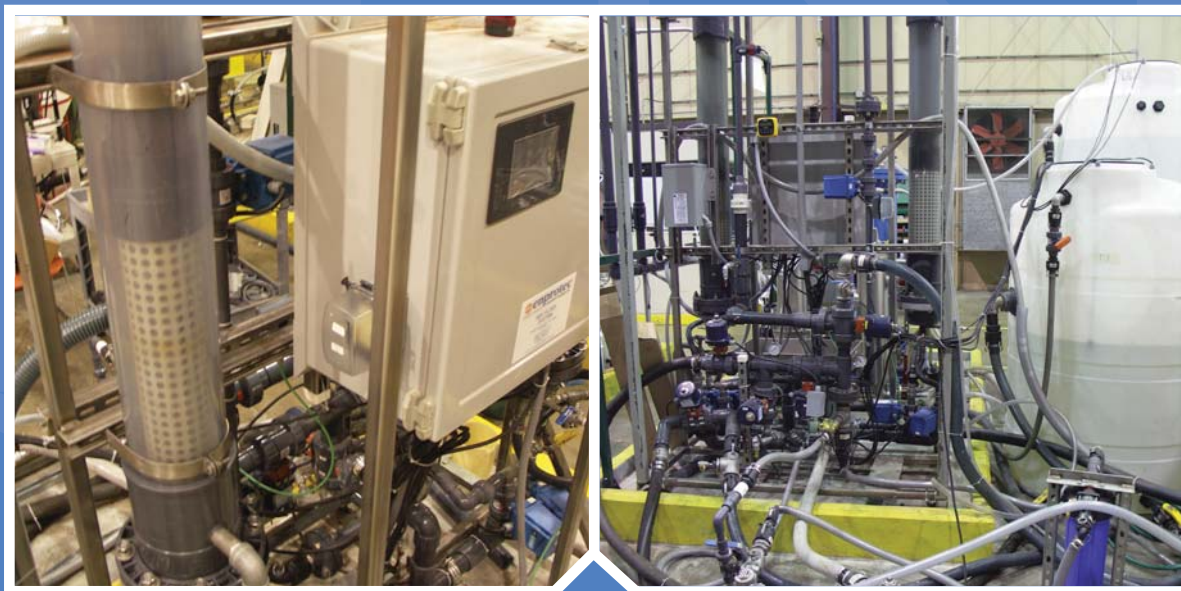


Comparative Evaluation of R3f Garnet Bead Filtration and Multimedia Filtration Systems - Final Report





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FINAL REPORT

COMPARATIVE EVALUATION OF R3f GARNET BEAD FILTRATION AND MULTIMEDIA FILTRATION SYSTEMS

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DISCLAIMER

The U.S. Environmental Protection Agency, through its Office of Research and Development, funded and managed, or partially funded and collaborated in, the research described herein. It has been subjected to the Agency's peer and administrative review and has been approved for publication. Any opinions expressed in this report are those of the author (s) and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

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1.0 Introduction

The Water Supply and Water Resources Division (WSWRD) of the U.S. Environmental Protection Agency (EPA) has been conducting tests on filtration systems since 1997 in response to the 1996 Reauthorization of the Safe Drinking Water Act (SDWA) that established standards for drinking water systems and required EPA to assess treatment technologies relevant to small systems serving fewer than 10,000 people. Initial tests were focused on packaged bag and cartridge filtration systems. Subsequently, the program has been expanded to test a variety of filtration systems, including a Radial Flow Fluidized Filter (R3f) glass bead/garnet system. Under contract to EPA, Shaw Environmental, Inc. (Shaw) has been providing technical support in the evaluation of various filtration systems at the EPA Test & Evaluation (T&E) Facility in Cincinnati, OH and at a number of field locations. This report has been prepared by Shaw for EPA's National Risk Management Research Laboratory (NRMRL), Office of Research and Development (ORD), WSWRD, in partial fulfillment of the requirements of Work Assignment 4-03 (Task 3) under Contract No. EP-C-04-034.

This report summarizes the results of tests conducted to date at the EPA T&E Facility on the R3f filtration system utilizing fine beads (such as garnet beads or glass beads) and a conventional multimedia filtration system. Both systems have been designed and built by Enprotec, a water treatment company based in Hebron, KY. These systems were installed at the T&E Facility in August 2007 and tests were initially conducted to establish the optimum configuration of the R3f system. Subsequent tests sought to provide a comparative evaluation of the performance of the R3f system versus a conventional multimedia filtration system in meeting the SDWA drinking water standards, while qualitatively evaluating run times and the factors impacting the cost of filtration. The R3f system was also tested as a pre-treatment device for gross turbidity removal prior to polishing the water in a secondary filtration device such as fine pore-size bag filters, cartridge filters and ultrafiltration (UF) systems. Results of tests conducted on four different post-filtration devices – Harmsco cartridge filter, Rosedale bag filter, a Nanoceram cartridge filter and a low-cost UF system – are also summarized in this report. Finally, tests were also conducted using a germicidal UV lamp as tertiary treatment for virus and bacteria inactivation.

1.1 Background on R3f Filtration

The R3f filtration system utilizes radial flow (similar to the flow pattern of a cartridge filter) through use of non-bonded media (glass beads or garnet) that can be fluidized and backwashed. The technology uses a very fine glass-bead or garnet media (as fine as 10 microns) and the vendor claims that it operates at a headloss similar to that of existing downflow and upflow multimedia bed systems. The vendor also claims that the cost and footprint requirements are 20% to 50% less than a typical multimedia system and that this technology provides a low-cost alternative to membrane filtration technology for drinking water treatment.

1.2 Document Organization

This document is organized into the following sections:

Section 1.0 – Introduction – This section presents a brief introduction to this report.

Section 2.0 – System Description, Operation and Testing Procedures – This section provides a summary description of the R3f glass bead/garnet and multimedia systems, and the operation and testing procedures employed at the T&E Facility.

Section 3.0 – Test Results – This section summarizes the results of the test runs conducted to date on the R3f and multimedia filtration system.

Section 4.0 – Summary and Conclusions – This section summarizes the test results and conclusions.

Section 5.0 – References

Appendix A – Tables presenting the raw data for turbidity challenges

2.0 System Description, Operation and Testing Procedures

This section provides a description of the R3f filtration system and conventional multimedia filtration systems and the operation and testing procedures employed at the T&E Facility. The test procedures are presented in the EPA-endorsed Quality Assurance Project Plan (QAPP) EPA QA ID: 627-Q-10-0 (Shaw, 2007) and QAPP Addendum QA ID: 627-Q-10-1 (Shaw, 2009).

2.1 R3f Filtration System

Figure 2-1 is a conceptual diagram of the filtration element and the flow patterns through the system. The filter system housing consists of an upper chamber and a lower chamber. The vessel size is a 6" diameter tube with a filter area of 2.5 square feet. 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. The treated water is either drained or collected in a clean water tank.

As the pressure drop across the media increases due to accumulation of filtered particles, the media is backwashed to remove the accumulated particles and restore design flow. Figure 2-1 also shows a conceptual diagram of the flow patterns through the system during backwashing. The water from the clean water tank flows upward and fluidizes the media and compressed air is used to enhance the fluidization of the media. The dirty water, along with the entrapped particles, enters the upper part of the inner core and exits to drain through the pipe connected at the top of the inner core.

The R3f system uses a fine glass bead or garnet as the filtration media. Effective treatment of water and the frequency of backwashing depend on the size of the glass bead or garnet. Based on initial optimization tests, a fine garnet media (33 μm) in the lead filter followed by a fine garnet media (33 μm) in the trailing filter was shown to provide the lowest effluent turbidity. All turbidity and microbial tests presented in this report were performed on this optimized filter configuration.

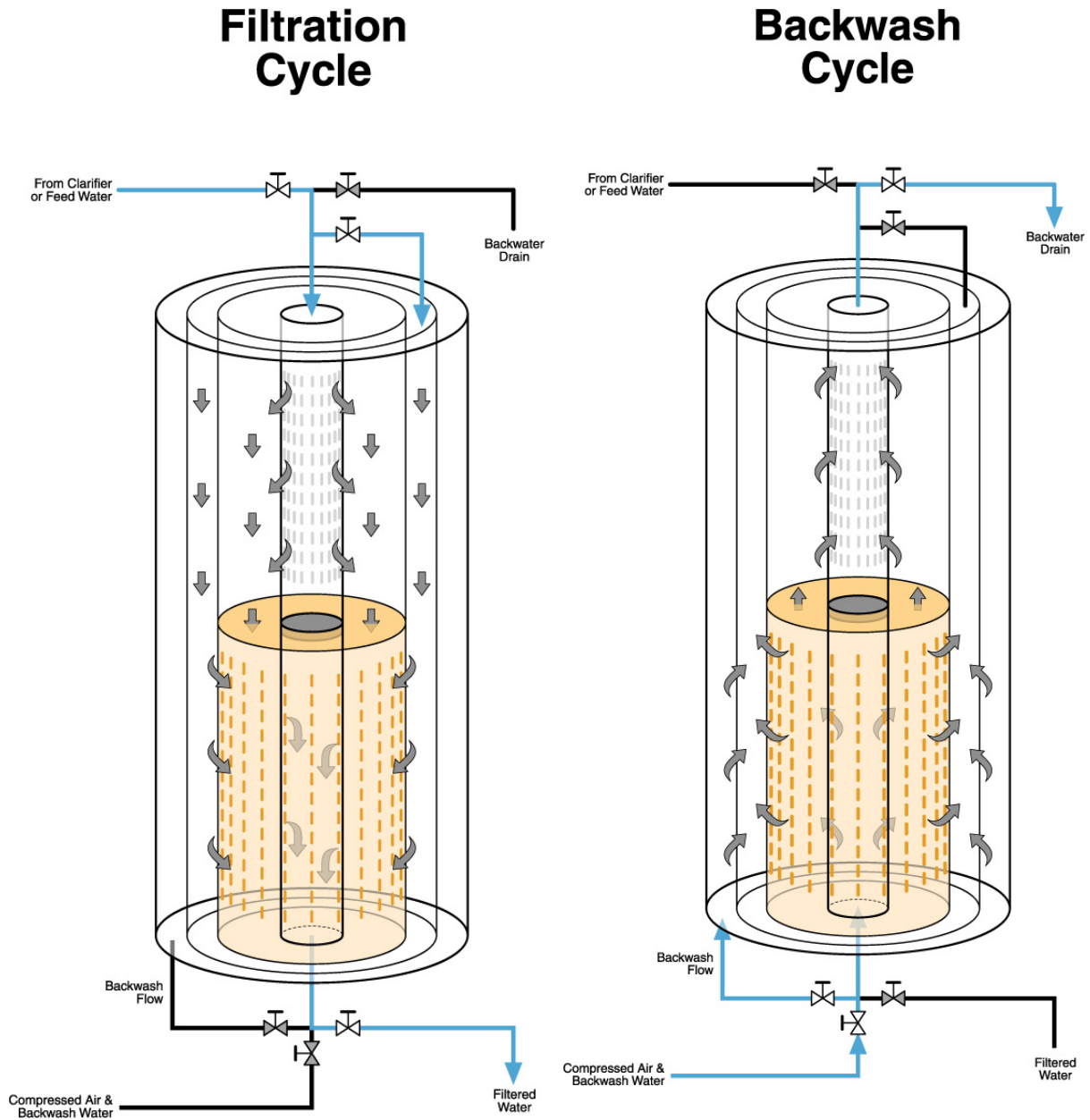


Figure 2-1. Conceptual Flow Diagram of the R3F Filtration System

2.2 Multimedia Filtration System

The multimedia system evaluated in this study comprises a cylindrical pressure vessel 15 inches in diameter and 50 inches high with a bed volume of 39 cubic feet and a cross-sectional area of 1.22 square feet. Table 2-1 specifies the different media used in the multimedia filtration system from the top layer (anthracite) of the system to the bottom layer (gravel). Approximately 18 inches of free board is available on the top of the media for supernatant water. The supernatant water provides the necessary head for flow through the filter. The multimedia filtration system is cleaned by periodic backwashing and rinsing based on pressure buildup in the system.

Table 2-1. Media Specification for Multimedia Filtration System

Media	Size (mm)	Depth (mm)	Depth (inch)
Anthracite	0.60 – 2.55	100	4
Sand	0.45 – 0.55	200	8
Garnet	0.18 – 0.35	100	4
Garnet	1.18 – 2.36	100	4
Gravel	3.00 – 6.00	300	12

2.3 System Setup at the T&E Facility

The R3f and multimedia filtration units have been installed side by side on a single concrete pad at the T&E Facility. Figure 2-2 shows the flow diagram for the two systems. The systems are configured to receive test water from the same feed tank to allow tests to be conducted on similar feed water. Figure 2-3 and Figure 2-4 depicts the setup of the R3f and multimedia filtration system, respectively.

R3f System

The two R3f filters can be operated either as individual units or as units in series and include the following elements (shown in Figure 2-2):

- Valves: Three way valves, BV5, BV1, and BV2, each with ports (1) and (2).
- Valves: Ball valves, BV3, BV1A, BV1B, BV1C, BV1D, BV2A, BV2B, BV2C, BV2D, BV4A, BV4B AND BV6.
- Valves: Air solenoid APV1

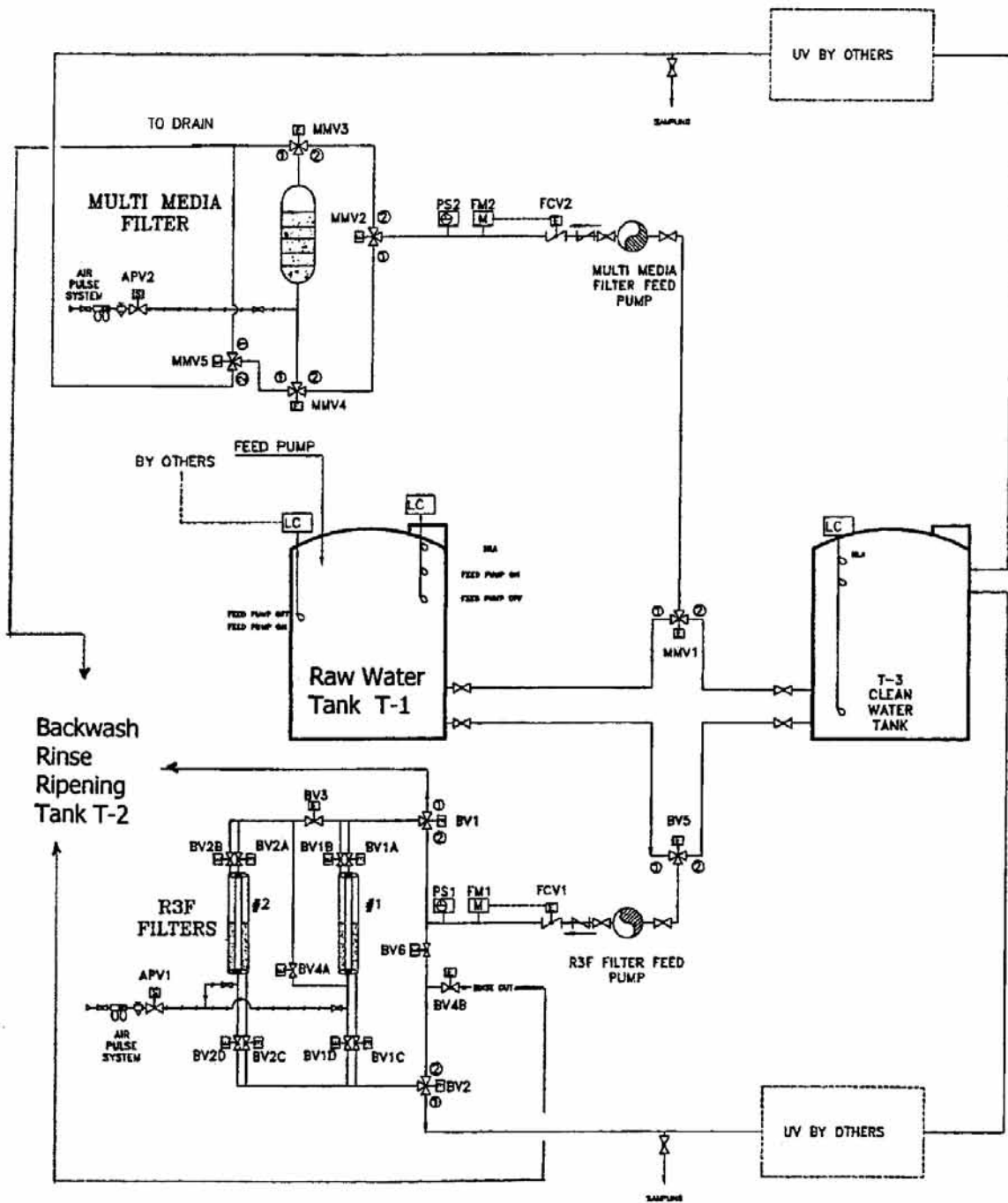


Figure 2-2. Flow Diagram of the R3f and Multimedia Systems

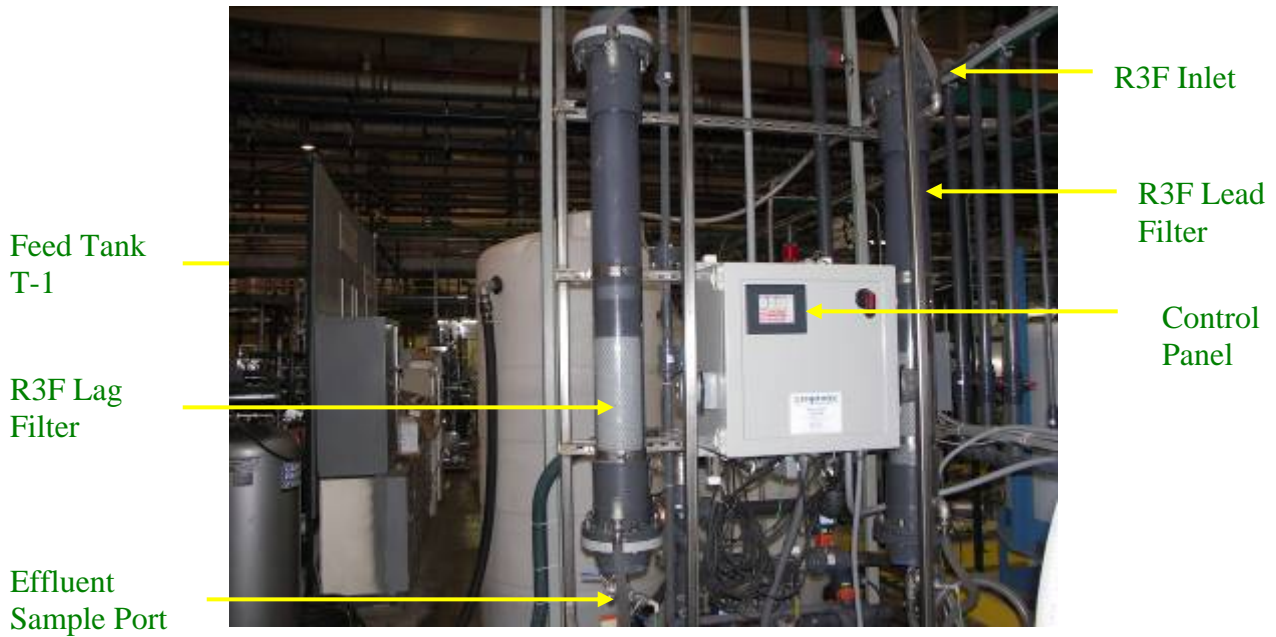


Figure 2-3. R3F Filter Setup at the EPA T&E Facility

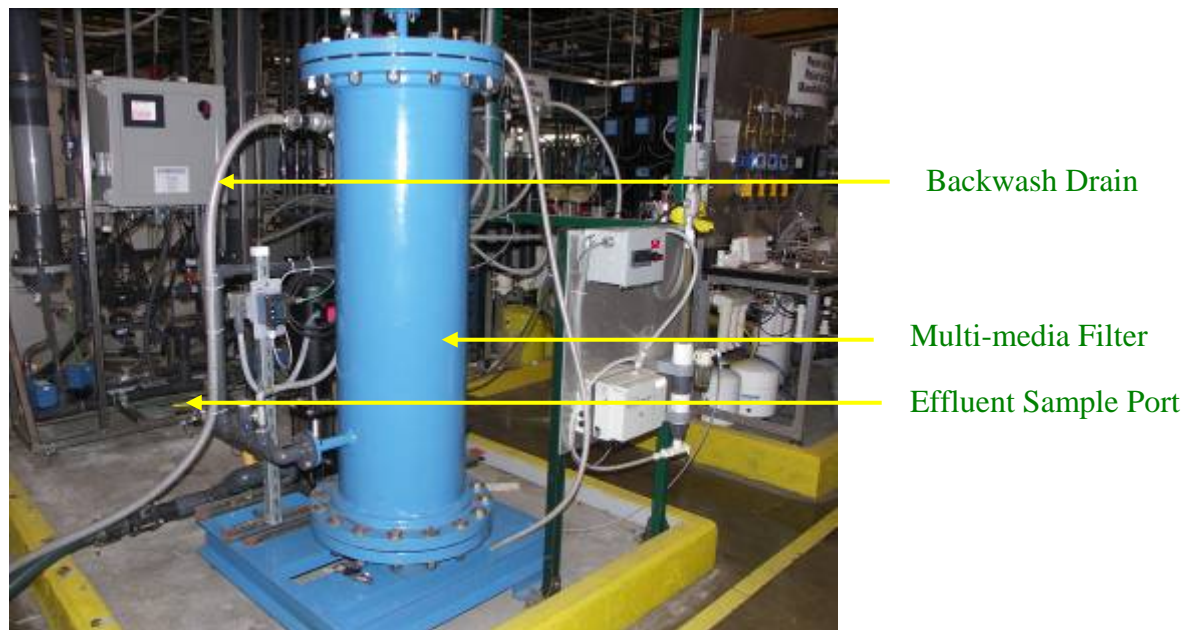


Figure 2-4. Multimedia Filter Setup at the EPA T&E Facility

The R3F filtration system is operated using an automated, touch screen, programmable logic controller (PLC) that allows the settings to be modified for the mode of operation, system configuration, filtration sequence, backwashing sequence, manual operation and alarm set points. The system is set for automatic backwashing for 2 minutes every two hours in a sequence that includes backwash water purging, rinsing and draining.

