An evaluation of high rate filtration using particle counting and turbidimetry for low turbidity waters

O.D. Schneider*, D. Nickols*, L. VandeVenter** and S. Leggiero***

* Hazen and Sawyer, P.C., 498 7th Ave., NY, NY, 10018, USA
** Metcalf and Eddy, Inc., 30 Harvard Mill Square, Wakefield, MA 01880, USA
*** New York City Department of Environmental Protection, Bureau of Environmental Engineering, 59-17 Junction Blvd, Corona, NY 11368, USA

Abstract A pilot-scale evaluation of high rate filtration using both on-line turbidimeters and optical on-line particle counters was performed. At turbidities approaching the detection limit of the equipment (less than 0.05 ntu), particle counting proved to be a much better indicator of filtration performance. In addition, at these low turbidities, large changes in particle counts (one to two orders of magnitude) would register with only minor changes in turbidity (less than 0.02 ntu).

Keywords High-rate granular media filtration; particle counting; water treatment

Introduction

As economic constraints become more prevalent in the design of water treatment facilities, the trend in design of treatment plants has been towards higher rate processes in order to minimize plant footprints and numbers of appurtenances. This is exemplified by the emergence in North America of such high rate processes as inclined plate settlers (up to 5 m/hr (2 gpm/sf)), dissolved air flotation (up to 20–25 m/hr (8–10 gpm/sf)), and micro-ballasted sand process such as Actiflow™ (up to 50–75 m/hr (20–30 gpm/sf)). In addition to these high-rate clarification steps, designers have been moving away from building “conventional” porous media filters and towards a new generation of filter designs. These “new” filters are characterized by higher filtration rates (from 15 up to 50 m/hr (6–20 gpm/sf)), deeper (up to 2.4 m (8 feet)), and coarser (up to 2–3 millimetres (mm)) media. These filters have been shown in many pilot and full-scale operations to effectively remove suspended solids from water. However, the use of higher filtration rates removes some of the conservatism built into “conventional” filter design. Additionally, because these high rate filters can operate at least some of the time out of the laminar flow regime (local Reynolds Number, \( N_{Re} > 10 \)), limitations are placed on the applicability of existing filtration models and the conceptual understanding of particle interactions with filter media. Moreover, because these filters are appearing simultaneously with an increased emphasis on removal of particles, monitoring of high-rate filter performance and new filtration models that consider fluid flow under high rates must be developed.

In order to confirm treatment options and optimize design parameters for treatment of New York City’s Croton water supply, a pilot-scale treatment plant was operated at the New Croton Reservoir from August 1996 to March 1999. The goal of this pilot operation was to confirm possible treatment alternatives and optimize design parameters so that cost estimates could be developed, leading to the process selection and design of a 12.7-m³/s (290-mgd) treatment plant. Currently, the Croton supply is unfiltered. The raw water is of very high quality and meets the quantitative filtration avoidance criteria under the Surface Water Treatment Rule. However, filtration is required for aesthetic reasons and because of concern over the extent of watershed control.
During the pilot testing of several proposed treatment processes for the Croton Reservoir, side-by-side turbidity and particle count data were collected for several filters and several processes. It quickly became apparent that, despite near optimal coagulation, particles were breaking through the deep-bed filters, even at turbidities below 0.05 ntu. More disturbingly, the size of the particles exiting the filters, 3–5 µm, is the same size range as Cryptosporidium oocysts. Particle breakthrough usually did not occur concurrently with turbidity breakthrough. In fact, when the particles broke through, only slight increases in turbidity (<0.02 ntu) were observed. Turbidity generally began to breakthrough only several hours after the particle breakthrough began. Thus, until these particles could be prevented from breaking through the filters, these filtration processes could not be assumed to be optimized.

Because certain sized particles were breaking through the filters while the filters were still removing other particle sizes, this phenomenon is more likely related to particle detachment rather than true breakthrough. Nonetheless, the breakthrough and detachment phenomena may overlap. However, for the purposes of this discussion, these two phenomena will be defined as follows:

**Breakthrough** – particles of many different sizes passing into the filtered water after the removal capacity of the filter bed has been exhausted. Breakthrough may occur because of improper coagulation (poor removal efficiency – the collision efficiency factor for filtration, \( \alpha_f \), is low) or because of high headloss (void spaces full, removal capacity of the bed is exhausted).

**Detachment** – hydrodynamic forces breaking off particles in discrete size ranges that were previously deposited. Detachment may occur early in a filter run despite optimum or near-optimum chemical conditioning. Because the particle removal capacity of the bed may not have been exhausted, continued removal of particles can still occur while other particles are breaking off.

