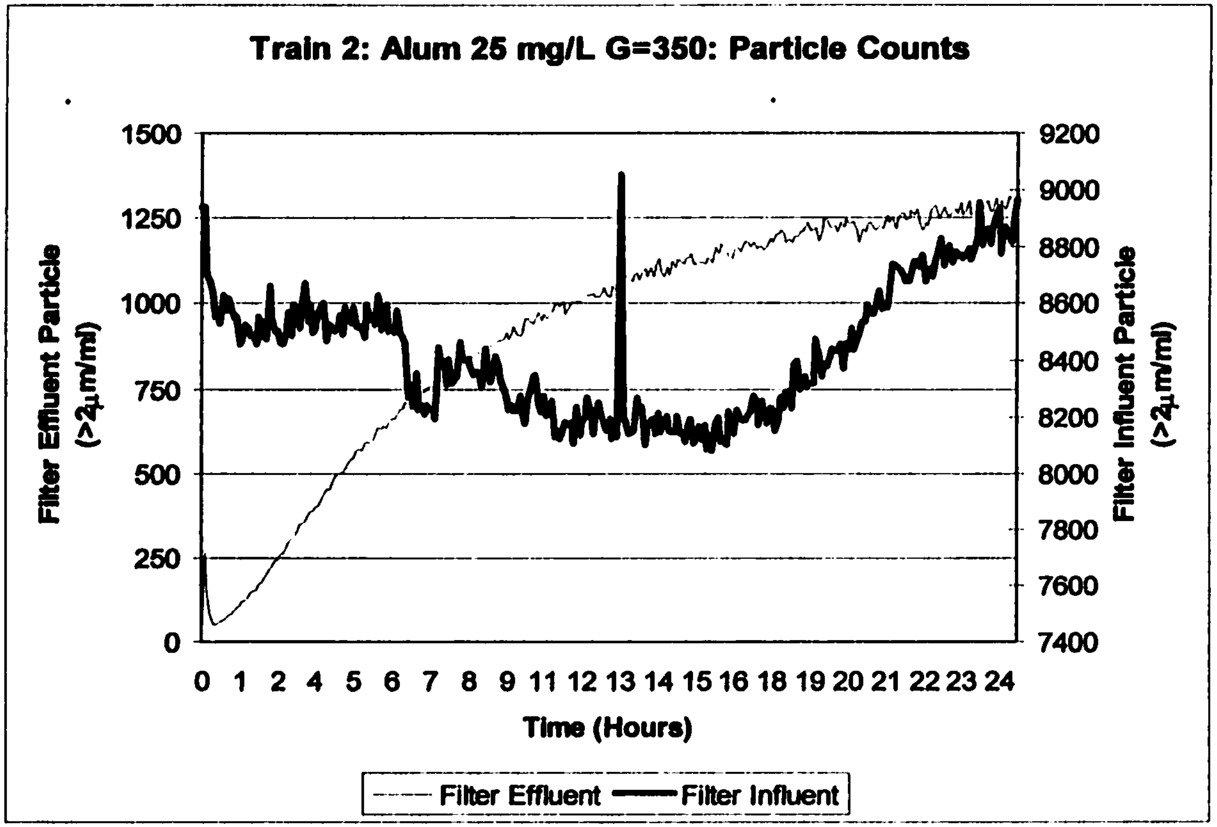
Train 2: Alum 10 mg/L G=500: Particle Counts

