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NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 02/14/90
Original Closeout Started ********

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Project Director AMIRTHARAJAH A________ School/Lab CE________
Sponsor MARIETTA WATER AUTH - COBB/________
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February 5, 1990

Dr. Philip Karr  
General Manager  
Cobb County-Marietta Water Authority  
1660 Barnes Mill Road  
Marietta, GA 30062

Dear Phil:

I am herewith enclosing three copies of the final report on the above project. The report is titled "Characteristics and Modelling of Particle Size Distribution in Water Filtration". As indicated to you last year, the preparation of the final report was somewhat delayed due to my travels to Brazil and London during the summer and fall of 1989.

The research discussed in the report will have wide dissemination during this year. Three papers, as indicated below, are to be presented at premier national and international conferences. The dates and titles of these presentations are noted below.


I am delighted that Tom's work has been recognized by the paper selection committees of these three conferences.
In terms of relevance to, and improvement of, plant operations at the Wyckoff Water Treatment Plant, our research has demonstrated the feasibility of using Particle Size Distributions for operational control. I believe that this may become increasingly important as more stringent drinking water regulations are promulgated.

Tom Ginn and I would like to express our great appreciation to the Cobb County-Marietta Water Authority and you for supporting our research. If you need further information or additional copies of the report, please let me know.

Yours sincerely,

A. Amirtharajah
Professor

AA/hb

Enclosure

cc:  Tom Ginn, Jr.
     T. Fennell, CE
     B. Lindberg, OCA
     Reports Coordinator, OCA
RESEARCH REPORT

CHARACTERIZATION AND MODELLING
OF PARTICLE SIZE DISTRIBUTIONS
IN WATER FILTRATION

by

Thomas M. Ginn, Jr.

CHEM HILL
220 Paschale St., N.E.
Suite 300 - Cain Tower
Atlanta, GA 30303

and

Appiah Antiharajah

School of Civil Engineering
Georgia Institute of Technology
Atlanta, GA 30332

submitted to

Dr. Philip Karl
General Manager
Cobb County-Marietta Water Authority

January 1990
RESEARCH REPORT

Characterization and Modelling of Particle Size Distributions in Water Filtration

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Dr. Philip Karr
General Manager
Cobb County-Marietta Water Authority

January 1990
ACKNOWLEDGEMENTS

This report was prepared by the senior author, Thomas M. Ginn, Jr. as a special research problem and presented to the Faculty of the School of Civil Engineering, Georgia Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering. The research was supervised by Dr. Appiah Amirtharajah, Professor of Civil Engineering. The report has been reviewed by Dr. E. S. K. Chian, Professor and Dr. E. A. Voudrias, Assistant Professor of the School of Civil Engineering at Georgia Institute of Technology.

The research was completed with support provided by Cobb County-Marietta Water Authority under Grant No. E-20-829. The authors would like to thank Dr. Philip Karr, General Manager and Sandeep Shrivastava, Process Engineer of the Cobb County-Marietta Water Authority for their support and the staff and plant operators of the Hugh A. Wyckoff Water Treatment Plant for their assistance throughout the duration of the study.
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ABSTRACT

The Brinkmann 2010 Particle Size Analyzer, a laser-type particle size analyzer, was used to characterize the raw, settled, and filtered water particle size distributions from the treatment train of the Hugh A. Wyckoff Water Treatment Plant of the Cobb County-Marietta Water Authority. The general particle size distribution trends through the conventional treatment steps were characterized and a pilot plant at the Wyckoff facility was used to characterize the particle size distributions in the direct filtration mode of operation.

The data obtained from the Brinkmann 2010 Particle Size Analyzer showed that the particle size distributions were shifting into larger size ranges as a result of the filtration step in both the conventional treatment and direct filtration modes of operation. This trend was used in the formulation of a conceptual filtration model for the prediction of particle size distribution changes through dual media filters.

At present, there is no widely accepted fundamental filtration theory for the prediction of particle size distributions through a granular media filter. The conceptual model includes both the attachment of particles to the filter grains and the detachment of accumulated material from the filter grains. The model is similar in form to present day trajectory theories.
that are based on fundamental considerations of attachment mechanisms. Similar fundamental considerations of detachment mechanisms can easily be incorporated into the proposed filtration model. The particle size data generated in this study was analyzed with some success using the basic form of the proposed filtration equation.
1. INTRODUCTION

1.1 Scope of This Project

This project involved using a modern, laser-type particle size analyzer to measure the particle size distribution changes through granular media filters used in treating potable water. Such particle size data is expected to be much more useful than traditional turbidity measurements in characterizing the performance of granular media filters. The Brinkmann 2010 Particle Size Analyzer was used in characterizing the raw, settled, and filtered water particle size distributions from the treatment train of the Hugh A. Wyckoff Water Treatment Plant of the Cobb County-Marietta Water Authority. The Wyckoff Water Treatment Plant is located northwest of Marietta, Georgia, near the town of Acworth. The lower detection limit for this instrument is 0.6 μm and the upper limit 60 to 150 μm, depending upon the desired resolution. Particle size distribution trends through the conventional treatment steps were characterized and a pilot plant at the Wyckoff facility was used to characterize particle size distributions in the direct filtration mode of operation.

The data obtained were used in the formulation of a conceptual filtration model for the prediction of particle size distribution changes through dual media filters. At present,
there is no widely accepted fundamental filtration model for the prediction of particle size distributions through a granular media filter. A literature review of particle detachment and filter pore flocculation indicated that a shift in the particle size distribution through conventional alum coagulation treatment filters could only be the result of particle detachment from the filter grains.

The literature review and the initial experimental particle size distribution data led to the formulation of a conceptual filtration model incorporating particle attachment and detachment as well as the phenomenon of "wormhole" flow in the filter bed. The proposed filtration equation, similar to those of Iwasaki¹ and Ives², has incorporated particle attachment and detachment in a form compatible with the present trajectory theories also being developed from fundamental considerations. Compatibility with present trajectory theories is this model's advantage over models having differing forms such as those presented by Mintz³ and Adin and Rebhun.⁴

The use of the Brinkmann Particle Size Analyzer to characterize the raw, settled, and filtered waters of the Wyckoff conventional water treatment plant and a pilot scale filter system quickly provided enormous amounts of particle size distribution data. The use of computerized spreadsheets and plotting programs to rapidly and repetitiously manipulate the data allowed the data to be represented by the use of simple
best fit coefficients which describe the shape of the particle size distributions.

1.2 Background of Turbidity and Particle Size Measurements

Sand filtration has long been used as a process for clarifying public water supplies. In 1892, when the city of Altona, Germany, was protected from a cholera epidemic which spread through neighboring Hamburg's water supply, sand filtration was recognized as a process which provided protection against microbial waterborne diseases.\(^5\)

Historically, the turbidity measurement has been used to measure the quality of potable water and the performance of granular media filters. Turbidity is a measure only of the clarity of the water. Turbidity was originally measured using the Jackson Candle Turbidimeter.\(^6\) This simple device measured the depth of a column of water necessary to completely block the light from a candle flame located at the bottom of the water column. Modern turbidity measurements are based on light scattering and/or absorbance using electric light sources.\(^6\)

In 1987 the Environmental Protection Agency proposed to lower the Maximum Contaminant Level (MCL) from 1 Nephelometric Turbidity Unit (NTU) to 0.5 NTU for filtered water supplies on the basis of health concerns. Prior to that, the Safe Drinking Water Act of 1986 set a MCL Goal of 0.1 NTU for filtered water
supplies. A MCL Goal is not an enforceable standard but is
considered to be a level at which there are no impacts on
public health and for which every utility should strive to
meet.

As the MCL for turbidity has decreased, and as particle size
measurement technologies have advanced, researchers have begun
to turn toward the use of particle counting and particle size
distribution (PSD) measurements as water quality parameters.
The main advantage of PSD measurements is that information
becomes available which describes not only the amount of
particulate matter in the water, but also the sizes of the
particles. This data has proven to be valuable in optimization
of the operation of each process step in water treatment
trains. Many researchers and water utilities are
recognizing particle counting as an excellent parameter for
evaluating and controlling filter performance, especially at
low turbidity levels.

During the past few years, many different technologies for the
measurement of particle size distributions in water have been
developed. Some utilize the Coulter Counter principle of
measuring changes in electrical resistance as the particles
pass through an aperture. Others utilize laser light
scattering, light obscuration, and laser light blockage
principles. Typical lower detection limits for many of these
instruments range from 1 to 0.3 μm. A recent test was
performed to compare five different technologies of particle size measurements. A single water sample was split into five fractions which were analyzed by different researchers in different parts of the country using different particle size analyzers. In the measurement of the raw water split sample, these technologies varied both in the total numbers of particles counted, some by orders of magnitude, and also in the shape of the size distributions measured. Some, but not all, of the inconsistencies in the measurements were attributable to differences in the lower limit of the detection range of each instrument.\textsuperscript{15}

The older technologies are generally cumbersome and time consuming. One of the most widely accepted methods, the Coulter principle, requires that the particles be suspended in an electrolytic solution and diluted to ensure that only a single particle at a time passes through the measurement aperture. This aperture may also cause problems with floc breakage due to high velocity gradients in the flow field around the aperture. One of the newer technologies, laser light blockage, is used in the Brinkmann 2010 Particle Size Analyzer and has the advantages of not requiring any special sample preparation and of having an open (1 cm. x 1 cm. x 3 cm.) measurement chamber to reduce floc breakage problems.
2. GRANULAR MEDIA FILTRATION THEORY

2.1 History of Phenomenological Theories

In 1937, Iwasaki proposed a first-order partial differential equation to describe filtration as a function of filter depth:

\[
\frac{\partial C}{\partial z} = -\lambda C
\]  

(1)

where \( C \) = concentration \([\text{mass/volume, volume/volume, turbidity, etc.}]
\)

\( z \) = media depth \([\text{length}]
\)

\( \lambda \) = filter coefficient \([\text{length}^{-1}]
\)

The equation is a partial differential because the time is a variable also. To solve the equation, instantaneous time is used. When integrated over the depth of the filter bed, the equation becomes:

\[
\frac{C}{C_0} = e^{-\lambda z}
\]

(2)

This equation states that the effluent concentration is directly proportional to the influent concentration and exponentially proportional to the depth of the filter bed. Iwasaki recognized that the filter coefficient was a function of time and that it would decrease during the length of the filter run.
Over the next few decades, filtration theory progressed slowly and by the 1960's two distinctly different views of the mechanisms responsible for the variation of the filtration coefficient developed. One group, led by K. Ives in London, maintained that the decrease in the filter coefficient leading to filter breakthrough was the result of increasing deposits in the filter causing constrictions in the tubular pores. The resulting changes in pore geometry and interstitial velocities caused the filter coefficient to decrease. The other group, led by D. Mintz in Moscow, maintained that the decrease in the filter coefficient leading to breakthrough was the result of the scouring of previously deposited particles from the filter grains and that the rate of deposition remained relatively constant throughout the filter run. Each group presented numerous experimental data to support its viewpoint.\textsuperscript{15}

Ives\textsuperscript{2} model has the same form as Iwasaki's\textsuperscript{1} first order partial differential equation (Equation 1). Ives\textsuperscript{2} modified the filter coefficient term to account for the increase in the removal efficiency during the initial stages of filtration, filter ripening, and for the subsequent decrease in removal efficiency leading to breakthrough. His model has the form:

\[
\frac{C}{C_0} = e^{-\left(\lambda_0 + c \sigma - \frac{\phi \sigma^2}{f - \sigma}\right)z}
\]

where \(C = \text{concentration [mass/volume, volume/volume,}\
\]

\textit{7}
turbidity, etc.]
z = media depth [length]
\( \lambda_o \) = filter coefficient [length\(^{-1}\)]
c = filter coefficient constant [length\(^{-1}\)]
\( \sigma \) = specific deposit [vol. solids/unit vol. bed]
\( \phi \) = second filter coefficient constant [length\(^{-1}\)]
f = clean media porosity [volume/volume]

The second term, \( c \sigma \), represents a linear increase in the filter coefficient during the filter ripening period as a result of increased surface area due to deposits acting as filter grains. The third term accounts for the decrease in the filter coefficient during constant rate filtration as a result of the increasing interstitial velocities caused by deposits. Fox and Cleasby\textsuperscript{17} gathered experimental evidence which suggested that, under normal conventional treatment operations, the alum and ferric flocs that are produced are not adequately modelled by Ives' formula. They concluded that the model's inadequacy was in the third term accounting for the clogging process.

Mintz\textsuperscript{3} model, accounting for both attachment and detachment, is a partial differential equation of the form:

\[
\frac{\partial C}{\partial z} = - \left( \lambda_o C - \frac{a \sigma}{u} \right)
\]

where \( C \) = concentration [mass/volume, volume/volume, turbidity, etc.]
z = media depth [length]
\( \lambda \) = filter coefficient [length\(^{-1}\)]
a = scour coefficient [length/time]
\[ \sigma = \text{specific deposit [vol. solids/unit vol. bed]} \]
\[ u = \text{approach velocity [length/time]} \]

It should be noted that this partial differential equation has a different form than those of Iwasaki and Ives. Solving for \( \frac{C}{C_0} \) leads to an infinite series solution. The first term, \( \lambda_0 C \), is the attachment term, and remains constant regardless of the amount of deposits in the filter. The second term, \( a\sigma/u \), is the detachment term and, for constant rate filtration, increases as the specific deposits increase.

