Removal of Microorganisms by Rapid Sand Filtration

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Emergence of Filtration

Well before Koch's proof of the "germ theory," water filtration was advocated and utilized for the protection of health. Sir Francis Bacon (1627) conducted water filtration studies "to improve health and increase the pleasure of the eye." As described by Baker (1948), the beneficial health effects of filtration became scientifically established over the century prior to the development of the rapid sand filter.

The 'American rapid' filter of the 1880's was the first major step in the engineering optimization of the filtration process. Twenty-fold increases in flow rates resulted in proportionately reduced filter area requirements. However, rapidly accumulated solids required more frequent, mechanical filter cleaning. Although not superior to slow sand filtration in effluent water quality, rapid sand filtration was quickly embraced world-wide as a more economic, less labor-intensive and more readily automated process. Today, rapid sand filtration, generally preceded by coagulation and sedimentation, has become the predominant final physical barrier to the passage of microbial pathogens into public drinking water systems.

As described in 'Water Treatment Plant Design' (ASCE, 1990), developmental efforts have continued to be directed at accelerating water filtration rates and lowering treatment costs. This has been achieved principally through substitution of coarser filter media and elimination of pretreatment processes, as in direct filtration. Historically rejected as ineffective (Baker, 1948), filtration without sedimentation (direct filtration) requires the filter unit to remove and store within the filter medium all of the source water suspended materials, including microorganisms. The engineering and economic optimization of water treatment has resulted in the conversion to filters which are progressively more porous, are operated at higher rates, and are increasingly dependent upon the use of synthetic polymeric coagulants. Coarser-grained, high-rate filters require more operational attention to avoid variable effluent quality. While less efficient than low-rate filters, they have been found capable of meeting prevailing turbidity standards (ASCE, 1990).

Evaluation of Filtration Effectiveness

Filtration is the passage of water through a porous medium for the removal of particles in suspension. Source water particles may include silt, clay, metal oxides, and organic fibers as well as a wide range of microorganisms, some of which are potentially harmful. Prominent biotic particles include 5 to 20 μm algal microcolonies, 3 to 10 μm protozoan cysts, 0.2 to 2 μm bacterial cells, and 0.01 to 0.1 μm virus particles.

The effectiveness of filters was initially evaluated for the removal of suspended solids (or turbidity), color (apparent), organic matter (volatile solids), and plate count bacteria (Fuller, 1898). With the advent of drinking water regulations, the evaluation of filtration performance rapidly narrowed to compliance monitoring for the reduction of *turbidity*, which served as a primary microbiological surrogate for physical removal processes. The combined effectiveness of filtration and disinfection is monitored through total *coliform bacteria*. Few utilities routinely monitor for heterotrophic plate count (HPC) bacteria. Only in the past decade have limited direct observations been made to demonstrate physical removal of specific pathogens, such as Giardia and Cryptosporidium (Rose, 1988).

Comprehensive assessments of the actual removal of total bacterial cells, particle-associated bacteria, algal microcolonies, and nematodes were conducted at a water treatment plant treating Missouri River water (Brazos and O'Connor, 1986, 1987, 1988, 1990). Direct microscopic observations of the effectiveness of comprehensive, two-stage pretreatment and rapid sand filtration revealed unexpectedly large seasonal differences in the physical removal of specific particles. During periods of low water temperature, microorganism removals were found to decline significantly, whereas consistent reductions in turbidity (silt, clay) made treatment appear effective year-round. As a result, winter periods of poor microorganism removals consistently passed unnoticed.

Turbidity as a Microbiological Surrogate for Evaluation of Filtration Efficiency

The rationale for the use of turbidity reduction for evaluation of filtration efficiency has been based on the assumption that microorganisms, many of which contribute little to turbidity because they are translucent and scatter light poorly, are removed with an efficiency equal to or better than that of inorganic, light-scattering, and light-absorbing particles such as silts and clays. This concept of "parallelism" was based on comparative observations of turbidity and overall bacterial (plate count) reductions during water treatment. It was generally assumed that most microorganisms were embedded in or attached to the surface of larger particles in suspension. From this hypothesis, it followed that the removal of those larger particles ensured the removal of virtually all the pathogenic microorganisms from the source water.

The 1986 reauthorization of the Safe Drinking Water Act necessitated reevaluation of the scientific basis for the use of turbidity as one of only two primary microbiological standards for drinking water. USEPA prepared a formal Turbidity Criteria Document (USEPA, 1986) to advance the justification for continued use of turbidity both as a Primary Drinking Water Standard and for the evaluation of water treatment plant performance. However, the data cited in the Document showed that water treatment processes did not accomplish parallel removals of turbidity and microbial indicators, such as total coliform, heterotrophic plate count, Giardia cysts, or virus. Ultimately, USEPA was unable to defend a rationale for establishing a Maximum Contaminant Level (MCL) for turbidity on the basis of any relationship to either the presence of microbial pathogens or their removal.

Instead, USEPA appended a modified turbidity limit ("operating criteria") of 0.5 ntu to the Surface Water Treatment Rule (USEPA, 1989). This more restrictive limit requires filtration of those low turbidity surface waters which were found to be the major source of giardiasis (Ongerth, 1989). Observing that even reducing turbidity to 0.5 ntu did not ensure effective cyst removal, Ongerth (1990) called for the production of drinking water with the lowest attainable turbidity.

A recurrent argument for another health implication of high finished water turbidity (>1 ntu) has been that suspended matter interferes with disinfection by creating a significant disinfectant demand (USEPA, 1986). However, a study which evaluated the chlorine demand in 160 drinking water sources determined that only 10 percent of their chlorine demand was associated with the suspended solids (Katz, 1986).

The events surrounding the waterborne outbreak of cryptosporidiosis at Carrollton, Georgia dealt a major blow to the reliance on finished water turbidity as a microbiological surrogate for monitoring for protection against pathogens. During the winter of 1986-1987, a large segment of the community contracted diarrhea. *Cryptosporidium spp.* was ultimately identified as the probable cause (Rose, 1988). Despite filtered water turbidity levels well within 1 turbidity unit, the absence of total coliform bacteria in the distribution system and the maintenance of a hypochlorous acid residual in the range of 1.4 to 1.7 g chlorine/m^3, the dual-media filtration plant was found to be passing 5μm oocysts of *Cryptosporidium spp.* (Logsdon et al., 1988). During the cold temperature period of filtration plant failure, finished water turbidity averaged 0.4 to 0.5 ntu with peaks up to 1.0 ntu. The following winter, improvements in coagulation reduced finished water turbidities to the range of 0.03 to 0.05 ntu. The occurrence of this substantial disease outbreak at a water utility which was in compliance with all regulations that presumed to guarantee the microbial safety of drinking water underscored the unreliability of existing microbiological standards as predictive tools.