During the filtration operation, inlet forward flow from T-1 is pumped by the R3F filter feed pump. A three-way ball valve, BV5, is in Position 1, which controls the suction side of the pump to draw from T-1. Flow meter FM1 displays the flow. The effluent control valve automatically controls the forward flow to the target flow of either 10 gpm (8.20 gal/ft²/minute) or 5 gpm (4.10 gal/ft²/minute). The forward flow enters the R3f filter through the top, through Valve BV1 Position 3 and ball valves BV1A and BV1B. If the second R3f column is to be engaged, BV1A and BV1B are closed and BV3, BV2A and BV2B are opened. If there is a need to operate two columns in series, BV1C and BV1D are closed and BV4A is opened. For flow through one column, the flow passes radially through the media and exits the filter through the center outlet and valve BV1D with valve BV1C closed. The filtered effluent passes through Valve BV2, in Position 1, and enters Tank T-3. When the pressure drop across the filter media builds to approximately 30 psi, the unit automatically goes into a Backwash/Air Scour cycle. The Backwash/Air Scour cycle lasts for 1.5 minutes.

During backwash, BV5 switches to Position 2, allowing clean water to be used for backwash. The flow rate for backwash is 25 gpm. The backwash water enters the filter through the bottom center and valve BV1D. The backwash water fluidizes the media and any trapped contaminants exit the filter through the top center and valve BV1A. The backwash water is directed through valve BV1, in Position 1, to a collection tank (Tank T2) so that the backwash volumes can be recorded. Air is pulsed into the filter during this cycle to assist in removing contaminants that remain on the screens. The air pulse valve, APV1, is opened for one second, every ten seconds. During the last 30 seconds of the cycle, the bottom annular valve BV1C opens to assist in removing any contaminants remaining on the screens as well as BV2 and BV4B. The filter automatically goes into a rinse cycle, to rinse out any remaining contaminants in the annular space of the filter. The rinse cycle lasts for one minute.

During the one-minute rinse cycle, BV5 remains in Position 2, so that clean water can be used for the rinse cycle. The effluent control valve automatically controls the forward flow to the set

point of either 10 gpm or 5 gpm. The rinse water drives the media back into place and exits through both bottom openings in the filter and valves BV1C and BV1D. The water flows through valve BV2, in Position 2 and exits out valve BV4B to drain. The rinse water is collected in Tank T-2 so that the backwash volume can be recorded. Air is added at the end of the rinse cycle to assist in leveling out the media in the filter column. Valve APV1 opens for one second at the end of the cycle.

After the rinse cycle is completed, forward flow with raw water begins again, as described previously. No filter ripening phase is implemented as ripening for the R3f is typically not required. However, if this cycle is required, BV2-2 and BV4B directs water to Tank T2.

Multimedia Filter

The multimedia filter system has been installed to run in parallel with the R3f filter and is designed for a flow rate of 2.0 gal/ft²/minute. The system includes the following elements:

- Valves: Three way valves, MMV1, MMV2, MMV3, MMV4 and MMV5 each with ports -1 and -2.
- Multimedia filter feed pump with flow meter and flow control valve.

The multimedia filtration system installed for these tests is operated manually. A multi-purpose valve regulates the filtration, backwashing and drain modes. The flow rate is regulated and recorded by a manually operated valve and flow meter. An automatic alarm system is installed to signal for backwashing. The clean water from both the R3f and multimedia filters is collected in a clean water tank that is either drained or used for backwashing.

During the filtration operation, a 3 gpm inlet forward flow from T-1 is pumped by the multimedia pump from MMV1-1, and enters the top of the unit through valves MMV2-2 and MMV3-2, passes through the filtration media and exits the bottom of the multimedia unit through valves MMV4-1 and MMV5-2. The normal filtration rate is 2.44 gal/ft²/minute. As the solids build up in the top layer of media, the pressure drop across the media increases until, at approximately 20 psi, the unit is placed in the backwash mode. The pressure drop at which backwash is initiated can be varied to extend the run time if the effluent turbidity does not exceed 0.3 Nephelometric Turbidity Units (NTU).

At the start of the backwash cycle, air solenoid valve APV2 is opened for 2 seconds, then closed and reopened during the backwash period to allow air to scour the bed and to help re-stratify the media. During backwash, valve MMV1 changes to Position 2, and clean water from tank T-3 is pumped at 30 gpm through MMV2-1 and into the bottom of the filter tank through MMV4-2. The backwash water expands the media bed to wash out any contained solids. The backwash water with the solids exits the multimedia filter at the top through MMV3-1 and goes to a backwash/rinse collection tank T-2. The backwash time period is approximately 2.5 minutes.

After backwash, forward flow begins again, but in a rinse/ripening cycle mode using water from T-1 through MMV1-2 and into MMV2-2 and MMV3-3. This water enters the filter tank at the top and exits at the bottom through MMV4-1 and MMV5-1 to the backwash/rinse collection tank T-2 for approximately 15 to 45 minutes, depending on the ripening cycle. The ripening cycle is terminated when the effluent turbidity is less than 0.5 NTU. After the rinse/ripening cycle is completed, forward flow with raw water begins again, as described above, and valve MMV5-1 changes to Position 2.

Both systems are fed from a feed water tank, T-1. The feed water tank receives the matrix water either from a 5000-gallon mix water tank or a 1000-gallon dechlorinated potable water tank, depending on the experiment being conducted. A flow totalizer that records the flow rate and total flow is installed in the effluent line.

The following polishing filtration units have been tested to date on the effluent of the R3f system:

- Rosedale PS 740 (0.5 μm absolute) bag filter shown in Figure 2-5
- Harmsco (1 μm) cartridge filter shown in Figure 2-6
- Nanoceram (0.2 – 0.6 μm) cartridge filter shown in Figure 2-7
- Low-cost, UF system (0.05 μm) filter shown in Figure 2-8

These polishing units were not tested on the effluent of the multimedia filter since the tests were conducted on the multimedia filter only to benchmark the performance of the R3f system.

A UV system using a lamp with radiation in the germicidal range (255 nm) was tested as tertiary treatment for virus and bacteria inactivation. This system is shown in Figure 2-9.



Figure 2-5. Rosedale PS 740 Filter Setup at the T&E Facility

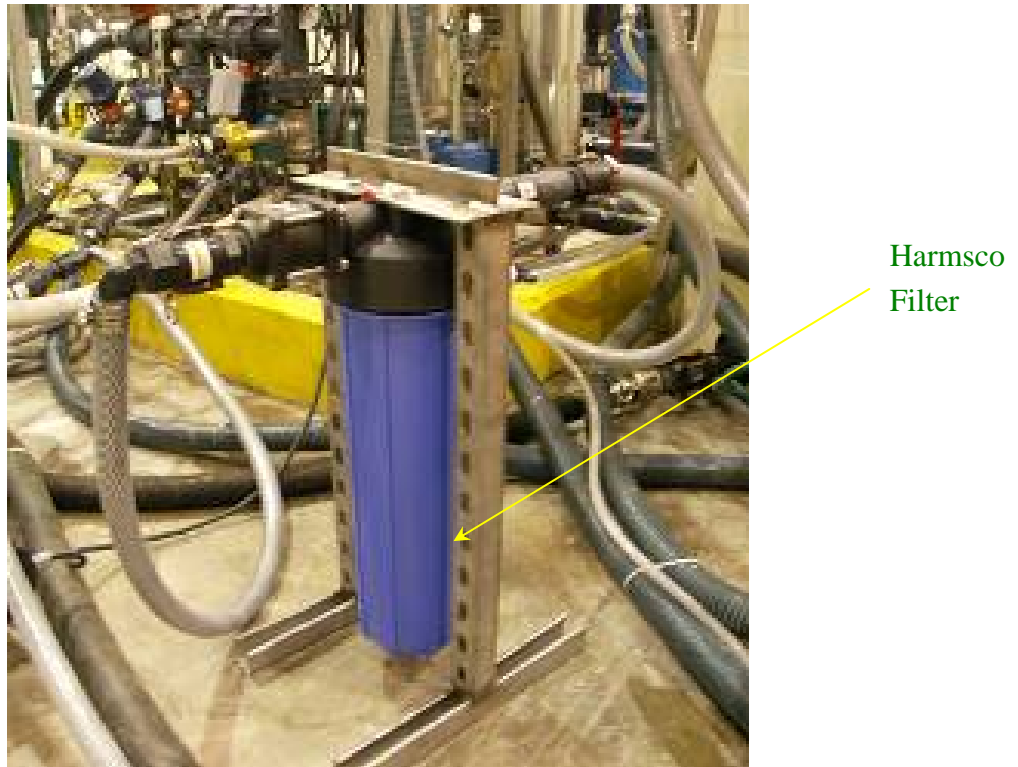


Figure 2-6. Harmsco Cartridge Filter Setup at the T&E Facility



Nanoceram
Filter

Figure 2-7. Nanoceram Filter Setup at T&E Facility



Ultrafilter

Figure 2-8. UF Filter Setup at T&E Facility



Figure 2-9. UV System at T&E Facility

2.4 Test Procedures and Conditions

The R3f and multimedia filter systems were both challenged with turbidity, Polystyrene Latex (PSL) beads, *Bacillus subtilis* and *Escherichia coli*. Additional challenge tests using *Cryptosporidium* oocysts and MS2 bacteriophage were conducted on the R3f system. The post R3f polishing filtration units – Rosedale, Harmsco, Nanoceram and UF filters - were evaluated individually. Tests were conducted using the following contaminants and surrogates:

- For evaluating turbidity removal, water from the Mill Creek (adjacent to the T&E Facility) was mixed with dechlorinated potable water in a 5000-gallon tank at the T&E Facility to achieve the influent target turbidity levels. The R3f and multimedia systems were evaluated for their ability to achieve a turbidity level of less than 0.3 NTU. Tests were conducted with and without the use of chemical coagulants to establish the baseline performance of the system. Heterotrophic plate count (HPC), total organic carbon (TOC), and dissolved organic carbon (DOC) were also measured during the turbidity challenges. An inline particle counter was used during the turbidity challenge tests to measure the removal of particles in the size range of 2-5 μm (that encompasses the size of *C. parvum*). This measurement was intended to provide an indirect, secondary measure of protozoa removal.
- For evaluating general bacteria removal, the HPC concentrations in the influent and effluent were compared.
- For evaluating protozoa removal, PSL beads with a mean size of 2.83 μm were used as a non-biological surrogate for *C. parvum* which have a mean size of 2 – 5 μm . A single test using *Cryptosporidium* oocysts was conducted on the R3f system to determine the equivalence of the PSL bead test results in predicting *Cryptosporidium* removal by the system.
- For evaluating specific bacteria removal performance, the system was challenged with *E. coli* (human pathogen) and *B. subtilis* endospores. The soil-based aerobic spore *B. subtilis* was also used to evaluate its potential as a surrogate for *Cryptosporidium*.
- For evaluating inactivation of virus, the R3f system was challenged with MS2 bacteriophage, a biological surrogate for enteric virus.

Details of the test plan are described in the QAPP QA ID: 627-Q-10-0 (Shaw, 2007) and the QAPP Addendum (QA ID: 627-Q-10-1) (Shaw, 2009).

2.5 Sampling Procedures and Quality Assurance

The sampling and analytical procedures for these tests are described in the QAPP (QA ID: 627-Q-10-0) (Shaw, 2007) and the QAPP Addendum (QA ID: 627-Q-10-1) (Shaw, 2009). Grab samples from the influent and effluent streams were collected during turbidity challenges. Turbidity samples were collected at an hourly interval and HPC and TOC/DOC samples were collected twice during the evaluation stage of the turbidity challenges. *E. coli*, *B. subtilis* and MS2 bacteriophage samples were collected from the influent and effluent streams at time 0 (T0), 5 (T5), 10 (T10), 20 (T20) and 40 (T40) minutes following the start of injection of the contaminants into the influent stream.

For PSL bead and *Cryptosporidium* challenges, the membrane sampling technique was used to collect the beads and oocysts from the effluent stream. The membrane sampling technique involves diverting a slip stream of the effluent through a 1 µm membrane in a manifold. The membrane sampling technique was used to provide a direct comparison of the results with PSL beads and evaluate the potential of the *B. subtilis* spores as a surrogate for *Cryptosporidium*. A 0.40 µm membrane was used for collecting the *B. subtilis* spores from the effluent.

3.0 Test Results

Table 3-1 summarizes the test runs conducted on the R3f system and multimedia filtration systems. From November 2007 to December 2008 a total of 45 challenges were conducted to optimize the system configuration and to evaluate the performance of the system under various configurations. Additional tests are planned on the system to evaluate the removal efficiency at field sites.

3.1 Turbidity Challenges

A total of twelve turbidity challenges were conducted during the test period. Seven of these turbidity tests were conducted to optimize the R3f system configuration and five turbidity tests were conducted to evaluate the performance of the system with the optimized configuration. During the system evaluation stage (Test Run Nos. 8, 9, 30, 31 and 32), post-filter units (Rosedale, Nanoceram, Harmsco and UF) were used as a final polishing system following the R3f system. Alum (4 mg/L) was used as a chemical coagulant during three turbidity challenges (Test Run Nos. 30, 31 and 32). Feed water with the target turbidity was prepared by mixing dechlorinated potable water and Mill Creek water in a 5000-gallon mix tank and pumped to the test systems. Basic experimental parameters monitored during the system optimization stage included turbidity, pressure, flow rate and total flow. During the system evaluation stage, additional parameters including TOC, DOC, and HPC were monitored along with the basic parameters. For ease of understanding, the turbidity test results during the optimization and evaluation stages are discussed separately in this section. Raw data for different parameters during the turbidity challenge tests are presented in Appendix A.

Table 3-1. Summary of Test Runs Conducted on the R3f and Multimedia Filtration System

Test Run No.	Test Run Date	Test Description	Filter Configuration
1	11/08/07	Turbidity Challenge 1	Glass bead (140-230 µm) + Glass bead (70-100 µm)
2	11/21/07	Turbidity Challenge 2	Glass bead (140-230 µm) + Glass bead (70-100 µm)
3	11/29/07	Turbidity Challenge 3	Glass bead (120-200 µm) + Garnet (33 µm)
4	12/04/07	Turbidity Challenge 4	Glass bead (120-200 µm) + Garnet (33 µm)
5	12/06/07	Turbidity Challenge 5	Glass bead (120-200 µm) + Garnet (33 µm);
6	12/12/07	Turbidity Challenge 6	Glass bead (70-100 µm) + Garnet (33 µm)
7	12/21/07	Turbidity Challenge 7	Garnet (33 µm) + Garnet (33 µm); Multimedia
8	01/22/08; 01/23/08; 01/24/08	Turbidity Challenge 8	Garnet (33 µm) + Garnet (33 µm) + Bag Filter; Multimedia
9	01/29/08; 01/30/08; 01/31/08	Turbidity Challenge 9	Garnet (33 µm) + Garnet (33 µm) + Bag Filter; Multimedia
10	02/07/08	PSL Bead Challenge 1	Garnet (33 µm) + Garnet (33 µm) + Rosedale Bag Filter
11	02/08/08	PSL Bead Challenge 2	Multimedia Filter
12	02/11/08	PSL Bead Challenge 3	Garnet (33 µm) + Garnet (33 µm) + Rosedale Filter
13	02/12/08	PSL Bead Challenge 4	Multimedia Filter
14	02/18/08	PSL Bead Challenge 5	Garnet (33 µm) + Garnet (33 µm) + Nanoceram Filter
15	02/19/08	PSL Bead Challenge 6	Multimedia
16	02/25/08	<i>E. coli</i> Challenge 1	Garnet (33 µm) + Garnet (33 µm) + Rosedale Filter
17	02/26/08	<i>E. coli</i> Challenge 2	Garnet (33 µm) + Garnet (33 µm) + Rosedale Filter
18	02/27/08	<i>E. coli</i> Challenge 3	Garnet (33 µm) + Garnet (33 µm) + Nanoceram Filter
19	02/28/08	PSL Bead Challenge 7	Garnet (33 µm) + Garnet (33 µm) + Nanoceram Filter
20	03/03/08	<i>E. coli</i> Challenge 4	Multimedia Filter
21	03/04/08	<i>E. coli</i> Challenge 5	Multimedia Filter
23	03/06/08	<i>B. subtilis</i> Challenge 1	Garnet (33 µm) + Garnet (33 µm) + Rosedale Bag Filter
24	03/10/08	<i>B. subtilis</i> Challenge 2	Garnet (33 µm) + Garnet (33 µm) + Rosedale Bag Filter
25	03/11/08	<i>B. subtilis</i> Challenge 3	Multimedia Filter
26	03/13/08	<i>B. subtilis</i> Challenge 4	Multimedia Filter
27	04/01/08	<i>B. subtilis</i> Challenge 5	Garnet (33 µm) + Garnet (33 µm) + Rosedale Bag Filter
28	04/08/08	<i>B. subtilis</i> Challenge 6	Multimedia Filter
29	04/10/08	<i>Cryptosporidium</i> Challenge 1	Garnet (33 µm) + Garnet (33 µm) + Rosedale Bag Filter

30	08/19/08; 08/20/08	Turbidity Challenge 10	Garnet (33 µm) + Garnet (33 µm) + UF Unit; Multimedia
31	08/27/08	Turbidity Challenge 11	Garnet (33 µm) + Garnet (33 µm) + UF Unit; Multimedia
32	09/11/08	Turbidity Challenge 12	Garnet (33 µm) + Garnet (33 µm) + UF Unit; Multimedia
33	09/24/08	<i>B. subtilis</i> Challenge 7	Garnet (33 µm) + Garnet (33 µm) + UF Unit
34	09/30/08	<i>B. subtilis</i> Challenge 8	Garnet (33 µm) + Garnet (33 µm) + UF Unit
35	10/07/08	<i>B. subtilis</i> Challenge 9	Garnet (33 µm) + Garnet (33 µm) + UF Unit
36	10/13/08	<i>B. subtilis</i> Challenge 10	Garnet (33 µm) + Garnet (33 µm) + UF Unit
37	10/27/08	PSL Bead Challenge 7	Garnet (33 µm) + Garnet (33 µm) + UF Unit
38	10/28/08	PSL Bead Challenge 8	Garnet (33 µm) + Garnet (33 µm) + UF Unit
39	11/26/08	PSL Bead Challenge 9	Garnet (33 µm) + Garnet (33 µm) + UF Unit
40		PSL Bead Challenge 10	Garnet (33 µm) + Garnet (33 µm) + UF Unit
41	12/03/08	<i>E. coli</i> Challenge 6	Garnet (33 µm) + Garnet (33 µm) + UF Unit
42	12/12/08	<i>E. coli</i> Challenge 7	Garnet (33 µm) + Garnet (33 µm) + UF Unit
43	12/16/08	MS2 bacteriophage Challenge 1	Garnet (33 µm) + Garnet (33 µm) + UF Unit + UV Unit
44	12/16/08	MS2 bacteriophage Challenge 2	Garnet (33 µm) + Garnet (33 µm) + UF Unit + UV Unit
45	12/16/08	MS2 bacteriophage Challenge 3	Garnet (33 µm) + Garnet (33 µm) + UF Unit + UV Unit

3.1.1 Selection of System Configuration

Tables 3-2 and 3-3 present the turbidity challenge results and operational parameters for the R3f system. Tables 3-4 and 3-5 present the turbidity challenge results and the operational parameters for the multimedia filtration systems. The results of turbidity challenges conducted to optimize the system configuration are summarized below:

Turbidity Challenge 1 [Filter Configuration: Glass bead (140-230 μm) + Glass bead (70-100 μm); Target flow: 10 gpm; Target feed water turbidity: 10 NTU]

This test was conducted using a coarse glass bead (140-230 μm) in the lead filter and a fine (70-100 μm) glass bead in the lag filter. This configuration was tested at 10 gpm using feed water with a target influent turbidity of 10 NTU. Chemical coagulants were not used in this challenge test. For an average influent turbidity of 7 NTU, the average effluent turbidity from the coarse glass bead filter was 2.49 NTU and from the fine glass bead filter was 1.5 NTU. The overall average turbidity removal efficiency was 78.5%. The initial operating pressure was 76 psi. This operating pressure was reset to 42 psi after two hours of the test run. During the entire test run, there was only a negligible increase in the pressure drop across the system. Subsequent investigations found a faulty screen in the fine glass bead filter that caused short-circuiting and hence the negligible pressure buildup.

Table 3-2. Summary of Turbidity Challenge Tests of R3f System during Optimization of System Configuration

Test No.	Turbidity (NTU)			Overall % Removal
	Influent	Effluent 1	Effluent 2	
1	7.00	2.49	1.50	78.5
2	11.80	6.90	1.90	83.8
3	9.70	5.00	1.84	81.0
4	4.74	3.43	1.67	64.7
5 ^a	4.60	3.30	1.20	73.9
5 ^b	5.00	2.50	0.90	82.0
6	5.33	2.57	1.20	77.3
7	4.30	0.92	0.61	84.6

^a Operational flow rate 10.0 gpm

^b Operational flow rate 5.0 gpm

Table 3-3. Summary of Operational Parameters of R3f System during Optimization of System Configuration

Test Run	Flow Rate (gpm)	Initial Pressure (psi)	Diff. Pres. 1		Diff. Pres. 2		Test Run (hours)	Total flow (gallons)
			Initial (psi)	Final (psi)	Initial (psi)	Final (psi)		
1	10.0	76.0	4	12	8	3	6	2223
2	10.0	50.0	10	20.5	17	63	2.5	1190
3	10.9	60.0	12	26	15	15	2.0	1196
4	10.0	64.0	13	18	20	20	2.0	1112
5 ^a	10.0	65.0	14	-	23	-	1.0	-
5 ^b	5.0	64.0	16	-	12	-	1.0	-
6	5.0	54.0	10	13	4	4	2.0	-
7	5.0	54.0	12	48	4	4	4.0	1128

^a Operational flow rate 10.0 gpm

^b Operational flow rate 5.0 gpm

Table 3-4. Summary of Turbidity Challenge Results of Multimedia System during Optimization of System Configuration

Test No.	Turbidity (NTU)		Overall % Removal
	Influent	Effluent	
5	4.6	2.3	50.0
6	5.3	2.5	51.6
7	4.3	1.9	56.1

Table 3-5. Summary of Operational Parameters of Multimedia System during Optimization of System Configuration

Test Run	Flow Rate (gpm)	Initial Pressure (psi)	Diff. Pres. 1		Test Run (hours)	Total flow (gallons)
			Initial (psi)	Final (psi)		
5	3.0	0.7	0.7	0.7	2	360
6	3.0	0.7	0.7	0.7	2	360
7	3.0	0.7	0.7	0.8	2	360

Turbidity Challenge 2 [Filter Configuration: Glass bead (140-230 μm) + Glass bead (70-100 μm); Target flow: 10 gpm; Target feed water turbidity: 10 NTU]

This test was conducted using a coarse glass bead (140-230 μm) in the lead filter and a fine glass bead (70-100 μm) in the lag filter (with the screen repaired) at 10.0 gpm using feed water with a target turbidity of 10 NTU. Chemical coagulants were not used in this challenge test. With an average influent turbidity of 11.8 NTU, the average effluent turbidity from the lead glass bead filter was 6.9 NTU and that for the fine glass bead filter was 1.90 NTU. The overall average turbidity removal efficiency was 83.9%. The initial operating pressure was 50 psi and the differential pressure increased from 10 psi to 20.5 psi in the coarse filter and from 17 psi to 63 psi in the fine filter in approximately two hours. The effluent turbidity, not being satisfactory, it was decided to use a smaller sized glass bead (120-200 μm) for the lead filter and a fine garnet (33 μm) instead of the fine glass bead filter for the lag filter.