**Literature**

While many models have been created to predict and explain the attachment of particles to collectors in filters (Yao, et al., 1971; Iwasaki, 1937; Rajagopalan and Tien, 1979), relatively little work has been done to understand the detachment of particles from filter media. Some of those models that do include detachment as a parameter simply include it as a parameter that is balanced by attachment to the media collector without giving any fundamental insight into how and why detachment occurs (Ginn et al., 1992).

In a fundamental study of particle detachment, Raveendran and Amirtharajah (1995) examined the forces that affect particle removal in porous media filters. Although this study was geared more towards backwashing issues, the principles involved can also be used to examine particle detachment during a filtration cycle. The calculations in this paper were based upon a transition flow regime \( \left(N_{Re} > 10\right)\). An analysis of Reynold's numbers for the two coagulation trains in the Croton pilot plant indicated that for most conditions, filtration was occurring in the transition flow regime. Only the very beginning of a filtration cycle at the lowest filtration rates tested occurred with laminar flow conditions. The common flow regime reinforces the applicability of these results for the filtration processes tested at the Croton pilot plant. Raveendran and Amirtharajah included non-Derjaguin, Landau, Verwey, and Overbeek (DLVO) hydrodynamic forces and hydrophobic/hydrophilic interactions along with the classical DLVO model of particle-particle interactions in order to calculate the force required to pull a particle off of a collector (filter media grain) and into the bulk fluid. As a basis of this work, the adhesion force for particles on a clean filter media (unripened) and for particles on previously deposited particles was calculated. Attractive van der Waals forces were calculated for varying thickness of deposited...
particles. The calculations showed that the attractive force is not affected by the thickness of deposit greater than approximately 0.1 µm (the lower limit of colloidal sizes). Therefore, detachment of particles after ripening has occurred is not a function of the amount of deposit (headloss).

A series of papers from the University of Texas (Moran, D. et al., 1993; Moran, M. et al., 1993; Lawler et al., 1995; Kau and Lawler, 1995) examined the dynamics of particle behavior during a filtration cycle. These studies evaluated sedimentation basin effluent from a lime softening plant. As such, the particles in the water consisted primarily of calcium carbonate. These studies found that filter ripening and breakthrough were strongly dependent on particle size. Surprisingly, during the filtration runs, the authors found that particles in the 3 to 7 micrometre range were susceptible to early breakthrough, although this breakthrough was not detectable by turbidity measurements. This breakthrough was attributed to detachment or breakoff of previously deposited materials in the filter bed. The one factor that had the greatest influence on detachment was specific deposit (amount of pore space occupied). During these studies, headloss, media size, and filtration rate did not seem to play important roles in detachment. Most importantly, the authors concluded that the particles that broke off were not primary particles but consisted of smaller particles that flocculated within the filter bed. The public health significance of this conclusion is important. If coagulation chemistry is properly performed, cysts initially captured by the filter and that detach will most likely be part of a larger size agglomerate. Consequently, the use of particle counters in a narrow size range as a surrogate for Giardia cysts or Cryptosporidium oocysts may be inappropriate.

Turbidimetry is based upon the measurement of Rayleigh scattering under special conditions. When light impinges on particles, the light will be scattered in all directions. The pattern of scattering by particles was first described by Lord Rayleigh. Modern turbidimeters use a single angle, 90° in the horizontal plane, to measure the ratio of scattered light to incident light. This is the basis of a nephelometry. Rayleigh scattering is dependent on the incident wavelength of light, the scatterers’ (particles’) refractive index, the number concentration of scatterers, and size of the scatterers (Heimenz, 1986). In the instance of many particles of interest to the potable water field, the size of the particles (0.7 to 15 µm) is not that much greater than the wavelength of the incident light (300 to 700 nm, equivalent to 0.3 to 0.7 µm). Thus, the intensity of the scattering is characterized by extreme scattering in the forward direction with development of maxima and minima of scattering intensity at wider angles (Rowell, 1992). Sethi et al. (1997) present an excellent discussion of optical detection methods, describing the physical components of turbidimeters and optical particle counters as well as the theory of Rayleigh and Lorenz-Mie light scattering.