Identification of Particles in Source Waters

Almost exclusive reliance on the conveniently-measured, light-scattering properties (turbidity) of diverse solids in water as a microbiological surrogate has delayed resolution of the major weakness in the performance evaluation of water filtration; the failure to characterize the diverse particles in suspension and observe their individual removal efficiencies. Naturally-occurring particles in drinking water sources are generally mixtures of metal silicates, oxides, carbonates, sulfides, natural and anthropogenic organic debris, plus a range of microorganisms. Different classes of biotic and abiotic particles, depending on size distribution, density, charge, shape, and surface characteristics, may both scatter light and respond to coagulation and filtration differently.

As early as 1977, the National Research Council called for the identification and quantification of particles in source, pretreated and filtered water. Despite the recognition of this deficiency, the panel was convinced that such studies would reveal that microorganisms were predominantly attached to larger particles. In its report on Drinking Water and Health (NRC, 1977), the Safe Drinking Water Committee stated:

> *"The tendency of microorganisms to form aggregates and to become concentrated at the surfaces of solid particles, rather than to be uniformly and individually dispersed, may have important consequences for their survival and for their reactions to the various processes of water treatment. It is doubtful that many of these microbial agglomerates will pass through an efficiently operating water-treatment process....*
>
> *"Studies of microbial aggregates in terrestrial environments... demonstrated that the most extensive microbial growth takes place in nature on the surfaces of particles and inside loose flocs of solid particles. This occurs because the nutrients required for microbial growth are also adsorbed at the surfaces of these particles. Only a few microorganisms are found free in the soil solution or in raw water because of the lack of dissolved nutrients.*
>
> *"River silt adsorbs viruses with moderate efficiency and does not relinquish them very easily...studies on viral adsorption to sand, silt, clays and organics (feces) to form particulates are consistent with what is known for bacterial aggregates."*
>
> The Committee concluded that: *"Investigations are required of the physical-chemical attachment of microorganisms to sand, silt, clays, and organic particles, and disaggregation of these particulate complexes."*

The widespread assumption that source water microorganisms were predominantly attached to surfaces of suspended particles might have been influenced by the interpretation of the (heterotrophic) plate count (HPC) as "total bacterial" count when, in fact, these bacteria may comprise 1 percent or less of the total number of the bacteria present in drinking water sources (Brazos and O'Connor 1984). However, these HPC colony-forming units have been found to be comprised largely of more active organisms or groups of organisms clustered on larger particles (Brazos and O'Connor, 1988). By far, the majority of cells in source waters have been found to be planktonic. Particularly during periods of cold water temperatures, organisms in source waters may also be in a state of exogenous dormancy (metabolically inactive). With the preferential physical removal (as well as chemical inactivation) of HPC particle-associated organisms during treatment, planktonic cells dominate the populations observed entering distribution systems.

Total Bacterial Populations

Field studies using direct microscopic counting techniques have shown that the total bacterial populations of source waters range from 10^4 (groundwater) to over 10^7 (surface water) cells per milliliter (Brazos and O'Connor, 1984). Bacterial cells are more abundant than the total of all other particles larger than 0.2 μm in filtered waters by three to four orders of magnitude. Even following comprehensive pre-treatment, rapid sand filtered surface waters may exhibit total bacterial cell counts of 10^6 per ml.

Electronic particle counters used by water utilities generally enumerate less than 1 percent of the total particles which would be observed microscopically. This lack of particle counter resolution makes it appear that bacterial-sized particles are nearly absent in rapid sand filtered waters (Cleasby et al., 1989).

Because USEPA staff were convinced that most microorganisms were associated with and removed along with turbidity, biotic particles were not even addressed as a separate class of particle in the Turbidity Criteria Document (USEPA, 1986) which contends that microorganisms constitute "an extremely small portion of the total number of particles in water."

Planktonic and Particle-Associated Microorganisms

Drinking water sources contain a seasonally variable mixture of planktonic and particle-associated microorganisms. The proportion of bacterial cells which are planktonic have been observed to range from 10 to 90 percent, largely depending upon water source, growth conditions, and temperature (Brazos and O'Connor, 1993). In a long-term study of highly turbid Missouri River water at Jefferson City, Missouri, total and particle-associated bacteria were enumerated seasonally after particle separation on a 3 μm polycarbonate membrane filter. In the summer, approximately one-third of the total bacteria were particle-associated. Despite the fact that this proportion increased to roughly two-thirds in the winter, 50 times as many cells passed through the rapid sand filtration plant and penetrated into the distribution system during the cold weather months.

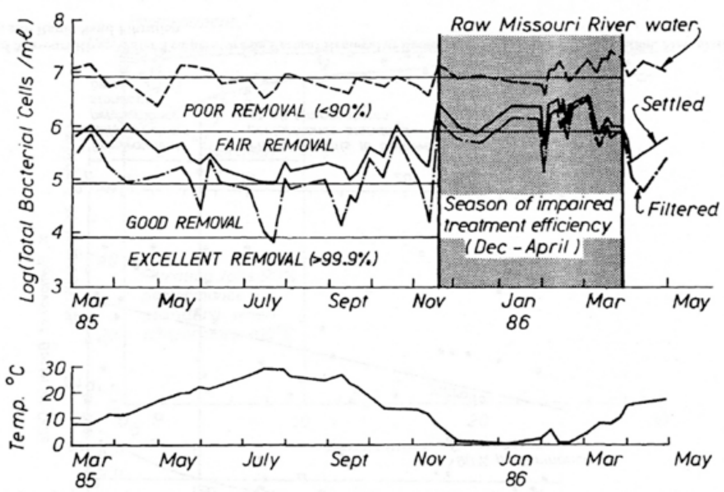
Seasonal (Temperature) Effects on Total Bacterial Removals

