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ABSTRACT

Using polymers as filter aids has become a widely accepted method to improve high rate filtration performance. However, the selection of polymers currently remains empirical. Furthermore, the effectiveness of filter aids is affected by the quality of influent, the characteristics of media, the operating conditions and the properties of the polymer. This study investigated the feasibility of polymers as filter aids for the removal of fine particles from lime softened water; explored the roles of polymer characteristics in the filtration processes; and examined major factors affecting the performance of polymer aided filtration.

Seven representative polymers with different molecular weights and charges were tested using a declining rate filter pilot plant. The results show that at a starting flow rate of 15 m/hr, all the tested polymers could produce the filtrate of around 0.03 NTU, as compared to the filtrate of 0.06 NTU without the use of polymer. In addition, the impacts of initial filter ripening could be substantially reduced and no turbidity breakthrough was observed after three days of operation. However, the use of polymer might significantly increase the filtration headloss, especially for the polymers with high molecular weight. To produce the high quality filtrate while ensuring the acceptable filtration productivity, low or moderately low molecular weight polymers are recommended. For a low molecular weight polymer, it was found that the optimum mixing intensity and polymer dose were around 700 sec^{-1} and 0.01 mg/L, respectively. On the basis of the results and particle properties, it is believed that interparticle bridging is the dominant mechanism underlying the interactions between polymers and particles of lime softened water.

Dedicated to my parents, my husband and my son

GUOXIONG ZHU

HUILANG LEI

HONGDE ZHOU

KEVIN ZHOU

for their encouragement, understanding and support.

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled: SELECTION OF POLYMERS AS FILTER AIDS FOR SOFTENED WATER submitted by: Honghui Zhu in partial fulfillment of the requirement for the degree of MASTER OF SCIENCE IN ENVIRONMENTAL ENGINEERING.

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SELECTION OF POLYMERS AS FILTER AIDS FOR SOFTENED WATER

by

HONGHUI ZHU ©

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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3. LITERATURE REVIEW

Filtration is a unit operation in which the particles are removed from water by accumulation on the surface of the medium or being collected throughout its depth as water passes through a filter. With the use of polymers as filter aids, the process includes various chemical and physical interactions and particle transport processes. An emphasis was placed on the four major topics in this review and relevant references will be discussed in this section. First, the types of particles to be removed during the water treatment processes and some of their properties are described. This is followed by a review of fundamental aspects of filtration in terms of mechanism of filtration, mathematical description and some engineering aspects of filtration. Then, an overview of characterisitics of polymers, actions of polymers as filter aids and factors affecting the polymer performance are presented. Finally, several methods previously employed for the selection of polymers as filter aids and their advantages and disadvantages are highlighted.

3.1 Particles in Water

Particles are defined as finely divided solids larger than molecules but generally not distinguishable by the unaided eye (Montgomery, 1985). In natural water, particles vary widely in origin, concentration and size. It is believed that they principally come from land-based or atmospheric sources, and chemical and biological processes (AWWA, 1990). For example, clay and pathogenic organisms are constituents of land-based or atmospheric sources. Algae and aquatic organic detritus are produced by chemical and biological processes. However, some water treatment

2. OBJECTIVES

The purpose of this study was to determine the most effective polymer to use as a filter aid for lime softened water and provide a guideline for its application at the E. L. Smith Water Treatment Plant. The major objectives of this study were as follows:

1. to determine the impacts of filtration rate increase on water quality;
2. to evaluate and compare the effectiveness of different polymers (cationic, anionic and nonionic of different molecular weight and charge density) as filter aids;
3. to investigate the effects of polymer addition on filter ripening and breakthrough;
4. to find the proper rapid mixing velocity gradient, G, and the optimum dosage for the most promising polymers;
5. to provide a better understanding of the role of polymer characteristics in the filtration of lime softened water; and
6. to recommend the type of polymers to be used for future expansion of the E. L. Smith Water Treatment Plant and the conditions of polymer addition, accordingly.

336 water treatment plants in the United States. Over 1100 polymers by name were approved by the US EPA that they could be used in water treatment, although most of them were made of a few basic monomers (Dental, 1991). These polymers range over a whole spectrum of molecular weights, type of charges, and charge densities. As a result, the selection of polymers is still based on the trial-and-error tests. The water utilities normally have to conduct the lengthy performance comparisons of competing products even when they were actually identical in composition.

This challenge in selecting a polymer as a filter aid is of particular importance for the E. L. Smith Water Treatment Plant. A literature review revealed that the previous studies and practices were concentrated on the application of polymers for the filtration of natural water or water after the coagulation with alum. In these studies, the suspended solids were usually negatively charged and relatively easy to remove from the water by filtration. Much less attention has been paid to polymer aided filtration of lime softened water. It contains a majority of particles which come from the carry-over of calcium carbonate precipitates. These particles have totally different characteristics. They are smaller, denser and uniform in size. At a pH of around 8.5, they are close to the isoelectric point (Montgomery, 1985). As a result, it is very easy for them to escape from the filter bed. Special attention is required to address the behavior of softening particles and their interaction with polymers as filter aids in high rate filtration.

This study was conducted to investigate the feasibility of using polymers as filter aids for lime softened water using a filtration pilot plant located at the E. L. Smith Water Treatment Plant. It also explored the role of polymer characteristics in the filtration processes and examined major factors affecting polymer aided filtration performance. A three-stage study was initiated: 1) preliminary filtration rate study to set forth the necessity of adopting polymers as filter aids; 2) polymer screening tests to

1 μm for which the transport efficiency is minimum. For smaller particles, diffusion plays an increasing role, and for larger particles, sedimentation becomes dominant. After being transported close to the filter media, the particles tend to attach to the filter by a number of different physical and chemical interaction forces. O'Melia (1985) identified that the surface properties of the particles and media were the two predominated factors in this step. The repulsive interaction would occur between suspended particles and filter media that carry a similar charge (Ghosh *et al.* 1975). When a polymer is used as a filter aid, the interparticle bridging can result in an increase in the size of particles. It may also neutralize the particle surface charge to reduce electrical repulsive forces and facilitate the mutual adsorption of a molecule or a group of molecules to both the filter media and particles. Thereby, both the transport and attachment mechanisms would be facilitated by the formed polymer-particle flocs. In addition, these flocs are usually stronger and may withstand the high shear forces in the filter bed.

However, the limited knowledge of filtration mechanisms, complexity of interactions between polymer molecules and particles, and difficulty in obtaining clear information about the polymer specific properties have prevented the development of rational approaches for the selection of filter aids. In addition, the quality of influent, the characteristics of filter media and operating conditions will significantly affect the effectiveness of polymers as a filter aid. A wide range of raw water quality and filtration flow rates covered in the previous studies and practices make it difficult to compare and extrapolate the results directly. A most appropriate polymer often seems to be site-specific. Furthermore, there are a great number of commercial polymers which can be used as filter aids. A survey conducted by the Water Quality Division's Coagulation and Filtration Committee in May 1979 (AWWA Committee Report, 1982) found that 48 different polymers were used in different water facilities among

For example, certain concerned pathogens, particularly *Giardia* and *Cryptosporidium*, are extremely resistant to conventional disinfectant doses and contact times when in the cyst form. However, they can be significantly removed by proper filtration. As a result, effective filtration has been stressed as an essential accompaniment to conventional disinfection by a committee of the American Water Works Association (Craun, 1988):

> "Simple disinfection as the only treatment for surface waters is ineffective in preventing waterborne transmission of giardiasis. All surface water should receive pretreatment and filtration in addition to disinfection.... Waterborne disease outbreaks...have occurred in systems [in which] the health-related turbidity limit has not been exceeded.... [S]afe drinking water can be assured only by properly designed and operated...plants that utilize coagulants or filter aids in addition to disinfection."

In deed, it has been reported that the use of polymer aids has benefits throughout the whole cycle of filtration, namely, an improvement of filtrate quality, a resistance to early breakthrough and a reduction in the magnitude and duration of the filter ripening sequence (Conley and Hsiung, 1969; Conley and Pitman, 1960; Tuepker and Buescher 1968). These improvements have been reasonably explained based on the current knowledge of filtration mechanisms. It is well known that the success of the filtration process requires two separate and distinct steps: the transport of the suspended particles to the filter media and the attachment of these particles to the media or to another particles that has previously been deposited in the bed (Ives and Gregory, 1967; O'Melia and Stumm, 1967). Among various transport mechanisms, diffusion and sedimentation are generally dominant (Amirtharajah, 1988). Their relative importance depends upon several physical parameters, the most significant of which can often be the size of the particles to be removed from suspension (Habibian and O'Melia, 1975). Yao *et al.* (1971) showed that there exists a critical size of about

1. INTRODUCTION

The E. L. Smith Water Treatment Plant has proposed to double its filtration capacity from 200 ML/day by operating seven filters to 400 ML/day by operating ten of their twelve existing filters at a time. Consequently, the average filtration rate has to be raised from 9.4 m/h to 13.2 m/h. With this increased filtration rate, concerns have been raised whether the excellent water quality the plant currently provides can be maintained. To address these concerns, an extensive literature review has shown that there are two common approaches that might be directed to improve the performance of filters at a high filtration rate: 1) modifying the pretreatment techniques so that most particles can be settled in the upstream sedimentation basin; and 2) changing the surface properties and sizes of particles entering the filter to enhance both transport and attachment mechanisms. Using polymers as filter aids is one of the most effective methods to achieve the desired characteristics of particles to be removed from water (AWWA, 1990).

The proper use of polymers as filter aids not only maximizes the removal of particulate matter, but can also lead to improvement in a variety of other water quality paramenters which are characterized by less conventional parameters (Dentel, 1991). This is mainly because the naturally suspended particles represent a transport vehicle for undesirable organic and inorganic contaminants, taste and odor causing compounds, colour chemicals and potentially disease causing microbial pathogens.

Parts of this thesis have been accepted for publication. (1) Zhu, H., Smith, D. W., Zhou, H., and Stanley, S. J. (1994) *Water Research*; (2) Zhu, H., Smith, D. W., Zhou, H., Stanley, S. J. and Kellendonk D. (1994) *Annual Conf. Proc. of Canadian Association for Civil Engineers*, Vol. 3, Winnipeg, 159 - 168.

LIST OF SYMBOLS

a, b, c = empirical exponents

C = concentration

C_d = coefficient of drag

C_o = initial concentration

D = grain diameter, m

D_p = influent particle diameter

D_s = sand grain diameter

f = friction factor

f(U) = Chi-square distribution function

g = gravity constant, 9.807 m/s^2

G = velocity gradient, sec^{-1}

h = head loss, m

i = hydraulic gradient

K = Kozeny filtration constant,

k_1 = accumulation coefficient

k_2 = detachment coefficient

K_d = Darcy's permeability coefficient

n = porosity

N_R = Reynolds number

P = input power, watt

t = time

v = filtration approach velocity, m/s

V = volume of water

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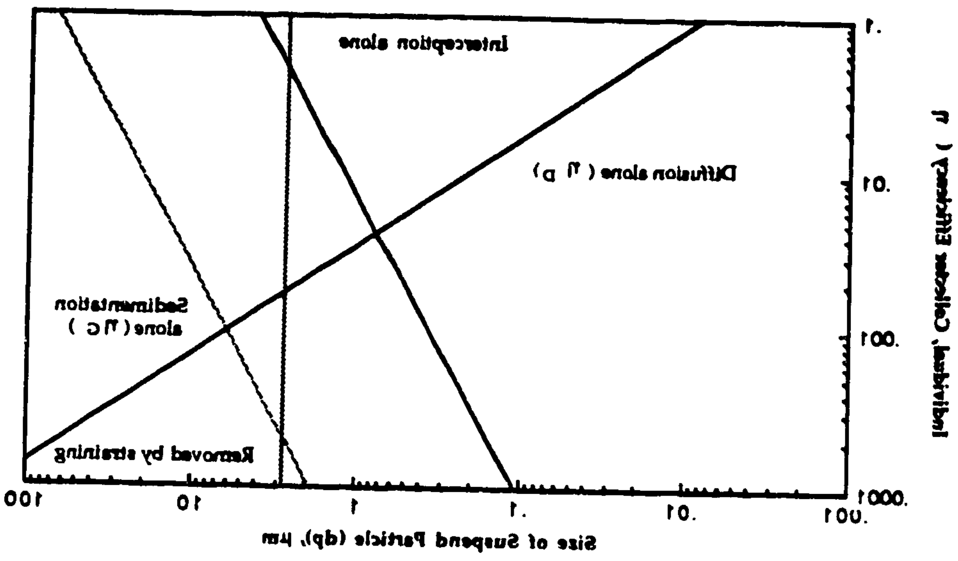
In summary, over the last three decades deep media filtration has been studied extensively. Various models aiming to predict the particle removal efficiency have been developed. These models have had some important success and some notable failures. In the absence of a successful, general and predictive theory of filtration, it is necessary, at the present time, to combine the theoretical prediction and the pilot plant studies to evaluate filtration design and performance for a given raw water supply, chemical pretreatment, and filter configuration. The qualitative effect of increasing each of parameters on the particle removal efficiency are summarized in Table 3.

3.2.2.3 Pressure Drop

The pressure drop (i. e., headloss) always occurs when water flows through the filter media. It was recognized as early as in the 1900's that this pressure drop is attributed to the combined effects of the drag friction at the surface of the media and the continuous contraction and expansion of the fluid as it passes through pore openings in the filter.

If straining is the controlling mechanism, the particles may form a layer of deposit on the surface of the filter medium. The headloss across this layer depends on the size distribution and mechanical properties of the filtered particles. The rate of headloss buildup per unit mass of filtered particles increases as the size of the particles increases and as the size distribution becomes increasingly narrow (more monodispersed).

Figure 2. Relative Importance of Different Particle Removal Mechanisms by Filtration



Attachment efficiency, although recognized as critical in removal, is often empirically determined because of a lack of understanding of how system chemistry affects deposition.

Given values for transport and attachment efficiency, the single collector removal efficiency η_R can be calculated as follows:

$$\eta_R = \alpha \eta_0 \qquad (10)$$

By considering the change in concentration dC that occurs in the suspension over an elemental depth dz and relating it to the single collector efficiency of grains within the clean porous filter media, it was shown by Yao et al. (1971) that

$$\frac{dC}{dz} = -\frac{3(1-\varepsilon)\alpha\eta_0}{2d_c} C \qquad (11)$$

Integration of above equation gives the prediction of overall removal of particles in the filter. In particular, comparison of model predictions with experimental observation reveals that submicron particles are transported primarily by Brownian motion, whereas larger particles are affected primarily by sedimentation and interception (see Figure 2). At a range of intermediate particle sizes (1 to 2 μm), a minimum collection efficiency exists in conventionally designed and operated filters. But when the surfaces have a repulsive potential, the collection efficiencies predicted from the trajectory analysis fail to describe the experimental observations due to a sudden decline in η_0 by two to three orders of magnitude. As a matter of fact, the actual collection efficiency under a repulsive double layer potential shows a gradual decline (Tobiason and O'Melia, 1988). The second limitation of trajectory theories is that they, at present, apply only to clean beds. The theories do not account for single-collector efficiency changes caused by previously retained material, nor do they account for detachment of deposits from the filter grains.

$$\eta = \frac{\text{rate at which particles strikes the collector}}{\text{rate at which particles approach the collector}} \quad (4)$$

Transport efficiency can be quantified in terms of fundamental physical characteristics of the suspension and media, and operating conditions. Expressions for η from the important transport mechanisms of diffusion, sedimentation and interception are given by (Amirtharajah, 1988):

Diffusion: $\eta_D = 4\ Pe^{-2/3} = 0.9\ (kT/\mu\ d_p\ d_c\ U)^{2/3}$ (5)

Sedimentation: $\eta_G = v_p/U = [(\rho_p - \rho)\ g\ d_p^2]/18\mu U$ (6)

Interception: $\eta_I = 1.5\ (d_p/d_c)^2$ (7)

in which P_e = Peclet number = (Ud_c / D);

$D = kT / (3\pi\ \mu\ d_p)$;

k = Boltzmann's constant;

μ = absolute viscosity;

T = absolute temperature;

v_p = settling velocity of particle;

ρ_p = density of particle;

ρ = density of water; and

g = acceleration resulting from gravity.

The total single collector efficiency is:

$$\eta_0 = \eta_D + \eta_G + \eta_I \quad (8)$$

The attachment efficiency, α, is:

$$\alpha = \frac{\text{rate at which particles attach to the collector}}{\text{rate at which particles strike the collector}} \quad (9)$$

Table 2. Summary of Phenomenological Models for Filtration (adapted from Finch et al., 1985)

Equation	Definition of Terms
Iwasaki: $-\frac{\partial C}{\partial z} = \lambda C$ $-\frac{\partial C}{\partial z} = \frac{1}{v}\frac{\partial C}{\partial t} + \frac{(n-\sigma)}{v}\frac{\partial C}{\partial t}$ Ives: $\frac{\lambda}{\lambda_o} = (1 + \frac{\beta\sigma}{n})^a (1 - \frac{\sigma}{n})^b (1 - \frac{\sigma}{\sigma_u})^c$ O'Melia and coworkers: $\eta_r = \alpha\eta + x\alpha_p\eta_p(\frac{D_p}{D_s})^2$ $\frac{\partial x}{\partial t} = \eta\alpha\varepsilon x_o v D_s^2 \frac{\pi}{4}$ $\frac{\partial x}{\partial t} + v_o\frac{\partial x}{\partial z} + \frac{3}{2}\frac{(1-n)}{D_s} v x \eta_r = 0$ Adin and Rebhun: $\frac{\partial\sigma}{\partial t} = k_1 v C(\sigma_u - \sigma) - k_2\sigma i$ $\frac{\partial\sigma}{\partial V} = k_1 C(\sigma_u - \sigma) - k_2\frac{\sigma}{K}$ Hsiung and Cleasby: $f(U) = \frac{U^{(v/2-1)}e^{(-U/2)}}{2^{(v/2)}\Gamma^{(v/2)}}$ $P_v = f(U)dU$	a, b, c = empirical exponents C = concentration C_o = initial concentration D_p = influent particle diameter D_s = sand grain diameter f(U) = Chi-square distribution function i = hydraulic gradient K = Darcy's permeability coefficient k_1 = accumulation coefficient k_2 = detachment coefficient n = porosity P_c = cumulative probability = C/C_o t = time V = volume of water v = filtration rate x = particles attached to sand x_o = initial particles in solution z = depth of filter bed α = attachment efficiency factor α_p = particle attachment efficiency factor β = geometric coefficient Γ = gamma function ε = fraction of attached particles acting as collectors η = single collector efficiency η_r = single collector removal efficiency η_p = contact efficiency of retained particle λ = filter coefficient λ_o = initial filter coefficient σ = specific deposit σ_u = ultimate specific deposit to clog filter v = degree of freedom = sample time interval

where λ = filter coefficient. The filter coefficient, λ, is an important parameter in filtration and occurs in all of the theories of filtration. Later experiments found that porosity is altered by deposits, so is the filter coefficient. Ives (1975) modified Iwasaki's model by considering the filter coefficient as a variable to account for the increase in removal efficiency during the initial filter ripening stage and for the subsequent decrease in removal efficiency leading to breakthrough. Mathematically,

$$\lambda = \lambda_0 \,[1 + \sigma/(1 - \varepsilon_0)]^a \times [1 - \sigma/\varepsilon_0]^b \times [1 - \sigma/\sigma_M]^c \qquad (3)$$

where a, b, c = empirical constants, ε_0 = porosity of clean filter bed, and σ_M = ultimate saturation value of the specific deposit ratio. Other similar models are listed in Table 2.

A major advantage of the above approach to modeling is that the entire filter cycle is modelled. However, it is a macroscopic approach that requires pilot-scale experiments to determine many of the parameters necessary for modeling, for example, the constants a, b, c, and σ_M in Eq 3. Another disadvantage is its lack of generality for predictive purposes, and it does not provide a fundamental understanding of the mechanisms of deposition.

3.2.2.2 Trajectory Theories.

The principle of trajectory analysis is to view a granular bed as an assembly of collectors and to determine the extent of particle deposition on the collectors in a probabilistic sense (O'Melia and Stumm, 1967; Yao et al., 1971). According to these theories, the transport efficiency of a single collector in a clean bed, η, is (Darby et al., 1992):

(b) the transport of particles results from advection alone, while the dispersion is negligible; and

(c) the mass of particles removed from suspension in the filter equals that accumulated in the filters.

The mass balance equation can be written as (Amirtharajah, 1988):

$$U\frac{\partial C}{\partial t} + \frac{\partial}{\partial t}\,[\,\sigma + \varepsilon C - (\sigma/\rho_S)] = 0 \qquad (1)$$

where: C = concentration in mass per unit volume, g/m^3

σ = specific deposit (mass of particles deposit / filter volume), mg/m^3

ε = porosity, m/m

z = depth, m

t = time, s

U = approach velocity, m/s, and

ρ_S = density of deposit

The terms εC and (σ/ρ_S) are opposite in sign and trivial as compared to the change in the deposited solids, so the equation is often simplified by omitting the εC and (σ/ρ_S) terms.

Various kinetic equations have been proposed to couple with the above mass balance equation. The original equation was developed by Iwasaki (1937), who stated that the rate of particle deposition within the filter at a given time was proportional to the particle concentration.

$$\frac{\partial C}{\partial z} = -\lambda C \qquad (2)$$

It should be noted that the most significnat achievement made previouly is the better understanding of relative significance of various processes involved on the removal efficiency of particles. Adin and Rebhun (1974) stated that the transport mechanism appears to be sufficient to accomplish their task even for the most difficult to transport particles. Thus, the transport mechanism is relatively insignificant in filter design. On other hand, the control of filtration should be directed to improve attachment efficiency, mainly through the use of polymers as filtration aids.

3.2.2 Mathematical Description of Filtration

With the better understanding of the mechanisms of particle removal within filters, efforts have been made to quantitatively describe the overall particle removal efficiency. Although a number of models have been proposed, they can generally be classified by two different modeling approaches: (1) phenomenological theories; and (2) trajectory theories.

3.2.2.1 Phenomenological Theories.

The phenomenological approach has developed from early attempts to describe the changes in the concentration or mass of particles in the influent water as the removal takes place within the filter (Amirtharajah, 1988). Essentially, this is a formulation of a non-steady-state or steady-state mass balance equation combined with the kinetic description of the accumulation of particles within the pores. Assuming that:

(a) the bed is a homogeneous, isotropic mass with a uniform media grain size, density, and porosity which remains constant with time;

Table 1. Summary of Transport and Attachment Mechanisms and Their Dependence on Operating Conditions (adapted from Boyd and Ghosh, 1974)

Transport or Attachment	λ_0		
Mechanism	d_p	V_o	ξ_o
Straining	$d_p^{3/2}$	*	*
Gravity Settling	d_p^2	V_o^{-1}	*
Interception	d_p^2	*	*
Brownian Diffusion	$d_p^{-3/2}$	$V_o^{-2/3}$	*
Electrostatic Force	d_p^{-1}	V_o^{-1}	ξ_o^{-1}
London Forces	d_p^2	weak	weak

* No predicted dependence

The attachment mechanisms involve either electrostatic interactions, van der Waals forces, or surface chemical interactions (O'Melia and Stumm, 1967). Attachment is affected by both physical and chemical factors. There are two models which are used to describe the mechanism (Adin and Rebhun, 1974). The "double-layer model" is based on an interaction between the electrostatic repulsive forces and van der Waals's forces. The "bridging model" explains effects that are not treated by the first model as resulting from chemical bonding and bridging of the suspension particles through reaction with the flocculant. It has been shown both theoretically and experimentally that particle capture will be favorable when surface charges of the particles and media are of opposite sign. Where the media surface is covered by deposited particles, the collection is effective only if the particles have been adequately destabilized. O'Melia and Stumm (1967) suggested that these conditions are exactly analogous to coagulation.

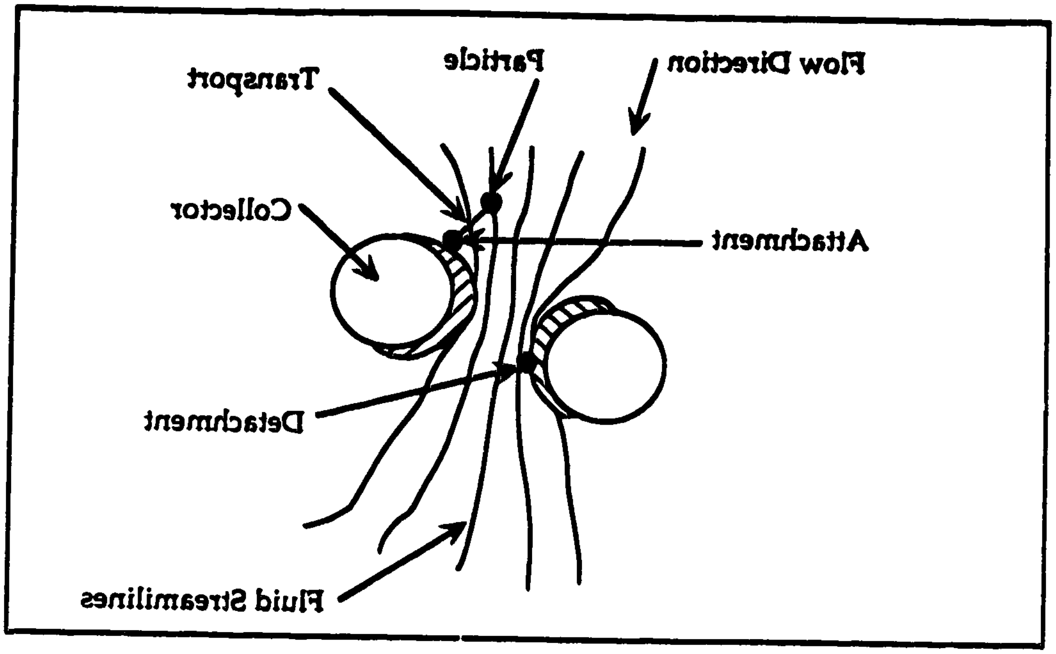
The detachment mechanisms include scour due to increased interstitial velocity gradients in the bed or as a result of floc shearing. Its magnitude would depend on the influent concentration, the length of filter run, the hydrodynamic forces and deposit morphology. Only until recently had quantitative description of the detachment mechanisms been developed by Adin and Rebhun (Ginn et al., 1992). It should be noted that the mechanisms of attachment and detachment may occur simultaneously and the detachment mechanisms often control the effluent particle concentration and particle size distribution as the significant portion of particles in the effluent come from the detached flocs (Ginn et al., 1992).

Table 1 summarizes the important transport and attachment mechanisms and shows the predicted functions of initial filter coefficient as the variations in diameter of particles d_p, approach flow velocity V_0 and zeta potential ξ_0.

filter grains but also to particles that were previously removed and are now acting as additional collectors. Some common configurations are spherical caps on the tops of grains and tubular structures within the pores. If the overall superficial filtration rate remains constant, then the fluid velocities will result in increasing drag forces on the deposited particles, and when the drag forces exceed the adhesive forces, particles are detached and reach lower depths within the filter. Alternatively, the detachment may be discerned as the avalanche effect of arriving particles. Thus, in a filter layer that has reached a saturated but metastable configuration of deposited particles, the mechanisms of attachment and detachment may occur simultaneously.

The transport of particles in the pores of the media is the combined effects of physical and hydrodynamic processes including diffusion, sedimentation, interception, inertia and hydrodynamic action. It is generally accepted that under the conditions of water filtration the dominant mechanisms are diffusion, sedimentation and interception (Habibian and O'Melia, 1975). The diffusion is the transport resulting from random Brownian motion from bombardment of the particle by molecules of water. It is obvious that particle motion by this mechanism is stochastic in nature and would become increasingly important for particles <1 μm in size. Sedimentation is due to the force of gravity and the associated settling velocity of the particle, which cause it to cross streamlines and reach the collector. For this mechanism, particle and fluid densities and viscosity play important roles. It becomes increasingly important for particles > 1 μm. Interception occurs when particle motion along a streamline is sufficiently close to the collector for attachment to occur. For large particles of low density, interception and sedimentation are about equally important in controlling particles removal. As the density of the particles increases, sedimentation becomes controlling (Amirtharajah, 1988).

Figure 1. Mechanisms of Filtration (adapted from Amirtharajah, 1988)



The particle size also influences the particle transport mechanism. Yao *et al.* (1971) found that there exists a critical size of about 1 µm for which the transport efficiency is minimum. For smaller particles, diffusion plays an increasing role, and for larger particles, sedimentation becomes dominant. It has been noted that when the particles and filter media carry a similar charge, the filter removal efficiency is reduced as compared to particles carrying different charges (Ghosh *et al.*, 1975). Some researchers (Boyd and Ghosh, 1974 and Shull, 1967) also found that when the ZP of a particle is close to zero the removal efficiency reaches optimum.