In the late 1970's, Adin and Rebhun formulated another phenomenological model for deep-bed filtration, also incorporating attachment and detachment mechanisms. This model is different from the previous models in that it is written in terms of a change in specific deposit with time rather than a change in concentration with depth:

\[
\frac{\delta \sigma}{\delta t} = k_1 v C (F - \sigma) - k_2 \sigma J \tag{5}
\]

where
\[
\begin{align*}
\sigma & = \text{specific deposit [mass solids/unit vol. bed]} \\
\tau & = \text{filtration time [time]} \\
v & = \text{approach velocity [length/time]} \\
C & = \text{concentration [mass/volume]} \\
F & = \text{theoretical filter capacity [mass solids/unit vol. bed]} \\
J & = \text{hydraulic gradient [length/length]} \\
k_1 & = \text{attachment coefficient} \\
k_2 & = \text{detachment coefficient}
\end{align*}
\]

The hydraulic gradient and the theoretical filter capacity are
found from Darcy's law and the porosity of the filter.

The advantage of the models presented by Iwasaki¹ and Ives² is their relationship to the present form of trajectory theories that are being developed.¹⁸ Trajectory theories view the filter bed as a group of collectors. Deposition on these collectors is defined by the flow field around them and the magnitude of the forces responsible for the attachment of a particle to the surface of the collector. It is usually considered that the forces responsible for particle-grain attachment are diffusion, sedimentation, and interception.¹⁸,¹⁹

By calculating the magnitude of these forces and the distances over which they are considered to operate, a criteria for particle-grain attachment based on the critical path of a particle flowing past the collector may be formulated. The ratio of the number of particles attaching to the collector surface, those within the critical path, to the total number particles flowing past the collector is defined as the single-collector efficiency, $\eta$.¹⁸,¹⁹

Expressions for the single collector efficiency as a function of a single transport mechanism may be calculated from fundamental knowledge of that transport mechanism. Single collector efficiencies for diffusion, sedimentation, and interception transport mechanisms have been developed and are given as the following equations:¹⁸,¹⁹
Diffusion:

\[ \eta_D = 0.9 \left( \frac{k \, T}{\mu \, d_p \, d_c \, U} \right)^{2/3} \]  

where \( \eta_D \) = single collector efficiency for diffusion transport mechanism [ratio]
\( k \) = Boltzmann's constant [mass*length\(^2\)/time\(^2\)*deg kelvin]
\( T \) = absolute temperature [degree kelvin]
\( \mu \) = absolute viscosity [force*time/length\(^2\)]
\( d_p \) = particle diameter [length]
\( d_c \) = collector diameter [length]
\( U \) = velocity [length/time]

Sedimentation:

\[ \eta_G = 0.9 \left( \frac{(\rho_p - \rho) \, g \, d_p^2}{18 \, \mu \, U} \right) \]  

where \( \eta_G \) = single collector efficiency for sedimentation transport mechanism [ratio]
\( \rho_p \) = density of particle [mass/volume]
\( \rho \) = density of water [mass/volume]
\( g \) = acceleration due to gravity [length/time\(^2\)]
\( d_p \) = particle diameter [length]
\( \mu \) = absolute viscosity [force*time/length\(^2\)]
\( U \) = velocity [length/time]

Interception:

\[ \eta_I = 1.5 \left( \frac{d_p}{d_c} \right)^2 \]  

where \( \eta_I \) = single collector efficiency for interception transport mechanism [ratio]
\( d_p \) = particle diameter [length]
\( d_c \) = collector diameter [length]
The sum of these three single collector efficiency expressions are assumed to be equal to the total collector removal efficiency, $\eta_o$. The resulting filtration equation based on trajectory analysis is a differential equation of the form:\textsuperscript{18,19}

$$\frac{dC}{dz} = -1.5 \left( \frac{1 - \xi}{d_c} \right) \alpha \eta_o C$$

(9)

where $C = \text{concentration [mass/volume]}$
$z = \text{media depth [length]}$
$\xi = \text{porosity of filter bed [volume/volume]}$
$d_c = \text{filter collector grain diameter [length]}$
$\alpha = \text{collision efficiency factor [ratio]}$
$\eta_o = \eta_0 + \eta_a + \eta_i = \text{total collector removal efficiency [ratio]}$

A comparison of this equation with that of Iwasaki\textsuperscript{1} (Equation 1) shows that the single-collector efficiency, $\eta$, when integrated over the depth of the filter bed, is directly proportional to the phenomenological filter coefficient, $\lambda$, by the following relationship:\textsuperscript{18}

$$\lambda = 1.5 \left( \frac{1 - \xi}{d_c} \right) \alpha \eta_o$$

(10)

where $\lambda = \text{filter coefficient [length}^{-1}])$
$\xi = \text{porosity of filter bed [volume/volume]}$
$d_c = \text{filter collector grain diameter [length]}$
$\alpha = \text{collision efficiency factor [ratio]}$
$\eta_o = \eta_0 + \eta_a + \eta_i = \text{total collector removal efficiency [ratio]}$
This is the advantage of the empirically derived Iwasaki and Ives filtration models: their form is directly proportional to present day trajectory theories which are based on theoretical considerations. One of the major disadvantages of trajectory theories at present is that they only apply to clean beds; they do not account for changes in the single-collector efficiency due to the role of previously retained material.

2.2 Visual Evidence for Detachment and Wormholes

In the Mintz-Ives Controversy, evidence, both visual and experimental with sophisticated methods such as radioactive labelling, was presented both for and against the mechanism of detachment. The most compelling evidence cited against detachment was work done by D. R. Stanley at Harvard in 1955. Stanley, using radioactively labelled floc particles, was able to measure the gamma emission distribution as a function of filter depth and plot deposit distribution curves. After 2.5 hours of filtration, the floc suspension was changed to an unlabelled suspension. The gamma emission distribution as a function of the filter bed depth, and therefore the position of the deposits, did not change. The most compelling evidence cited for detachment was that of a film presented by Mintz et al which showed visually larger particles leaving a filter than those entering the filter.
Payatakes et al.\textsuperscript{22} set up a glass plate "cross section" of a granular media deep bed filter (i.e. a vertical "slice" of a filter) and visually recorded the filtration mechanisms using a microscope and video recorder. They found that, even using polymers, detachment of the 2 \( \mu \)m latex particles occurred. They also found that clogging was often due to the sudden blockage of a constricted passage by a reentrained particle and that such blockages sometimes caused a local reversal of flow in an upward direction.

Ives and Clough\textsuperscript{23}, using fiber optics, were able to visually observe events within the filter to demonstrate deposition and reentrainment. Using clay suspensions, they observed dome deposits on top of the grains and detachment of these deposits. The detachment phenomena appeared to be related to instabilities caused by arriving particles and "avalanches".

In 1987, Baumann and Ives published a paper entitled "The Evidence for Wormholes in Deep Bed Filters".\textsuperscript{24} In this paper, they cited evidence from 7 authors dating back to 1937 indicating that some channels in a clogged filter bed remain open and carry the majority of the flow in the filter. Figure 1 shows a section view of the "wormhole" concept. Presently there is no conclusive evidence that these "wormholes" extend in an unbroken channel from the top of the bed to the bottom. Such flow channels, because of their high pore velocities, would not allow for particle deposition and could carry
Figure 1  Wormhole Flow Channels (from Baumann and Ives\textsuperscript{24} after Baylis\textsuperscript{25})
particulate matter rapidly through the filter bed.\textsuperscript{24}

2.3 Filter Pore Flocculation

Two mechanisms could possibly result in increases in the size distribution of the particles coming out of the filter: the detachment of deposits from filter grains and the flocculation of suspended particles while in the filter pores. In 1986, Graham\textsuperscript{26} attempted to quantify orthokinetic filter pore flocculation using a specific nonionic polymer-polymer system to substantially separate the effects of flocculation and filtration. He filtered suspensions of monodisperse porous silica microspheres using a bed of nonporous glass spheres and a specific polymer system to discourage filter-grain attachment. Using a Coulter Counter, he concluded that he was able to quantify filter pore flocculation based on changes of collision efficiency factors with fluid shear rates in the filter pores.

In 1988, Graham\textsuperscript{27} simulated filter pore flocculation in a clean filter bed with a computer model incorporating the clean bed single-collector capture efficiency and Smoluchowski's flocculation equation. His experimental filter system consisted of kaolin suspensions, cationic polymer, and nonporous glass sphere filter grains. He found that the single most important factor affecting filter pore flocculation was the magnitude of the particle collision efficiency factor.
Graham concluded that filter pore flocculation, while appreciable, was the least important of three removal mechanisms: particle-grain attachment, particle-particle attachment by previously retained particles, and filter pore flocculation. The resulting increase in particle removal due to filter pore flocculation was minor.

In Graham's work, only systems with polymers were addressed. In systems using inorganic coagulants, such as alum, alone, the results may be significantly different. First, an alum system might not achieve the same degree of charge neutralization that Graham obtained for his polymer systems. Secondly, the alum system almost surely would not have as high a collision efficiency factor as the "sticky" polymer system. Thirdly, the polymer system should have stronger particle-grain and particle-particle bonds than the alum system. These stronger bonds would cause less detachment and more pore flocculation tendencies in a polymer system. Therefore in an alum system with no polymer additions, the effects of filter pore flocculation can probably be ignored and any increases in particle sizes through the filter can be attributed entirely to detachment mechanisms.

2.4 Proposed Conceptual Filtration Model

The proposed conceptual filtration model attempts to incorporate the mechanisms of attachment, detachment, and
wormhole flow. The proposed filtration equation is such that the form is compatible with trajectory theories. Therefore, the proposed filtration equation has the same basic form as those of Iwasaki\(^1\) and Ives\(^2\), where the filter coefficient, \(\lambda\), is analogous to the single collector efficiency, \(\eta\).\(^{18}\) It is also reasonable to expect that the detachment mechanism can be represented in the same manner as the attachment mechanism. The sum of the attachment and detachment mechanisms is equal to the overall filter coefficient. The basic phenomenological model resembles Iwasaki's\(^1\) model, except that the filter coefficient will be split into an attachment and a detachment coefficient as follows:

\[
\frac{C}{C_0} = e^{- (\lambda_a + \lambda_d) z}
\]

where \(C\) = concentration [mass/volume, volume/volume, turbidity, etc.]
\(\lambda_a\) = filter coefficient of attachment [length\(^{-1}\)]
\(\lambda_d\) = filter coefficient of detachment [length\(^{-1}\)]
\(z\) = media depth [length]

The attachment coefficient is conceptually similar to Iwasaki's\(^1\) filter coefficient and may be formulated in terms of the single-collector efficiency from trajectory analysis. The similarity of this model to the trajectory analysis model (Equation 9) is an advantage over the models presented by Mintz\(^3\) and Adin and Rehun.\(^4\) The attachment coefficient is expected to vary during the length of the run, as in Ives'\(^2\)
Effective Filtration

Figure 2 Proposed Conceptual Filtration Model (see Table 1)
filtration model. The detachment coefficient is also expected to vary during the length of the run and to be dependent upon hydrodynamic forces (interstitial flowrate, fluid drag) and deposit morphology (quantity and structure of deposits, adhesive strength).

Figure 2 graphically demonstrates the conceptual filtration model by plotting hypothetical attachment and detachment filter coefficients as a function of filtration time. Although this study did not do so, an equation for the filter coefficient as a function of time could be developed once enough fundamental considerations are incorporated into the model. The filter coefficients may also be plotted as a function of specific deposit, \( \sigma \), which tends to increase with time, but not linearly, until the ultimate specific deposit, \( \sigma_u \), of the filter bed is reached, at which time the filtering capacity of the bed is exhausted. The ultimate specific deposit value will be attained at the same time as the sum of the attachment and detachment filter coefficient becomes zero, assuming that the filter coefficients are measured based on particle volume concentrations in the influent and effluent of the filter. Further discussion of the mathematics of the filter coefficients may be found in Section 5.3, Filter Coefficient Analysis, Run 10.

The filter equation (Equation 11) is directly applicable to mono media filters. When applying the equation to a dual or
multi-media filter, the effluent from the top media layer may be used as the influent to the lower media layer. Simple substitution of the influent and effluent concentrations of each layer can then yield an equation for the entire media depth. The depths and filter coefficients for each layer can then be combined to apply the model to the entire multi-media filter. When applying the filtration equation in this manner, care must be taken to keep the individual media layer depths at the same ratio when comparing data from multiple filters.

Table 1 lists and describes the four possible phases of filtration. The first phase of flow is the "Filter Ripening" stage. As particles are deposited onto the filter grains and act as collectors, the attachment coefficient increases. At the beginning of the run, the filter media is assumed to be clean and without deposits, therefore the detachment coefficient is initially be equal to zero (i.e. no deposits, no detachments). As the deposits in the filter bed begin to accumulate, the detachment coefficient begins to increase in magnitude.

The second phase of flow is the "Effective Filtration" stage. Due to increasing interstitial flow velocities, the attachment coefficient begins to decrease, but is still high enough to remove many of the influent particles. With the increasing specific deposits in the filter and the increasing interstitial flow velocities, the detachment coefficient will increase in
<table>
<thead>
<tr>
<th>Region</th>
<th>Description</th>
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| 1      | "FILTER RIPENING"  
Increase in attachment due to increased collector area caused by previously retained particles.  
Increase in detachment (from zero) as deposits begin to form. |
| 2      | "EFFECTIVE FILTRATION"  
Decrease in attachment due to increasing interstitial flow velocities.  
Increase in detachment due to increases in interstitial flow velocities and avalanche effects. |
| 3      | "BREAKTHROUGH"  
Continued decrease in attachment due to increasing interstitial flow velocities caused by both clogging and increasing predominance of wormholes.  
Decrease in detachment due to the concentration of flow in wormholes where there is little deposition. |
| 4      | "WORMHOLE FLOW"  
Very little attachment or detachment due to flow concentration primarily in wormholes. |
magnitude more rapidly. Avalanche effects will become more pronounced as the quantity of deposits increase.