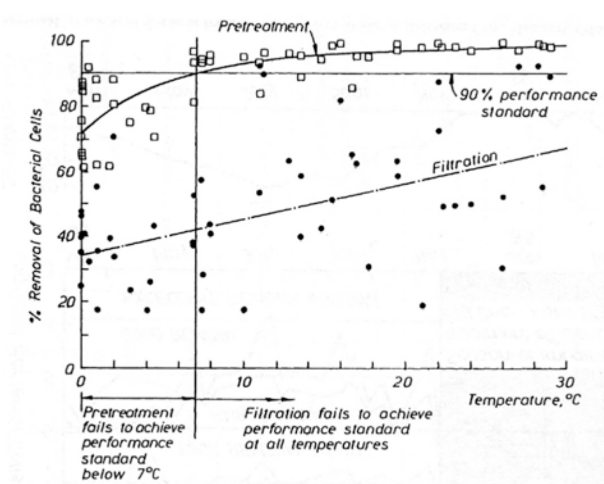
The results of a fifteen-month evaluation of the removal of total bacteria by *pretreatment* (coagulation and sedimentation) and conventional rapid sand *filtration* is summarized in Figure 1. The Missouri River source water consistently contained approximately 10^7 cells per ml throughout the study period. This large number of biotic particles contributed only approximately 1 ntu to the 100 ntu average raw water turbidity. Comprehensive pretreatment (presedimentation, two-stage lime softening, coagulation with ferrous chloride, flocculation and sedimentation) was found to physically reduce bacterial populations by 99 percent (to 10^5 cells per ml) during the summer months. However, in the winter, bacterial removals after settling declined to as low as 60 percent (Fig. 2). Rapid sand filtration performed poorly throughout the year, averaging only 50 percent removal of the total bacterial cells entering the filter. The removals attained by the rapid sand filters declined to as low as 17 percent, while averaging 35 percent, in the winter months.

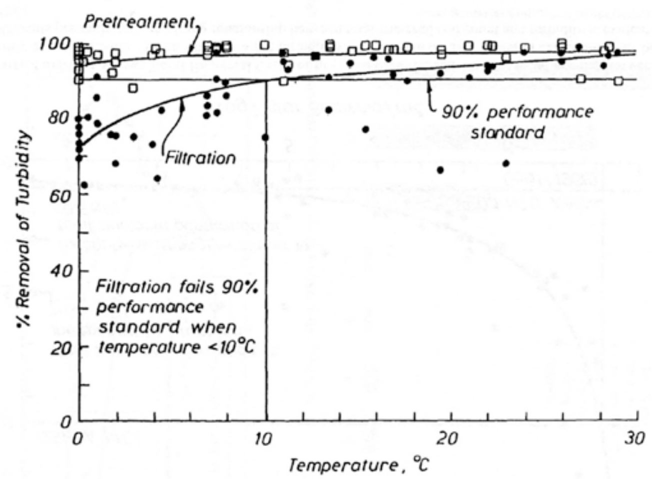
Overall, total bacterial removals through the treatment plant ranged from over 99.9 percent in the summer to less than 70 percent in the winter. Most cell removal occurred during *sedimentation* rather than filtration. Alternately, overall turbidity reductions ranged from summer highs of 99.9 percent to winter lows of 99 percent (Figure 3). Turbidities appeared strongly related to total bacterial populations only when finished water turbidities were less than 0.3 ntu (Figure 4). When finished water turbidities had been reduced to 0.1 ntu, total bacterial populations in treated Missouri River water approached those found in regional groundwater supplies (10^4 cells/ml).

Figure 1. Seasonal Removal of Bacteria from Missouri River Water at Jefferson City, Missouri (March 1985 - May 1986)

Bacterial cell removals by *pretreatment* (coagulation, flocculation, sedimentation) and *filtration* decline significantly when Missouri River water temperature falls below 7 °C (December to April).







Effect of Missouri River Water Temperature on Percent Removal of *Bacteria* (Figure 2) and *Turbidity* (Figure 3) by Pretreatment (Coagulation, Flocculation and Sedimentation) and Rapid Sand Filtration

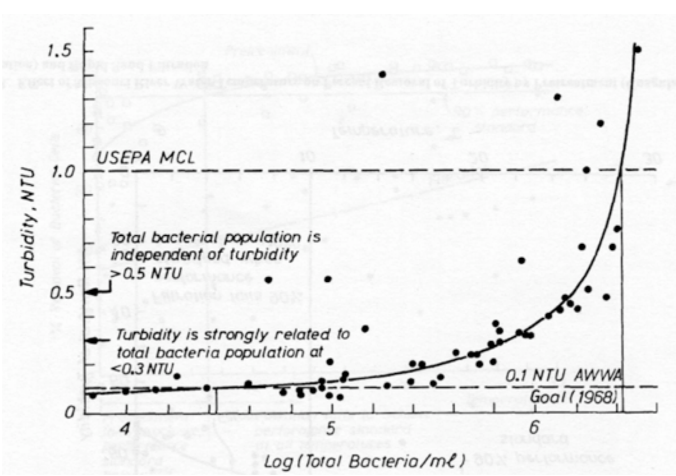


Figure 4. Finished Water Turbidity versus Total Bacterial Cell Count

Total bacterial cell counts exceed one million per milliliter when finished water turbidity exceeds 0.5 ntu. When finished water turbidities are less than 0.1 ntu, bacterial cell counts may be two orders of magnitude lower (10,000 cells per milliliter).

A strong relationship between total bacterial cell count and turbidity is evident only when turbidity is less than 0.3 ntu.

In summary, this microscopic study of the particle removal performance of a full-scale rapid sand filtration plant indicated that silt and clay particles, which contribute most to measured turbidity, are readily removed throughout the year by both pretreatment and filtration. Alternately, microorganism (bacterial cell) removals, averaging 90 percent, were primarily achieved by cell entrainment in settleable floc during pretreatment. The extent of floc entrainment of bacterial cells, in turn, was markedly influenced by water temperature. The conventional rapid sand filters studied exhibited little ability to remove planktonic organisms not embedded in larger microfloc. When coagulation and flocculation were effective in entraining bacteria in floc, rapid sand filters removed those 10 to 20 μm microflocs that passed through the sedimentation tanks. Alternately, planktonic cells passed the conventional rapid sand filters largely unimpeded.

