Development of New Methodology for the Assessment of Water Treatment Plant Performance with Respect to the Removal of Cyst-Sized Particles

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INTRODUCTION

This is the fourth in a four-part series of year-long studies conducted at the Capital City Water Treatment Plant, Jefferson City, Missouri, over the period of 1985 to 1989, to evaluate the effect of temperature on water treatment plant performance and to observe the subsequent changes in water quality during distribution.

The first study in this series was the first comprehensive evaluation of the ability of physical water treatment processes to remove bacterial cells. Conducted over a fifteen-month period using direct microscopic counting techniques, the study showed the previously unrecognized dramatic effect of water temperature on the efficiency of bacterial cell removal. It was observed that cell removal was controlled by coagulation and sedimentation rather than filtration (1).

The second study in this series evaluated the fate of the organisms which penetrated into the distribution system in an attempt to explain the origin of bacteria found at the consumer's tap (2). Adjusted for travel time, the total number of bacterial cells found throughout the distribution system was found to correlate exactly with the number discharged to the system through the treatment plant. No significant evidence of aftergrowth, the recruitment of organisms from distribution piping, was found.

If a large fraction of microorganisms (primarily bacteria) found in surface water supplies can penetrate a comprehensive water treatment plant and be transported throughout the distribution system without reduction in number, it becomes especially important to establish how many of the invasive cells are particle-associated and, therefore, of potential health significance owing to the protection that particles may afford such microorganisms from the action of disinfectants. Since the water utility industry had never determined the removal of such particles in a water treatment plant, the third study in this series was conducted to determine the effect of temperature on the removal of particle-associated bacteria (3). While the removal of particle-associated bacteria was found to be extensive throughout the year, very pronounced seasonal effects were again observed. In this unique study, both the seasonal variation in the number of particle-associated bacteria entering the distribution system was observed and the numbers of particles of potential health concern quantified.

In each of these previous studies, extensive micrographic documentation of the particles found in source and treated water was made. In many cases, it was also possible to observe particles generated within the plant or recruited during treatment.

The results obtained from the third study provided the experimental background data for the design of the present study in which seasonal changes in the numbers of microorganisms and other particles which occur during distribution were quantified. In addition to generating original data on the predominance and fate of particles during distribution, this study was directed at determining the origin of the bacteria and particles of potential health significance found in the distribution system. Based on turbidity, coliform and heterotrophic plate count data, it is presently believed that treated water is virtually organism-free as it leaves the treatment plant. As a result, it is assumed that bacteria and particles observed subsequently must have been recruited from the distribution system piping.

For over fifty years, it has been assumed that increases in organism populations during distribution were the result of the "dirty" distribution system piping contaminating the virtually organism-free purified water (4-5). The presence and tenacity of slime-forming organisms was cited in a 1944 review of distribution system treatment methods (4). The authors noted "that because of the new U.S. Public Health Service requirement of distribution system sampling, many

water works men are just beginning to find out what we have known for many years, that is, that all kinds of growing organisms will thrive in the distribution pipe systems though an apparently "perfect" water has been produced at the plant."

Serious distribution system problems were detailed in a 1960 article describing remedial actions taken in the Hammond, Illinois water system (5). The authors expressed confidence that "treatment practices commonly employed can produce any quality of water that may be desired" but lamented that a perfectly clear, soft and safe water entering the distribution system may be unrecognizable as such at the household tap."

In 1972, USEPA researchers concluded that "once microorganisms enter the distribution system, they may be harbored in protective slime and sediments that develop in portions of the system (6)." They reported that this population could be controlled by maintaining a residual chlorine level in the distribution system. A subsequent report noted the "potential for bacterial regrowth during warm water periods" and recommended a systematic flushing program in addition to the maintenance of a chlorine residual (7). A third report reaffirmed earlier observations that "whereas the water quality is excellent as it leaves the treatment plant, the consumer may be using tap water of considerably lower quality (8)."

Despite finding relatively low surface populations of bacteria on distribution piping, other researchers concluded that "a likely explanation for the similarity between microorganisms on pipe surfaces and in drinking waters is that detachment of microorganisms from the pipe surface and their re-entrainment into the passing water may account for the majority of bacteria in potable water (9)." Overall, "biofilms" on distribution system piping are viewed as the source of microbial contamination of treated waters.

Since no scientific evidence has been advanced to support that assumption, the present study was undertaken to quantitate the particles generated or recruited during distribution. Therefore, the present study was, in part, an attempt to distinguish between regrowth and aftergrowth during distribution in particular with respect to the contribution from particle-associated bacteria.

In order to describe the concept and develop the rationale for determining the origin of particles found in distributed drinking water, the necessary terminology was defined during the second study (2). Briefly, "regrowth" was defined as "to grow again (after chlorine dissipation and time for metabolic repair of the cells passing through the plant)." Because of their origin, regrowth organisms are best controlled at the treatment plant. "Aftergrowth" was defined as "microbial contamination of distributed water during distribution from internal pipe surfaces or cross-connections."

This distinction, while of obvious importance from the standpoint of public health protection against organisms which may have their origin in the source water, was not previously made because it is generally assumed, in distribution system studies, that the organism-free treated water is simply degraded during passage through a "dirty" water distribution system from which particles are constantly or periodically sloughed. This assumption would make any distinction between regrowth and aftergrowth unnecessary. Indeed, the terms have been used interchangeably in the waterworks literature. Worse, this assumption would obviate concerns about regrowth since the organisms observed would be assumed to be free from organisms found in contaminated source waters.

MATERIALS AND METHODS

The study was conducted at the Capital City Water Treatment Plant, Jefferson City, Missouri. This well-operated system, which has been described in detail in earlier papers (2,3),

serves a population of 30,000 with an annual daily flow of 20,000 m^3/day (5.2 MGD). The treatment plant provides Missouri River water with comprehensive, two-stage treatment, including lime softening. Of special interest for the present study is data from which the USEPA "Ct" disinfectant requirement can be calculated. Table 1 shows the applied disinfectant concentration and corresponding retention times. A persistent residual of 0.3 mg/L is maintained during distribution. Water taken from the distribution system sampling point employed in the present study has been in the pipeline for an average of 48 hours (2).

Table 1
Ct Data for Capital City Water Treatment Plant

Disinfectant Concentration, mg/L	Retention Time, hours
0.5 (chlorine)	16 (plant)
1.5 (chloramine)	14 (clear wells)
0.3 (chloramine)	48* (distribution system)

*Travel time to distribution system sampling point.

The summer sampling spanned a 17-day sampling period (31 August to 16 September) when temperatures ranged from 19°C to 26 °C. Samples were collected daily for 16 days in the winter (12 February to 27 February) when the temperature ranged from 0°C to 3°C. Equivalent sample periods were used to ensure comparable statistical validity of the seasonal data.

As during earlier studies, water production was approximately 30% lower during cold weather, thus reducing the hydraulic loading on all unit processes during the winter.

On each sampling date, samples were collected of Missouri River water, settled water (filter influent), filtered water from Filter #6 (consistent with previous studies), finished water from the clear well (for comparison with filtered water) and from a remote location in the predominantly linear distribution system. Settled water samples consisted of lime-softened, iron-coagulated, two-stage settled, recarbonated water. Clear well samples represented a composite of all six plant filters. When compared with the analyses of Filter #6, the clear well samples provided a means to detect filter upsets, transients, and anomalies. It also made it possible to observe the effect of backwash on filtrate quality. In all studies to date, including the present, the results obtained have been entirely comparable between Filter #6 and the clear well samples indicating remarkably consistent filter performance throughout the filtration period.

The percent reductions during treatment were calculated from the differences in the Missouri River and filtered water analyses. Changes during distribution were calculated by comparing the results of filtered water analysis, adjusted for two days travel time during distribution, with the distributed water analysis.

Various parameters were used for the evaluation of water treatment plant performance during the present study. These included the conventional parameters, turbidity, coliform and

heterotrophic plate count (HPC). Bacterial removals were assessed by nonconventional parameters, including total, planktonic and particle-associated bacteria by direct microscopic count. Particle removals were assessed by direct measurement of the most numerous microscopic particles, other than planktonic bacterial cells. They included total particles larger than 3 μm, long bacterial rods, algal cells and colonies, carbon fines and nematodes. Many of these particles may be considered to be particles of potential health significance. All were retained on a 3.0 μm membrane filter. The rationale for this method of discrimination was articulated in a previous paper (3) in which aggregates of cells or particles retained on a 3.0 μm neutron-track-etched polycarbonate membrane filter with five or more bacterial cells attached were enumerated as particles of potential health significance.

