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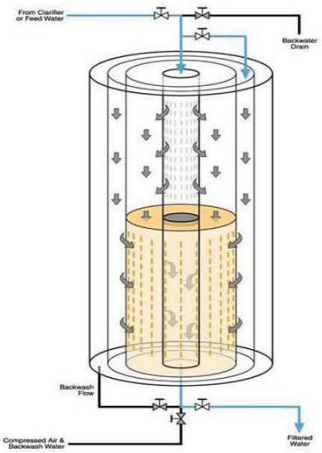
Evaluation of Radial Flow Fluidized Filter (R3F) Followed by Microfiltration and Ultrafiltration Systems in Calimesa, California



SCIENCE

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EVALUATION OF RADIAL FLOW FLUIDIZED FILTER (R3F) FOLLOWED BY MICROFILTRATION AND ULTRAFILTRATON SYSTEMS IN CALIMESA, CALIFORNIA

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Notice

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EPA Contributors

Dr. John Ireland served as Project Officer on EPA Contract No. EP-C-04-034 and Mr. Craig L. Patterson P.E., served as the Work Assignment Manager for this research project. Mr. Jeffrey Q. Adams and Dr. Joel Allen performed technical reviews of the document. Mr. John Olszewski was the EPA Quality Assurance Managers, and was responsible for the quality assurance review of the document. Dr. Bruce Macler with U.S. EPA Region 9 in San Francisco, California reviewed the experimental plan for this research study.

Abstract

U.S. EPA coordinated a field study with South Mesa Water Utility to look for treatment alternatives for California State Project Water in the small community of Calimesa, California. EPA evaluated the performance of a system comprised of Radial Flow Fluidized Filtration (R3f) followed by microfiltration (MF) and ultrafiltration (UF) through a series of turbidity and microbial challenges. The R3f and MF-UF system was challenged to remove turbidity, particles, and bacteria and viral surrogates (B. Subtilis, MS-2) from State Project Water. Turbidity, particle counts and Total Organic Carbon (TOC) were also monitored to obtain additional information on the performance and maintenance requirements of the systems. The report documents the results of these tests and also summarizes the critical observations on the maintenance of the R3f-MF-UF system and the use of turbidity and particle count as a surrogate for measuring the performance of the treatment plant.

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Acronyms and Abbreviations

B. subtilis	*Bacillus subtilis*
E. coli	*Escherichia coli*
gpm	gallons per minute
L	liter
LRV	log removal value
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
mg	milligram
mL	milliliter
MF	microfiltration (microfilter)
MS2	MS2 bacteriophage
NTU	Nephelometric Turbidity Unit
psi	pounds per square inch
PSL	polystyrene latex
QA	quality assurance
QAPP	Quality Assurance Project Plan
QC	quality control
R3f	Radial Flow Fluidized Filter
Shaw	Shaw Environmental & Infrastructure (E&I), Inc.
SMWC	South Mesa Water Company
Std. Dev.	standard deviation
T&E	Test and Evaluation
TOC	total organic carbon
UF	ultrafiltration (ultrafilter)
µg	microgram
µm	microns

1.0 Introduction

The U.S. Environmental Protection Agency (EPA) evaluated the performance of a system comprised of Radial Flow Fluidized Filtration (R3f) followed by Microfiltration (MF) and Ultrafiltration (UF) through a series of turbidity and microbial challenges. The tests were performed at the EPA Test and Evaluation (T & E) Facility in Cincinnati, Ohio and at the South Mesa Water Company (SMWC) site in Calimesa, CA. These tests were performed by EPA and Shaw Environmental & Infrastructure (E&I), Inc. (Shaw) under Contract No. EP-C-09-041, Work Assignment No. 0-03 with the EPA and under a separate contract with SMWC.

The R3f and MF-UF system was challenged with the following contaminants:

- *Escherichia coli (E. coli)* as a representative organism for bacterium
- *Bacillus subtilis (B. subtilis)* as a representative organism for aerobic spores
- MS2 bacteriophage, a surrogate for enteric virus
- Polystyrene Latex (PSL) beads as a surrogate of *Cryptosporidium*
- *Cryptosporidium*. One test was conducted on the R3f system only using *Cryptosporidium* to confirm the surrogacy equivalence of PSL beads.

SMWC had previously evaluated the use of the R3f system as a treatment device for a surface water source. The R3f system had successfully produced water that met the required turbidity standard of 0.30 Nephelometric Turbidity Unit (NTU). However, California required SMWC to achieve at least a 1-log removal of viruses from the filtration step. Since the media size in the R3f system (33 μm) is too large for removal of bacteria and viruses, a MF and UF system downstream of the R3f system was considered for inclusion for microbial removal.

EPA had evaluated the R3f system at the T&E facility and then had evaluated an R3f system followed by a MF and UF system at a field site in Ely, Minnesota and the results showed nearly complete removal of bacteria and viruses. The same treatment system was shipped to SMWC and tested in this study to confirm the removal of bacteria and viruses in this water matrix as well as to evaluate the likely cartridge backwash and changeout frequency. Turbidity, particle counts and Total Organic Carbon (TOC) were also monitored to obtain additional information on the performance and maintenance requirements of the systems. This report documents the results of these tests and also summarizes the critical observations on the maintenance of the R3f-MF-UF system and the use of turbidity and particle count as surrogate for measuring the performance of the treatment plant.

2.0 System Description, Operation and Testing Procedures

This section provides a summary description of the systems evaluated and the associated operation and testing procedures employed at the field site and at the T&E Facility in Cincinnati, OH. The test procedures employed are presented in the following EPA-endorsed Quality Assurance Project Plans (QAPPs):

- EPA QA ID No. 627-Q-10-0 (EPA and Shaw, 2007a)
- Amendment 1 to EPA QA ID No. 627-Q-10-0 (EPA and Shaw, 2008)

2.1 Field Test Site

The field test site was located at SMWC in Calimesa, California. The tested units were installed in the test trailer owned and operated by SMWC.