On average, rapid sand filtration alone removed just 5 percent and passed another 5 percent of the bacterial cells entering the plant.

Fate of Organisms Passing Through Filtration Plant

Extensive sampling at five locations on the Jefferson City, Missouri water distribution system has shown that the organisms passing through the filtration plant account for virtually all the cells observed throughout the distribution system (Brazos and O'Connor, 1987). Neither cell lysis following chlorination nor recruitment of cells from distribution pipe surfaces (aftergrowth) had a measurable effect on the total number of bacterial cells enumerated by direct microscopic count. These results indicated that only treatment that was effective in physically removing cells at the plant controlled the number of cells arriving at the consumer's tap.

Table 1 provides a comparison of total bacterial cell count, heterotrophic plate count (HPC) and turbidity at progressively more distant locations in the Jefferson City distribution system. HPC bacterial colonies, reduced 99.9 percent during treatment, were consistently observed, first, to decrease at near-plant distribution system sampling locations; then, to increase moderately at more remote locations. Conversely, turbidity progressively decreased during distribution. Chloramine residuals were persistent throughout the system. Only one total coliform colony was detected in 318 samples taken in conjunction with the long-term distribution system study. These results confirm the integrity of the distribution system and indicate that only increased effectiveness of organism removals during cold weather will reduce consumer’s exposure to the fraction of organisms that originated in the Missouri River.

In addition to the population of bacterial cells, the rapid sand filtration plant controls the input of particulate organic carbon, largely in the form of bacterial cell mass, to the distribution system.

Removal of Planktonic Bacteria Versus Particle-Associated Bacteria During Filtration

Based on the results of the initial study of total bacterial cell removals, a second seasonal study was undertaken at Jefferson City, Missouri to determine the relative removals of planktonic and particle-associated bacteria (PAB). Owing to the protection provided, PAB are considered to be organisms of potential health significance. Alternately, planktonic bacteria are considered to be of lesser concern since they are more vulnerable to chemical inactivation.

Samplings conducted for 18 consecutive winter days and 27 consecutive summer days yielded estimates of planktonic and particle-associated bacteria in the Missouri River and their overall removal (Table 2). The removals of particle-associated bacteria were found to be consistently extensive (>99.99 percent in winter; >99.999 percent in summer). These removals greatly exceeded measured turbidity reductions. At Jefferson City, turbidity appears to result from river sediment in the influent and calcium carbonate in the effluent.

Overall plant removals of planktonic cells averaged only 78 percent in the winter. Summer planktonic cell removals increased 100-fold, so that, even though summer planktonic Missouri River water cell counts were twice that observed in winter, plant finished water contained 50-fold fewer planktonic bacteria.

Planktonic bacterial cells clearly serve as the most abundant and sensitive particle indicator of effective coagulation, flocculation, sedimentation, and filtration. The passage of as much as 22 percent of the total number of planktonic microorganisms initially present in the Missouri River into the distribution system during the winter must be considered a massive failure of the coagulation process and the physical removal barrier with respect to planktonic biotic particles.

The seasonal effects of temperature on various measures of finished water quality are given in Table 3. Total particles retained on a 3 μm membrane filter varied greatly seasonally, as did total (primarily, planktonic) bacterial cell count. Separation of these 3 μm particles had no measurable effect on finished water turbidity, again indicating that planktonic bacterial cells were primarily responsible for the residual light-scattering observed following filtration. Seasonal variations were muted, but not absent, in all measures of filtered water, including HPC, turbidity, and nematode populations.

One of the most significant results of this microscopic evaluation of filtration plant performance was the indication that particle-associated microorganisms, which are most likely to be afforded protection against disinfection, are removed with efficiencies far exceeding that indicated by either turbidity or HPC reductions (Table 4). The planktonic cells not entrained in microfloc, however, penetrated filters readily, contributing both organic carbon and establishing the population of organisms to be found in the distribution system. Algae, which are biotic particles comparable in size to the cysts of pathogenic protozoans, were 26 times more abundant in filtered water in the winter owing to a significant decline in their low temperature removal efficiency.

Table 1 Mean Values of Total Bacteria, HPC, Turbidity, and Chloramine in Clear Well and Five Distribution System Locations, Jefferson City, Missouri. (n = 34 samples; March 1985 to May 1986)

Distribution System Location	Mean values			
	Total Bacteria log cell count/ml	HPC Cfu/ml	Turbidity ntu	Chloramine gCl/m^3
Clear Well (nearest)	5.72	35	0.42	1.65
Missouri Dept. of Conservation	5.68	23	0.37	1.67
Southridge Pump Station	5.66	22	0.41	1.47
1205 East High Street	5.68	91	0.35	1.59
1600 East McCarty	5.69	82	0.44	1.20
Arro Mini-Mart (most distant)	5.74	140	0.33	1.41

Table 2 Seasonal Effect on Removal of Total and Planktonic Bacteria by Water Treatment(Jefferson City, Missouri, 1988) Bacteria, 10^6 cells/ml

Season	Fraction of Cells	Missouri River	Filtered Water	Ratio Missouri River: Filtered Water	Percent Removal
Winter (18 Consec.Samplings)	Total	12.9	1.0	13:1	92.3
	Planktonic*	4.6	1.0	4.6:1	78
	Particle-Associated	8.3(64%)	0.00	-	>99.9
Summer (27 Consec.Samplings)	Total	14.0	0.021	667:1	99.85
	Planktonic*	9.5	0.021	452:1	99.78
	Particle-Associated	4.5(32%)	0.000	-	>99.99

*Bacteria passing 3µm polycarbonate filter

Table 3 Comparison of the Seasonal Effect of Temperature on Various Measures of Finished Water Quality

Measure	Winter (Mean Value)	Summer (Mean Value)	Winter/Summer Ratio
Temperature, °C	4.7	29.5	-
Total Particles >3µm, number/ml	1793	28	64:1
Total Bacteria, cells/ml	$1x10^6$	$21x10^3$	50:1
HPC, cfu/ml	64	8.5	8:1
Turbidity, ntu	0.26	0.07	4:1
Nematodes, number/liter	0.37	0.09	4:1
Long Bacterial Rods, cells/ml	380	113	3:1
Algae, cells/ml	659	25	26:1
Particles larger than 3µ*m* having ≥5 bacteria attached, number/ml	1.93	0.31	6:1
Bacteria on Particles Hosting ≥5 cells, 10^6 cells/ml	0.00	0.00	-