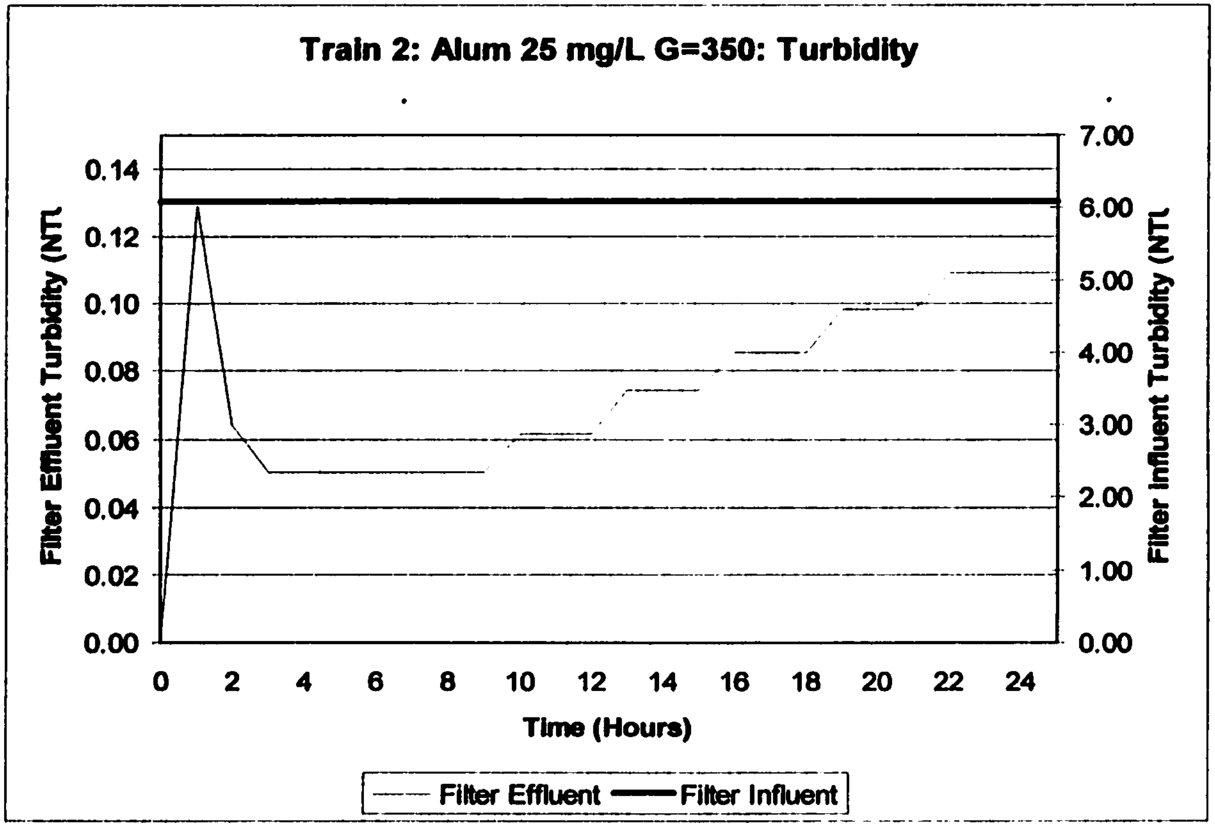


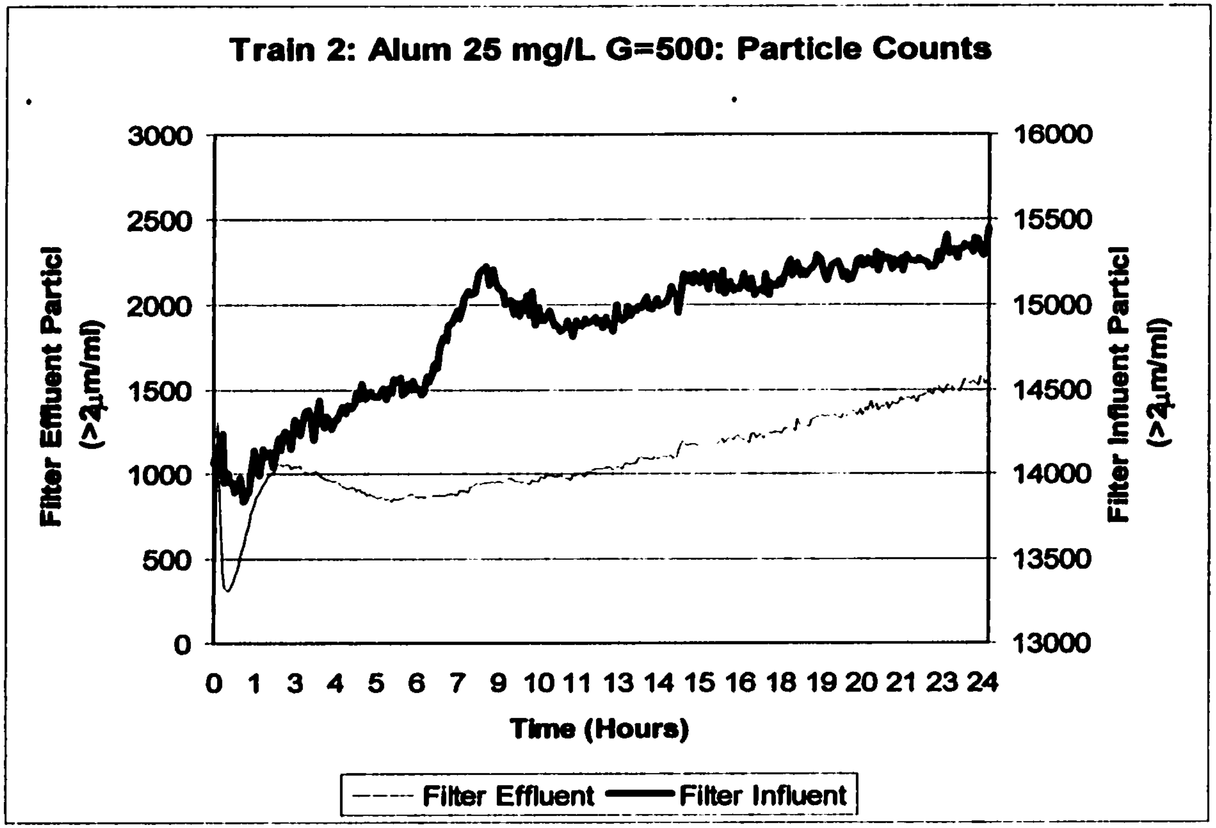
Train 2: Alum 10 mg/L G=500: Turbidity

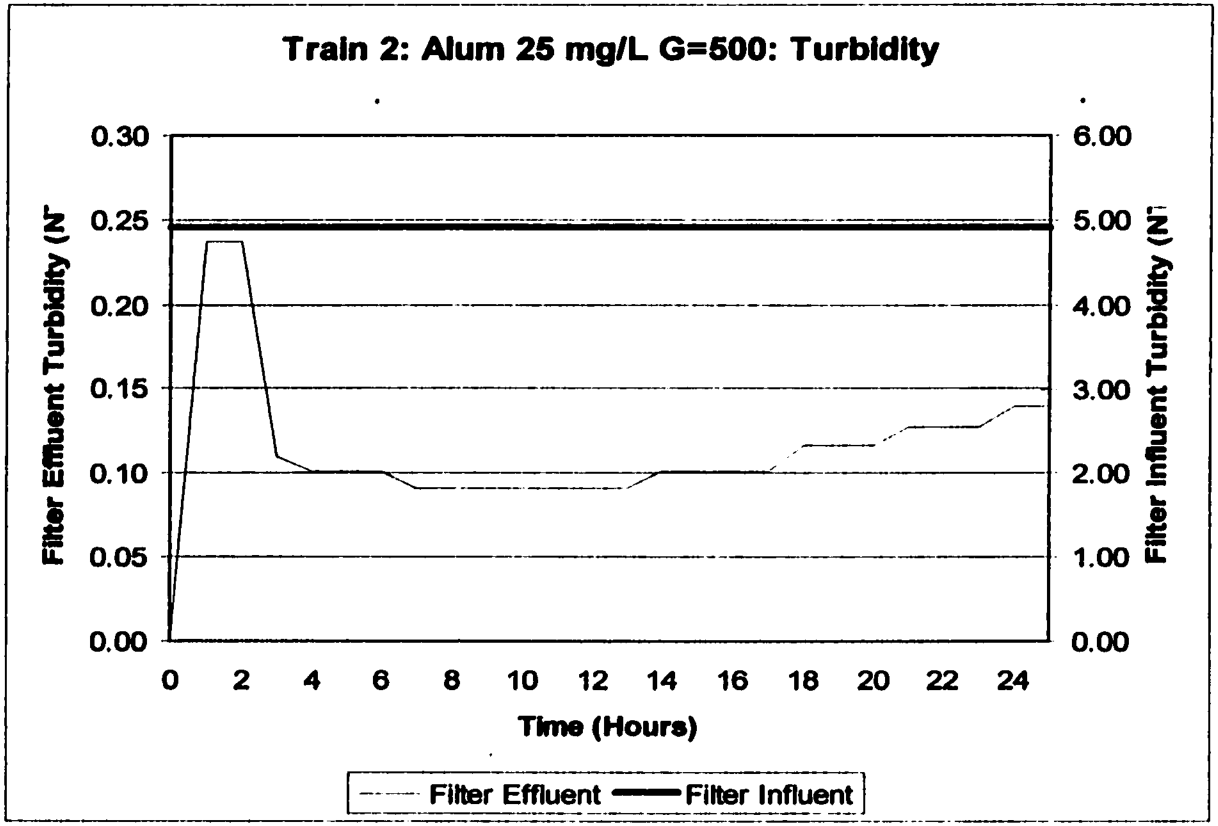

Train 2: Alum 25 mg/L G=60: Particle Counts
2500
2000
1500
1000
500
0
Filter Effluent Partic (>2µm/ml)
15000
14500
14000
13500
13000
12500
Filter Influent Partic (>2µm/ml)
0 1 2 4 5 6 7 8 9 11 12 13 14 15 16 18 19
Time (Hours)
Filter Effluent
Filter Influent