2.2 Radial Flow Fluidized Filter (R3f) with MF and UF Membrane Polishing Filters

The radial flow fluidized filtration (R3f) system utilizes radial flow (similar to the flow pattern of a cartridge filter) through use of non-bonded garnet media that can be fluidized and backwashed. The technology uses fine garnet media (33 microns) for depth filtration. The filter system housing consists of an upper chamber and a lower chamber. The upper chamber provides the necessary head for flow through the media and for backwashing. Water to be treated enters the system through the annular section at the top of the inner core. The lower chamber contains the media and water travels radially from the annular section through the media to the bottom inner core as a plug flow. The treated water then flows out of the system through the pipe connected at the bottom of the inner core. The plug in the inner core prevents any reverse flow. A typical R3f system is 150 mm (6 inches) in diameter and 1.8 m (6 feet) high as shown in Figure 1. The media can be fluidized and backwashed very quickly resulting in backwash volumes significantly lower than other technologies. The R3f system is suitable for small community potable water systems. It can also serve as pre-filter to membranes or disposable final filtration system. The R3f system is comprised of one lead and one lag unit in series. A typical R3f system setup is shown in Figure 2.

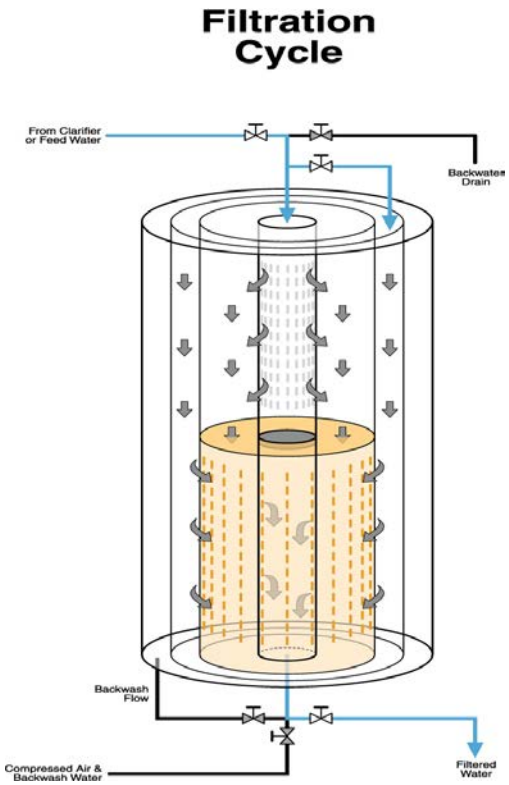

Figure 1. Conceptual Flow Diagram of the R3f System

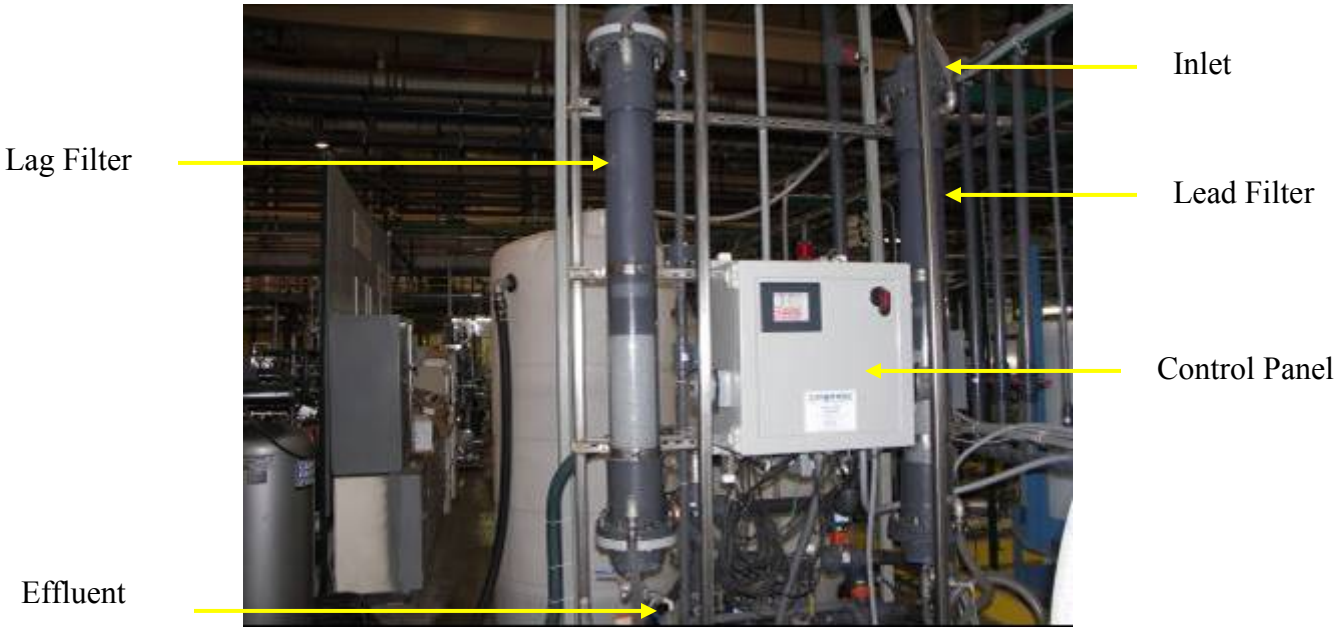

Figure 2. Typical R3f Filter Setup

The UF and MF polishing filters were tested by placing them in a 7-cartridge Shelco Multifilter Cartridge Housing (Figure 3). Two Shelco housings were placed in series – the first housing contained MF cartridges while the second housing contained UF cartridges. The system was configured so that both Shelco housing units could be backwashed at the same frequency as the R3f system.

Figure 3. MF Filters Placed in a Shelco Multi-Cartridge Housing Unit

2.3 System Operation and Test Conditions

2.3.1 Microbial and Turbidity Challenges

Tests were carried out to evaluate the performance of the R3f–MF–UF systems in removing bacteria and virus using the following test matrix, organisms or surrogates:

- For bacteria removal, the systems were challenged with *B. subtilis* endospores,
- For evaluation of virus removal potential, the systems were challenged with MS2 bacteriophage, a surrogate for enteric viruses.
- For evaluation of turbidity removal performance, the systems were operated using surface water from the lake as the feed source with as-received turbidity levels. Samples were collected for turbidity and particle count during the microbial challenges. Additional samples were collected for TOC analysis for evaluating removal of organic matter.

For *B. subtilis* and MS2 bacteriophage, a 1-mL stock suspension with an approximate concentration of 10^9 cells/surrogates per mL was mixed with 500 mL of 0.01% Tween 20 in a 1-L glass beaker. A sub-sample was collected to determine the actual concentration of the injection suspension. The 500 mL suspension and the rinseate were added into the influent stream of the system using a peristaltic pump. The total injection time was approximately 60

minutes. The *B. subtilis* and MS2 bacteriophage stock solutions were obtained from the Raven (Omaha, NE) and BioVir (Benicia, CA) laboratories, respectively.