In waters with a low number concentration of particles, it may be better to think of a turbidimeter as measuring a property of the particles in the water, i.e., light scattering, rather than measuring a property of the water. Under this frame of reference, the turbidity is a function of the size, number, and refractive index of the particles. Thus, for a single particle, the response of a turbidimeter will be greater to a particle with a higher refractive index. Typically, mineral phases such as amorphous aluminium or iron hydroxide will have a higher refractive index, while biological particles will have lower refractive indices (often close to 1). Thus, this makes turbidity a relatively poorer surrogate measurement for small numbers of biological particles in the water as compared to particles that are mineral in nature. This is because in a system comprised of a single biological particle among many mineral particles, the response of the turbidimeter to the bioparticle will be lower than the response to a mineral particle and could well appear as electronic noise to an observer.
**Experimental system**

The New York City Department of Environmental Protection (NYCDEP) has decided to begin filtering its Croton watershed supply. In order to determine the best treatment option for the Croton supply, an extensive pilot program was performed over several years.

The pilot plant consisted of four distinct treatment trains – a direct filtration train with preozonation, a dissolved air flotation (DAF) train with intermediate ozonation, a diatomaceous earth filtration train with preozonation and intermediate GAC contactors acting in a biological filtration mode, and several micro- and ultrafiltration membrane systems.

Because diatomaceous earth and membrane filtration operate on a sieving principle rather than the attachment principle that is the primary removal mechanism in deep-bed porous media filtration, the results of these filtration processes are not discussed in this paper.

The New Croton Reservoir raw water is of high quality and is typical of many protected surface waters found in the northeastern US. The water has moderate alkalinity (54 mg/l as CaCO₃) and is typically near-neutral pH. The turbidity averages about 1.2 ntu and counts of particles larger than 3 µm in diameter are moderate (9,700/ml). The true color of the water averages 8 scu and the TOC averages 2.9 mg/l. The uniform formation condition (UFC) formation of total trihalomethanes (TTHM) and five haloacetic acids (HAA5) average 78 µg/l and 52 µg/l, respectively.

The Ozone-Direct Filtration train consisted of a three-stage ozone contactor (total hydraulic detention time was 21.8 min.), a four-stage flocculator (detention time = 4 min.), and seven filters. These filters were configured as shown in Table 1. A Process flow schematic for this process train is shown on Figure 1. The filters were cleaned with an air scour followed by conventional backwash to expand the media 10 to 20%. In order to enhance biological growth on the filter media, the filters were backwashed with unchlorinated water. The preozone dose was varied between 0.75 and 2.0 mg/l. The coagulant doses generally were 4.5 to 9 mg/l of alum with 1.0 mg/l of cationic polymer (Superfloc® C-572 (from Cytec Corporation, Wayne, NJ, USA), a low molecular weight, high charge, polyamine). Several manufacturers non- and anionic filter aid polymers were also tested as coagulant aids. These coagulation conditions resulted in filtered water turbidities routinely below 0.05 ntu and counts of particles larger than 3 µm less than 20/ml.

The DAF-Intermediate Ozone-Filtration train consisted of a three-element static mixer, two-stage flocculation (total detention time was 8 minutes), a dissolved air flotation basin typically operated at 6–8 gpm/sf (15–19 m/hr), but tested as high as 10 gpm/sf (24 m/hr), a three-stage intermediate ozone contactor (hydraulic detention time was 19.4 min.), and five

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Granular media configurations</th>
</tr>
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<td>Train</td>
<td>Number of Filters</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Ozone – Direct Filtration</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Ozone – Filtration</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>DAF – Ozone – Filtration</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Notes:</td>
<td></td>
</tr>
<tr>
<td>1. Reynolds Number is based on a clean bed, 21C, and 40% bed porosity. Values for 4C are approximately 37% lower</td>
<td></td>
</tr>
</tbody>
</table>
monomedium filters composed of either GAC or anthracite. The configuration of these filters is also shown in Table 1. A process flow schematic for this train is shown on Figure 2. The filters were cleaned with an air scour followed by conventional backwash to expand the media 10 to 20%. In order to enhance biological growth on the filter media, the filters were backwashed with unchlorinated water. The intermediate ozone dose was varied between 0.6 and 1.5 mg/l. The coagulant doses generally were 10 to 20 mg/l of alum with 1.0 to 1.5 mg/l of cationic polymer (Superfloc® C-572). Several non- and anionic filter aid polymers were also tested as coagulant aids. These coagulation conditions resulted in floated water turbidities of approximately 0.4 to 0.8 ntu and filtered water turbidities routinely below 0.05 ntu and counts of particles larger than 3 µm less than 20/ml.