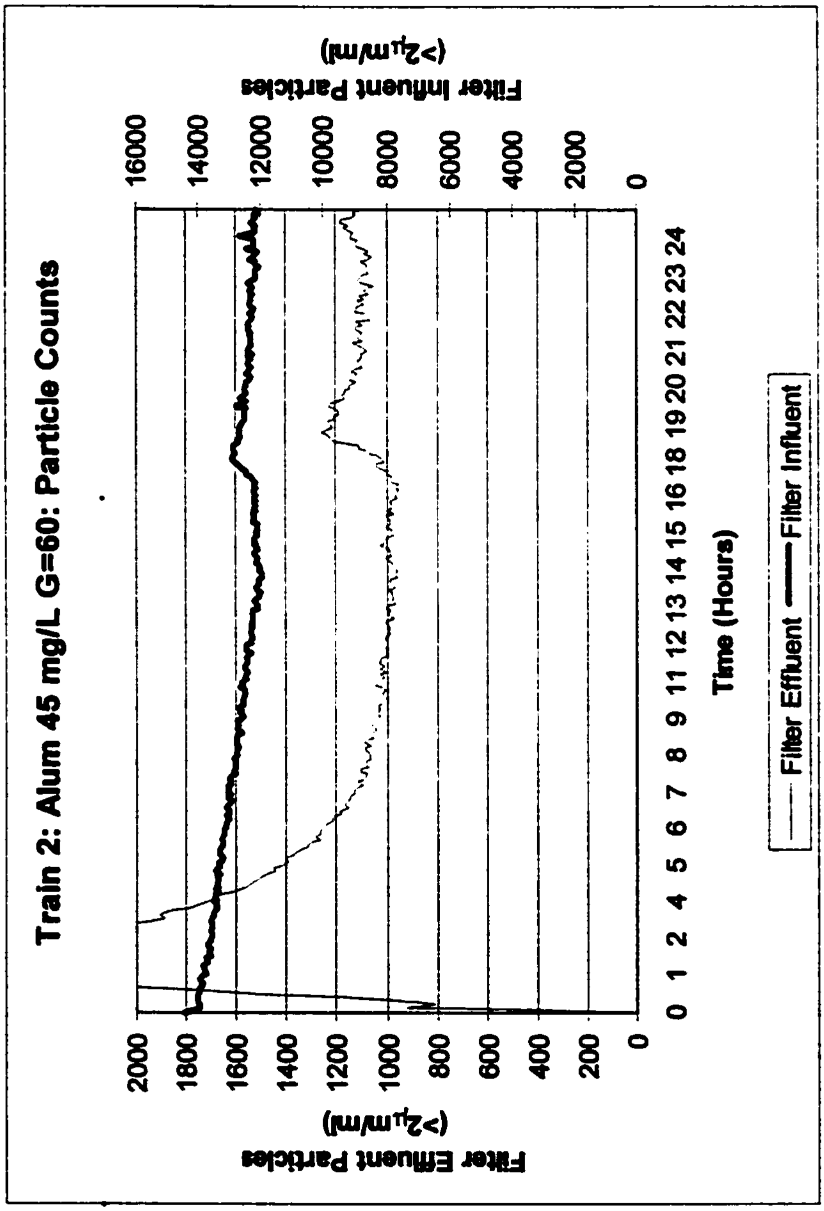

Train 2: Alum 25 mg/L G=60: Turbidity
Filter Effluent Turbic (NTU)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Filter Influent Turbidity (N
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
2
4
6
8
10
12
14
16
18
20
Time (Hours)
Filter Effluent
Filter Influent