3.2 Filtration

3.2.1 Mechanisms of Filtration

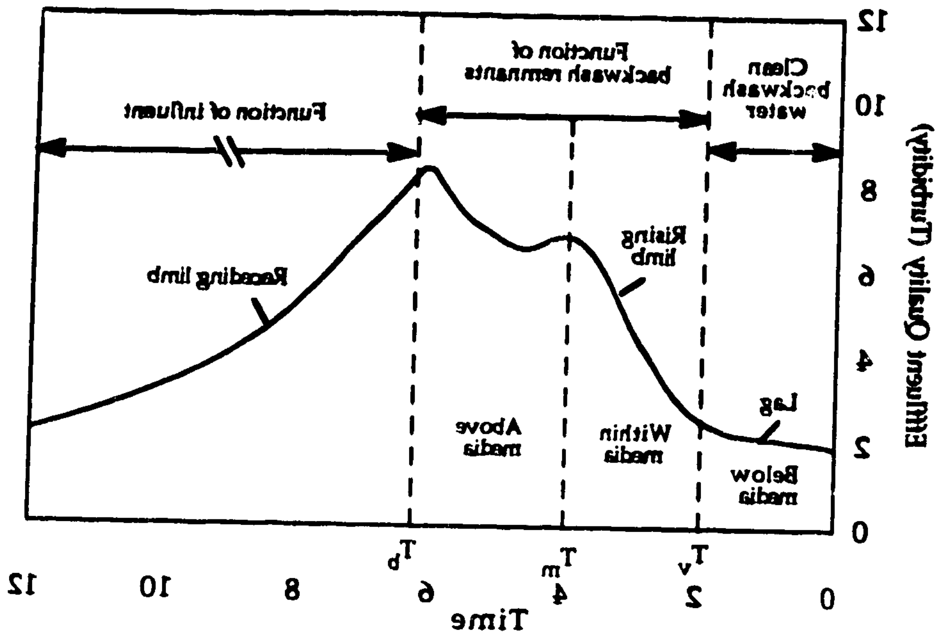
The mechanisms of particle removal from liquid during filtration are complicated. For deep-bed filters, the mechanisms are considered at least in three steps: transport, attachment and detachment (Amirtharajah, 1988), as illustrated in Figure 1.

The removal of particles within the pores of a filter is first mediated by transport mechanisms that carry the small particles close to the filter grain surfaces. The filter grains are also called collectors. When the particles are very close to the collectors, surface forces may cause capture of the particle and its attachment to the collector. As particles are removed on the filter grains, they tend to accumulate in a variety of geometric configurations. These configurations are related not only to the processes, notably coagulation and softening, can also produce other insoluble chemical products.

The charge, floc size and density are the most important characteristics of particles in filtration. Because of their small size, particles are usually electrically charged, either through adsorption of ions on their surface, ionization of the particles, or both. In natural waters, particles usually carry a negative surface charge in the neutral pH range. So do the alum coagulation flocs. In contrast, the calcium carbonate particles in the lime softened water have positive charge up to pH of 8, with a zero point of charge (neutral) at a pH around 8.5. Because of the surface charge, the particles move toward the opposite electrode when an electrical potential is applied across a suspension. Thus, the charge of particles can be quantitatively measured by the potential that causes the motion of the particles. This potential is called *zeta potential* (ZP) or electrokinetic potential. The pH and ionic strength of water are two major factors which affect the ZP value. In natural waters the ZP on clay particles ranges from -12 to -25 mv (Shull, 1967). For the lime softened water from the E. L. Smith Water Treatment Plant, it was found that the ZP was close to zero at pH of around 8.5, in agreement with the expectation from the zero point of charge theory. However, it should be realized that a colloidal system as a whole does not have a net electrical charge, and the primary charge on the particle must be counterbalanced. This is significant in explaining the stability of some colloidal suspensions by the electric double layer theory (Stumm and Morgan, 1981).

With the understanding of the physical and chemical properties of particles in water, the dominant mechanisms of water filtration can be decided. When particle size is greater than the pore opening of filter media, straining is considered the only possible removing mechanism. When particle sizes are smaller than the pore opening, the particles are collected inside the filter bed, and various mechanisms are involved.

Figure 4. General Pattern of Initial Filter Ripening (adapted from Amirtharajah and Westein, 1980)



the first corresponding with the turbidity of the backwash water remnants remaining within the media, and the second corresponding with the backwash water remnants standing above the filter media, up to the backwash water gutter, following backwash.

Francois and Van Haute (1985) described the filter ripening phase, modifying Amirtharajah and Wetstein's theory. They indicated the initial degradation in quality was composed of 95 percent of particles from the influent water and 5 percent of particles from the backwash remnant water. It was also concluded that by over-dosing the coagulant during the initial stages of filtration, the filter ripening peak could be reduced. This observation was consistent with Yapijakis (1982), who indicated that the addition of polymer to the backwash water serve to minimize the filter ripening duration and magnitude. The results were again confirmed by Bucklin et al. (1988). They further stated that the optimum coagulant type to be used during backwash will generally be alum or the polymer used as the primary coagulant. It was also suggested that the backwash coagulants appear to work by one or both of the following mechanisms: (1) by preventing partial stabilization of the initial influent particles or (2) by providing additional aluminum hydroxide microflocs which accelerate the filter ripening process. At the present, the addition of polymers to backwash water has become widely accepted as a means of minimizing the filter ripening stage of filtration.

3.3 Polymers as Filtration Aids

3.3.1 Characteristics of Polymers

Polymers are long-chain molecules consisting of repeating chemical units with a structure designed to provide distinctive physicochemical properties to the polymer (Montgomery, 1985). They must have a capability of reacting with suspended

When polymers are used as filter aids, backwashing becomes more difficult because of the higher attachment forces between the particles and the filter media. Adin and Rebhun(1974) suggested that auxiliaries such as surface wash or air scour are necessary to be used in the filtration process when using polymers as filter aids. Amirtharajah (1988) also indicated that simultaneous air scour (0.9 to 1.5 $m^3/m^2/min.$) and subfluidization water wash (4.08 to 5.44 mm/s) provide the best cleaning for solids with higher adhesive forces (polyelectrolytes or wastewater solids).

3.2.3.4 Filter Ripening and Initial Degradation of Filter Effluent

The filter ripening, happens during the period which the backwashed filter's initial effluent turbidities are higher than the average effluent turbidities. During this period, the filtrate has been observed to deteriorate for a few minutes and then improve over about 30 minutes before reaching the best level of the entire run (AWWA, 1990).

A number of studies have been reported in the literature for investigating the initial degradation of filter effluent. Amirtharajah and Westein (1980) first showed that the initial effluent quality from a repeatedly used filter could be divided into three stages: the lag period, the rising limb culminating in two turbidity peaks and the long receding limb (Figure 4). They proposed that the lag period was due to the clear backwash water remaining in the underdrain system up to the bottom of the filter media, that the rising limb was due to particles detached during collisions of settling media at the end of the backwash, particles from the backwash water and also the agitation in the collection and clear well channel, and that the receding limb was due to the dispersion and mixing of the media-derived particles from the filter with the influent and the accumulation of influent particles within the media pores. The peaks, successful service of a filter. The aim of the backwashing operation is to keep the filter acceptably clean, so that no progressive evidence of the development of dirty-filter problems, such as mud balls and filter cracks, occurs.

A number of alternative systems of backwashing used currently includes upflow with full fluidization, surface wash plus fluidized-bed backwash, and air scour-assisted backwash (Cleasby et al., 1977). Upflow wash with full fluidization is the traditional backwash system used in most water treatment plants. The backwash water is introduced into the bottom of the filter bed through the underdrain system at a sufficient velocity to suspend solid particles in the fluid. The surface wash systems uses the injection jets of water from orifices located about 25 to 50 mm above the fixed-bed surface. Surface wash jets are operated for 1 to 2 minutes before the upflow wash and usually are continued during most of the upflow wash, during which time they are immersed in the fluidized filter media. Air scour-assisted backwash is supplying air to the full filter area from orifices located under the filter media. Air scour can be used in three different ways: (1) air scour is used before the water backwashing, (2) air scour is used as a portion of the water backwash, and (3) air scour and water backwash are used simultaneously.

The best criteria for backwash effectiveness are the quality of the filtered water and the long-term absence of dirty filters and mudball formation. A number of investigators (Hudson, 1935; Balis, 1959a; Cleasby *et al.*, 1977; Amirtharajah 1988) have indicated that few or no contact occur between fluidized media particles. Hence, particulate fluidization with water alone is an intrinsically weak cleaning process. Air scour, which causes abrasions between particles throughout the depth of the bed, and surface wash, which causes collisions at the top of the bed, are effective auxiliaries for cleaning.

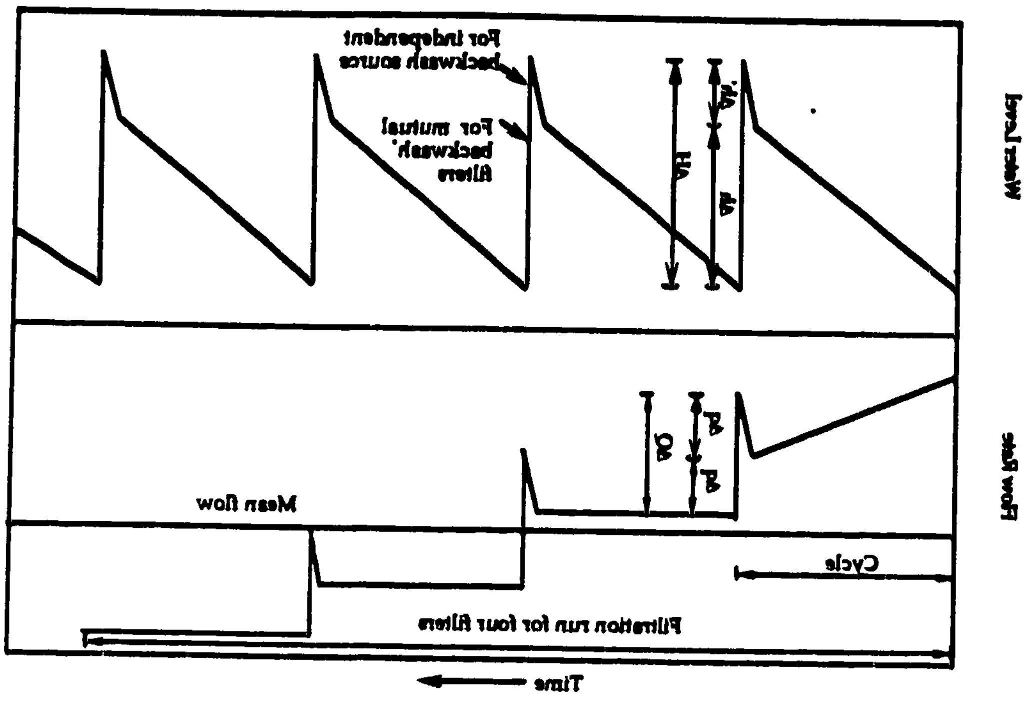
Similar study was carried out by Bernardo and Cleasby (1980). In their study, a single constant-rate filter and four declining-rate filters were used to compare headloss, filter run time, and effluent water quality characteristics while filtering a lime-softened groundwater. The research was conducted using dual-media filters at rates of 7.33, 12.22, and 17.22 m/h. Their results included: (1) "substantially better" average declining-rate filtration effluent turbidity, (2) longer declining-rate filtration run length when both filter units were operated at the same filter media headloss increase, and (3) smaller backwash rate variations with declining-rate filtration than with constant-rate filtration.

Cleasby (1969) also described his experiences at the Taipei water treatment plant in Taiwan, where the rate-of-flow controllers were eliminated and the filters converted to a declining-rate operation. Later, he summarized (1981) that there are several advantages of declining-rate system over the effluent constant-rate control: (1) when one filter is taken out of service for backwashing, the water level gradually rises in the remaining filters and, as a result, the filtration rate variations are slow and smooth; (2) the headloss is evident to the operator, who can observe the water level in the filters. As a result, headloss gages on each filter are not required; (3) effluent quality is better when the filtration rate declines toward the end of the run; (4) the water volume produced per unit of headloss is greater; (5) less available headloss is required for the same filter run length.

3.2.3.3 Backwashing of Rapid Filter

After operation for a period of time, the filter, in terms of either available headloss or turbidity limitation, is exhausted and needs backwashing to renew its filter capacity. It was recommended that this effective backwashing is essential to long-term

Figure 3. Hydraulic Behaviors of a Variable Declining Rate Filter (adapted from Arboleda - Valencia, 1985)



In constant-rate filtration, the filtration rate is regulated by an effluent flow control valve. In the first stages of a filter run, the filter bed is relatively clean and provides little resistance to flow. At the start of a filter run, the effluent control valve is kept almost closed to provide the additional headloss necessary to maintain the flow rate at the desired level. As a filter run progresses, solids are captured and the resistance (or headloss) across the bed increases. The control valve gradually opens to counteract headloss in the filter bed, thereby maintaining a constant filtration rate.

In declining-rate filtration, the resistance of the clean bed is low at the beginning of a run and the corresponding filtration rate is higher than average. A flow-restricting orifice is used in the effluent piping to control this maximum rate at a reasonable level. As the filter clogs with solids, resistance through the filter bed increases, which causes the flow rate to decrease as a result of a shift in flow to the cleaner filters. As the flow decreases through an individual filter, the headloss decreases through the piping, underdrains, and the orifice (to the power 2), resulting in a recovery of head.

A number of advantages have been observed with the declining rate filtration as compared to the constant rate filtration. Baylis (1959b) reported on the results from an experimental filtration plant at Chicago, where no rate controllers were used on some filters. The filtration rate was allowed to decline from a maximum value at the beginning of the run when the media was clean to minimum value when the filter was backwashed. It was concluded the effluent quality under variable filtration rate was neither worse nor better than that produced at constant rate, but water production was higher. The results of similar tests of declining-rate filtration conducted by Hudson (1959) at Wyandotte, Mich. water treatment plant confirmed that a longer filter run was achieved. In addition, the study showed that better quality water was produced by the declining-rate filter than by the conventional constant-rate filter.

distributions of media size, the filtration rate, and the size distribution of the influent suspension. In general, if a suspension is effectively destabilized by the coagulant, the filtration rate is low, the media grains are small, and the influent particles are large, the rate at which the filtration zone penetrates the bed will be low.

The most widely used dual media filters are the high rate or rapid granular bed filters. Representative design and operating characteristics of a rapid sand filters are (Letterman, 1987):

(a) type of medium - sieved silica sand + anthracite;

(b) effective size range of medium (diameter) - about 0.5 mm with a uniformity coefficient less than 1.65 for sand and 0.9 to 1.0 mm with a uniformity coefficient less than 1.7 for anthracite;

(c) depth of media - 0.6 m;

(d) filtration rate (fluid approach velocity) - 4.8 m/h (constant during filter operation);

(e) fluid driving force - gravity;

(f) limiting head loss - 2.4 m of water; and

(g) cleaning - upflow by pumping through the media at velocities up to 36.6 m/h for 10 minutes (backwashing or air scouring).

3.2.3.2 Modes of Filter Operation

There are two primary methods of operating filters: constant-rate filtration and declining-rate filtration. These two operating methods differ primarily in the way the driving force is controlled across the filter. The concepts of constant-rate filtration and declining-rate filtration were described by Cornwell et al. (1984) (see Figure 3).

on the rate of filtration (rapid sand filters and slow sand filters). In addition, they can also be classified as in-depth filtration if the solids are removed with the filter material or cake filtration if the solids are removed on the entering face of the filter material (AWWA, 1990). Since the E. L. Smith Water Treatment Plant is currently using rapid dual-media filter, the rapid granular media filter performance will be the focus of this review.

The dual-media filters have gradually replaced the mono-medium filters in most new water treatment plants. They consist of a layer of coarser anthracite coal on top of a layer of silica sand, and have advantages because, by using layers of media with different densities, a coarse (top of bed) to fine (bottom of bed) media grain size distribution can be maintained during the backwashing process. This gradation promotes filtration within the interstitial spaces of the bed rather than filtration by straining at the top of the bed as is the case when a stratified mono-medium is used. The benefits of the dual-media filters include reducing the rate at which headloss is developed, giving longer filter runs and decreasing the amount of treated water needed to backwash the filter.

As dual-media filter operation continues, the region within the bed where most of the particles are deposited moves downward. This region is sometimes referred to as the clogging front or filtration zone (Adin, and Rebhun, 1974; Letterman, Sama and Didomenico, 1979). Above this zone, particles are removed but at a relatively low rate because of the high interstitial velocity within the filled pores. Below this zone, the medium is relatively clean.

The rate at which the filtration zone moves downward through the bed is determined by the concentration of particles in the influent and by the design and operational parameters, such as the type and the concentration of the coagulant, the clogging cause the increase in the headloss. In an attempt to refine the theory of water flow through clean granular media, Herzig (1970) proposed that the increase in headloss due to the accumulation of solids can be approximated by an infinite series. His work has not been widely accepted though it was important in introducing the problem of filter clogging.

The effects of increasing certain parameters on the rate of development of headloss could be calculated using a mathematical model. The qualitative results are listed in Table 5.

3.2.3 Engineering Aspects of Filtration

The headloss buildup and particle removal in filtration are mainly determined by the characteristics of particles, water quality and pretreatment employed in water treatment processes. However, a number of engineering aspects of filtration are also important for obtaining successful filtration performance. The important engineering aspects include the type of filters, modes of filter operation, control of backwashing and initial filter ripening.

3.2.3.1 Type of Filters

Many different types of filters have been used in water and wastewater treatment plants. Various classification schemes have been introduced to describe the types of filters in practice. The first classification scheme is based on the type of granular media used (sand filters, precoat filters, and anthracite coal filters, etc.); the second is based on the hydraulic arrangement provided to pass water through the media (declining rate filters, constant rate filters and pressure filters); the third is based

Table 5. The Effects of Increasing Certain Parameters on Headloss (adapted from Letterman, 1987)

Parameter	Change in Parameter	Change in Rate of Development of Headloss
Rate of particle deposition (mass basis)	Increase	Increase
Filtration rate	Increase	Increase
Filter pore diameter (medium grain diameter)	Increase	Decrease
Length of the filter pore (depth of the medium)	Increase	Decrease
Depth of the medium over which there is deposition	Increase	Decrease

Table 4. Summary of Clean Bed Headloss Models (adapted from Finch *et al.*, 1985)

Equation	Definition of Terms
Carman-Kozeny: $h = \frac{f}{\phi}\frac{(1-n)}{n^3}\frac{z}{D^2}\frac{v^2}{g}$ $f = 150\frac{(1-n)}{N_R} + 1.75$ $N_R = \frac{Dv}{\upsilon}$ Fair-Hatch: $h = K\upsilon S^2\frac{(1-n)^2}{n^3}\frac{z}{D^2}\frac{v}{g}$ Rose: $h = \frac{1.067}{\phi}C_d\frac{1}{n^4}\frac{z}{D}\frac{v^2}{g}$ $C_d = \frac{24}{N_R} + \frac{3}{N_R^{1/2}} + 0.34$	C_d = coefficient of drag D = grain diameter, m f = friction factor g = gravity constant, 9.807 m/s^2 h = head loss, m K = Kozeny filtration constant, = 5 based on sieve openings = 6 based on size of separation z = depth, m N_R = Reynolds number S = shape factor (varies between 6.0 and 7.7) v = filtration approach velocity, m/s n = porosity υ = kinematic viscosity, m^2/s ϕ = shape factor (usually 1)

The development of headloss in deep bed filters (where deposition occurs at least in part within the interstitial void spaces) are much more complicated. Its rate depends on the rate of particle volume removal, the filtration rate, and the size and total volume of the interstitial spaces. The lowest rates of development of headloss and the longest filter runs are obtained when the region in which deposition takes place is deep (long pore lengths) and the mean grain size is large (large pore diameters). The development of headloss is minimized by effective utilization of all the void space in the bed. Low filtration rates also tend to yield low rates of headloss development. For a given mass concentration of particles, increasing particle density decreases the volume of interstitial void space consumed in the deposition process and therefore decreases the rate of development of headloss (Letterman, 1987).

At ordinary filtration velocities the flow through a clean filter would in the laminar range which can be depicted by the Kozeny equation (Montgomery, 1985).

$$\frac{\Delta H}{L} = \frac{180\mu V_0}{\rho_L g d_m^2}\frac{(1-\varepsilon_0)^2}{\varepsilon_0^3} + \frac{1.75V_0^2}{d_m g}\frac{1-\varepsilon_0}{\varepsilon_0^3} \qquad (12)$$

This equation was derived from the fundamental Darcy-Weisbach equation for flow through circular pipes and assumed that the flow through media is analogous to flow through a group of capillary tubes. Past experiences showed that the Kozeny equation is generally acceptable for most filtration headloss calculations and still remains the most widely used to predict clean bed headloss. Other similar equations have been proposed for larger filter media or higher velocities used in some applications and are summarized in Table 4. Deposition of particles in filter beds and subsequent

Table 3. Effects of Different Parameters on Particle Efficiency (adapted from Letterman, 1987)

Parameter	Change in Parameter	Removal Efficiency
Influent particle concentration	Increase	No change
Particle density	Increase	Increase
Interstitial velocity (filtration rate)	Increase	Decrease
Filter pore diameter (medium grain diameter)	Increase	Decrease
Length of the filter pore (depth of the medium)	Increase	Increase
Particle attachment efficiency (degree of destabilization	Increase	Increase

problems involved in this test: (1) the basic principle of this method is using straining mechanism to evaluate the filter performance. It is well known that straining is not the principal mechanism in deep bed filtration; (2) less than 10 per-cent of filter paper area contains the pores, so not all of the particles less than critical size of pores will pass through the filter; (3) the method lacks reproducibility and fails to accurately predict full-scale filter performance.

3.4.2 Bench Scale filter

An alternative to the paper filter test is the bench scale filter method to avoid the costly and time consuming of pilot scale filter. Typically, such a unit uses a small cylinder containing the filter media. Initial and filtered water turbidities are recorded, as is the headloss in the small filter. Results from such bench scale filters are mixed. Bowers *et al.* (1982) reported that the Metropolitan Water District of Southern California was using a modified jar test following a bench scale filter to determine filter aid dosages for a full scale plant. Brink et al. (1988) described a simple bench-scale filtration test for successfully determining the optimum polymer dosage on coagulation for low turbidity water. In this test, the filter column he used was an tube with an inside diameter of 50.8 mm which was partially filled with 250 mm anthracite on the top and 250 mm sand on the bottom. Tekippe and Ham (1970), using a 300 mm sand depth in their filters, indicated limits to the reproducibility of turbidity, but not headloss results. Yeh and Ghosh (1981) used a 150 mm sand depth and obtained continuous trends in residual turbidities vs. polymer dose, suggesting the experimental reproducibility. Such trends were not evident in their headloss results. Dentel *et al.* (1987) found the optimum dose predicted from in-plant bench filter experiments did not correspond with either pilot-scale results or plant-scale results. The controversies such as headloss and backwash characteristics require more complex procedures. Currently, three different methods are found in literature to supplement or replace the jar test method. They are included paper filter, bench scale filter and pilot scale filter methods.

3.4.1 Paper Filter Method

The paper filter method was first suggested by Hudson and Wagner in 1980. They found that the traditional jar test was not effective for low turbidity water because a visible floc does not form after coagulation, flocculation and sedimentation. The paper filter was suggested as a surrogate after jar test for granular media filtration. In this method, the time required to filter the sample was recorded, and the filtered turbidity was measured. Various filter paper types may be used which affect the filtered turbidities and filtration times obtained, however, the same optimal dose was shown to be obtained. Hudson and Wagner (1980) recommended discarding the first 100 mL of sample filtrate and measuring the turbidity of the second 100 mL, presumably to allow the paper filter and deposited solids to establish operational characteristics. However, comparison of turbidities from the first and second 100 mL volumes in another study (Dentel et al. 1987) showed little difference in trends. After reviewing previous investigations, Dental *et al.* (1989) later proposed a module for the paper filter test to determine an optimal filtration aid dosage. The results can be simply graphed as two separate sets of data vs. chemical dose. The measured filtration time is used to indicate the headloss that would develop across the plant filter bed. In turn, this provides a rough estimate of the filter run length which will result. The filtrate turbidity indicates the effectiveness on water quality of filter aids. This method is considered the simplest, easiest, cheapest and fastest test, but there are several same reasons. Amirtharajah and Kawamura (1983) also suggested using cationic polymers as filter aids.

A recent survey made by Cleasby et al. (1989) revealed that a majority of lime softening plants used cationic polymer as filter aid. However, no polymer molecular weight information was given in the report.

In summary, the removal of particles by a filtration process involves the two steps of mechanisms: transport and attachment. Correspondingly, efficient particle removal requires that: (1) the filter bed be designed and operated to provide sufficient contact opportunities; and (2) the particles to be filterd be rendered unstable or "stickily" so that they may attach to each other or to the filter media upon contact. Numerical theoretical and experimental studies concluded that the typical filter designs can provide sufficient contact opportunities between the particles and media or the retained particles. As a result, the improvement of attachment efficiency by using the proper type and optimum dosage of filtration aids such as polymers and alum, etc., is the most important aspect to enhance the apparent particle capture efficiency. But an increase in the headloss might be encountered. The existing information and practical experiences do not allow the selection of a proper polymer rationally as a filter aid for the E. L. Smith Water Treatment Plant.

3.4 Current Methods for Polymer Selection

Since particle destabilization is critical for effective filtration, the selection of filter aids seems somewhat similar to those for coagulant aid selection. For example, zeta potential measurements and residual turbidity following jar tests have been used previously to characterize filtration phenomena. However, other aspects of filtration of the filter, causing high headloss but producing good quality water. In the winter, the floc usually penetrates deeply; then the problem is not headloss but poor water quality. Using polyacrylamides and activated silica as filter aids can not only control floc penetration in the winter but also improve filter performance at high rate filtration. He also suggested that a typical polyacrylamide feed rate is 0.01 to 0.02 mg/L for each 3 mg/L of average quality alum floc. For very coarse filter media or very weak alum floc, it may be necessary to feed as much as 0.05 mg/L for each 3 mg/L of floc.

The AWWA Water Quality Division's Coagulation and Filtration Committee, with the assistance of personnel at the American Water Works Association's headquarters, mailed a questionnaire to approximately 300 utilities throughout the United States (AWWA Committee Report, 1982). The results indicated that there were 45 out of 115 responses for using polymers in both the raw water and the filter influent flow. It was also reported that in answer to a query about how polymers are used, the second largest response was combined with alum and as a filter aid.

Much less attention has been paid to the application of polymers in the treatment of lime softened water. Kasper and Reichenberger (1983) suggested that after lime-soda ash and hot softening process, the colloidal particles are positively charged and so hence anionic polymers as filter aids may be effective. Anionic polymers used as filter aids were also found elsewhere (Edzwald, 1983).

On the contrary, Luttinger (1981) reported that in polymer-assisted filtration, particularly when using finely divided media such as diatomaceous earth or even fine filter sand and anthracite, lower-molecular-weight cationic polymers preferred. He explained that this is largely a consequence of the lower pressure drop encountered with such polymers in comparison with materials of higher molecular weight. For the

3.3.3 Application of Polymers in High Rate Filtration

As early as 1949, Baylis (1949) had already used acid-treated sodium silicate as a coagulant-strengthening agent and showed that activated silica could be used to increase floc strength so that filter breakthrough could be controlled under high flow rate conditions. It was considered that Baylis was the first person to clearly state that polymers could increase the floc strength and improve the filtered water quality.

Conley and Pitman (1960) showed the detrimental effect of high filtration rates up to 37 m/h in the treatment of Columbia River water by alum coagulation followed by short-detention flocculation and sedimentation before filtration. A proper dose of nonionic polymer added to the water as it entered the filters, however, resulted in the same filtrate quality from 5 to 85 m/h. Conley and Pitman (1960) indicated that breakthrough can be controlled if enough polyacrylamide or activated silica is fed. These materials would control breakthrough but increase filter head loss.

Robeck et al. (1964) compared performance of pilot filters at 4.9, 9.8, 14.6 m/h when filtering alum-coagulated surface waters through single-medium and dual media filters. With proper use of a polymer as filter aid ahead of the filters, the effluent turbidity, coliform bacteria, polio virus, and powdered carbon removals were the same at 14.6 m/h as at 9.8 and 4.9 m/h.

Conley and Hsiung (1969) also reported on operation data for a groundwater being treated for iron and manganese removal at rates 8.5, 11.2, 15.1, 19.0 m/h. It was found that the same effluent quality was achieved at all filtration rates when using polyacrylamide just before filtration.