As part of the optimization, side-by-side on-line turbidity and particle count measurements were conducted. The on-line turbidimeters were Hach 1720C process turbidimeters (Hach Company, Loveland, CO, USA). Two particle counters were used, Chemtrac (Chemtrac Systems, Inc., Norcross, GA, USA) digital counters with four separate channels: 2–3 µm, 3–5 µm, 5–8 µm, and >8 µm and Met-One (Met-One, Grants Pass, OR, USA) digital counters with five separate channels: 2–3 µm, 3–5 µm, 5–8 µm, 8–15 µm and >15 µm. The turbidity and particle counts along with filter flow rates and differential
pressure across the filters were collected at 15 minute intervals and stored by a data acquisition system.

Results

Discovery of problem

Early during the testing, it was discovered that particles would begin to breakthrough the filters at very low filtered water turbidity (as low as 0.035 ntu) with only a slight rise in turbidity (less than 0.02 ntu). During this small change in turbidity, particles would often increase from fewer than 20/ml to more than 200/ml over a few hours. Typical results for the Ozone-Direct Filtration train and the DAF-Ozone-Filtration train are shown in Figures 3 and 4. Table 2 shows average particle and turbidity results for 32 DAF filter runs conducted between April and August 1997. Data from the Direct Filtration runs are not included in this table as the particle breakthrough problem experienced with this train was eliminated early in the testing.

Particle breakthrough occurred at different points during filtration runs. Sometimes breakthrough occurred near the end of a run when terminal headloss was nearly reached. However, particle breakthrough also occurred when only half of the allowable headloss had accumulated. The breakthrough was found to occur in filters of different size media (0.9-mm to 1.4-mm effective size), different media types (GAC and anthracite), different filtration rates (6 to 14 gpm/sf) and different processes (both DAF and direct filtration).

An examination of the particle count data and turbidity indicated that in every run where particle breakthrough was observed prior to turbidity breakthrough, particles in the 3–5 µm range first broke through followed by the 5–8 µm particles, and then followed by the

![Figure 3](https://iwaponline.com/ws/article-pdf/2/1/249/408705/249.pdf)  
**Figure 3** Typical filter run results for Ozone-Direct Filtration train

![Figure 4](https://iwaponline.com/ws/article-pdf/2/1/249/408705/249.pdf)  
**Figure 4** Typical filter run results for DAF-Ozone-Filtration train
2–3 µm particles. Figure 5 shows a typical breakthrough curve for the DAF-Ozone-Filtration train.

Analysis of particles and turbidity

When the turbidity data is plotted against the particle count data, several regions with straight-line responses (ripening and detachment) are seen, as shown in Figure 6. A similar figure showing the turbidity plotted against the measured particle surface area (the arithmetic sum of the surface area from individual particle counted) is shown in Figure 7. For the entire data set, the statistical correlation between turbidity and particle surface area is 0.91. In other words, 91% of the variation in turbidity can be explained by the variation in measured particle counts. During the detachment phase of the filtration cycle, the statistical correlation between particle surface area and turbidity exceed 98%. This appears to indicate that very few sub-micron particles (those that scatter light very well and are an important component of turbidity) were passing through the filter. Conversely, during the ripening phase of the filtration cycle, a lower percentage (93%) of the variation in turbidity can be explained by the measured particle surface area. Therefore, it is possible to infer that

Table 2  Particle and turbidity data for DAF filter runs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run length to 50 counts/ml (hr)</td>
<td>31.7</td>
<td>10.0–60.8</td>
</tr>
<tr>
<td>Run length to 0.1 ntu (hr)</td>
<td>40.5</td>
<td>18.0–68.0</td>
</tr>
<tr>
<td>Maximum turbidity during run (ntu)</td>
<td>0.054</td>
<td>0.036–0.079</td>
</tr>
<tr>
<td>Minimum turbidity during run (ntu)</td>
<td>0.040</td>
<td>0.028–0.056</td>
</tr>
<tr>
<td>Minimum particle counts during run (#/ml &gt;2 µm)</td>
<td>6</td>
<td>1–23</td>
</tr>
<tr>
<td>Headloss at particle breakthrough (m H2O)</td>
<td>1.4</td>
<td>0.2–2.4</td>
</tr>
<tr>
<td>Ripening time to 50 counts/ml (hr)</td>
<td>0.26</td>
<td>0–10.3</td>
</tr>
<tr>
<td>Ripening time to 0.1 ntu (hr)</td>
<td>0.16</td>
<td>0–6.3</td>
</tr>
<tr>
<td>Unit Filter Run Volume (m³/m²)¹</td>
<td>900</td>
<td>350–1,350</td>
</tr>
<tr>
<td>Extra water production (m³/m²)²</td>
<td>200</td>
<td>0–685</td>
</tr>
</tbody>
</table>

Notes:
1 UFRV was determined at either particle breakthrough or accumulated headloss, whichever was less
2 Extra water production is defined as the water production to 0.1 ntu minus the water production to 50 counts/ml larger than 2 µm
more sub-micron particles are present in the filtered water during ripening than during the detachment phase.