Turbidity Challenge 3 [Filter Configuration: Glass bead (120-200 μm) + Garnet (33 μm); Target flow: 10 gpm; Target feed water turbidity: 10 NTU]

This test was conducted using a glass bead media with the size range of 120-200 μm (which is one size smaller than the previous configuration) in the lead filter followed by garnet (33 μm) in the lag filter. This system was tested at 10 gpm using feed water with a target turbidity of 10 NTU. Chemical coagulants were not used in this challenge test. For an average influent turbidity of 9.7 NTU, the average effluent turbidity from the modified lead glass bead unit was 5 NTU and from the lag fine garnet filter was 1.84 NTU. The overall average turbidity removal efficiency was 81.0%. The initial operating pressure was 60 psi and the differential pressure increased from 12 psi to 26 psi in the coarse filter while remaining unchanged at 15 psi in the fine garnet filter over approximately two hours. The overall turbidity removal performance was similar to the previous configuration. The initial differential pressure in the modified coarse glass bead filter was high and it increased rapidly during the test run. The initial differential pressure in the fine garnet filter was high and it did not increase rapidly during the two hours of the test run. Thus, it was decided to conduct the next test using the same configuration with lower feed water turbidity.

Turbidity Challenge 4 [Filter Configuration: Glass bead (120-200 μm) + Garnet (33 μm); Target flow: 10 gpm; Target feed water turbidity: 5 NTU]

This test was conducted on the same filtration configuration as the previous test, i.e., a coarse glass bead (120-200 μm) media in the lead filter followed by a fine garnet (33 μm) media in the lag filter but at a lower target turbidity of 5 NTU instead of 10 NTU as in the previous test. Chemical coagulants were not used in this challenge test. With an average influent turbidity of 4.74 NTU and at 10 gpm, the average effluent turbidity from the lead glass bead filter was 3.63 NTU and for the lag fine garnet filter was 1.67 NTU. Thus, the final effluent turbidity remained the same as for the previous test. The initial operating pressure was 64 psi and the differential pressure increased from 13 psi to 18 psi in the coarse filter while remaining unchanged at 20 psi in the fine garnet filter during the two-hour runtime. It was decided to conduct the next test using the same configuration along with the multimedia filter.

Turbidity Challenge 5 [Filter Configuration: Glass bead (120-200 μm) + Garnet (33 μm); Target flow: 10 gpm and 5.0 gpm; Target feed water turbidity: 5 NTU]

This test was conducted on the modified coarse glass bead (120-200 μm) and fine garnet (33 μm) configuration at 10 gpm and 5 gpm using feed water with a target turbidity of 5.0 NTU. Only two samples, one at 10 gpm and the other at 5 gpm flow rate were collected. Chemical coagulants were not used in this challenge test. At 10 gpm, for an influent turbidity of 4.60 NTU, the average effluent turbidity from the lead glass bed filter was 3.30 NTU and from the lag garnet filter was 1.20 NTU. At 5 gpm, for an influent turbidity of 5 NTU, the average effluent turbidity from the lead glass bead filter was 2.50 NTU and from the lag garnet filter was 0.90 NTU. Thus, the lower flowrate resulted in improved effluent quality.

The multimedia filter did not perform adequately in removing turbidity. For an average influent turbidity of 4.60 NTU, the average effluent turbidity from the multimedia filter was 2.30 NTU with an associated 50% removal efficiency.

It was decided to conduct the next test using a finer glass bead media in the lead filter and the same fine garnet media in the lag filter at 5 gpm with 5 NTU feed water.

Turbidity Challenge 6 [Filter Configuration: Fine glass bead (70-100 μm) + Garnet (33 μm); Target flow: 5.0 gpm; Target feed water turbidity: 5 NTU]

This test was conducted using a finer glass bead media (70-100 μm) in the lead filter and the same garnet (33 μm) media in the lag filter. This configuration was operated at 5 gpm using feed water with a target turbidity of 5.0 NTU. Chemical coagulants were not used in this challenge test. For an average influent turbidity of 5.33 NTU, the average effluent turbidity from the lead fine glass bead filter was 2.57 NTU and that from the lag garnet filter was 1.20 NTU. Thus, this test produced a poorer final effluent than the previous test. The initial operating pressure was 54.0 psi and the differential pressure in the fine glass bead filter increased from 10 to 13 psi and that in the finer garnet filter remained unchanged at 4.0 psi in approximately two hours.

The multimedia filter did not perform adequately in removing turbidity. For an average influent turbidity of 5.33 NTU, the average effluent turbidity for the multimedia filter was 2.54 NTU with an associated 51.6% removal efficiency.

It was decided to conduct the next test using the fine garnet-garnet configuration.

Turbidity Challenge 7 [Filter Configuration: Garnet (33 μm) + Garnet (33 μm); Target flow: 5.0 gpm; Target feed water turbidity: 5 NTU]

This test was conducted using the fine garnet (33 μm) media in both the lead and lag filters. The tests were conducted at 5 gpm using feed water with a target turbidity of 5 NTU. Chemical coagulants were not used in this challenge test. For an average influent turbidity of 4.30 NTU, the average effluent turbidity from the lead filter was 0.92 NTU and from the lag filter was 0.61 NTU. The initial operating pressure was 54.0 psi and the differential pressure increased from 12 to 48 psi in the lead filter while remaining unchanged in the lag filter after operating for almost four hours. This configuration provided the best effluent quality of all the configurations previously tested.

Although the multimedia filter was cleaned thoroughly by backwashing prior to the test, it did not perform adequately in removing turbidity. For an average influent turbidity of 4.30 NTU, the average effluent turbidity for the multimedia filter was 1.92 NTU with an associated 56.1%

removal efficiency. It was decided to review the depth and media specification for the multimedia filter.

Final Configuration for System Evaluation

As the garnet (33 µm) – garnet (33 µm) in-series configuration yielded relatively improved effluent quality, this configuration was selected for further turbidity and planned contaminant challenges. As the existing multimedia filter did not perform adequately in removing turbidity, it was decided to re-design the multimedia filter to increase the overall media depth/ media diameter ratio (L/D) for the contaminant challenges. The revised media specifications for the multimedia filter are shown in Table 3-6. The total L/D ratio for the existing design was 1100 (less than the generally recommended ratio of 1200) and was increased to 1600 for the re-designed filter. The bottom garnet and gravel layers are the underdrainage system.

Table 3-6. Revised Media Specification for the Multimedia Filter

Media	Size Range (mm)	Effective Size (D10) (mm)	Depth (mm)	Depth (inch)	L/D Ratio
Anthracite	0.6 – 2.55	1.0	100	4	100
Sand	0.35 – 0.45	0.4	300	12	750
Garnet	0.18 – 0.35	0.2	150	6	750
Garnet ^a	1.18 – 2.36	-	100	4	-
Gravel ^a	3.00 – 6.00	-	150	6	-
Total	-	-	800	32	1600

^a Underdrainage

3.1.2 Evaluation of System Performance

Two turbidity challenges (Challenges 8 and 9) were conducted at a 5.0 gpm flow rate using feed water with 5.0 NTU and 10.0 NTU on the selected garnet-garnet configuration and re-designed multimedia filter without using chemical coagulants to evaluate the system performance. Rosedale, Nanoceram, and Harmsco filters were individually tested following the R3f effluent as the final polishing stage. Three additional turbidity challenges (Challenges 10, 11 and 12) were conducted at a 5.0 gpm flow rate using feed water with 5.0 NTU turbidity on the selected garnet-garnet configuration and re-designed multimedia filter using chemical coagulant (4 mg/L alum)

to evaluate the system performance. A UF unit was tested following the R3f effluent as the final polishing stage.

The turbidity test results from this evaluation phase are presented in tabular form and graphical form at the end of Section 3.1.2. Tables 3-7, 3-8 and 3-9 present the results of turbidity tests for the R3f filter, the multimedia filter and the tested post-filters, respectively, during the five turbidity challenges. The operational parameters corresponding to these tests are summarized in Tables 3-10, 3-11 and 3-12. Figures 3-1 to 3-5 show the influent and effluent turbidities for the R3f system during the five turbidity challenges. Figures 3-6 to 3-10 show the development of differential pressure in the garnet-garnet R3f configuration during the five challenges. Figures 3-11 to 3-15 show the influent and effluent turbidity for the multimedia filter during the five challenges. As the headloss development in the multimedia filter was negligible during the five challenges, it is not shown graphically. Tables 3-13, 3-14 and 3-15 present the summaries of TOC/DOC results for the garnet-garnet R3f filter, multimedia filter and post-filters, respectively, during the five turbidity challenges. Tables 3-16, 3-17 and 3-18 present the HPC results of the garnet-garnet R3f filter, multimedia filter and post-filters, respectively during the five challenges. Table 3-19 presents the particle count results for the R3f system.

With reference to the above tables and figures, the results of the Turbidity Challenge Tests 8, 9, 10, 11 and 12 are discussed below.

Turbidity Challenge 8 [Filter Configuration: Garnet (33 μ m) + Garnet (33 μ m); Target flow: 5.0 gpm; Target feed water turbidity: 5 NTU]

This test was conducted on the R3f unit using garnet (33 μ m) in the lead filter and lag filters at 5.0 gpm using feed water with a target turbidity of 5.0 NTU. Chemical coagulants were not used during this test. For an average influent turbidity of 4.70 NTU, the average effluent turbidity from the lead filter was 0.83 NTU and that from the lag filter was 0.60 NTU. The effluent turbidity improved gradually with time and after 10 hours of filtration run, the lag filter started producing effluent with 0.5 NTU turbidity. The garnet-garnet R3f system treated 4508 gallons of water during 17 hours of test run. The total headloss developed in the lead filter was 34 psi and that in the lag filter was only 8 psi.

The volume of clean water required for backwashing of the system was 75 gallons, which was 1.7% of the total production. No noticeable removal of TOC/DOC and HPC by the R3f system was observed. The R3f system performed adequately in removing *Cryptosporidium* size (2-5 μm) particles. For influent particle counts of >20000/mL, the effluent particle counts for Filter 1 was 1200/mL and that for Filter 2 was 925/mL with an overall removal of >95.4%.

An attempt was made to quantify the Silt Density Index (SDI) test on the R3f system. However, it was not possible to determine the SDI15 values (measured after 15 minutes) for the garnet system due to rapid blockage of the SDI Kit filter; SDI10 values (measured after 10 minutes) were measured instead. The SDI10 values for influent, effluent from the lead filter and effluent from the lag filter were 8.63, 8.15, and 8.13, respectively. The estimated SDI15 values calculated from these SDI10 values are 5.75, 5.43, and 5.41, respectively.

The Rosedale PS 740 bag filter used as a final polishing filter consistently produced effluent with < 0.5 NTU turbidity. The Harmsco 1 μm cartridge filter also produced effluent with < 0.5 NTU. The Rosedale bag filter developed an additional 2 psi headloss during 12 hours of test run and no headloss developed in the Harmsco filter during 5 hours of test run. TOC, DOC and HPC samples were only collected from the Rosedale system and no noticeable removals of these parameters were observed.

The multimedia filter did not perform adequately in removing turbidity without chemical coagulants. For an average influent turbidity of 4.30 NTU, the average effluent turbidity was 1.95 NTU and the associated average removal efficiency was 53.3%. Although the effluent quality improved gradually with time, the effluent turbidity was consistently >1.5 NTU for the multimedia filter. The multimedia filter treated 3060 gallons of water during 17 hours of the test run. The total additional headloss was only 0.3 psi. It was not necessary to clean the multimedia filter. No noticeable TOC/DOC and HPC removals by the multimedia filter were observed during the test.

Turbidity Challenge 9 [Filter Configuration: Garnet (33 μm) + Garnet (33 μm); Target flow: 5.0 gpm; Target feed water turbidity: 5 NTU]

This test was conducted on the R3f unit with garnet (33 μm) and garnet (33 μm) in the lead and lag filters at 5 gpm using feed water with a target turbidity of 10 NTU. Chemical coagulants

were not used during this test. For an average influent turbidity of 9.70 NTU, the average effluent turbidity from the lead filter was 1.15 NTU and that from the lag filter was 0.91 NTU. The overall average turbidity removal efficiency was 90.5%. The effluent turbidity improved gradually with time, however, the values were consistently >0.50 NTU. The garnet R3f system treated 2015 gallons of water during 7.25 hours of the test run before backwashing. The total additional headloss developed in the lead filter was 42 psi and that in lag filter was only 5 psi. The volume of clean water required for backwashing of the system was 75 gallons which was 3.7% of the total production. After backwashing, the test was continued and showed rapid development of pressure in the lead filter (26 psi in 2.5 hours), indicating insufficient cleaning of the filter in one backwashing cycle. No noticeable removal of TOC/DOC by the R3f system was observed. The HPC removal performance improved significantly in comparison with the previous challenge. The overall removal performance was 77.6%. The relatively inferior performance during Challenge 8 was attributed to the leaching of HPC from the media. The R3f system performed adequately in removing *Cryptosporidium* size (2-5 μm) particles. For influent particle counts of >20000/mL, the effluent particle counts for Filter 1 was 2321/mL and that for Filter 2 was 1632/mL with an overall removal value of >91.8%. Silt Density Index test was not conducted during this challenge.

The Rosedale PS 740 bag filter used as the final polishing filter consistently produced effluent with >0.5 NTU during this challenge. The test was continued after backwashing of the garnet filter, and Nanoceram filter was used instead of Rosedale filter as the final polishing filter. For an average influent turbidity of 0.57 NTU, the average effluent turbidity of the Nanoceram filter was 0.38 NTU. One measurement was conducted on the Harmsco 1 μm cartridge filter and the effluent turbidity was 0.55 NTU. The Rosedale bag filter developed an additional 2 psi headloss during 7.25 hours of the test run and no headloss developed in the Nanoceram filter during 2 hours of the test run. Additional HPC removal (33%) was achieved by the Rosedale filter, but no additional removal of HPC was achieved by the Nanoceram filter. No noticeable removal of TOC/DOC was achieved by the Rosedale and Nanoceram filters.

The multimedia filter did not perform adequately in removing turbidity without chemical coagulants. For an average influent turbidity of 9.70 NTU, the average effluent turbidity was 2.85 NTU and the associated average removal efficiency was 70.3%. Although the effluent quality improved gradually with time, the effluent turbidity was consistently >2.0 NTU for the multimedia filter. The multimedia filter treated 1305 gallons of water during 7.25 hours of the

test run. The total additional headloss was only 0.2 psi, and, thus, it was not necessary to clean the multimedia filter. No noticeable TOC/DOC removal by the multimedia filter was observed during the test. The HPC removal performance improved significantly in comparison with the previous challenge. The overall removal performance was 75.2%. The relatively inferior performance during Challenge 8 was probably due to leaching of HPC from the media.

Turbidity Challenge 10 [Filter Configuration: Garnet (33 μ m) + Garnet (33 μ m); Target flow: 5.0 gpm; Target feed water turbidity: 5 NTU]

This test was conducted on the R3f unit using garnet (33 μ m) in the lead filter and lag filter at 5.0 gpm using feed water with a target turbidity of 5.0 NTU. Alum was used a chemical coagulant at a concentration of 4mg/L to aid in filtration. For an average influent turbidity of 5.00 NTU, the average effluent turbidity from the lead filter was 0.79 NTU and that from the lag filter was 0.31 NTU thus showing an improved removal performance. However, the effluent turbidity of the lead filter was relatively high at the beginning of the test but improved after 2 hours of filtration run. The average final effluent turbidity (0.31 NTU) from the R3f series configuration came close to satisfying the LT2ESWTR regulation (<0.30 NTU) (U.S. EPA, 2006) for turbidity removal. The R3f system performed adequately in removing *Cryptosporidium* size (2-5 μ m) particles. For influent particle counts of >20000/mL, the effluent particle count for Filter 1 was 1000/mL and that for Filter 2 was 445/mL with an overall removal value of >97.8%. Samples for TOC/DOC and HPC were not collected during this test.

The R3f system treated 750 gallons of water during 3.4 hours of test run. The total headloss developed in the lead filter was 54 psi and that in the lag filter was only 11 psi. The volume of clean water required for backwashing of the system was 150 gallons, which was 20% of the total production. The system had to be backwashed twice to restore the original flow rate. The rate of headloss development and backwash water requirement were relatively high due to the addition of alum.

The UF unit used as a final polishing filter consistently produced effluent with 0.15 NTU turbidity. Therefore, the combination of the R3f system followed by the UF system consistently produced effluent that satisfied the LT2ESWTR regulation (<0.30 NTU) for turbidity removal.

The performance of the multimedia filter improved due to the addition of 4 mg/L alum as chemical coagulant. For an average influent turbidity of 3.44 NTU, the average effluent turbidity was 0.34 NTU and the associated average removal efficiency was 90.1%. The effluent turbidity was close to the LT2ESWTR requirement (<0.30 NTU) for turbidity removal. The multimedia filter treated 420 gallons of water during 2.33 hours of the test run. No noticeable headloss was observed during the test period.

Turbidity Challenge 11 [Filter Configuration: Garnet (33 µm) + Garnet (33 µm); Target flow: 5.0 gpm; Target feed water turbidity: 5 NTU]

This test was conducted on the R3f unit using garnet (33 µm) in the lead filter and lag filter at 5.0 gpm using feed water with a target turbidity of 5.0 NTU. Alum was used a chemical coagulant at a concentration of 4 mg/L to aid in filtration. For an average influent turbidity of 5.59 NTU, the average effluent turbidity from the lead filter was 0.23 NTU and that from the lag filter was 0.20 NTU. The average final effluent turbidity (0.20 NTU) from the R3f series configuration satisfied the LT2ESWTR regulation (<0.30 NTU) for turbidity removal. Samples for TOC/DOC were not collected during the test. The R3f system performed adequately in removing HPC; the overall removal performance was 86.3%. The R3f system performed adequately in removing *Cryptosporidium* size (2-5 µm) particles. For an influent particle counts of >20000/mL, the effluent particle counts for Filter 1 was 820/mL and that for Filter 2 was 485/mL with an overall removal value of >97.4%.

The R3f system treated 522 gallons of water during 3.0 hours of test run. The total headloss developed in the lead filter was 68 psi and that in the lag filter was only 4 psi. The volume of clean water required for backwashing of the system was 150 gallons, which was 26% of the total production. The system had to be backwashed twice to restore the original flow rate. Following the use of alum, the rate of headloss development and backwash water requirement increased.

The UF unit used as a final polishing filter consistently produced effluent with 0.15 NTU turbidity. Therefore, the combination of R3f series configuration and UF system produced effluent that satisfied the LT2ESWTR regulation (<0.30 NTU) for turbidity removal. The UF system performed adequately in removing HPC; the overall removal performance was 91.9%.

The performance of the multimedia filter improved due to the addition of 4 mg/L alum as a chemical coagulant. For an average influent turbidity of 5.64 NTU, the average effluent turbidity was 0.29 NTU and the associated average removal efficiency was 94.8%. The effluent turbidity (0.29 NTU) satisfied the LT2ESWTR requirement (<0.30 NTU) for turbidity removal. The multimedia filter treated 540 gallons of water during 3.0 hours of the test run. The total headloss developed during the test was 2.3 psi. The multimedia system performed adequately in removing HPC; the overall removal performance was 84.4%.

Turbidity Challenge 12 [Filter Configuration: Garnet (33 µm) + Garnet (33 µm); Target flow: 5.0 gpm; Target feed water turbidity: 5 NTU]

This test was conducted on the R3f unit using garnet (33 µm) in the lead filter and lag filter at 5.0 gpm using feed water with a target turbidity of 5.0 NTU. Alum was used as a chemical coagulant at a concentration of 4 mg/L to aid in filtration. For an average influent turbidity of 4.22 NTU, the average effluent turbidity from the lead filter was 0.27 NTU and that from the lag filter was 0.22 NTU showing an improvement in performance. The average final effluent turbidity (0.22 NTU) from the R3f series configuration satisfied the LT2ESWTR regulation (<0.30 NTU) for turbidity removal. No noticeable removal of TOC/DOC was observed during this test. The R3f system performed adequately in removing HPC; the overall removal performance was 48.5%. The relatively lower percent removal of HPC during this test was attributed to a lower influent concentration. Particle counts were not monitored during this test.

The R3f system treated 966 gallons of water during 4.25 hours of test run. The total headloss developed in the lead filter was 28 psi and that in the lag filter was only 5 psi. The volume of clean water required for backwashing of the system was 150 gallons which was 15.1% of the total production. The system had to be backwashed twice to restore the original flow rate. The rate of headloss development and backwash water requirement were relatively high due to the addition of 4 mg/L alum.

The UF unit used as a final polishing filter consistently produced effluent with 0.16 NTU turbidity. Therefore, the combination of R3f series configuration and UF system produced effluent that satisfied the LT2ESWTR regulation (<0.30 NTU) for turbidity removal. The UF system performed adequately in removing HPC; the overall removal performance was 88.8%.

The performance of the multimedia filter improved due to the addition of 4 mg/L alum as a chemical coagulant. For an average influent turbidity of 6.32 NTU, the average effluent turbidity was 0.42 NTU and the associated average removal efficiency was 94.8%. The effluent turbidity (0.42 NTU) was close to the LT2ESWTR requirement (<0.30 NTU) for turbidity removal. The multimedia filter treated 630 gallons of water during 3.5 hours of the test run. The total headloss developed during the test was 2.0 psi. The multimedia system performed adequately in removing HPC; the overall removal performance was 30%. The relatively lower percent removal of HPC during this test was attributed to the lower influent concentration. Particle counts were not monitored during this test. No noticeable removal of TOC/DOC was observed during this test.