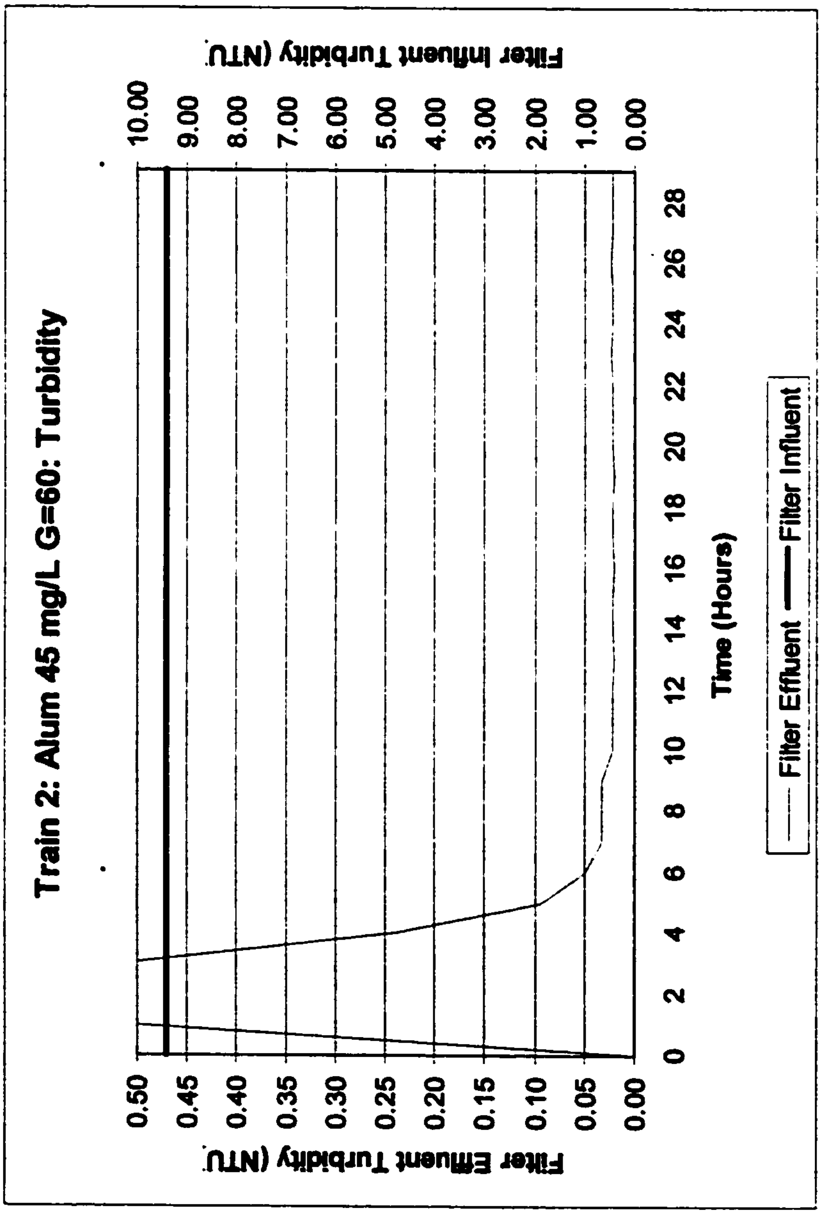

Train 2: Alum 25 mg/L G=350: Particle Counts

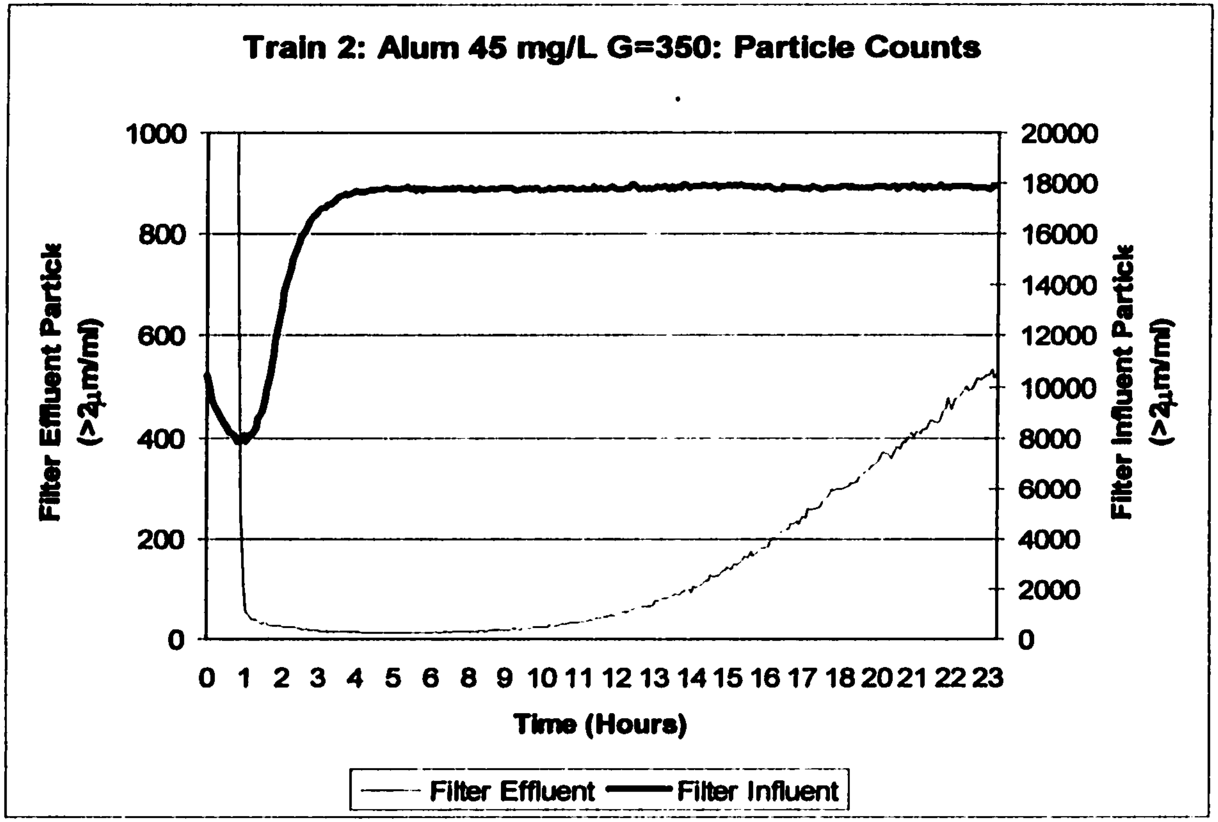

Train 2: Alum 25 mg/L G=350: Turbidity
Filter Effluent Turbidity (NTL
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Filter Influent Turbidity (NTL
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (Hours)
Filter Effluent
Filter Influent