2.3.2 Sampling and Analytical Procedures

Tables 1 and 2 summarize the sampling strategies and analytical procedures used in this study. The detailed sampling and analytical procedures are described in aforementioned QAPPs.

Table 1. Summary of the Sampling Strategy

Parameter	Sampling Frequency in Each Test
MS2 bacteriophage	At T0, T5, T15, T15 dup, T30 and T60 minutes after the start of the injection from the influent and effluent streams of different treatment units.
B. subtilis	At T0, T5, T15, T15 dup, T30 and T60 minutes after the start of the injection from the influent and effluent streams of different treatment units.
Turbidity and Particle Counts	At T0, T30 and T60 minutes after the start of the injection from the influent and effluent streams of different treatment units.
TOC	At T30 minutes after the start of the injection from the influent and effluent streams of different treatment units.

Table 2. Analytical Methods For Physical and Microbial Parameters in this Study

Parameter	Analytical Method/Instrument
Turbidity	T&E SOP 507 Using Hach Turbidity Meter, Model 2100P (EPA and Shaw, 2006a; Hach Co., 1991)
B. subtilis	T&E SOP 301 Using Heat Shock and Membrane Filtration (EPA and Shaw, 2006b; Rice et al. 1994)
MS2 bacteriophage	T&E SOP 302 Based on the EPA method 1602 (EPA and Shaw, 2007b; EPA, 2001)
Particle Count	HIAC Royco particle count analyzer (Pharmspec Version 1.4)
TOC	Phoenix TOC Analyzer, Model 8000 (EPA, 1999)

3.0 Test Results

This section summarizes the results of tests conducted on the R3f-MF-UF systems to evaluate the performance in removing different microbiological contaminants, turbidity and particle counts. Table 3 summarizes the challenge tests conducted on the R3f-MF-UF systems at the field site

Table 3. Summary of Challenge Tests Conducted on R3f-MF-UF System

Date	Test ID	System Configuration
2/24/10	MS2 bacteriophage Test 1	R3f Lead + R3f Lag + MF + UF
2/24/10	MS2 bacteriophage Test 2	R3f Lead + R3f Lag + MF + UF
2/24/10	MS2 bacteriophage Test 3	R3f Lead + R3f Lag + MF + UF
2/24/10	*B. subtilis* Test 1	R3f Lead + R3f Lag + MF + UF
2/25/10	*B. subtilis* Test 2	R3f Lead + R3f Lag + MF + UF
2/25/10	*B. subtilis* Test 3	R3f Lead + R3f Lag + MF + UF

3.1 MS2 bacteriophage Test Results

Table 4 presents the results of the MS2 bacteriophage challenge tests conducted on the R3f-MF-UF system. The log removal value (LRV) for each system component is summarized in Table 5. The average influent concentration in the three challenge tests ranged from 2.4×10^3/100 mL (3.38 log) to 1.2×10^3/100 mL (4.08 log). The complete system (R3f-MF-UF) achieved complete removal of MS2 bacteriophage with the UF system responsible for the majority of the removal. The overall LRV of the system in removing MS2 bacteriophage is at least >4.10 based on the highest influent concentrations. The R3f system achieved an average LRV of 0.65 in the three tests; however, the performance of the lag unit deteriorated after the first test indicating continuous desorption of MS2 bacteriophage from the R3f system. The MF system achieved a LRV of 0.88 of MS2 bacteriophage in the first test but in subsequent tests the LRV deteriorated indicating breakthrough of MS2 bacteriophage. No breakthrough of MS2 bacteriophage was observed in the UF system.

These test results are similar to the performance demonstrated by the R3f-MF-UF in tests conducted at Ely, Minnesota where the system showed an overall LRV of 3.70 (EPA and Shaw, 2009a). Negligible removal of MS2 bacteriophage was achieved by the R3f system alone in tests conducted at the T&E Facility (EPA and Shaw, 2009b).

Table 4. Results of MS2 bacteriophage Challenges on the R3f-MF-UF System

Sample ID	MS2 bacteriophage Conc./100 mL				
	Influent	**Effluent R3f Lead**	**Effluent R3f Lag**	**Effluent MF**	**Effluent UF**
Test 1: 02/24/10					
T0	N/A[a]	N/A[a]	N/A[a]	N/A[a]	N/A[a]
T5	3.7×10^3	1.1×10^3	N/A[a]	N/A[a]	N/A[a]
T15	1.2×10^4	6.0×10^3	7.7×10^3	370	N/D[e]
T15 Dup	8.0×10^3	9.0×10^3	4.0×10^2	400	1
T30	1.6×10^4	1.2×10^4	5.0×10^2	370	N/D[e]
T60[d]	28	181	N/A[a]	N/A[a]	N/A[a]
Mean [Std. Dev.] ± CI[b]	**9.9×10^3 [5.3×10^3] ± 5.2×10^3**	**7.0×10^3 [4.6×10^3] ± 4.6×10^3**	**2.9×10^3 [7.9×10^4] ± 3.7×10^3**	**3.8×10^2 [14] ± 4.3×10^2**	N/D[e]
Test 2: 02/24/10					
T0[d]	8	0	0	0	N/D[e]
T5	1.5×10^4	130[c]	0[c]	60[c]	N/D[e]
T15	1.5×10^4	1.4×10^3	1.7×10^3	8.2×10^3	N/D[e]
T15 Dup	9.4×10^3	1.5×10^3	1.5×10^3	1.5×10^3	N/D[e]
T30	9.1×10^3	1.6×10^3	1.0×10^3	1.7×10^3	N/D[e]
T60[d]	14	530	48	15	N/D[e]
Mean [Std. Dev.] ± CI[b]	**1.2×10^4 [3.3×10^3] ± 3.3×10^3**	**1.5×10^3 [100] ± 97**	**1.4×10^3 [3.6×10^2] ± 3.2×10^2**	**3.8×10^3 [3.1×10^3] ± 4.3×10^3**	N/D[e]
Test 3: 02/24/10					
T0[d]	0	0	0	0	N/D[e]
T5[d]	9.5×10^2	17	7	2	N/D[e]
T15	1.1×10^3	8.0×10^2	6.0×10^2	7.3×10^2	N/D[e]
T15 Dup	1.2×10^3	6.0×10^2	7.0×10^2	9.2×10^2	N/D[e]
T30	4.8×10^3	9.5×10^2	1.3×10^3	2.3×10^3	N/D[e]
T60[d]	70	10	43	41	N/D[e]
Mean [Std. Dev.] ± CI[b]	**2.4×10^3 [2.1×10^3] ± 2.1×10^3**	**7.8×10^2 [1.8×10^2] ± 1.7×10^2**	**8.7×10^2 [2.4×10^2] ± 3.3×10^2**	**9.9×10^2 [2.4×10^2] ± 2.7×10^2**	N/D[e]

[a] Not available, plaques did not grow probably due to either slightly overgrown host *E. coli* or problems in media caused by malfunction of autoclave.