Table 3-7. Summary of Turbidity Challenge Results of R3f System during Evaluation of System Performance

Test No.	Turbidity (NTU)			Overall % Removal
	Influent	Effluent 1	Effluent 2	
Without Chemical Coagulant				
8	4.30	0.83	0.60	81.5
9	9.70	1.15	0.91	90.5
With Chemical Coagulant (4 mg/L Alum)				
30	5.0	0.79	0.31	93.8
31	5.59	0.23	0.20	96.4
32	4.22	0.27	0.22	94.8

Table 3-8. Summary of Turbidity Challenge Results of Multimedia System during Evaluation of System Performance

Test No.	Turbidity (NTU)		Overall % Removal
	Influent	Effluent	
Without Chemical Coagulant			
8	4.30	1.95	53.3
9	9.70	2.85	70.3
With Chemical Coagulant (4 mg/L Alum)			
30	3.44	0.34	90.1
31	5.64	0.29	94.8

32	6.32	0.42	93.3
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Table 3-9. Summary of Turbidity Challenge Results for the Polishing Filter during Evaluation of System Performance

Test No.	Turbidity (NTU)		Overall % Removal
	Influent	Effluent	
Rosedale PS 740 (0.5 µm absolute); Without Chemical Coagulant			
8	0.62	0.46	25.8
9	0.92	0.58	36.9
Harmsco (1.0 µm); Without Chemical Coagulant			
8	0.47	0.41	12.7
9	0.57	0.55	3.5
Nanoceram (0.3 – 0.6 µm); Without Chemical Coagulant			
8	-	-	-
9	0.57	0.38	33.3
UF System (0.01 µm); With Chemical Coagulant (4 mg/L Alum)			
30	0.31	0.15	51.6
31	0.20	0.17	15.0
32	0.22	0.16	27.2

Table 3-10. Summary of Operational Parameters of R3f System during Evaluation of System Performance

Test Run	Flow Rate (gpm)	Initial Pressure (psi)	Diff. Pres. 1 (psi)		Diff. Pres. 2 (psi)		Test Run (hours)	Total flow (gallons)
			Initial	Final	Initial	Final		
Without Chemical Coagulant								
8	5.0	60.0	8	34	4	8	17	4508
9	5.0	56.0	14	42	4	4	7.5	2015
With Chemical Coagulant (4 mg/L Alum)								
30	5.0	64	12	54	6	0	3.5	750
31	5.0	70	19	68	4	0	3.0	572
32	5.0	10	10	28	5	0	4.25	966

Table 3-11. Summary of Operational Parameters of Multimedia Filter during Evaluation of System Performance

Test Run	Flow Rate (gpm)	Initial Pres. (psi)	Diff. Pressure (psi)		Test Run (hours)	Total flow (gallons)
			Initial	Final		
Without Chemical Coagulant						
8	3.0	1.3	1.3	1.6	17	3060
9	3.0	1.2	1.2	1.6	7.25	1305
With Chemical Coagulant (4 mg/L Alum)						
30	3.0	6.9	1.9	0	2.33	420
31	3.0	6.2	1.2	2.3	3.0	540
32	3.0	6.6	1.1	2.0	3.5	630

Table 3-12. Summary of Operational Parameters of Polishing Filters during Evaluation of System Performance

Test Run	Flow Rate (gpm)	Initial Pres. (psi)	Diff. Pressure (psi)		Test Run (hours)	Total flow (gallons)
			Initial	Final		
Rosedale PS 740 (0.5 µm absolute); Without Chemical Coagulant						
8	5.0	6.0	6.0	8.0	12	3258
9	5.0	7.0	7.0	11.0	7.25	1305
Harmsco (1.0 µm); Without Chemical Coagulant						
8	5.0	0.0	0.0	0.0	5	1250
9	5.0	0.0	0.0	0.0	1	300
Nanoceram (0.3 – 0.6 µm); Without Chemical Coagulant						
8	-	-	-	-	-	-
9	5.0	0.0	0.0	0.0	2	600
UF Unit; With Chemical Coagulant (4 mg/L Alum)						
30	5.0	42	42	36	3.5	750
31	5.0	52	52	22	3.0	572
32	5.0	40	40	62	4.25	996

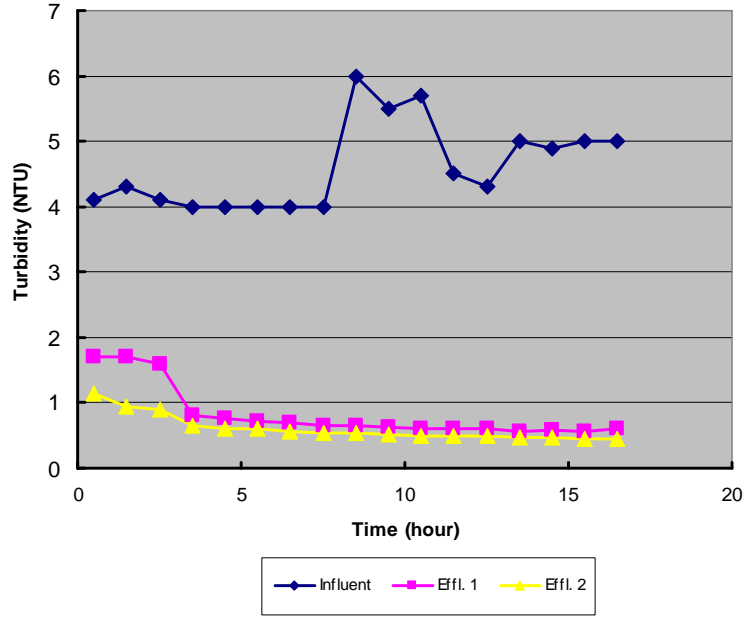


Figure 3-1. Influent and Effluent Turbidity in R3f Filter during Turbidity Challenge 8 (Without Chemical Coagulant)

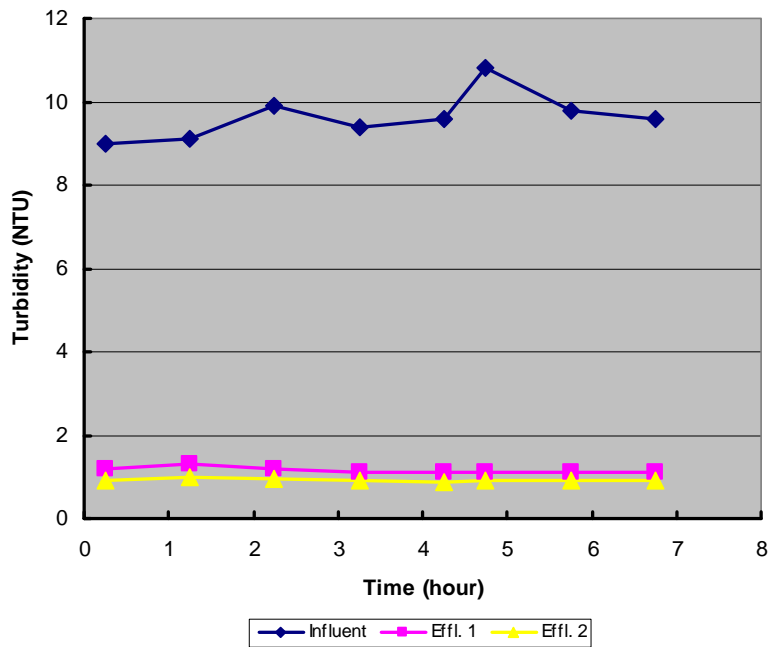


Figure 3-2. Influent and Effluent Turbidity in R3f Filter during Turbidity Challenge 9 (Without Chemical Coagulant)

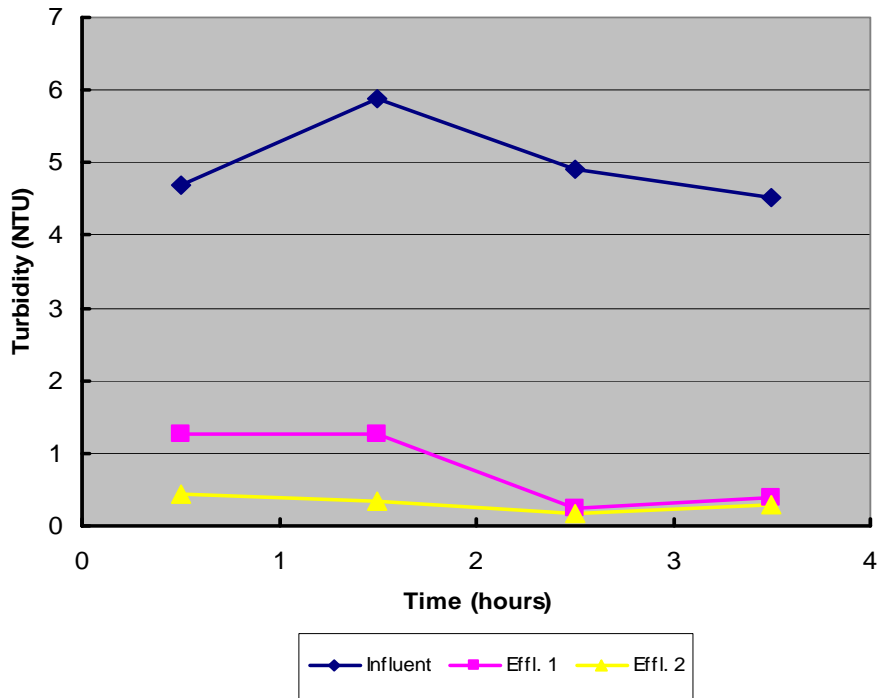


Figure 3-3. Influent and Effluent Turbidity in R3f Filter during Turbidity Challenge 10 (With 4 mg/L Alum)

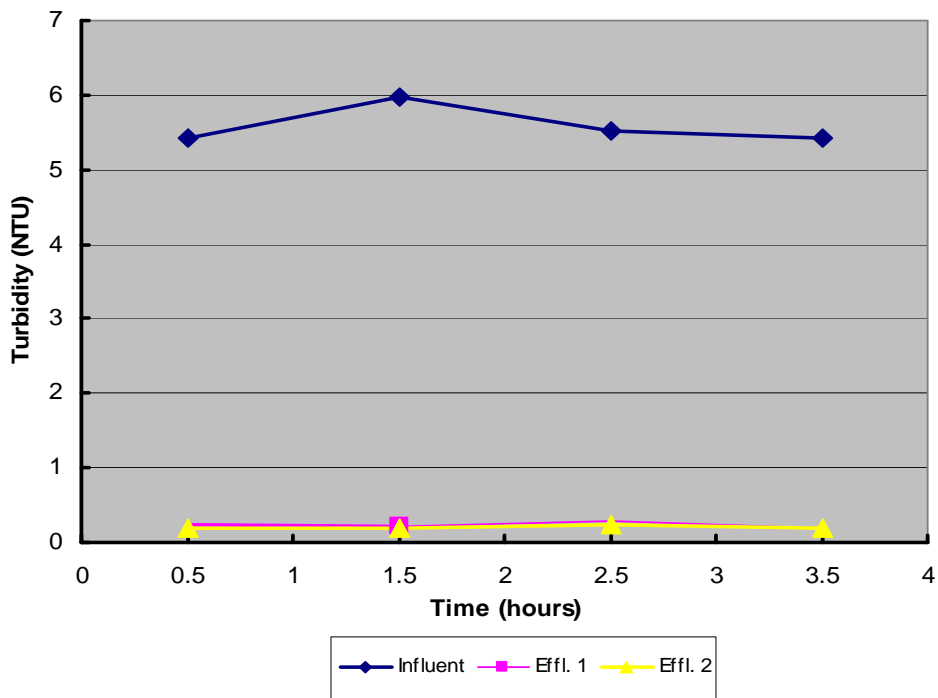


Figure 3-4. Influent and Effluent Turbidity in R3f Filter during Turbidity Challenge 11 (With 4 mg/L Alum)

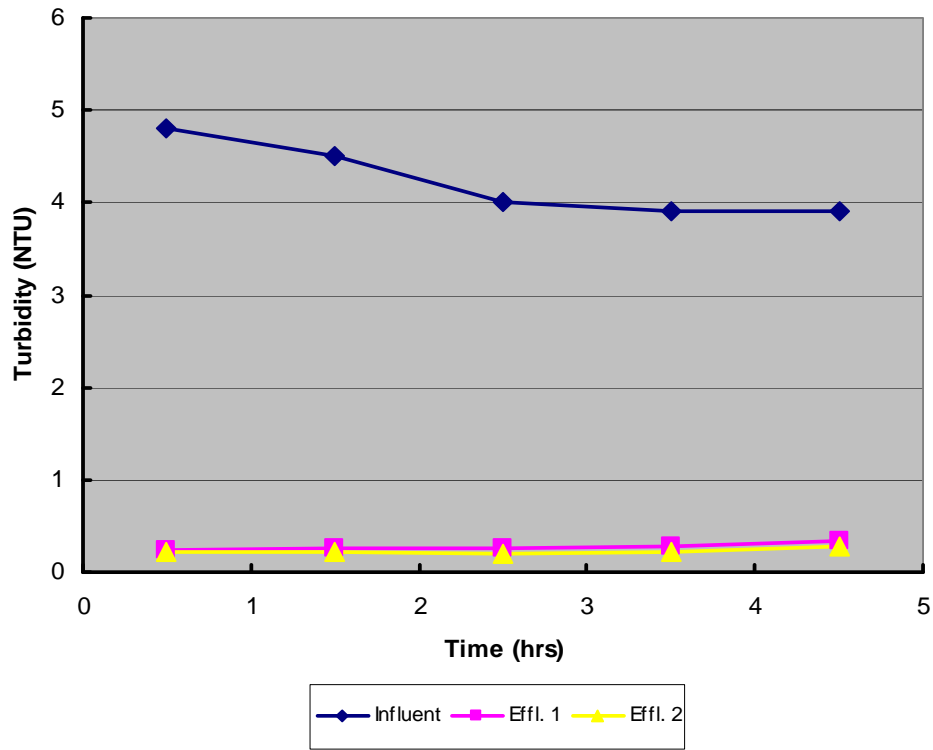


Figure 3-5. Influent and Effluent Turbidity in R3f Filter during Turbidity Challenge 12 (With 4 mg/L Alum)

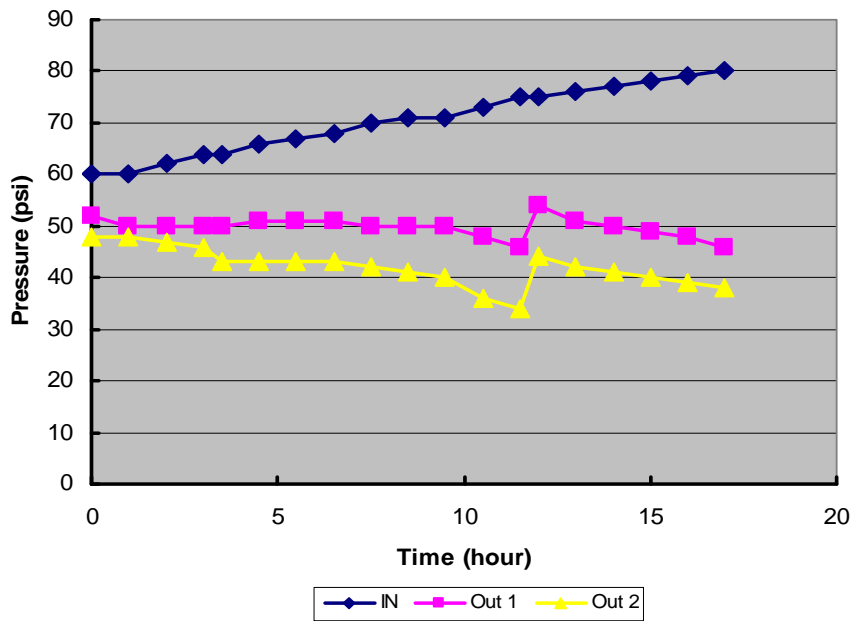


Figure 3-6. Headloss in R3f Filter during Turbidity Challenge 8 (Without Chemical Coagulant)

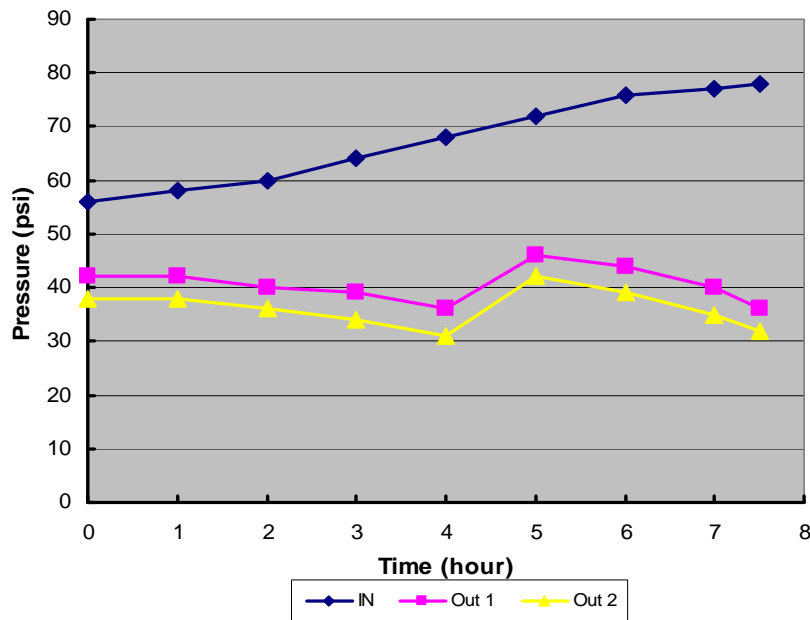


Figure 3-7. Headloss in R3f Filter during Turbidity Challenge 9 (Without Chemical Coagulant)

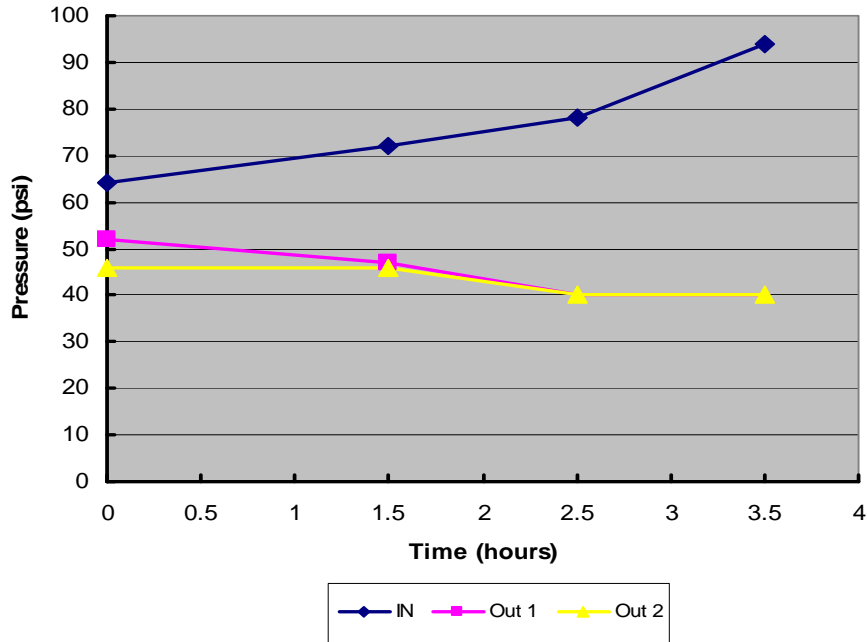


Figure 3-8. Headloss in R3f Filter during Turbidity Challenge 10 (With 4 mg/L Alum)

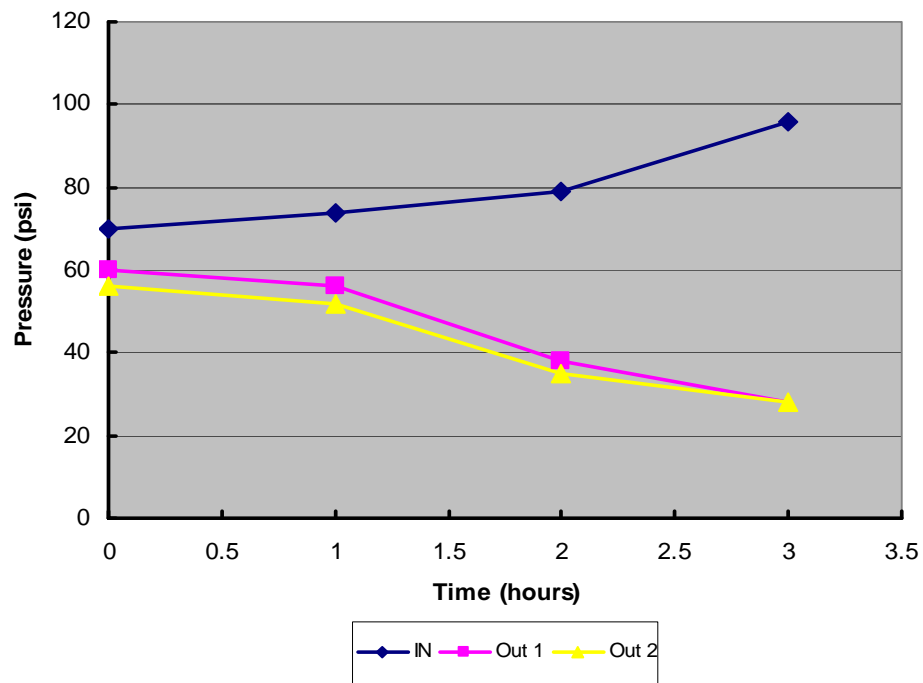


Figure 3-9. Headloss in R3f Filter during Turbidity Challenge 11 (With 4 mg/L Alum)