Rice (1974) indicated that the nature of the floc in a given water treatment plant will vary seasonally. In summer, it is common for the floc to stick near the top

Figure 7. Schematic Representation of the Destabilization and Aggregation of Humic acid by Polymer (adapted from Edzwald, 1983)

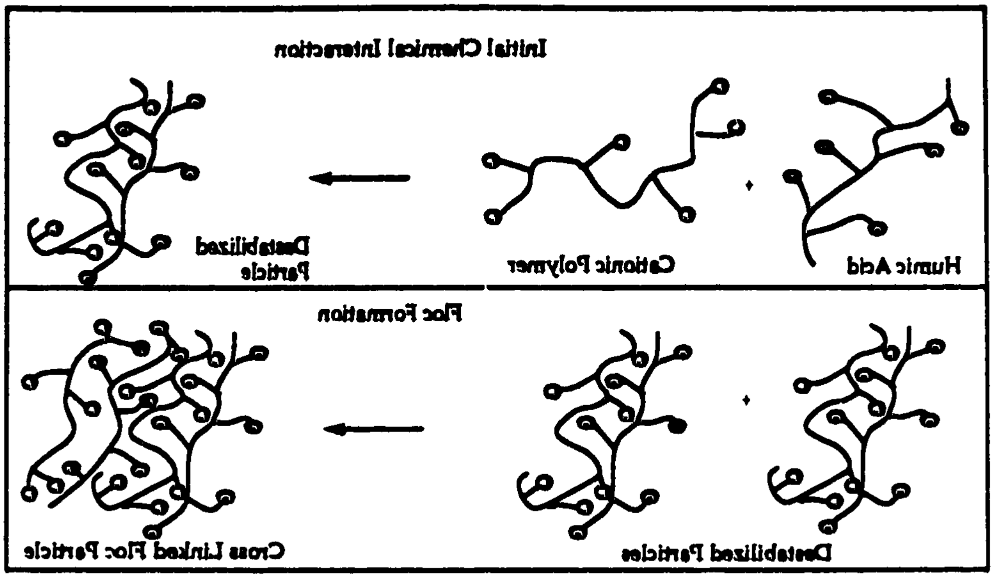
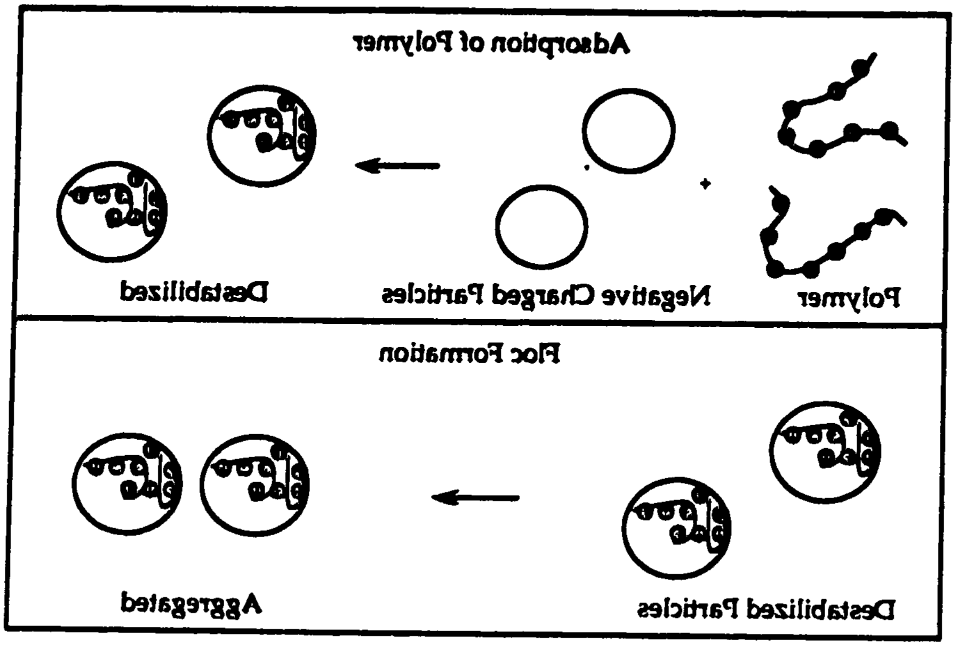


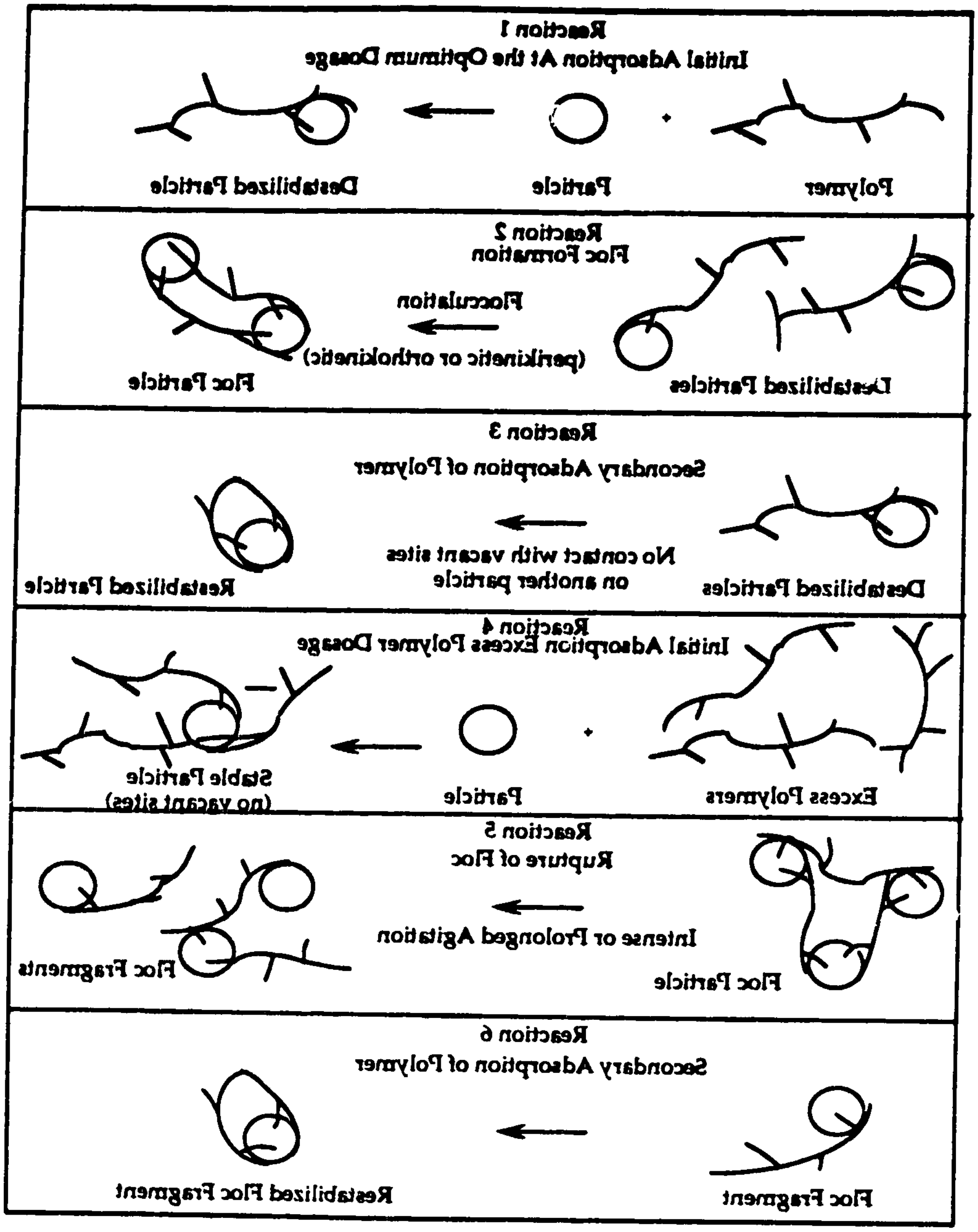
Figure 6. Schematic Representation of the Patch Model (adapted from Edzwald, 1983)



Charge Neutralization. The charge neutralization occurs when the particle destabilization is accomplished by adsorption of oppositely charged polymers on particle surfaces. The principles of this mechanism have been known for around thirty years. It has been postulated that the polymer assumes a flat configuration on the colloidal surface, rather than a configuration with many segments extending into the solution. An excellent modified charge neutralization model, patch model, used to describe the adsorption of relatively low molecular weight cationic polymers on negatively charged particles was proposed by Gregory (1973). Figure 6 schematically shows the situation of polymer molecules adsorbed in a flat planar configuration. The polymer is assumed to adsorb in a small patch on the surface of the colloid. The resulting pattern on the colloidal surface consists of small patches of high-density positive charge surrounded by a sea of lower density negative charge. The particles flocculate as the positive patches bond to the negative surface of a colliding particle. In recent years, this model has been used increasingly to explain the flocculation behavior of colloids when strong polymers carrying the opposite charge are used.

Charge neutralization/participation model. This model was used to explain the mechanism of the coagulation of humic substances by cationic polymers. During the coagulation of humic substance by cationic polymers, charge neutralization is important, but the mechanism is different than that traditionally described for cationic polymers adsorbing on colloidal solid surfaces. Aggregates (precipitates of humic matter and cationic polymers) are formed from a cross-linking between the negatively charged humic macromolecules and the cationic polymers (see Figure 7).

Figure 5. Schematic Representation of the Bridging Model (adapted from Edzwald, 1983)



surface of a colloid, all the segments of the polymer are not in contact with the surface. Many of the segments will extend into the solution phase of the suspension. The segments adsorbed onto the surface are called trains, the segments extending into the solution phase are called loops, and the ends of the polymer are called tails. This polymer arrangement on the colloids surface is the basis for the interparticle bridging. Figure 5 is the schematic representation of bridging model for the destabilization of colloids polymers.

As shown, the polymer molecule must contain chemical groups that can interact with sites on the colloidal particle in order for destabilization to occur. When a colloidal particle and a polymer molecule come into contact, some of the chemical groups of the polymer are adsorbed by the particle surface. The remainder of the polymer-particle complex with the polymer as a bridge (Reaction 1 and 2). If a second colloidal particle is unavailable, the extended polymer chain will eventually adsorb on other sites on the original particle, and the polymer will no longer be available to serve as a bridge (Reaction 3). The degree to which particle destabilization and aggregation occur is a function of polymer dose. High polymer dosage can saturate the colloidal surface, leaving no available reactive sites on the colloid thus producing a restabilized colloid (Reaction 4). Low polymer dose results in partial destabilization of the colloidal dispersion, leaving reactive sites available on the colloids but no polymer chains available for bridging. Finally, a system which has been destabilized and aggregated can be restabilized by prolonged agitation. By extending or intensifying agitation, the polymer-surface bonds can be broken allowing extended polymer segments to folded back onto the surface of the particles (Reactions 5 and 6).

3.3.2 Mechanisms of Polymer and Particle Interaction

It is well accepted that the mechanisms of polymer-particle interactions is considered similar to the coagulants used in the coagulation-flocculation process. For example, the overall rate of coagulation process has been evaluated by determining the rate at which collisions occur between particles by fluid motion and by Brownian diffusion, multiplied by a "collision efficiency factor" which reflects the ability of chemical coagulants to destabilize colloidal particles and thereby permit attachment when contact occurs. A similar approach is used to describe filtration by the collector efficiency times attachment efficiency. In addition, optimum dosage, overdosing and stoichiometry that are characteristic of destabilization in coagulation are also characteristic of polymer aided filtration. Chemicals which are effective in coagulation are also effective in filtration. In most cases, standard jar (coagulation) tests may be used to determine the type and dose of chemical required for destabilization in filtration though some recent studies showed the failure of jar tests to predict filter performance due to the lack of information for estimating headloss patterns or solids deposition in filter media. Thus, the vast knowledge of coagulation is adopted to explain the actions of polymer in the filtration process. The interactions between polymer molecules and particles for filter aids are generally described in two models: interparticle bridging and charge neutralization. Another three-model description proposed by Edzwald (1983) are: interparticle bridging, charge neutralization, and charge neutralization\precipitation. The particle destabilization by compression of the electrical double layer and pure emmeshment which often occurs in coagulation is believed to be insignificant in the filtration, and thus will not be discussed further.

Interparticle bridging. The model was initially postulated by LaMer and Healy (1963) to explain the destabilization of colloidal suspension by a neutral or like-charged high molecular weight polymer. In this model, when adsorbing onto the

Table 6. Molecular Weight Definitions (adapted from Mangravite, 1983)

MW description	Estimate relative MW (g/mole)
Low	10^4 to 10^5
Medium	10^5 to 10^6
High	1×10^6 to 5×10^6
Very high	Greater than 5×10^6

polymers have both negative and positive charges on the same chain and are called amphoteric or polyampholyte polymers. At the present time, it is believed that polyampholyte polymers have little commercial utility for water treatment. It should be noted that the net charge on polymers of this type is strongly dependent upon the pH of the medium.

The second important property of polymers is the polymer molecular weight. It ranges from 1000 to greater than $5x10^6$ in water treatment. Typically, they are classified as low-, medium-, and high-molecular-weight polymer. No cut-off molecular weight range is reported. One of molecular weight range definitions was found in Mangravite's report (1983) (see Table 6). However, it should be realized that the molecular weight given by manufacture is only an approximate value because of the large variance known to occur in different molecular weight tests. In addition, different manufacturers assign different molecular weight ranges to these designations. The product comparisons based solely on the average molecular weights (particularly if they are within the same order of magnitude) may be misleading, since the different molecular weight distributions could affect performance independently of the average value.

Polymer charge density refers to the concentration of positive or negative charges on a polymer, either per unit weight or as a percent of potentially ionized monomer content. It is a function of polymer type, polymer content in the product, and product concentration when added to water. For some polymers, especially anionic and nonionic ones, the charge density is also strongly affected by the pH of solutions (Ghosh et al. 1985). This pH's dependence is useful in explaining the possible variations in polymer performance if significant pH changes are anticipated.

particles to form larger and stronger flocs. The polymer chemical units usually have a ionic nature that imparts an electrical charge to the polymer chain, so the organic polymers are also called as polyelectrolytes. The important properties of organic polymers include charge types, molecular weight, charge density and molecular structure of polymers. More detailed information on polymer chemistry is available (Dentel et al. 1989; Letterman and Pero, 1988; Mangravite, 1983).

Traditionally, three charge types of polymers are classified: anionic, cationic, or nonionic polymers according to the sign of the charge of their ionic groups. Another classification found in Schlauch's report (1981) are: anionic, cationic, nonionic, or amphoteric. The term of amphoteric polymer is not usually used in water treatment. All the polymers can be manipulated to produce different molecular weight, charge density and structure (linear or branched).

Polymers that have a preponderance of negative sites are called anionic polymers. Carboxyl-containing anionic polymers are by far the most important class of these anionic polymers, they can be both in the high- and low-molecular-weight range. A wide range of charge level for this group of polymer is possible. The polymers with positively charged groups, are called as cationic polymers. The charge groups usually include amino ($-{}^{+}NH_3$), imino ($-CH_2-{}^{+}NH_2-CH_2-$), or quaternary amino ($-{}^{+}NR_4$). The levels of charge for some of these polymers are strongly dependent on pH, while some are not. This type of polymers has relatively low molecular weight due to the difficulty in the synthesis process, but get the widest use as filtration aids in water treatment plants. The third class of polymers with no charged sites or with a very low tendency to develop them in aqueous solution is known as nonionic polymers. The true nonionic polymers used in water treatment are very few because the polymerization of these polymers are difficult. Most commercially available "nonionic" actually contain about 1 or 2 % of hydrolyzed amide groups. Finally some

Plate 6. Filter Column Underdrain System

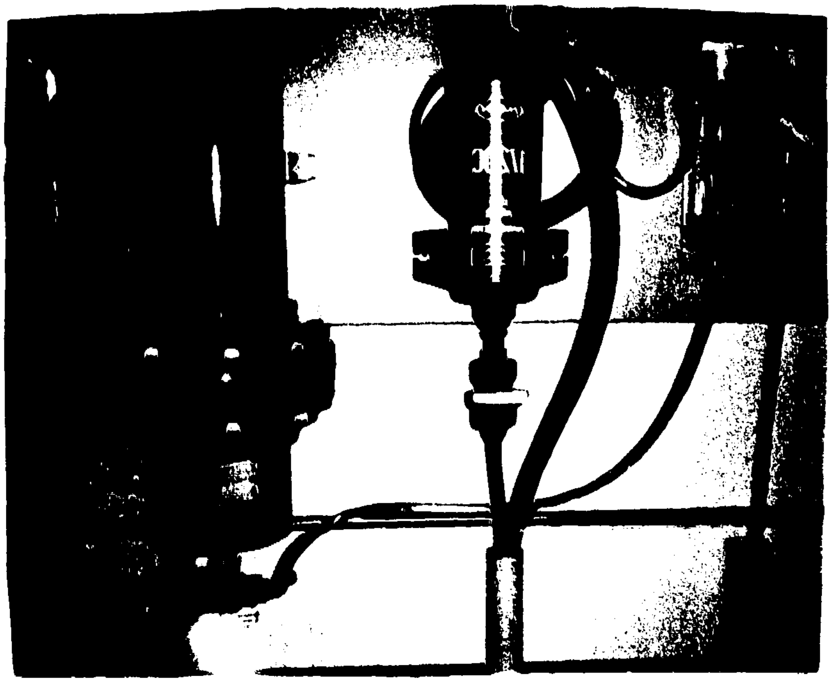


Plate 5. Pilot Plant Data Acquisition System

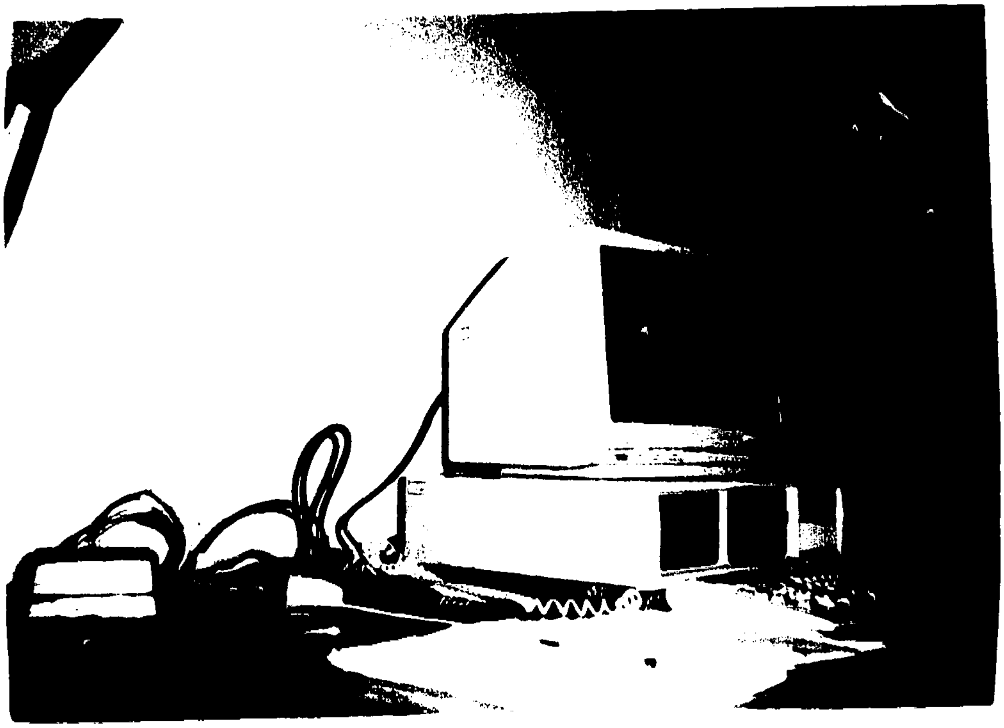


Plate 4. Pilot Plant Measurement and Control Instruments

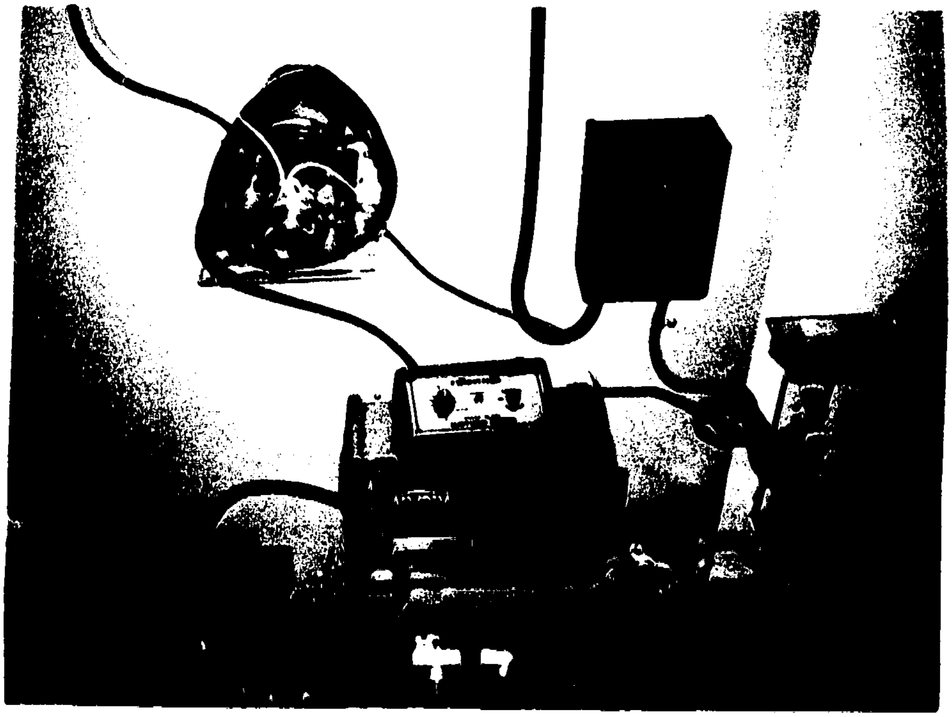


Plate 3. A Close Up View of One Filter Column

Plate 2. A Close Up View of the Pilot Plant as a Whole

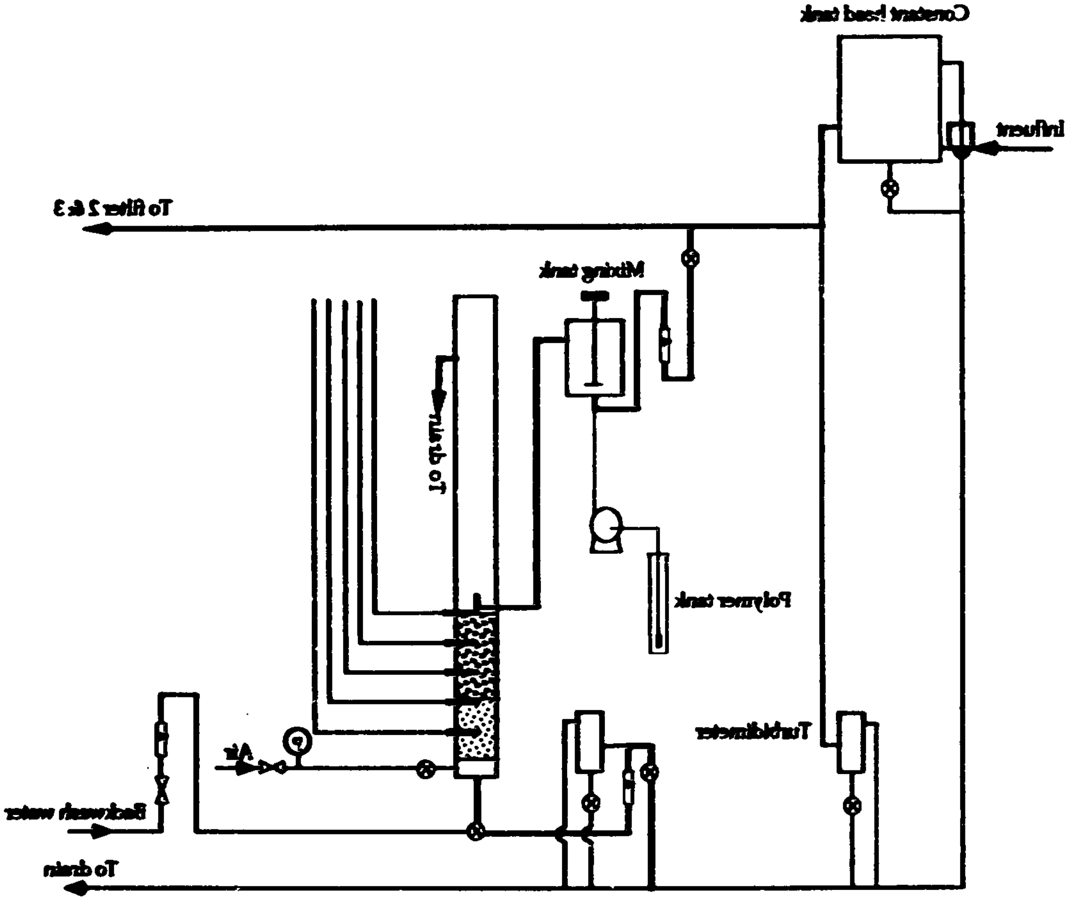


Figure 9. Schematic of Pilot Plant Filters

4.3 Pilot Plant Setup

The experimental pilot plant, located at the E. L. Smith Water Treatment Plant, was especially designed and constructed for this study. It consists of three identical filters in parallel. Its schematic is shown in Figure 9. Plates 2 to 6 provide a close up view of the filter column, piping, flow control, turbidity monitoring apparatus and automatic data acquisition system. Each filter consists of a Plexiglas column with an inside diameter of 160 mm and a height of 2.5 m. It was partially filled with 450 mm of anthracite coal with an effective size 1 mm over 300 mm of sand with an effective size 0.45 mm. As the ratio of the diameter of the column to those of media is greater than 160, it was expected that there is little wall effects on filter performance (Lang *et al.*, 1993).

To measure the headloss profile along the height of media, each filter was equipped with five piezometers. The piezometers were located at the right side of the column with 150 mm intervals, with one end penetrated into the center of media and the other end attached to the piezometer tubes. The piezometer tubes were made from a glass tube with an inside diameter of 5/16 inches. To eliminate filter media flowing into the piezometers, the tube-end in the media was covered with a stainless steel screen. A stop valve was provided for each piezometer to prevent the ejection of backflow during filter backwash and to provide the discharge of the dirty water inside the inserted piezometer end after the backwash.

Each filter was equipped with two rotameters and their associated flow control valves. One was used for controlling the constant influent rate into the polymer mixing tank. With the polymer solution pumping at a preset rate, the constant polymer dose could be easily maintained. Another was used to monitor the change of filter effluent flow rate as the filtration process proceeds.

Plate 1. Apparatus for Polymer Solution Preparation

specifications. This makes the direct comparison between them difficult, in some cases, even invalid.

All the polymers used are within the manufacturer's recommended storage period. To make sure that the polymers were of good condition, the polymers were first prepared into stock solutions (higher concentration) and then diluted into working solutions. The stock solutions were prepared by using a beaker and a magnetic stirrer. The working solutions were made by using a Hudson jar and a mechanical stirrer (see Plate 1). The storage time of the stock solutions and their concentrations were based on the manufacture's suggestions. The working solutions were made fresh each day.

Stock solution was prepared as follows:

(1) Pour 500 mL Milli-Q water into a 1000 mL soap washed clear beaker and agitate rapidly into vortex by using a magnetic stirrer;

(2) Add 1.5 g of solid (or liquid) polymer;

(3) Continue mixing for 1 hour (or 20 minutes for liquid polymers) to obtain a concentration of 0.3 % stock solution.

Working solution was prepared as follows:

(1) Pour 1960 mL of Milli-Q water into a soap washed clear Hudson jar and agitate at 400 G^{-1} by using a magnetic stirrer;

(2) Pour 40 mL of stock solution into the jar;

(3) Stop mixing after 10 minutes of the stock solution addition to obtain a concentration of 0.006 % working solution.

The prepared working solution was then poured into a 2-L aduate cylinder. Based on the filter influent rate and the amount polymer requirement, a peristeric pump delivered the solution at a constant speed to the polymer mixing tank where the filter influent are mixed with the polymer solution.

Table 8. Tested Polymer Specifications Provided by Manufacturers

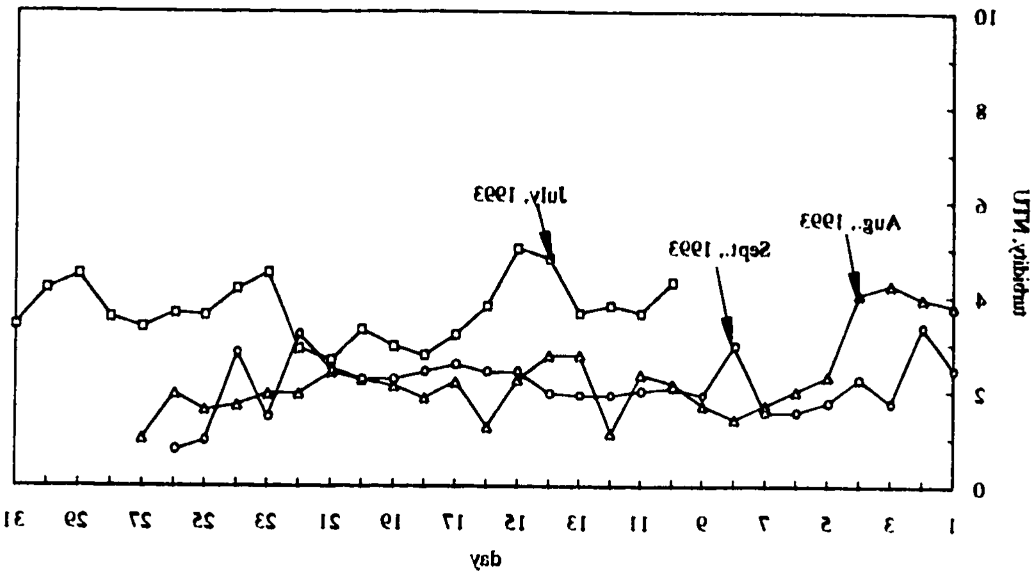
Polymer Name	Molecular Weight	Type	Charge Density	Monomer Name	Manufacture
PERCOL LT 35	Low	Cationic	High	Acrylamide	Allied Colloid
Cat-Floc T-2	Low	Cationic	High	DDAC	Calgon
PAM A-502	Medium	Anionic	Medium	Acrylamide	JES-CHEM
Cat-Floc L	High	Cationic	High	DDAC	Calgon
PERCOL LT 22	High	Cationic	Medium	Acrylamide	Allied Colloid
PERCOL LT 27	Very High	Anionic	Medium	Acrylamide	Allied Colloid
PERCOL LT 20	High	Nonionic	N/A	Acrylamide	Allied Colloid

Note: DDAC = diallyl dimethyl ammonium chloride
N/A = not available

Table 7. Summary of Main Influent Quality Parameters during the Study Period

Time		pH	Turbidity NTU	Total Hardness mg/L @ CaCO3	Calcium Hardness mg/L @ CaCO3	Total Alkalinity mg/L @ CaCO3	Color TCU	Chloride mg/L	Fluoride mg/l
July	Average	8.61	3.7	108	66	56	1.8	2.51	0.95
	Range	8.02 to 9.00	2.2 to 6.4	102 to 120	56 to 82	38 to 72	1.0 to 3.5	2.40 to 2.65	0.89 to 1.02
Aug.	Average	8.64	2.3	109	65	62	1.4	2.51	0.93
	Range	8.13 to 8.99	1.1 to 5.4	102 to 120	60 to 74	50 to 76	1.0 to 2.0	2.45 to 2.70	0.88 to 1.04
Sept.	Average	8.70	2.1	109	65	67	1.3	2.42	0.92
	Range	8.16 to 8.97	0.7 to 5.6	102 to 116	58 to 76	58 to 76	1.0 to 3.0	2.35 to 2.50	0.87 to 0.94

Figure 8. Recorded Daily Average Turbidities of Filter Influent at E. L. Smith during the Study Period



4. METHODS AND MATERIALS

4.1 Filter Influent Quality

The filter influent was obtained from the full scale E. L. Smith Water Treatment Plant after the upflow lime softening clarifier. Prior to the lime softening process, it was pumped from the North Saskatchewan River and has been treated with alum coagulation, flocculation and sedimentation. Figure 8 presents the daily average turbidities of filter influent after softening during the study period. Table 7 summarizes the main characteristics for both the river raw water and the softened water during the period of study. The raw water quality varies from time to time, mainly due to the storm water runoff. But under normal operation, the plant can maintain a rather stable quality for the softened water with a relatively high pH value of around 8.5, alkalinity of 60 mg/L as $CaCO_3$, hardness of 110 mg/L as $CaCO_3$, and moderate turbidity of around 3 NTU. Only once did an upset in the proceeding clarification process produce the water with a turbidity as high as 10 NTU for a very short period. The turbidity data from that event were thus excluded from Table 7.