Table 4 Summary of Seasonal Reductions Achieved During Treatment of Missouri River Water

Treatment Evaluation Parameter	Reductions During Treatment (percent)	
	Winter	Summer
Conventional		
Turbidity	98.9	99.98
HPC	99.6	99.97
Direct Microscopic Counts		
Total Bacteria	83.9	99.3
Planktonic Bacteria	73.7	97.6
Particle-Associated Bacteria	>99.9	>99.99
Particles w/ ≥5 Bacterial Attached	99.997	99.99995
Algal Cells	95.2	99.9

Bacterial Cell Removal at Kansas City, Missouri

The results of an evaluation of total bacterial cell removals from Missouri River water at Kansas City, Missouri (December, 2000), is illustrated in Figure 5. Direct microscopic counts show that cell removal takes place, primarily, during primary and secondary sedimentation. The return of softening sludge to the primary basin for recovery of magnesium as a recycled coagulant was found to increase cell removal. The subsequent addition of lime plus iron coagulant led to an overall cell removal of 98.5 percent following secondary sedimentation.

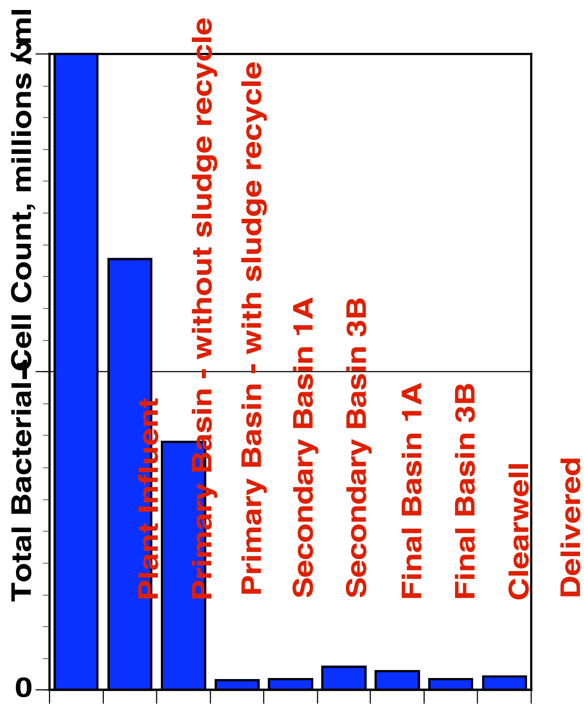


Figure 5. Bacterial Cell Removals at Kansas City, Missouri

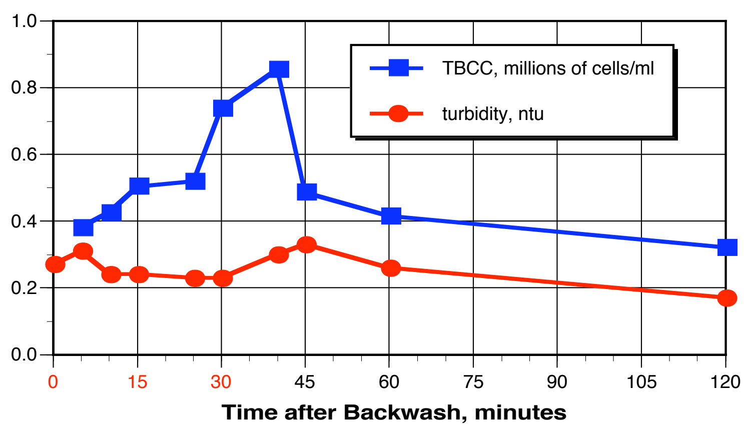
Maintaining Filter Performance following Backwash

The attachment of particles to filter media during water production leads to organism accumulation and, to some extent, surface colonization and growth. Effective backwashing is expected to loosen most accumulations and return them to suspension. However, upon return of the filter to service, those loosened particles that have not been purged during backwash may penetrate freshly-cleaned filters. Concern over the passage of microorganisms following backwash has led to remedial operational practices. These practices include filtering to waste for a prescribed period of time or returning filters to service using a programmed, gradual increase in filter hydraulic loading ('ramping').

At Bloomington, Illinois, studies were undertaken to observe the benefit of gradual flow increases on filter performance following backwash (H_2O'C, 1999). The performance of one filter in a gallery of twelve filters was evaluated by parallel measurements of turbidity, electronic particle counts and total bacterial cell counts. Filter effluent samples were taken just prior to backwash and over a period of two hours following backwash. Computer-controlled ramping takes place over the first thirty minutes of filter return to service. Dedicated, on-line turbidimeters monitor each filter effluent and the data is recorded continuously throughout each filter cycle. Periodically, turbidity is also monitored using a laboratory (ratio) turbidimeter to confirm the stability of the on-line turbidimeters.

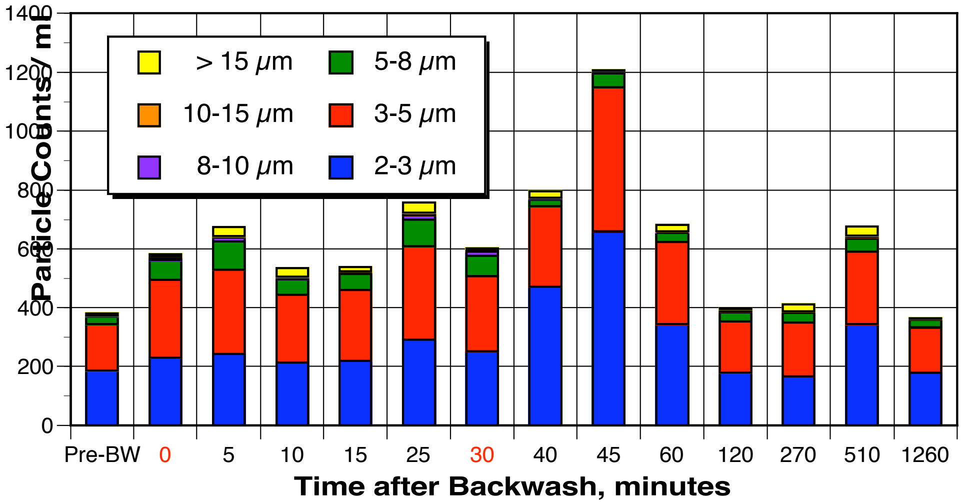
Filter monitoring data obtained in the comparative study indicate that turbidities remained low both immediately following backwash and throughout the 30-minute period during which the hydraulic loading was brought back to full service flow. Even for most of the first hour of filter operation, turbidities were less than 0.3 ntu. Both on-line and laboratory turbidity measurements indicated that filter being evaluated performed satisfactorily following backwash, producing an effluent which would consistently meet a turbidity limit of 0.5 ntu throughout the entire filter cycle.