The third phase of flow is the "Breakthrough" stage. The attachment coefficient continues to decrease due to the clogging of pores causing increasing interstitial flow velocities. The concentration of flows in "wormhole" passages begins and causes an increasing fraction of the total flow to experience the higher interstitial flow velocities in the "wormhole" passages. The attachment coefficient decreases significantly in these "wormhole" passages. The detachment coefficient peaks in magnitude and begins to decrease toward zero due to the concentration of flows in the "wormhole" passages where there is little deposition occurring. During this stage of flow, the effluent turbidity begins to increase and turbidity breakthrough occurs.

Once "wormhole" flow has been established, the few remaining open flow channels have such high pore velocities that attachment, and therefore detachment, do not occur and both the attachment and detachment coefficients equal zero. After breakthrough has occurred and the filtering capacity of the bed is almost exhausted, the attachment and detachment filter coefficients are equal to each other and the overall filter coefficient is therefore equal to zero.

The incorporation of a detachment mechanism into the filtration
model does not change the overall predictions of filtration efficiency or predict phenomena that are not generally observed in experiments. However, it does better explain the particle size distribution changes observed in this study during conventional alum coagulation treatment and raises the possibility of the passage of destabilized particulate matter through well-operated deep-bed filters.
3. PARTICLE SIZE DISTRIBUTION

3.1 Theory

Although experimental work in past research has often used monodisperse size distributions, in reality continuous particle size distributions are usually the case in most waters. Technology has progressed to the point where it is possible with modern instruments to obtain continuous particle size distribution data on a sample in a matter of minutes if not seconds. Such data may be plotted on a cumulative concentration \((N)\) versus particle size \((dp)\) plot. The slope of the resulting curve is \(dN/d(dp)\) and may be defined as \(n(dp)\), the particle size distribution function for diameter, having units of \#/((volume\cdot length)), usually \#/((mL\cdot micron)). The concentration of particles \((N_{1-2})\) between two sizes, \((d_p)_1\) and \((d_p)_2\), could be written as the integral of \(dN\) from \((d_p)_1\) to \((d_p)_2\). If the right hand side of the integral is multiplied and divided by \(d\{\log(dp)\}\), then the resulting equation is:

\[
N_{1-2} = \int_{(d_p)_2}^{(d_p)_1} \frac{dN}{d\{\log(d_p)\}} \, d\{\log(d_p)\} \tag{12}
\]

The number distribution function, \(dN/d\{\log(d_p)\}\), may be calculated from concentration \((N)\) and particle size \((d_p)\) data.
by noting that \( \ln(x) = 2.3 \log(x) \) and \( d(\ln(x)) = dx/x \). Thus, 
\[
\begin{align*}
    d\log(d_p) & = d(\ln(d_p))/2.3 = d(d_p)/2.3 \cdot d_p \quad \text{and} \\
    \frac{dN}{d\log(d_p)} & = 2.3 \cdot d_p \cdot n(d_p)
\end{align*}
\]

(13)

Similar manipulations yield an equation for the particle volume distribution function as:
\[
\begin{align*}
    \frac{dV}{d\log(d_p)} & = \frac{2.3\pi}{6} \cdot (d_p)^4 \cdot n(d_p)
\end{align*}
\]

(14)

Experimentally the particle size distribution function, \( n(dp) \), has been found to often follow a power law function of the form
\[
    n(d_p) = A_\circ \cdot (d_p)^\beta
\]

(15)

where the \( A_\circ \) coefficient may be related to the total concentration of material in the system and the beta (\( \beta \)) coefficient may be related to the predominant transport process governing the particles in the system. By taking the log of both sides of the power law function, or by plotting the data on a log-log plot, and generating the best fit line through the data, the \( \beta \) value and the \( A_\circ \) coefficient can be determined.\(^8,^9,^28,^30\) Most natural water systems have measured beta (\( \beta \)) coefficients of 2 to 5 for particles above 1 micron (\( \mu \text{m} \)) in size.\(^29\) The relative value of the \( \beta \) coefficient for particle size distributions obtained under similar conditions indicates
the relative fractions of large and small particles: larger beta (\(\beta\)) values indicate proportionally more small particles while smaller beta (\(\beta\)) values indicate proportionally more large particles. This is conceptually shown in Figure 3. The \(A_0\) coefficient is related to the amount of material in the system. The larger the \(A_0\) coefficient, the greater total mass of particles in the system.

Hunt\(^{29}\), in his work with oceanic particle size distributions, assumed that at any given particle size range the particle size distribution would be dominated by a single coagulation mechanism. Hunt assumed that coagulation mechanisms consisted of Brownian coagulation, shear coagulation, differential sedimentation, and gravity settling. Brownian coagulation is caused by particle collisions which result from the natural Brownian diffusion motion of suspended particles and is temperature dependent. Shear coagulation is caused by particle collisions which result from velocity gradients due to mixing of the suspension. Differential sedimentation is caused by particle collisions which result when one particle which is settling due to gravity is overtaken by another particle which has a higher settling velocity. Gravity settling does not involve collisions between particles but rather the removal of particles from the suspended distribution by sedimentation.

Hunt\(^{29}\) did not include any electrostatic or hydrodynamic forces in the coagulation model. Therefore, his model does not
Figure 3  \( \beta \) Value as an Indicator of Particle Size
account for repulsion or attraction due to electrical charge or for hydraulic forces which resist the movement of water molecules between two approaching particle surfaces. By considering the basic collision function of each of the coagulation mechanisms mentioned above, Hunt was able to use dimensional analysis to define dimensionless groups for each of the coagulation mechanisms.

This procedure, along with the assumption that only a single coagulation mechanism is important in any given size range, resulted in the formulation of particle size distribution functions for the size regions dominated by the appropriate coagulation mechanism. These predicted particle size distribution functions were of the power law form previously discussed. For a particle size distribution created by the mechanism of Brownian motion, $\beta = 2.5$. Similarly the mechanism of shear gives $\beta = 4$, differential sedimentation gives $\beta = 4.5$, and gravity settling gives $\beta = 4.75$. By substituting $n(d_p)$ into the volume distribution equation in the respective regions dominated by each mechanism, a plot of the volume distribution versus $\log(d_p)$ should yield regions where the volume distribution has slopes of 1.5, 0, -0.5, and -0.75 for the Brownian, shear, differential sedimentation, and settling dominated regions, respectively.29

Pearson et al.31, using Monte Carlo simulation techniques to model a non-interacting particle size distribution, found
particle size distribution functions which agreed with those found by Hunt using dimensional analysis. However, Valioulis et al.\textsuperscript{32}, also using Monte Carlo simulation techniques but now including electrostatic and hydrodynamic forces in the model, suggested that the major assumption behind Hunt's reasoning, that for a given size range only one mechanism would dominate the particle size distribution, was valid only for the shear induced region. The Monte Carlo simulation results numerically suggested that a power law function form of the particle size distribution function would only occur in the shear induced coagulation region.

3.2 History of Particle Size Distribution Use in Water Treatment

Kavanaugh et al.\textsuperscript{9} used particle size distribution data in the selection of treatment processes for water treatment. At that time the lower detection limit for electrical sensing and light measuring methods was 1 μm. Kavanaugh pointed out that the $\beta$ value from the power law function used to characterize particle size distributions gives a rapid estimate of the distribution of the number, surface area, and volume of the distribution: $\beta = 1$, means equal numbers of particles across each logarithmic size interval; correspondingly $\beta = 3$ implies equal surface area and $\beta = 4$ indicates equal volume across each logarithmic size interval. Because of the information on particle size given by the $\beta$ value, Kavanaugh maintained that this measurement may be
used in choosing treatment processes, knowing which processes remove which sizes of particles.

Kavanaugh\(^9\) also pointed out that particle size distribution measurements were useful in evaluating predesign studies as well as plant scale processes. He quoted a Los Angeles Department of Water and Power study which used turbidity and particle size distribution measurements to evaluate flocculation experiments. The particle size distribution measurements showed that decreasing the velocity gradient from 175 sec\(^{-1}\) to 30 sec\(^{-1}\) caused the $\beta$ value to decrease from 3.1 to 2.1. This decrease in $\beta$ indicates that the particle size distribution shifted into larger size ranges, which was advantageous for the following sedimentation step. Since the turbidity measurement remained constant (2.4 TU) during the flocculation tests, this evaluation would not have been possible without particle size distribution measurements. This example illustrates one of the major advantages of particle size distribution measurements. During the same study, particle size distribution measurements also showed that a flocculation step prior to filtration could be bypassed without a statistically significant change in the particle size distribution of the filter effluent as measured by the $\beta$ value.

Kavanaugh\(^8\) also quoted direct filtration studies in which the particle concentration and size distribution began to change and increase hours before turbidity began increasing. The $\beta$
value of the effluent shifted from 2.5 to 3.5 during breakthrough.

In 1980 Lawler et al. developed mathematical models of the flocculation, sedimentation, and filtration treatment processes based upon the influent water characteristics and the plant design parameters. Lawler et al. used Smoluchowski's flocculation equation and sedimentation equations to develop particle size distribution models for the flocculation and sedimentation processes. For filtration, a model by O'Melia and Ali was used. The filtration model addressed only effluent solids concentration and headloss. Assuming a standard treatment system and a raw water $\beta$ value of 4.0, the model predicted a flocculated water $\beta$ value of 3.8 and a settled water $\beta$ value of 4.2.

It should be noted that the $\beta$ value for the flocculated water was smaller than for the raw water. This indicates a shift in the particle size distribution toward larger particles, which is the expected treatment goal of the flocculation process. Furthermore, the $\beta$ value for the settled water was larger than the flocculated and raw waters. This indicates a shift in the particle size distribution toward smaller particles, which is what one might expect from a theoretical analysis of a settling basin due to removal of the larger particles.

However, settling basin performance usually does not approach
theoretical predictions so that in a real settling basin, not all of the flocs which are formed during flocculation will settle and be removed in the basin. This can cause the particle size distribution in a real coagulation-flocculation-sedimentation treatment train to actually shift toward larger sizes. This is especially true if the raw water is from a lake environment. A large lake can be more efficient, in terms of percentages of removal of settleable particles, than the basins in the treatment train because the retention time in the lake may be weeks, months, or years compared to hours in the settling basins.

Lawler and Wilkes\textsuperscript{10} modelled and measured particle size distributions after flocculation in a softening plant with various degrees of success. They applied the previously\textsuperscript{8} developed Smoluchowski model with a slight modification for the high density of the calcium carbonate particles. Lawler and Wilkes\textsuperscript{10} presented the particle size distribution measurements as number distribution and volume distribution curves, noting that number distribution curves best characterize changes in small particles and volume distribution curves best characterize changes in large particles.

Yeh and Ghosh\textsuperscript{34} measured optimum floc size distributions for the optimum filtration conditions when selecting cationic polymers. They found that the particle size distribution functions for the clay system fit a power law distribution while the clay-
polymer system fit a log normal distribution (5 - 300 μm range). Optimal filtration was found to occur at the polymer dosage which yielded number-volume average diameters of 20 μm, regardless of which polymer was used. The use of particle size distribution measurements over turbidity in the selection of optimal dosages was recommended.

Tanaka and Pirbazari\textsuperscript{35} used the volume distribution function to follow changes in the particle size distributions of direct filtration with cationic polymers. They also used the particle size distribution measurements to calculate filter coefficients and specific deposits. They found that the volume distribution function tended to shift towards larger sizes with increasing depth in the filter. While this phenomenon could possibly be attributed to the increased presence of reentrained particles in the suspension as the flow passed through the filter bed, Tanaka and Pirbazari\textsuperscript{35} attributed this increase in particle sizes to contact flocculation within the filter bed (filter pore flocculation). In this case, they found that this behavior occurred significantly only at high polymer dosages and high effluent turbidities of 1 to 2.5 NTU. As previously discussed, the conditions of high particle concentrations and polymer doses would provide much more favorable conditions for a significant degree of filter pore flocculation than would the conditions of relatively low particle concentrations and alum doses in the charge neutralization region, as used in this study.
Monscovitz and Rexing\textsuperscript{11} reported on an on-line particle size distribution measurement control system for the Alfred Merritt Smith Water Treatment Facility of the Southern Nevada Water System. The authors proposed that the key to optimal direct filtration is to control the particle size distribution at the coagulation step. The previous use at the same plant of a laboratory particle counter and a controlled optimum dosage scheme, reduced chemical costs by 32\%, with reductions in filter backwash frequency, and sludge handling costs. The authors also proposed the use of the \( \beta \) value (Equation 15: \[ n(d_p) = A_0 (d_p)^\beta \] ) to backwash a filter: when the \( \beta \) value deviated from the trend set during the majority of the length of the filter run, backwashing was required.
4. EXPERIMENTAL APPARATUS

4.1 Pilot Plant

The pilot filter system used in this study was located at the Hugh A. Wyckoff Water Treatment Plant of the Cobb County-Marietta Water Authority. The Wyckoff Water Treatment Plant draws up to 72 mgd of water from Lake Allatoona, a Corps of Engineers reservoir. The pilot filters, as shown in Figure 4, were effluent flow controlled using constant level tanks with near constant influent flow pressures up to 25 psi supplied by sample pumps. A set of four 5-inch diameter filters (F1 - F4) were available from a previous study. In order to decrease the coagulant chemical volumes required, two similar 2.25-inch diameter filters (F5 and F6) were added to the system. The majority of the data presented in this report were collected from these 2.25-inch diameter filters.