RESULTS

Conventional Parameters

Table 2 shows the mean turbidity and HPC of the raw and treated water during the 16-day winter sampling period summarized from Table 15. On the average, both turbidity and HPC were reduced by approximately 99% by treatment. Most of observed reduction takes place during sedimentation which is impaired at low temperatures.

During distribution, turbidity was found to increase marginally (0.12 NTU) whereas HPC declines by one-half. The decline in HPC may have resulted from the continued bacteriostatic action of the chloramine residual. HPC provided no evidence of regrowth under winter conditions.

Table 2
Average Winter Turbidity and HPC:
Reductions by Treatment and Changes during Water Distribution

	Turbidity, NTU	HPC, CFU/mL
Missouri River	18.8	37400
Filtered	0.22	144
% Reduction by Treatment	98.8%	99.6%
Distribution System	0.34	63
Changes during Distribution	(+0.12)	(-71)

A previous study showed that HPC did not increase significantly in the Jefferson City, Missouri, distribution system as long as the chloramine residual persisted (2). Instead, rapid increases in HPC were only observed following depletion of the residual in household plumbing systems (16).

While Missouri River water turbidities and heterotrophic plate counts were far higher in the summer, filtered water averages were as low as the winter averages. During warm weather, approximately four order of magnitude reductions in both parameters were being achieved during treatment.

Since both the winter and summer averages of filtered water turbidity and HPC were comparable, the dramatic seasonal temperature effects on their reductions during treatment were not readily evident. However, since summer turbidity and HPC values were 64 and 17 times winter values, respectively, summer percent removals were proportionately higher than winter removals.

Table 3
Average Summer Turbidity and HPC
Reductions by Treatment and Changes During Water Distribution

	Turbidity, NTU	HPC, CFU/mL
Raw	1200	629000
Filtered	0.15	170
% Reduction	99.99%	99.97%
Distribution System	0.32	882
Change during Distribution	(+0.17)	(+712)

During distribution, as shown in Table 3, turbidity again increased slightly (+0.17 NTU) summarized from Table 15. However, in contrast with the winter averages, HPC increased significantly (five-fold) during distribution despite the persistence of a combined chloramine residual which averaged 0.4 mg/L at the remote sampling site. In justifying the use of chloramine as a disinfectant, the long retention time in the distribution system has been cited as a factor which partially compensates for the poorer disinfecting capability of chloramine as compared with chlorine. From this reasoning, it would be inferred that heterotrophic plate count organisms entering the distribution system from the treatment plant would progressively decrease during distribution, particularly during periods of high water temperature when disinfecting action is accelerated. Observed increases in HPC during distribution could then only be interpreted as organisms recruited from the distribution system itself. These would, presumably, be organisms which were protected from the disinfectant or resistant to it.

Although the observed increases in turbidity were small, they were consistent throughout the year. Since the water has been softened, the increase in turbidity may result from the post-precipitation of calcium carbonate. Alternately, the reagglomeration of iron floc or the recruitment of corrosion products from the mains may result in increased turbidities. Increases in bacterial populations are highly unlikely to have a measurable effect on increased turbidity during distribution (17). Sporadically, increases in turbidity may be due to the resuspension of accumulated settled sediments in the mains due to increased flow.

While coliform organisms are also used to evaluate distribution water quality, they were of no value in the present study since, as in previous studies, no coliform were found either in the plant effluent or the distribution system samples.

Total, Planktonic and Particle-Associated Bacteria

The total bacterial population of Missouri River water, during the winter, averaged approximately 6×10^6 cells/mL (Table 4). Of these, 39% were particle-associated and 61% were planktonic. After treatment, the filtered water contained approximately 10^6 planktonic bacteria/mL and few particle-associated bacteria. With small error, the total bacteria entering the distribution system was equal to the planktonic population. This number decreased by an average of 4% during distribution. There was no evidence of aftergrowth contributing to the total bacterial population.

Table 4
Total, Planktonic and Particle-Associated Bacteria:
Average Winter Removals by Treatment and Changes During Distribution

	Bacteria by Direct Count, 10^6 Cells/mL		
	Total	Planktonic	Particle-Associated
Missouri River	5.90	3.58	2.32 (39% of total)
Filtered Water	0.95	0.95	0.00
% Reduction	83.9%	73.5%	>99.9%
Distribution System Change during Distribution	0.91 (-0.04)	0.91 (-0.04)	-- --

The low winter bacterial removals merely confirmed previous observations that the planktonic bacteria offer the greatest challenges to water treatment particle removal processes (1-3). If the planktonic cells are not entrained in larger precipitates to form a settleable coagulant floc, they appear to be able to penetrate filters almost completely. Because the efficiency of physical removal of planktonic bacteria is so poor, particularly by filtration and during periods of low temperature, these particles may serve as a critical assessment of the overall efficacy of water treatment. Only if effective entrainment and removal of planktonic bacteria is achieved, can water treatment plant particle removal processes be considered to be performing optimally.

Bacterial populations in the Missouri River were far higher in the summer, averaging 35 x 10^6 bacterial cells/mL or roughly six times the winter population. Despite the far larger number of cells, most (71%) were particle-associated. Partly because of the greater degree of attachment to particles, better physical removals might be expected. Bacterial removals were, however, far better than would have been predicted solely based on the higher percentage of attached cells present. As before, particle-associated cells were near-completely removed. In addition, the removal of planktonic cells increased dramatically with temperature, approaching an average of 98 percent.

Once more, the cells entering the distribution system were predominantly, planktonic bacteria (Table 5). During distribution, this population decreased an average of 20%, possibly due to lysis of dead cells. However, if one assumes that most of the planktonic bacteria had been killed by lime treatment and primary disinfection, an even larger fraction of the cells might have been expected to lyse within two days.

Table 5
Total, Planktonic and Particle-Associated Bacteria:
Bacterial Removals by Treatment and Changes during Distribution

	Bacteria by Direct Count, 10^6 Cells/mL		
	Total	Planktonic	Particle-Associated
Missouri River	34.6	10.1	24.5 (71% of total)
Filtered Water	0.24	0.24	0.00
% Reduction	99.3%	97.6%	>99.9%
Distribution System Change during Distribution	0.19 (-0.05)	0.19 (-0.05)	-- --

Particles with Associated Bacteria

Although very small in number when compared with the population of total and planktonic bacteria entering the distribution system, the particles of greatest potential health significance are those with particle-associated bacteria attached. In order of decreasing abundance, those particles which might provide protection for organisms against disinfection include clumps of organic matter, clumps of bacteria, silt (in the winter), microfloc (winter), senescent algae (summer), post-precipitated coagulant (summer) and nematodes (summer). The summer incidence of nematodes occurred during a period of high river flows under flood conditions when benthic deposits were resuspended. During this period, the nematodes were observed both in the finished and distributed water.

Total Particles Larger than 3 µm

As previously shown, direct microscopic particle counting, while requiring interpretation, is rapid, precise, and offers unparalleled quantitative information (1-3). Its value can be enhanced by using membrane separation techniques to assist in size fractionation of suspended material. For example, filtration of treated water samples through 3 µm membrane filters results in separation of the numerous planktonic bacteria (1 µm) from larger particles which are retained on the filter surface. This separation facilitates the characterization and photographing of the comparatively few larger particles retained.

From observation of the total number of particles larger than 3 µm, seasonal temperature effects are again readily evident as are changes during distribution (Table 6).

Table 6
Total Particles Larger than 3 µm in Filtered and Distributed Water

	Total Particles > 3 µm, number/mL	
	Winter	Summer
Filtered water	1229	186
Distribution system	1116	293
Change during distribution	(-113)	(+107)

The numbers of total particles recovered on 3 µm membranes are similar to the numbers obtained using electronic particle counters (18,19). The microscope, however, allows these numbers to be determined with great accuracy and reproducibility. A comparison of the averages of the total particle numbers shows that summer counts are only 15 percent of those observed in the winter. This result is yet another indication of the marked seasonal difference in the particles entering the distribution system.

Changes during distribution reverse with season, however. The average number of total particles larger than 3 µm decreased 9 percent during the winter, possibly due to sedimentation or attachment to pipe surfaces during periods of low flow. Conversely, the number of these particles increased during distribution in the summer. The calculated 58 percent particle increase was, in reality, small in absolute terms. The increase would be only a fraction of the observed increase in

HPC, for example. Even so, the increase in particles, coupled with the increase in HPC, indicate the possibility of a small degree of aftergrowth.

Long Bacterial Rods and Algal Cells

The direct microscopic particle count allows identification of the major particle groups entering the distribution system (Table 7). In this instance, long, needle-like rods were found to comprise about 31 percent of the total particles in the winter and 61 percent in the summer. Algae constituted 54 percent of the total particles in the winter and 13 percent in the summer. Together, these two particles comprised the majority of the particles larger than 3 μm entering the distribution system.