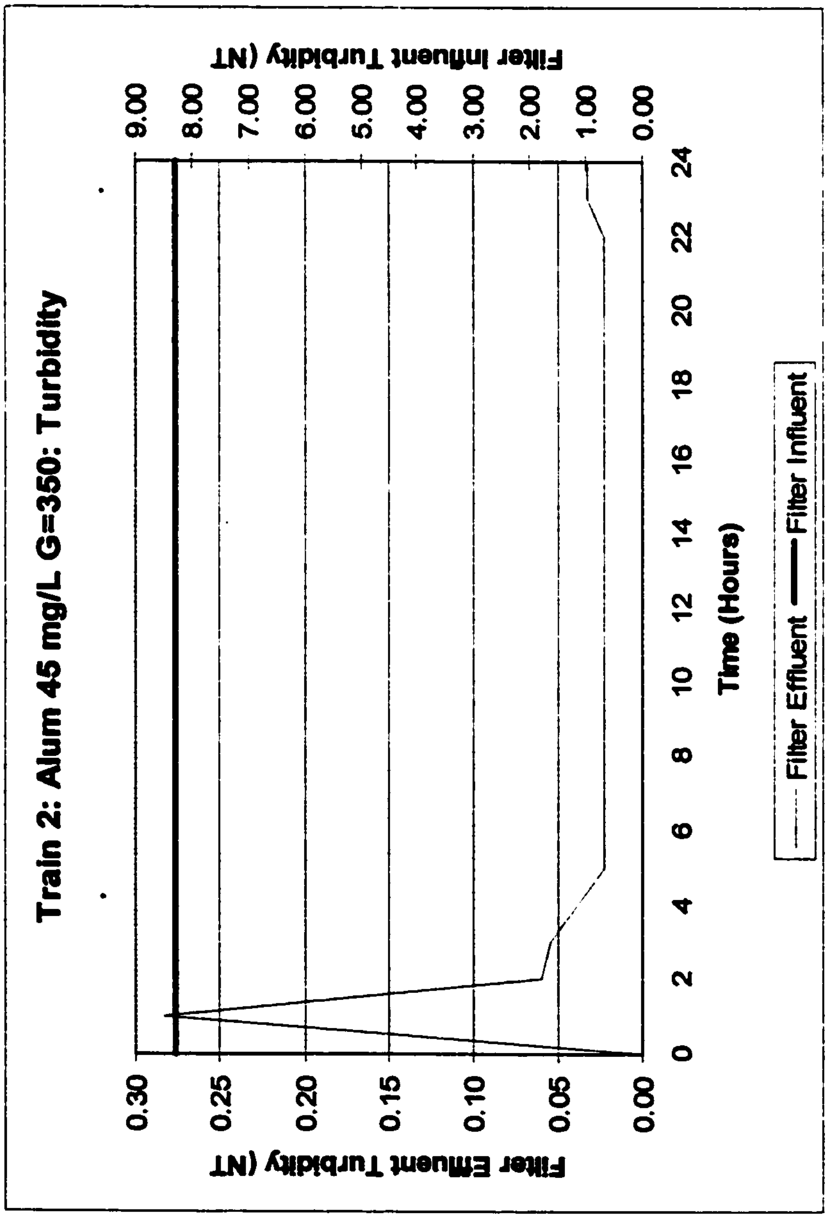

Train 2: Alum 25 mg/L G=500: Particle Counts
Filter Effluent Particl (>2µm/ml)
3000
2500
2000
1500
1000
500
0
Filter Influent Particl (>2µm/ml)
16000
15500
15000
14500
14000
13500
13000
0 1 3 4 5 6 7 9 10 11 13 14 15 16 18 19 20 21 23 24
Time (Hours)
Filter Effluent
Filter Influent


Train 2: Alum 25 mg/L G=500: Turbidity
Filter Effluent Turbidity (N
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Filter Influent Turbidity (N