At the minimum measured turbidity (0.037 ntu), the total particle counts were on the order of 10/ml. An increase of one order of magnitude in the total number of particles larger than 2 microns occurs over a change in turbidity of less than 0.02 ntu. This demonstrates that with relatively few particles in the water, particle counters are more sensitive to increases in the number concentration of large particles than turbidimeters. In combination with turbidimeters, particle counters can tell operators about the nature of the particles in the water.

Control of particle detachment
In order to reduce the likelihood of particle detachment several operational changes to the pilot experiments were tried. Coagulant doses were increased, ozone doses were adjusted,
and mixing intensities were changed. However, no clear answer emerged as to the cause of the problem and these attempts to control the detachment did not work. The use of both nonionic and anionic filter aid polymers was investigated. The use of nonionic polymers did not seem to aid in particle retention and increased headloss in the filters. However, the use of several different anionic polymers resulted in increased particle retention without significantly increasing filter headloss gradients. For the direct filtration train, anionic polymer doses as low as 0.005 mg/l were able to achieve particle retention. However, for the DAF train, polymer doses in the range of 0.05 to 0.1 mg/l were required to retain the particles in the filter media until terminal headloss was achieved.

**Conclusions**

Although the coagulation appeared to be optimized as indicated by the very low filtered water turbidities, both coagulation trains experienced particle detachment for different media types and flow rates. The role of proper coagulation to achieving low concentrations of particles in the filter effluent cannot be downplayed. However, it appears that the physical parameters of a system (loading rate, media type, and media size) are also important factors in the detachment of particles.

For both of the coagulation trains, the use of anionic polymers helped retain particles in the media longer into the filtration cycle. While the use of filter aids does add capital and operational costs to the plant, the increase in water production provided by these polymers more than makes up for these costs.

Without the presence of on-line particle counters, slight increases in filtered water turbidity could easily be ignored as noise or as insignificant. However, the pilot data showed that large changes in particle counts might not register as noticeable changes in turbidity. This demonstrates the efficacy of individual particle counters for filters in order to understand filtration dynamics. Because, as shown in the literature (Moran, D. et al., 1993; Moran, M. et al., 1993; Lawler et al., 1995; Kau and Lawler, 1995), it appears that particles that detach from filters are actually flocs of smaller primary particles, the use of particle counts as a surrogate for pathogenic cysts may be incorrect as the particle counts would severely overestimate the number of cysts passing through the filters. For filtered waters with turbidities approaching the detection limit of the equipment, the data from well-calibrated particle counters should be given greater weight than turbidity data. The particle counters will give information that is more valuable and will show increases in particles due to detachment well before turbidity responds to the surface area of additional particles in the filter effluent.

While the cause of the particle breakthrough was not clearly established, this phenomenon is consistent with the findings of Moran et al. (1993). Rather than true particle breakthrough (as defined earlier in this paper), it is more likely that detachment of previously deposited particles is occurring. Whether the particles that pass into the filtered water effluent are the same size as when they entered the filter bed is unknown. Interestingly, the particle size that was the first to detach during these pilot studies was of the same size as those found in the University of Texas studies (Moran, D. et al., 1993; Moran, M. et al., 1993; Lawler et al., 1995; Kau and Lawler, 1995) despite very different particle chemistry (amorphous aluminum hydroxide flocs compared to crystalline calcium carbonate). This may indicate that some basic forces are at work and that these size particles, regardless of their chemical composition, are particularly susceptible to detachment. Thus, further studies of particle detachment during filtration would seem to be warranted.

The 3 to 7 µm particles that are most likely to pass into the filtered water are Cryptosporidium oocyst-sized, which may have profound public health significance. If these particles are composed of smaller particles that flocculated in the filter bed and then
broke off, it is unlikely that public health will be significantly compromised by a small number of particles in the filtered water. However, if the particles are primary particles that detached from the filter after being collected, these cyst-sized particles could pose a significant public health risk.

References