Figure 6. Effect of Ramping during Filter Return to Service



Electronic particle count data also indicated little disturbance of filter performance due to backwash. Electronic counts of particles larger that 2 μm were under 800 per millilitre except for the sampling at 45 minutes. This was also the time when turbidity peaked at 0.33 ntu. However, electronic particle count data did indicate that some relatively large particles (>8 μm) continually passed into the filter effluent.

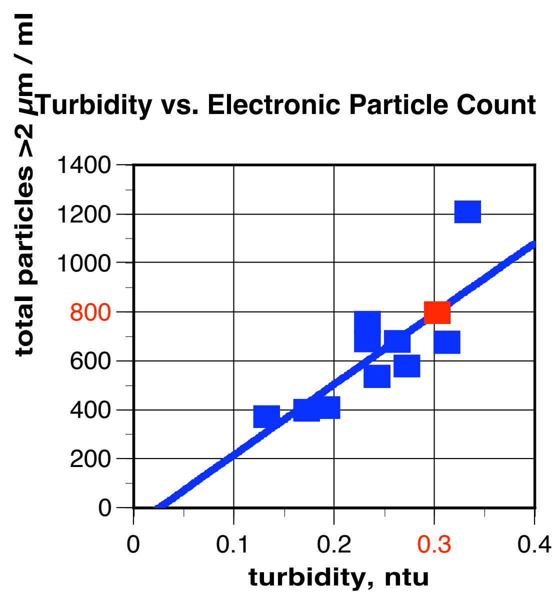
Figure 7. Electronic Particle Count Assessment of Filter Return to Service



Alternately, microscopic cell counts showed a well-defined peak following backwash. This may be an indication of the detachment of attached cells and organic debris from filter media during backwash. Total bacterial cell counts were low prior to and immediately following backwash (0.18 million cells/ml). After 45 minutes, cell numbers had increased to 0.85 million cells/ml. The micrographs also showed that many calcium carbonate crystals were present. Occasionally, algal cells were observed. These algal cells may have been recruited from growth on the walls of the filter boxes.

Correlation of Turbidity and Particle Count

The plot shown in Figure 8 indicates a relationship between turbidity and particle count. For these specific particles, a line of 'best fit' intersects a turbidity of 0.3 ntu at a total particle count of 800 per millilitre. These results tend to confirm the similarity of these two measurement techniques.



While all three measurements reflect the impact of backwash on filter performance, each may be sensitive to different component parts of the spectrum of particles present in the filtered water. Turbidity is most strongly influenced by small (in the range of the wavelength of visible light), opaque, inorganic particles which absorb or scatter light most effectively. These would include calcium carbonate and inorganic precipitates as well as silt and clay particles. The electronic particle counter appears to be most sensitive to larger particles or aggregates and progressively less responsive to the more numerous smaller particles.

Alternately, microscopic observations indicate that the electronic particle counter may be overestimating the number of larger particles. Since larger particles that may provide organisms protection against subsequent disinfection represent a potential health concern, the reliability of the particle counter in enumerating larger particles should be validated using direct microscopic counting techniques.

Operationally, the effectiveness of alternative protocols for the return of filter to service can be assessed by both turbidity measurements and particle counting. Since the results appear parallel, the on-line monitoring of turbidity may be the most convenient means of establishing the backwash and flow ramping protocols for each individual filter.

Bacterial cell counts may also be utilized following backwash to evaluate the impact of detachment of bacterial cell mass from filter media.

Removal of Virus by Water Filtration

If rapid sand filtration plants permit the passage of increased numbers of micrometre-sized, planktonic bacterial cells when temperatures are low, how effective are they against the far smaller virus particle?

In an early survey of Missouri River water at Lexington, Missouri, human enterovirus particle concentrations were enumerated in the range of 0 to 25 pfu/m^3 (O'Connor et al., 1980). The higher virus concentrations were found when water temperatures fell below 10 °C, indicating that low water temperatures increased virus survival time. In addition, due to flow regulation at upstream dams of the U.S. Army Corps of Engineers, there is less flow in the Missouri River during the winter months. There is, therefore, less dilution of the comparatively constant flow of virus-bearing effluent from wastewater treatment plants along the Missouri River. These factors indicate that viruses pose their greatest challenge to Missouri River water supplies during cold weather periods. This is also the period when entrainment by coagulants and particle removal processes may be markedly impaired.

Other results from the longitudinal survey of human enterovirus in the Missouri River indicated that most of the virus recovered were not attached to larger particles of suspended matter (O'Connor et al., 1980). Less than 10 percent of the total number of virus particles recovered from Missouri River water over the two-year survey were found on the 5 µm prefilter that retained most of the source water suspended solids. The remaining 90 percent of the virus particles were recovered from the filtrate by flocculation and adsorption on aluminum hydroxide floc.

These results indicate that most virus particles in the Missouri River are not attached to, or entrained in, suspended solids. Since Missouri River virus concentrations are highest during winter months when both sedimentation and filtration are least effective, the likelihood of the passage of virus into the distribution system may be highest in the winter.

An early study of conventional treatment that included settling by Robeck et al. (1962), indicated that effective (99.7 percent) virus removal was dependent on effective (alum) coagulation. Filter breakthrough of weak floc allowed virus penetration even though finished water turbidity was less than 1 jtu. When relatively clear water was treated, virus penetration increased. Studies were conducted to test the assumption that virus were associated with the floc particles that caused the filtered water turbidity. Finding no relationship, the authors concluded that "virus penetration could increase without a turbidity increase, and the alum dose could be too low, even though the effluent turbidity was less than 0.01 Jackson unit."