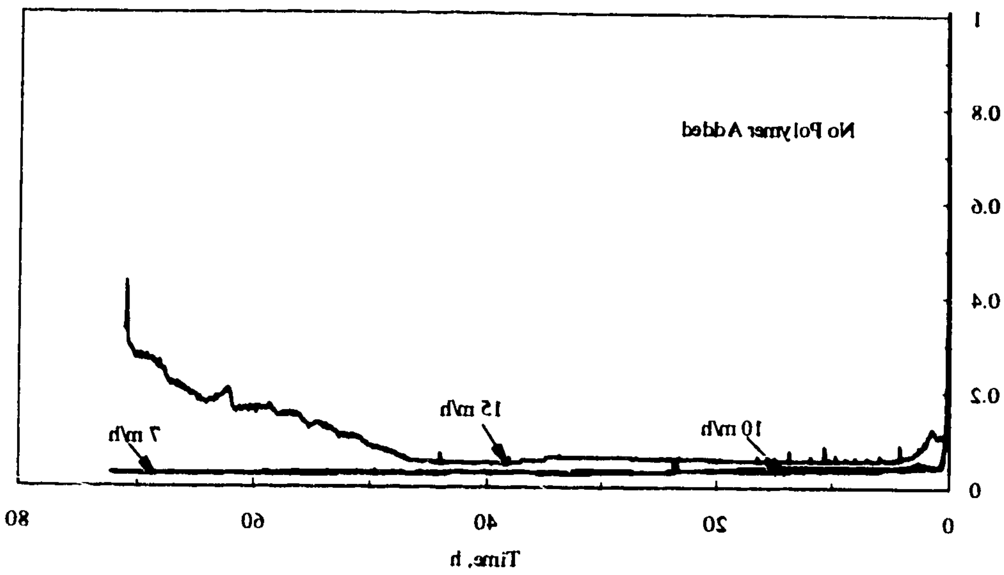
4.2 Polymer Preparation

Seven commercial polymers kindly provided by Allied Colloids (Canada) Inc., Calgon Corporation and Jes-chem Ltd. were tested during the study. They were selected as to represent different categories of polymers. Table 8 shows their specifications provided by the manufactures. It should be noted that the different manufacturers often use different systems of classifications to define their own may result from the difficulties in reproducing some full-scale operation conditions in the experiment. It includes: (1) the filtration flow rate can not be controlled in this experiment; (2) after backwash the filter can not perform the full-scale filter media configuration; (3) wall effect is another important factor which will affect the filter performance.

3.4.3 Pilot Scale Filter Method

The pilot scale filter method normally uses the filters which have the same depth of filter media as full scale filters they are intended to simulate. It offers a number of advantages over the paper filter and bench scale filter methods when using evaluating the effects of polymers. With providing similar media depth to the actual filters, results do not have to extrapolated to greater depth, run time and head loss to the actual filters. They can be fed exactly same water as full scale plant. After each run, the filters can be washed in a manner similar to that in the plant, enabling evaluating the backwashing effectivenes and characterisitics of the resulting backwash water. It has been shown by many studies that the pilot plants are the most indicative of full scale filtration behavior. However, the effort and investment required will be substantially increased. Water utilities are not always able or are willing to accept the high cost associated with the construction and operation of pilot scale filters.

Figure 10. Effects of Filtration Rates on Filtrate Turbidities with No Polymer Addition



5. RESULTS AND DISCUSSION

5.1 Impacts of Filtration Rate Increase on Water Quality

As mentioned before, one of key concerns currently raised at the E. L. Smith Water Treatment Plant is the possible deterioration of water quality with the increase in water production. An evaluation of this problem was essential to determine whether the measures should be taken to improve the filtration process at the high rate. Figure 10 compares the filtered water turbidities with filtration time at different flow rates. As shown, little deterioration of filtered water turbidities was evident during the stable filtration period when the starting filtration rate increased from 7 m/h to 10 m/h, which were very similar to the full scale plant filter effluent turbidities when operated at similar conditions. However, a further increase in the flow rate up to 15 m/h resulted in a substantial increase in the filtered water turbidities. In addition, the turbidity breakthrough occurred after 47 hours at 15 m/h, while no turbidity breakthrough was observed at 7 m/h. Clearly, the results suggested that it is imperative to seek some remedial alternatives in order to maintain the current excellent water quality with the possible future plant expansion.

The phenomenon can be explained by the fundamentals of hydraulic shear produced by the water flowing in the filter pores. In a filter, there exists a very delicate balance between the hydraulic shear forces and the particle adhesive force to the filter media. If the particle adhesive force is greater than the hydraulic shear forces, the particles can be removed from suspension and held in the filter media. If the hydraulic shear forces are greater than the particle adhesive force, the increased shear forces tend to dislodge previously deposited material from filter media, as well as to prevent deposition of material presently being applied in the filter. Experimentally, where: P = input power,

V = fluid volume, and

μ = viscosity of fluid.

The results were plotted in Appendix B and a standard curve was obtained by linear regression with a correlation coefficient of 0.97.

4.6.5 Calibration of Mixing Intensity in Hudson Jar

Two litres of tap water was used as the tested fluid in this experiment. Following the exactly same procedures as used in calibrating the mixing intensity in the polymer mixing tank, the mixing intensities in the Hudson square jar were determined as a function of the mixer speed. The results were also shown in Appendix B. A standard curve was obtained with a correlation coefficient of 0.96.

4.6.3 Calibration of Flowmeters

To ensure the accurate measurement of flow rates through the filter columns and the correct calculation of polymer dosages, all the flowmeters used in the pilot plant were calibrated prior to the use. This is accomplished by measuring the time required for the certain volume of water at different meter scales. The time was measured by a stop watch and the volume of water by a two-liter volumetric cylinder. Each calibration point was measured in triplicate. The average values were then plotted against the meter readings, as show in Appendix A.

4.6.4 Calibration of Mixing Intensity in Polymer Mixing Tanks

The polymer mixing is attained within a square tank with a 4 paddle mixer which was installed a height of 31 mm from the tank bottom. Since it was not a standard mixing unit, the relationship between its stirrer speed and the mixing intensity, quantified by gradient velocity G, had to been determined on site. Lightnin® TS2010 mixer apparatus supplied by Lightnin Cop was used for this purpose. It provided the stirring speed from 0 to 2400 rpm and could be connected to different mixing paddles. The measurements were performed by connecting the pilot plant mixing paddle to the Lightnin® LabMaster II mixer and then inserting it into the polymer mixing tank. The water level was maintained by the height of tank outlet port (266 mm from the bottom). The input power values were recorded from the control panel for different selected mixing speeds. The velocity gradient G, was determined according to the following expression by Camp and Stein (1943):

$$G = \sqrt{\frac{P}{V\mu}} \qquad (13)$$

These calibrated turbidimeters would be contaminated with the substances deposited on the lens and body cell wall during their use. Therefore, they were maintained every run by draining the water inside completely, cleaning the lens with the copper cleaner, flushing with the Milli-Q water. They were put into the operation after the filtered water flowed through over 10 minutes.

4.6.2 Data Acquisition Signal Fine Tuning

To receive and record the turbidities measured from the turbidimeters, the connected data log needed to be calibrated. This was accomplished by using the 1720C turbidimeter self-calibrating capability to ensure that a 4 to 20 mA output is exactly 4 to 20 mA. It included two steps: 1) a coarse adjustment to set the current limit; and 2) fine tuning. Detailed procedures are as follows:

1) Select the 4-20 mA CAL switch on with the recorder output selector switch, while all the other switches should be off;
2) Using the keyboard, enter 3 DIAG;
3) Using the recorder output selector switch, turn the 4-20 mA CAL switch off and then on again;
4) Press 0 DIAG, and observe the recorder reading. If higher than zero, press 8 DIAG and hold until the recorder reading is zero. Contrarily, if lower than zero, press 7 DIAG and hold until the recorder reading is zero.
5) Press 1 DIAG and observe the recorder reading. If higher than the selected high end of recorder output, press 6 DIAG and hold until the recorder reading is the selected value. Contrarily, if lower than the selected high end of recorder output, press 5 DIAG and hold until the recorder reading is the selected value.

manufacturer for Model 1720C turbidimeters. A formazin primary standard (4000 NTU) was used to make working standard solution of 20.0 NTU). The ultrapure water with a turbidity of zero was supplied from Millipore Co.. Both of the solutions were kindly provided from the City of Edmonton. Since the response of the instrument is completely linear from zero to 20, this method has an advantage of great accuracy. The detail calibration procedure is as follows:

(1) Clean two calibration cylinders with Milli-Q water, seal with the aluminum foil and dry in the oven for the calibration use.

(2) Pour 1 litre of 0.0 NTU standard solution into one calibration cylinder.

(3) Remove the head assembly from the turbidimeter body and use glass cleaner to clean the lamp, lens and photocell window thoroughly. Place the head assembly in the 0.0 NTU calibration cylinder.

(4) Gently swirl the cylinder a few times to free any bubbles adhering to the photocell window. Press SYS RESET and 6 SIG AVG and allow the water to stand a few minutes until the turbidity reading stabilized. Press 0.0 STD.

(5) Pour 1 litre of 20.0 NTU standard solution into another calibration cylinder. Remove the head assembly from the calibration cylinder with 0.0 NTU and place it in the calibration cylinder with 20.0 NTU.

(6) Gently swirl the cylinder a few times to free any bubbles adhering to the photocell window. Allow to stand until the readings be stabilized. Press 20.0 STD.

(7) Clean the head assembly in Milli-Q water and replace it in the turbidimeter body.

(8) After all of the turbidimeters are calibrated, pour 1 litre of tap water into a clean calibration cylinder and place one of the calibrated head assembly in it. The procedure is complete if all of the turbidimeters get almost the same turbidity readings (± 0.001 NTU).

The feasibility of polymers as filter aids in the filtration of lime softened water was studied using screening tests. With the different properties of polymers being tested, a comparison of their performances could be used to determine the most appropriate polymers or type of polymers. It was expected that the results could also provide a deep insight into the role of polymer properties (molecular weight, types of charge and charge density) in the filtration of lime softened water. In all the tests, the starting filtration rate of 15 m/hr was set based on future requirements of the E. L. Smith Water Treatment Plant. The mixing intensity and polymer dosage were chosen at the G value of 700 sec^{-1} and 0.01 mg/L, respectively, which are within the common ranges recommended to form pin flocs (Amirtharajah and Trusler, 1986).

Finally, a set of tests were planned to optimize the polymer aided filtration. Only the most promising polymers selected from the screening tests were studied further. In general, the most important factors which affect the process performance include the filtration rate, mixing intensity and polymer dosage. As the filtration rate was set based on needs of the full scale plant, no further study was performed. Therefore, only the effects of mixing and polymer dose on filtration were investigated. The tests were conducted by varying one operating parameter while holding the others constant. The mixing intensity was varied from the 100 sec^{-1} to 1100 sec^{-1}, and the polymer dosage from the 0.005 mg/L to 0.03 mg/L.

4.6 Quality Control and Quality Assurance

4.6.1 Calibration of Turbidimeters

To accurately measure the turbidities in water, all the four turbidimeters were calibrated prior to the use. The calibration kit method was used as recommended by

Table 11. Experimental Arrangement for Stage 3 Study

Run	Polymer	Dose mg/L	Starting Flowrate, m/h		Mixing sec^{-1}	Time hour
			Influent	Effluent		
OA1	Cat-Floc T2	0.005	18	15	700	72
OA2		0.01				
OA3		0.02				
OB1	Cat-Floc T2	0.007	18	15	700	72
OB2		0.03				
OB3		0.01				
OC1	Cat-Floc T2	0.01	18	15	700	72
OC2					1100	
OC3					300	
OD1	Cat-Floc T2	0.01	18	15	400	72
OD2					100	
OD3					700	

Table 10. Experimental Arrangement for Stage 2 Study

Run	Polymer	Dose	Starting Flowrate, m/h		Mixing	Time
		mg/L	Influent	Effluent	sec-1	hour
SA1	No	0	18	15	700	72
SA2	PERCOL LT20	0.01				
SA3	PERCOL LT27	0.01				
SB1	No	0	18	15	700	72
SB2	PAM A502	0.01				
SB3	Cat-Floc L	0.01				
SC1	No	0	18	15	700	72
SC2	Cat-Floc T2	0.01				
SC3	PERCOL LT35	0.01				
SD1	No	0	18	15	700	72
SD2	PERCOL LT22	0.01				
SD3	PERCOL LT35	0.02				
SE1	No	0	18	15	700	72
SE2	PERCOL LT27	0.03				
SE3	PERCOL LT20	0.03				

Table 9. Experimental Arrangement for Stage 1 Study

Run	Starting Flowrate, m/h		Filtration Time, h	Mixing, sec^{-1}
	Influent	Effluent		
PA1	18	18	72	700
PA2	18	12	72	700
PA3	18	7	72	700
PB1	18	15	72	700
PB2	18	10	72	700

(3) when the air wash was finished, open the backwash water valve slowly and close the air injection valve simultaneously;

(4) gradually increase the backwash flow in a period of 1.5 minutes to reach a flow rate of 38 m/hr;

(5) backwash at this high flow rate for 10 minutes and then gradually reduce the flow rate to 0 in 1.5 minutes in order to settle the media evenly.

This backwash method is to simulate the full scale operating procedures currently employed at E. L. Smith Water Treatment Plant. It was found that this procedure would not cause the significant lose of the filter media, and at the same time, produced a clean well stratified filter bed. After backwashing, the computer was reset and the lamp, lens and photocell window of the turbidimeters were cleaned. The apparatus was then ready for the next test run.

4.5 Experimental Design

To accomplish the objectives set previously for this study, experimental work was divided into three stages. Tables 9 to 11 listed the arrangements of three stage tests done in this study. First, the filtration performances with no addition of polymers were conducted at different starting flow rates, ranging from 7 m/h to 15 m/h. The lowest flow rate corresponds to the operating condition currently employed at E. L. Smith Water Treatment Plant, while the highest is to meet the requirement of the proposed plant expansion. The results will be used to see whether the filtrate quality would be deteriorated at high filtration rates so that the modification of filtration operations is necessary to maintain the current excellent water quality.

water pressure regulating valve. The air for backwash was adjusted by an air pressure relieving valve. Both of the backwash water and the air were introduced from the bottom of the columns.

4.4 Pilot Plant Operation

During each run, the filtration system was run under constant head and in the declining rate mode. The three filters were operated in parallel. One filter was used as a control and the others were fed polymer solutions. Except for the studies on the effects of filtration rates on the filter performance, all experiments were conducted at a starting filtration rate of 15 m/hr. At that flow rate the mixing tank provided a mean detention time of about 1 minute for polymer mixing. The polymer solutions were made fresh every day. The turbidities were continuously monitored and recorded every 5 minutes. The headloss and the flow rates were measured every 24 hours. Most filter runs were conducted for 72 hours which corresponded to the longest operating time at the E. L. Smith Water Treatment Plant.

After each filtration run, the filters were backwashed by using air scour followed by a water wash. The backwash water was using the full scale filter effluents at the E. L. Smith Water Treatment Plant. A constant air pressure was maintained such that a constant air flow would provide full fluidization of media during air scouring. The filters were then backwashed at a water flow rate of about 38 m/hr for approximately 10 minutes. At this flow rate, it was observed that over 30 per cent bed expansion could be achieved. The detail backwash procedure is as follows:

(1) close the filter influent valve and piezometer stop valves, drain the water up to its level about 500 mm over the media, and then close the effluent valve;

(2) open the air injection valve for about three minutes at the air pressure 30 psi;

The turbidity was measured by four in-line turbidimeters (HACH 1720C): one for each effluent of the filters and the additional one for the common influent. A data acquisition device was devised to record the measured turbidities from the turbidimeters. It consisted of a Lakewood® data logger from which the data were downloaded to an IBM computer.

As shown in Figure 9, the water was first pumped into the constant head tank (CHT) with a capacity of 42 L. Overflow from it was discharged into the drain. Due to low concentration of particles in the water, no mixing was provided. However, it was flushed prior to each run to minimize the effects of precipitated particles on the filter influent.

From the CHT, a 25 mm diameter main header pipe distributed the water into three parallel filters with each receiving the same influent quality. It is also necessary to drain it continuously in order to prevent the deposit of particles in the pipeline. For each of the filters, the water first went to a polymer mixing tank where a polymer solution was supplied from the bottom of the tank by a peristaltic pump. The mixing tank was a square jar (160 mm x 160 mm x 300 mm) with a variable speed mixer capable of providing the G values from 0 to 2500 sec^{-1}. After rapid mixing with the polymer, the water was then fed by gravity into the filter. An overflow outlet on the top of the filter kept the water level constant during all the tests.

At the bottom of the columns, the filter effluent went through a flowmeter and was split into two lines. One line was connected to a turbidimeter, and another line through a flow regulating valve into the drain. The splitting of the line was necessary to ensure flow through the turbidimeter was within required values.

The full scale filtered water was used as backwash water and the rate of backwash water flow was measured by a flowmeter, and controlled by a backwash

Figure 22. Significance of PERCOL LT 20 on Filtrate Turbidities (0.03 mg/L)

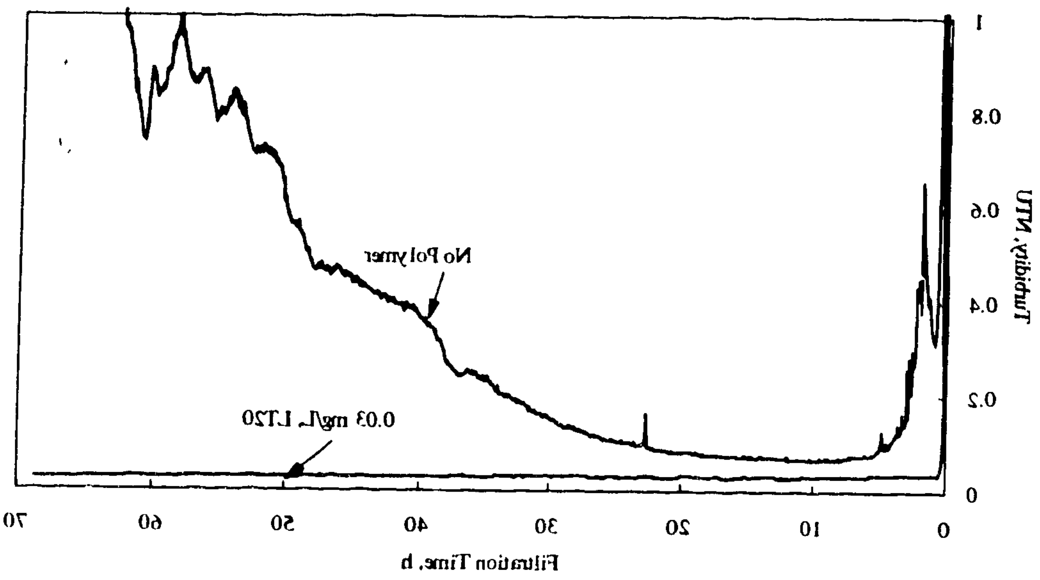


Figure 21. Significance of PERCOL LT 20 on Filtrate Turbidities

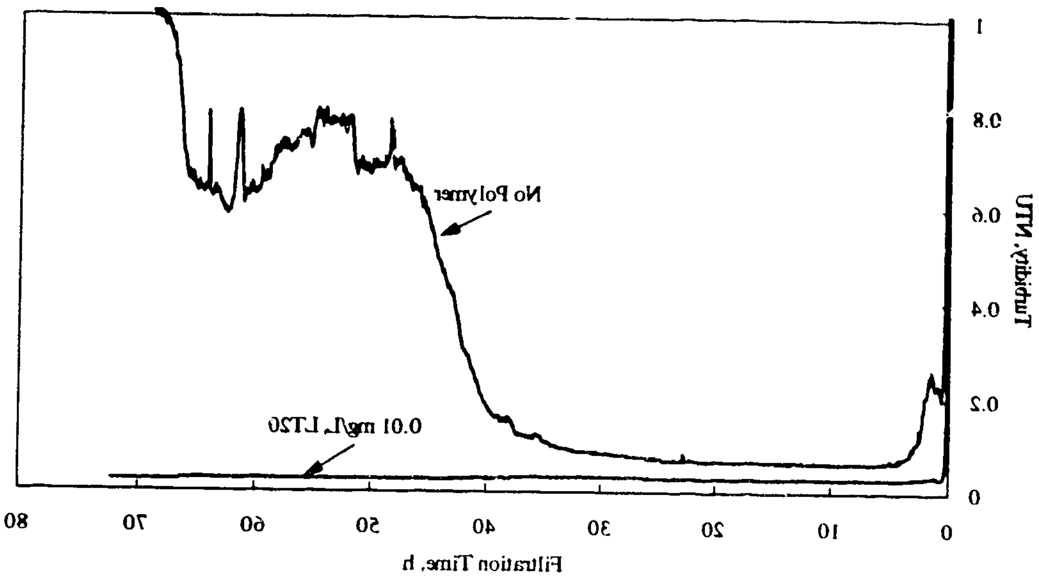
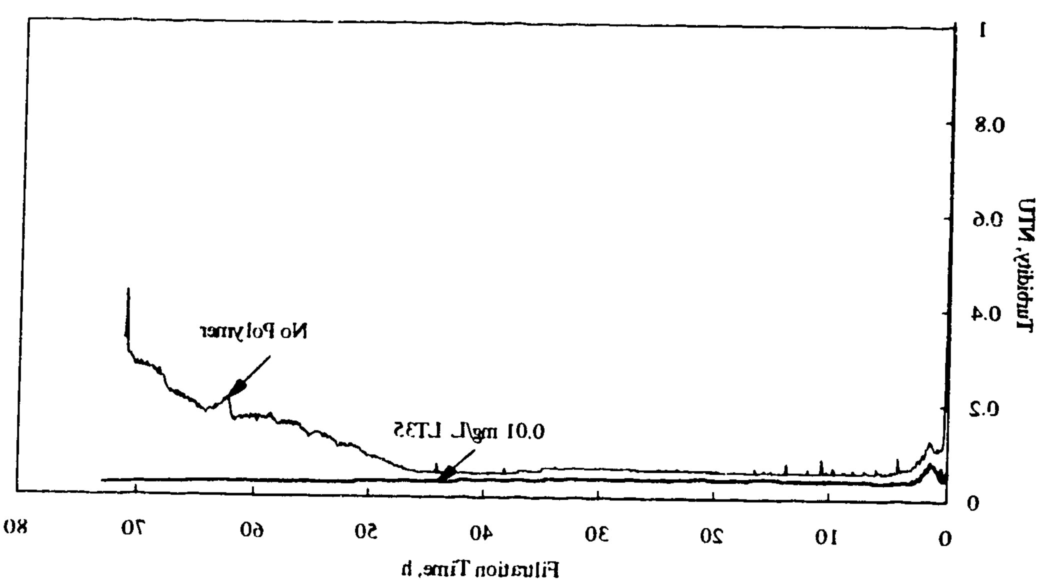


Figure 20. Significance of PERCOL LT 35 on Filtrate Turbidities



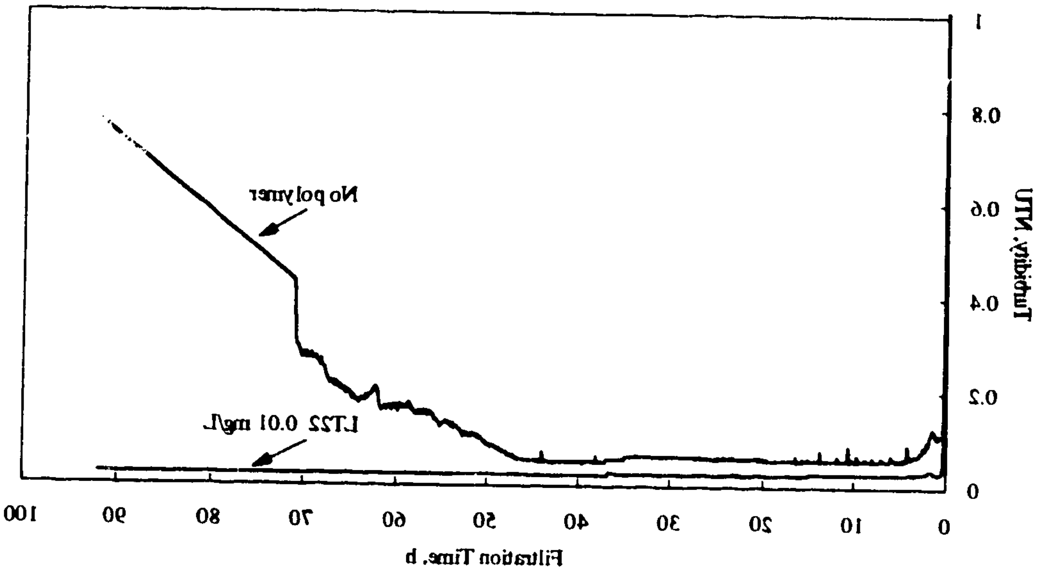


Figure 19. Significance of PERCOL LT22 on Filtrate Turbidities

Figure 18. Significance of PAM A502 on Filtrate Turbidities

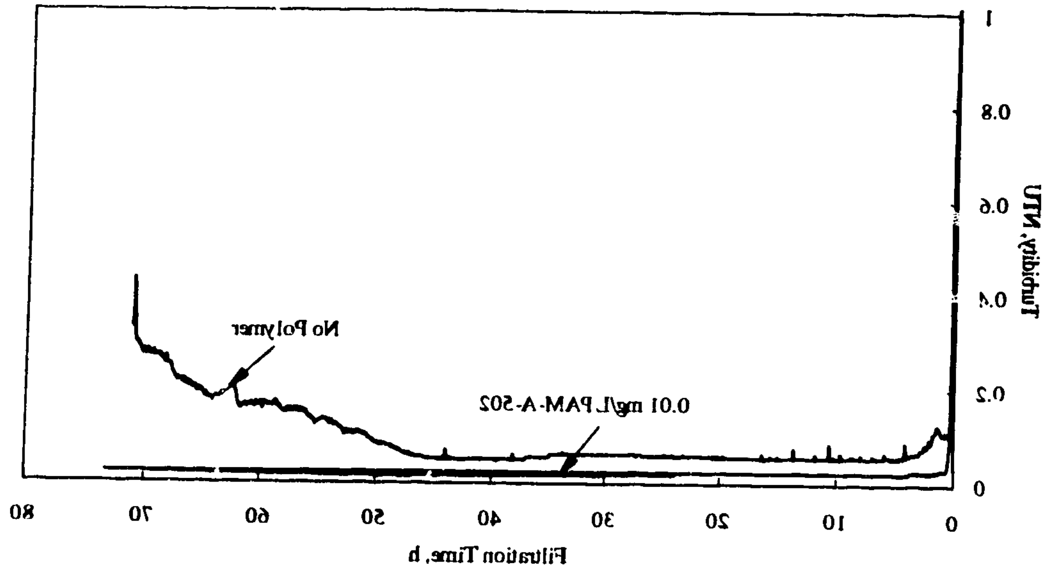


Figure 17. Significance of Cat-Floc L on Filtrate Turbidities

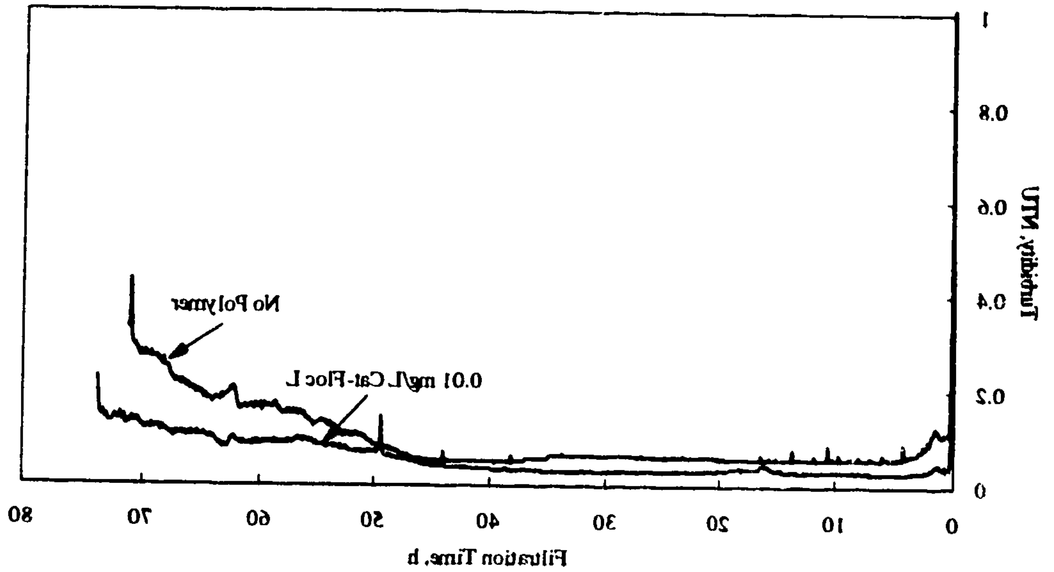


Figure 16. Significance of PERCOL LT 27 on Filtrate Turbidities (0.03 mg/L)