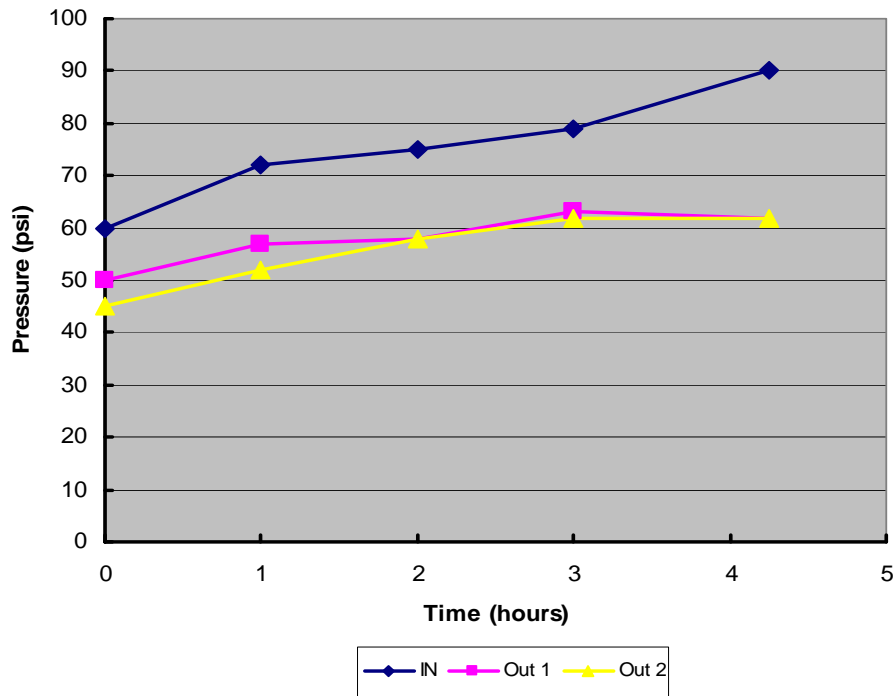


Figure 3-10. Headloss in R3f Filters during Turbidity Challenge 12 (With 4 mg/L Alum)

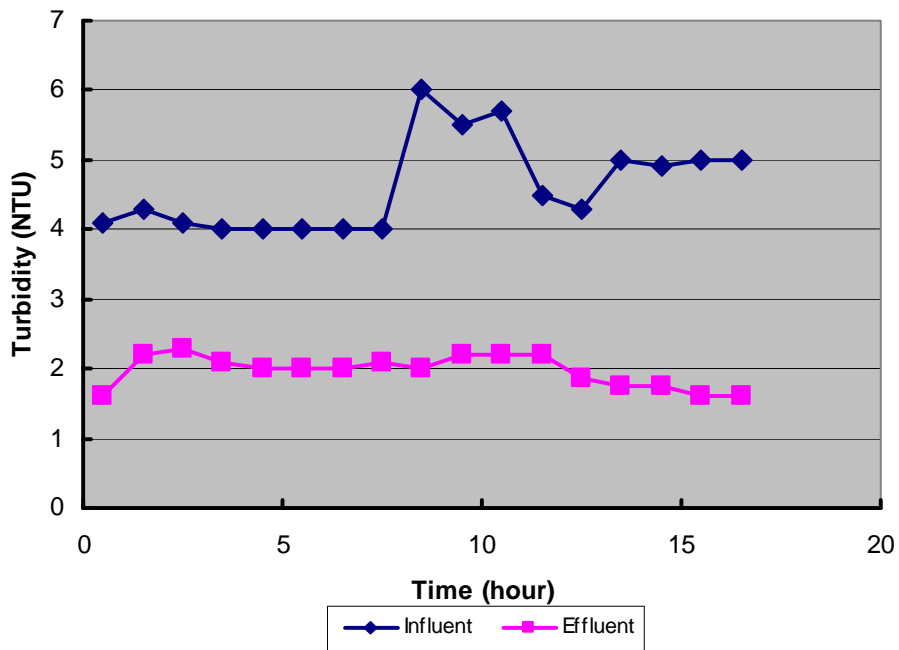


Figure 3-11. Influent and Effluent Turbidity in Multimedia Filter during Turbidity Challenge 8 (Without Chemical Coagulant)

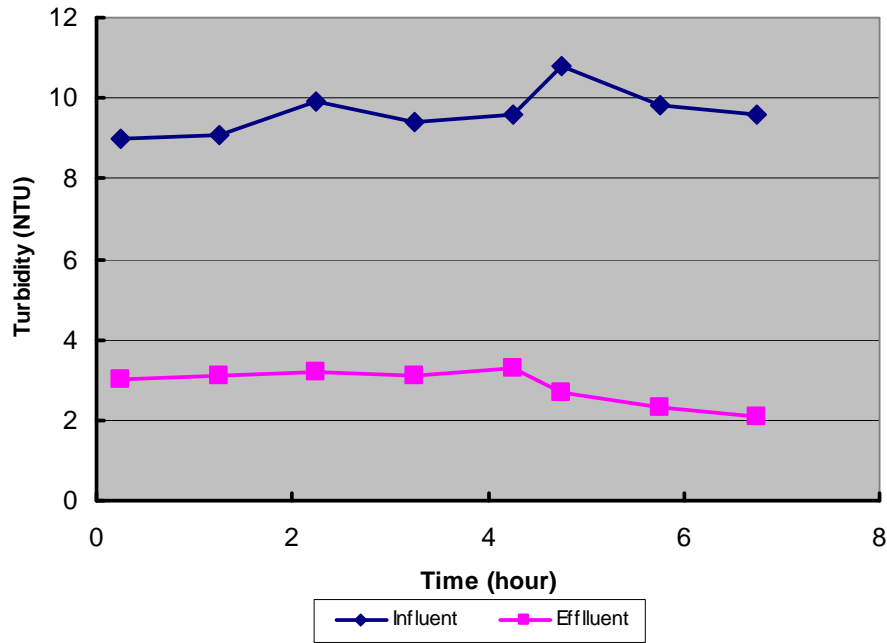


Figure 3-12. Influent and Effluent Turbidity in Multimedia Filter during Turbidity Challenge 9 (Without Chemical Coagulant)

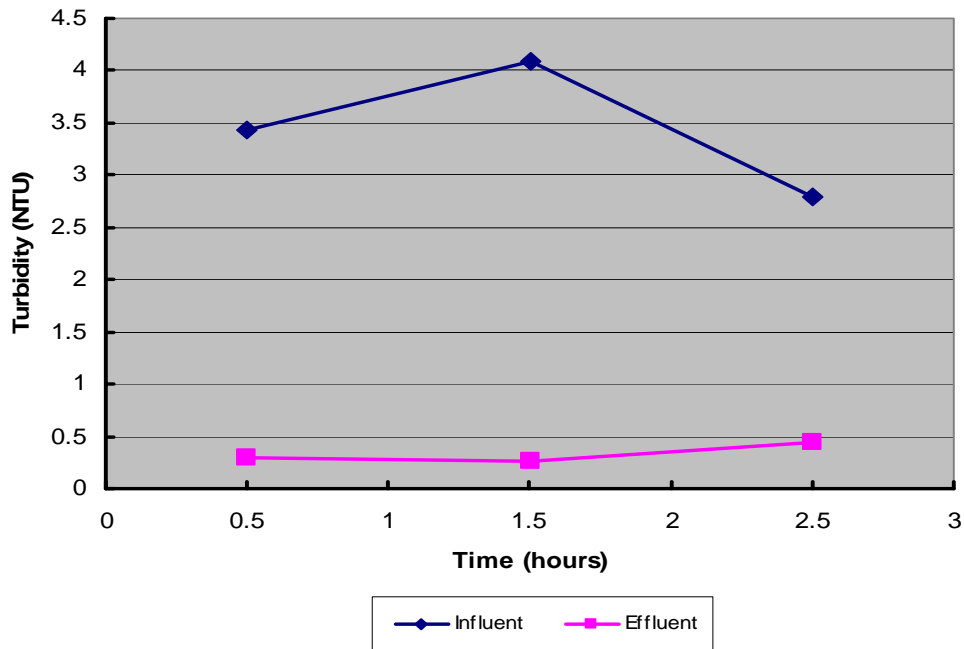


Figure 3-13. Influent and Effluent Turbidity in Multimedia Filter during Turbidity Challenge 10 (With 4 mg/L Alum)

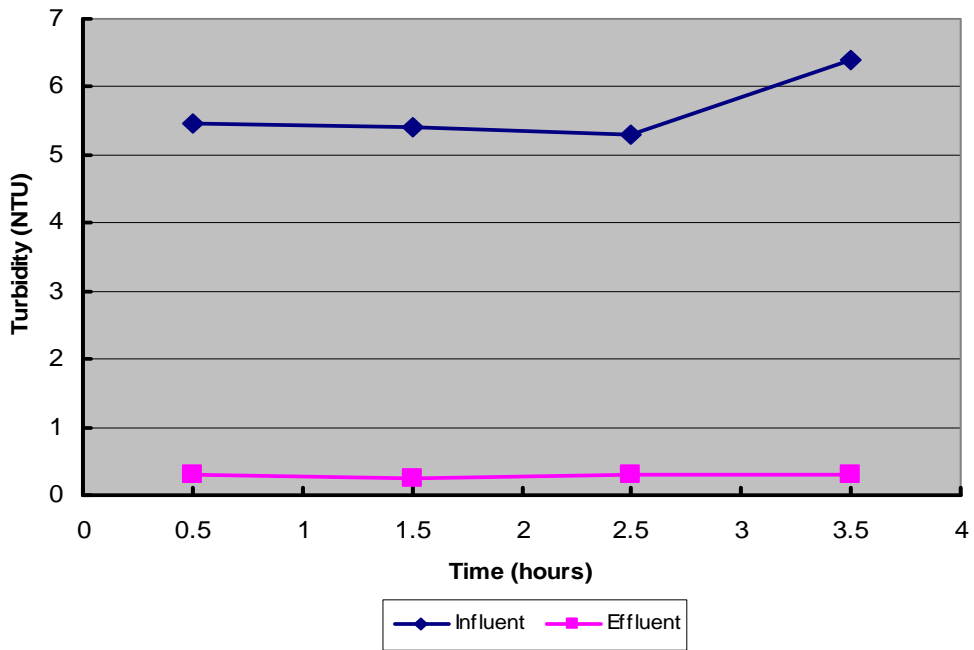


Figure 3-14. Influent and Effluent Turbidity in Multimedia Filter during Turbidity Challenge 11 (With 4 mg/L Alum)

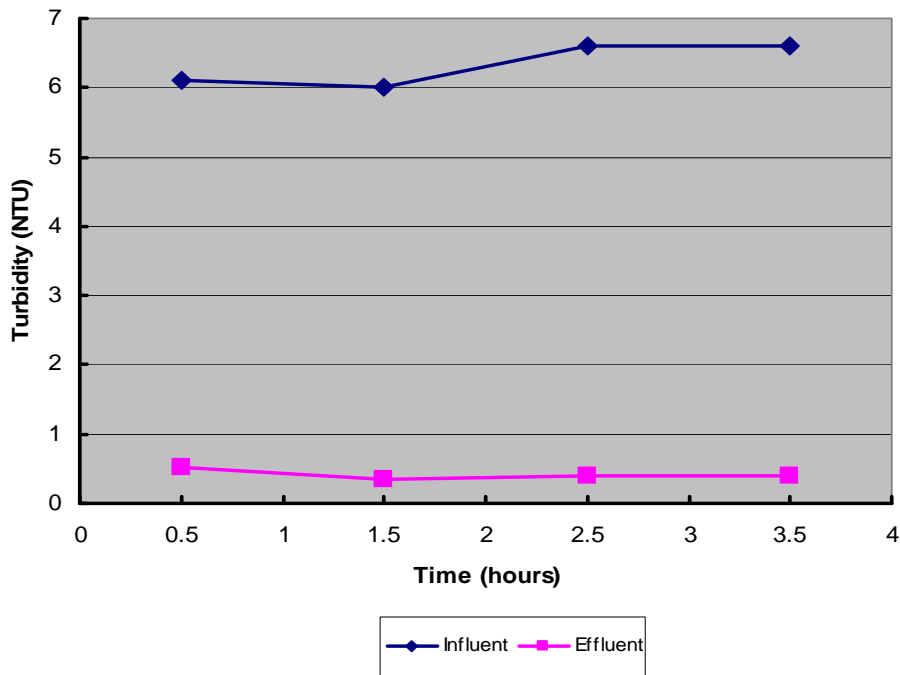


Figure 3-15. Influent and Effluent Turbidity in Multimedia Filter during Turbidity Challenge 12 (With 4 mg/L Alum)

Table 3-13. Summary of TOC and DOC Results of R3f System during Evaluation of System Performance

Test No.	TOC/DOC (mg/L)			Overall % Removal
	Influent	Effluent 1	Effluent 2	
TOC; Without Chemical Coagulant				
8	4.42	4.35	4.33	0.46
9	2.41	2.38	2.39	0.81
DOC; Without Chemical Coagulant				
8	4.47	4.29	4.28	4.3
9	2.37	2.23	2.26	4.6
TOC; With Chemical Coagulant (4 mg/L Alum)				
30	-	-	-	
-	-	-	-	
32	1.38	1.33	1.33	3.6
DOC; With Chemical Coagulant (4 mg/L Alum)				
30	-	-	-	-
31	-	-	-	-
32	1.46	1.30	1.32	9.6

Table 3-14. Summary of TOC and DOC Results of Multimedia System during Evaluation of System Performance

Test No.	TOC/DOC (mg/L)		Overall % Removal
	Influent	Effluent	
TOC; Without Chemical Coagulant			
8	4.42	4.32	2.26
9	2.41	2.45	0.00
DOC: Without Chemical Coagulant			
8	4.47	4.29	4.00
9	2.37	2.25	5.10
TOC; With Chemical Coagulant (4 mg/L Alum)			
30	-	-	-
31	-	-	-
32	1.30	1.44	0.0
DOC; With Chemical Coagulant (4 mg/L)			
30	-	-	-
31	-	-	-
32	1.34	1.29	3.7

Table 3-15. Summary of TOC and DOC Results of Post-filters during Evaluation of System Performance

Test No.	TOC/DOC (mg/L)		Overall % Removal
	Influent	Effluent	
TOC; Without Chemical Coagulant			
8 ^a	4.33	4.30	0.69
9 ^b	2.39	2.35	1.67
DOC; Without Chemical Coagulant			
8 ^a	4.28	4.29	0.00
9 ^b	2.26	2.42	0.00
TOC; With Chemical Coagulant (4 mg/L Alum)			
30	-	-	-
31	-	-	-
32 ^c	1.33	1.28	3.8
DOC; With Chemical Coagulant (4 mg/L Alum)			
30	-	-	-
31	-	-	-
32 ^c	1.32	1.31	0.8

^aTest conducted on Rosedale bag filter

^bTest conducted on Nanoceram bag filter

^cTest conducted on UF system

Table 3-16. Summary of HPC Results of Garnet-Garnet R3f System during Evaluation of System Performance

Test No.	HPC/mL			Overall % Removal
	Influent	Effluent 1	Effluent 2	
Without Chemical Coagulant				
8	7.5×10^4	7.8×10^4	6.1×10^4	18.7
9	2.1×10^5	6.2×10^4	4.7×10^4	77.6
With Chemical Coagulant (4 mg/L)				
30	-	-	-	-
31	1.9×10^5	5.7×10^4	2.6×10^4	86.3
32	9.9×10^4	7.7×10^4	5.1×10^4	48.5

Table 3-17. Summary of HPC Results of Multimedia System during Evaluation of System Performance

Test No.	HPC/mL		Overall % Removal
	Influent	Effluent	
Without Chemical Coagulant			
8	7.5×10^4	1.29×10^5	0.0
9	2.1×10^5	5.2×10^4	75.2
With Chemical Coagulant (4 mg/L)			
30	-	-	-
31	1.41×10^5	2.20×10^4	84.4
32	3.00×10^4	2.10×10^4	30

Table 3-18. Summary of HPC Results of Polishing Filters during Evaluation of System Performance

Test No.	HPC/mL		Overall % Removal
	Influent	Effluent	
Without Chemical Coagulant			
8 ^a	6.1×10^4	7.4×10^4	0.0
9 ^a	9.0×10^4	6.0×10^4	33.3
9 ^b	4.0×10^3	4.0×10^3	0.0
With Chemical Coagulant (4 mg/L Alum)			
30	-	-	-
31 ^c	2.6×10^4	2.1×10^3	91.9
32 ^c	5.1×10^4	5.7×10^3	88.8

^aTest conducted on Rosedale bag filter

^bTest conducted on Nanoceram bag filter

^cTest conducted on UF unit

Table 3-19. Summary of Particle Counts (2-5 µm) Results of Garnet-Garnet R3f System during Evaluation of System Performance

Test No.	Particle Counts/mL			Overall % Removal
	Influent	Effluent 1	Effluent 2	
Without Chemical Coagulant				
8	>20000	1200	925	>95.4
9	>20000	2321	1632	>91.8
With Chemical Coagulant (4 mg/L Alum)				
30	>20000	1000	445	>97.8
31	>20000	820	485	>97.4

3.2 PSL Bead Challenges

A total of eleven PSL bead challenges - eight on the R3f system and three on the multimedia system - were conducted without chemical coagulants during the test period. Of the eight PSL bead challenges conducted on the R3f system, two challenges were conducted to differentiate the performance of the lead and lag filters. For the PSL bead challenges, a suspension of the beads was prepared by adding 1 mL of 2.83 µm size PSL beads to 500 mL of 0.01% Tween-20 in a 1-L glass beaker. A 1 mL sub-sample was collected and analyzed for determining the total concentration of the injected beads. The 500 mL suspension and the additional 500 mL rinseate were added to the influent stream of the R3f and multimedia system using a peristaltic pump. The total injection time for both systems was 40 minutes. The system was run for an additional 3 – 4 hours to flush out any residual PSL beads from the systems. The effluent from the R3f system was passed through an additional polishing filter (Rosedale or Nanoceram) filter prior to discharge to drain. The effluent from the conventional multimedia filter was directly discharged to drain. A slip stream of the effluent was diverted through a 1 µm membrane in a manifold membrane system to collect the beads from the effluent. The beads were then extracted from the membrane using a squeegee followed by rinsing with 0.01% Tween-20 and analyzed to determine the total bead counts in the effluent. The membrane sampling technique was used to keep the analytical method consistent with the previous bead samples analysis. Log removal performance was evaluated by comparing the total effluent bead count with the total challenge bead count. All the tests were conducted at 5.0 gpm using dechlorinated potable water. Table 3-20 presents the results of the PSL bead challenges conducted on the R3f, post-filters and

multimedia systems. Table 3-21 presents the results of the two PSL bead challenges conducted on the R3f system for evaluating differential performance of the lead and lag filters.

The R3f system performed effectively in removing 3.0 μm PSL beads with an average log removal of 3.40 achieved in six challenge runs. The Rosedale PS 740 bag filter used as the final polishing filter for the R3f effluent (Challenges 10 and 12) achieved complete removal of the remaining PSL beads from the effluent of the garnet system with an average log removal of greater than 5.65 (based on the influent total bead concentration). The total log removal value achieved by the R3f system followed by the Rosedale PS 740 bag filter was 9.05 (based on the influent total bead concentration).

A Nanoceram filter was tested as the final polishing filter in Challenge 14 and 19. No noticeable removal of PSL beads was observed in Challenge 14 conducted on the Nanoceram cartridge. A poor seal between the cartridge and the housing was suspected of causing the poor removal of PSL beads. A new cartridge with a revised seal was installed and challenged with PSL beads (Challenge 19^b). These results also showed no noticeable removal of PSL beads.

A UF unit was tested as the final polishing filter in Challenges 37 and 38. The UF system achieved complete removal of PSL beads; the average log removal value was 5.51 (based on the influent total bead concentration). The total log removal value achieved by the R3f and the UF filter series combination was 8.91 (based on the influent total bead concentration). During the analyses of PSL bead effluent samples, visible amounts of garnet media were observed in the concentrated samples indicating that some media was escaping the system during different challenges. This observation was supported by a pressure build-up of 70 psi in the UF post-filter after treating approximately 5500 gallons of water.

The multimedia filter did not perform adequately in removing 3.0 μm PSL beads. The average log removal achieved in three challenges was 0.20.

Table 3-21 shows that, based on Challenges 39 and 40, the average log removal values achieved by the lead and lag R3f filters were 3.17 and 0.74, respectively. These results indicate that a single R3f filter is capable of satisfying the LT1ESWTR requirement (2.0 log) (U.S. EPA, 2004) for *Cryptosporidium* removal.

Table 3-20. Summary of PSL Bead Test Results for R3f, Rosedale, Nanoceram, UF and Multimedia Systems

Test No.	Total Beads		Log Removal	Avg. Log Removal
	Influent	Effluent		
Garnet-Garnet R3f System				
10	1.68×10^9	2.41×10^5	3.84	3.40
12	1.55×10^9	8.31×10^5	3.27	
14	2.41×10^9	2.51×10^6	2.99	
19	1.99×10^9	1.61×10^6	3.10	
37	1.48×10^9	2.87×10^5	3.70	
38	1.30×10^9	3.80×10^5	3.52	
Rosedale PS 740/Nanoceram Filter/UF Filter				
10 ^a	2.41×10^5	0	5.38	5.65
12 ^a	8.31×10^5	0	5.92	
14 ^b	2.51×10^6	2.39×10^6	0.02	0.01
19 ^b	1.61×10^6	2.14×10^6	0	
37 ^c	2.87×10^5	0	5.45	5.51
38 ^c	3.80×10^5	0	5.57	
Multimedia Filter				
11	1.90×10^9	1.30×10^9	0.17	0.20
13	1.26×10^9	5.17×10^8	0.39	
15	1.56×10^9	1.46×10^9	0.03	

^aRosedale PS 740

^bNanoceram

^cUF Filter

Table 3-21. Summary of PSL Bead Test Results for Garnet-Garnet R3f Lead and Lag Filters

Test No.	Total Beads			Log Removal		Total Log Removal
	Influent	Effluent Lead Filter	Effluent Lag Filter	Lead Filter	Lag Filter	
39	1.50×10^9	1.90×10^6	4.70×10^5	2.90	0.60	3.50
40	1.79×10^9	6.61×10^5	8.52×10^4	3.43	0.88	4.31

3.3 *Bacillus subtilis* Challenge Tests

A total of ten *B. subtilis* challenges - seven on the R3f system and three on the conventional multimedia system - were conducted without chemical coagulants during the test period. For the R3f system, three challenges were conducted using the membrane sampling technique and four challenges were conducted using the grab sampling method. A suspension of the *B. subtilis* spores was prepared by adding 1 mL of *B. subtilis* stock to 500 mL of 0.01% Tween-20 in a 1-L glass beaker. A 1 mL sub-sample was collected and analyzed to determine the total injected *B. subtilis* concentration. The 500 mL suspension and an additional 500 mL rinseate were added to the influent stream of the R3f and multimedia system using a peristaltic pump. The total injection time for both systems was 40 minutes.