As a result of a number of recent studies, concern over the passage of virus through treatment plants has increased. Viruses have been isolated from drinking waters receiving conventional treatment including coagulation, sedimentation, filtration and post-chlorination. Once more, these chlorinated waters met standards for total coliform and turbidity (Payment, 1981; Keswick et al., 1984; Payment et al., 1985; Rose et al., 1986). Two of the studies that evaluated the removal of microorganisms at each step in the treatment process concluded that total coliform, turbidity, and HPC bacteria were more effectively removed than enterovirus. (Payment et al., 1985; Rose et al., 1986).

The health significance of low numbers of virus in drinking water has been debated for years. The "Low-Level Transmission Theory" (Berg, 1966), speculates that low numbers of viruses in water may infect susceptible individuals who later spread the virus in the community by person-to-person contact. A review of the literature on viruses in drinking water (Bitton et al., 1986) concluded that the question of the health significance of low concentrations of virus had not been answered.

Numerous laboratory studies have been performed which indicate extensive virus aggregation as well as virus adsorption (99.9 percent) to sand, silt, and clays (Fuhs, 1987). However, desorption is reportedly enhanced by natural dissolved organic matter and high pH, as in lime softening.

The attachment of virus particles to larger particles has been assumed to result in more efficient removal of the virus by physical removal processes. However, either the spontaneous aggregation of virus or their attachment to associated cell debris, sewage particles, bacteria, or clay particles could result in their becoming associated with those micrometre-sized particles which are believed to penetrate granular media filters most readily.

Coarse media filtration theory (O'Melia, 1985) predicts far better removal of 0.03 μm monodisperse particles than 1 μm monodisperse particles, whereas incorporation of virus particles into 10 μm-sized microfloc would, presumably, result in markedly enhanced virus removals. Alternately, virus particles may attach to 1 μm source water particles, e.g., the size of the abundant planktonic bacterial cells, to penetrate filters.

Filtration for Removal of Pathogenic Protozoans

The increasingly frequent detection of Giardia cysts and Cryptosporidium oocysts in drinking water sources and supplies has prompted studies of the effectiveness of filtration processes in protecting public health. A comparison of epidemiological data for Portland, Oregon, which utilizes an unfiltered, protected water supply, provided no evidence of a greater incidence of giardiasis transmission than that observed in a community utilizing a well-operated, filtered water supply (Glicker and Edwards, 1991). However, modeling studies have indicated that source waters having geometric mean concentrations of 0.7, 7, and 70 Giardia cysts per 100 liters should achieve 3, 4, and 5 orders of magnitude inactivation, respectively, to ensure a risk of less than one infection per 10,000 people per year (Regli et al., 1991).

To observe the relative removal of Giardia cysts and turbidity, Ongerth et al. (1989) conducted studies on low turbidity waters in Washington and California. Treating raw water having turbidities in the range of 0.25 to 0.6 ntu, the conventional treatment plant (Washington) achieved turbidity reductions of 55 to 60 percent along with 40 percent removals of cyst-sized particles. Cyst-sized particle removals were not clearly related to turbidity reductions. However, carefully controlled alum and polyelectrolyte additions in pilot plant studies increased cyst removals to the range of 98 to 99 percent. Filtered water turbidity ranged from 0.03 to 0.07 ntu during maximum removal. In California, a dual media, direct filtration plant, treating water having an average turbidity of 0.3 ntu, obtained an 85 percent cyst removal efficiency while turbidity reductions averaged 70 to 75 percent. The researchers noted that observed cyst removals from low turbidity waters were significantly less than previously reported and that filtered water turbidity, by itself, was not a useful parameter for estimating cyst removal. Although filtered water turbidity at both plants was consistently less than l ntu, Giardia cysts were found in more than one-half of the filtered water samples. Most important, the researchers concluded that effective chemical conditioning increases cyst removal efficiency by, at least, one order of magnitude.

Despite increasing evidence of the adverse effect of low water temperature on organism removals by conventional surface treatment, no studies have been reported on the influence of temperature on the removal of pathogenic protozoans. However, the five major cryptosporidiosis outbreaks in Carrollton, Georgia (January - February 1987), Thames Water, England (February, 1989), Jackson County, Oregon (January - June 1992), Milwaukee, Wisconsin (January - April 1993), and Las Vegas, Nevada (January- April, 1994) all began during periods of low surface water temperature. Only the four cryptosporidiosis outbreaks which occurred in well water supplies (near-constant temperature) or the three that were attributed to backsiphonage of wastewater to the distribution system appeared to occur at other times in the year (Solo-Gabriele and Neumeister, 1996).

The observed decreases in efficiency of physical water treatment processes (coagulation, sedimentation and filtration) at seasonal low water temperatures may be a major contributor to waterborne disease outbreaks. Increased seasonal finished water turbidities were reported at other water plants treating Lake Michigan water during the Milwaukee outbreak (Fox and Lytle, 1996). This evidence, alone, casts doubt on any implication that the type of coagulant used at Milwaukee was responsible for the passage of the pathogens present in the source water.

Future Evaluation of Microorganism Removals by Filtration Plants

Scientific evaluations of the removal of specific groups of microorganisms (bacteria, algae, cysts and virus) are increasingly necessary as conventional and high rate water filtration plants are modified to produce more water with less capital investment. To date, engineering assessments of the effectiveness of reduced pretreatment and direct filtration has been guided by the removal of microbial surrogates, such as turbidity.

Advanced analytic methodologies are now making it possible to evaluate the validity of previous assumptions, many of which now appear overly optimistic. Over the next decade, more scientific evaluations will be made, both of natural source waters and at operating water utilities, to observe the seasonal changes in metabolic state and actual removal patterns of biotic particles.

Microorganisms are far more complex, largely due to their seasonal activity, dormancy and variation in adsorptive behavior, than inorganic particles. Microorganisms may, or may not, conform to removal patterns predicted by present filtration theory. Their aggregation or association with protective particles (carbon ‘fines’, sewage ‘pellets’, organic debris, nematodes) may inhibit chemical disinfection and increase the need for improved operating conditions which maximize microbial particle removal processes. For some source waters and treatment processes, credible correlations between microorganism removals and turbidity reductions will justify continued reliance on the use of turbidity for operational control of rapid sand filtration plants. Otherwise, there may be little alternative to direct microscopic particle identification and enumeration to assess actual organism removals.