Table 7
Seasonal Occurrence of Long Bacterial Rods and Algae in Filtered and Distributed Water

	Long Bacterial Rods, cells/mL		Algae, cells/mL	
	Winter	Summer	Winter	Summer
Missouri River	--	--	14500	28700
Filtered water (% of total part.)	380 (31%)	113 (61%)	659 (54%)	25 (13%)
% Removal	--	--	95.2%	99.91%
Distribution System	405	97	542	25
Change during distribution	(+25)	(-16)	(-117)	(0)

The removal of algal cells during treatment was of special interest in this study because of their possible resemblance in size and surface characteristics to the cysts of pathogenic protozoans. Summer algal cell removals which averaged 99.9%, deteriorated to 95% under low temperature conditions. If there were parallelism between algal cell and cyst removal, winter conditions would limit removals to 1.3 logs. However, where water has been treated for particle removal, any remaining Giardia or Cryptosporidium cysts, while possibly resistant, are not likely to be entrained in larger, protective particles. They should, therefore, be readily exposed to the applied disinfectant.

Particles with Five or More Attached Bacteria

From studies of the distribution of the number of bacteria attached to particles in raw Missouri water, it was decided that particles with five or more bacteria attached might serve as an index of particles which might protect bacteria from disinfection (3, Figure 35). The effective removal of such particles would, therefore, be especially important. The rationale for the selection of five or more attached cells was articulated in the previous study. Basically, the particles with five or more cells attached are larger (5-10 μm) silt and clay particles with some organic material present.

Particles with less than five cells attached tended to approach the size of the cells themselves. Presumably, such small particles would offer little protection to the attached cells from the disinfectant.

Particles larger than 3 μm having five or more bacteria attached were removed with great efficiency both in winter and summer (Table 8). Despite the fact that many more such particles were present in the source water in the summer, removals exceeded six orders of magnitude. The extensive removal of these particles confirms and quantifies the effectiveness of water treatment in removing particles which may protect bacteria from the action of disinfectants.

Table 8
Seasonal Occurrence of Particles Larger than 3 μm
Having Five or More Bacteria Attached

	Particles >3 μm Having ≥5 Bacteria Attached, number/mL	
	Winter	Summer
Missouri River	74400	610000
Filtered water	1.93	0.31
% Removal	99.997%	99.99995%
Distribution system	1.87	3.51
Change during distribution	(-0.06)	(+3.20)

During distribution, an increase in the number of particles with five or more attached bacteria was observed only during the summer when the average number increased eleven-fold to 3.5 particles/mL. Even if all of this modest increase was attributable to particles recruited from the surface of distribution system piping, it would not represent a significant contribution of aftergrowth to bacterially-colonized particles in the distributed water. At most, this would contribute three colonies to the heterotrophic plate count. This result is direct evidence that bacterial cell masses are not sloughing from distribution piping in significant numbers.

In a previous study, observations were made of increases in HPC following sample dechlorination (2). Since HPC generally increased from approximately 10^2 initially to over 10^6 after two days, it was concluded that most of the HPC was regrowth having originally entered the system as planktonic bacteria. The contribution of the distribution system to the HPC observed following dechlorination would be expected to be negligible based on the few colonized particles observed. Instead, regrowth, as indicated by increased HPC, could be minimized by enhanced removal of the planktonic bacteria entering the distribution system.

Removal of Bacteria on Particles

The number of bacteria on particles having five or more attached cells averaged 11 percent of the total bacteria in the raw water during the winter and 21% in the summer (Table 9). While the challenge of these protected bacteria was significant year-round, these bacteria were essentially absent in the filtered water. If such bacteria are indeed an index of the cells which are most likely to transmit waterborne disease, then their removal to the extent of more than 99% and 99.9% in the winter and summer, respectively, is reassuring.

Table 9
Removal of Bacteria on Particles

	Bacteria on Particles Hosting ≥ 5 Cells, 10^6 Cells/mL (% of the Total)	
	Winter	Summer
Missouri River	0.67 (11.4%)	7.38 (21.3%)
Filtered water	0.00	0.00
% Reduction	>99%	>99.9%

Summary of Results of Treatment Plant Performance Evaluation

The adverse effect of low temperature on water treatment effectiveness is evident from the percent reductions obtained with respect to each parameter tested (Table 10). While the absolute value of filtered water turbidity showed little seasonal effect because summer raw water turbidity values were higher than winter values, turbidity treatment plant reductions were two orders of magnitude greater in the summer.

A comparison of the differences in seasonal reductions would indicate that planktonic bacteria, total bacteria and algal cell removals would be the most critical parameters for assessing water treatment plant performance.

Table 10
Summary of Seasonal Reductions Achieved During Treatment of Missouri River Water

Treatment Parameter	% Reductions during Treatment	
	Winter	Summer
Turbidity	98.8	99.98
HPC	99.6	99.97
Total Bacteria	83.9	99.3
Planktonic Bacteria	73.5	97.6
Particle-Associated Bacteria	>99.9	>99.99
Particle-Associated Bacteria w/≥5 bacteria attached	99.997	99.99994
Algal Cells	95.2	99.91

Of the parameters investigated, the planktonic bacteria appear to be the most sensitive for optimization of integrated water treatment particle removal processes. These dispersed sub-micrometer particles will particularly challenge the coagulation (destabilization)-flocculation (agglomeration) processes. Studies of the removal of the larger algal cells may be more appropriate for estimating the effectiveness of removal of pathogenic protozoans of similar size.

Summary of Results of Distribution System Evaluation

Based on the recovery of particles from distributed water on 3 μm membranes, it is evident that biotic particles, including the long bacterial rods and algal cells, are predominant (Table 11). This contrasts with raw Missouri River water where abiotic particles predominate.

Table 11
Seasonal Differences in Particles Found in Distribution Systems

	Number of Particles/mL	
Parameter	Winter	Summer
Total Particles larger than 3 μm	1116	293
Long Bacterial Rods	405	97
Algal Cells	542	25
Particles larger than 3 μm with ≥5 bacteria attached	1.9	3.5

As previously indicated, distribution piping appears to contribute little to the numbers of particles observed. This is an important result with respect to understanding the microbial ecology in the water distribution system.

Powdered Activated Carbon

During the study, powdered activated carbon was fed for taste and odor control over a six-day period. Particle counts were made to determine the number of carbon particles ("fines") in settled, filtered and distributed water (Table 12). Although the numbers were not high, the carbon particles could be readily detected and enumerated by microscopic counting. Electronic particle counters would not be able to identify or enumerate the carbon fines. In addition, particles formed by post-precipitation of calcium carbonate or coagulant, which were not present in the source water, would confound electronic particle counter-generated information.

Table 12
Carbon Fines in Treated and Distributed Water

	Carbon Fines, Particles/mL		
	Settled	Filtered	Distribution System
12-17*February	0	0	0
19 February	19000	321	31
20 February	1780	1620	1620
21 February	--	10	20
22 February	--	8	13
23*February	11	29	13
24 February	--	2	49
25 February	--	2	15
26 February	--	2	16
27 February	--	0	13

*Powdered activated carbon was added prior to sedimentation during the period, 17-23 February 1989.

Nematodes

Nematodes were enumerated in 2 to 6 liter samples of filtered, stored (clear well) and distributed water (Table 13). The decrease in the number of nematodes during distribution indicated lysis of the organism. Such lysis would contribute to the dissolved organic carbon content of the water during distribution. More complete nematode removal would reduce this contribution to biologically assimilable organic carbon in the distribution system.

Table 13
Nematodes in Treated Water

	Nematodes/L		
	Filtered	Clear Well	Distribution System
31 August	6	8	1
1 September	21	15	2
2 September	18	24	12
3 September	22	25	13
4 September	18	19	14
5 September	7	11	5
6 September	3	5	2
7 September	2	2	3
8 September	0.5	3	0.5
9 September	30	9	1
10 September	24	21	1
11 September	38	33	1
12 September	56	--	--
13 September	66	--	34
14 September	--	--	13
15 September	--	--	1
16 September	--	--	31

DISCUSSION

Conventional Parameters for Evaluation of Water Treatment Plant Performance

Turbidity: The arguments against the use of turbidity for water treatment plant performance evaluation have been advanced in each paper in this series. Briefly, turbidity is not a specific material. It is often caused by dense, opaque material (silt, clay) which is readily agglomerated. Because silt and clay agglomerate readily, they are more readily removed than bacteria, algae and, possibly, virus. For this reason alone, turbidity is inappropriate as a regulated surrogate to indicate removal of microbial pathogens.