The pilot filters contained filter media taken from plant filter No. 1. The plant filters contain 20 inches of anthracite coal over 10 inches of silica sand. A prior study had characterized the coal media as having an effective size of 0.90 mm and an uniformity coefficient of 1.44 and the sand media as having an effective size of 0.52 mm and an uniformity coefficient of 1.56. For most of the pilot plant experiments presented here, the pilot filter media depth was the same as
Figure 4  Pilot Filter Schematic
the plant filters, 20 inches of coal over 10 inches of sand. In subsequent experiments when thin layer filters were used, the same 2:1 ratio between coal and sand was usually maintained.

The pilot filters were equipped with both water and air backwash supplies. The typical backwashing procedure was as follows:

1. Use water only to break up the filter bed
2. Use water and air or air only to clean the media
3. Use water only to remove the resuspended deposits

Steps 2 and 3 were repeated until the air scouring procedure caused no further detachment of deposits as evidenced by a clear backwash water flow.

As shown in Figure 4, the pilot filter system could be operated to accept either plant settled water from the settled water flume in the filter gallery when the pilot filter system was operated in the conventional filtration mode or raw water from the plant's 60-inch diameter raw water line prior to chemical additions when in the direct filtration mode. In the conventional filtration mode, there was a single chemical addition point at the influent to each pilot filter. In the direct filtration mode, the raw water passed through a plumbing system which contained four chemical addition points in series, each followed by a Komax static inline mixer, before entering the flow splitting manifold to each pilot filter.
Pilot filter flowrates were measured just prior to the constant head level control tank. Pilot filter headlosses up to 8 feet could be measured using a manometer board pressurized to the influent water supply pressure. The manometer was connected to the filter effluent piping and to a tap on top of the filter column. Pilot filter influent samples were taken from a valve on the manometer tap on top of either filter. Pilot filter effluent samples were taken at the effluent of the float valve in the constant level flow control tank. Raw, settled and filtered water samples from the Wyckoff plant train were taken from sample taps in the operators' laboratory.

While the plant settled and the pilot influent samples were from the same step of the plant treatment train, the two samples often had different turbidity and particle size analysis characteristics. This effect might have been a result of each sample having a separate sample pump or of each sample having a different physical sampling location. Although individual samples often showed a variations in turbidity and particle size analysis characteristics, the statistical analysis to be presented later shows that the measured parameters of the two samples are statistically identical.

4.2 Instrumentation

Turbidities were measured at the plant site using a Hach Ratio
Turbidimeter provided by the treatment plant staff. Zeta potential and specific conductivity were measured using a Zeta Meter in the Daniel Laboratory of Environmental Engineering at the Georgia Tech campus. Aluminum was measured in the Daniel Laboratory using a Perkin-Elmer Model 703 Atomic Absorption Spectrophotometer with a Model 2200 Heated Graphite Furnace. Particle size analysis was performed using the Brinkmann Particle Size Analyzer Model 2010 also in the Daniel Laboratory.

The Brinkmann Particle Size Analyzer\textsuperscript{37} was coupled with an IBM XT which performed the necessary data manipulation to present the particle size distribution analysis in a variety of formats. The sample analysis was performed in standard spectrophotometer cuvettes with a 1 cm light path. The cuvette may be glass or disposable plastic.

The Brinkmann Particle Size Analyzer Model 2010 utilizes a scanning Helium-Neon laser beam to directly measure the diameters of the particles. The laser beam is focused and projected through a rotating wedge prism which gives the laser beam a known scanning velocity. The laser beam is then scanned through the measurement area where it is blocked by particles and its intensity is measured by a photodiode on the opposite side of the sample measurement area. The time period for which the scanning laser beam is blocked by a particle is multiplied by the scanning velocity to determine the diameter of the
particle.  

The laser beam is scanned through a conical section to produce a focal plane much like the focal plane of a camera. Particles which are in front of or behind this focal plain do not block the laser beam and are therefore not seen in the analysis. By measuring the rate at which the laser beam is blocked, the analyzer edits the pulses to determine which pulse is the true diameter. Assuming that the particle is spherical, the scanning laser beam will only cross normal to the particle surface at one point, the diameter. The measurement of any other chord will produce a tangential angle and a slower rate of laser blockage, which will be rejected in favor of the pulse with the most rapid rate of blockage, the diameter.  

Brinkmann advertises the Model 2010's size detection range as 0.5 to 150 µm (standard lenses). However, the wavelength of a He-Ne laser is 6328 Angstroms or 0.6 µm. Personnel in the New York office of Brinkmann confirmed that the analyzer's true lower detection limit was 0.6 µm and that data below that size was extrapolated. Although the Brinkmann Analyzer reports the particle concentrations as numbers of particles above 0.5 µm, for the purposes of particle size distribution analysis in this research, the particle size data below 0.6 µm were deleted from the analysis.  

The analyzer has two different modes of analysis and two
different analysis resolutions. Brinkmann provides software for a Regular Mode of analysis for spherical, nontransparent particles and a Special Mode of analysis for nonspherical, transparent particles. In the Special Mode of analysis, the lower detection limit becomes 1.0 μm.\textsuperscript{37} Because the submicron data are important in terms of transport mechanisms, it was initially decided to use the Regular Mode of analysis.

Brinkmann provides a Normal Resolution of 0.5 μm for the analysis range 0.5 to 150 μm and a High Resolution of 0.2 μm for the analysis ranges of 0.5 to 60 μm and smaller.\textsuperscript{37} Since the measured particle sizes from the Wyckoff Water Treatment Plant were consistently below 60 μm in experimental Runs 1-5, it was decided to use the High Resolution mode and the analysis range of 0.5 to 60 μm. Using the Regular, High Resolution mode of analysis, the Brinkmann instrument correctly identified National Bureau of Standards certified particle size standards of 0.8, 2.0, and 10 μm as shown in Figures 5-7.
SAMPLE NAME: DUKE 0.8 MICRON STDS (3RD)
FILE NAME: DUKE08S

DATE: 17/01/1989  |  ACQ. RANGE: 0.5-60  |  COUNTS: 10460
TIME: 23:16  |  ACQ. MODE: SAMPLE  |  S.N.F.: 1.0
CONFIG.: 1 (0.7 SI)  |  ACQ. TIME: 30 SEC  |  S.D.U.: 6093
CELL TYPE: MAGNETIC (2)  |  SAMPLE SIZE: 3  |  CONCENTR.: 1.3E+07 #/ml
SAMPLE TYPE: REGULAR  |  REQ. CONF.: None  |  SOLIDS: 3.0E-04 %

**MEAN Diameter**

| Number, Length | 0.72 µm | 0.15 µm |
| Number, Area  | 0.74 µm | 0.15 µm |
| Number, Volume | 0.75 µm | 0.15 µm |
| Length, Area  | 0.75 µm | 0.14 µm |
| Length, Volume | 0.77 µm | 0.14 µm |
| Area, Volume  | 0.78 µm | 0.13 µm |
| Volume, Moment | 0.80 µm | 0.12 µm |

**MEDIAN Diameter**

| Number  | 0.73 µm | 0.70 µm | 100.00% |
| Area    | 0.79 µm | 0.90 µm | 100.00% |
| Volume  | 0.82 µm | 0.90 µm | 100.00% |

**PROBABILITY NUMBER DENSITY GRAPH**

Name: DUKE 0.8 MICRON STDS (3RD)
1.3E+87 #/ml(100.8x)
Mode at 8.78 µm
<< SCALE RANGE (µm): ADJUSTED >>

Median: 8.73 µm
Mean(µm): 8.72 µm
S.D.(µm): 0.15 µm
Conf(µm): 100.88 %

Figure 5 0.8 µm Standard
SAMPLE NAME: X50 DILUTION OF 2.0UM PARTICLES INTO DI
FILE NAME: Data Not Saved.

DATE: 12/02/1988
TIME: 04:37
CONFIG.: 1 (0.7 S1)
CELL TYPE: MAGNETIC (2)
SAMPLE TYPE: REGULAR

MEAN Diameter

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<td>Number, Area</td>
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<td>Number, Volume</td>
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<td>Area, Volume</td>
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MEDIAN Diameter

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<td>Number</td>
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<tr>
<td>Area</td>
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<tr>
<td>Volume</td>
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PROBABILITY NUMBER DENSITY GRAPH

Figure 6 2.0 µm Standard
SAMPLE NAME: X10 DIL OF 10UM PART IN DI, FRESH
FILE NAME: Data Not Saved.

DATE: 15/02/1988  |  ACQ. RANGE: 0.5-40  |  COUNTS: 27692
TIME: 04:35  |  ACQ. MODE: SAMPLE  |  S.N.F.: 0.9
CONFIG.: 1 (0.7 S1)  |  ACQ. TIME: 249 SEC  |  S.D.U.: 1040
CELL TYPE: MAGNETIC (2)  |  SAMPLE SIZE: 2  |  CONCENTR.: 1.4E+05 #/ml
SAMPLE TYPE: REGULAR  |  RED. CONF.: None  |  SOLIDS: 5.9E-03 %

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<td>Number :</td>
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<td>Area :</td>
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<td>Volume :</td>
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<td>11.70 µm</td>
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</tbody>
</table>

**PROBABILITY NUMBER DENSITY GRAPH**

- Name: X10 DIL OF 10UM PART IN DI, FRESH
- Mode at 18.88 µm
- Median: 9.12 µm
- Mean: 7.59 µm
- S.D.: 4.15 µm
- Confidence: 85.22%

**Figure 7 10 µm Standard**
5. CONVENTIONAL TREATMENT MODE EXPERIMENTAL RESULTS:

DEEP BED FILTERS

5.1. Pilot Plant Data, Runs 5-10

The initial runs (Runs 1-5) were used to determine standardized procedures for best operation of the filter plant and also to use the instrumentation, particularly the particle size analyzer, to get results that were consistent and reproducible. A typical conventional filtration run was 20 to 30 hours in duration, with 4 or 5 sets of 0.5 liter samples taken to Daniel Laboratory at Georgia Tech for particle size and zeta potential analysis. Samples for turbidity were taken with more frequency than samples for particle size analysis. In all cases, the target filtration rate was 5.0 gpm/ft$^2$. The filters generally were supervised for 15 to 40% of the duration of the run and left unsupervised for a period of 6 to 10 hours overnight.

For Runs 5-13 the pilot plant was operated in the conventional filtration mode. For Runs 5-10 (Nov. 88 to Feb. 89), the pilot filter media depths were the same as the plant filters (20 inches coal over 10 inches sand), while shallower depths were used for Runs 11-13. Runs 5-10 were primarily used to characterize the particle size distributions through the entire conventional treatment train, from raw water to settled water to filtered water. During this characterization, evidence of
increasing particle size distributions through the filters was recognized and the proposed conceptual filtration theory formulated. Runs 11-13 were used to attempt to gather data during the breakthrough phase, hence the shallow filter beds.

Data from Run 7 is shown in Figures 8-12 and is generally typical of Runs 5-10. Although there were minor variations between runs, all of the runs for the conventional treatment portion of the study demonstrated similar characteristics, as shown by statistical analyses to be discussed later. For this reason, only Runs 7 and 10 are discussed in detail here.

Figure 8 shows the turbidity measurements during Run 7. During Runs 5-10, the raw water turbidity varied from 5 to 13 NTU for various runs. The plant settled water and filtered water turbidities were relatively consistent at 1 to 2 NTU and 0.1 to 0.3 NTU, respectively. The turbidity of the influent to the pilot filters generally agreed with that of the plant settled water. The pilot filtered water turbidity was generally the same as that of the plant filtered water, generally less than 0.1 NTU higher or lower.

For all conventional treatment runs, the pilot filters typically exhibited a filter ripening phase with an initial turbidity peak occurring within ten minutes of the start of filtration. The filter ripening phase often continued for several hours, with the turbidity falling below 0.5 NTU within
Figure 8  Influent and Effluent Turbidities, Run 7
Figure 9  Filtration Rate Variations, Run 7
Figure 10  Pilot Filter Headlosses, Run 7
Figure 11 Particle Concentrations, Run 7
Figure 12 Particle Mean Diameter, Run 7
approximately one hour. Except for Run 10, which was over 200 hours long, all of the other conventional treatment filtration runs were too short (less than 40 hours) to exhibit turbidity breakthrough.

Figure 9 shows the filtration rates and Figure 10 shows the filter headlosses for Run 7. The target filtration rate for the pilot filters was 5.0 gpm/ft². Although the effluent flow control constant level tanks should theoretically provide a stable, nearly constant filtration rate regardless of pressure variations on the flow control valve, the filtration rates generally varied by ± 20% regardless of the frequency of manual flow adjustment. The headlosses, when normalized to 5.0 gpm/ft² by assuming a linear dependence on flowrate (laminar headlosses), typically formed a smooth profile with a slight upward curvature.

Figures 11 and 12 show the particle concentrations and the mean diameters of the size distribution analyses for Run 7. The particle concentration, like the turbidity, shows roughly an order of magnitude decrease for each treatment step. The particle concentrations are large, with even the filtered water samples measuring on the order of thousands of particles per mL. The majority of the particles measured for each sample are on the order of 1 μm, as seen by the mean diameter sizes. It is also important to notice that the mean diameter as measured by the Brinkmann PSA for the range of 0.5-60 μm does not change
appreciably or consistently with the treatment processes. Because the mean diameter is a number averaged value, the predominance of small particles does not allow the mean diameter to reflect small to moderate changes in the size distribution which might be occurring in the larger, less populated size ranges. In contrast to the above, by using the particle size distribution function and the volume distribution function to describe the particle distributions, changes in the larger, less populated size regions can be described as easily as changes in the smaller, more populated size regions.