References

ASCE, AWWA (1990), *Water Treatment Plant Design*, McGraw-Hill, N.Y.

Bacon, Francis (1627), *Sylva Sylvarum*, or a Natural History in Ten Centuries.

Baker, M. N. (1948), *The Quest for Pure Water*, AWWA, through Lancaster Press, Lancaster, Pennsylvania.

Berg, G. (1966), "Virus Transmission by the Water Vehicle I. Viruses." *Health Lab. Sci.,* 3:86.

Bitton, G., S.R. Farrah, C. C. Montague, and E. W. Akin (1986), "Viruses in Drinking Water." *Environ. Sci. Tech.,* 201:216.

Brazos, B. J. and J. T. O'Connor (1984), "Enumeration Methods for Bacteria in Water Distribution Systems," *Proc. AWWA Ann. Conf.*, Dallas, TX.

Brazos, B. J. and J. T. O'Connor (1986), "Seasonal Effects on Total Bacterial Removal in a Rapid Sand Filtration Plant," *Proc. AWWA Water Quality Tech. Conf.,* Portland, Oregon, pp. 795-854.

Brazos, B. J. and J. T. O'Connor (1987) "Relative Contributions of Regrowth and Aftergrowth to the Number of Bacteria in a Drinking Water Distribution System," *Proc. AWWA Water Quality Tech. Conf.,* Baltimore, Maryland, p. 433.

Brazos, B. J. and J. T. O'Connor (1988), "Seasonal Effects on Removal of Particle-Associated Bacteria in a Rapid Sand Filtration Plant," *Proc. AWWA Water Quality Tech. Conf.,* St. Louis, Missouri, pp. 577-630.

Brazos, B. J. and J. T. O'Connor (1990) "Seasonal Effects on the Generation of Particle-Associated Bacteria during Distribution," *Proc. AWWA Water Quality Tech. Conf.,* San Diego, California, pp. 1073-1101.

Cleasby, J. L., A. H. Dharmarajah, G. L. Sindt and E. R. Baumann (1989), *Design and Operation Guidelines for Optimization of the High-Rate Filtration Process: Plant Survey Results,* AWWA Research Foundation, Denver, Colorado.

Fox, K. R. and D. A. Lytle, (1996), "Milwaukee's Crypto Outbreak: Investigations and Recommendations," *J. AWWA* 88:9:87-94.

Fuhs, G. W. (1987), "Mechanisms of Adsorption and Elution of Viruses to Solids in the Natural Environment, (Chapter 8)," *Methods for Recovering Viruses from the Environment*, Gerald Berg, Editor, CRC Press.

Fuller, G. W. (1898), *Report on the Investigation Into the Purification of the Ohio River Water at Louisville, Kentucky,* D. Van Nostrand, N.Y.

Glicker, J. L. and R. A. Edwards (1991), "Giardiasis Risk from an Unfiltered, Protected Surface Water Source," *J. AWWA,* 83(11):46-51.

H_2O'C (1999) "Evaluation of Bloomington Water Treatment Plant Performance: Evaluation of Ramping to Improve Filter Performance following Backwash," Report for the City of Bloomington, IL.

IAWPRC (1983), Study Group on Water Virology. "The Health Significance of Viruses in Water," *Water Research,* 17:121.

Katz, E. L. (1986) "The Stability of Turbidity in Raw Water and Its Relationship to Chlorine Removal," *Journal AWWA,* 78:72.

Keswick, B. H., C. P. Gerba, H. L. Dupont, J. B. Rose (1984) "Detection of Enteric Viruses in Treated Drinking Water." *Appl. Env. Micro.,* 47:1290.

Logsdon, G. S., M. Lewis and J. B. Stanley, Jr. (1988) "Troubleshooting an Existing Treatment Plant," *Proceedings, AWWA Seminar on Filtration: Meeting New Standards,* Orlando, Florida.

National Academy of Sciences, National Research Council, Safe Drinking Water Committee (1977), *Drinking Water and Health,* Washington, D.C.

O'Connor, J. T., L. Hemphill and C.D. Reach, Jr. (1980*) Removal of Virus from Public Water Supplies,* USEPA, Municipal Environmental Research Laboratory, ORD, Cincinnati, Ohio.

O'Melia, C. R. (1985) "Particles, Pretreatment and Filtration", ASCE *Journal of Environmental Engineering*, 111(6): 874.

Ongerth, J. R. (1989) "Giardia Cyst Concentrations in River Water," *Journal AWWA,* 81(9): 81-86.

Ongerth, J. R., J. Riggs and J. Crook (1989) *A Study of the Water Treatment Practices for the Removal of Giardia lamblia Cysts,* AWWA Research Foundation, Denver, Colorado.

Ongerth, J. R. (1990) "Evaluation of Treatment for Removing Giardia Cysts," *Journal AWWA,* 82(6): 85-96.

Payment, P. (1981) "Isolation of Viruses from Drinking Water at the Pont-Viau Water Treatment Plant," *Canadian J. Microbiol.,* 27:111.

Payment, P., M. Trudel, and R. Plante (1985), "Elimination of Viruses and Indicator Bacteria at Each Step of Treatment during Preparation of Drinking Water at Seven Water Treatment Plants," *Appl. Environ. Microbiol.,* 49:1418.

Regli, S., J. B. Rose, C. N. Haas and C. P. Gerba (1991), "Modeling the Risk from Giardia and Viruses in Drinking Water," *J. AWWA,* 83(11):76-84.

Robeck, G. G., N. A. Clarke and K. A. Dostal, "Effectiveness of Water Treatment Processes in Virus Removal," *Journal AWWA,* 54(10):1275-1290.

Rose, J. B., C. P. Gerba, S. N. Singh, G. A. Toranzos, and B. Keswick (1986), "Isolating Viruses from Finished Water." *Journal AWWA,* 78:56.

Rose, J. B. (1988) "Occurrence and Significance of Cryptosporidium in Water," *Journal AWWA,* 80(2): 53-58.

Solo-Gabriele, H. and S. Neumeister (1996), "U.S. Outbreaks of Cryptosporidiosis," *Journal AWWA,* 88(9): 76-86.

USEPA (1986) Drinking Water Research Division, MERL, ORD and Office of Drinking Water,*Turbidity Criteria Document,* Washington, D.C.

USEPA (1989) *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources,* Washington, D. C.