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
2
4
6
8
10
12
14
16
18
20
22
24
Time (Hours)
Filter Effluent
Filter Influent

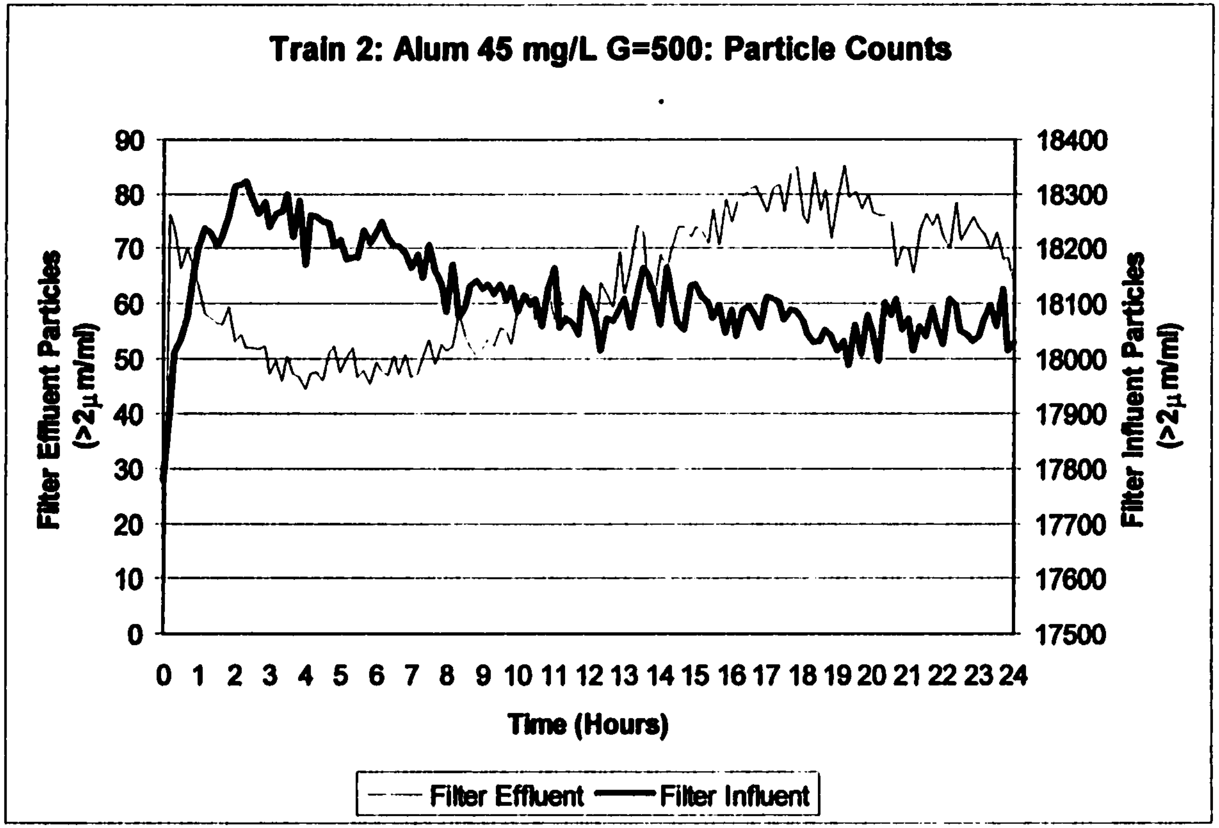

Train 2: Alum 45 mg/L G=60: Particle Counts
Filter Effluent Particles (>2μm/ml)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Filter Influent Particles (>2μm/ml)
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 4 5 6 7 8 9 11 12 13 14 15 16 18 19 20 21 22 23 24
Time (Hours)
Filter Effluent
Filter Influent