5.2. Particle Size Distribution Analysis, Runs 5-10

Data from the Brinkmann PSA, in the form of a fraction of total particles in each size range, was downloaded into a spreadsheet format. For the Regular, High Resolution Mode of operation, the Brinkmann PSA downloads data in 300 size channels from 0 to 60 μm in steps of 0.2 μm. Each size channel contains a fraction, the sum of which equals 100%. By multiplying the fraction in each size channel by the total number of particles reported by the Brinkmann PSA, the size frequency histogram for that particle size distribution is obtained.

To manipulate the data in these 300 size channels, the three channels below 0.6 μm were deleted because of the detection limits of the instrument. The remaining 297 size channels were combined into 18 by the combination of adjacent size
channels until the logs of each were roughly equivalent across the entire size range.

Since the particle size distribution functions are calculated from log-log relationships, any channels which contain zero particles will not contribute to the analysis. However, it may be assumed that with a sufficiently large sample the particle size distribution is continuous. By assuming a continuous size distribution, it is logical to expect that the channels which contain zero particles would contain a representative number of particles if the sample was sufficiently large. For a large sample, the representative number of particles in each channel containing zero particles would fall onto the continuous size distribution as defined by the channels containing particles. The deletion of the channels containing zero particles may therefore be assumed to not have an adverse effect on the particle size distribution analysis. This is shown in the experimental data to be presented.

The particle size distribution power law function (Equation 15: \( n(d_p) = A_0 (d_p)^\beta \)) is calculated from the best fit of the data points using the least squares method. The two size channels below 1.0 \( \mu m \) were consistently deleted from the best fit determination because these data points usually deviated from the linear portion of the PSD function to which the least squares analysis was applied. While deleting these sizes affects the \( A_0 \) and \( \beta \) values, there is a basis for deleting
these sizes in the volume distribution function data. These two size channels appear to form a separate region on the volume distribution function graph and are therefore not part of the same power law function relationship that characterizes the remainder of the particle size distribution. Each $A_o$ and $\beta$ value, therefore, was calculated using data from up to 16 size channels, depending on the number of size channels containing zero particles.

The volume distribution function typically exhibits two distinct areas as defined by the slope of the function. This is as predicted by Hunt's theory. The lower region, defined as the "Brownian" region, consists of data below 1.2 µm which consists only of the 3 lower size channels. The upper region, defined as the "Shear" region, consists of data above 1.0 µm which consists of the upper 16 size channels, with the size channel 1.0-1.2 µm common to both analyses. The PSD Function and the "Shear" region of the volume distribution function contain the same raw data points in different representations. Any statistical properties of one are therefore equivalent to the same statistical properties of the other.

Figures 13-17 show the particle size distribution power law functions for the samples taken during Run 7. As previously mentioned, these data are generally typical of the other runs. Each figure shows the best fit lines for that sampling period. Figures 18-23 show the individual samples at 28.25 hours. By
Figure 13  Particle Size Distribution Function, Run 7 (0 hrs)
Figure 14  Particle Size Distribution Function, Run 7 (6 hrs)
Figure 15 Particle Size Distribution Function, Run 7 (11.5 hrs)
Figure 16 Particle Size Distribution Function, Run 7 (20.75 hrs)
Figure 17  Particle Size Distribution Function, Run 7 (28.25 hrs)
Figure 18  PSD Function, Run 7 (28.25 hrs) Raw Water
Figure 19 PSD Function, Run 7 (28.25 hrs) Plant Settled Water
Figure 20  PSD Function, Run 7 (28.25 hrs) Pilot Influent Water
Figure 21  PSD Function, Run 7 (28.25 hrs)  Plant Filtered Water
Figure 22  PSD Function, Run 7 (28.25 hrs)  Pilot Filter 5 Effluent
Figure 23  PSD Function, Run 7 (28.25 hrs) Pilot Filter 6 Effluent
Figure 24  Power Law Function $A_0$ Constant, Run 7
Figure 25  Power Law Function $\beta$ Value, Run 7
Figure 26 Volume Distribution Function, Run 7 (0 hrs)
Figure 27 Volume Distribution Function, Run 7 (11.5 hrs)
Figure 28: Volume Distribution Function, Run 7 (28.25 hrs)
plotting the samples individually, the "zero" channels in the analysis are apparent. From Figures 21-23, it is also apparent that the slope of the particle size distribution function best fit line as defined by the smaller particles present in the analysis is not dramatically altered by the presence of the larger particles. This confirms the assumption that the presence of the large particles in only one size channel should not bias the analysis.

Figures 24 and 25 show the $A_o$ and $\beta$ values for Run 7 as a function of time. The roughly one order of magnitude decrease in the $A_o$ coefficient from the raw water to the settled water and then to the filtered water corresponds to the decreases in the turbidity measurements and the particle concentrations for the same samples. The decrease in the $\beta$ value from about 3.5 to 4 for the raw and settled water samples to about 2 to 3 for the filtered water samples points to a shift in the particle size distribution toward larger sizes. This trend is not indicated in other measurement techniques such as turbidity or even total particle counting. In this analysis, Run 7 is somewhat different from the other runs in that it does not demonstrate an obvious difference between the $\beta$ values for the raw and settled waters. The general trend for Runs 5-10 was for the $\beta$ value to decrease through the treatment steps, as will be shown in statistical analyses to be reported later.

Figures 26-28 show the volume distribution function for Run 7
at selected times. Two distinct regions are evident from the slopes of the best fit lines for the regions 0.6-1.2 µm and 1.0-60 µm. The first region defines the "Brownian" transport mechanism and the second the "shear" transport mechanism, respectively. Figures 29 and 30 show the values of the slope of the volume distribution function for Run 7 as a function of time. Figure 29 is the slope of the "Brownian" region, which typically shows a large amount of scatter for all analyses performed here. In keeping with Valioulis et al. 32, this data does not show the trends predicted by Hunt 29. Figure 30 is the slope of the "Shear" region, which shows the same trends of increasing particle size distributions through the treatment steps as the β value analysis.

Figures 31-33 show the mean and 95% confidence intervals averaged for the all of the β value and volume distribution function slope data from Runs 5-10. Figure 31 shows the decrease in the β values from the raw (β = 3.8) to the settled (β = 3.3) to the filtered (β = 2.8) water. Since a decrease in the β value of a PSD points to an increase in the particle sizes, the particle size may thus be seen to be increasing through the filtration step. This phenomenon provides evidence for the mechanism of detachment.

Statistical analyses were performed on each subgroup of plant and pilot scale β value data to determine whether the populations from which the data were collected were
Figure 29 "Brownian" Region Slope of VDF, Run 7
Figure 30 "Shear" Region Slope of VDF, Run 7
Figure 31  β Value Statistical Summary, Runs 5–10
Figure 32 "Brownian" Region Slope Statistical Summary, Runs 5–10
Figure 33  "Shear" Region Slope Statistical Summary, Runs 5–10
statistically independent or not. Using the Student t-distribution test, the plant data and pilot data subgroups were found to be statistically independent to less than 50% certainty for both the settled (plant settled and pilot influent) and filtered water samples. This indicates that, although individual samples might have had differing values, the statistical properties of the total datasets comprising the pilot data and the plant data were identical and the pilot system data may be assumed to be identical to the plant system data. Next, similar analyses were performed on the raw, settled, and filtered water data groups to determine whether the populations were statistically independent. These groups were found to be statistically independent to greater than 99.9% certainty. Because of the total number of samples analyzed, over 200, the time frame over which they were analyzed, four months, and the number of data points constituting each analysis, up to 16 size channels, the evidence of increasing particle size distributions through granular media filters using conventional alum coagulation treatment must be viewed as quantitative evidence of a detachment mechanism.

Figure 32 shows the scatter of the data for the mean of the "Brownian" region slope of the volume distribution function. From Hunt's work, the theoretical slope of the volume distribution function for a particle size distribution dominated by Brownian coagulation should be 1.5. The slopes
here are much larger than 1.5. This may be explained by Valioulis et al.\textsuperscript{32}, who stated that the assumptions that Hunt made are not valid in this region. Also, only three size channels are used to calculate the slope of the "Brownian" region, which also might extend lower than 0.6 \(\mu\)m. Although the Brinkmann instrument correctly identified a 0.8 \(\mu\)m standard, higher resolution than the present 0.2 \(\mu\)m is probably needed for proper analyses in this region.

Figure 33 shows the mean of the "Shear" region of the volume distribution function. From Hunt's\textsuperscript{29} work, the theoretical slope of the volume distribution function for a particle size distribution region dominated by shear coagulation should be 0. The slopes here are close to 0 for the raw water, which is from Lake Allatoona, a Corps of Engineers' reservoir. However, the settled water and filtered water samples have progressively higher slopes, indicating that the particle size distributions are shifting to larger size intervals.

Theoretically, the settling basin effluent should exhibit the slope of 0. However, the settling basins are probably far from ideal and therefore do not allow a stable particle size distribution to develop in the upper size ranges where settling of large particles is occurring. Since some settleable particles are still in the suspension, the particle concentrations, and therefore the size distribution function, might be expected to be higher than the theoretically predicted
values in the upper size ranges. This skewing would tend to increase the slope of the volume distribution function in the shear coagulation region.

The increased slope of the volume distribution function in the shear coagulation region for the filtered water above the slope obtained for the settled water points to a shift in the particle size distribution toward larger size ranges and therefore to some type of detachment mechanism for the filtration process. Statistically, the spread of the data for the slopes of the "shear" region of the volume distribution function (Figure 33) is the same as that for the $\beta$ values (Figure 31) because the two consist of the same database and have the same standard deviation.

5.3 Filter Coefficient Analysis, Run 10

With the $\beta$ value analysis, evidence for a detachment mechanism has been obtained. The proposed filtration model (Equation 11) requires the measurement of particles which have been detached from the filter grains:

$$\frac{C}{C_0} = e^{- (\lambda_a + \lambda_d) z}$$

(11)

where $C =$ concentration [mass/volume, volume/volume, turbidity, etc.]

$\lambda_a =$ filter coefficient of attachment [length$^{-1}$]
\[ \lambda_d = \text{filter coefficient of detachment [length}^{-1}] \]
\[ z = \text{media depth [length]} \]

It is at present impossible to differentiate between effluent particles which have passed through the filter bed and effluent particles which have been deposited on the filter grains and subsequently reentrained into the flow. However, using the evidence that the particle size distributions are shifting toward larger sizes through the filtration process, the distinction between attachment and detachment might possibly be made strictly on the basis of particle size.

In the settled water influent to the pilot filters, roughly 90-99% of the particles are below 2.4 \( \mu \)m in size. By assuming that any particles in the effluent which are below 2.4 \( \mu \)m in size have merely passed through the filter bed without being retained and that any particles in the effluent which are above 2.4 \( \mu \)m in size have been detached from the filter deposits, an attempt has been made to measure the attachment and detachment filter coefficients in the proposed model.

The attachment and detachment filter coefficients were calculated using the volume of particles removed (or produced) when the suspension passed through the filter bed. When there is no net removal of particle volume, the filter coefficient(s) equal zero. When the attachment filter coefficient, \( \lambda_a \), increases in magnitude there is less volume of particles in the
filter effluent and there is more attachment of particles to the filter grains occurring. When the detachment filter coefficient, \( \lambda_d \), increases in magnitude (becomes more negative), there is more volume of particles in the filter effluent and there is more detachment of particles from the filter grains occurring.

The assumptions of spherical particles and volume conservation were used in the calculating the filter coefficients. By taking the natural log of both sides of Equation 11, the filter coefficients may be calculated from the concentration of particle volume in the influent and effluent of the filter:

\[
\lambda_a + \lambda_d = -\frac{1}{z} \ln \frac{C}{C_0}
\]  

(16)

where \( C = \) effluent particle volume concentration
[mass/volume, volume/volume, turbidity, etc.]
\( C_0 = \) influent particle volume concentration
[mass/volume, volume/volume, turbidity, etc.]
\( \lambda_a = \) filter coefficient of attachment [length\(^{-1}\)]
\( \lambda_d = \) filter coefficient of detachment [length\(^{-1}\)]
\( z = \) media depth [length]

If the concentration, \( C \), is the particulate volume only above or below the particle size used to differentiate between attachment and detachment mechanisms, then either the attachment or detachment filter coefficient is zero. For
instance, if the concentration, \( C \), is the particle volume concentration below 2.4 \( \mu m \), then the filter coefficient calculated using Equation 16 is the attachment filter coefficient, \( \lambda_a \). Conversely, if the concentration, \( C \), is the particle volume concentration above 2.4 \( \mu m \), then the filter coefficient calculated using Equation 16 is the detachment filter coefficient, \( \lambda_d \).

Assuming spherical particles, the particle volume concentration in a single size range, or channel, may be calculated by taking the number concentration of particles in that size range and multiplying by the spherical volume of the average particle diameter in that size range:

\[
C(d_1-d_2) = N(d_1-d_2) \frac{\pi ((d_1 + d_2)/2)^3}{6}
\]  

(17)

where \( C(d_1-d_2) = \) particle volume concentration between particle diameters \( d_1 \) and \( d_2 \)

\( N(d_1-d_2) = \) particle number concentration between particle diameters \( d_1 \) and \( d_2 \)

This can be done for each size range. The summation of the particle size ranges below 2.4 \( \mu m \) is the particle volume concentration used to calculate an attachment filter coefficient and the summation of the particle size ranges above 2.4 \( \mu m \) is the particle volume concentration used to calculate a detachment filter coefficient. The summation of all particle size ranges measured by the particle size analyzer may be used to calculate an overall filter coefficient.
The mathematics of the filtration equation are such that a positive filter coefficient indicates that the concentration parameter has decreased through the filter bed and a negative filter coefficient indicates that the concentration parameter has increased through the filter bed. In terms of particle volume and attachment and detachment filter coefficients, a positive attachment filter coefficient indicates that attachment of particles is occurring and a negative detachment filter coefficient indicates that detachment of particles is occurring. This is the condition predicted by the proposed filtration equation. However, because a strict particle size criteria is being used to differentiate between the attachment and detachment filter coefficients, the detachment coefficient as measured was often positive. This indicates that the particle volume concentration measured in the size ranges used to determine the detachment filter coefficient experienced a net removal through the filter bed rather than a net increase.