[b] Confidence Interval at 95% significance

[c] Not considered for performance evaluation due to inconsistent value

[d] Not considered for performance evaluation due lower influent concentration

[e] Not detected, no plaques were observed on any of the 10 plates for the sample

Table 5. Summary of the R3f-MF-UF System Performance in Removing MS2 bacteriophage

Test ID	Contribution to Log Removal Value (LRV)				
	R3f Lead	**R3f Lag**	**MF**	**UF**	**Overall**
1	0.15	0.38	0.88	Complete Removal (>2.58[a])	Complete Removal (>4.00[b])
2	0.90	0.03	0.00	Complete Removal (>3.58[a])	Complete Removal (>4.10[b])
3	0.49	0.00	0.00	Complete Removal (>3.00[a])	Complete Removal (>3.38[b])

[a] LRV based on the influent concentration of the UF unit.

[b] LRV based on the influent concentration of the overall system

3.2 *B. subtilis* Test Results

Table 6 presents the results of the *B. subtilis* challenges conducted on the R3f-MF-UF system. The log removal value (LRV) for each system component is summarized in Table 7. The average influent concentration in the three challenge tests ranged from 7.4×10^5/100 mL (5.86 log) to 8.6×10^5/100 mL (5.93 log) and the whole system achieved complete removal of *B. subtilis* with the MF system responsible for majority of the removal. The overall LRV of the system in removing MS2 bacteriophage is at least >5.93 based on the highest influent concentrations. The R3f system achieved an average log removal value of 1.0 in the three tests; however, the performance of the R3f system deteriorated after the first test indicating continuous desorption of *B. subtilis* from the R3f system. No breakthrough of *B. subtilis* was observed in the MF system.

These test results are similar to the performance demonstrated by the R3f-MF-UF system in tests conducted at Ely, Minnesota where the whole system achieved complete removal of *B. subtilis*. The R3f system alone achieved a 1.0 log removal (EPA and Shaw, 2009a). The R3f system achieved an average log removal value of 0.44 in removing *B. subtilis* in tests conducted at the T&E Facility (EPA & Shaw, 2009b).

Table 6. Results of *B. subtilis* Challenges on the R3f-MF-UF System

Sample ID	*B. subtilis* Conc./100 mL				
	Influent	**Effluent R3f Lead**	**Effluent R3f Lag**	**Effluent MF**	**Effluent UF**
Test 1: 02/24/10					
T0[d]	0	0	0		
T5	8.1×10^5	1.2×10^5	9.0×10^3	N/D[e]	N/D[e]
T15	7.8×10^5	2.6×10^5	1.7×10^4	N/D[e]	N/D[e]
T15 Dup	7.4×10^5	3.2×10^5	1.7×10^4	N/D[e]	N/D[e]
T30	6.3×10^5	3.0×10^5	5.4×10^4	N/D[e]	N/D[e]
T60	N/A[a]	N/A[a]	1.4×10^4	N/D[e]	N/D[e]
Mean [Std. Dev.] ± CI[b]	**7.4×10^5 [7.9×10^4] ± 7.7×10^4**	**2.5×10^5 [9.0×10^4]± 8.8×10^4**	**2.4×10^4 [2.0×10^4] ± 1.8×10^4**	N/D[e]	N/D[e]
Test 2: 02/25/10					
T0[d]	N/A[a]	8.6×10^3	8.0×10^3	N/D[e]	N/D[e]
T5	8.6×10^5	1.1×10^5	1.0×10^3	1.6×10^3 [c]	N/D[e]
T15	8.8×10^5	4.8×10^5	1.0×10^5	N/D[e]	N/D[e]
T15 Dup	9.0×10^5	4.9×10^5	1.1×10^5	N/D[e]	N/D[e]
T30	8.1×10^5	5.6×10^5	1.1×10^5	N/D[e]	N/D[e]
T60	5.0×10^3[c]	1.6×10^4	1.0×10^4	N/D[e]	N/D[e]
Mean [Std. Dev.] ± CI[b]	**8.6×10^5 [3.9×10^4] ± 3.8×10^4**	**4.1×10^5 [2.0×10^5] ± 2.0×10^5**	**1.1×10^5 [5.8×10^3] ± 5.1×10^3**	N/D[e]	N/D[e]
Test 3: 02/25/10					
T0[d]	600	500	28	N/D[e]	N/D[e]
T5	6.9×10^5	2.1×10^5	N/A[a]	N/D[e]	N/D[e]
T15	8.6×10^5	5.2×10^5	1.5×10^5	N/D[e]	N/D[e]
T15 Dup	7.2×10^5	4.8×10^5	1.8×10^5	N/D[e]	N/D[e]
T30	9.8×10^5	5.2×10^5	1.6×10^5	N/D[e]	N/D[e]
T60	1.2×10^5	9.1×10^4	3.9×10^4	N/D[e]	N/D[e]
Mean [Std. Dev.] ± CI[b]	**7.9×10^5 [1.6×10^5] ± 1.6×10^5**	**4.4×10^5 [1.5×10^5] ± 1.5×10^5**	**1.6×10^5 [1.5×10^4] ± 1.4×10^4**	N/D[e]	N/D[e]

[a] Not available due to under-dilution of samples

[b] Confidence Interval at 95% significance

[c] Not considered for performance evaluation due to inconsistent value

[d] Not considered for performance evaluation due to lower influent concentration

[e] Not detected, no plaques were observed on any of the 10 plates for the sample

Table 7. Summary of the R3f-MF-UF System Performance in Removing *B. subtilis*

Test ID	Log Removal Value (LRV)				
	R3f Lead	**R3f Lag**	**MF**	**UF**	**Overall**
1	0.47	1.0	Complete Removal (>4.38[a])	Not Applicable[c]	Complete Removal (>5.86[b])
2	0.32	0.57	Complete Removal (>5.04[a])	Not Applicable[c]	Complete Removal (>5.93[b])
3	0.25	0.43	Complete Removal (>5.20[a])	Not Applicable[c]	Complete Removal (>5.90[b])

[a] LRV based on the influent concentration of the UF unit.