According to the membrane sampling protocol, it was recommended that the systems run for an additional 3 to 4 hours after the completion of injection to flush out any remaining spores from the systems. However, it was not possible to run any of the systems for this recommended period due to clogging in the fine (0.4 μm) sampling membrane. The R3f followed by the Rosedale system could be operated for a total of 1.5 to 2 hours and the multimedia system for only 40 minutes prior to clogging of the membrane. The effluent from the multimedia filter was discharged directly to drain. A slip stream of the effluent was diverted through a 0.40 μm membrane in a manifold membrane system to collect the *B. subtilis* spores from the effluent. The spores were then extracted from the membrane using a squeegee followed by rinsing with 0.01% Tween-20 and analyzed for determining the total *B. subtilis* concentrations in the effluent. Log removal performance was evaluated by comparing the total effluent *B. subtilis* count with the total challenge *B. subtilis* count. Table 3-22 presents the results of *B. subtilis* challenges conducted on the R3f and multimedia filter systems using the membrane sampling technique.

According to the grab sampling technique, 100 mL samples were collected from the influent and effluent streams at specific time intervals during the test and the performance of the system was evaluated by comparing the influent and effluent *B. subtilis* concentrations. Tables 3-23 to 3-26 present the results of *B. subtilis* challenges conducted using the grab sampling method.

The R3f system did not perform adequately in removing *B. subtilis* spores. The average log removal value achieved in three *B. subtilis* challenges conducted using membrane sampling

technique was 0.44. The average log removal value achieved in the four challenges conducted using the grab sampling method was 0.72.

The Rosedale PS 740 bag filter used as the final polishing filter contributed an additional 2.12 log removal of the remaining *B. subtilis* from the effluent of the R3f system. The effluent from the R3f system was used as the influent *B. subtilis* concentration (total) for the Rosedale PS 740 bag filter. No *B. subtilis* challenge was conducted on the Nanoceram bag filter.

The multimedia filter did not perform adequately in removing *B. subtilis* achieving only negligible removal (log removal of 0.11) as shown in Table 3-22.

As shown in Tables 3-23 and 3-24, the UF filter did not perform adequately during *B. subtilis* Challenge Nos. 7 and 8. The filter was taken out of the housing and was found to be deformed (Figure 3-16). This was attributed to the high pressure (maximum 62 psi) development during the turbidity challenges. Two additional tests (*B. subtilis* Challenge Nos. 9 and 10) were conducted on a new UF unit and a much higher log removal value of 3.5 was achieved as shown in Figures 3-25 and 3-26.

Table 3-27 shows the summary of differential performance of the lead and lag R3f filter during *B. subtilis* challenges. Results of Test Nos. 33 and 34 show similar performance between the lead and lag filters. However, results of the last two tests (Test Nos. 35 and 36) are not consistent with the previous two tests, potentially indicating that *B. subtilis* spores were being washed out of the filters.



Figure 3-16. Deformed UF Filter

Table 3-22. Summary of Six *B. subtilis* Test Results Using Membrane Sampling Technique for R3f, Rosedale/Nanoceram and Multimedia Systems

Test No.	Total <i>B. subtilis</i> Conc. (No. of Cells/100 mL)		Log Removal	Avg. Log Removal
	Influent	Effluent		
R3f system				
23	6.00×10^8	1.23×10^8	0.68	0.44
24	7.30×10^8	3.67×10^8	0.30	
27	7.30×10^8	3.30×10^8	0.35	
Rosedale PS 740 Filter				
23	1.23×10^8	1.78×10^6	1.84	2.12
24	3.67×10^8	2.19×10^6	2.22	
27	3.30×10^8	1.60×10^8	2.31	
Multimedia Filter				
25	7.50×10^8	7.10×10^8	0.02	0.11
26	1.15×10^9	6.80×10^8	0.22	
28	1.10×10^9	9.00×10^8	0.09	

Table 3-23. Results of *B. subtilis* Challenge 7 Using Grab Sampling Technique in R3f and UF System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
R3f System					
33	T0	0	5	N/A	0.65
	T5	1.4×10^5	3.2×10^4	0.64	
	T10	1.6×10^5	3.0×10^4	0.73	
	T20	1.6×10^5	2.4×10^4	0.82	
	T40	2.4×10^4	9.0×10^3	0.42	
UF System					
33	T0	5	15	N/A	0.97
	T5	3.2×10^4	2.9×10^3	1.04	
	T10	3.0×10^4	3.0×10^3	1.00	
	T20	2.4×10^4	5.0×10^3	0.68	
	T40	9.0×10^3	6.2×10^2	1.16	

Table 3-24. Results of *B. subtilis* Challenge 8 Using Grab Sampling Technique in R3f and UF System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
R3f System					
34	T0	150	1030	N/A	0.62
	T5	1.5×10^5	2.4×10^4	0.80	
	T10	1.4×10^5	2.9×10^4	0.68	
	T20	1.2×10^5	3.3×10^4	0.56	
	T40	6.0×10^4	2.3×10^4	0.42	
UF System					
34	T0	1030	140	N/A	0.87
	T5	2.4×10^4	6.0×10^3	0.60	
	T10	2.9×10^4	5.4×10^3	0.73	
	T20	3.3×10^4	6.4×10^3	0.71	
	T40	2.3×10^4	8.0×10^2	1.45	

Table 3-25. Results of *B. subtilis* Challenge 9 Using Grab Sampling Technique in R3f and UF System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
R3f System					
35	T0	190	150	N/A	0.83
	T5	1.4×10^5	1.5×10^4	0.97	
	T10	1.6×10^5	3.0×10^4	0.72	
	T20	1.6×10^5	2.5×10^4	0.80	
	T40	4.0×10^4	-	N/A	
UF System					
35	T0	150	0	N/A	3.25
	T5	1.5×10^4	10	3.17	
	T10	3.0×10^4	10	3.48	
	T20	2.5×10^4	20	3.10	
	T40	-	25	N/A	

Table 3-26. Results of *B. subtilis* Challenge 10 Using Grab Sampling Technique in R3f and UF System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
R3f System					
36	T0	510	680	N/A	0.78
	T5	1.2×10^5	2.5×10^4	0.68	
	T10	1.1×10^5	2.4×10^4	0.66	
	T20	1.2×10^5	2.5×10^4	0.68	
	T40	5.8×10^4	6.7×10^3	0.93	
UF System					
36	T0	680	0		3.75
	T5	2.5×10^4	10	3.40	
	T10	2.4×10^4	10	3.38	
	T20	2.5×10^4	0	4.40	
	T40	6.7×10^3	0	3.83	

Table 3-27. Summary of *B. subtilis* Test Results for R3f Lead and Lag Filters

Test No.	No. of Cells/100 mL			Avg. Log Removal	
	Influent	Effluent Lead Filter	Effluent Lag Filter	Lead Filter	Lag Filter
33	1.2×10^5	5.5×10^4	2.4×10^4	0.34	0.36
34	1.2×10^5	6.8×10^4	2.8×10^4	0.25	0.39
35	1.5×10^5	5.7×10^3	2.3×10^4	1.42	0.00
36	1.1×10^5	7.6×10^3	2.1×10^4	1.16	0.00

3.4 *E. coli* Challenges

A total of seven *E. coli* challenges - five on the R3f system and two on the conventional multimedia system - were conducted without chemical coagulants during the test period. For these challenges, a suspension of *E. coli* was prepared by adding 1 mL of *E. coli* stock to 500 mL of 0.01% Tween-20 in a 1-L glass beaker. For the purpose of analysis, a 1 mL sub-sample was collected to determine the injection concentration. The 500 mL suspension and an additional 500 mL rinseate were added to the influent stream of the R3f filter and multimedia system using a peristaltic pump. The total injection time for both systems was 40 minutes. The effluent from the R3f system was passed through an additional polishing filtration stage using a Rosedale or Nanoceram filter prior to discharge to drain. The effluent from the multimedia filter was directly discharged to drain. Grab samples were collected from the influent and effluent streams at 0 (T0), 5 (T5), 10 (T10), 20 (T20) and 40 (T40) minutes after the start of the injection. A duplicate sample was collected at the T10 sampling event during Challenges 1 and 2.

Tables 3-28, 3-29, and 3-30 present the results of three *E. coli* challenges conducted on the R3f system and two polishing filters (Rosedale and Nanoceram filters). Table 3-31 presents the results of two *E. coli* challenges conducted on the conventional multimedia filter. Tables 3-32 and 3-33 present the results of two *E. coli* challenges conducted on the R3f and UF systems.

The R3f system achieved a log removal range of 0.65 to 1.36 for *E. coli*. The effluent concentrations of *E. coli* from the R3f system were considered as the influent concentrations for the Rosedale or Nanoceram filter. As the final polishing filter, the Rosedale bag filter contributed an additional log removal of 0.78 to 0.90 for *E. coli*. A single test conducted on the Nanoceram filter demonstrated an additional 2.10 log removal of *E. coli*. As the final polishing filter, the UF filter contributed an additional log removal of 4.05 to 4.40 for *E. coli* as shown in tables 3-32 and 3-33.

As shown in Table 3-31, the multimedia filter demonstrated 0.42 to 0.52 log removal of *E. coli*.

Table 3-34 shows the summary of differential performance of lead and lag R3f filter during *E. coli* challenges. Results showed that the lead filter contributed more than the lag filter in removing *E. coli*.

Table 3-28. Results of *E. coli* Challenge 1 in R3f and Rosedale System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
R3f System					
16	T0	0	0	N/A ^a	0.65
	T5	4.80×10^5	4.45×10^4	1.03	
	T10	5.00×10^5	1.00×10^5	0.70	
	T10 Dup	4.70×10^5	1.00×10^5	0.67	
	T20	1.00×10^5	4.20×10^4	0.40	
	T40	2.00×10^3	7.00×10^2	0.45	
Rosedale PS 740 Filter					
16	T0	0	0	N/A ^a	0.78
	T5	4.45×10^4	2.40×10^3	1.30	
	T10	1.00×10^5	1.40×10^4	0.85	
	T10 Dup	1.00×10^5	2.10×10^4	0.68	
	T20	4.20×10^4	2.00×10^4	0.30	
	T40	7.00×10^2	3.70×10^3	N/A ^a	

^a Not considered for performance evaluation due to inconsistency with other results.

Table 3-29. Results of *E. coli* Challenge 2 in R3f and Rosedale System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
R3f System					
17	T0	20	60	N/A ^a	0.69
	T5	3.90×10^5	9.00×10^4	0.64	
	T10	4.00×10^5	1.10×10^5	0.56	
	T10 Dup	4.20×10^5	9.00×10^4	0.67	
	T20	4.00×10^5	5.20×10^4	0.89	
	T40	4.80×10^4	3.60×10^4	0.13 ^a	
Rosedale PS 740 Filter					
17	T0	60	0	N/A ^a	0.90
	T5	9.00×10^4	6.00×10^3	1.18	
	T10	1.10×10^5	1.45×10^4	0.89	
	T10 Dup	9.00×10^4	1.65×10^4	0.74	
	T20	5.20×10^4	1.20×10^4	0.64	
	T40	3.60×10^4	3.10×10^3	1.06	

^a Not considered for performance evaluation due to inconsistency with other results.

Table 3-30. Results of *E. coli* Challenge 3 in R3f and Nanoceram System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
R3f System					
18	T0	10	90	N/A ^a	1.01
	T5	5.00×10^5	1.00×10^4	1.70	
	T10	5.20×10^5	6.20×10^4	0.92	
	T20	6.00×10^5	7.50×10^4	0.90	
	T40	1.40×10^5	4.10×10^4	0.53	
Nanoceram Filter					
18	T0	90	100	N/A ^a	2.10
	T5	1.00×10^4	600	1.22	
	T10	6.20×10^4	500	2.09	
	T20	7.50×10^4	200	2.57	
	T40	4.10×10^4	120	2.53	

^a Not considered for performance evaluation due to inconsistency with other results.

Table 3-31. Results of Two *E. coli* Challenges in Multimedia Filter

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
20	T0 ^a	0	0	NA	0.42
	T5 ^a	6.0×10^5	6.0×10^5	NA	
	T10	8.0×10^5	2.7×10^5	0.47	
	T10 Dup	9.0×10^5	3.1×10^5	0.46	
	T20	8.0×10^5	3.8×10^5	0.32	
	T40 ^a	2.0×10^4	1.2×10^5	NA	
21	T0 ^a	0	600	NA	0.52
	T5 ^a	8.5×10^5	2.0×10^3	2.62	
	T10	9.5×10^5	2.9×10^5	0.52	
	T10 Dup	9.0×10^5	2.8×10^5	0.51	
	T20	1.2×10^6	3.6×10^5	0.52	
	T40 ^a	7.0×10^4	8.0×10^4	NA	

^a Not considered for performance evaluation due to inconsistency with other results.

Table 3-32. Results of *E. coli* Challenge 6 in R3f and UF System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
R3f System					
41	T0	0	0	N/A	1.19
	T5	6.3×10^5	4.2×10^4	1.20	
	T10	6.1×10^5	3.9×10^4	1.22	
	T20	6.3×10^5	4.3×10^4	1.16	
	T40 ^a	1.0×10^4	1.2×10^3	0.67	
UF System					
41	T0	0	0		4.05
	T5	4.2×10^4	0	4.62	
	T10	3.9×10^4	5	3.89	
	T20	4.3×10^4	10	3.63	
	T40 ^a	1.2×10^3	0	3.10	

^a Not considered for performance evaluation due to inconsistency with other results.

Table 3-33. Results of *E. coli* Challenge 7 in R3f and UF System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Removal	Avg. Log Removal
		Influent	Effluent		
R3f System					
42	T0	0	0	N/A	1.36
	T5	5.2×10^5	2.4×10^4	1.34	
	T10	5.7×10^5	2.4×10^4	1.38	
	T20	6.4×10^5	2.8×10^4	1.36	
	T40 ^a	1.3×10^4	9.0×10^2	1.16	
UF System					
42	T0	0	0		4.40
	T5	2.4×10^4	0	4.38	
	T10	2.4×10^4	0	4.38	
	T20	2.8×10^4	0	4.45	
	T40 ^a	9.0×10^2	0	2.95	

^a Not considered for performance evaluation due to inconsistency with other results.

Table 3-34. Summary of *E.coli* Test Results for R3f Lead and Lag Filters

Test No.	No. of Cells/100 mL			Avg. Log Removal	
	Influent	Effluent Lead Filter	Effluent Lag Filter	Lead Filter	Lag Filter
41	6.1×10^5	7.6×10^4	4.1×10^4	0.90	0.26
42	5.8×10^5	5.8×10^4	2.5×10^4	1.00	0.37

3.5 *Cryptosporidium* Challenge

A single *Cryptosporidium* challenge was conducted on the R3f system to examine equivalency with the PSL Beads tests. For this challenge, a suspension of the *Cryptosporidium* oocysts was prepared by adding 1 mL of the oocysts to 500 mL of 0.01% Tween-20 in a 1-L glass beaker. A 1 mL sub-sample was collected and analyzed for determining the total concentration of the injected oocysts. The 500 mL suspension and the additional 500 mL rinseate were added to the influent stream of the R3f system using a peristaltic pump. The total injection time was 40 minutes. The system was run for an additional 3 to 4 hours to flush out any remaining oocysts from the system. The effluent from the R3f system was passed through an additional polishing filtration stage using the Rosedale filter prior to discharge to drain. A slip stream of the effluent was diverted through a 1 µm membrane in a manifold membrane system to collect the oocysts from the effluent. The oocysts were then extracted from the membrane using a squeegee followed by rinsing with 0.01% Tween-20 and analyzed to count the total oocysts in the effluent. Log removal performance was evaluated by comparing the total effluent oocysts count with the total challenge oocysts count. The test was conducted at 5 gpm using dechlorinated tap water.

Table 3-35 presents the results of this *Cryptosporidium* challenge test. The R3f system showed an average log removal of 3.47 for *Cryptosporidium*. The Rosedale PS 740 bag filter used as the final polishing filter contributed to the complete removal of the remaining oocysts from the effluent of the R3f system (a calculated average log removal of 5.50 based on the total influent oocysts concentration). The performance of the R3f garnet and Rosedale PS 740 bag filter in removing *Cryptosporidium* oocysts is similar to the performance of the systems in removing 3.0 µm PSL beads.

Table 3-35. Summary of *Cryptosporidium* Test Results for R3f and Rosedale Bag Filter

Test No.	Total <i>Cryptosporidium</i> oocysts/mL		Log Removal	Avg. Log Removal
	Influent	Effluent		
R3f System				
29	9.34×10^8	3.14×10^5	3.47	3.47
Rosedale PS 740 Filter				
29	3.14×10^5	0	5.50	5.50

3.6 MS2 Bacteriophage Challenges

A total of three MS2 bacteriophage challenges were conducted without chemical coagulants on the R3f system. Similar tests were not conducted on the multimedia filter since there was no expectation that the very small sized (20 nm) MS2 bacteriophage would be removed by this system. For these challenges, a suspension of MS2 was prepared by adding 1 mL of MS2 stock to 500 mL of 0.01% Tween-20 in a 1-L glass beaker. For the purpose of analysis, a 1 mL sub-sample was collected to determine the injection concentration. The 500 mL suspension and an additional 500 mL rinseate were added to the influent stream of the R3f and multimedia system using a peristaltic pump. The total injection time for both systems was 40 minutes. The effluent from the R3f system was passed through additional polishing filtration stages using a UF filter and UV system prior to discharge to drain. Grab samples were collected from the influent and effluent streams at 0 (T0), 5 (T5), 10 (T10), 20 (T20) and 40 (T40) minutes after the start of the injection.

Tables 3-36, 3-37 and 3-38 present the results of three MS2 bacteriophage challenges conducted on the R3f system and the polishing units (UF filter and UV system). The R3f system achieved negligible removal of MS2 bacteriophage with an average log removal between 0 and 0.22. The UF unit removed little MS2 bacteriophage with an average log removal value between 0.29 and 1.23. The UV unit performed adequately in inactivating MS2 bacteriophage with average log removal values during the three challenges that varied between 2.09 and 2.26. The overall log removal values of the R3f, UF system and UV unit series in combination varied between 2.71 and 3.33.

Table 3-36. Results of MS2 Bacteriophage Challenge 1 in R3f, UF and UV System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Inactivation	Avg. Log Inactivation
		Influent	Effluent		
R3f System					
43	T0	0	0	N/A	0.22
	T5	1.55×10^5	8.90×10^4	0.24	
	T10	1.75×10^5	1.54×10^5	0.06	
	T20	N/A	1.79×10^5	N/A	
	T40	4.27×10^4	2.00×10^4	0.35	
UF System					
43	T0	0	0	N/A	0.56
	T5	8.90×10^4	4.31×10^4	0.31	
	T10	1.54×10^5	3.34×10^4	0.66	
	T20	1.79×10^5	4.37×10^4	0.61	
	T40	2.00×10^4	4.20×10^3	0.65	
UV System					
43	T0	0	0	N/A	2.12
	T5	4.31×10^4	4.13×10^2	2.02	
	T10	3.34×10^4	3.23×10^2	2.02	
	T20	4.37×10^4	3.80×10^2	2.07	
	T40	4.20×10^3	19	2.35	

Table 3-37. Results of MS2 Bacteriophage Challenge 2 in R3f, UF and UV System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Inactivation	Avg. Log Inactivation
		Influent	Effluent		
R3f System					
44	T0	0	20	0	0.00
	T5	8.6×10^4	2.92×10^5	0	
	T10	1.12×10^5	3.14×10^5	0	
	T20	1.34×10^5	2.92×10^5	0	
	T40	2.06×10^4	9.53×10^4	0	
UF System					
44	T0	20	15	N/A	1.23
	T5	2.92×10^5	1.73×10^4	1.23	
	T10	3.14×10^5	2.69×10^4	1.07	
	T20	2.92×10^5	2.44×10^4	1.08	
	T40	9.53×10^4	2.58×10^3	1.56	
UV System					
44	T0	15	0	N/A	2.09
	T5	1.73×10^4	2.00×10^2	1.93	
	T10	2.69×10^4	2.06×10^2	2.11	
	T20	2.44×10^4	2.03×10^2	2.08	
	T40	2.58×10^3	15	2.23	

Table 3-38. Results of MS2 Bacteriophage Challenge 3 in R3f, UF and UV System

Test No.	Sampling Time (Min)	No. of Cells/100 mL		Log Inactivation	Avg. Log Inactivation
		Influent	Effluent		
R3f System					
45	T0	0	-	N/A	0.16
	T5	3.04×10^5	1.98×10^5	0.19	
	T10	1.96×10^5	2.24×10^5	0	
	T20	3.13×10^5	2.74×10^5	0.06	
	T40	1.16×10^5	5.42×10^4	0.39	
UF System					
45	T0	-	-	N/A	0.29
	T5	1.98×10^5	1.13×10^5	0.24	
	T10	2.24×10^5	1.20×10^5	0.27	
	T20	2.74×10^5	1.19×10^5	0.36	
	T40	5.42×10^4	2.80×10^4	0.29	
UV System					
45	T0	-	-	N/A	2.26
	T5	1.13×10^5	6.50×10^2	2.24	
	T10	1.20×10^5	2.52×10^2	2.68	
	T20	1.19×10^5	1.14×10^3	2.02	
	T40	2.80×10^4	2.30×10^2	2.09	

4.0 Summary and Conclusions

The major regulations governing small drinking water systems that use surface water are the LT1ESWTR and the LT2ESWTR. These regulations rely on turbidity and challenge testing to demonstrate the efficiency of filtration in removing contaminants such as *Cryptosporidium* from drinking water. The LT1ESWTR requires the effluent turbidity of a single filtration device to be less than 0.3 NTU and demonstrate a 2.0 log removal for *Cryptosporidium*. The LT2ESWTR requires increasingly higher treatment efficiency based on the results of monitoring for *Cryptosporidium* in the source water supply to the drinking water system. Thus, all filtration devices intended for small drinking water systems are benchmarked according to their ability to meet a turbidity level of 0.3 NTU and a 2-log *Cryptosporidium* removal. The LT2ESWTR also specifies that challenge testing may be conducted to establish the log removal credit for a filtration device or a combination of filtration devices. At the T&E Facility, PSL beads and *B. subtilis* are typically used as challenge surrogates for *Cryptosporidium* to evaluate filtration performance. In addition, filtration devices may also be evaluated for their ability to remove bacteria (as represented by *B. subtilis* and *E. coli*) and viruses (using MS2 Bacteriophage as a surrogate).