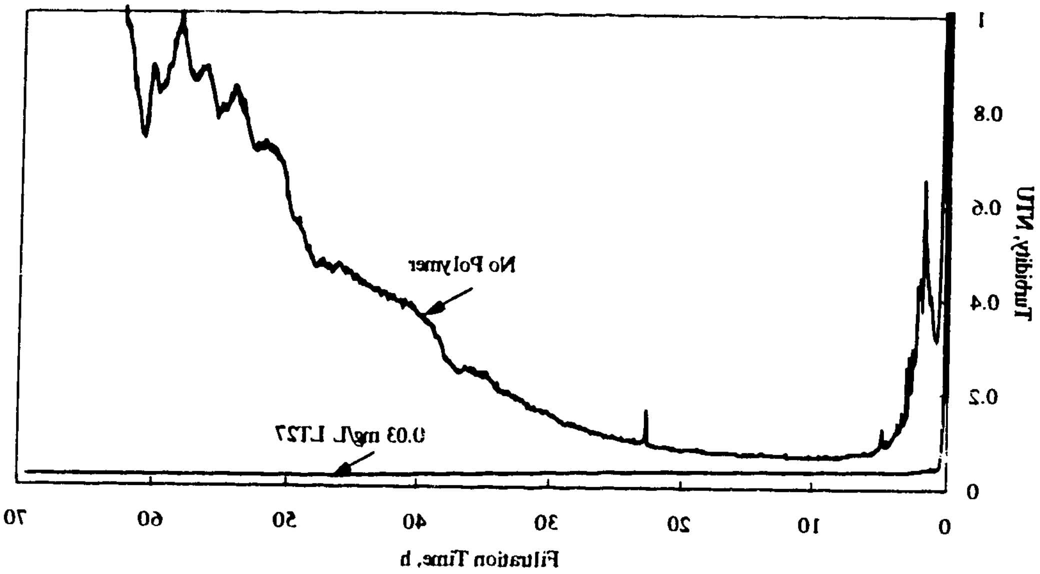
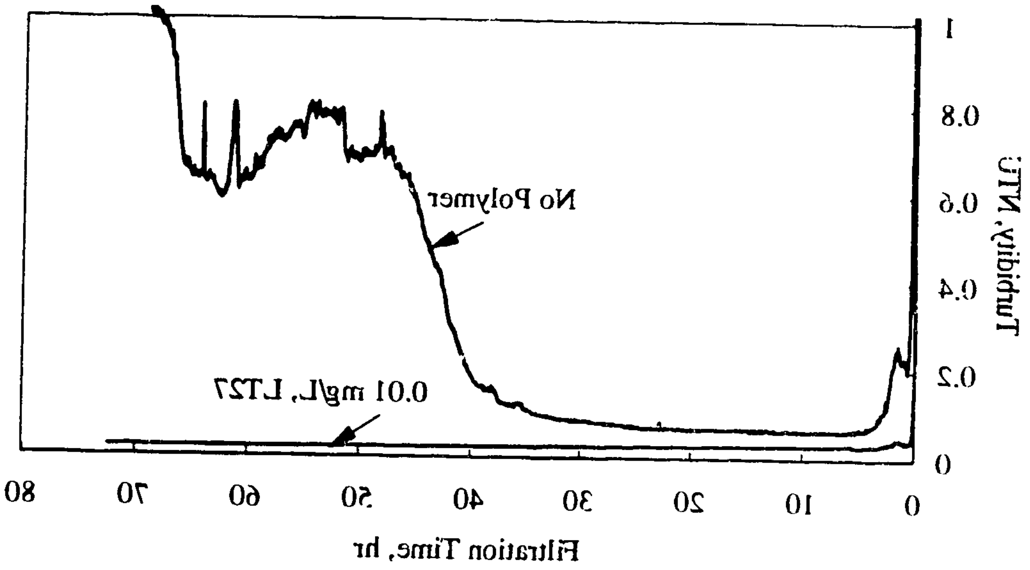


Figure 15. Significance of PERCOL LT 27 on Filtrate Turbidities (0.01 mg/L)



polymers for the treatment of softened water. Both the filtrate quality and headloss during filter ripening, production of stable filtrate and breakthrough were assessed. In all the tests, filter 1 was used as a control while filter 2 and filter 3 had polymer addition. The use of filter 1 as a control was to account for the influent quality variation and to eliminate the possible interference of polymer residues within the filter media.

5.2.1 Effluent Turbidity

The main objective of the filtration process is to efficiently remove particles from the water while ensuring filter production efficiency. Therefore, the filtrate quality was considered as one of the most important parameters for characterizing the filtration performance. Figures 15 to 23 presents results of filtrate turbidity recorded during a filtration run. A summary of the filtrate quality after the filtration of 1, 2 and 3 days was shown in Table 12. After the initial water quality degradation during ripening, the filtrate quality tends to be stable for all the polymers. Almost all the polymers could consistently achieve effluent quality between 0.02 to 0.04 NTU, regardless of the fluctuations in influent turbidity. In comparison, the filtration with no polymer addition (control filtration) would produce the filtrates of over 0.06 NTU. Furthermore, with no polymer addition filtrate quality was very sensitive to variations in influent quality. Only Cat-Floc L had relatively poor performance compared to the other polymers. It reached a filtrate turbidity of 0.06 NTU during the test. This abnormality could be explained by the contamination of turbidimeter photocell and the possible leakage of light from the turbidity meter body during that batch of tests.

Figure 14. Relationship of Water Production with Headloss for No Polymer Addition

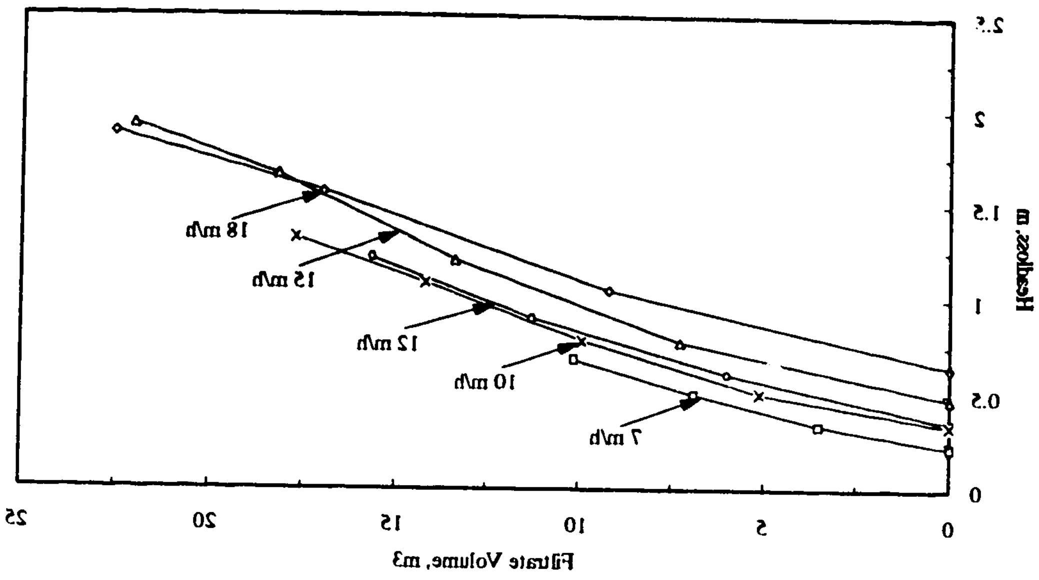


Figure 12. Headloss Buildup at Starting Filtration Rate of 12 m/h with No Polymer Addition

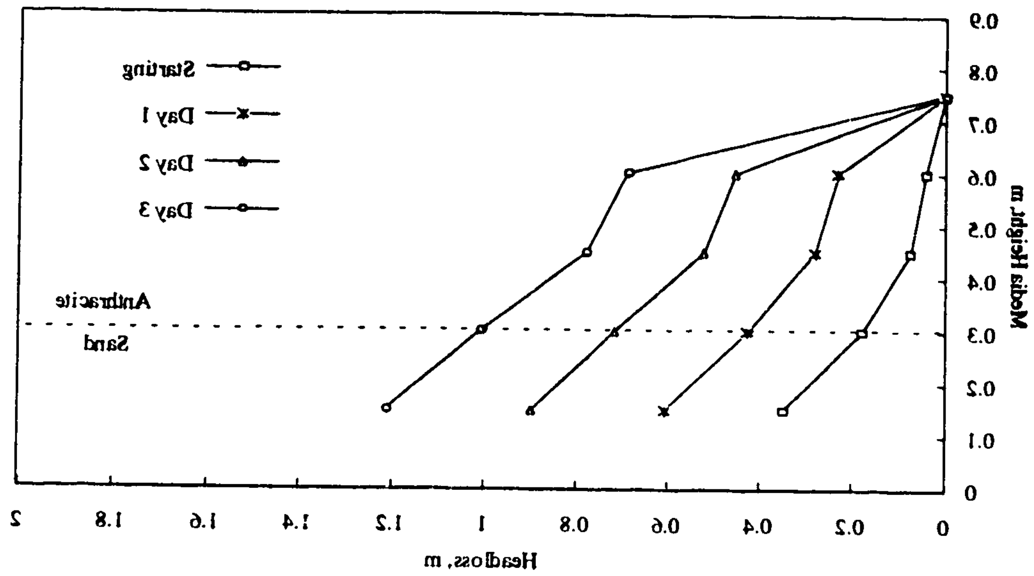


Figure 11. Headloss Buildup at Starting Filtration Rate of 7 m/h with No Polymer Addition

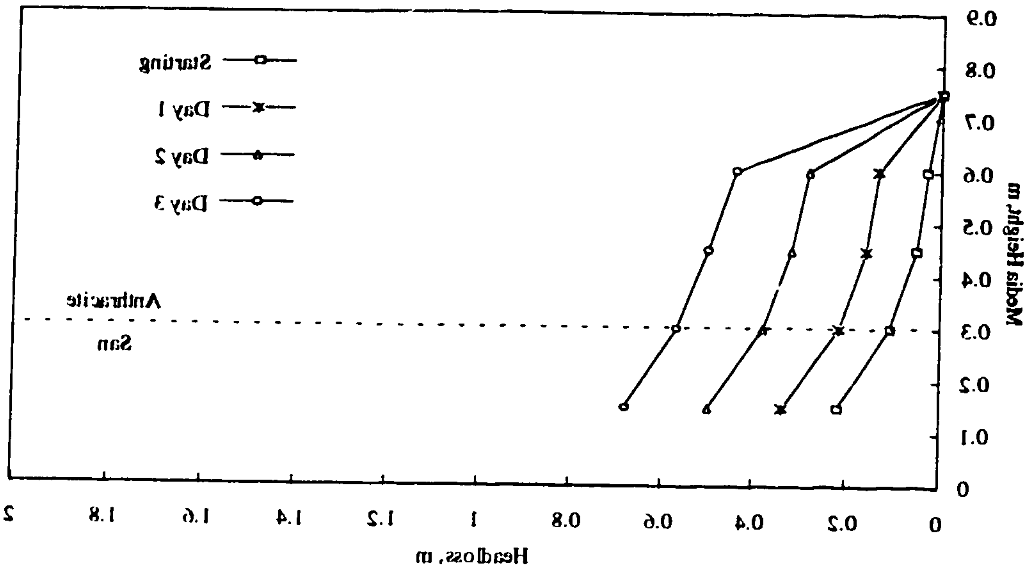


Figure 29. Headloss Profile along the Media (0.01 mg/L PERCOL LT22)

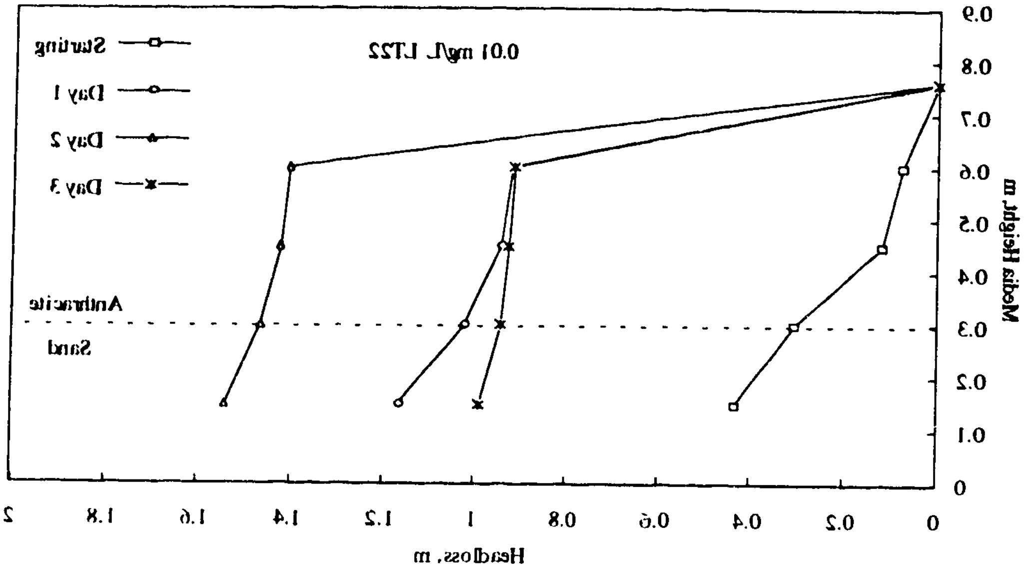


Figure 28. Headloss Profile along the Media (0.01 mg/L PERCOL LT 27)

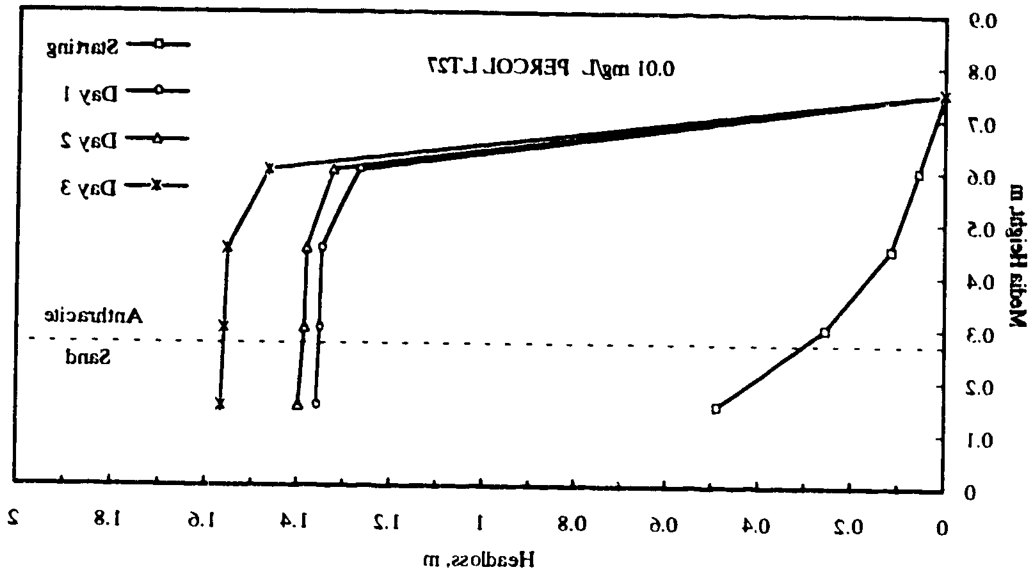


Figure 27. Headloss Profile along the Media (0.01 mg/L PERCOL LT 20)

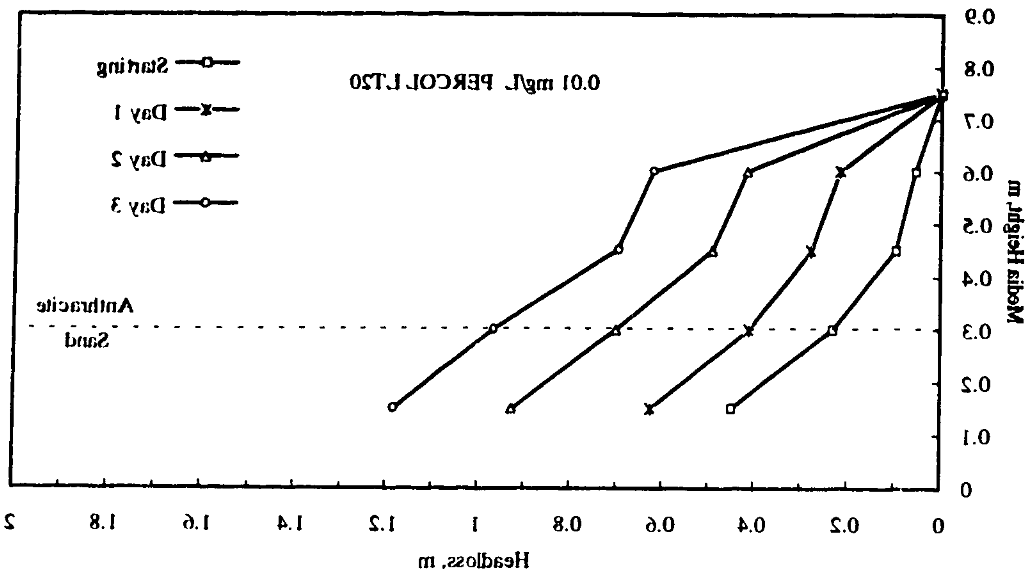
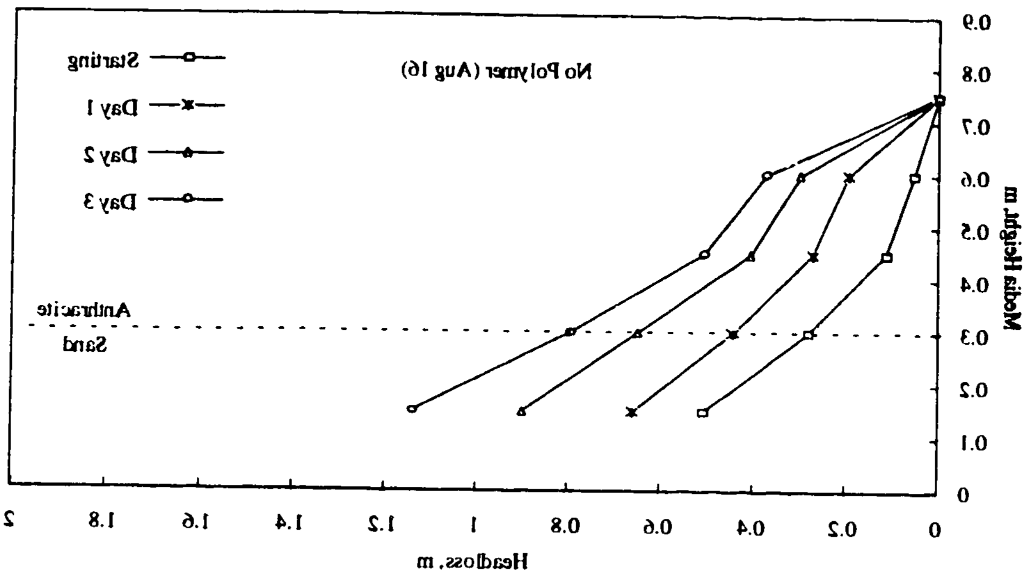


Figure 26. Headloss Profile along the Media (No Polymer)



receding limb, as shown in Figure 5. The disappearance of the second turbidity peak resulted from the limitation of the data collection method employed. As the filtrate quality was recorded throughout a operation of 72 hours, the data had to be collected by 5 minute interval due to limited storage capacity of the data logger.

It should be pointed out that other factors may also affect the capture efficiency of particles in filtration which may affect the selection of the most appropriate polymers. Among them are the filtration flow rate and shocks in loading rates. When the filtration rate is increasing, the particles attached to the filter media have to withstand higher shear forces. To avoid escaping from the filter, the formation of larger and stronger flocs is preferable. Similarly, the shocks in loading rates would suddenly disturb the balance that exits between the attachment forces of deposited particles and the hydraulic shear forces. Some particles might be sheared from the media and pass through the filter. In either case, the use of relatively higher molecular weight polymers might be necessary to ensure the good filtrate quality.

5.2.4 Filtration Headloss

Headloss development in a filter is just as important as filtrate quality to evaluate the filtration performance, because the filtration cycle must be terminated either by the turbidity breakthrough or the headloss breakthrough. Figures 26 to 34 present the headloss profiles at different heights in the media bed. Figure 26 exhibits the headloss development for the control filter with no polymer addition. Figures 27 and 34 present the results for the low, high molecular weight and the very high molecular weight polymers, respectively. As the curves in these figures are plotted with media height versus the headloss, the negative inverse of curve slopes represent polymers, PERCOL LT 27 and LT 20 reduced the peak turbidity to approximately 40 per cent of that found with no polymer, and the duration of filter ripening sequence to about 30 per cent of the control filter. By comparison, the low molecular weight polymers, PERCOL LT 35 and Cat-Floc T2, reduced the peak turbidity and duration of filter ripening sequence to 65 and 70 percent of the control filter value, respectively. Again, the phenomenon can be contributed to alteration of particle characteristics due to interparticle bridging mechanism. It is well known that after backwashing the clean filter is in a loose configuration. The pore sizes in the filter bed are much larger than during normal operating conditions. During ripening, the small unbridged calcium carbonate particles can very easily penetrate through the filter bed and deteriorate the initial filtrate quality. The larger and stronger polymer-particle flocs are more easily captured and less likely to pass through the filter bed. After the filter has been operated for a while, the filter media becomes denser as a result of hydraulic forces, resulting in smaller pore sizes. In addition, due to the collection of particles, the size of the pores further decrease, and the geometry of flow channels are changed. This tends to increase the capture efficiency of the filter media. As high molecular weight polymers are more effective in forming larger and stronger flocs than the low molecular weight ones, the magnitude and duration of the initial filter ripening is substantially reduced with the use of higher molecular weight polymers. This is consistent with the experimental observations.

Only one turbidity peak during the period of filter ripening was recorded in this study. Although similar observations have been extensively reported previously (Cranston and Amirtharajah, 1987; Tuepker and Buescher 1968), it has been shown that two peaks may be involved in the filter ripening sequence and separated by a very short interval (Amirtharajah and Wetstein, 1980). These two peaks can be divided into three periods: the lag period, the rising limb culminating in the two peaks, and a long

Figure 25. Effects of Low Molecular Weight Polymers on Filter Ripening Sequence

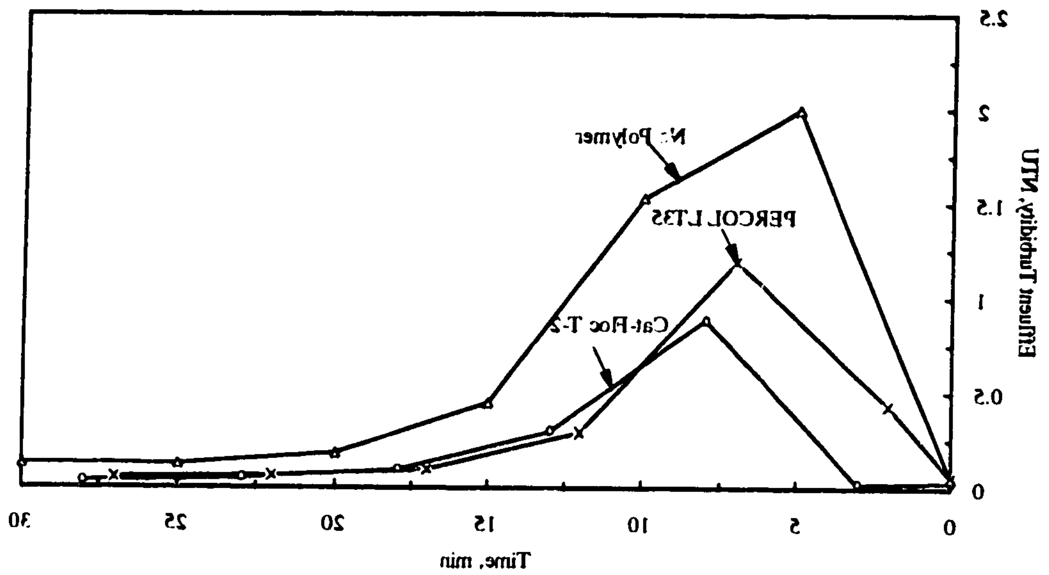
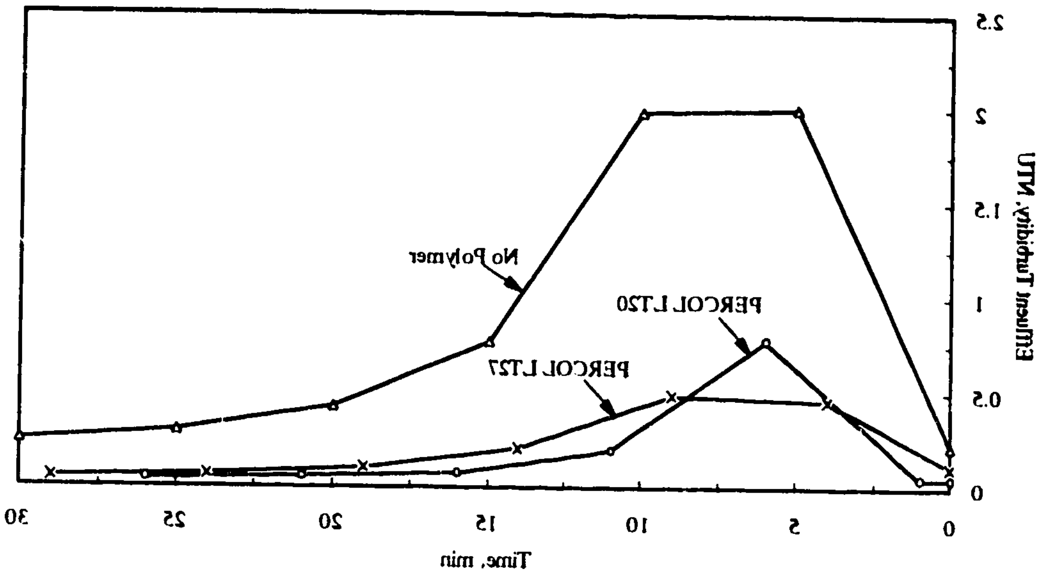


Figure 24. Effects of High Molecular Weight Polymers on Filter Ripening Sequence



breakthrough to be delayed. As shown in Figures 15 to 23, with polymer additions, no turbidity breakthroughs were observed throughout the run after the initial ripening period. However, the breakthroughs were noted after 30 to 45 hours of operation for no polymer addition, with the exact time of breakthrough was dependent on filter influent quality.

This general pattern of filtrate quality during the filter cycle strongly suggested that the polymer-particle flocs are mechanically stronger than the calcium carbonate particles originated in softened water. It was known (Robeck et al., 1964) that under the strong floc conditions, the filtrate quality was nearly constant after the initial filter ripening period. In some cases, the filtrate quality might even improve throughout the run. No terminal breakthrough would be observed. Under the weak floc conditions, however, the terminal turbidity breakthrough was rather abrupt, and would occur at the earlier stage.

5.2.3 Initial Filter Ripening

Another advantage of using polymers as filter aids is to accelerate the initial ripening of filter. Ripening refers to the initial improvement in removal efficiency that occurs as previously retained particles begin to serve as additional collectors for suspended particles after backwashing. Figures 24 and 25 show the typical filter ripening sequence with the addition of different molecular weight polymers. As shown, both the magnitude and duration of the filter ripening sequence are substantially reduced as compared to no polymer addition. The figures also indicate that higher molecular weight polymers can improve the filter ripening sequence more effectively than the lower molecular weight ones. For example, high molecular weight predominates the polymer reaction (Luttinger, 1981). In filtration, for a given type of polymer, the higher molecular weight, the more effective. The reason for this is a result of the greater extension into the liquid phase of the higher molecular weight polymers. The larger number of binding hydrogen or other bonds (capable of being formed on filter media and colloids by the longer chains) makes for stronger binding to both filter media and colloids, and hence enhances both the collection mechanism and the resistance of the polymer to be scoured from the filter media at higher flow rates. However, some researches (Habibian and O'Melia, 1975 and Leu and Ghosh, 1988) have shown that excessively high molecular weight might cause the increase in the headloss and the formation of large flocs deposited at the surface of filter.