[b] LRV based on the influent concentration of the overall system

[c] Not applicable as complete removal was achieved by the MF unit

3.3 Turbidity, Particle Count and TOC Results

3.3.1 Turbidity Results

Table 8 presents the results of turbidity monitoring during the microbial challenges. The performance of each system component in removing turbidity is summarized in Table 9. The average influent turbidity was 0.60 NTU and the R3f-MF-UF system achieved an average effluent turbidity of 0.13 NTU. This effluent turbidity satisfies the Long Term 2 Enhanced Surface Water Treatment Regulation (LT2ESWTR) requirement of effluent turbidity < 0.30 NTU (EPA, 2006). The R3f system alone produced water with an effluent turbidity of 0.27 NTU which also satisfies the LT2ESWTR requirements. The R3f-MF-UF system removed an average of 78.3% of turbidity of which 55% removal was contributed by the R3f system. The MF and UF systems contributed 23.3 % turbidity removal.

These test results are similar to the performance demonstrated by the R3f-MF-UF system in tests conducted at Ely, Minnesota where the final effluent turbidity for a feed water of 1.88 NTU was 0.10 NTU (EPA and Shaw, 2009a). The R3f system achieved effluent turbidity of 0.61 NTU from an influent turbidity of 4.30 NTU in tests conducted at the T&E Facility without the use of any coagulant (EPA and Shaw 2009b).

Table 8. Turbidity Results for the R3f-MF-UF System

Date & Time	Turbidity (NTU)					
	Influent	**Effluent R3f Lead**	**Effluent R3f Lag**	**Effluent MF**	**Effluent UF**	**Blank**
2/24/10; 10:00	0.52	0.70[a]	0.42	0.20	0.15	0.09
2/24/10; 10:30	0.60	0.40	0.28	0.14	0.70[a]	0.09
2/24/10; 11:00 *	0.70	0.33	0.64[a]	0.14	0.14	0.09
2/24/10; 13:15	0.93	0.31	0.28	0.20	0.16	0.10
2/24/10; 13:45	0.90	0.36	0.30	0.16	0.14	0.11
2/24/10; 14:15 *	0.70	0.30	0.24	0.14	0.13	0.11
2/24/10; 15:00	0.52	0.36	0.32	0.15	0.12	0.11
2/24/10; 15:30	0.84	0.36	0.25	0.13	0.12	0.11
2/24/10; 16:00 *	0.70	0.40	0.30	0.13	0.12	0.11
2/24/10; 17:55	0.42	0.24	0.24	0.13	0.12	0.11
2/24/10; 18:25	0.42	0.27	0.19	0.15	0.12	0.11
2/24/10; 18:55 *	0.58	0.29	0.22	0.14	0.14	0.11
2/25/10; 08:45	0.52	0.31	0.25	0.14	0.11	0.10
2/25/10; 09:15	0.61	0.28	0.22	0.18	0.11	0.10
2/25/10; 09:45 **	0.54	0.31	0.24	0.15	0.10	0.10
2/25/10; 11:40	0.39	0.29	0.22	0.19	0.14	0.11
2/25/10; 12:20	0.45	0.29	0.40	0.18	0.10	0.11
2/25/10; 12:40***	0.54	0.34	0.26	0.18	0.14	0.11
Mean [Std. Dev.] ± CI[b]	**0.60 [0.16] ± 0.07**	**0.32 [0.04] ± 0.02**	**0.27 [0.06] ± 0.03**	**0.16 [0.02] ± 0.01**	**0.13 [0.02] ± 0.01**	**0.10 [0.01] ± 0.003**

[a] Inconsistent data

[b] Confidence Interval at 95% Significance.

* R3f system was flushed and allowed to run for 10 minutes. MF and UF systems were stopped during backflush.

** Both MF and UF units was replaced.

*** Test completed; MF and UF systems continued to run.

Table 9. Summary of the R3f-MF-UF System Performance in Removing Turbidity

Test ID	Contribution to % Removal				
	R3f Lead	**R3f Lag**	**MF**	**UF**	**Overall**
Whole Test Period	46.7	8.3	18.3	5.0	78.3

3.3.2 Particle Count Results

The particle counts of the influent and effluent samples were monitored for obtaining secondary information on the performance of the system in removing contaminants. Particle count data was also used to evaluate the potential of R3f system in reducing particle load to the MF and UF systems. Table 10 shows the particle count results for 1.2 µm size particle which is the approximate equivalent size of *B. subtilis*. Table 11 describes the particle count results for the 2 µm - 5 µm size range particles which are the approximate equivalent size of *Cryptosporidium*. Table 12 summarizes the performance of the R3f-MF-UF system in removing particles of the

aforementioned sizes. The average influent concentration of the 1.2 µm size particle was 2198/mL and the final effluent concentration of the 1.2 µm size particle achieved by the R3f-MF-UF system was 173/mL. The R3f system contributed noticeably to the reduction of 1.2 µm size particle. The overall performance in removing 1.2 µm size particles by the whole system was 92.2% of which 71.0% reduction was contributed by the R3f system. The average influent concentration of the 2 - 5 µm size particles is 247/mL and the final effluent concentration of the 2-5 µm size particle achieved by the R3f-MF-UF system was 32/mL. The R3f system contributed noticeably to the reduction of 2-5 µm size particles. The overall performance in removing 2 - 5 µm size particles by the whole system is 87.0% of which 60.0% reduction was contributed by the R3f system. For the R3f system, most of the reduction was contributed by the R3f lead filter. Most of the additional reduction was contributed by the MF system; no additional removal was contributed by the UF system. Particle counts were not monitored for the system during the tests conducted at Ely, Minnesota.

Table 10. Results of 1.2 µm Size Particle Count Monitoring for the R3f-MF-UF System

Date & Time	Turbidity (NTU)					
	Influent	**Effluent R3f Lead**	**Effluent R3f Lag**	**Effluent MF**	**Effluent UF**	**Blank**
2/24/10; 10:00	2032	8101[a]	3149[a]	805[a]	1090[a]	4.2
2/24/10; 10:30	1509	586	522	299	3974[a]	4.8
2/24/10; 11:00 *	2748	408	6746[a]	112	4079[a]	3.2
2/24/10; 13:15	2684	702	669	198	534[a]	1.8
2/24/10; 13:45	4155	922	2993[a]	54	172	2.0
2/24/10; 14:15 *	4576	966	411	67	92	1.0
2/24/10; 15:00	3334	1706	1123	58	102	3.3
2/24/10; 15:30	5050	1395	606	84	78	4.1
2/24/10; 16:00 *	5673	1156	1709	92	190	2.1
2/24/10; 17:55	630	217	203	68	52	0.11
2/24/10; 18:25	813	982	553	226	49	0.11
2/24/10; 18:55 *	1436	138	300	40	114	2.1
2/25/10; 08:45	1298	889	192	50	70	3.8
2/25/10; 09:15	753	768	672	96	133	1.7
2/25/10; 09:45 **	563	184	196	65	124	2.3
2/25/10; 11:40	418	95	900	215	217	3.0
2/25/10; 12:20	550	419	1057	250	750	2.7
2/25/10; 12:40***	1342	225	368	239	283	2.7
Mean [Std. Dev.] ± CI[b]	**2198 [1701] ± 786**	**692 [449] ± 223**	**632 [420] ± 213**	**130 [86] ± 40**	**173 [179] ± 88**	**2.5 ± 0.60**