Coliform: Monitoring of coliform organisms plays a major role in the protection of drinking water supplies from wastewater discharges. However, because coliform organisms are readily inactivated so that coliform are generally absent in treated waters, they have no value for the monitoring of water treatment plant performance. Their sensitivity to chemical disinfection renders coliform useless for evaluation of physical removal treatment processes. No coliform were found

in this or previous studies at Jefferson City, Missouri. For all practical purposes, coliform was undetectable in treated or distributed water.

HPC: During water treatment, total HPC reductions are due to chemical inactivation plus physical removal. This confounds the two processes so that their individual effects cannot be separated in field evaluations of operating water treatment plants. Still, HPC data indicated greater physical removal of HPC organisms attached to particles than of planktonic HPC organisms. Table 14 gives comparative data on the reduction of planktonic and particle-associated HPC. While the contribution of disinfection to the calculated reductions is unknown, it is evident that planktonic HPC bacteria are dominant in the treated water. Therefore, the HPC organisms entering the distribution system are primarily planktonic cells which have not been inactivated by the primary disinfectant.

Table 14
Physical Removal of HPC Associated with Particles

	Heterotrophic Plate Count, Colonies/mL		
	Total	Planktonic (3 μm Membrane-Filtered)	Particle-Associated (calculated)
Missouri River (19 Feb 89) (% of total)	63,000	18,000 (29)	45,000 (71)
Filter Effluent (% of total)	167	117 (70)	50 (30)
% Reduction	99.7	99.4	99.9

Alternate Parameters for Evaluation of Water Treatment Plant Performance with Respect to the Removal of Microbial Particles of Potential Health Significance

Total Bacterial Cells: Bacteria are generally the most numerous particles larger than 0.2 μm in water supply sources, often ranging from 10^6 to 10^7 particles per mL. Direct enumeration gives a measure of the removal of all particles larger than 0.2 μm. While coagulated, settled and filtered waters may contain 10^5 to 10^6 cells/mL, comparatively few particles larger than 3 μm are found (10^3/mL). Therefore, the effective removal of total bacteria is a strong indication of the effective removal of all particles larger than 0.2 μm. Achieving a goal of 99 percent bacterial removal would require significant treatment modifications during winter months.

Planktonic and Particle-Associated Bacteria: Of the total bacterial population in drinking water sources, a fraction are attached to particles and a fraction are planktonic. The fraction attached to particles appears to vary with season in the Missouri River, averaging 39% in the winter and 71% in the summer. The fraction of bacteria attached to larger particles is as well removed as the larger solids, validating the long-held contention that surface attachment to particles in natural water provides a major advantage for the removal of bacteria.

Alternately, the planktonic bacteria tend to remain highly dispersed . They appear to be less readily coagulated than silt and clay particles which appear to have a tendency to aggregate spontaneously. As a result, planktonic bacteria offer an outstanding challenge to the coagulation process. If such bacteria are not entrained in precipitates or coagulant floc during pretreatment of water prior to filtration, they appear to penetrate filters readily. Because of the comparatively poor efficiency of physical removal of planktonic bacteria, particularly during periods of low

temperature and high hydraulic loads, this measure may be taken as the most critical test presently available of the removal of sub-micrometer and larger particles during water treatment. In the present study, the removal of planktonic bacteria by two-stage sedimentation plus filtration averaged 73.6% in the winter and 97.6% in the summer. In the winter, 58% of the removal of planktonic bacteria took place prior to filtration whereas, in the summer, 94% of the single cells were removed by coagulation and sedimentation. This again indicates the failure of pretreatment under cold weather conditions since filtration provided only marginal removals both in the winter (37%) and in the summer (59%). From examining micrographs of filter influent and effluent, there is reason to believe that even these modest removals resulted largely from the removal of larger particles of unsettled microfloc in which the planktonic bacteria were imbedded rather than from the direct removal of the planktonic cells themselves.

Removal of Bacteria on Particles of Potential Health Significance: To further refine the measurement of the effectiveness of water treatment physical removal processes

relative to the protection of public health, a fraction of bacteria was evaluated with respect to the degree of protection that they received from the particles to which they were attached. Recognizing the difficulty in establishing a scientific rationale for this selection, the distribution of the number of bacteria on particles was carefully assessed (3). In most instances, only a few bacteria were attached per particle. The selection of five or more attached bacteria, therefore, identified only a small fraction of the total bacterial population which colonized larger particles. In the winter of the present study, the number of bacteria on particles having five or more attached cells was 11% of the total in the raw water. In the filtered water, these bacteria were essentially absent. If such bacteria are, indeed, an index of the particles which are most likely to transmit disease, then their removals to the extent of greater than 99% in the winter and greater than 99.9% in the summer is reassuring.

Total Particles: While the enumeration of total particles by electronic particle counting provides more information on particle size than the measurement of turbidity, the results are no more specific. Clay particles cannot be distinguished from bacterial cells or algal colonies. A wood fiber cannot be distinguished from a maggot.

Because the larger, denser particles in water supply contribute most to the light scattering observed, there is an apparent relationship between turbidity and the total number of particles in finished water. This observation simply highlights the inability of electronic particle counters to observe the numerous sub-micrometer particles present in filtered water. Whereas a particle counter may record 10^4 particles/mL in a water having a turbidity of 1 NTU, that same water may contain well in excess of 10^6 bacteria/mL. This confirms the observation that the numerous microbial cells contribute little to turbidity and are not readily detected by particle counters. While electronic particle counters add to the expense of particle detection, they offer little advantage over the well-established and documented measurement of turbidity, particularly if there is a good correlation between the two parameters.

Direct microscopic particle counting, while requiring analytical expertise, is very precise and offers unparalleled scientific information. In the present study, since microscopic examination had shown that most particles smaller than 3 μm were, indeed, microbial cells, treated water samples were passed through a 3 μm membrane filter prior to direct particle counting. The number of particles enumerated on the membrane averaged 1116/mL in the winter and 293/mL in the summer. This seasonal difference again sharply delineated the increased effectiveness of treatment under warm water temperature conditions.

More important, the direct microscopic count allowed the observer to identify the major particles penetrating the water treatment plant. In this instance, about one-third of the particles

present were long, almost needle-like, bacterial rods. This percentage was the same, both summer and winter. Because of the unusual shape of the cells, which may be actinomycetes, the percentage recovery of cells from the sample was found to vary even with the flow rate through the membrane filter. One can also envision the removal of these rather large, flexible cells varying with flow through a full-scale water filter.

Overall, algal cells and colonies were second in abundance, ranging from 49% in the winter to 9% in the summer. This, despite higher influent algal populations in the summer.

Both these results highlight the difference in the effective removal of the most abundant silt and clay particles in the raw water.

Since powdered activated carbon was fed for taste and odor control over a six-day emergency period, particle counts were undertaken to determine the number of carbon fines in settled, filtered and distributed water. Although the numbers were not

high, the particles have previously been studied because of concern over their potential health significance. Carbon fines can support attached bacteria and will reduce chlorine. Their presence in the distribution system is to be minimized..

Nematodes were enumerated in concentrates of 2 to 6 liters of treated and distributed water. The decrease in nematodes during distribution would indicate that they are probably settling out as they do in natural streams at low flow. Some investigators have tried to determine the seasonality of the appearance of nematodes. In this study, the nematodes were found to be most abundant when river flows were highest, indicating that they were resuspended from the benthos.

Overall, the direct microscopic count has the enormous advantage of permitting the assessment of natural and physical treatment practice in influencing the concentration of specific recognizable particles. In this respect, it is a revolutionary tool for the scientific evaluation and management of water treatment processes.

Implications of Particle Morphology for the Theory of Filtration

Whereas the particles used to establish theoretical filtration models were uniformly charged, rigid latex spheres (20), the particles observed in natural water sources are incredibly varied (Figure 1). Some scatter light well, others are translucent. Some are dense and settle readily, others approach the density of water. Many biotic particles are flexible and deformable, able to squeeze through pores and narrow passages. Still others are motile. Particle surfaces may have a high charge density or virtually none. In the case of microorganisms, surface properties and their tendency to attach may even vary with metabolic activity. In the present series of studies, particle attachment was found to vary markedly with seasonal temperature changes.

The most obvious difference in waterborne particles to the observer is their shape. The long, thin, flexible (needle-like) rods commonly observed in the finished water in the present study would clearly be expected to have different filtration properties than their equivalent spheres.

A willingness to observe and characterize the particles present in natural waters, with a special emphasis on the biotic particles of potential health significance, is a prime prerequisite to the establishment of a rational filtration theory. This is particularly important if reliance for particle removal is to be shifted from conventional coagulation and sedimentation to polymer-assisted direct filtration. Since turbidity and electronic particle counting are inadequate for quantitating or characterizing the particles in the treated water, it is especially important that direct observations be made when traditional particle removal technologies are not utilized.