5.2.2 Filter Turbidity Breakthrough

As a filter run proceeds, more and more particles accumulate in the media. These particles are held in an equilibrium between attachment forces and hydraulic shear forces. If shear forces are greater than attachment forces, the particles tend to be dislodged and will penetrate deeper into or be transported through the filter media. As deposits build, the velocities through the narrower voids of the upper layers of the filter increases. Since the shear forces are directly related to the velocity in the media pores, the increasing shear forces make these upper layers less effective for removal. The burden of removal moves progressively deeper and deeper into media, and if operated for long enough, turbidity breakthrough occurs. The use of polymers as a filter aid can bridge particles together into flocs. These flocs tend to be more resistant to hydraulic shear forces than calcium carbonate particles alone. In addition, any unreacted polymer residual can provide a bridging mechanism between the flocs and the media or previous deposited flocs. It is thus possible for the turbidity with vacant adsorption sites, forming a polymer-particle complex with the polymer as a bridge. The particles are thus bound into a floc which can grow to a size limited by the shear forces in the system and the amount of polymer initially adsorbed upon the surfaces of the particles. This mechanism would be expected to be the most dominant, when the charge attraction between the polymer and particles was weak (Ghosh *et al.*, 1985). This is exactly the situation for the softened water, as the majority of particles come from the precipitation of calcium carbonate. These particles are close to the isoelectric point at the pH value of around 8.5, thus, their net surface charge would be approximately zero. It must be recognized that although the particle as a whole has little net charge, the particles can still possess the active sites at the surface. Both negative and positive sites exist according to the theory of the zero point of charge. When a small amount of polymer is added to water, polymer adsorption takes place, forming the relatively larger and stronger flocs. As these flocs are easier to be captured either on the surface of the filter media or within the media, the performance of filtration should be improved. On the other hand, it is difficult for the charge neutralization to occur, due to the small amount of polymer added. This was further supported by the fact that the charge density and type of polymer played little role in the improvement of filtrate quality.

The hypothesis could be very useful to explain a number of previous observations. After a series of experiments with 12 commercially available polymers, Ghosh *et al.* (1985) claimed that the polymer charge density would exert a profound effect on polymer performance only when the destabilization of particles was dominant with charge neutralization. In this cases, the oppositely charged polymers were better for the direct filtration, while the filtration performance is almost independent of polymer molecular weight. In contrast, the polymer molecular weight would become more important than the polymer charge density, when the bridging mechanism

However, it was still evident that a reduction of turbidity of over 100 % could result with the use of polymer Cat-Floc L as a filter aid, as compared to its control filtration with no polymers. It was thus concluded that using the polymers as a filter aid can effectively improve the filtrate quality of deep bed granular filtration of softened water.

With the tested polymers having different characterisitcs, a comparison of their performances also provided a glimpse into the effects on the filtrate quality of polymer types (anion, cationic and nonionic), molecular weights (extremely high, high, medium and low) and charge densities (high, medium and low). From Table 12, higher molecular weight polymers generally produce only slightly better filtrate as compared to those with the lower molecular weight ones. For the polymers in the same category of molecular weight, the charge density and type seemed to have little impact on filtrate quality. PAM A502, specified as a "medium" molecular weight polymer, produced a filtrate even better than some of high molecular weight polymers. It was believed that this might be the result of different criteria used to classify the polymers by different manufacturers. It was indeed observed that at the same concentration, polymer PAM A502 had the highest viscosity among the tested polymers.

The improvement of filtrate quality using polymers could be contributed to the mechanism of the interparticle bridging between the polymer and particles. As aforementioned, the theory was initially developed for explaining the interaction between colloidal particles and high molecular weight polymers (LaMer and Healy, 1963). However, the bridging mechanism was also applicable to low molecular weight polymers (Habibian and O'Melia, 1975; Yeh and Ghosh, 1981). In bridging, it means that when a polymer molecule and a suspended particle come into contact, some of the chemical groups of the polymer will absorb onto the surface of the suspended particle at one or more adsorption sites, and some of the polymer segments will extend into the solution phase. These extended segments may attach to other suspended particles

Table 12. Effects of Polymer Addition on Filter Performance

Polymer	Dose	Influent, NTU		Effluent, NTU		
	mg/L	average	range	day 1	day 2	day 3
No	0	5.5	2.3 to 10.2	0.66	0.847	1.018
PERCOL LT 20	0.01			0.029	0.024	0.023
PERCOL LT 27	0.01			0.025	0.021	0.020
No	0	1.5	1.0 to 6.7	0.049	0.143	0.310
PAM A502	0.01			0.020	0.016	0.022
Cat-Floc L	0.01			0.031	0.062	0.049
No	0	1.4	0.6 to 2.9	0.058	0.051	0.328
Cat-Floc T2	0.01			0.024	0.022	0.019
PERCOL LT 35	0.01			0.040	0.034	0.025
PERCOL LT 22	0.01			0.027	0.022	0.023

Figure 23. Significance of PERCOL LT 20 on Filtrate Turbidities (0.03 mg/L)

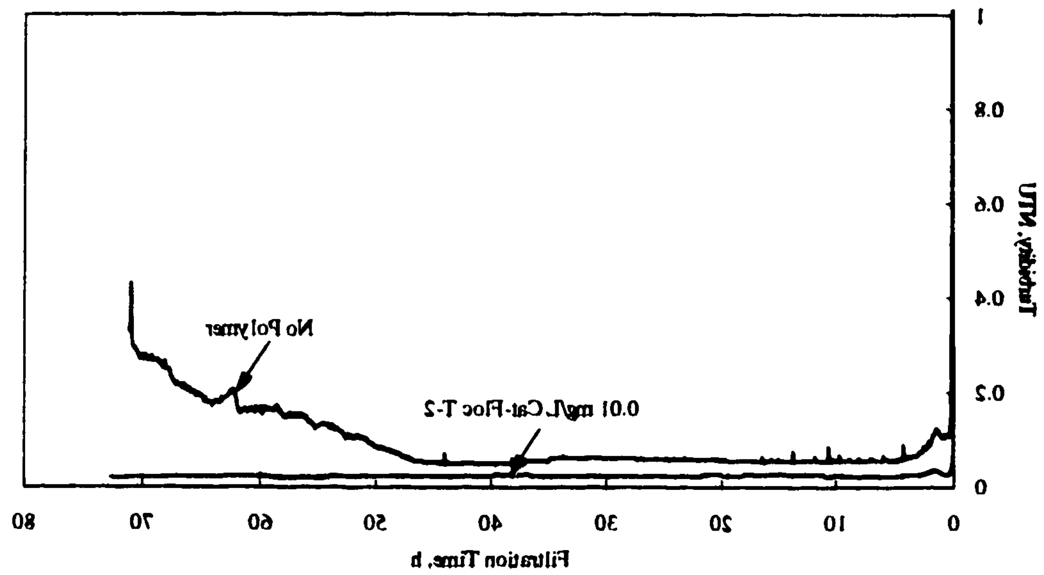


Figure 38. Effects of PERCOL LT 20 and LT 27 Addition on Filtration Rate (0.03 mg/L)

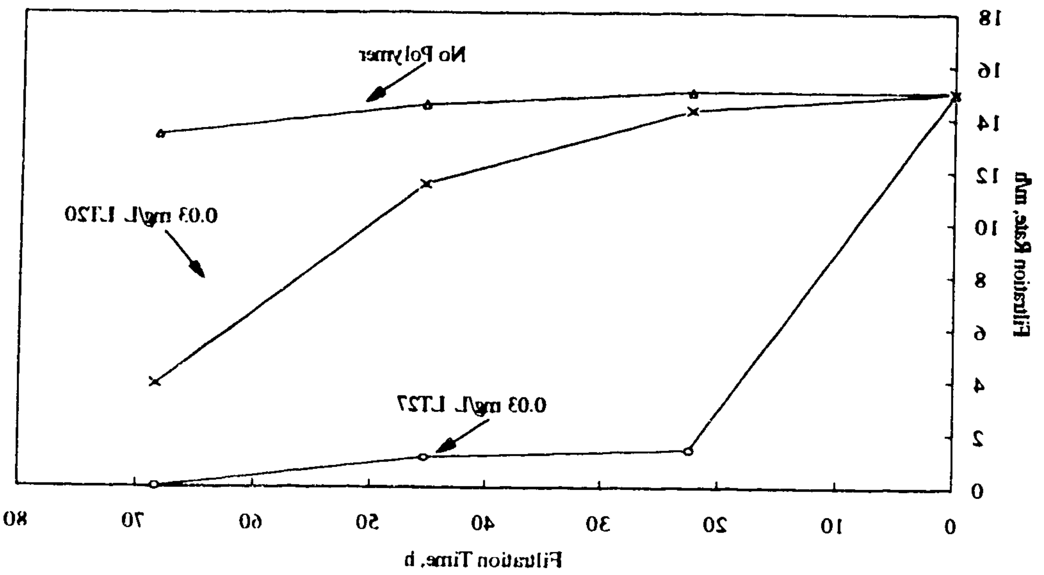


Figure 37. Effects of PERCOL LT 20 and LT 27 Addition on Filtration Rate

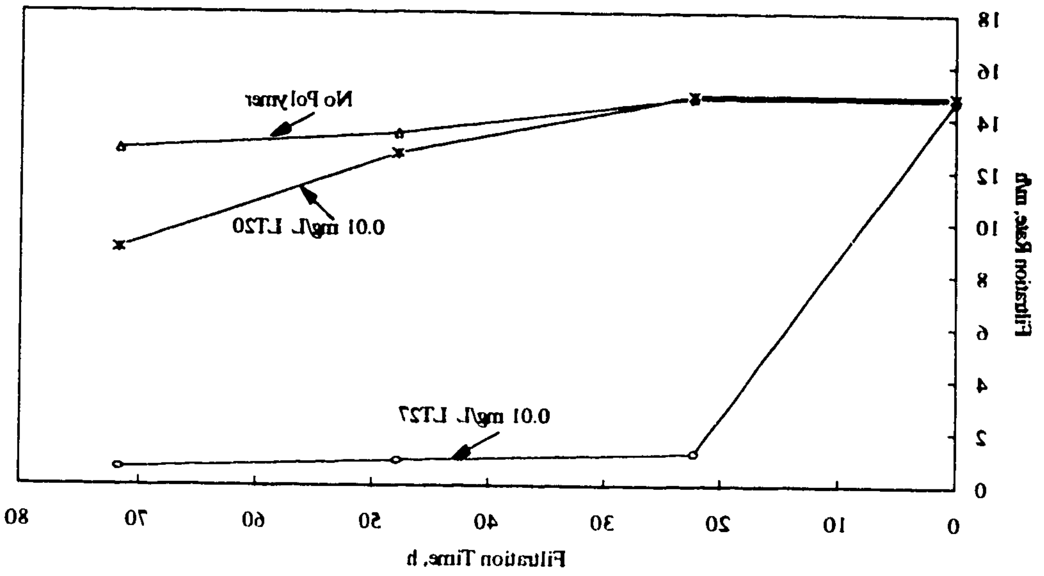


Figure 36. Effects of Cat-Floc L and PAM A502 Addition on Filtration Rate

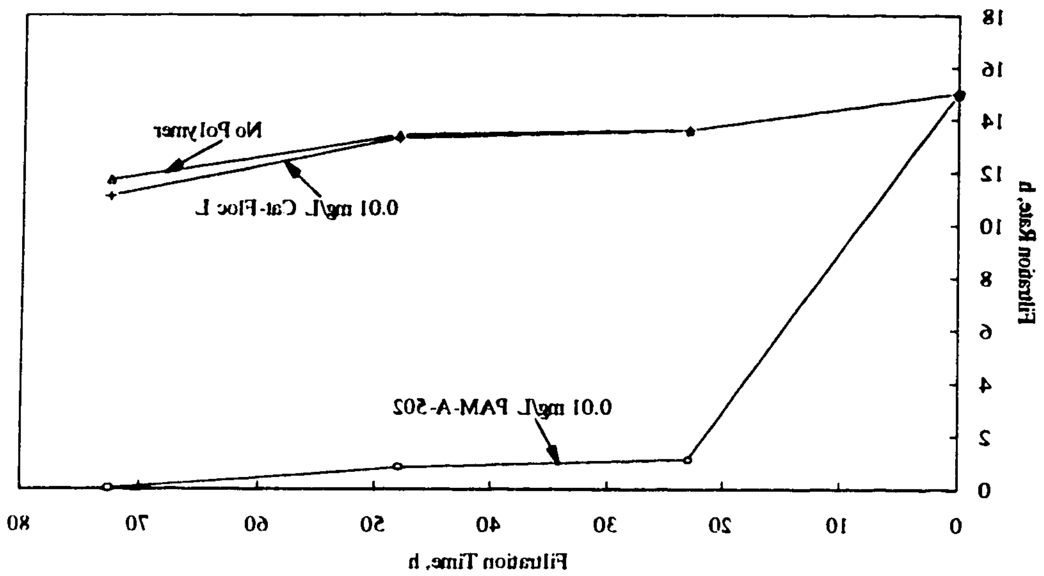
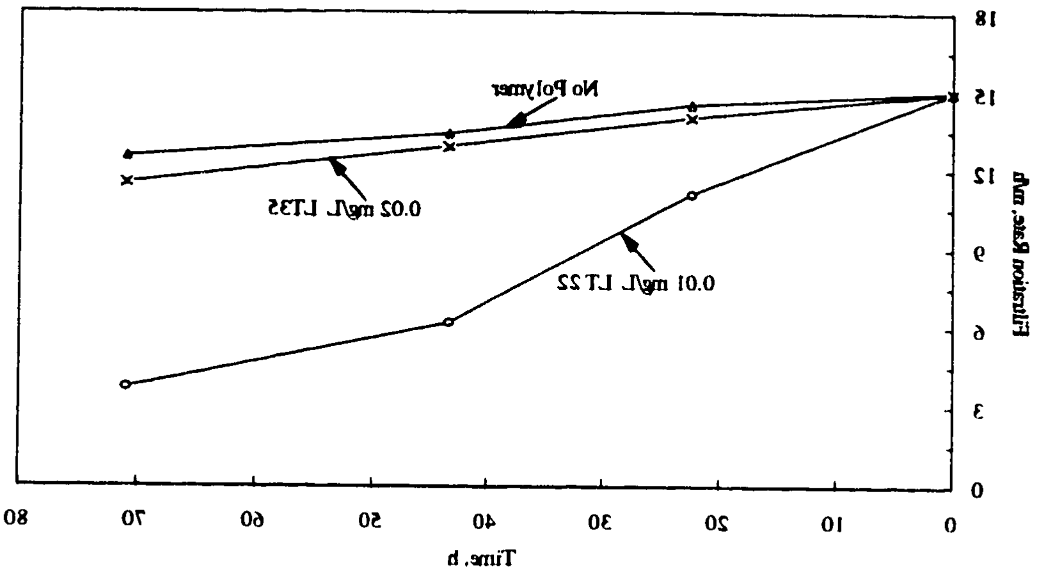


Figure 35. Effects of PERCOL LT 35 and LT 22 Addition on Filtration Rate



very high molecular weight PERCOL LT 27. Consequently, almost all the headloss occurred in this top surface cake layer, suggesting removal of particles results predominately from simple interstitial straining mechanisms. In comparison, Plate 8 shows that a relatively thin layer of surface cake was formed with the use of lower molecular weight polymer. Correspondingly, the headloss is distributed relatively evenly along the bed indicating that particles are able to penetrate deep into the bed. Thus, precautions should be taken to select the polymer with a proper molecular weight for the high rate filtration of softened water.

5.2.5 Water Production

With the build-up of headloss, the flow rate through the filter decreases when filters are operated in a declining mode. Figures 35 to 39 present the effect of polymer addition on flow rate as a function of filtration time for the different polymers tested. It shows that with no polymer addition, the flow rates slowly decline from the starting flow rate of 15 m/hr to the terminal flow rate of 13 m/hr after three days of operation. However, with the polymer addition the change of flow rates seems to be dependent on the kind of polymer used. For the high or very high molecular weight PERCOL LT 27, the flow rate sharply diminishes to as low as 1.2 m/hr after only one day operation. For the low molecular weight polymers, the flow rates declined at a much more moderate rate. After three days operation, the terminal flow rates were still higher than 10 m/hr for most of low molecular weight polymers.

As the filtration rates varied substantially with the use of different polymers, the quantity of filtrate would differ substantially. Considering that the termination of filtration run would be determined more likely by the headloss breakthrough, it is more reasonable to present the headloss versus the filtrate volume for comparing the

Plate 9. Evidence of Surface Cake Formation with the Use of PERCOL LT22

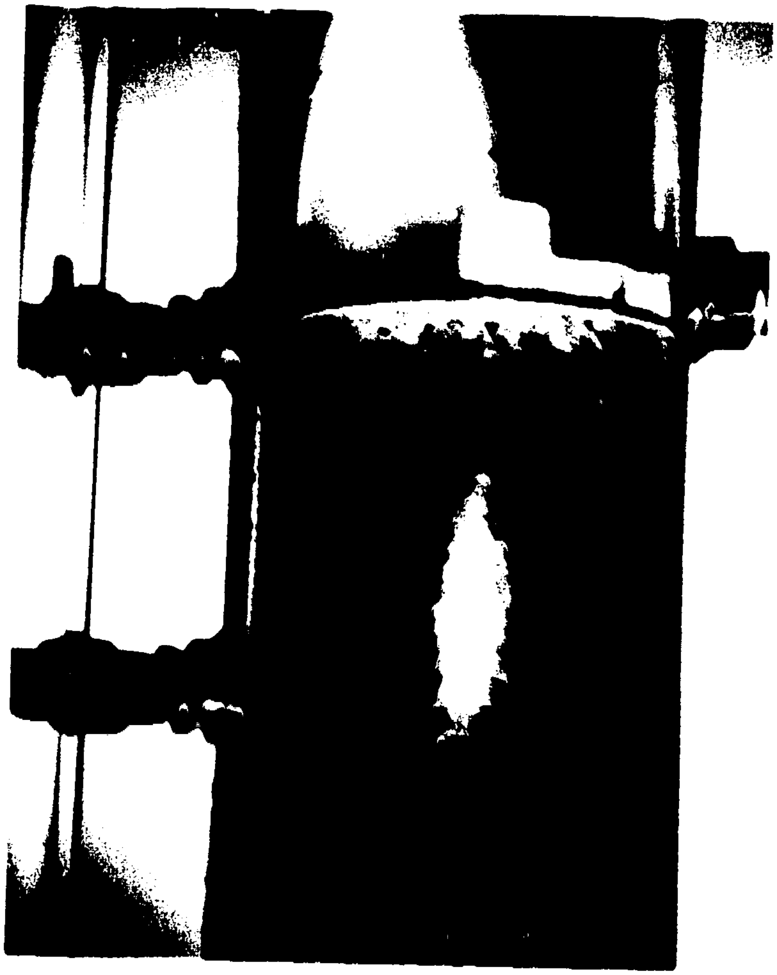


Plate 8. Evidence of Surface Cake Formation with the Use of PERCOL LT35

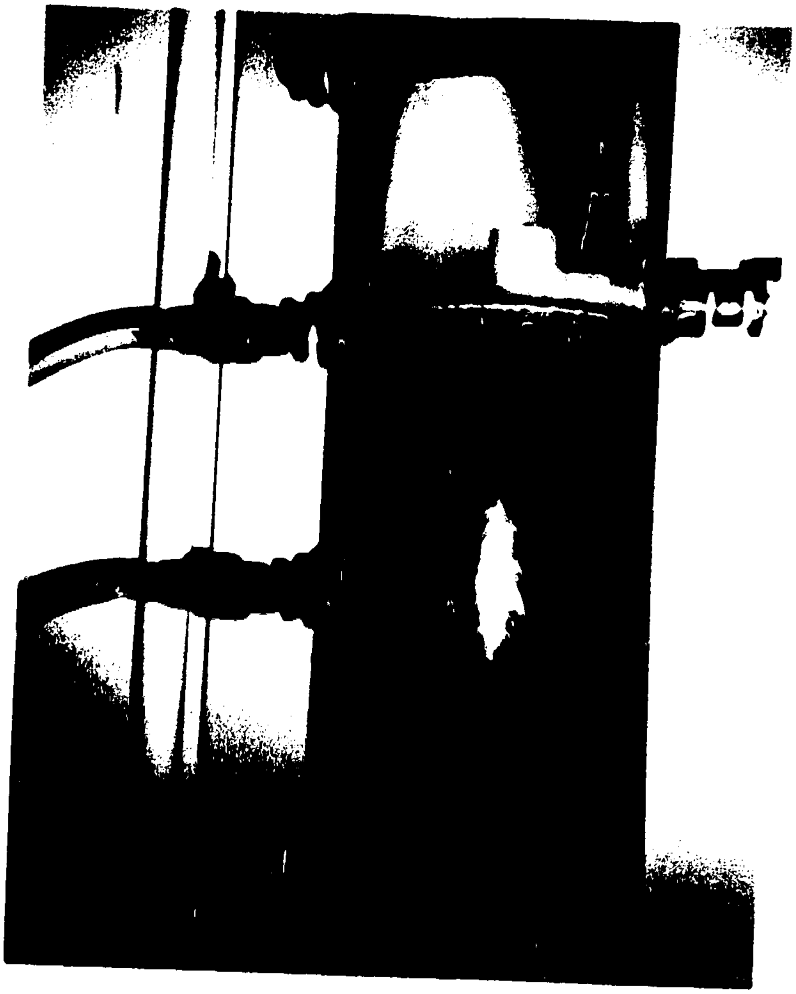


Plate 7. Evidence of Surface Cake Formation without the Use of Polymer

the headloss gradient. The greater the headloss gradient, the greater the headloss per unit length of the filter media.

At the start of filter run, the headloss depends only on media properties and flow rate as the water flows through the clean pore media at a certain temperature. As seen in the figures, it is evident that the headloss gradient is higher in the fine sand layer than in the coarse anthracite layer. This is because the headloss is inversely proportional to the size of media in the clean bed, as governed by Eq. 12. No sudden headloss increase is evident around the intermixing layer, indicating that these two media are compatible at the employed backwash rate. As the filtration proceeds, the headloss gradually builds up. With the use of polymers, the total headloss in the filter tends to increase at a greater rate as compared to no use of polymers. The phenomenon could be explained that the polymers facilitated the formation of stronger and larger flocs which, in turn, affect the distribution of headloss in a filter. As evident in Figure 26 with no use of polymers, the headloss is distributed over the whole depth of the filter indicating that particles are able to penetrate deep into the media bed. When polymers are used the larger and stronger flocs are captured in the top portion of filter, resulting in most of the headloss occurring near the top of the filter. Some polymers caused the formation of a surface cake on the top of filter media, as a result, less particles penetrating deep into the filter (see Plates 7 to 9). Similar observations were reported for the filtration of dense particles (AWWA, 1990). However, the magnitude of difference in headloss is dependent on molecular weight, mixing, polymer type and filter operating conditions. In general, a polymer with high molecular weight produces greater headloss than polymers with lower molecular weights, mostly because of the larger particles they form. The difference between high and low molecular weight polymers is especially evident in the top layer of the filter. Plate 9 exhibits that a thick layer of surface cake was quickly formed with the use of

Figure 34. Headloss Profile along the Media (0.02 mg/L PERCOL LT 35)

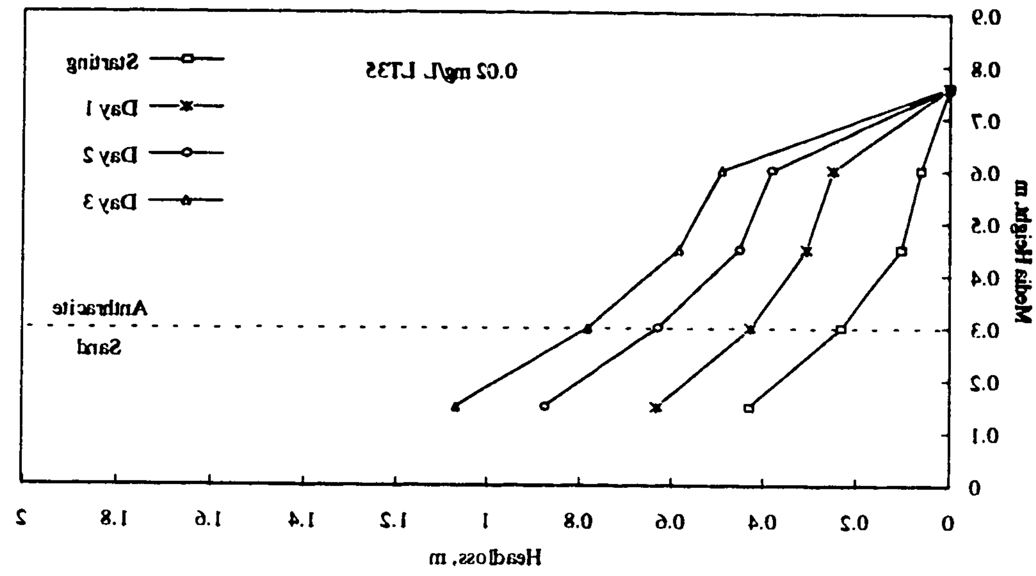


Figure 33. Headloss Profile along the Media (0.03 mg/L PERCOL LT 20)

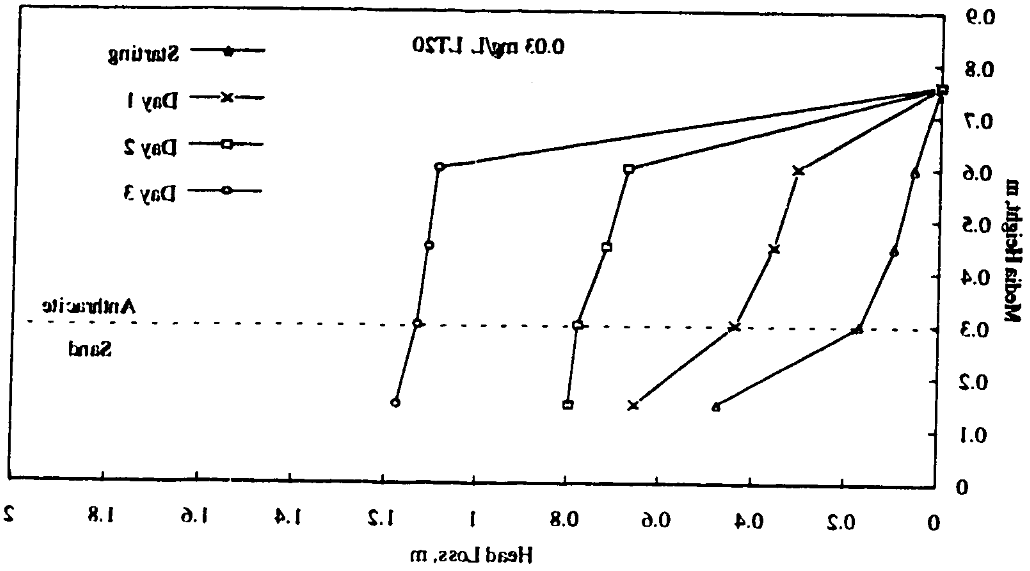


Figure 32. Headloss Profile along the Media (0.01 mg/L PERCOL LT 35)

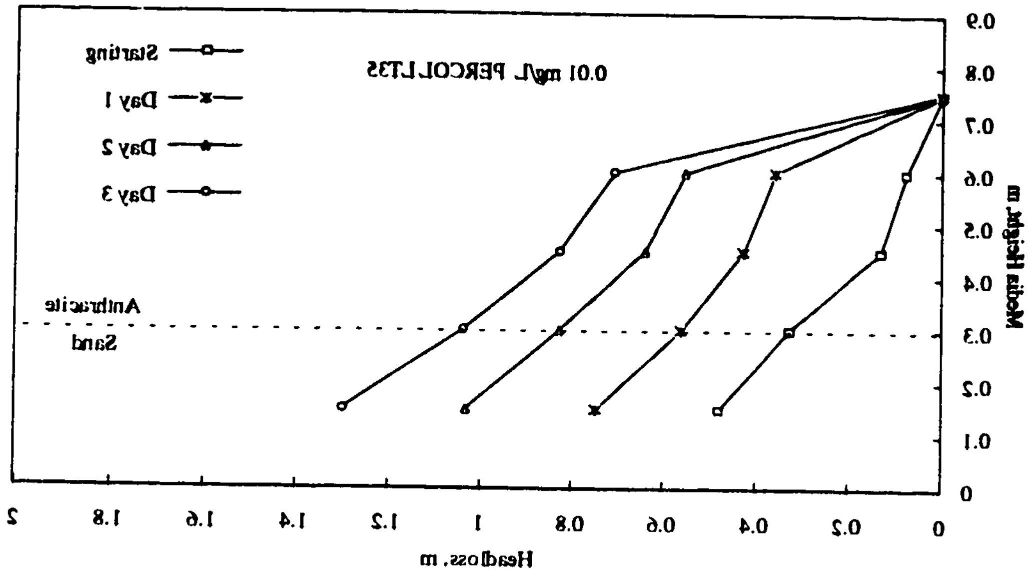


Figure 31. Headloss Profile along the Media (0.01 mg/L Cat-Floc L)

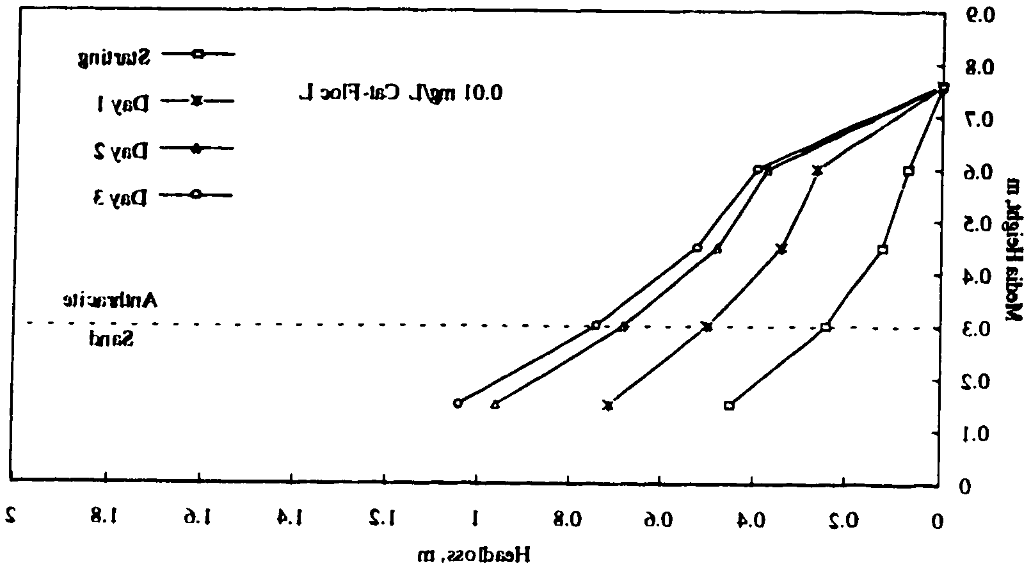
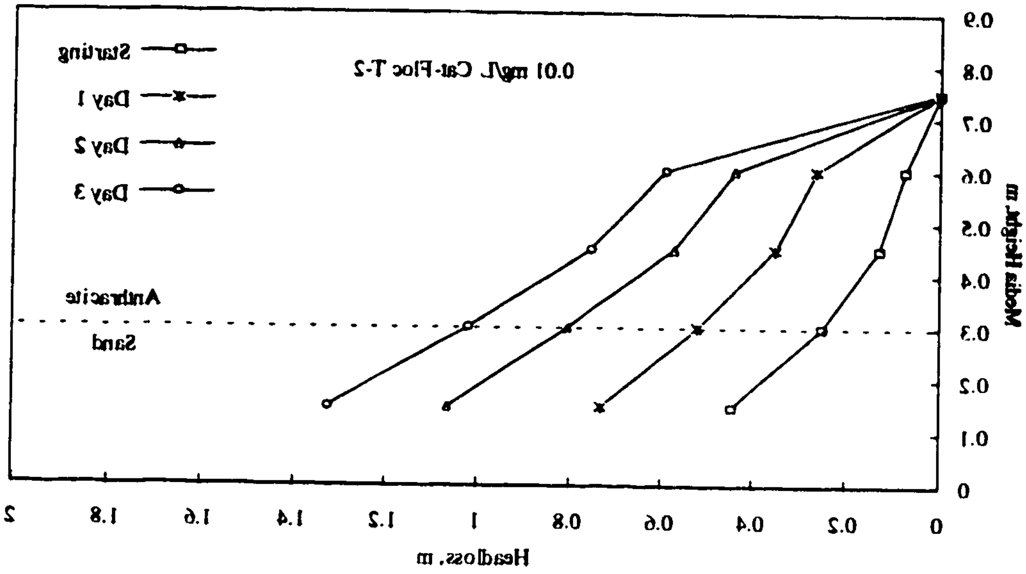


Figure 30. Headloss Profile along the Media (0.01 mg/L Cat-Floc T2)



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7. RECOMMENDATIONS

In order to further understand and improve the operation of polymer aided filtration of softened water, following recommendations were made for future studies:

1. The bench-scale filter test and the paper filter test should be conducted to compare the results from this study. If the conformity between them could be achieved, it would provide an easier, simpler and cheaper approach for screening the most appropriate polymers in practice. As well, it would help provide a quick and convenient way to control the operation of polymer aided filtration.