[a] Inconsistent data, probably due to backflush of the R3f system and inappropriate startup of the MF and UF systems. Not considered for performance evaluation.
[b] Confidence Interval at 95% significance
* R3f system was flushed and allowed to run for 10 minutes. MF and UF systems were stopped during backflush.
** Both MF and UF units was replaced.
*** Test completed; MF and UF systems were continued to run.

Table 11. Results of 2 - 5 µm Size Particle Count Monitoring for the R3f-MF-UF System

Date & Time	Turbidity (NTU)					
	Influent	**Effluent R3f Lead**	**Effluent R3f Lag**	**Effluent MF**	**Effluent UF**	**Blank**
2/24/10; 10:00	372	1849[a]	957[a]	247[a]	214[a]	4.2
2/24/10; 10:30	168	166	85	36	1774[a]	4.8
2/24/10; 11:00 *	353	50	1832[a]	39	1841[a]	3.2
2/24/10; 13:15	247	63	60	49	129[a]	1.8
2/24/10; 13:45	494	35	689[a]	10	41	2.0
2/24/10; 14:15 *	416	40	38	16	20	1.0
2/24/10; 15:00	317	360	96	14	23	3.3
2/24/10; 15:30	447	190	54	11	20	4.1
2/24/10; 16:00 *	334	112	271	21	47	2.1
2/24/10; 17:55	113	46	19	12	13	0.11
2/24/10; 18:25	113	104	81	30	11	0.11
2/24/10; 18:55 *	375	15	48	15	23	2.1
2/25/10; 08:45	197	405	30	9	12	3.8
2/25/10; 09:15	94	119	94	13	16	1.7
2/25/10; 09:45 **	63	21	21	12	21	2.3
2/25/10; 11:40	88	16	155	49	36	3.0
2/25/10; 12:10	61	69	272	34	101	2.7
2/25/10; 12:40***	209	36	41	28	60	2.7
Mean [Std. Dev.] ± CI[b]	**247 [143] ± 66**	**108 [115] ± 54**	**91 [81] ± 41**	**23 [14] ± 6**	**32 [25] ± 12**	**2.5 ± 0.60**

[a] Inconsistent data, probably due to backflush of the R3f system and inappropriate startup of the MF and UF systems. Not considered for performance evaluation.

[b] Confidence Interval at 95% significance

* R3f system was flushed and allowed to run for 10 minutes. MF and UF systems were stopped during backflush.

** Both MF and UF units was replaced.

*** Test completed; MF and UF systems were continued to run.

Table 12. Summary of the R3f-MF-UF System Performance in Removing Particles

Particle Size	Contribution to % Removal				
	R3f Lead	**R3f Lag**	**MF**	**UF**	**Overall**
1.2 µm	68.5	2.7	22.9	None	92.2
2 – 5 µm	56.2	7.0	27.5	None	87.0

Although the R3f-MF-UF system achieved complete removal of *B. subtilis* and MS2 bacteriophage, a small number of 1.2 µm and 2 – 5 µm size particles were detected in the final effluent of the system. This is probably due to either the limitations of the particle size analyzer or characteristics of the non-biological particles. However, a good correlation was observed

between the turbidity and the 1.20 µm particle count data (R^2: 9683) (Figure 4) and the 2 – 5 µm size particle count data (R^2: 0.9915) (Figure 5). This implied that the particle count data may be used as secondary information on the performance of the system in removing turbidity and biological contaminants.