The tests performed on the R3f system were intended to evaluate the system for its ability to meet the requirements of the LT1ESWTR and LT2ESWTR. They were also aimed at verifying vendor claims that, unlike most multimedia filters, the system has the ability to meet these filtration requirements without the use of chemical coagulants while operating at a headloss similar to that of existing downflow and upflow multimedia bed systems but with cost and footprint requirements that are 20% to 50% less than a typical multimedia system. Thus, parallel tests were performed on a multimedia filter using the same challenge protocols. The R3f unit was also tested as a pre-treatment unit for the bulk of turbidity removal prior to polishing filters that can meet the LT1ESWTR and LT2ESWTR requirements but would be quickly blinded by high turbidity levels. Lastly, a UV unit was also tested as final microbial barrier to form a complete treatment system.

The R3f system was first evaluated for its ability to meet the LT1ESWTR turbidity level of 0.3 NTU. Tests were conducted at 10 gpm and 5 gpm using feed water with 10 NTU and 5 NTU turbidity on two media types (glass beads and garnet beads) in various sizes until one

configuration consistently produced effluent water with a turbidity <1 NTU. This configuration used a fine garnet media (0.33 micron) in both the lead and the lag filter. Once established as the optimal configuration, all subsequent challenge tests were performed using this media. The average effluent turbidity from the R3f unit ranged between 0.50 NTU and 0.91 NTU, depending on the influent turbidity and the length of operation. All the tests for optimization of the R3f system were conducted without the use of chemical coagulants.

Under similar operating conditions, the best effluent quality produced by the multimedia filter without chemical coagulants was 1.92 NTU. To improve this performance, the multimedia filter media configuration was re-designed to increase the total L/D (media depth to media size) ratio. However, this re-designed multimedia filter showed comparable turbidity results (1.95 NTU) and, thus, it appears that the multimedia filter is unable to produce acceptable effluent water quality (<1 NTU) without the use of coagulants. The R3f unit was able to achieve low turbidity levels (<0.5 NTU) without the use of coagulants or other filtration aids for an influent feed water with a turbidity level of 5 NTU and at a flow rate of 5 gpm.

Addition of alum as a chemical coagulant with a dosage of 4 mg/L improved the performance of the R3f system to an average effluent turbidity of 0.24 NTU from the final filter when challenged with an influent feed turbidity of 4.9 NTU at 5 gpm. The average effluent turbidity of the lead filter was 0.43 NTU. Addition of 4 mg/L alum as a chemical coagulant to the multimedia filter produced an effluent quality of 0.35 NTU which is comparable to the effluent from the R3f unit.

Four polishing filters were tested on the R3f effluent to improve the effluent quality. The units tested were the Rosedale PS740, the Nanoceram cartridge filter, the Harmsco cartridge filter, and a low-cost UF filter. Both the Rosedale PS740 and Harmsco post-filtration units produced effluent water consistently with a turbidity of less than 0.5 NTU during the challenge tests conducted at 5.0 gpm using feed water with a target turbidity of 5.0 NTU without chemical coagulant. The effluent turbidity for the both the Rosedale and Harmsco filters was more than 0.5 NTU during the challenge conducted at 5.0 gpm using feed water with a higher turbidity (10.0 NTU). However, the Nanoceram filter which was only tested during this challenge, produced effluent with turbidity less than 0.5 NTU. The UF filter produced effluent with 0.15 NTU during the turbidity challenge tests conducted at 5.0 gpm using feed water with a turbidity of 4.9 NTU and 4 mg/L alum as chemical coagulant.

Neither the R3f filter nor the multimedia filter showed any appreciable removal of TOC or DOC with or without the use of alum. The polishing filters (Rosedale, Nanoceram, Harmsco, and UF filter) also did not show any appreciable removal of TOC or DOC. TOC and DOC may be of importance in surface water systems that use chlorine disinfection because of their propensity to form regulated disinfection byproducts (DBPs).

Challenge testing on the R3f system using 3.0 µm PSL beads as a non-biological surrogate for *Cryptosporidium* showed an average log removal in three challenges of 3.40 which satisfies the 2.0-log removal requirement in the LT1ESWTR. The Rosedale PS 740 bag filter as a polishing filter completely removed any remaining PSL beads in the R3f system effluent. Based on the influent PSL beads concentration, the average log removal by the Rosedale bag filter was 5.65, which satisfies the 5.5 log removal standard in the LT2ESWTR for source waters in Bin 4. The UF unit tested as the final polishing filter also showed complete removal of PSL beads and the average log removal based on influent PSL beads concentration was 5.51, which also satisfied the 5.5 log removal criteria under LT2ESWTR for Bin 4 systems. The Nanoceram filter demonstrated poor removal of PSL beads which was attributed to poor seal between the cartridge and the housing which could not be repaired despite several attempts.

One test with *Cryptosporidium* oocysts was performed on the R3f system to validate the representativeness of PSL beads as a surrogate. The test showed a log removal of 3.47 which is slightly more conservative than the average log removal value of 3.40 achieved using PSL beads. The Rosedale PS 740 bag filter used as the final polishing filter again completely removed all remaining oocysts from the effluent of the R3f system.

Two PSL bead challenges were conducted to differentiate the performance of the lead and lag R3f filters. The lead filter showed an average log removal of 3.17 while the lag filter showed a log removal of 0.74 (which reflects the low inlet beads concentration following the high removal in the lead filter). These results indicate that a single R3f filter is capable of satisfying the 2.0-log *Cryptosporidium* LT1ESWTR criteria.

The multimedia filter did not perform adequately in removing 3.0 µm PSL beads without chemical coagulants. The average log removal achieved in three challenges was 0.20. The multimedia filter was not tested with *Cryptosporidium* oocysts.

Neither the R3f system nor the multimedia system was very effective in removing HPC, achieving approximately 75% removal. This suggested that both systems would not be very effective in removing bacteria and this was confirmed by tests conducted using *B. subtilis* spores and *E. coli*. The R3f system showed an average log removal value of 0.44 from three *B. subtilis* challenges conducted using the membrane sampling technique and 0.72 from four challenges conducted using the grab sampling method. At these low removal values, there is little difference between the two sampling methods. The Rosedale PS 720 bag filter used as the final polishing filter contributed an additional 2.03 log removal of the remaining *B. subtilis*. The UF filter did not perform adequately during the two initial challenges and the unit was found to be damaged, probably due to excessive pressure development during turbidity challenges. However, the same damaged UF unit had continued to produce low turbidity effluent water during the turbidity challenge tests. This highlights the importance of biological challenge tests to evaluate the integrity of filtration treatment systems. Two additional tests were performed after a new UF unit was installed and the results showed an average log removal of 3.5 for *B. subtilis*. *B. subtilis* challenge tests were not conducted on the Nanoceram and Harmsco bag filters.

The multimedia filter achieved a log removal value of only 0.12 in two *B. subtilis* challenges

The R3f system achieved a log removal range of 0.65 to 1.36 for *E. coli* while the multimedia filter demonstrated 0.42 to 0.52 log removal of *E. coli*. The Rosedale bag filter contributed an additional 0.78 to 0.90 log removal of *E. coli*. The results of a single test conducted on the Nanoceram filter demonstrated an additional 2.10 log removal of *E. coli*. The UF filter contributed an additional log removal of 4.05 to 4.40 for *E. coli*.

The R3f system achieved negligible removal of MS2 bacteriophage. The performance of the UF unit was also very poor in removing MS2 bacteriophage (with a best performance of 1.23 log removal). The UV unit showed an average log inactivation value of 2.2 from three challenge tests.

Backwash volumes for the R3f filter ranged from 75 gallons or 1.7% of the total production for the 5 NTU test to 75 gallons or 3.7% of the total production for the 10 NTU test during the turbidity challenges conducted without chemical coagulant. In both cases, the pressure drop across the lag filter was low and did not require backwashing. This indicates that the backwash

volumes required may be even lower since only the lead filter may require backwashing frequently, with the lag filter requiring only infrequent backwashing. It was later observed that a single backwashing cycle was not enough for the proper cleaning of the system as evidenced by the rapid buildup of pressure with continued operation.

The multimedia filter showed a headloss of only 0.2 psi and did not require backwashing. This is reflective of lower solids buildup due to the poor removal performance of the unit.

Backwash volumes for the R3f filter increased to 150 gallons or 15 - 26% of the total production for the 5 NTU tests during the turbidity challenges conducted with 4 mg/L alum as a chemical coagulant. Thus, the improved effluent turbidity due to the addition of the coagulant was compromised by quicker development of headloss and higher backwash volumes when compared to the tests conducted without the coagulant. The multimedia filter did not develop any pressure loss, and thus did not require backwashing during turbidity challenges conducted with 4 mg/L alum as the chemical coagulant.

SDI15 test results had to be estimated due to early blockage of the 0.45 μm membrane in the SDI test apparatus. The SDI10 values after 10 minutes for influent, effluent from the lead filter and effluent from the lag filter were 8.63, 8.15, and 8.13, respectively. The estimated SDI15 values calculated from these SDI10 values are 5.75, 5.43, and 5.41, respectively.

5.0 References

EPA. “The Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) Implementation Guidance,” EPA 816-R-04-008., 2004.

EPA. “The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) Implementation Guidance,” EPA 816-F-06-005., 2006.

Shaw. “Quality Assurance Project Plan for Glass Bead R3f and Multimedia Systems,” EPA QA ID: 627-Q-10-0, 2007.

Shaw. “Quality Assurance Project Plan Addendum for Glass Bead R3f and Multimedia Systems,” EPA QA ID: 627-Q-10-1, 2009

Appendix A
Raw Data for Different Parameters During Turbidity Challenges

Date: 11/08/07

Test ID: Turbidity Challenge 1

Filter Configuration: Glass bead (140-230 μm) + Glass bead (70-100 μm)

Target flow: 10 gpm

Target feed water turbidity: 10 NTU

Table A1: Turbidity Results during Challenge 1

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effluent 1	Effluent 2	Blank	
11/08/05; 10:58	6.80	3.81	2.09	0.13	69.3
11/08/05; 12:45	7.27	2.15	1.30	-	82.1
11/08/05; 14:05	7.0	1.50	1.15	0.14	83.6

Table A2: Particle Count (2 – 5 μm) Results during Turbidity Challenge 1

Date & Time	Particle Counts (2 – 5 μm)/ mL			Overall % Removal
	Influent	Effluent 1	Effluent 2	
11/08/05; 10:58	> 20,000	> 20,000	6700	66.5
11/08/05; 12:45	> 20,000	> 20,000	4211	78.9
11/08/05; 14:05	> 20,000	> 20,000	3400	83.0

Table A3: Operational Parameters during Turbidity Challenge 1

Date & Time	Pressure (psi)					Flow (gpm)	Totalizer (gallons)	Flow (gallons)
	In	Out 1	Out 2	ΔP1	ΔP2			
11/08/07; 09:50	76	72	64	4	8	10	16538	0
11/08/07; 10:58	76	67	58	9	8	10	17205	667
11/08/07; 11:33	76	65	58	11	7	10	17579	374
11/08/07; 11:41 ^a	42	27	18	15	9	10.2	17671	92
11/08/07; 12:45	44	25	18	19	7	10.0	18250	579
11/08/07; 13:07 ^b	43	32	30	11	2	5.5	18460	210
11/08/07; 14:05	44	32	29	12	3	5.2	18761	301
							Total	2223

^aOperational pressure reset

^bFlow rate reset

Date: 11/21/07

Test ID: Turbidity Challenge 2

Filter Configuration: Glass bead (140-230 μm) + Glass bead (70-100 μm)

Target flow: 10 gpm

Target feed water turbidity: 10 NTU

Table A4: Turbidity Results during Challenge 2

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effluent 1	Effluent 2	Blank	
11/21/07; 11:50	14.0	7.3	2.1	0.14	85.0
11/21/07; 12:50	11.0	6.50	1.90	-	82.7
11/21/07; 13:50	10.5	6.90	1.60	0.14	84.7

Table A5: Operational Parameters during Turbidity Challenge 2

Date & Time	Pressure (psi)					Flow (gpm)	Totalizer (gallons)	Flow (gallons)
	In	Out 1	Out 2	ΔP1	ΔP2			
11/21/07; 11:50	50	40	23	10	17	10.2	23330	0
11/21/07; 12:50	56	39	19	17	20	10.0	23881	551
11/21/07; 14:00	90	69	6	20.5	63	4.0	24520	639
11/21/07; 14:00	Backwashed the system using approximately 60 gallon of clean water							
11/21/07; 14:15	47	38	11	9	27	12.0	24638	118
							Total	1308

Date: 11/29/07

Test ID: Turbidity Challenge 3

Filter Configuration: Glass bead (120-200 μm) + Garnet (33 μm)

Target flow: 10 gpm

Target feed water turbidity: 10 NTU

Table A6: Turbidity Results during Challenge 3

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effluent 1	Effluent 2	Blank	
11/29/07; 11:10	10.00	5.00	1.90	0.14	81.0
11/29/07; 12:10	9.50	4.80	1.80	-	81.0
11/29/07; 13:10	9.50	5.20	1.80	0.14	81.0

Table A7: Operational Parameters during Turbidity Challenge 3

Date & Time	Pressure (psi)					Flow (gpm)	Totalizer (gallons)	Flow (gallons)
	In	Out 1	Out 2	ΔP1	ΔP2			
11/29/07; 11:10	60	48	33	12	15	10.0	25807	0
11/29/07; 12:10	62	42	28	20	14	10.0	26330	523
11/29/07; 14:10	66	40	25	26	15	9.2	27003	673
							Total	1196

Date: 12/04/07

Test ID: Turbidity Challenge 4

Filter Configuration: Glass bead (120-200 μm) + Garnet (33 μm)

Target flow: 10 gpm

Target feed water turbidity: 5 NTU

Table A8: Turbidity Results during Challenge 4

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effluent 1	Effluent 2	Blank	
12/04/07; 12:40	4.80	3.80	2.10	0.12	56.3
12/04/07; 13:40	4.80	3.30	1.60	-	66.7
12/04/07; 14:40	4.60	3.20	1.30	0.14	71.7

Table A9: Operational Parameters during Turbidity Challenge 4

Date & Time	Pressure (psi)					Flow (gpm)	Totalizer (gallons)	Flow (gallons)
	In	Out 1	Out 2	ΔP1	ΔP2			
12/04/07; 12:40	64	51	31	13	20	10.0	30003	0
12/04/07; 13:40	64	48	30	16	18	9.0	30458	455
12/04/07; 14:40	66	48	28	18	20	9.0	31117	659
							Total	1114

Date: 12/06/07

Test ID: Turbidity Challenge 5

Filter Configuration: Glass bead (120-200 μm) + Garnet (33 μm)

Target flow: 10 gpm; 5 gpm

Target feed water turbidity: 5 NTU

Table A10: Turbidity Results for R3f System during Challenge 5

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effluent 1	Effluent 2	Blank	
12/06/07; 14:45	4.60	3.30	1.20	0.13	73.9
12/06/07; 16:45	5.00	2.50	0.9	-	82.0

Table A11: Operational Parameters for R3f System during Turbidity Challenge 5

Date & Time	Pressure (psi)					Flow (gpm)	Totalizer (gallons)	Flow (gallons)
	In	Out 1	Out 2	ΔP1	ΔP2			
12/06/07; 14:45	65	51	28	14	23	9.2	-	-
12/06/07; 16:45	64	48	36	16	12	5.0	-	-

Table A12: Turbidity Results for Multimedia System during Challenge 5

Date & Time	Turbidity (NTU)			Overall % Removal
	Influent	Effluent	Blank	
12/06/07; 14:45	4.6	2.3	0.13	50.0
12/06/07; 16:45	4.6	2.3	-	50.0

Table A13: Operational Parameters for Multimedia System during Turbidity Challenge 5

Date & Time	Pressure (psi)			Flow (gpm)
	In	Out	$\Delta P1$	
12/06/07; 14:45	0.7	0.0	0.7	3.0
12/06/07; 16:45	0.7	0.0	0.7	3.0

Date: 12/12/07

Test ID: Turbidity Challenge 6

Filter Configuration: Glass bead (70-100 μm) + Garnet (33 μm)

Target flow: 5 gpm for R3f and 3.0 gpm for Multimedia System

Target feed water turbidity: 5 NTU

Table A14: Turbidity Results for R3f System during Challenge 6

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effluent 1	Effluent 2	Blank	
12/12/07; 14:00	6.00	3.40	1.20	0.13	80.0
12/12/07; 15:00	5.00	2.40	1.20	-	76.0
12/12/07; 16:00	5.00	2.30	1.20	0.13	76.0

Table A15: Turbidity Results for Multimedia System during Challenge 6

Date & Time	Turbidity (NTU)			Overall % Removal
	Influent	Effluent	Blank	
12/12/07; 14:00	6.00	2.6	0.13	56.7
12/12/07; 15:00	5.00	2.6	-	48.0
12/12/07; 16:00	5.00	2.5	0.13	50.0

Table A16: Operational Parameters for R3f System during Turbidity Challenge 6

Date & Time	Pressure (psi)					Flow (gpm)	Totalizer (gallons)	Flow (gallons)
	In	Out 1	Out 2	$\Delta P1$	$\Delta P2$			
12/12/07; 14:00	54	44	40	10	4	5.0	-	-
12/12/07; 15:00	55	44	40	11	4	5.0	-	-
12/12/07; 16:00	57	44	40	13	4	4.9	-	-

Date: 12/21/07

Test ID: Turbidity Challenge 7

Filter Configuration: Garnet (33 μm) + Garnet (33 μm)

Target flow: 5 gpm for R3f and 3.0 gpm for Multimedia System

Target feed water turbidity: 5 NTU

Table A17: Turbidity Results for R3f System during Challenge 7

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effluent 1	Effluent 2	Blank	
12/21/07; 11:30	5.4	1.38	0.68	0.14	87.4
12/21/07; 12:30	4.0	0.80	0.58	-	80.0
12/21/07; 13:30	4.1	0.78	0.56	0.15	86.3
12/21/07; 14:30	4.0	0.82	0.60	-	85.0
12/21/07; 15:30	4.0	0.84	0.62	0.14	84.5

Table A18: Turbidity Results for Multimedia System during Challenge 7

Date & Time	Turbidity (NTU)			Overall % Removal
	Influent	Effluent	Blank	
12/21/07; 11:30	5.4	3.0	0.14	44.5
12/21/07; 12:30	4.0	1.7	-	57.5
12/21/07; 13:30	4.1	1.7	0.15	58.5
12/21/07; 14:30	4.0	1.6	-	60.0
12/21/07; 15:30	4.0	1.6	0.14	60.0

Table A19: Operational Parameters for R3f System during Turbidity Challenge 7

Date & Time	Pressure (psi)					Flow (gpm)	Totalizer (gallons)	Flow (gallons)
	In	Out 1	Out 2	$\Delta P1$	$\Delta P2$			
12/21/07; 11:30	54	42	38	12	4	5.0	657	0
12/21/07; 12:30	56	40	35	16	5	4.9	998	341
12/21/07; 13:30	63	36	32	27	4	4.4	1290	292
12/21/07; 14:30	68	32	28	36	4	4.0	1532	242
12/21/07; 15:30	74	26	22	48	4	3.9	1785	253
							Total	1128

Table A20: Operational Parameters for Multimedia System during Turbidity Challenge 7

Date & Time	Pressure (psi)			Flow (gpm)
	In	Out	$\Delta P1$	
12/21/07; 11:30	0.7	0.0	0.7	3.0
12/21/07; 12:30	0.7	0.0	0.7	3.0
12/21/07; 13:30	0.7	0.0	0.7	3.0
12/21/07; 14:30	0.7	0.0	0.7	3.0
12/21/07; 15:30	0.8	0.0	0.8	3.0

Date: 01/22/07

Test ID: Turbidity Challenge 8

Filter Configuration: Garnet (33 µm) + Garnet (33 µm)

Target flow: 5 gpm for R3f and 3.0 gpm for Multimedia System

Target feed water turbidity: 5 NTU

Table A21: Turbidity Results for R3f System during Challenge 8

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effl. 1	Effl. 2	Blank	
01/22/08; 16:00	4.1	1.70	1.15	0.13	72.0
01/22/08; 17:00	4.3	1.70	0.94	-	78.2
01/22/08; 18:00	4.1	1.60	0.9	0.13	78.0
01/23/08; 10:00	4.0	0.90	0.76	0.14	81.0
01/23/08; 10:30	4.0	0.80	0.64	-	
01/23/08; 11:30	4.0	0.77	0.60	0.13	85.0
01/23/08; 12:30	4.0	0.72	0.60	-	85.0
01/23/08; 13:30	4.0	0.69	0.55	0.13	86.3
01/23/08; 14:30	4.0	0.66	0.54	0.14	86.5
01/23/08; 15:30	6.0	0.65	0.53	-	91.2
01/23/08; 16:30	5.5	0.63	0.51	0.14	90.8
01/23/08; 17:30	5.7	0.61	0.50	-	91.2
01/23/08; 18:30	4.5	0.61	0.50	0.14	88.9
01/24/08; 13:00	4.3	0.6	0.5	0.14	88.4
01/24/08; 14:00	5.0	0.56	0.48	-	90.4
01/24/08; 15:00	4.9	0.58	0.48	0.14	90.2
01/24/08; 16:00	5.0	0.56	0.44	-	91.2
01/24/08; 17:00	5.0	0.6	0.44	0.14	91.2

Table A22: Turbidity Results for Multimedia System during Challenge 8

Time	Turbidity (NTU)		% Removal
	Influent	Effluent	
01/22/08; 16:00	4.10	1.60	61.0
01/22/08; 17:00	4.30	2.20	48.9
01/22/08; 18:00	4.10	2.30	43.9
01/23/08; 10:00	4.00	2.10	47.5
01/23/08; 10:30	4.00	2.00	50.0
01/23/08; 11:30	4.00	2.00	50.0
01/23/08; 12:30	4.00	2.00	50.0
01/23/08; 13:30	4.00	2.10	47.5
01/23/08; 14:30	4.00	2.00	50.0
01/23/08; 15:30	6.00	2.20	65.0
01/23/08; 16:30	5.50	2.20	60.0
01/23/08; 17:30	5.70	2.20	61.4
01/23/08; 18:30	4.50	1.85	58.9
01/24/08; 13:00	4.30	1.75	59.3
01/24/08; 14:00	5.00	1.75	65.0
01/24/08; 15:00	4.90	1.70	65.3
01/24/08; 16:00	5.00	1.60	68.0
01/24/08; 17:00	5.00	1.62	67.6