2. Most of the filtrate turbidities measured in this study are lower than 0.05 NTU. Within this range, the commonly used in-line turbidimeters are insensitive due to the limitation of instrumentation itself. An evaluation of particle removal efficiency of filtration should be based on a particle counter and a turbidimeter together.

3. The properties of polymers, namely, molecular weight, charge density and structure, should be measured in future studies, as different manufacturers often use different classification for protecting their proprietary rights. The resultant information would be very valuable to provide a deeper and unambiguous insight in the role of polymer characteristics in polymer aided filtration.

4. It would be very significant to explore the roles of polymers in the filter backwash. This could lead to substantially accelerating the filter initial ripening, in turn, reducing the amount of water that should be wasted and improving the filtrate quality.

a very high molecular weight polymer was fed to the filter, a surface cake formed quickly and the total headloss was concentrated in a thin top layer of the media. However, the increase in headloss was much less for low or moderately high molecular weight polymers. As a result, the filtration rate did not differ substantially as compared to the filtration with no polymer addition. It is therefore important to select polymers for the improvement of filtrate quality which ensure their use also results in good filtration productivity. At the filtration rate of 15 m/hr, low or moderately high molecular weight polymers are recommended for the treatment of softened water.

4. The performance of polymers was significantly affected by the mixing intensity during the addition of polymers into water. For a low molecular weight polymer such as Cat-Floc T2, it was found that a mixing intensity around 700 sec^{-1} can achieve the best filtration performance in terms of effluent turbidity and filter breakthrough. When the mixing intensity was reduced to less than 400 sec^{-1}, not only was the filtrate quality deteriorated, but also the turbidity breakthrough occurred earlier, after about 50 hours of operation.

5. The polymer dose was identified as an another important factor to consider for polymer aided filtration. It was found that the optimum polymer dose was 0.01 mg/L for the polymers tested. No further improvement in the filtrate quality was achieved when increasing the polymer dose up to 0.03 mg/L. However it was found that by lowering the dose to 0.005 mg/L, the filtrate turbidity was considerably degraded.

6. CONCLUSIONS

Based on the experimental results, the following conclusions can be made:

1. For lime softened water, the interparticle bridging seems to be the dominant mechanism underlying the interactions between polymers and particles. As the particles are around the isoelectric point at pH 8.5, the neutralization mechanism could be expected to be insignificant in forming stronger and larger flocs. The postulation was consistent with the little influence of polymer type (anionic, cationic, nonionic) on turbidity performance.

2. The use of polymers as a filter aid can offer several advantages for the high rate filtration of softened water. It produced the stable filtrate at an average of 0.03 NTU, as compared to above 0.06 NTU without polymer addition. It was also found that filter ripening sequences were also accelerated considerably and no turbidity breakthrough was observed after 72 hours of operation. By comparison, the breakthrough for no polymer aided filtration occurred around 30 to 40 hours, depending on the influent quality. It appears that the reduction in filter ripening magnitude and duration was directly related to polymer molecular weight. Higher molecular weight polymers reduce magnitude and duration more than the lower molecular weight ones. After the completion of ripening, the filtrate turbidity was little affected by using the different polymers.

3. However it was also found that the use of polymers as a filter aid could increase the development of headloss and reduce the penetration of particles deep into the media. These impacts were related mostly to the molecular weight of polymers, with other characteristics being relatively insignificant. In the extreme case where

Figure 43. Effects of Cat-Floc T2 Dosages on Effluent Turbidity (Test 2)

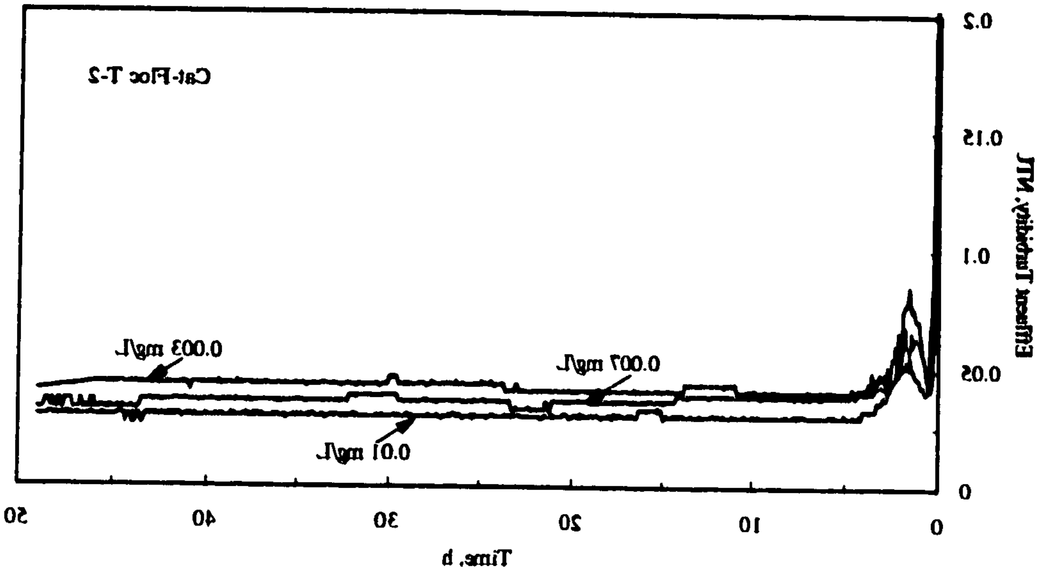
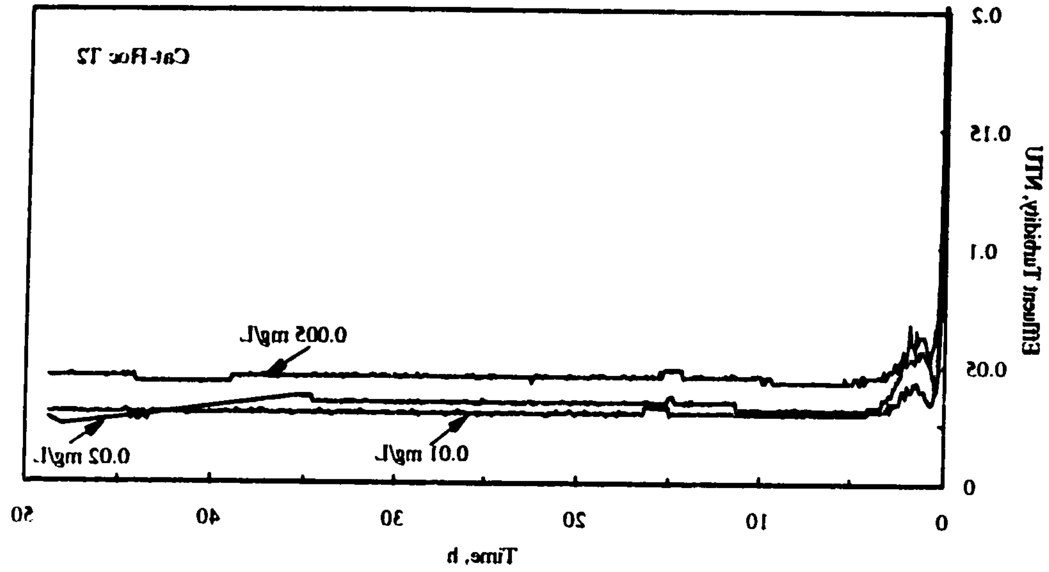


Figure 42. Effects of Cat-Floc T2 Dosages on Effluent Turbidity (Test 1)

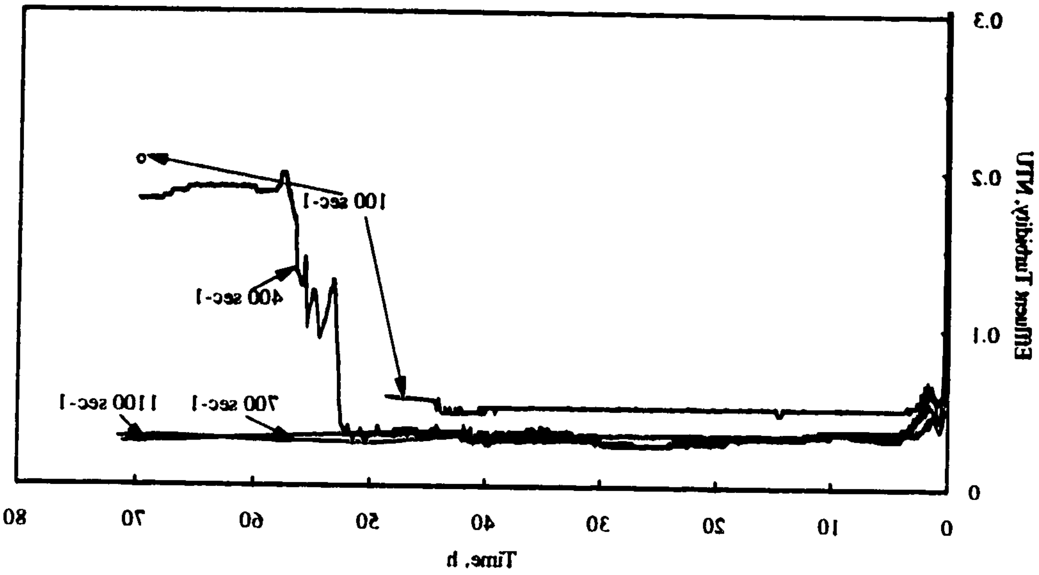


essential when low molecular weight polymers are used as coagulants prior to direct filtration. They also concluded that the Gt values corresponding to the onset of floc breakup ranged from 280000 to 450000 for several polymers, and the higher values being associated with polymers of the higher molecular weight. Later, Leu and Ghosh (1988) further studied the effects of polymer addition on the size, strength and density of flocs. An optimum Gt product for the rapid mixing was found to be 2 x 10^5 for three to four minutes. Thus, the effects of mixing intensity on the performance of filtration aids are quite controversial. This may be explained by the different characteristics of water samples, the application of different treatment processes (direct filtration, contact filtration or conventional water treatment), and the different materials used in the experiment. More complicatedly, the flocculation would continue inside the filter media, which is strongly affected by the filtration rate. It is very possible that the polymer molecular weight will play an important role in determining the requirement of mixing intensity. This is shown by Luttinger (1981) that the higher molecular weight polymers had the greater ability to extend into the liquid phase. In general, it seems that the necessary rapid mixing for the organic polymers should be from the 400 to 1000 sec^{-1} in order to accomplish the uniform distribution of polymers into water and provide the sufficient collision between polymer molecules and particles.

5.3.2 Polymer Dose

At the optimum polymer mixing condition, the effects of polymer dosage on the filtrate quality are shown in Figures 42 to 43. The data clearly indicate that when the polymer dosage was greater than 0.01 mg/L, the filtrate turbidity is near the minimum. Higher dosages did not reduce the effluent turbidity any further. However,

Figure 41. Effects of Mixing Intensity on Polymer Aided Filtration



Therefore, only the effects of mixing and polymer dose on filtration were investigated. The tests were conducted by varying one operating parameter while holding the others constant. The mixing intensity was varied from the 100 sec^{-1} to 1100 sec^{-1}, and the polymer dosage from the 0.005 mg/L to 0.03 mg/L.

5.3.1 Mixing

Figure 41 presents the effects of mixing intensity on the filtrate quality as a function of filtration time. At the applied polymer dose of 0.01 mg/L, the filtrate turbidity with an average turbidity of 0.03 NTU was consistently produced when the velocity gradient G is within a range from 700 sec^{-1} to 1100 sec^{-1}. No turbidity breakthrough was evident after three days of operation. However, if the velocity gradient was reduced to 400 sec^{-1}, a similar filtrate turbidity was produced for a period but turbidity breakthrough occurred after 50 hours of operation. Further lowering of the mixing intensity to 100 sec^{-1} resulted in both degradation of filtrate quality and early breakthrough.

Importance of mixing on the interactions between the polymers and particles has been extensively reported. From a plant survey, Cleasby *et al.* (1989) noticed that inadequate mixing may lead to the failure of using polymers as filter aids. Proper rapid mixing for polymer addition can be beneficial to ensure the uniform distribution of the polymer into water. Stamp and Novak (1979) reported that cationic polymers used for water treatment have proved to be very effective either as filter aids or as primary coagulants. They found that the polymers in the higher molecular weight range (>100000) perform best with intense mixing at 600 to 1000 s^{-1}. Polymers of lower molecular weigh (10000 to 50000) do well with G values in the 300 s^{-1} range. Yeh and Ghosh (1981) found that the velocity gradients of 300 sec^{-1} to 650 sec^{-1} is polymers' role in filtration. Figure 40 shows that the headloss almost linearly relates to volume of filtrate, that is, to the amount of particles captured in the filter bed for no use of polymer or the use of low molecular weight polymers. For the use of very high molecular weight polymers, the deviation from this linearity was evident. Again, this difference may attribute to the different effects of polymer molecular weight on the strength of flocs. Cleasby and Baumann (1962) found that there are two general patterns of headloss encountered in filtration. The most common one is linear with respect to volume of filtrate. This linear headloss would be typical for relatively soft flocs or at high filtration rates. In these cases, the particles will be penetrated deep into the filter media. Another headloss pattern is exponentially increasing with the filtrate volume. It often occurs when the particles are stronger and are filtered at low filtration rate. The particles would be removed by a partial capture in a surface cake and/or within a thin layer of medium at the top. This is exactly case for the treatment of the E. L. Smith Water Treatment Plant softened water. Using the low molecular weight polymers will reduce the exponential tendency by encouraging the greater penetration of particles into the deep media.

5.3 Optimum Tests for Selected Polymers

Based on the results from the screening tests, the low or moderately low molecular weight polymers seem to be the most appropriate to produce the acceptable quality filtrate while ensuring the high water production. Therefore, the low molecular weight Cat-Floc T2 was chosen as the representative for the optimization of polymer aided filtration. In general, the most important factors which affect the process performance include the filtration rate, mixing intensity and polymer dosage. As the filtration rate was set based on needs of the full scale plant, no further study was performed.

Figure 40. Relationship of Total Headloss with Filtrate Volume

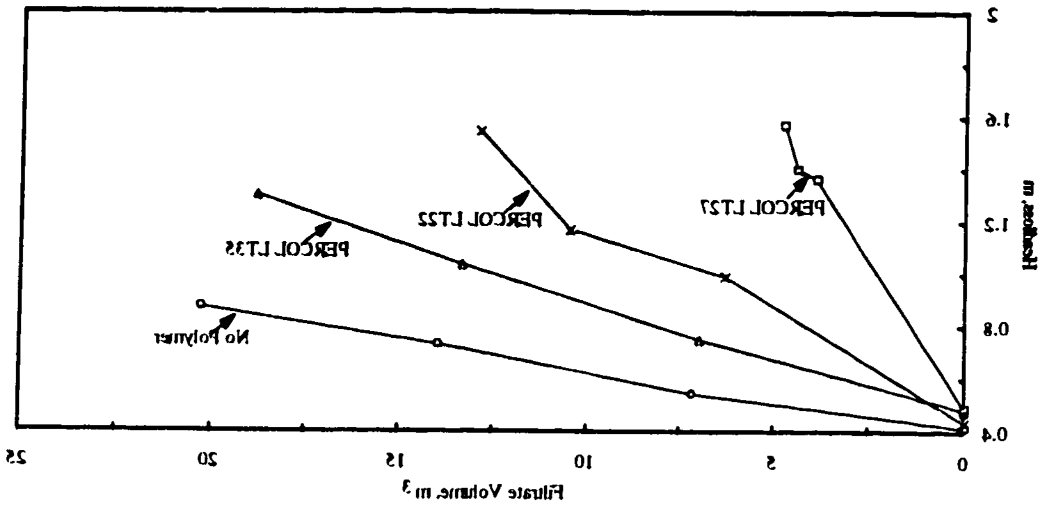
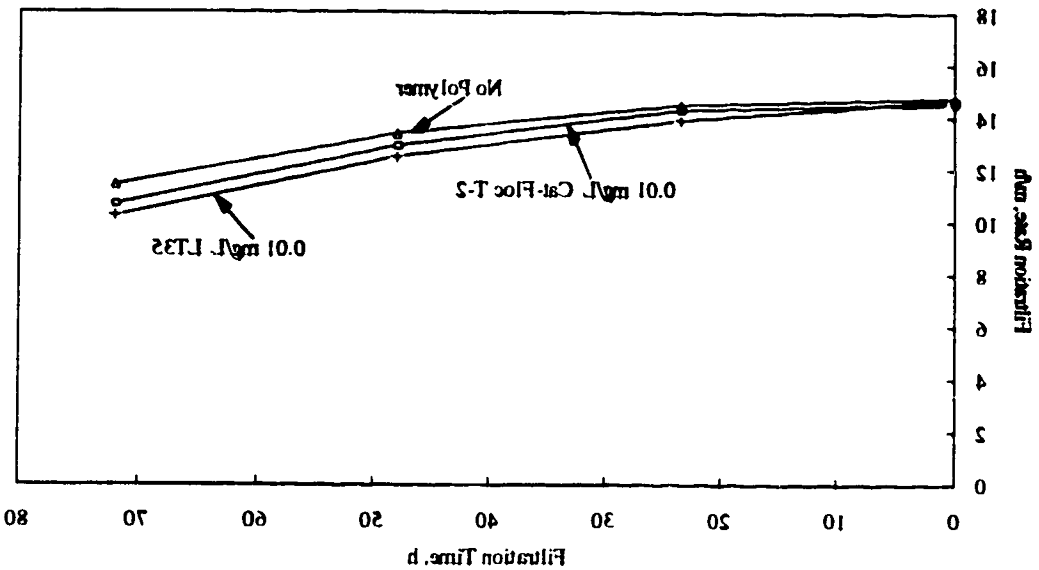
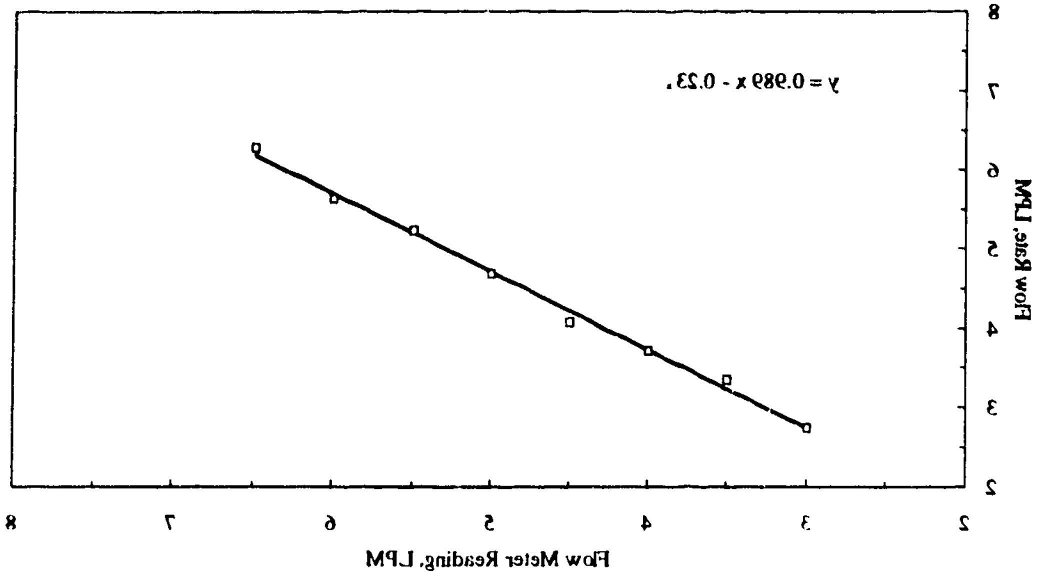


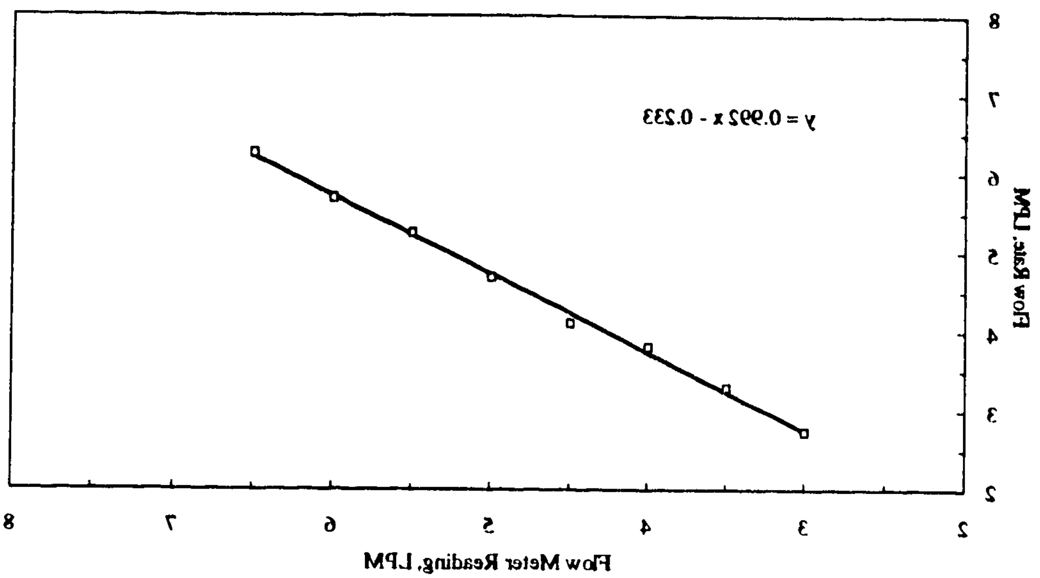
Figure 39. Effects of Cat-Floc T2 and PERCOL LT 35 Addition on Filtration Rate



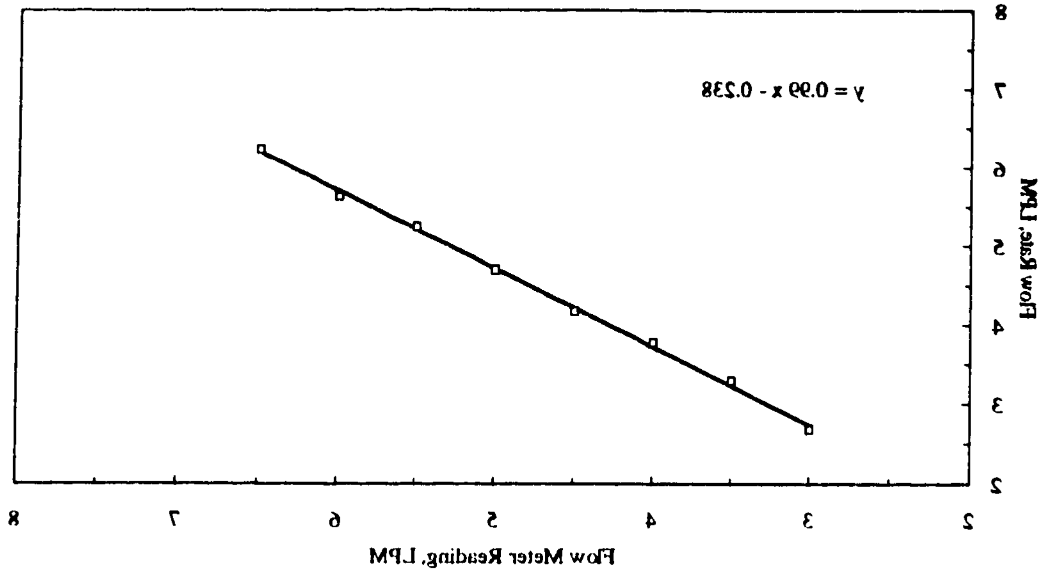
Influent Flowmeter #3 Calibration Curve



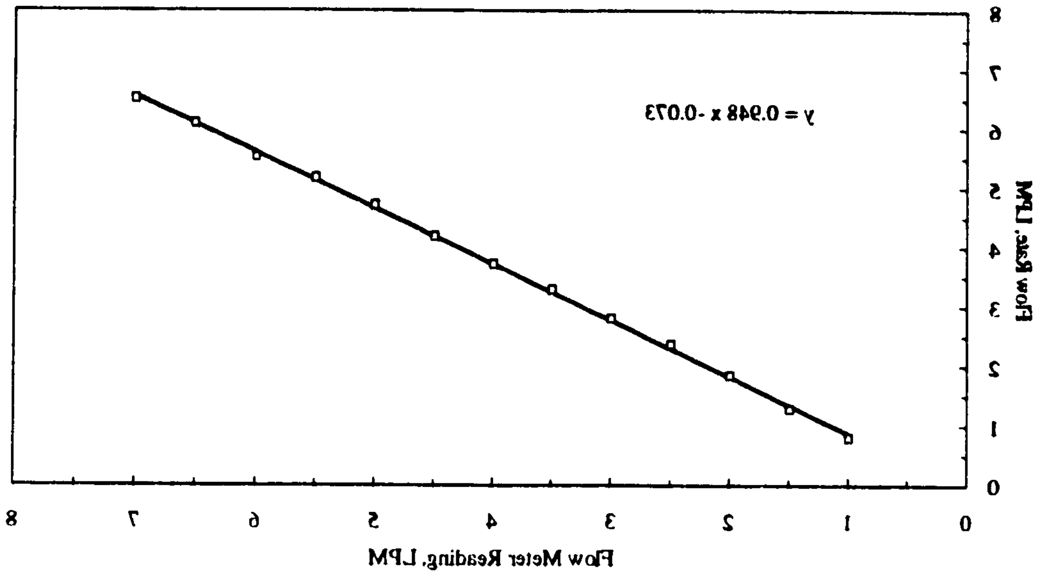
Influent Flowmeter #2 Calibration Curve



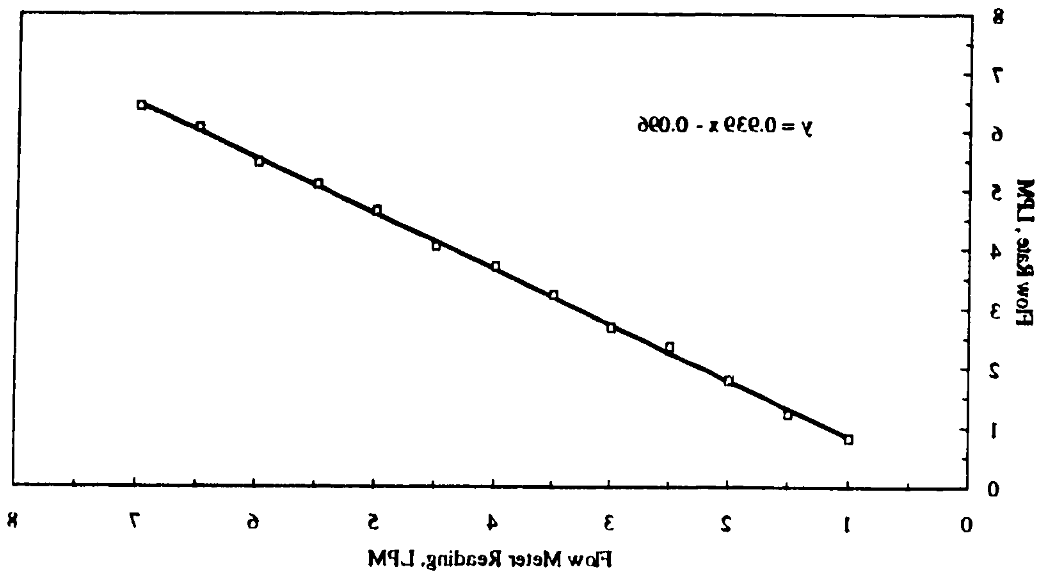
Influent Flowmeter #1 Calibration Curve



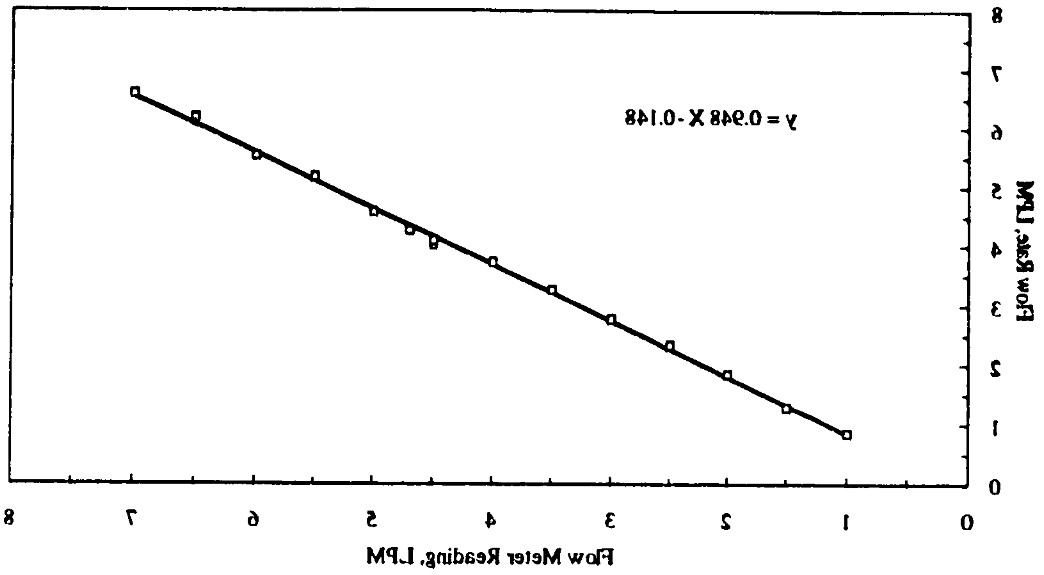
Effluent Flowmeter #3 Calibration Curve



Effluent Flowmeter #2 Calibration Curve



Effluent Flowmeter #1 Calibration Curve



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Date: 6-08-1993
Folw Rate: 15 m/h
Mixing: 700 sec^{-1}