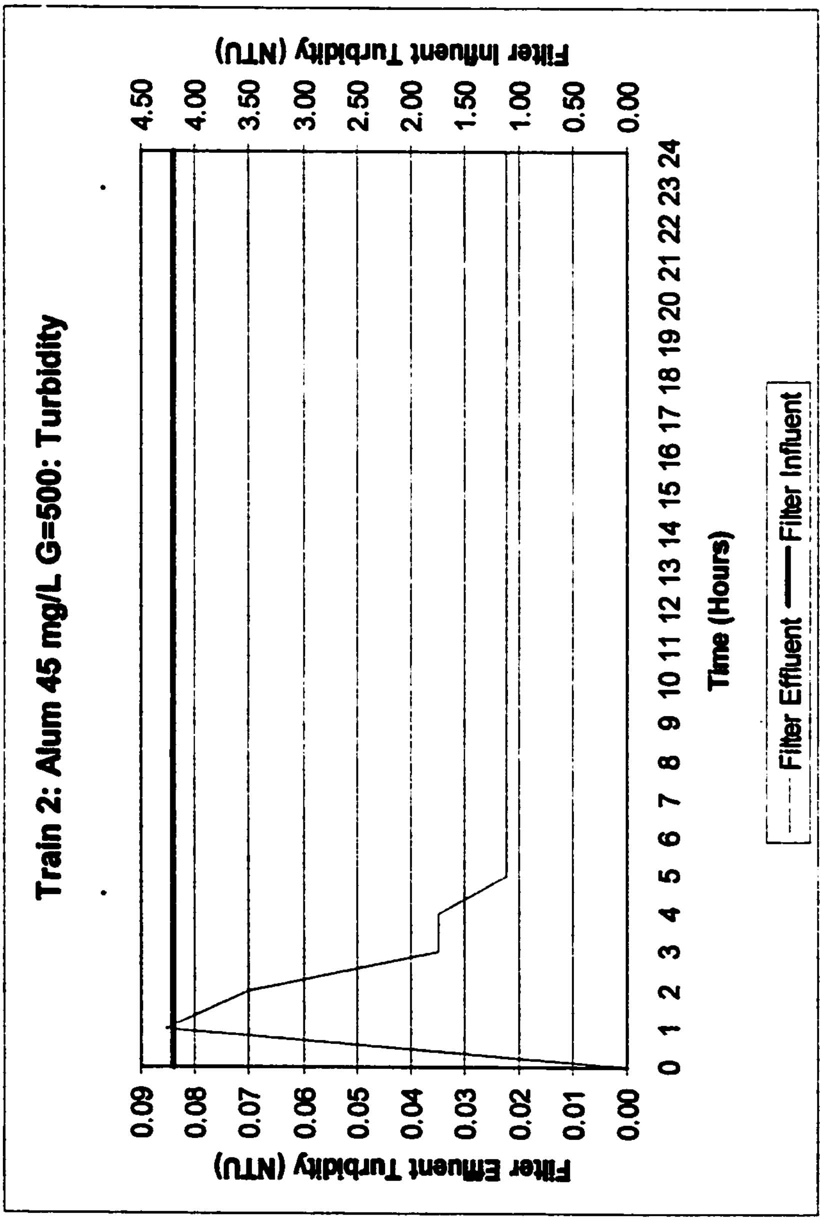

Train 2: Alum 45 mg/L G=60: Turbidity
Filter Effluent Turbidity (NTU)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Filter Influent Turbidity (NTU
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Time (Hours)
Filter Effluent
Filter Influent


Train 2: Alum 45 mg/L G=350: Particle Counts
Filter Effluent Particle (>2μm/ml)
1000
800
600
400
200
0
Filter Influent Particle (>2μm/ml)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 8 9 10 11 12 13 14 15 16 17 18 20 21 22 23
Time (Hours)
Filter Effluent
Filter Influent



Train 2: Alum 45 mg/L G=350: Turbidity


Train 2: Alum 45 mg/L G=500: Particle Counts
Filter Effluent Particles (>2μm/ml)
90
80
70
60
50
40
30
20
10
0
Filter Influent Particles (>2μm/ml)
18400
18300
18200
18100
18000
17900
17800
17700
17600
17500
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (Hours)
Filter Effluent
Filter Influent


Train 2: Alum 45 mg/L G=500: Turbidity
Filter Effluent Turbidity (NTU)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Filter Influent Turbidity (NTU)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time (Hours)
Filter Effluent
Filter Influent