For the purpose of applying this analysis, Run 10 was continued over an extended duration so that filter breakthrough could be observed and analyzed. However, as shown in Figure 34, the turbidity never achieved a traditional "breakthrough curve". It is believed that, during periods where there was no supervision of the pilot filters, the filtration rates increased and rapidly scoured deposits from the filter bed, thereby extending the length of the run beyond the normal
Figure 34  Influent and Effluent Turbidities, Run 10
ultimate bed capacity. Even during periods of continuous supervision, the filtration rates would fluctuate. At least once, there was scum observed in the effluent flow control tanks. Figure 35 shows the filtration rates for Run 10 and one such flow surge.

Figure 36 shows the overall filter coefficient (Equation 1) for Run 10 as a function of time. Some of the negative values, which are defined as a net production of particle volume, might be attributable to excessive detachment during high or increasing flowrates. Figures 37 and 38 show the attachment and detachment coefficients for Run 10 as functions of time. When the detachment coefficient lines rise to the top of the graph, there are no particles above 2.4 μm in the effluent, the removal of particles above 2.4 μm is 100%, and the coefficient equals infinity.

It should be noted here that the attachment coefficient in Figure 37 shows the predicted trends: an initial increase followed by a decrease towards zero. The increase of the attachment coefficient after 200 hours follows the turbidity decrease and could be the result of increased filtration capacity due to scouring effects during flow surges. The best fit curve shown in Figure 37 is a non-linear least-squares sixth-order polynomial. It should also be noted that the detachment coefficient, shown in Figure 38, for particles above 2.4 μm, controls the overall filter coefficient, shown in
Figure 35 Filtration Rate Variations, Run 10
Figure 36 Overall Filter Coefficient, Run 10
Figure 37 Attachment Filter Coefficient, Run 10
Figure 38 Detachment Filter Coefficient, Run 10
Figure 36. This infers that, when particle volume passes through the filter, it is in the form of large, not small particles. However, these large particles are deposits which have been reentrained into the flow. The deposits which form on the filter grains are composed of smaller particles which are captured one at a time by the mechanisms of filtration.
6. CONVENTIONAL TREATMENT MODE EXPERIMENTAL RESULTS:

THIN MEDIA FILTERS

6.1 Pilot Plant Data, Run 13

In an attempt to better observe the breakthrough phase, a series of runs were made using thin layers of media. The initial media depths were considered to be too shallow for effective filtration but were used in an attempt to greatly accelerate the breakthrough process. Run 11 used shallow, single media layers, i.e. 3.5 inches and 6.2 inches, of anthracite coal media and did not achieve better than a 25% removal of turbidity. Runs 12 and 13 used 1.7 inches of sand and 3.5 inches of coal for Filter 5 and 3.3 inches of sand and 6.0 inches of coal for Filter 6. Both runs achieved better than 50% reduction in turbidity, but Run 12 was interrupted due to plant operational problems. Neither run achieved a turbidity breakthrough curve. Run 13 was analyzed for thin media filter coefficients.

Figure 39 shows the effluent turbidity for Run 13 as a function of time. The plant settled water and the pilot influent waters show a distinct deviation from each other at 3 hours. These deviations are, as previously discussed, not statistically significant when all of the data points are analyzed. Figure 40 shows the flowrate variations and Figure 41 shows the
Figure 39 Influent and Effluent Turbidities, Run 13
Figure 40  Filtration Rate Variations, Run 13
Figure 41  Pilot Filter Headlosses, Run 13
Figure 42  Particle Concentrations, Run 13
headlosses for Run 13. Figure 42 shows the particle concentrations for Run 13 as a function of time. On the surface, the thin filter data appears to be similar to the data collected in Runs 5-10 for deep bed filters, except that particulate removal in terms of turbidity and particle concentration is smaller.

6.2 Particle Size Distribution Analysis, Run 13

Figure 43 shows the $\beta$ value for Run 13 as a function of time. Here, the characteristic drop of the $\beta$ value through the filtration step is not evident. Figure 44 shows the statistical summary of the $\beta$ values for Run 13. While the 95% confidence limits are not as narrow as those for the analysis of Runs 5-10, the trend of decreasing $\beta$ values with treatment, and therefore increasing particle size distributions, is absent.

There is no reason to doubt that the detachment mechanisms are present and working in a thin filter. There are two possible reasons for the absence of the increasing particle size distributions. First, since the thin filters do not remove as many influent particles as the deep-bed filters, the detached particles could be "hidden" by the large number of unattached influent particles in the effluent. Second, since the detached particles are assumed to be larger than the influent particles, the number concentration of the detached particles would be
Figure 43  Power Law Function β Value, Run 13
Figure 44 β Value Statistical Summary, Run 13

- Wyckoff Plant
- Pilot Filter System
- Combined Data
- Mean and 95% C.I.

- Raw: \( \beta = 3.27 \), # pts. = 5
- Settled: \( \beta = 2.99 \), # pts. = 19
- Filtered: \( \beta = 3.08 \), # pts. = 38
necessarily smaller than the number concentration of the attached particles that formed the detached particle and with a thin filter this number concentration of detached particles may be too small to detect with the Brinkmann Particle Size Analyzer.

The necessary conclusion here is that thin filter experiments might not be useful in determining filter coefficients because of problems in detecting the detached particles.

6.3 Filter Coefficient Analysis, Run 13

Figures 45-47 show the filter coefficients for Run 13 as a function of time. Figure 45 shows the overall filter coefficient. Figure 46 shows the attachment coefficient, which appears to be relatively constant during the constant flowrate periods and does not show a decreasing trend during the length of the run. Since the effluent turbidity consistently decreased during the run, the filter did not approach breakthrough so that the attachment coefficient should not be expected to decrease. Figure 47 shows the detachment coefficient, which again appears to control the variations in the overall filter coefficient.
Figure 45 Overall Filter Coefficient, Run 13

Filter Coefficient, $\lambda$
(based on volume removal, depth = 5" and 9"

Time, hours

Figure 45 Overall Filter Coefficient, Run 13
Figure 46 Attachment Filter Coefficient, Run 13
Figure 47 Detachment Filter Coefficient, Run 13
7. DISCUSSION OF CONVENTIONAL TREATMENT STUDY

The experimental work done thus far has provided some quantitative evidence of particle detachment in deep-bed filters using conventional alum coagulation treatment. Particle size distribution shapes may be characterized by the $\beta$ value from the particle size distribution function. Decreases in this $\beta$ value indicate increases in the particle size distribution function to larger size ranges. A statistical analysis of over 200 water samples from both the plant and the pilot system has shown that the raw water has $\beta = 3.8$, the settled water has $\beta = 3.3$, and the filtered water has $\beta = 2.8$. This consistent decrease in the $\beta$ value indicates a consistent increase in the particle size distributions and is therefore evidence of particle detachment in the filters.

Some data has been analyzed using the proposed filtration model. While there are problems with separately identifying the non-attached and the detached particles in the effluent, an initial attempt at using a size criteria to make the distinction has not been entirely unsuccessful. However, attempts to enhance the study of detachment by using thin filters to speed the particulate breakthrough process met with failure primarily because of the absence of measurable concentrations of large particles in the effluent from the thin filters.

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In order to further characterize particle size distributions, the pilot filter system was operated in the direct filtration mode. By increasing the loading of particulate matter on the filters and using deep-bed filters, it was hoped that the breakthrough process could be accelerated to a reasonable time frame and that there would be greater quantities of large particles in the effluent from the filter.
8. DIRECT FILTRATION MODE EXPERIMENTAL RESULTS

For Runs 14-17 (June 89 to July 89), the pilot plant filters were operated in the direct filtration mode. Raw water, taken from the 60-inch plant influent line prior to the chemical addition point, was used as the pilot plant influent. Alum was added to the raw water just upstream of the inline static mixers. The target alum concentration was 8 mg/l as alum, which was the concentration being used in the full scale plant at that time. The alum was dosed according to the same formula used by the plant operators: 5.4 lbs. dry alum/gal. of feed stock. The plant laboratory measured the feed concentration to two places to the right of the decimal point for each shipment of alum received. The raw, filter influent, and filter effluent water samples were analyzed in the same manner as during the conventional treatment portion of this study.

Because of operational difficulties with maintaining the alum feed at a constant concentration, the direct filtration runs were not as successful as the conventional treatment runs. The alum was fed into the pilot filter system using a pump set at a constant flowrate. Because the chemical feedrate was constant, the alum concentration of the coagulated water, also called the pilot filter influent, varied as the filtration rate. During Runs 16 and 17, there were problems with the chemical feed pump which resulted in lower chemical feed rates than expected.
Also, between Runs 15 and 16, the 2.25-inch diameter plexiglas filter columns, filters 5 and 6, both developed hairline cracks. For this reason, Runs 16 and 17 utilized filters 1 and 2, the 5-inch diameter filter columns which predated this study. The granular media in filters 1 and 2 was also taken from the full scale plant filters, but at an earlier date than the granular media in filters 5 and 6, which were used throughout Runs 5 through 15.

Because there were so many operational difficulties during the direct filtration portion of this study, each run was different in its characteristics. For this reason, operating data for each run is presented and discussed individually. From the discussion of each run, a decision was made as to the validity of the run and whether to include the data in the statistical summary of direct filtration data.

8.1 Pilot Plant Direct Filtration Data, Run 14

For Run 14, shallow media depths were used with the goal of accelerating the breakthrough phase of filtration. Filter 5 used 9.5 inches of coal over 5.0 inches of sand while filter 6 used 6.0 inches of coal over 3.3 inches of sand. While the calculated alum concentration was 8 mg/L, the measured alum concentrations were approximately 6 mg/L. Figure 48 shows the filtration rate variations during Run 14, which are not sufficient to explain the discrepancy between the measured and
Figure 48 Filtration Rate Variations, Run 14

Flowrate, % off 5.0 gpm/ft²

Target flowrate
Alum = ±6ppm

- Filter 5 (9.5" coal; 5.0" sand)
- Filter 6 (6.0" coal, 3.3" sand)
calculated alum concentrations. Figure 49 shows the influent and effluent turbidity for Run 14. The peak in the influent turbidity is believed to be a "flushing out" of the raw water feed line from the 60-inch plant influent line to the pilot filter system.

The run was terminated at 3 hours because of the, at that time, questionable effects of the influent turbidity peak on the subsequent particulate deposits within the filter bed and the duration of the high effluent turbidity. Since the effluent turbidity was continuing to decrease, continued operation of the filters during this run might have produced the effluent turbidities of 0.1 NTU which were expected from prior filtration runs. However, at that time, the influent turbidity peak and the higher than expected effluent turbidity at 3 hours of filtration time led to the conclusion that the initial influent turbidity peak had affected the performance of the filters.

Figure 50 shows the power law function $\beta$ value for Run 14. There was no discernible difference between the influent and effluent $\beta$ values for this run. It was unclear what might have been the cause for this, since it had been expected that the filtered water $\beta$ values in the direct filtration mode would be the same as in the conventional treatment mode due to the detachment mechanism, which is not dependent on whether the treatment mode is conventional or direct filtration. If the
Figure 49 Influent and Effluent Turbidities, Run 14
**Figure 50**  Power Law Function $\beta$ Value, Run 14
effluent particle size distribution is controlled by the detachment of deposits from the filter bed rather than the influent particle size distribution, then the differences of the shape of the influent particle size distributions in conventional and direct filtration modes would have little effect on the effluent particle size distributions.

8.2 Pilot Plant Direct Filtration Data, Run 15

For Run 15, the same depths of media were used as in Run 14. The same calculated alum concentration of 8 mg/L was fed to the filters. This time, however, the resulting alum concentrations were approximately 10 mg/L. Figure 51 shows the filtration rate variations for Run 15, which again are not sufficient to explain the discrepancy between the measured and calculated alum concentrations. Figure 52 shows the influent and effluent turbidities for Run 15. Again, the influent turbidity peak was attributed to "flushing out" of the raw water sample line. Because the filtered water turbidity dropped to 0.15 NTU, the influent turbidity peak was assumed to have no serious adverse effects. Unfortunately, this run was terminated because of time constraints. Figure 53 shows the headlosses across the pilot filters. A surface mat and heavy deposits were visible in the top of the filter. Figure 54 shows the influent and effluent particle concentrations for Run 15. As with the conventional treatment data presented previously, the turbidity and particle concentration changes correspond on an order of
Figure 51 Filtration Rate Variations, Run 15

Flowrate, % off 5.0 gpm/ft²

- Filter 5 (9.5" coal; 5.0" sand)
- Filter 6 (6.0" coal, 3.3" sand)
- Target flowrate

Alum = ±10 ppm
Figure 52 Influent and Effluent Turbidities, Run 15
Figure 53 Pilot Filter Headlosses, Run 15
Figure 54  Particle Concentrations, Run 15
Figure 55 shows the zeta potentials of the raw and coagulated waters for Run 15. One possible explanation of the difference between Runs 14 and 15 could be that the 6 mg/L of alum used for coagulation during Run 14 was not sufficient to destabilize the particles to the degree required for effective filtration. Figure 56 shows the power law function $\beta$ values for Run 15. Unlike Run 14, the raw and filtered waters show a difference in $\beta$ values. The raw and influent, or coagulated, waters in Run 15 do not show a difference in $\beta$ values. This should be expected if only a chemical change, such as destabilization, were occurring during the coagulation step.