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Figure 1. Particle Morphology and the Theory of Filtration

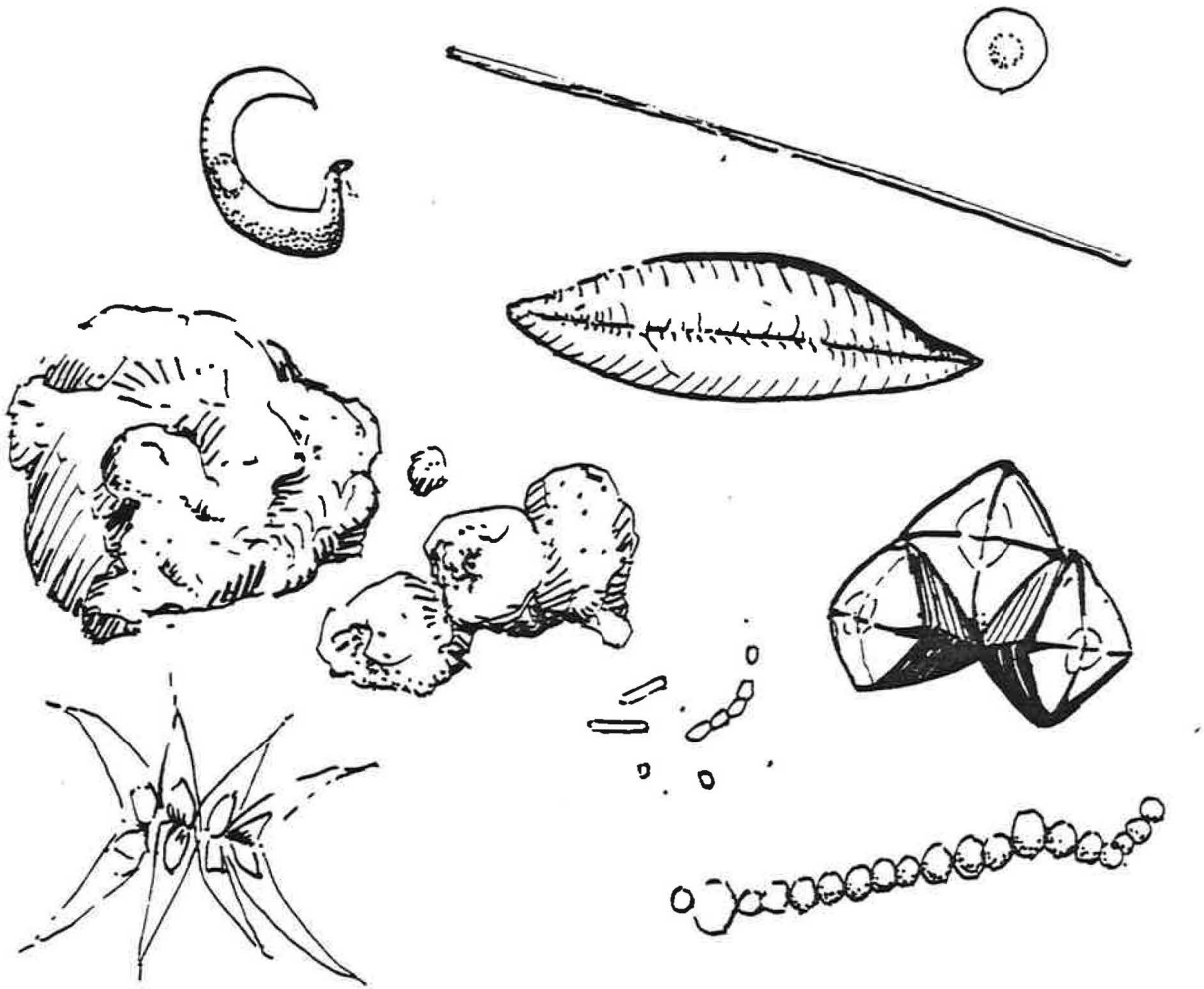

TABLE 15. RAPID SAND FILTRATION PLANT PERFORMANCE AND INFLUENCE OF DISTRIBUTION SYSTEM ON FINISHED WATER PARTICLES AND BACTERIA

(WINTER DATA)

				Bacteria by Direct Count, 10^6 Cells/mL				Particles >3 µm,** Number/mL			
DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
12 FEB 89											
Raw	0.0	16.0	37200(18500)	6.32	5.18	1.13(17.9)	0.31(4.9)	–		45000	–
Settled	0.5	2.4	–	2.51	2.51	0.00	0.00	–	–	–	–
Filtered	0.5	0.61	66	1.67	1.67	0.00	0.00	1060	–	6.2	–
Clear Well		0.44	68	1.67	1.67	0.00	0.00	–	–	–	–
% Reduction		96.2	99.82	73.6	67.8	>99.9	>99	–	–	99.986	–
Dist. System	5.5	.36	69	–	–	0.00	0.00	2090	1030	5.5	–
13 FEB 89											
Raw	0.5	19.0	62000(30900)	7.94	5.57	2.37(29.8)	0.57(7.1)	–	–	58000	–
Settled	0.5	1.2	–	1.51	1.51	0.00	0.00	–	–	–	–
Filtered	0.3	0.17	152	0.88	0.88	0.00	0.00	1790	1040	1.8	–
Clear Well	2.0	0.30	129	1.24	1.24	0.00	0.00	–	–	–	–
% Reduction		99.1	99.75	88.9	84.2	>99.9	>99	–	–	99.997	–
Dist. System	6.3	0.62	48	1.57	1.57	0.00	0.00	982	220	3.6	–
14 FEB 89											
Raw	0.3	20.0	50700(22600)	6.42	3.99	2.43(37.9)	0.57(8.8)	–	–	84000	18000
Settled	0.5	1.6	–	2.00	2.00	0.00	0.00	–	–	–	–
Filtered	0.5	0.21	153	0.99	0.99	0.00	0.00	784	177	1.1	561
Clear Well	2.0	0.26	96	1.07	1.07	0.00	0.00	–	–	–	–
% Reduction		99.0	99.70	84.6	75.2	>99.9	>99	–	–	99.999	96.9
Dist. System	6.0	0.44	63	1.23	1.23	0.00	0.00	771	232	0.7	470
(Δ)		(-0.17)	(-3)	(-0.44)	(-0.44)	(0.00)	(0.00)	(-289)	(–)	(-5.5)	(–)

DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Bacteria by Direct Count, 10^6 Cells/mL				Particles >3 µm,** Number/mL			
				Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
15 FEB 89											
Raw	0.3	30.0	47200(12500)	6.16	2.85	3.30(53.7)	0.76(12.4)	–	–	130000	21000
Settled	0.5	1.6	–	1.91	1.91	0.00	0.00	–	–	–	–
Filtered	0.5	0.30	202	1.34	1.34	0.00	0.00	1900	494	0.8	1310
Clear Well	2.0	0.28	114	1.28	1.28	0.00	0.00	–	–	–	–
% Reduction		99.0	99.6	78.2	52.9	>99.9	>99	–	–	99.999	93.8
Dist. System	6.0	0.35	45	0.93	0.93	0.00	0.00	940	423	1.9	436
(Δ)		(+0.18)	(-107)	(+0.05)	(+0.05)	(0.00)	(0.00)	(-850)	(-617)	(+0.1)	(–)
16 FEB 89											
Raw	0.5	27.0	61400(30300)	7.32	3.82	3.50(47.8)	.99(13.5)			104000	23000
Settled	0.5	1.5	–	1.56	1.56	0.00	0.00	–	–	–	–
Filtered	0.5	0.21	485	1.05	1.05	0.00	0.00	1290	382	1.3	829
Clear Well	2.0	0.27	325	1.18	1.18	0.00	0.00	–	–	–	–
% Reduction		99.2	99.2	85.7	72.5	>99.9	>99	–	–	99.999	96.4
Dist. System	6.0	0.40	143	1.12	1.12	0.00	0.00	1040	360	–	598
(Δ)		(+0.19)	(-10)	(+0.13)	(+0.13)	(0.00)	(0.00)	(+256)	(+183)	(–)	(+37)
17 FEB 89											
Raw	0.5	26.0(5.8)	–(30000)	7.03	3.82	3.21(45.6)	1.13(16.1)	–	–	71000	18000
Settled	0.5	1.3	–	1.28	1.28	0.00	0.00	–	–	–	–
Filtered	0.5	0.20	313	0.79	0.79	0.00	0.00	996	332	7.6	557
Clear Well	2.0	0.20	293	0.81	0.81	0.00	0.00	–	–	–	–
% Reduction		99.2	–	88.8	79.3	>99.9	>99	–	–	99.989	96.9
Dist. System	6.0	0.49	153	0.77	0.77	0.00	0.00	646	230	1.5	81
(Δ)		(+0.19)	(-49)	(-0.67)	(-0.67)	(0.00)	(0.00)	(-1254)	(-264)	(+0.7)	(-1229)