SD1: No polymer

Time	Port #				
day	1	2	3	4	5
0	20.57	20.1	19.65	18.4	15.62
1	20.57	19	18.43	16.94	15.09
2	20.59	18.33	17.57	15.64	13.13
3	20.62	17.75	16.88	14.73	11.95

SD2: 0.01 mg/L PERCOL LT22

Time	Port #				
day	1	2	3	4	5
0	20.55	19.8	19.36	17.48	16.21
1	20.58	11.45	11.32	.13	10.7
2	20.57	11.38	11.12	10.34	8.9
3	20.6	6.54	6.34	5.95	5.18

SD3: 0.02 mg/L PERCOL LT35

Time	Port #				
day	1	2	3	4	5
0	20.56	19.94	19.52	18.24	16.24
1	20.56	18.05	17.48	16.27	14.23
2	20.58	16.74	16.03	14.27	11.8
3	20.58	15.65	14.73	12.76	9.87

Date: 16-08-1993
Folw Rate: 15 m/h
Mixing: 700 sec^{-1}

SC1: No polymer

Time	Port #				
day	1	2	3	4	5
0	20.58	20.05	19.45	17.77	15.53
1	20.58	18.64	17.87	16.15	14
2	20.61	17.62	16.55	14.13	11.62
3	20.62	16.87	15.56	12.66	9.2

SC2: 0.01 mg/L Cat-Floc T2

Time	Port #				
day	1	2	3	4	5
0	20.56	19.93	19.19	17.48	15.13
1	20.56	17.8	16.98	15.17	13.05
2	20.58	16.26	15.08	12.76	10.32
3	20.59	15	13.47	10.68	7.58

SC3: 0.01 mg/L PERCOL LT35

Time	Port #				
day	1	2	3	4	5
0	20.54	19.75	19.2	17.26	15.74
1	20.57	16.97	16.29	14.95	13.09
2	20.57	15.03	14.15	12.28	10.23
3	20.58	13.48	12.28	10.17	7.57

Date: 10-08-1993
Folw Rate: 15 m/h
Mixing: 700 sec^{-1}

SB1: No polymer

Time	Port #				
day	1	2	3	4	5
0	20.58	20.08	19.59	18.16	16.03
1	20.58	18.77	18.02	16.16	13.91
2	20.61	17.98	16.96	14.5	11.68
3	20.61	17.67	16.48	13.85	10.84

SB2: 0.01 mg/L PAM A502

Time	Port #				
day	1	2	3	4	5
0	20.57	19.89	19.38	18.02	15.77
1	20.66	19.8	19.75	13.95	13.92
2	20.66	5.63	5.33	5.32	5.24
3	20.66	7.76	7.58	7.48	7.24

SB3: 0.01 mg/L Cat-Floc L

Time	Port #				
day	1	2	3	4	5
0	20.55	19.83	19.28	18.09	16.03
1	20.55	17.88	17.13	15.55	13.42
2	20.48	16.73	15.68	13.64	10.88
3	20.48	16.49	15.23	13.02	10.06

Date: 02-08-1993
Folw Rate: 15 m/h
Mixing: 700 sec^{-1}

SA1: No polymer

Time	Port #				
day	1	2	3	4	5
0	20.57	20.04	19.63	18.2	16.44
1	20.57	19.22	18.68	17.24	15.13
2	20.58	18.33	17.6	15.81	13.28
3	20.6	17.76	16.95	14.8	11.87

SA2: 0.01 mg/L PERCOL LT20

Time	Port #				
day	1	2	3	4	5
0	20.54	19.97	19.56	18.23	16.03
1	20.54	18.36	17.78	16.43	14.28
2	20.56	16.38	15.65	13.54	11.3
3	20.58	14.35	13.58	10.9	8.73

SA3: 0.01 mg/L PERCOL LT27

Time	Port #				
day	1	2	3	4	5
0	20.53	19.95	19.37	17.96	15.63
1	20.63	7.92	7.14	7.1	7.03
2	20.64	7.4	6.81	6.77	6.65
3	20.65	6	5.12	5.05	4.98

Date: 19-09-1993
Polymer: No
Mixing: 700 sec^{-1}

PB1: 15 m/h filtration rate

Time	Port #				
day	1	2	3	4	5
0	20.5	19.75	19.27	18.05	15.73
1	20.43	17.44	16.76	15.14	12.68
2	20.34	13.85	13.02	10.88	8.28
3	20.5	10.58	9.5	6.98	3.97

PB2: 10 m/h filtration rate

Time	Port #				
day	1	2	3	4	5
0	20.54	20.09	19.79	18.87	17.2
1	20.57	18.75	18.34	17.32	15.55
2	20.57	16.43	15.82	14.43	12.74
3	20.58	14.3	13.5	11.65	9.75

Date: 16-09-1993
Polymer: No
Mixing: 700 sec^{-1}

PA1: 18 m/h filtration rate

Time	Port #				
day	1	2	3	4	5
0	20.44	19.52	18.87	17.1	14.03
1	20.4	16.6	15.67	13.3	9.95
2	20.5	13.02	11.81	8.73	4.83
3	20.57	9.96	8.68	5.52	1.82

PA2: 12 m/h filtration rate

Time	Port #				
day	1	2	3	4	5
0	20.55	20.12	19.79	18.77	17.05
1	20.56	18.26	17.75	16.3	14.48
2	20.59	16.05	15.37	13.42	11.6
3	20.62	13.72	12.82	10.53	8.48

PA3: 7 m/h filtration rate

Time	Port #				
day	1	2	3	4	5
0	20.52	20.23	20	19.44	18.33
1	20.54	19.2	18.95	18.38	17.18
2	20.54	17.72	17.34	16.74	15.55
3	20.56	16.13	15.54	14.87	13.74

APPENDIX D SUMMARY OF HEADLOSS DATA

Filter Influnet Quality Data during September, 1993

date	pH		Turbidity, NTU		Total H, mg/L		Ca H, mg/L		Alk., mg/L		Color, TCU		Chloride, mg/L		Fluoride, mg/L	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
1	8.87	8.55	3.3	1.6	110	106	64	62	74	66	1	1	2.4	2.4	0.94	0.88
2	8.85	8.16	5.6	1.1	116	108	70	62	72	68	1.5	1	2.5	2.4	0.96	0.92
3	8.87	8.46	2.4	1.1	110	106	68	66	68	66	3	1	2.45	2.45	0.94	0.89
4	8.84	8.43	2.5	2	110	106	70	64	66	58	2	1.5	2.45	2.45	0.95	0.9
5	8.92	8.52	2.4	1.1	110	106	68	66	68	62	1.5	1.5	2.45	2.45	0.94	0.9
6	8.75	8.37	1.9	1.2	112	106	68	66	66	60	1.5	1	2.45	2.45	0.94	0.91
7	8.84	8.65	2.9	0.2	112	110	70	68	72	68	2	1	2.45	2.45	0.95	0.92
8	8.87	8.56	3.8	2.1	114	108	66	60	72	62	2	1	2.45	2.45	0.97	0.89
9	8.87	8.31	2.4	1.4	112	102	66	64	72	64	2	1	2.45	2.45	0.93	0.86
10	8.9	8.58	2.2	1.9	112	108	66	62	76	70	2.5	1	2.45	2.45	0.93	0.85
11	8.85	8.5	2.2	1.8	112	100	76	62	76	70	1.5	1	2.45	2.45	0.92	0.91
12	8.78	8.45	2.1	1.7	112	110	68	62	72	66	1	1	2.45	2.4	0.99	0.92
13	8.92	8.57	2.3	1.5	112	106	66	58	68	64	1	1	2.4	2.4	0.92	0.89
14	8.54	8.16	2.4	1.5	112	108	68	62	68	62	1	1	2.4	2.4	0.93	0.89
15	8.86	8.66	2.7	2.1	114	104	70	58	70	58	1.5	1	2.4	2.4	0.93	0.91
16	8.85	8.46	2.7	2.1	112	100	64	58	67	58	1.5	1	2.45	2.4	0.92	0.89
17	8.87	8.69	3	2.1	110	104	66	64	66	64	1	1	2.4	2.4	0.91	0.89
18	8.78	8.66	2.7	2.1	108	106	64	64	66	62	1.5	1	2.4	2.4	0.93	0.88
19	8.9	8.72	2.7	1.8	106	104	64	62	66	62	1	1	2.4	2.4	0.94	0.92
20	8.86	8.71	2.7	1.8	110	106	62	60	66	62	1	1	2.4	2.4	0.93	0.9
21	8.89	8.79	2.8	2.1	114	110	64	62	72	66	1.5	1	2.4	2.4	0.93	0.9
22	8.87	8.4	3.9	2.5	112	106	68	62	70	58	1.5	1	2.4	2.35	0.94	0.87
23	8.84	8.68	1.7	1.2	110	106	68	64	72	66	1	1	2.35	2.35	0.94	0.9
24	8.85	8.66	4.3	1.3	110	104	64	60	68	66	1.5	1	2.45	2.35	0.93	0.89
25	8.97	8.68	1.3	0.6	112	108	68	60	70	68	1	1	2.45	2.35	0.93	0.92
26	8.87	8.74	0.8	0.7	114	108	68	62	74	64	2.5	1	2.35	2.35	0.92	0.89
ave	8.7		2.1		109		65		67		1.3		2.42		0.92	

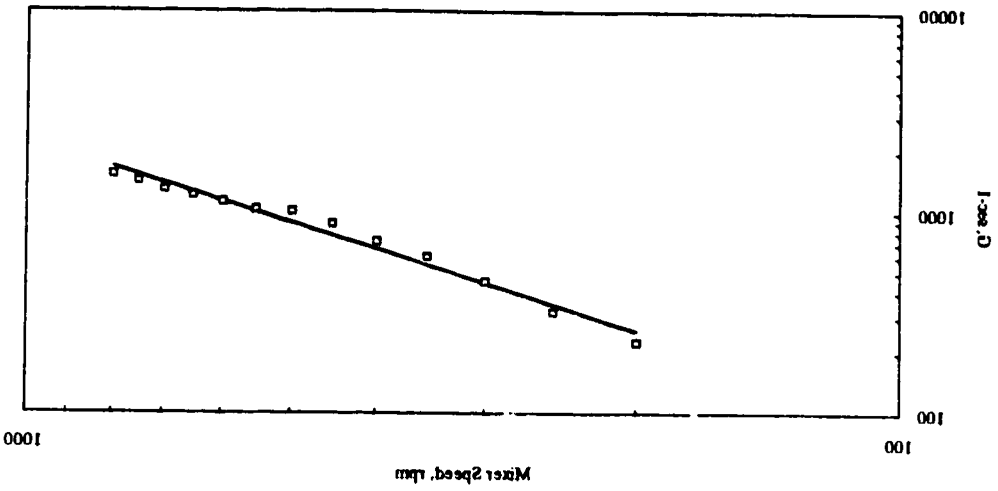
Filter Influnet Quality Data during August, 1993

date	pH		Turbidity, NTU		Total H, mg/L		Ca H, mg/L		Alk., mg/L		Color, TCU		Chloride, mg/L		Fluoride, mg/L	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
1	8.83	8.33	4.5	3.1	112	106	70	58	56	52	2	1.5	2.5	2.5	0.95	0.91
2	8.97	8.33	4.3	3.6	112	106	70	66	64	50	2	1.5	2.5	2.5	0.97	0.91
3	8.86	8.66	4.8	3.7	112	106	68	62	57	52	1.5	1.5	2.5	2.5	0.98	0.92
4	8.8	8.43	5.4	2.7	118	104	70	64	58	54	1.5	1	2.5	2.5	0.94	0.93
5	8.85	8.37	3	1.6	114	108	70	66	66	60	1	1	2.5	2.5	0.94	0.91
6	8.81	8.39	2.3	1.7	112	106	68	64	62	56	1	1	2.5	2.5	0.89	0.89
7	8.72	8.56	2	1.4	110	106	68	64	64	60	1.5	1	2.5	2.5	0.93	0.89
8	8.86	8.68	1.7	1.1	106	104	66	62	60	56	1.5	1	2.5	2.5	0.93	0.9
9	8.82	8.25	2	1.4	110	104	66	64	62	58	2	1	2.5	2.5	0.92	0.9
10	8.76	8.35	2.4	1.9	110	104	66	62	62	60	1.5	1	2.5	2.5	0.93	0.91
11	8.98	8.13	3.1	1.6	120	108	74	62	76	64	1.5	1	2.5	2.5	1.04	0.89
12	8.86	8.7	1.5	0.7	116	110	68	64	72	62	2	1	2.5	2.5	0.93	0.91
13	8.82	8.62	3.1	2.4	114	104	66	64	68	62	1.5	1	2.5	2.5	0.96	0.91
14	8.84	8.7	3.1	2.4	108	106	66	64	68	64	1.5	1	2.5	2.5	N/A	N/A
15	8.8	8.62	2.7	1.8	110	106	66	62	66	64	1.5	1	2.45	2.45	N/A	N/A
16	8.99	8.37	2.2	0.3	112	108	68	64	72	64	3	1.5	2.5	2.5	0.94	0.93
17	8.94	8.32	2.7	1.7	110	102	66	62	68	62	2.5	1	2.5	2.5	0.96	0.89
18	8.87	8.63	2.2	1.5	112	108	66	62	66	64	2	1.5	2.5	2.5	0.93	0.91
19	8.81	8.2	2.5	1.7	118	102	74	68	76	66	1.5	1	3.1	2.5	0.99	0.91
20	8.93	8.51	3.2	1.3	114	102	68	64	66	62	1.5	1	2.7	2.5	0.96	0.82
21	8.63	8.54	3.4	1.4	110	104	68	64	60	56	1	1	2.65	2.65	0.95	0.92
22	8.88	8.6	2.4	1.5	108	102	68	60	60	58	2.5	1.5	2.6	2.5	0.97	0.94
23	8.85	7.64	2.1	1.8	112	106	68	62	60	56	2	1	2.5	2.5	0.95	0.92
24	8.71	8.43	2.1	1.3	112	106	65	62	64	62	1.5	1	2.5	2.5	0.97	0.97
25	8.78	8.58	2	1.2	112	106	64	60	64	62	1.5	1	2.5	2.45	1.02	0.95
26	8.8	8.55	2.3	1.6	112	102	62	60	70	58	1.5	1	2.45	2.4	0.98	0.91
27	8.72	8.52	1.5	0.5	114	105	70	66	70	60	1	1	2.4	2.4	0.98	0.88
ave	8.64		2.2		109		65		62		1.4		2.51		0.93	

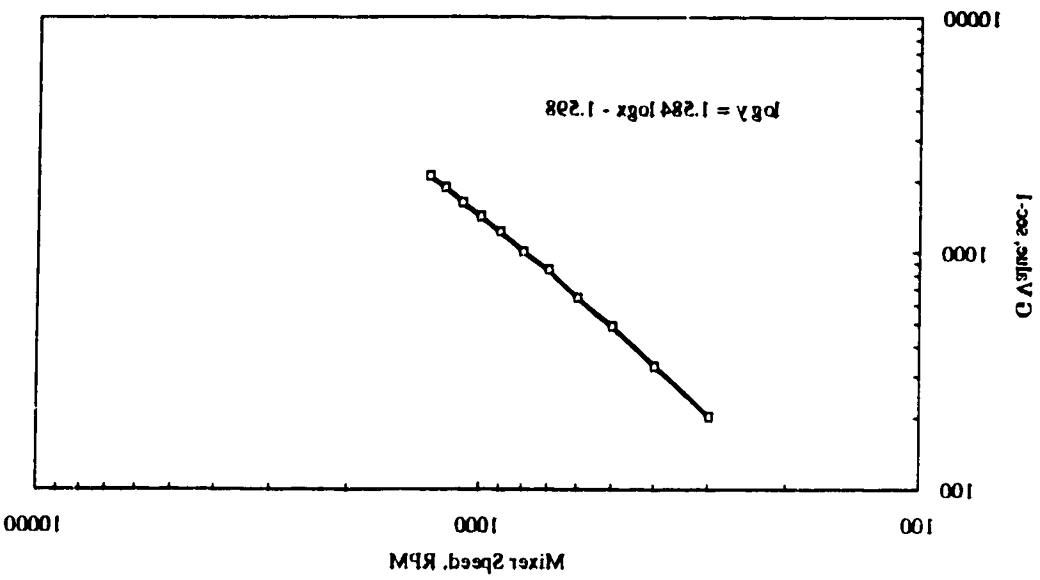
Filter Influnet Quality Data during July, 1993

date	pH		Turbidity, NTU		Total H, mg/L		Ca H, mg/L		Alk., mg/L		Color, TCU		Chloride, mg/L		Fluoride, mg/L	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
10	8.76	8.57	4.9	3.7	110	102	74	62	56	54	1.5	1	2.6	2.5	0.96	0.91
11	8.76	8.5	4.3	3	110	104	66	64	58	54	1.5	1	2.5	2.5	0.97	0.91
12	8.77	8.55	4.4	3.2	110	106	68	64	60	56	1.5	1	2.6	2.5	0.97	0.92
13	8.71	8.57	4.1	3.2	120	108	68	64	66	60	2	1.5	2.5	2.5	0.97	0.93
14	8.86	8.22	6.2	3.4	116	106	66	60	60	58	2	1	2.5	2.5	0.95	0.92
15	8.85	8.02	6.4	3.6	110	104	66	60	56	54	1	1	2.5	2.4	0.94	0.9
16	8.83	8.52	4.3	3.3	114	106	70	64	66	58	1	1	2.45	2.4	0.94	0.91
17	8.9	8.52	3.4	3	114	106	68	62	70	64	1	1	2.4	2.4	0.94	0.9
18	8.72	8.28	3.3	2.2	112	106	70	64	66	64	1.5	1	2.4	2.4	0.96	0.93
19	8.72	8.37	3.4	2.5	110	104	68	60	66	56	1	1	2.4	2.4	0.98	0.93
20	8.83	8.2	4.3	2.3	110	104	68	68	66	62	1.5	1	2.45	2.45	0.95	0.89
21	8.41	8.31	3	2.3	110	106	66	62	64	60	1.5	1	2.65	2.45	0.99	0.92
22	8.66	8.44	3.5	2.3	110	104	66	60	64	60	1	1	2.65	2.45	0.98	0.93
23	8.71	8.41	6	3	112	104	70	62	66	62	2	1	2.55	2.55	0.99	0.93
24	8.91	8.48	5.1	3.2	108	106	77	66	66	52	3.5	2	2.55	2.55	0.97	0.94
25	8.89	7.85	4.1	3.1	106	102	70	62	52	44	2.5	2	2.55	2.55	1.01	0.94
26	8.86	8.35	4	3.3	112	106	71	66	48	48	2.5	2	2.55	2.45	0.99	0.97
27	8.98	8.6	3.8	2.9	114	102	70	66	50	38	2.5	1	2.55	2.45	0.98	0.96
28	8.9	8.4	3.9	3.2	114	110	72	68	48	46	3.5	1	2.6	2.6	0.99	0.94
29	8.89	8.65	5.1	3.8	112	108	68	62	50	40	2	1.5	2.6	2.6	0.99	0.95
30	8.93	8.76	5.1	3.2	112	102	68	62	48	42	2	1.5	2.6	2.6	1.02	0.96
31	8.74	8.49	3.9	2.9	110	104	68	56	52	44	2	15	2.55	2.55	1.01	0.92
Ave	8.61		3.7		108		66		56		1.8		2.51		0.951	

Mixing Intensity "G" Value Calibration Curve for Satandard Jar



Mixing Intensity "G" Value Calibration Curve for Polymer Mixing Tank



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Stage 3 Flow Rate Data

Batch	Run	Time, day			
		0	1	2	3
OA	1	5.3	4.9	4	3.3
	2	5.3	4.8	3.8	3.4
	3	5.3	4.7	3.8	3.2
OB	1	5.3	5	4.2	3.5
	2	5.3	4.8	4	3.3
	3	5.3	5	4.2	3.2
OC	1	5.3	5	4	3.2
	2	5.3	5	4	2.8
	3	5.3	4.9	4	2.8
OD	1	5.3	4.8	4	3.2
	2	5.3	4.9	4	3.2

Stage 2 Flow Rate Data

Batch	Run	Time, day			
		0	1	2	3
SA	1	5.3	5.3	4.8	4.6
	2	5.4	5.4	4.6	3.3
	3	5.3	0.5	0.4	0.3
SB	1	15	13.6	13.4	11.7
	2	15	1.1	0.8	0
	3	15	13.6	13.3	11.1
SC	1	5.3	5.2	4.8	4.1
	2	5.3	5.2	4.7	3.9
	3	5.3	5	4.5	3.7
SD	1	15	14.5	13.4	12.5
	2	15	14	12.9	11.5
	3	15	11.1	6.2	3.7
SE	1	15	15	14.5	13.4
	2	15	1.4	1.1	0
	3	15	14.3	11.5	3.9

Stage 1 Flow Rate Data

Batch	Run	Time, day			
		0	1	2	3
PA	1	6.5	6.3	4.5	3.2
	2	4.4	4	3.3	2.8
	3	2.5	2.4	2.3	2.2
PB	1	5.3	4.8	3.7	3
	2	3.6	3.5	3.2	2.7

APPENDIX E SUMMARY OF FLOW RATE DATA

Date: 23-09-1993
Folw Rate: 15 m/h
Dose: 0.01 mg/L Cat-Floc T2

OD1: 400 sec^{-1}

Time	Port #				
day	1	2	3	4	5
0	20.46	19.82	19.33	17.82	15.7
1	20.48	17.83	17.04	15.06	12.62
2	20.54	15.53	14.52	12.03	9.38
3	20.62	13.37	12.14	9.7	5.77

OD2: 100 sec^{-1}

Time	Port #				
day	1	2	3	4	5
0	20.53	19.72	19.33	18	15.43
1	20.56	17.63	16.88	15.18	12.27
2	20.59	15.18	14.18	12.13	8.7
3	20.57	13.35	12.08	9.17	6.14

Date: 13-09-1993
Folw Rate: 15 m/h
Dose: 0.01 mg/L Cat-Floc T2

OC1: 700 sec^{-1}

Time	Pont #				
day	1	2	3	4	5
0	20.52	19.72	19.2	17.33	15.35
1	20.53	17.68	16.83	14.85	12.24
2	20.56	15.44	14.28	11.75	8.64
3	20.62	13.8	12.61	10.18	7.35

OC2: 1100 sec^{-1}

Time	Pont #				
day	1	2	3	4	5
0	20.54	19.78	19.26	17.88	15.34
1	20.56	17.77	16.98	15.1	12.34
2	20.6	15.46	14.3	11.88	8.63
3	20.62	13.56	12.42	10.13	7.25

OC3: 300 sec^{-1}

Time	Pont #				
day	1	2	3	4	5
0	20.59	19.95	19.46	17.96	15.75
1	20.6	18.13	17.33	15.4	12.86
2	20.62	16.06	14.97	12.44	9.52
3	20.63	13.9	12.58	9.72	6.52

Date: 10-09-1993
Folw Rate: 15 m/h
Mixing: 700 sec^{-1}

OB1: 0.003 mg/L Cat-Floc T2

Time	Port #				
day	1	2	3	4	5
0	20.56	19.82	19.29	17.77	15.33
1	20.57	17.87	17.02	14.92	12.43
2	20.58	16.24	14.98	12.25	9.18
3	20.59	14.74	13.3	10.44	7.5

OB2: 0.07 mg/L Cat-Floc T2

Time	Port #				
day	1	2	3	4	5
0	20.54	19.82	19.24	17.8	15.68
1	20.56	17.97	17.03	15.04	12.78
2	20.58	16.34	15.03	12.45	9.62
3	20.58	14.57	12.84	9.78	6.56

OB3: 0.01 mg/L Cat-Floc T2

Time	Port #				
day	1	2	3	4	5
0	20.58	19.94	19.4	16.82	15.57
1	20.59	18.13	17.25	14.88	12.82
2	20.61	16.24	15.02	12.26	9.48
3	20.62	14.53	12.77	9.58	6.3

Date: 07-09-1993
Folw Rate: 15 m/h
Mixing: 700 sec^{-1}

OA1: 0.005 mg/L Cat-Floc T2

Time	Port #				
day	1	2	3	4	5
0	20.57	19.84	19.18	17.82	15.15
1	20.58	17.68	16.71	15.18	12.63
2	20.61	15.47	14.16	12.09	8.85
3	20.62	13.63	12	9.48	5.72

OA2: 0.01 mg/L Cat-Floc T2

Time	Port #				
day	1	2	3	4	5
0	20.53	19.78	19.23	18.03	16.07
1	20.56	17.92	17.03	15.34	13.24
2	20.58	16.17	14.82	12.53	9.93
3	20.57	14.63	13.02	10.35	7.3

OA3: 0.02 mg/L Cat-Floc T2

Time	Port #				
day	1	2	3	4	5
0	20.56	19.77	19.13	17.46	14.98
1	20.56	17.38	16.37	14.26	11.7
2	20.57	15.38	13.87	11.16	8.13
3	20.58	13.66	11.92	9.05	6.13

Date: 30-07-1993
Folw Rate: 15 m/h
Mixing: 700 sec^{-1}

SE1: No polymer

Time	Port #				
day	1	2	3	4	5
0	20.58	20.07	19.65	17.34	16.37
1	20.58	19.63	19.15	16.95	15.77
2	20.57	19.62	19.14	16.87	14.8
3	20.6	18.73	17.97	15.68	13.65

SE2: 0.03 mg/L PERCOL LT27

Time	Port #				
day	1	2	3	4	5
0	20.54	19.58	19.18	18.12	16.16
1	20.65	6.85	6.8	6.75	6.67
2	20.66	6.48	6.45	6.43	6.35
3	20.67	6.3	6.27	6.25	6.22

SE3: 0.03 mg/L PERCOL LT20

Time	Port #				
day	1	2	3	4	5
0	20.53	19.97	19.57	18.85	15.76
1	20.56	17.48	16.98	16.17	14.03
2	[illegible]	13.8	13.35	12.75	12.57
3	20.63	9.73	9.52	9.3	8.87