However, since there are usually some amount of solids present in an alum feed, the particle size distribution could be changed by the addition of these solids. If charge neutralization by small dosages of alum is being practiced, then the effects on the particle size distribution will be less than if sweep coagulation using larger dosages of alum is being practiced. The larger dosages of alum will form aluminum hydroxide flocs, thereby altering the particle size distribution.

As evidenced by the turbidity and particle concentration data, the addition of alum to the raw water and the mixing due to the static mixers, and probably the pipe fittings leading into the
Figure 55 Zeta Potentials, Run 15

- **Raw**
- **Pilot Influent (raw)**
- **Influent (raw + alum)**
- **F5 (9.5” coal; 5.0” sand)**
- **F6 (6.0” coal; 3.3” sand)**

Alum = ±10 ppm
Figure 56 Power Law Function $\beta$ Value, Run 15
filter column, do result in a decrease in both the turbidity
and the particle concentration. Therefore, the particle size
distribution must have undergone a change. This change,
however, might be the result of a flocculating action which
shifted the particle mass into larger sizes while still
retaining the same shape of the particle size distribution
function in the region bounded by the Brinkmann's detection
limits. Indeed, millimeter sized flocs were visually observed
in the influent to the filters.

8.3 Pilot Plant Direct Filtration Data, Run 16

For Run 16, 5-inch diameter filter columns 1 and 2 were used
because the 2.25-inch diameter filter columns 5 and 6 developed
hairline cracks and subsequently leaked water when pressurized.
Filters 1 and 2 had media depths of 20 inches of anthracite
coal over 10 inches of sand. Operating conditions and
filtration rates for these larger filters were identical to the
smaller filters used in Runs 5 - 15. During Run 16,
operational difficulties developed between 2 and 6 hours into
the run which caused the alum feed to malfunction at 6 hours.
Because of this, only data up to 2 hours was collected for Run
16. An alum analysis was not performed on the small number of
samples. Figure 57 shows the filtration rate variations for
Run 16 up to 2 hours. Figure 58 shows the influent and
effluent turbidities for Run 16. Because the effluent
turbidities and filtration rates were similar to those for Run
Figure 57  Filtration Rate Variations, Run 16

- Filter 1 (20" coal; 10" sand)
- Filter 2 (20" coal; 10" sand)
- Target flowrate
Target alum = 8 mg/L
Figure 58 Influent and Effluent Turbidities, Run 16
it can be assumed that both runs received similar alum
doses. The zeta potential measurements for Run 16, shown in
Figure 59, do not vary from those in Run 15. Figure 60 shows
the particle concentrations for Run 16. The particle
concentrations for the raw and filtered waters show roughly a
one order of magnitude decrease which reflects a similar order
of magnitude decrease in turbidity.

Figure 61 shows the power law function $\beta$ value for Run 16.
Although there are only three samples for this run, the trend
of the filtered water $\beta$ values being lower than the raw water $\beta$
values is evident. As with Run 15, the $\beta$ values of the raw and
influent, or coagulated, waters are similar but the particle
concentration in the influent, or coagulated, water is less
than that of the raw water.

8.4 Pilot Plant Direct Filtration Data, Run 17

For Run 17, the same 5-inch diameter filter columns and media
depths were used as in Run 16. The same calculated alum
concentration of 8 mg/L was fed to the filters. However, as
the filters clogged during the length of the run, the
filtration rates dropped as shown in Figure 62. Because the
pilot filter system had been initially modified to operate with
2.25-inch diameter filter columns, the increased flowrates
through the 5-inch diameter filter columns stretched the flow
capacity of the system and there was not enough pressure to
Target Alum = 8 mg/L

Figure 59  Zeta Potentials, Run 16
Figure 60 Particle Concentrations, Run 16
Figure 61  Power Law Function $\beta$ Value, Run 16
Figure 82 Filtration Rate Variations, Run 17

- Filter 1 (20" coal; 10" sand)
- Filter 2 (20" coal; 10" sand)
- Target flowrate
Target Alum = 8 mg/L

Flowrate, % off 5.0 gpm/ft²

Time, hours
maintain the filtration rate through the clogged filters. This can be illustrated by Figure 63, which shows the headlosses across the filters for the first seven hours of the run. Beyond this time, the headlosses became greater than the maximum of eight feet of water differential which the manometer board could measure. The water pressure in the system compounded problems with the alum chemical feed pump which caused the pump to intermittently cease feeding alum into the system at about eighteen hours into the run. Figure 64 shows the zeta potentials during Run 17. At approximately eighteen hours the zeta potential begins increasing. This indicates poor particle destabilization.

In all of the direct filtration runs, there was an accumulation of solids in the inline static mixers and the influent piping. Due to the length of Run 17, this problem was greater in Run 17 than in any of the other runs. In addition to the difficulties which this caused with the particle size distribution analysis, it also contributed to problems in Run 17 with the alum measurements. Due to maintenance problems with the atomic adsorption spectrophotometer, the samples were not analyzed for aluminum until approximately three weeks after the pilot filter run. When the aluminum analysis was performed, the coagulated water samples were found to have very poor reproducibility, sometimes varying by as much as a factor of three. This poor reproducibility was partially attributed to inhomogeneity caused by the solids, which were at least partly alum.
Figure 63 Pilot Filter Headlosses, Run 17
Figure 64 Zeta Potentials, Run 17

- Raw
- Pilot Influent (raw)
- F1 (20" coal; 10" sand)
- F2 (20" coal; 10" sand)
- Influent (raw + alum)

Target Alum = 8 mg/L
Figure 65 shows the influent and effluent turbidities for Run 17. The turbidity data displays what appears to be a turbidity breakthrough curve but is probably a decrease in filtration efficiency due to poor particle destabilization. Figure 66 shows the particle concentrations during Run 17. The particle concentration data coincides with the turbidity curve. Figure 67 shows the power law function $\beta$ values for Run 17. Note that up until the time at which the chemical feed system began malfunctioning, the filtered water $\beta$ values were lower than the raw and coagulated water $\beta$ values during Run 17. This trend is similar to Runs 15 and 16. After eighteen hours, the $\beta$ values of the filtered water increased to the same range as the $\beta$ values of the raw and coagulated waters.

Since alum was not being fed into the system at the correct doses, the particles were probably not being destabilized and therefore the attachment of particles to filter grains inside the filter was not occurring at an appreciable rate. The effluent particle size distribution would therefore be identical to the influent particle size distribution since no removal was occurring. This condition is not the same as the condition of a well operated filter experiencing breakthrough, although its effects are similar to the effects of the "wormhole" flow phase of the proposed conceptual filtration model.
Figure 65 Influent and Effluent Turbidities, Run 17
Figure 66 Particle Concentrations, Run 17

Particle Concentration, #/mL
(range: 0.5(d_p<60μm))
Figure 67  Power Law Function $\beta$ Value, Run 17
In this case, the influent particles were not destabilized to the degree where any particle removal could occur. In the case of a well operated filter experiencing breakthrough, the influent particles are still being destabilized and particle removal can still occur, as proposed previously, for a period of time until the filter enters "wormhole" flow condition. During turbidity breakthrough and until the time the filter enters the "wormhole" flow condition, the removal of particles is balanced by the reentrainment of previously attached particles. The particle size distribution of the influent and effluent should be different as long as some attachment of particles is occurring. Once attachment and detachment cease, however, the particle size distribution of the influent would be identical to the effluent. This could be caused either by "wormhole" flow, where pore velocities are too great for attachment to occur, or by ineffective coagulation, where the particles are not destabilized to the point at which the attachment mechanisms can cause removal of particles from the flow stream.

8.5 Particle Size Distribution Analysis, Runs 14-17

With the assumption that the filter effluent particle size distribution is controlled by the detachment of particles from the filter grains, the direct filtration runs were expected to show the same particle size distribution trends as the conventional filtration runs. The statistical analysis and
summary of the particle size distribution data from the conventional filtration runs are shown in Figures 31-32 in Section 5.2. Because of plant scale operational difficulties, no more direct filtration work with the pilot filter system was possible until a much later date. For this reason, the database used to perform the following statistical analysis was smaller than the database used to perform the statistical analysis of the conventional treatment portion of this study. This in itself would tend to make the scatter of the data more pronounced in the direct filtration statistical summaries than in the conventional treatment statistical summaries.

Figures 68-70 show the mean and 95% confidence intervals for the $\beta$ value (Figure 68) and volume distribution slope data (Figures 69 and 70) from Runs 14-17. Figures 68-70 include all data from all samples taken during the direct filtration runs. Figure 68 shows the trends for the $\beta$ value through the plant and pilot raw water, the coagulated pilot influent water, and the filtered water. While the pilot plant raw water average $\beta$ value of 3.71 was similar to the average raw water $\beta$ value of 3.77 measured during the conventional treatment portion of this study, the plant raw water average $\beta$ value during this direct filtration study had dropped to 3.4. There appears to be no explanation for this difference in $\beta$ value between the plant raw water and the pilot system raw water. The sample streams were taken from the raw water pipeline prior to any chemical addition and were transported through sample pipes of similar
Figure 68  β Value Statistical Summary, Runs 14–17
Figure 69 "Brownian" Region Slope Statistical Summary, Runs 14–17
Figure 70 "Shear" Region Slope Statistical Summary, Runs 14–17
material, size, and length. The samples from the plant and pilot raw waters did not show a consistent difference in turbidity measurements during Runs 14-17.

The coagulated water $\beta$ value of 3.55 is near that of the pilot system raw water. This would be expected with a mixing unit where only destabilization and no flocculation was taking place. The particles in a flash mix should be destabilized through the chemical processes occurring but should not be flocculating because of the high mixing gradients. However, the chemicals in this system were added in a static inline mixer, not a mechanical flash mixer. There was also opportunity for flocculation to occur in the pipe fittings downstream of the mixers. The sample point for the coagulated water was at the top of the filter column, not at the end of the static mixer. For these reasons, the coagulated pilot influent water $\beta$ value might instead be expected to be lower than raw water $\beta$ value as larger particles are formed through flocculation in the pipe fittings. Another factor to consider here is that Figure 68 contains all of the samples taken during Runs 14-17, not all of which had a correct alum feed. The particle size distribution of those samples that did not have a proper coagulant dose would be similar to the raw water because, even if hydraulic conditions for flocculation occurred, the particles were not properly destabilized for particle-particle attachments to occur.
The direct filtration filtered water average $\beta$ value of 3.23 shown in Figure 68 is much higher than the conventional treatment filtered water average $\beta$ value of 2.81 shown in Figure 31. From previous discussions on particle attachment and detachment in granular media filter beds, this is not the expected result. However, as will be shown later, this may also be the result of the samples which did not receive proper coagulant doses.

Figure 69 and 70 show the volume distribution function slope data statistical summaries for Runs 14-17. The "Brownian" region of the volume distribution function for the direct filtration samples is similar to the conventional treatment data shown in Figure 32 in that the value of the slope has much wider 95% confidence limits than the other particle size distribution parameters and does not agree with Hunt's theoretical predictions. However, the "Brownian" region slopes of the direct filtration data are consistently lower (slope = 2.4) than those from the conventional filtration data (slope = 3.0) for all steps in the water treatment train. The only evident explanation lies in the fact that the two portions of this study, the conventional treatment and the direct filtration studies, were performed during different seasons of the year. The varying water temperatures perhaps changed the characteristics of the "Brownian" region of the volume distribution function since Brownian motion is closely related to temperature. The volume distribution function "shear"
region data is statistically related to the \( \beta \) value data so that the discussion of the \( \beta \) value data also applies to the "shear" region of the volume distribution function.

To gain the most understanding out of the direct filtration data, it was necessary to delete the samples which were believed not to be representative of a well operated filter. In order to do this objectively, the decision to delete a data point was made on the basis of the turbidity measurement and alum dose at that sampling period, not the value of the particle size distribution parameter. In reviewing the turbidity data, it was decided to delete Run 14 in its entirety because of the high effluent turbidity and questions about the adequacy of the alum dose (see discussion in Section 8.1). It was also decided to delete the first sample point in Run 15, which fell in the time period during which the influent turbidity was much higher than normal. The last four data points in Run 17 were deleted because of the high effluent turbidity and the problems with the alum feed during this time period. The 11 sampling periods remaining, although a numerically small data base, are believed to be representative of the pilot filters under well operated conditions in the direct filtration mode. Figures 71-73 show the revised statistical summary of particle size distribution data for Runs 15-17.

Figure 71 shows the revised trends of the \( \beta \) value through the
Figure 71 \( \beta \) Value Statistical Summary, Runs 15–17 (Selected data)

\[ \beta = 3.73 \text{ (pilot)} \quad \beta = 3.43 \quad \beta = 2.92 \]

\# pts. = 11 (each) \quad \# pts. = 11 \quad \# pts. = 22

Note: Analysis includes only those samples acceptable on the basis of turbidity.
Figure 72  "Brownian" Region Slope Statistical Summary, Runs 15–17 (Selected data)
Figure 73 "Shear" Region Slope Statistical Summary, Runs 15-17 (Selected data)
direct filtration treatment steps. The raw water $\beta$ values of both the plant and pilot systems did not change and still have the same relationship with the raw water $\beta$ values from the conventional treatment portion of this study. The coagulated water $\beta$ values dropped from 3.55 to 3.43. As discussed previously, those samples for which coagulation was not effective would exhibit no change of $\beta$ value as a result of the coagulation step whereas those samples for which coagulation was effective would exhibit a change of $\beta$ value as a result of flocculation in the downstream pipe fittings. By removing those data points for samples which underwent ineffective coagulation, the average $\beta$ value should, and did, decrease as a result of the increased particle sizes due to flocculation.