				Bacteria by Direct Count, 10^6 Cells/mL				Particles >3 µm,** Number/mL			
DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
18 FEB 89											
Raw	0.5	23.0(6.0)	26200(17800)	5.65	2.93	2.72(48.1)	1.22(21.6)	–	–	100000	12000
Settled	0.5	1.7	–	1.49	1.49	0.00	0.00	–	–	–	–
Filtered	0.5	0.24	310	1.11	1.11	0.00	0.00	1300	454	1.6	758
Clear Well	2.0	0.25	290	0.98	0.98	0.00	0.00	–	–	–	–
% Reduction		99.0	98.8	80.3	62.1	>99.9	>99	–		99.998	93.7
Dist. System	5.8	0.29	100	0.72	0.72	0.00	0.00	685	290	1.1	318
(Δ)		(+0.08)	(-385)	(-0.33)	(-0.33)	(0.00)	(0.00)	(-605)	(-92)	(-0.2)	(-511)
19 FEB 89											
Raw	1.0	21.0(5.5)	63000(18000)	6.30	3.32	2.98(49.9)	1.28(20.3)	–	–	97000	16000
Settled	1.0	1.5	–	1.59	1.59	0.00	0.00	–	–	–	–
Filtered	1.0	0.31	167(117)	1.13	1.13	0.00	0.00	3090	920	1.9	170
Clear Well	2.0	0.22	47	0.90	0.90	0.00	0.00	–	–	–	–
% Reduction		98.5	99.7(99.4)	82.1	66.0	>99.9	>99	–	–	99.998	98.9
Dist. System	6.0	0.30	80(87)	0.81	0.81	0.00	0.00	826	314	0.8	434
(Δ)		(+0.10)	(-233)(–)	(+0.02)	(+0.02)	(0.00)	(0.00)	(-170)	(-18)	(-6.8)	(-123)
20 FEB 89											
Raw	1.3	17.0(6.1)	18000(27300)	5.75	3.53	2.22(38.6)	0.62(10.7)	–	–	55000	8800
Settled	1.3	1.4	–	1.14	1.14	0.00	0.00	–	–	–	–
Filtered	1.3	0.17	155(108)	0.77	0.77	0.00	0.00	689	136	0.65	491
Clear Well	3.0	0.20	38(32)	0.69	0.69	0.00	0.00	–	–	1.13	–
% Reduction		99.0	99.1(99.6)	86.6	78.2	>99.9	>99	–	–	99.999	94.4
Dist. System	6.0	0.36	83(78)	1.66	1.66	0.00	0.00	1080	264	1.46	724
(Δ)		(+0.12)	(-227)(–)	(+0.55)	(+0.55)	(0.00)	(0.00)	(-120)	(-190)	(-0.1)	(-34)

				Bacteria by Direct Count, 10^6 Cells/mL				Particles >3 µm,** Number/mL			
DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
21 FEB 89											
Raw	1.5	18.0(8.1)	33200(26300)	5.05	2.84	2.22(43.9)	0.63(12.5)	–	–	75000	11000
Settled	1.5	1.5	–	1.30	1.30	0.00	0.00	–	–	–	–
Filtered	1.5	0.19	90(100)	0.76	0.76	0.00	0.00	1390	253	–	1040
Clear Well	3.0	0.22	78(108)	0.70	0.70	0.00	0.00	1480	345	1.3	1020
% Reduction		98.9	99.7(89.4)	85.0	73.2	>99.9	>99	–	–	99.998	90.5
Dist. System	6.0	0.33	30(37)	0.62	0.62	0.00	0.00	893 1510	235 539	3.2 2.6	565 863
(Δ)		(+0.02)	(-137(-80))	(-0.51)	(-0.51)	(0.00)	(0.00)	(-1889)	(-524)	(+1.0)	(-544)
22 FEB 89											
Raw	1.3	17.0(7.5)	26900(11200)	6.03	3.30	2.72(45.2)	1.00(16.7)	–	–	68000	9720
Settled	1.5	0.13	–	1.37	1.37	0.00	0.00	–	–	–	–
Filtered	1.5	0.14	41(38)	0.74	0.74	0.00	0.00	666	178	1.30	433
Clear Well	2.3	0.18	55(73)	0.90	0.90	0.00	0.00	15	541	0.49	846
% Reduction		99.1	99.8(99.7)	87.7	77.6	>99.9	>99	–	–	99.998	95.5
Dist. System	6.0	0.32	21(38)	0.65	0.65	0.00	0.00	745	220	1.78	457
(Δ)		(+0.15)	(+55(+272))	(-0.12)	(-0.12)	(0.00)	(0.00)	(+56)	(+84)	(+1.13)	(-34)
23 FEB 89											
Raw	1.0	15.0(6.8)	34200(26700)	4.89	3.11	1.78(36.4)	0.23(4.6)	–	–	71000	14500
Settled	1.0	1.0	–	1.22	1.22	0.00	0.00	–	–	–	–
Filtered	1.0	0.18	52	0.80	0.80	0.00	0.00	1100	288	1.9	726
Clear Well	2.8	0.17	50	0.77	0.77	0.00	0.00	–	–	–	–
% Reduction		98.8	99.8	83.6	74.3	>99.9	>99	–	–	99.997	95.0
Dist. System	6.0	0.31	–	0.66	0.66	0.00	0.00	1200	557	1.6	89
(Δ)		(+.12)	(–)	(-0.10)	(-0.10)	(0.00)	(0.00)	(-190)	(+304)	(+0.3)	(-951)

DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Bacteria by Direct Count, 10^6 Cells/mL: Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Particles >3 µm,** Number/mL: Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
24 FEB 89											
Raw	1.0	14.0(6.9)	39700(26300)	4.83	3.05	1.78(36.9)	0.53(11.1)	–	–	55000	12000
Settled	1.0	1.0	–	1.18	1.18	0.00	0.00	–	–	–	–
Filtered	1.0	0.16	38(32)	0.81	0.81	0.00	0.00	1060	358	1.0	638
Clear Well	2.8	0.16	23(27)	0.87	0.87	0.00	0.00	744	220	1.3	470
% Reduction		98.9	99.9(99.9)	83.2	73.4	>99.9	>99	–	–	99.998	94.7
Dist. System	6.0	0.28	51(52)	0.73	0.73	0.00	0.00	1680	667	–	857
(Δ)		(+0.14)	(–)	(-0.01)	(-0.01)	(0.00)	(0.00)	(+1014)	(+489)	(–)	(+424)
25 FEB 89											
Raw	1.8	14.0(6.4)	25200(24500)	4.70	3.34	1.36(29.0)	0.34(7.2)	–	–	55000	14800
Settled	1.8	0.92	–	1.13	1.13	0.00	0.00	–	–	–	–
Filtered	1.8	0.15	35	0.62	0.62	0.00	0.00	923	249	0.5	630
Clear Well	3.3	0.17	30	0.67	0.67	0.00	0.00	664	175	0.8	437
% Reduction		98.9	99.9	86.8	81.4	>99.9	>99	–	–	99.999	95.7
Dist. System	6.0	0.23	24	0.63	0.63	0.00	0.00	1080	392	1.6	583
(Δ)		(+0.05)	(-496)	(-0.17)	(-0.17)	(0.00)	(0.00)	(-20)	(+104)	(-0.3)	(-143)
26 FEB 89											
Raw	2.3	12.0(5.9)	19100(11300)	4.86	3.37	1.49(30.7)	0.39(8.0)	–	–	71300	11700
Settled	2.3	1.3	–	1.44	1.44	0.00	0.00	–	–	–	–
Filtered	2.3	0.16	24	0.83	0.83	0.00	0.00	758	220	0.2	504
Clear Well	4.0	0.20	21	0.87	0.87	0.00	0.00	946	230	0.5	658
% Reduction		98.7	99.9	82.9	75.3	>99.9	>99	–	–	99.999	95.7
Dist. System	6.0	0.19	16	0.61	0.61	0.00	0.00	1970	648	1.3	1190
(Δ)		(+0.30)	(-16)	(-0.20)	(-0.20)	(0.00)	(0.00)	(+910)	(+290)	(+0.3)	(+552)