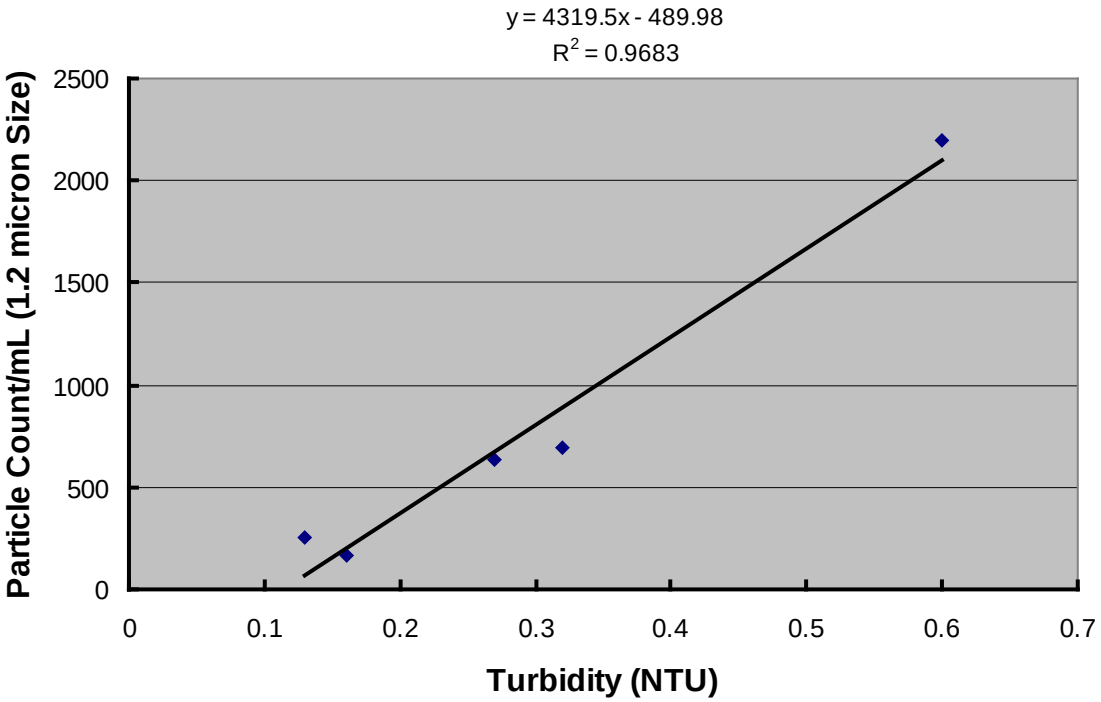

Figure 4. Correlation between Turbidity and 1.2 µm Size Particle

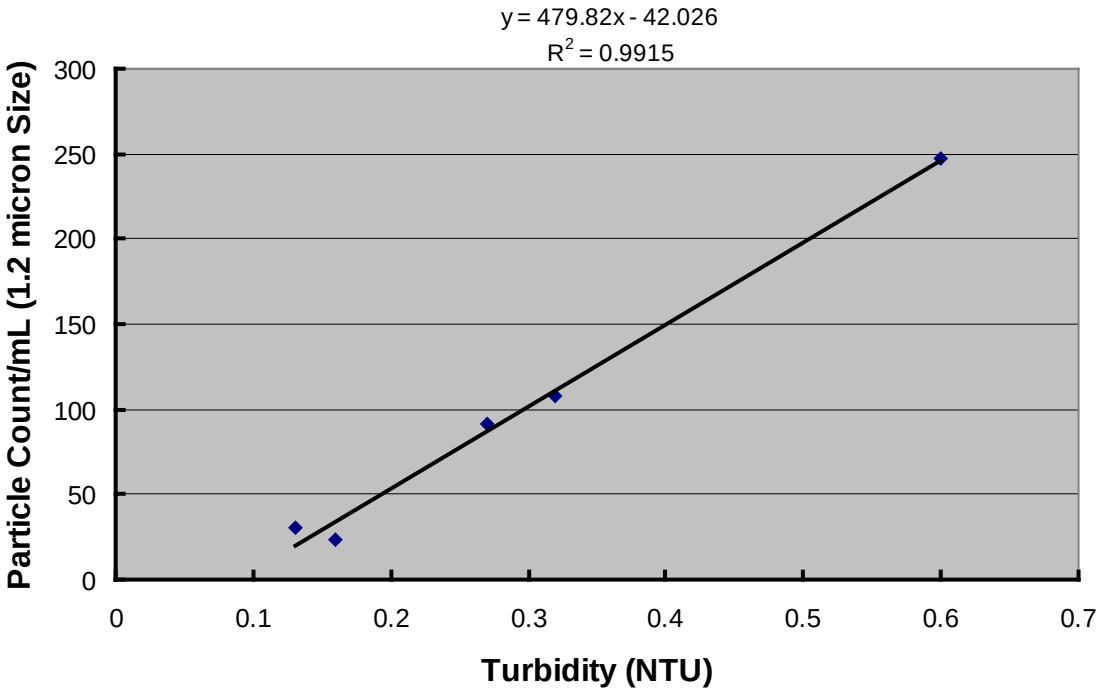

Figure 5. Correlation between Turbidity and 2 - 5 µm Size Particles

3.3.3 Pressure Buildup during the Challenge Tests

Table 13 shows the pressure buildup in the R3f system during the challenge tests. The initial differential pressure in the R3f lead filter was 9 psi and it did not increase during the challenge tests. The initial differential pressure in the R3f lag filter was 0 psi indicating that this unit was experiencing some back pressure due to the addition of MF and UF systems at the downstream location. However, the differential pressure in the R3f lag filter did not increase during the challenge tests. Although the differential pressure did not increase during the challenge tests, the R3f systems were flushed at the end of each test.

Table 14 shows the pressure buildup in the MF and UF units during the challenge tests. The initial differential pressure in the MF unit of 2 psi did not increase during the challenge tests. The initial differential pressure in the UF unit of 12 psi increased to 20 psi at the end of the second *B. subtilis* test. Both the MF and the UF units were replaced before the start of the next test. The MF and the UF were stopped during the flush of the R3f units.

The flow rate remained at 2.5 gpm during the challenge tests.

Table 13. Pressure Buildup in R3f System during the Challenge Tests

Date & Time	Pressure (psi)			Differential Pressure (psi)	
	In	Out 1[a]	Out 2[b]	ΔP1[a]	ΔP2[b]
2/24/10; 10:00	59	50	52	9	0
2/24/10; 10:15	59	50	51	9	0
2/24/10; 10:30	58	50	52	8	0
2/24/10; 11:00 *	58	51	52	7	0
2/24/10; 13:15	61	52	52	9	0
2/24/10; 13:45	61	52	54	9	0
2/24/10; 14:00	60	54	55	6	0
2/24/10; 14:15 *	60	53	54	7	0
2/24/10; 15:00	60	53	54	7	0
2/24/10; 15:30	60	53	54	7	0
2/24/10; 16:00	60	53	54	7	0
2/24/10; 16:00 *	60	53	55	7	0
2/24/10; 17:55	60	52	54	8	0
2/24/10; 18:10	60	52	54	8	0
2/24/10; 18:25	60	52	54	8	0
2/24/10; 18:55 *	60	52	54	8	0
2/25/10; 08:45	60	53	54	7	0
2/25/10; 09:00	60	53	54	7	0
2/25/10; 09:15	60	53	55	7	0
2/25/10; 09:45 **	60	53	54	7	0
2/25/10; 11:40	60	53	54	7	0
2/25/10; 11:55	60	53	55	7	0
2/25/10; 12:10	60	53	54	7	0
2/25/10; 12:40***	60	53	55	7	0

* R3f system was flushed and allowed to run for 10 minutes. MF and UF systems were stopped during backflush.

** Both MF and UF units was replaced.

*** Test completed; MF and UF systems were continued to run

[a] R3f Lead Filter

[b] R3f Lag Filter

Table 14. Pressure Buildup in the MF and UF Units during the Challenge Tests

Date & Time	Pressure (psi)			Differential Pressure (psi)	
	In	MF Out	UF OUT	ΔP MF	ΔP UF
2/24/10; 10:00	48	46	34	2	12
2/24/10; 10:15	47	45	33	2	12
2/24/10; 10:30	48	47	34	1	13
2/24/10; 11:00 *	48	46	33	2	13
2/24/10; 13:15	50	48	32	2	16
2/24/10; 13:45	50	48	34	2	14
2/24/10; 14:00	50	48	34	2	14
2/24/10; 14:15 *	50	48	33	2	15
2/24/10; 15:00	50	48	34	2	14
2/24/10; 15:30	50	48	33	2	15
2/24/10; 16:00	50	48	33	2	15
2/24/10; 16:00 *	50	48	32	2	16
2/24/10; 17:55	49	46	31	3	15
2/24/10; 18:10	49	46	30	3	16
2/24/10; 18:25	50	46	29	3	17
2/24/10; 18:55 *	50	47	29	3	18
2/25/10; 08:45	50	48	29	2	19
2/25/10; 09:00	50	48	29	2	19
2/25/10; 09:15	50	48	28	2	20
2/25/10; 09:45 **	50	48	28	2	20
2/25/10; 11:40	50	47	38	3	9
2/25/10; 11:55	50	48	36	2	12
2/25/10; 12:10	50	48	35	2	13
2/25/10; 12:40***	50	48	35	2	13

* R3f system was flushed and allowed to run for 10 minutes. MF and UF systems were stopped during backflush.