The $\beta$ value of the filtered water decreased from 3.23 to 2.92 by removing the ineffective coagulation data points. Because filtration during periods of ineffective coagulation is not going to significantly affect the particle size distribution, the $\beta$ value of the filter effluent during such periods will be similar to the $\beta$ value of the influent water. However, during periods of effective coagulation and filtration, the $\beta$ value of the filter effluent will be lower than the filter influent if the effluent particle size distribution is controlled by the detachment of large, previously attached deposits. The fact that the filtered water $\beta$ value dropped when the ineffective coagulation data points were removed supports the theory that the detachment mechanism controls the effluent particle size.
distribution.

Figure 72 shows the slope of the "Brownian" region of the volume distribution function for the revised data points from Runs 15-17. As with the conventional treatment data and the previous whole set of direct filtration data, the slope of the "Brownian" region of the volume distribution function does not agree with Hunt's theoretical predictions and does not appear to show any trend through the treatment steps of the plant and pilot systems in the conventional treatment or direct filtration mode. With only 11 data points in the database, the 95% confidence intervals show that the data exhibits a very large spread. The volume distribution function "shear" region data, Figure 73, is statistically related to the $\beta$ value data so that the discussion of the $\beta$ value data also applies to the "shear" region of the volume distribution function.

8.6 Filter Coefficient Analysis, Runs 15 and 17

Consider the proposed filtration model (Equation 11):

$$\frac{C}{C_0} = e^{-(\lambda_a + \lambda_d)z}$$

(11)

where $C =$ concentration [mass/volume, volume/volume, turbidity, etc.]
$\lambda_a =$ filter coefficient of attachment [length$^{-1}$]
$\lambda_d =$ filter coefficient of detachment [length$^{-1}$]
$z =$ media depth [length]
The distinction between effluent particles which have passed through the filter bed and effluent particles which have been deposited on the filter grains and subsequently reentrained into the flow was again made strictly on the basis of particle size, with all particles below 2.4 µm being considered as particles which have passed through the filter and all particles above 2.4 µm being considered as particles which were deposited onto the filter grains and subsequently detached and reentrained into the flow (see discussion in Section 5.3).

Figures 74-76 show the overall, attachment, and detachment filter coefficients for Run 15 as functions of time. Run 15 did not exhibit any type of breakthrough curve with turbidity or particle size distribution data nor does it with filter coefficient data. The data point at 0.25 hours, which has overall, attachment, and detachment filter coefficients all below zero, falls under the influence of the high influent turbidity peak previously discussed (see Section 8.2). The magnitude of the filter coefficients, corrected for filter media depth differences, is comparable to the conventional treatment data from Run 10.

Figures 77-79 show the overall, attachment, and detachment filter coefficients for Run 17 as functions of time. Run 17 exhibited a turbidity breakthrough due to ineffective coagulation. This breakthrough is also reflected in the filter
Figure 74  Overall Filter Coefficient, Run 15
Figure 75  Attachment Filter Coefficient, Run 15
Figure 76 Detachment Filter Coefficient, Run 15

Filter Coefficient, $\lambda_d$
(based on volume removal, depth = 14.5", and 9")

Time, hours

Figure 76 Detachment Filter Coefficient, Run 15
Figure 77  Overall Filter Coefficient, Run 17

Filter Coefficient, $\lambda$ (based on volume removal, depth = 30')

- ■ Filter 1 (0.6–60 μm)
- Filter 2 (0.6–60 μm)

Time, hours

0  5  10  15  20  25  30

-0.2  -0.1  0.0  0.1  0.2  0.3  0.4

Figure 77  Overall Filter Coefficient, Run 17
Figure 78 Attachment Filter Coefficient, Run 17
Figure 79  Detachment Filter Coefficient, Run 17
coefficient analysis. Figure 77 shows the general trend of an initial increase of the overall filter coefficient followed by a decrease to zero. This also corresponds to the trend of the turbidity breakthrough curve in terms of the time frame of the breakthrough curve. Figure 78 shows the same general trend of an initial increase of the attachment filter coefficient followed by a decrease to zero with the same time frame as the turbidity breakthrough curve. The magnitude of the filter coefficients, corrected for filter media depth differences, is comparable to both Run 15 and the conventional treatment data from Run 10.

With some interpretation the detachment filter coefficient shown in Figure 79 also demonstrates the breakthrough curve. Recalling the proposed conceptual filtration model (see Section 2.4), a negative filter coefficient is indicative of a net production of particle volume through the filter media in a certain size range. This can only happen as a result of the detachment of particles in that certain size range from the filter grains. However, since this analysis uses strictly particle size as the identifying criteria for detached particles, the detachment filter coefficient will often have a positive value when the particle range above the determining size experiences a net removal of particulate volume through the filter bed.

As with previous filter coefficient analyses presented here,
the detachment filter coefficient in Figure 79 has many positive data points. Those points that are off the graph have a filter coefficient equal to infinity as a result of the complete removal of all particulate volume above the determining size of 2.4 µm. By 22 hours, however, the detachment filter coefficient is zero. At this time, the effluent turbidity and particle concentrations were only slightly less than the influent because there was no filtration occurring due to ineffective coagulation and destabilization of the particles in the influent water. The effects of this condition on the filter coefficient analysis should be equivalent to those of the "wormhole" flow conditions from the proposed conceptual filtration theory. There is no attachment or detachment occurring to change the turbidity or particle size distribution so that both filter coefficients are zero.
9. DISCUSSION OF DIRECT FILTRATION STUDY

Although both pilot scale and plant scale operational problems plagued the direct filtration portion of the study, more evidence to support detachment as the mechanism controlling the particle size distribution shape of dual media filter effluent was gathered. Remembering that there were problems with flocculation occurring in the system which changed the shape of the particle size distribution function between the coagulation and filtration steps, the $\beta$ value from the particle size distribution function power law was again seen to decrease as a result of filtration in the direct filtration mode of operation. Since decreases in this $\beta$ value indicate increases in the particle size distribution function to larger size ranges, this provides evidence of particle detachment in the filters.

An analysis of Runs 15 and 17 using the proposed conceptual filtration model and equation (Equation 11), again showed that using particle size as the criteria to determine whether an effluent particle is a non-attached influent particle or a detached particle from the filter grain deposits is not an entirely unsuccessful method. Although operational problems which resulted in ineffective coagulation caused detrimental effects on the performance of the filters, these effects were explained using the proposed conceptual filtration model and
equation.
10. OVERALL SUMMARY OF WORK

The Brinkmann Particle Size Analyzer was used to characterize the particle size distributions, between 0.6 µm and 60 µm, of the raw, settled, and filtered waters of the Hugh A. Wyckoff Water Treatment Plant, a conventional treatment facility. Data was collected from both the plant treatment train and a pilot filter system at the plant site. The pilot filter system used filter columns which contained filter media identical to that in the plant filters. The pilot system was operated both in the conventional treatment mode, parallel with the plant filters, and in the direct filtration mode, independent of the plant treatment train.

During the initial part of this characterization, the trend of increasing particle size through the filtration step was noted using the power law function form of the particle size distribution function. The $\beta$ value exponent parameter from this power law function was seen to decrease through both the coagulation-flocculation-sedimentation treatment step and the dual media filtration treatment step. The mathematics of the power law form of the particle size distribution function are such that a decrease in this $\beta$ value indicates a shift in the particle size distribution towards larger particle sizes. This $\beta$ value is also indicative of the mechanisms responsible for forming and shaping the particle size distribution.
A literature review of filtration mechanisms indicated that an increase of particle sizes through a dual media filter could be the result of either filter pore flocculation or of particle detachment from the filter grains. A study of the available filter pore flocculation work indicated that filter pore flocculation in a system using polymer coagulants was less important than particle-grain and particle-particle attachments. In a system using inorganic coagulants only, the effects of filter pore flocculation should be even less. On the other hand, a study of available particle detachment studies revealed a large amount of experimental observations confirming particle detachment.

The literature review and the evidence that particle size was increasing through the dual media filtration step led to the formulation of a conceptual filtration model incorporating filter ripening, attachment and detachment mechanisms, and "wormhole" flow conditions. The conceptual model, shown in Figure 2, led to the following basic filtration equation (Equation 11):

\[
\frac{C}{C_0} = e^{- (\lambda_a + \lambda_d) z}
\]

(Equation 11)

where \( C \) = concentration [mass/volume, volume/volume, turbidity, etc.]

\( \lambda_a \) = filter coefficient of attachment [length\(^{-1}\)]
\[ \lambda_d = \text{filter coefficient of detachment \ [length}^{-1}\text{]} \]
\[ z = \text{media depth \ [length]} \]

This equation does not predict any phenomena that are not now generally observed, but it does incorporate a method for describing particle detachment in the filtration equation. This has been done by others (Mintz\(^3\), Adin and Rebhun\(^4\)), but not in a form directly compatible with the present day trajectory theories.

The attachment and detachment filter coefficients may be applied to both mono and dual media filter beds. However, when measuring the filter coefficients across a dual media filter bed, the ratio of the depths of the respective filter media layers must be held constant in order to compare filter coefficients measured from two or more different filters.

The disadvantage of this model is in measuring the attachment and detachment filter coefficients separately. The measurement of each coefficient separately is dependent upon being able to differentiate between effluent particles which were present in the influent to the filter but were not retained upon the filter grains and effluent particles which are deposits which were reentrained into the flowstream from the filter grains.

However, once a method of separating the effluent particles which have merely passed through the filter bed, without being
captured by a filter grain, from the effluent particles which have been detached from the filter grains is chosen, analysis using this filtration model is simple and rapid. The problem lies in accurately differentiating the non-attached particles in the effluent from the detached particles. Here, a strict size criteria was used with limited success.

In this study, characterization of the particle size distributions in the conventional treatment mode continued until over 200 raw, settled, and filtered samples had been analyzed to provide a significant database. The statistical analysis of these samples is presented in Figures 31-33. From this analysis, the particle size distributions of the raw, settled, and filtered waters were characterized as having $\beta$ values of 3.77, 3.33, and 2.81, respectively, indicating a consistent increase of particle sizes through the conventional treatment process.

In an attempt to closely study and model the breakthrough process, the pilot filter system was operated using shallow bed filters in the conventional treatment mode. However, the lower removal efficiency of shallow bed filters yielded generally unsatisfactory performance in terms of the particle size analysis, probably due to detection limitations of the particle size analyzer.

The pilot filter system was also operated in the direct
filtration mode in order to compare particle size distribution
trends of conventional treatment filtration with those of
direct filtration. However, problems at both the plant scale
and pilot scale levels limited the amount of data collection in
comparison with that obtained for the conventional treatment
portion of this study. A statistical analysis of the 44
samples comprising the direct filtration dataset are presented
in Figures 71-73. From this analysis, the particle size
distributions of the raw, coagulated, and filtered waters were
characterized as having $\beta$ values of 3.73, 3.43, and 2.92,
respectively.

One of the operational difficulties encountered with the pilot
filter system in the direct filtration mode, that of
flocculation occurring in the plumbing between the static
inline mixer and the filter influent point, is reflected in the
coaugulated water $\beta$ value being very similar to the settled
water $\beta$ value from the conventional treatment portion of this
study. This operational difficulty renders a
comparison/contrast of the conventional treatment and direct
filtration data almost meaningless.
11. CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

The following conclusions may be drawn from this study:

1. Particle size distributions in water treatment plants may be effectively and rapidly characterized, using modern, laser type particle size analyzers such as the Brinkmann Particle Size Analyzer.

2. The particle size distribution data obtained from the laser type instruments can be analyzed in terms of a power law function of the form $n(d_p) = A_0(d_p)^{-\beta}$ (Equation 15). The values of $\beta$ in this equation may be used to compare changes in the particle size distribution and to make associations with the predominant transport mechanism.

3. Such particle size characterization has provided a significant data base of both pilot scale and plant scale data from which to conclude that the particle size distribution in the effluent from dual media filters is controlled by the detachment of deposits from the filter bed.

4. The conclusion that detachment of deposits from the filter bed control the filter effluent particle size distribution has led to the development of a conceptual filtration model and equation (Equation 11) which incorporates both attachment and detachment terms in a form directly compatible with present day
The use of particle size analyzers to measure the quality of treated water will continue to increase as the regulations continue to become more strict. As treatment plants become more efficient at treating potable water, the use of turbidity as the primary indicator of water quality will become less effective. Eventually, regulatory agencies may turn towards regulations based on particle size distributions.

The conclusion that the particle size distribution in the effluent from dual media filters is controlled by the detachment of deposits from the filter bed raises the possibility of the passage of destabilized particles through a well operated filter. Moreover, these particles will be bound together as flocs and as dense filter grain deposits. Therefore, subsequent disinfection processes, such as chlorination, which rely on direct contact with the individual microorganisms, could be negated. This could become of more importance as, due to increased water demands, water treatment plants begin optimizing their operations, increasing filtration rates, and lengthening filter runs, thereby allowing more opportunity for deposits to become reentrained into the flowstream. Also, as concerns over trihalomethanes and other disinfection byproducts increase, use of less effective doses of disinfectants will tend to further shield microorganisms which are embedded in reentrained filter grain deposits.
Further experimental studies in this area should address both the continued characterization of various types of waters and treatment processes as well as the continued development of the filtration model and theory. The next step in the development of the proposed filtration equation (Equation 11) will be to relate the attachment and detachment coefficients to fundamental considerations of the mechanisms responsible for filtration and for the reentrainment of deposits from the filter grains. The trajectory theories under development today may be directly related to the attachment coefficient. Development of fundamental theories for the detachment mechanism will require knowledge of interactions between the forces of attraction between materials and hydrodynamic shearing.
# REFERENCES


37. Brinkmann Particle Size Analyzer Model 2010. Sales brochures, operating manual, and personal communication with staff.