				Bacteria by Direct Count, 10^6 Cells/mL				Particles >3 µm,** Number/mL			
DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
27 FEB 89											
Raw	3.0	12.0(5.9)	16800(12700)	5.10	3.32	1.78(34.9)	0.16(3.2)	–	–	51800	12000
Settled	3.0	1.1	–	1.44	1.44	0.00	0.00	–	–	–	-
Filtered	3.0	0.16	17	0.89	0.89	0.00	0.00	875	214	1.1	575
Clear Well	4.0	0.15	7	0.92	0.92	0.00	0.00	782	230	1.8	509
% Reduction		98.7	99.9	82.5	73.2	>99.9	>99	–	–	99.998	95.2
Dist. System	6.0	0.32	14	0.89	0.89	0.00	0.00	920	238	0.5	629
(Δ)		(+0.18)	(-21)	(+0.27)	(+0.27)	(0.00)	(0.00)	(-3)	(-11)	(0.0)	(-1)
Averages for 16-day period: 12 FEB - 27 FEB 89											
Raw	1.0	18.8	37400	5.90	3.58	2.32(39.3)	0.67(11.4)	–	–	74400	14466
Settled	1.0	–	–	–	–	0.00	0.00	–	–	–	–
Filtered	1.0	0.22	144	0.95	0.95	0.00	0.00	1229	380	1.93	659
Clear Well	2.6	–	–	–	–	0.00	0.00	–	–	–	–
% Reduction		98.8	99.6	83.9	73.5	>99.9	>99	–	–	99.997	95.2
Dist. System	6.0	0.34(0.2-0.6)	63	0.91	0.91	0.00	0.00	1116	405	1.87	542
(Δ)		(+0.12)	(-81)	(-0.04)	(-0.04)	(0.00)	(0.00)	(-225)	(-20)	(-0.85)	(-213)

TABLE 15. RAPID SAND FILTRATION PLANT PERFORMANCE AND INFLUENCE OF DISTRIBUTION SYSTEM ON FINISHED WATER PARTICLES AND BACTERIA

(SUMMER DATA)

				Bacteria by Direct Count, 10^6 Cells/mL				Particles >3 µm,** Number/mL			
DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
31 AUG 89											
Raw	23	1030(38)	348000(56800)	19.1(5.5)	6.87	12.2(63.9)	0.78(4.1)	–	–	1100000	25000
Settled	27	1.40	--	0.44	0.44	0.00	0.00	–	–	–	–
Filtered	27	–	52	0.07	0.07	0.00	0.00	143	–	–	45
Clear Well	27	0.075	2	0.13	0.13	0.00	0.00	130	–	0.7	50
% Reduction		99.93	99.99	99.6	99.0	>99.99	>99.9	–	–	99.99993	99.8
Dist. System	25	0.27	1650	0.11	0.11	0.00	0.00	–	–	–	–
1 SEPT 89											
Raw	26	1740(58)	300000(84500)	34.6(5.6)	6.35	28.3(81.6)	12.7(36.7)	–	–	622000	81600
Settled	26	1.2	--	0.28	0.28	0.00	0.00	–	–	–	–
Filtered	26	0.17	3	0.05	0.05	0.00	0.00	59	9	0.05	20
Clear Well	28	0.16	0	0.05	0.05	0.00	0.00	63	17	0.43	23
% Reduction		99.99	99.99	99.9	99.2	>99.99	>99.9	–	–	99.99999	99.98
Dist. System	25	0.31	3100	0.18	0.18	0.00	0.00	192	57	2.2	32
2 SEPT 89											
Raw	26	1180(56)	505000(67000)	29.4(4.6)	8.42	21.0(71.4)	5.31(18.1)	–	–	343000	38900
Settled	26	1.8	--	0.26	0.26	0.00	0.00	–	–	–	–
Filtered	26	0.08	157	0.07	0.07	0.00	0.00	44	10	0.11	9
Clear Well	27	0.07	1	0.10	0.10	0.00	0.00	68	15	0.43	23
% Reduction		99.99	99.97	99.8	99.2	>99.99	>99.9	–	–	99.99996	99.98
Dist. System	26	0.54	200(189)	0.07	0.07	0.00	0.00	212	24	1.6	15
Δ		(–)	(+148)	(0.00)	(0.00)	(0.00)	(0.00)	(+69)	(–)	(–)	(-30)

DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Bacteria by Direct Count, 10^6 Cells/mL: Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Particles >3 µm,** Number/mL: Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
3 SEPT 89											
Raw	26	1056(50)	286000(60500)	32.4(6.2)	11.1	21.3(65.6)	7.26(22.4)	–	–	590000	—
Settled	26	1.4	–	0.49	0.49	0.00	0.00	–	–	–	–
Filtered	26	0.14	259	0.17	0.17	0.00	0.00	148	57	0.41	13
Clear Well	26	0.11	3	0.18	0.18	0.00	0.00	99	49	1.86	30
% Reduction		99.99	99.91	99.5	98.5	>99.99	>99.9	–	–	99.99993	
Dist. System	26	0.47	158(132)	0.14	0.14	0.00	0.00	321	19	4.2	29
(Δ)		(+0.30)	(+155)	(+0.09)	(+0.09)	(0.00)	(0.00)	(+262)	(-10)	(+4.1)	(+9)
4 SEPT 89											
Raw	25	732(52)	188000(54300)	27.9(7.8)	9.46	18.8(67.4)	6.74(24.2)	–	–	389000	10700
Settled	25	1.4	–	0.31	0.31	0.00	0.00	-	–	–	–
Filtered	25	0.09	301	0.10	0.10	0.00	0.00	63	23	0.16	5
Clear Well	26	0.09	6	0.10	0.10	0.00	0.00	63	23	0.41	11
% Reduction		99.99	99.84	99.6	98.9	>99.99	>99.9	–	–	99.99995	99.95
Dist. System	26	0.28	62(52)	0.14	0.14	0.00	0.00	136	39	2.8	11
(Δ)		(+0.20)	(-95)	(+0.07)	(+0.07)	(0.00)	(0.00)	(+92)	(+29)	(+2.7)	(+2)
5 SEPT 89											
Raw	25	380(52)	177000(49000)	20.6(7.9)	8.29	12.3(59.7)	1.94(9.4)	–	–	266000	19400
Settled	25	0.86	–	0.33	0.33	0.00	0.00	–	–	–	–
Filtered	25	0.14	222	0.06	0.06	0.00	0.00	30	15	0.11	3
Clear Well	25	0.13	41	0.09	0.09	0.00	0.00	40	15	0.30	7
% Reduction		99.96	99.87	99.7	99.0	>99.99	>99.9	–	–	99.99995	99.98
Dist. System	25	0.23	81(86)	0.13	0.13			180	41	1.30	21
(Δ)		(+0.09)	(-178)	(-0.04)	(-0.04)	(0.00)	(0.00)	(+32)	(-16)	(+0.9)	(+8)

				Bacteria by Direct Count, 10^6 Cells/mL				Particles >3 µm,** Number/mL			
DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
6 SEPT 89											
Raw	25	190(36)	83000(29000)	13.3(8.6)	6.06	7.23(54.4)	1.81(13.7)	–	–	240000	26600
Settled	25	1.2	–	0.27	0.27	0.00	0.00	–	–	–	–
Filtered	25	0.08	135	0.04	0.04	0.00	0.00	22	7	0.09	3
Clear Well	25	0.08	–	0.05	0.05	0.00	0.00	36	17	0.27	5
% Reduction	99.96	99.84	9.7	99.3	>99.99	>99.9	>99.9	–	–	99.99996	99.98
Dist. System	25	0.21	1020(1270)	0.12	0.12	0.00	0.00	115	19	1.6	8
(Δ)		(+0.12)	(+719)	(+0.02)	(+0.02)	(0.00)	(0.00)	(+52)	(-4)	(+1.4)	(+3)
7 SEPT 89											
Raw	26	145(30)	48500(26000)	12.3(7.4)	5.25	7.10(57.5)	2.04(16.5)	–	–	220000	10400
Settled	26	1.6	–	0.15	0.15	0.00	0.00	–	–	–	–
Filtered	26	0.09	17	0.03	0.03	0.00	0.00	47	25	0.30	8
Clear Well		0.09	27	0.03	0.03	0.00	0.00	31	10	0.24	10
% Reduction		99.94	99.96	99.8	99.4	>99.99	>99.9	–	–	99.99986	99.92
Dist. System	25	0.23	1110(1190)	0.08	0.08	0.00	0.00	159	24	2.6	8
(Δ)		(0.09)	(+888)	(+0.02)	(+0.02)	(0.00)	(0.00)	(+129)	(+9)	(+2.5)	(+5)
8 SEPT 89											
Raw	26	316(25)	123000(37500)	18.0(7.8)	6.42	11.6(64.5)	4.57(25.3)	–	–	492000	16800
Settled	26	0.83	–	0.13	0.13	0.00	0.00	–	–	–	–
Filtered	26	0.08	3	0.02	0.02	0.00	0.00	25	2	0.04	8
Clear Well	26	0.09	3	0.04	0.04	0.00	0.00	29	4	0.30	8
% Reduction		99.97	99.99	99.9	99.7	>99.99	>99.9	–	–	99.99999	99.95
Dist. System	25	0.20	683(610)	0.06	0.06	0.00	0.00	168	24	1.1	8
(Δ)		(+0.12)	(+548)	(+0.02)	(+0.02)	(0.00)	(0.00)	(+146)	(+17)	(+1.0)	(+5)

DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 μm MF) (3)	HPC, CFU/mL* (3 μm MF) (4)	Bacteria by Direct Count, 10^6 Cells/mL: Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Particles >3 μm,** Number/mL: Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
9 SEPT 89											
Raw	25	1450(76)	825000(92000)	31.8(8.0)	13.1	18.7(58.8)	4.67(14.7)	–	–	434000	–
Settled	25	2.1	–	0.35	0.35	0.00	0.00	–	–	–	–
Filtered	25	0.09	39	0.15	0.15	0.00	0.00	99	29	0.11	38
Clear Well	26	0.09	17	0.09	0.09	0.00	0.00	61	20	0.29	16
% Reduction		99.99	99.99	99.5	98.9	>99.99	>99.9	–	–	99.99997	–
Dist. System	26	0.28	573(433)	0.03	0.03	0.00	0.00	37	0	1.3	3
(Δ)		(+0.19)	(+556)	(0.00)	(0.00)	(0.00)	(0.00)	(-10)	(-25)	(+1.0)	(-5)
10 SEPT 89											
Raw	24	2022(64)	$1.2x10^6$ ($1.2x10^5$)	65.2(8.0)	18.7	46.5(71.4)	19.8(30.4)	–	–	868000	–
Settled	24	2.1	–	0.29	0.29	0.00	0.00	–	–	–	–
Filtered	24	0.09	79	0.10	0.10	0.00	0.00	64	35	0.07	13
Clear Well	25	0.10	186	0.11	0.11	0.00	0.00	95	55	0.24	19
% Reduction		99.99	99.99	99.8	99.2	>99.99	>99.9	–	–	99.99999	–
Dist. System	26	0.47	90(93)	0.03	0.03	0.00	0.00	36	16	2.3	3
(Δ)		(+0.39)	(+87)	(+0.01)	(+0.01)	(0.00)	(0.00)	(+11)	(+14)	(+2.3)	(-5)
11 SEPT 89											
Raw	23	2240(64)	767000(68000)	48.9(6.7)	7.78	41.1(84.1)	13.2(27.1)	–	–	826000	
Settled	23	2.0	–	0.85	0.85	0.00	0.00	–	–	–	–
Filtered	23	0.21	200	0.46	0.46	0.00	0.00	863	585	1.30	79
Clear Well	24	0.16	325	0.35	0.35	0.00	0.00	439	287	0.81	58
% Reduction		99.99	99.97	99.1	94.1	>99.99	>99.9	–	–	99.99984	–
Dist. System	24	0.23	1400(1450)	0.11	0.11	0.00	0.00	196	50	4.2	29
(Δ)		(+0.14)	(+1361)	(-0.04)	(-0.04)	(0.00)	(0.00)	(+97)	(+21)	(+4.1)	(-9)

				Bacteria by Direct Count, 10^6 Cells/mL				Particles >3 µm,** Number/mL			
DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
12 SEPT 89											
Raw	22	2540(56)	$1.7x[10]^6$ (118000)	61.2(7.7)	9.85	51.3(83.9)	11.9(19.5)	–	–	1000000	–
Settled	22	2.6	–	0.56	0.56	0.00	0.00	–	–	–	–
Filtered	22	0.12	140	0.26	0.26	0.00	0.00	449	266	0.73	62
Clear Well	23	0.13	784	0.36	0.36	0.00	0.00	488	316	0.81	63
% Reduction		99.99	99.99	99.6	97.3	>99.99	>99.9	–	–	99.999927	–
Dist. System	24	0.24	1660(1410)	0.18	0.18	0.00	0.00	172	88	1.6	13
(Δ)		(+0.15)	(+1581)	(+0.08)	(+0.08)	(0.00)	(0.00)	(+108)	(+50)	(+1.5)	(0)
13 SEPT 89											
Raw	20	1760(77)	$1.4x[10]^6$ 150000	58.1(7.3)	16.2	41.9(72.1)	14.9(25.7)	–	–	907000	–
Settled	20	3.1	–	1.06	1.06	0.00	0.00	–	–	–	–
Filtered	20	0.16	410	0.51	0.51	0.00	0.00	544	411	0.57	49
Clear Well	21	0.17	123	0.48	0.48	0.00	0.00	646	479	0.49	60
% Reduction		99.99	99.97	99.1	96.9	>99.99	>99.9	–	–	99.99993	–
Dist. System	24	0.64	1830(1320)	0.34	0.34	0.00	0.00	907	201	1.6	62
(Δ)		(+0.43)	(+1630)	(-0.12)	(-0.12)	(0.00)	(0.00)	(+44)	(-384)	(+0.3)	(-17)
14 SEPT 89											
Raw	19	1260(66)	$1.2x[10]^6$ (162000)	43.3(7.5)	13.3	29.9(69.2)	6.74(15.6)	–	–	729000	–
Settled	19	2.5	–	1.28	1.28	0.00	0.00	–	–	–	–
Filtered	19	0.19	63	0.64	0.64	0.00	0.00	–	–	–	–
Clear Well	20	0.24	317	0.68	0.68	0.00	0.00	–	–	–	–
% Reduction		99.98	99.99	98.5	95.2	>99.99	>99.9	–	–	–	–
Dist. System	24	0.28	347(317)	0.48	0.48	0.00	0.00	604	397	12.5	55
(Δ)		(+0.16)	(+207)	(+0.22)	(+0.22)	(0.00)	(0.00)	(+155)	(+131)	(+11.8)	(-7)

				Bacteria by Direct Count, 10^6 Cells/mL				Particles >3 µm,** Number/mL			
DATE/ SAMPLE (1)	Temperature °C (2)	Turbidity NTU (3 µm MF) (3)	HPC, CFU/mL* (3 µm MF) (4)	Total Bacteria (5)	Planktonic Bacteria (6)	Particle-Associated Bacteria (% of Total) (7)	Bacteria on Particles host to ≥5 Cells (% of Total) (8)	Total Particles (9)	Long Bacterial Rods (10)	Particles with ≥5 Attached Bacteria (11)	Algal Cells (12)
15 SEPT 89											
Raw	19	1320(0.8)	973000 (156000)	36.8(9.5)	12.1	24.8(67.4)	6.35(17.3)	–	–	71900	–
Settled	19	2.7	–	1.28	1.28	0.00	0..00	–	–	–	–
Filtered	19	0.27	587	0.65	0.65	0.00	0.00	–	–	–	–
Clear Well	20	0.19	33	0.65	0.65	0.00	0.00	–	–	–	–
% Reduction		99.98	99.94	98.2	94.6	>99.99	>99.9	–	–	–	–
Dist. System	23	0.34	907(887)	0.63	0.63	0.00	0.00	807	411	6.8	88
(Δ)		(+0.18)	(+497)	(+0.12)	(+0.12)	(0.00)	(0.00)	(+263)	(0)	(+6.1)	(+39)
16 SEPT 89											
Raw	19	1050(61)	577000(80000)	34.9(11.6)	13.1	218(62.5)	4.80(13.8)	–	–	622000	–
Settled	19	3.2	–	1.68	1.68	0.00	0.00	–	–	–	–
Filtered	19	0.19	230	0.73	0.73	0.00	0.00	–	–	–	–
Clear Well	20	0.17	24	0.56	0.56	0.00	0.00	–	–	–	–
% Reduction		99.98	99.96	97.9	94.4	>99.99	>99.9	–	–	–	–
Dist. System	23	0.28	125(163)	0.47	0.47	0.00	0.00	442	140	8.4	21
(Δ)		(+0.09)	(+62)	(-0.17)	(-0.17)	(0.00)	(0.00)	–	–	–	–
Averages for 17-day period: 31 AUG-16 SEPT 1989											
Raw	23.4	1200	629000	34.6	10.1	24.5(70.8)	7.38(21.3)	–	–	610000	28700
Settled	23.7	–	–	–	–	0.00	0.00	–	–	–	–
Filtered	23.7	0.15	170	0.24	0.24	0.00	0.00	186	113	0.31	25
Clear Well	24.4	–	–	–	–	0.00	0.00	–	–	–	–
% Reduction		99.99	99.97	99.3	97.6	>99.99	>99.9	–	–	99.99994	99.91
Dist. System	24.6	0.32	882	0.19	0.19	0.00	0.00	293	97	3.51	25
(Δ)		(+0.17)	(+712)	(-0.05)	(-0.05)	(0.00)	(0.00)	(+107)	(-16)	(+3.20)	(0)