** Both MF and UF units was replaced.

*** Test completed; MF and UF systems were continued to run

3.3.4 TOC Results

Table 15 describes the results of TOC monitoring during the microbial challenges. The average influent concentration of TOC was 3.85 mg/L. No reduction of TOC was achieved the R3f-MF-UF system.

Table 15. Results of TOC Monitoring for the R3f-MF-UF System

Test ID	TOC (mg/L)				
	IN	**Effluent R3f Lead**	**Effluent R3f Lag**	**Effluent MF**	**Effluent UF**
MS2 Test 1	3.63	3.75	3.76	3.71	3.64
MS2 Test 2	3.59	3.67	3.75	3.73	3.64
MS2 Test 3	3.65	3.71	3.74	3.77	3.75
BS Test 1	4.38	4.45	4.47	4.43	4.29
BS Test 2	3.98	N/A[a]	3.92	3.92	4.02
Mean [Std. Dev.] ± CI[b]	**3.85 [0.34] ± 0.30**	**3.90 [0.37] ± 0.33**	**3.93 [0.31] ± 0.27**	**3.91 [0.30] ± 0.26**	**3.87 [0.28] ± 0.25**

[a] Not Available, sample was not collected.

[b] Confidence Interval at 95% Significance.

4.0 Conclusions

The R3f-MF- UF system achieved complete removal of MS2 bacteriophage with most of the removal achieved by the UF system. The overall performance of the whole system was similar to that observed in previous experiments conducted on the same system at Ely, Minnesota.

The R3f-MF- UF system achieved complete removal of *B. subtilis* with most of the removal achieved by the MF system. The overall performance of the whole system was similar to that observed in previous experiments conducted on the same system at Ely, Minnesota. The performance of the R3f system alone in removing *B. subtilis* was similar to that observed in tests conducted at the T&E Facility in Cincinnati, Ohio.

For an influent turbidity of 0.60 NTU, the R3f-MF-UF system achieved an average effluent turbidity of 0.13 NTU which satisfied the LT2ESWTR requirement of effluent turbidity < 0.30 NTU (EPA, 2006). The R3f system contributed considerably in removing turbidity. The overall performance of the whole system was similar to that observed in experiments conducted on the same system at Ely, Minnesota. The performance of the R3f system alone in removing turbidity was better than that observed in tests conducted at Ely, Minnesota and at the T&E Facility in Cincinnati, Ohio.

The R3f-MF-UF system demonstrated excellent removal of bacteria size (1.2 µm) and *Cryptosporidium* size (2 – 5 µm) particles. The overall performance in removing 1.2 µm size particles by the whole system was 92.2% of which 71.0% reduction was contributed by the R3f system. . The overall performance in removing 2 - 5 µm size particles by the whole system is 87.0% of which 60.0% reduction was contributed by the R3f system. The R3f system demonstrated good potential for use as a pretreatment unit to reduce particle load on the MF and UF systems.

Although the R3f-MF-UF system achieved complete removal of *B. subtilis* and MS2 bacteriophage, a small number of 1.2 µm and 2 – 5 µm size particles were detected in the final effluent of the system. A good correlation was observed between the turbidity and the particle counts. Therefore, the particle count data may possibly be used as secondary information in assessing the performance of the system in removing turbidity and biological contaminants.

Although no pressure buildup was observed in the R3f system during the challenge tests, the R3f units were backflushed at the end of each test. The MF did not experience any additional pressure buildup during the challenge tests. There was an 8 psi pressure buildup in the UF system during the challenge tests.

The R3f-MF-UF system did not reduce TOC from the source water. The R3f system was not capable of reducing TOC in tests conducted at the T&E Facility.

5.0 References

EPA (1999). "Method 415.2: Total Organic Carbon in Water (UV Promoted, Persulfate Oxidation)", Washington, D.C.

EPA (2001). "Method 1602 for Detection and Enumeration of MS2 Bacteriophage in Drinking Water", Washington, D.C.

EPA (2006). The Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) Implementation Guidance, EPA-816-06-005, Washington, D.C.

EPA and Shaw (2006a). T&E SOP 507: Turbidity Analysis, EPA T&E Facility, Cincinnati, OH.

EPA and Shaw (2006b). T&E SOP 301: Enumeration of *B. subtilis* Using Membrane Filtration Method, EPA T&E Facility, Cincinnati, Ohio.

EPA and Shaw (2007a). "Quality Assurance Project Plan for Glass Bead R3f and Multimedia Systems", EPA QA ID: 627-Q-10-0, EPA T&E Facility, Cincinnati, Ohio.

EPA and Shaw (2007b). T&E SOP 302: Enumeration of MS2 Bacteriophage Based on EPA Method 1622, EPA T&E Facility, Cincinnati, Ohio.

EPA and Shaw (2008). "Addendum to Quality Assurance Project Plan for Glass Bead R3f and Multimedia Systems", EPA QA ID: 627-Q-10-1, EPA T&E Facility, Cincinnati, Ohio.

EPA and Shaw (2009a). "Final Report: Evaluation of Small System Filtration Technologies for the Treatment of Color, Disinfection Byproducts and Microbiological Contaminants in Surface Waters", EPA T&E Facility, Cincinnati, Ohio.

EPA and Shaw (2009b). "Final Report: Comparative Evaluation of Glass Bead/Garnet R3f and Multimedia Filtration Systems", EPA T&E Facility, Cincinnati, Ohio.

Hach Co. (1991). Hach 2100P Portable Turbidity Meter Procedure Manual, Denver, Colorado.

Rice, E.W., Fox, K.R., Miltner, R.J., Lytle, D.A. and Johnson, J.H. (1994). "A Microbiological Surrogate for Evaluating Treatment Efficiency." In *Proceedings of AWWA Water Quality Technology Conference (WQTC,* San Francisco, California.