Table A23: Turbidity Results for Bag Filters during Challenge 8

Time	Turbidity (NTU)		Overall % Removal
	Influent	Effluent-Final	
Rosedale PS 740 (0.5 µm)			
01/22/08; 16:00	1.15	0.48	58.3
01/22/08; 17:00	0.94	0.48	48.9
01/22/08; 18:00	0.90	0.50	44.5
01/23/08; 10:00	0.76	0.60	21.0
01/23/08; 10:30	0.60	0.35	41.7
01/23/08; 11:30	0.60	0.40	33.3
01/23/08; 12:30	0.60	0.40	33.3
01/23/08; 13:30	0.55	0.40	27.3
01/23/08; 14:30	0.54	0.40	25.9
01/23/08; 15:30	0.53	0.40	24.5
01/23/08; 16:30	0.51	0.38	25.5
01/23/08; 17:30	0.51	0.38	25.5
01/23/08; 18:30	0.50	0.38	24.0
Harmsco (1 µm)			
01/24/08; 13:00	0.50	0.44	12.0
01/24/08; 14:00	0.48	0.38	20.8
01/24/08; 15:00	0.48	0.42	12.5
01/24/08; 16:00	0.44	0.42	4.5
01/24/08; 17:00	0.44	0.41	7.3

Table A24: Operational Parameters for the R3f System during Challenge 8

Date & Time	Pressure (Psi)					Flow (gpm)	Totalizer (gallon)	Flow (gallon)
	In	Out 1	Out 2	ΔP1	ΔP2			
01/22/08; 15:24	60	52	48	8	4	5	2482	0
01/22/08; 16:24	60	50	48	10	2	5.1	2776	294
01/22/08; 17:24	62	50	47	12	3	5.0	3080	304
01/23/08; 18:24	64	50	46	14	4	5.0	3390	310
01/23/08; 10:15	64	50	43	14	7	5.0	3587	197
01/23/08; 11:15	66	51	43	15	8	4.9	3860	273
01/23/08; 12:15	67	51	43	16	8	4.8	4161	301
01/23/08; 13:15	68	51	43	17	8	4.6	4466	305
01/23/08; 14:15	70	50	42	20	8	4.6	4732	266
01/23/08; 15:15	71	50	41	21	9	4.4	4973	241
01/23/08; 16:15	71	50	40	21	10	4.2	5230	257
01/23/08; 17:15	73	48	36	25	12	4.1	5490	260
01/23/08; 18:15	75	46	34	29	12	4.0	5740	250
01/24/08; 12:35	75	54	44	21	10	4.0	5815	75
01/24/08; 13:35	76	51	42	25	9	4.0	6060	245
01/24/08; 14:35	77	50	41	27	9	3.9	6300	240
01/24/08; 15:35	78	49	40	29	9	3.9	6526	226
01/24/08; 16:35	79	48	39	31	9	3.9	6755	229
01/24/08; 17:35	80	46	38	34	8	3.9	6990	235
							Total	4508

Table A25: Operational Parameters for the Multimedia System during Challenge 8

Time	Pressure (Psi)			Flow (gpm)
	In	Out	$\Delta P1$	
01/22/08; 15:24	1.3	0	1.3	3.0
01/22/08; 16:24	1.3	0	1.3	3.0
01/22/08; 17:24	1.3	0	1.3	3.0
01/23/08; 18:24	1.3	0	1.3	3.0
01/23/08; 10:15	1.4	0	1.4	3.0
01/23/08; 11:15	1.4	0	1.4	3.0
01/23/08; 12:15	1.4	0	1.4	3.0
01/23/08; 13:15	1.4	0	1.4	3.0
01/23/08; 14:15	1.4	0	1.4	3.0
01/23/08; 15:15	1.4	0	1.4	3.0
01/23/08; 16:15	1.4	0	1.4	3.0
01/23/08; 17:15	1.5	0	1.5	3.0
01/23/08; 18:15	1.6	0	1.6	3.0
01/24/08; 12:35	1.6	0	1.6	3.0
01/24/08; 13:35	1.6	0	1.6	3.0
01/24/08; 14:35	1.6	0	1.6	3.0
01/24/08; 15:35	1.6	0	1.6	3.0
01/24/08; 16:35	1.6	0	1.6	3.0
01/24/08; 17:35	1.6	0	1.6	3.0

Table A26: Operational Parameters for the Bag Filter during Challenge 8

Time	Pressure (Psi)				Flow (gpm)	
	In	Out-Pre	Out-Final	$\Delta P1$		$\Delta P2$
Rosedale PS 740 (0.5 μm)						
01/22/08; 15:24	6	6	0	0	6	5
01/22/08; 16:24	6	6	0	0	6	5.1
01/22/08; 17:24	6	6	0	0	6	5.0
01/23/08; 18:24	6	6	0	0	6	5.0
01/23/08; 10:15	8	8	0	0	8	5.0
01/23/08; 11:15	8	8	0	0	8	4.9
01/23/08; 12:15	8	8	0	0	8	4.8
01/23/08; 13:15	8	8	0	0	8	4.6
01/23/08; 14:15	8	8	0	0	8	4.6
01/23/08; 15:15	8	8	0	0	8	4.4
01/23/08; 16:15	8	8	0	0	8	4.2
01/23/08; 17:15	8	8	0	0	8	4.1
01/23/08; 18:15	8	8	0	0	8	4.0
Harmsco (1μm)						
01/24/08; 12:35	0	0	0	0	0	4.0
01/24/08; 13:35	0	0	0	0	0	4.0
01/24/08; 14:35	0	0	0	0	0	3.9
01/24/08; 15:35	0	0	0	0	0	3.9
01/24/08; 16:35	0	0	0	0	0	3.9
01/24/08; 17:35	0	0	0	0	0	3.9

Table A27: TOC/DOC Results for the R3f System during Challenge 8

Time	Concentration (mg/L)			% Removal		
	Influent	Effl. 1	Effl. 2	Filter 1	Filter 2	Overall
Total Organic Carbon (TOC)						
01/23/08; 12:00	4.39	4.36	4.33	0.7	0.7	1.4
01/23/08; 13:00	4.45	4.33	4.33	2.7	0	2.7
Dissolved Organic Carbon (DOC)						
01/23/08; 12:00	4.48	4.32	4.34	3.5	0	3.5
01/23/08; 13:00	4.45	4.25	4.21	4.5	0.9	5.4

Table A28: TOC/DOC Results for the Multimedia System during Challenge 8

Time	Concentration (mg/L)		% Removal
	Influent	Effluent	
Total Organic Carbon (TOC)			
01/23/08; 12:00	4.39	4.33	1.4
01/23/08; 13:00	4.45	4.30	3.4
Dissolved Organic Carbon (DOC)			
01/23/08; 12:00	4.48	4.38	2.3
01/23/08; 13:00	4.45	4.25	4.5

Table A29: TOC/DOC Results for Bag Filters during Challenge 8

Time	Concentration (mg/L)			Overall % Removal
	Influent	Effluent-pre	Effluent-Final	
Total Organic Carbon (TOC)				
01/23/08; 12:00	4.33		4.32	0.2
01/23/08; 13:00	4.33		4.27	1.4
Dissolved Organic Carbon (DOC)				
01/23/08; 12:00	4.34		4.31	0.7
01/23/08; 13:00	4.21		4.27	0

Table A30: HPC Results for R3f System during Challenge 8

Time	HPC/mL			% Removal		
	Influent	Effluent 1	Effluent 2	Filter 1	Filter 2	Overall
01/23/08; 12:00	1.0×10^5	1.0×10^5	$>7.4 \times 10^4$	-	-	0
01/23/08; 13:00	4.9×10^4	5.6×10^4	4.8×10^4	-	-	2%

Table A31: HPC Results for Multimedia System during Challenge 8

Time	HPC/mL		% Removal
	Influent	Effluent	
01/23/08; 12:00	1.0×10^5	1.7×10^5	0
01/23/08; 13:00	4.9×10^4	8.8×10^4	0

Table A32: HPC Results for Bag Filters during Challenge 8

Time	HPC/mL		% Removal
	Influent	Effluent	
01/23/08; 12:00	$>7.4 \times 10^4$	$>7.4 \times 10^4$	0
01/23/08; 13:00	4.8×10^4	5.1×10^4	0

Table A33: Particle Counts (2-5 µm) Results for R3f System during Challenge 8

Time	Particle Counts/ mL			% Removal		
	Influent	Effl. 1	Effl. 2	Filter 1	Filter 2	Overall
01/23/08; 14:00	> 20000	960	750	>95.2	21.9	>96.3
01/23/08; 15:30	> 20000	1440	1100	>92.8	23.6	>94.5

Table A34: SDI10 Results for R3f System during Challenge 8

Time	Silt Density Index 10 (SDI 10)				
	Influent	Effluent 1	Effluent 2	Δ SDI 1	Δ SDI 2
01/25/08; 15:00	8.63	8.15	8.13	0.48	0.02

Date: 01/29/07

Test ID: Turbidity Challenge 9

Filter Configuration: Garnet (33 µm) + Garnet (33 µm)

Target flow: 5 gpm for R3f and 3.0 gpm for Multimedia System

Target feed water turbidity: 10.0 NTU

Table A35: Turbidity Results for R3f System during Challenge 9

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effl. 1	Effl. 2	Blank	
01/29/08; 14:14	9.00	1.20	0.90	0.14	90.0
01/29/08; 15:14	9.10	1.30	1.00	-	89.0
01/29/08; 16:14	9.90	1.20	0.95	0.14	90.4
01/29/08; 17:14	9.40	1.10	0.90	-	90.4
01/29/08; 18:14	9.60	1.10	0.86	0.14	91.0
01/30/08; 13:45	10.80	1.10	0.9	0.13	91.7
01/30/08; 14:45	9.80	1.10	0.9	-	90.8
01/30/08; 15:45	9.60	1.10	0.9	0.14	90.6
Conducted Backwashing					
01/31/08; 14:45	6.50	0.80	0.57	0.14	91.3
01/31/08; 15:45	6.50	0.75	0.57	-	91.3
01/31/08; 16:45	6.30	0.70	0.57	0.14	91.0
01/31/08; 17:30	6.30	0.70	0.57	-	91.0

Table A36: Turbidity Results for the Multimedia System during Challenge 9

Time	Turbidity (NTU)		% Removal
	Influent	Effluent	
01/29/08; 14:14	9.00	3.0	66.7
01/29/08; 15:14	9.10	3.1	66.0
01/29/08; 16:14	9.90	3.2	67.7
01/29/08; 17:14	9.40	3.1	67.0
01/29/08; 18:14	9.60	3.3	65.6
01/30/08; 13:45	10.80	2.7	75.0
01/30/08; 14:45	9.80	2.3	76.5
01/30/08; 15:45	9.60	2.1	78.2
Test Continued with Lower Feed Water Turbidity			
01/31/08; 14:45	6.50	1.4	78.5
01/31/08; 15:45	6.50	1.2	81.5
01/31/08; 16:45	6.30	1.2	81.0
01/31/08; 17:30	6.30	1.2	81.0

Table A37: Turbidity Results for the Bag Filters during Challenge 9

Time	Turbidity (NTU)		Overall % Removal
	Influent	Effluent	
Rosedale PS 740 (0.5 µm)			
01/29/08; 14:14	0.90	0.48	46.7
01/29/08; 15:14	1.00	0.60	40.0
01/29/08; 16:14	0.95	0.60	36.8
01/29/08; 17:14	0.90	0.60	33.3
01/29/08; 18:14	0.86	0.58	32.6
01/30/08; 13:45	0.90	0.56	37.8
01/30/08; 14:45	0.90	0.60	33.3
01/30/08; 15:45	0.90	0.62	31.1
Nanoceram			
01/31/08; 14:45	0.57	0.25	56.1
01/31/08; 15:45	0.57	0.45	21.0
01/31/08; 16:45	0.57	0.44	22.8
Harmsco (1µm)			
01/31/08; 17:30	0.57	0.55	3.50

Table A38: Operational Parameters for R3f System during Challenge 9

Date & Time	Pressure (Psi)					Flow (gpm)	Totalizer (gallon)	Flow (gallon)
	IN	Out 1	Out 2	ΔP1	ΔP2			
01/29/08; 14:00	56	42	38	14	4	5.0	7775	0
01/29/08; 15:00	58	42	38	16	4	5.0	8080	305
01/29/08; 16:00	60	40	36	20	4	4.8	8364	284
01/29/08; 17:00	64	39	34	25	5	4.6	8639	275
01/29/08; 18:00	68	36	31	32	5	4.2	8900	261
01/30/08; 13:40	72	46	42	26	4	4.8	9126	226
01/30/08; 14:40	76	44	39	32	5	4.4	9395	269
01/30/08; 15:40	77	40	35	37	5	4.1	9650	255
01/30/08; 16:15	78	36	32	42	4	3.9	9790	140
Conducted Backwashing								
01/31/08; 14:25	52	38	32	14	6	5.0	10036	246
01/31/08; 15:30	55	36	31	19	5	4.8	10390	354
01/31/08; 16:30	58	34	30	24	4	4.5	10666	276
01/31/08; 17:30	60	34	29	26	5	4.4	10890	224
							Total	3115

Table A39: Operational Parameters for Multimedia System during Challenge 9

Time	Pressure (Psi)			Flow (gpm)
	In	Out	Δ P1	
01/29/08; 14:00	1.2	0	1.2	3.0
01/29/08; 15:00	1.4	0	1.4	3.0
01/29/08; 16:00	1.5	0	1.5	3.0
01/29/08; 17:00	1.5	0	1.5	3.0
01/29/08; 18:00	1.6	0	1.6	3.0
01/30/08; 13:40	1.5	0	1.5	3.0
01/30/08; 14:40	1.5	0	1.5	3.0
01/30/08; 15:40	1.6	0	1.6	3.0
01/30/08; 16:15	1.6	0	1.6	3.0
Test Continued with Lower Feed Water Turbidity				
01/31/08; 14:25	1.4	0	1.4	3.0
01/31/08; 15:30	1.4	0	1.4	3.0
01/31/08; 16:30	1.6	0	1.6	3.0
01/31/08; 17:30	1.6	0	1.6	3.0

Table A40: Operational Parameters for Bag Filters during Challenge 9

Time	Pressure (Psi)					Flow (gpm)
	In	Out-Pre	Out-Final	Δ P1	Δ P2	
Rosedale PS 740 (0.5 μm)						
01/29/08; 14:00	7	7	0	0	7	5.0
01/29/08; 15:00	8	8	0	0	8	5.0
01/29/08; 16:00	8	8	0	0	8	4.8
01/29/08; 17:00	8	8	0	0	8	4.6
01/29/08; 18:00	9	9	0	0	9	4.2
01/30/08; 13:40	10	10	0	0	10	4.8
01/30/08; 14:40	10	10	0	0	10	4.4
01/30/08; 15:40	11	11	0	0	11	4.1
01/30/08; 16:15	11	11	0	0	11	3.9
Nanoceram						
01/31/08; 14:45	0	0	0	0	0	5.0
01/31/08; 15:45	0	0	0	0	0	4.8
01/31/08; 16:45	0	0	0	0	0	4.5
Harmsco (1μm)						
01/31/08; 17:30	0	0	0	0	0	4.4

Table A41: TOC/DOC Results for R3f System during Challenge 9

Time	Concentration (mg/L)			% Removal		
	Influent	Effl. 1	Effl. 2	Filter 1	Filter 2	Overall
Total Organic Carbon (TOC)						
01/30/08; 14:00	2.37	2.41	2.45	0	0	0
01/31/08; 16:30	2.44	2.35	2.32	3.70	1.3	4.9
Dissolved Organic Carbon (DOC)						
01/30/08; 14:00	2.50	2.21	2.29	11.6	0	8.4
01/31/08; 16:30	2.23	2.24	2.22	0	0.5	0.5

Table A42: TOC/DOC Results for Multimedia System during Challenge 9

Time	Concentration (mg/L)		% Removal
	Influent	Effluent	
Total Organic Carbon (TOC)			
01/30/08; 14:00	2.37	2.52	0
01/31/08; 16:30	2.44	2.37	2.9
Dissolved Organic Carbon (DOC)			
01/30/08; 14:00	2.50	2.31	7.6
01/31/08; 16:30	2.23	2.18	2.24

Table A43: TOC/DOC Results for Bag Filters during Challenge 9

Time	Concentration (mg/L)		% Removal
	Influent	Effluent	
Total Organic Carbon (TOC)			
01/30/08; 14:00 ^a	2.45	2.44	0.4
01/31/08; 16:30 ^b	2.32	2.26	2.6
Dissolved Organic Carbon (DOC)			
01/30/08; 14:00 ^a	2.29	2.26	1.3
01/31/08; 16:30 ^b	2.22	2.58	0

^aRosedale Filter^bNanoceram Filter

Table A44: HPC Results for R3f System during Challenge 9

Time	HPC/mL			% Removal		
	Influent	Effluent 1	Effluent 2	Filter 1	Filter 2	Overall
01/30/08; 14:00	4.0×10^5	1.2×10^5	9.0×10^4	70	25	77.5
01/31/08; 16:30	1.7×10^4	4.0×10^3	4.0×10^3	76.5	0	76.5

Table A45: HPC Results for Multimedia System during Challenge 9

Time	HPC/mL		% Removal
	Influent	Effluent	
01/30/08; 14:00	4.0×10^5	1.0×10^5	75
01/31/08; 16:30	1.7×10^4	4.0×10^3	76.5

Table A46: HPC Results for Bag Filter during Challenge 9

Time	HPC/mL		% Removal
	Influent	Effluent	
01/30/08; 14:00 ^a	9.0×10^4	6.0×10^4	33.3
01/31/08; 16:30 ^b	4.0×10^3	4.0×10^3	0

^aRosedale Filter^bNanoceram Filter**Table A47: Particle Counts (2-5 µm) Results for R3f System during Challenge 9**

Time	Particle Counts/mL			% Removal		
	Influent	Effl. 1	Effl. 2	Filter 1	Filter 2	Overall
01/31/08; 16:00	> 20000	2332	1794	>88.3	23.0	>91.0
01/31/08; 17:00	> 20000	2309	1770	>88.5	23.3	>91.2

Date: 08/19/08

Test ID: Turbidity Challenge 10

Filter Configuration: Garnet (33 µm) + Garnet (33 µm)

Target flow: 5 gpm for R3f and 3.0 gpm for Multimedia System

Target feed water turbidity: 5.0 NTU

Chemical Coagulant: 4 mg/L Alum

Table A48: Turbidity Results for R3f System during Challenge 10

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effl. 1	Effl. 2	Blank	
08/19/08; 14:20	4.68	1.26	0.44	0.20	90.6
08/19/08; 15:20	5.87	1.26	0.33	-	94.4
08/19/08; 16:20	4.91	0.25	0.18	-	96.3
08/19/08; 17:20	4.52	0.39	0.30	0.16	93.4

Table A49: Turbidity Results for the Multimedia System during Challenge 10

Time	Turbidity (NTU)		% Removal
	Influent	Effluent	
08/20/08; 12:30	3.44	0.30	91.3
08/20/08; 13:20	4.09	0.26	93.6
08/20/08; 14:20	2.80	0.45	83.9

Table A50: Turbidity Results for the UF system during Challenge 10

Time	Turbidity (NTU)		Overall % Removal
	Influent	Effluent	
08/19/08; 14:20	0.44	0.15	65.9
08/19/08; 15:20	0.33	0.16	51.5
08/19/08; 16:20	0.18	0.14	22.2
08/19/08; 17:20	0.30	0.14	53.3

Table A51: Operational Parameters for R3f System during Challenge 10

Date & Time	Pressure (Psi)					Flow (gpm)	Totalizer (gallon)	Flow (gallon)
	In	Out 1	Out 2	$\Delta P1$	$\Delta P2$			
08/19/08; 13:55	64	52	46	12	6	4.7	25864	0
08/19/08; 15:20	72	57	46	15	11	3.5	26156	292
08/19/08; 16:20	78	40	40	38	2	3.3	26346	190
08/19/08; 17:20	94	40	40	54	0	4.0	26616	270
							Total	752

Table A52: Operational Parameters for Multimedia System during Challenge 10

Time	Pressure (Psi)			Flow (gpm)
	In	Out	$\Delta P1$	
08/20/08; 12:00	6.9	5.0	1.9	3.0
08/20/08; 12:30	6.9	5.0	1.9	3.0
08/20/08; 13:20	6.6	5.0	1.6	3.0
08/20/08; 14:20	5.9	5.0	0.9	3.0

Table A53: Operational Parameters for UF system during Challenge 10

Time	Pressure (Psi)			Flow (gpm)
	In	Out	ΔP	
08/19/08; 13:55	42	0	42	4.7
08/19/08; 15:20	42	0	42	3.5
08/19/08; 16:20	36	0	36	3.3
08/19/08; 17:20	36	0	36	4.0

Table A54: Particle Counts (2-5 μm) Results for R3f System during Challenge 10

Time	Particle Counts/mL			% Removal		
	Influent	Effl. 1	Effl. 2	Filter 1	Filter 2	Overall
08/19/08; 16:20	> 20000	1060	450	> 94.7	57.5	>97.8
08/19/08; 17:20	> 20000	940	440	> 95.3	53.2	>97.8

Date: 08/27/08

Test ID: Turbidity Challenge 11

Filter Configuration: Garnet (33 µm) + Garnet (33 µm)

Target flow: 5 gpm for R3f and 3.0 gpm for Multimedia System

Target feed water turbidity: 5.0 NTU

Chemical Coagulant: 4 mg/L Alum

Table A55: Turbidity Results for R3f System during Challenge 11

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effl. 1	Effl. 2	Blank	
08/27/08; 12:30	5.43	0.25	0.20	0.20	96.3
08/27/08; 13:15	5.98	0.22	0.19	-	96.8
08/27/08; 14:15	5.53	0.28	0.24	0.18	95.7
08/27/08; 14:50	5.42	0.18	0.18	-	96.7

Table A55: Turbidity Results for the Multimedia System during Challenge 11

Time	Turbidity (NTU)		% Removal
	Influent	Effluent	
08/27/08; 15:00	5.45	0.30	94.5
08/27/08; 16:00	5.41	0.26	95.2
08/27/08; 17:00	5.31	0.29	94.5
08/27/08; 18:00	6.40	0.30	95.3

Table A56: Turbidity Results for the UF system during Challenge 11

Time	Turbidity (NTU)		Overall % Removal
	Influent	Effluent	
08/27/08; 12:30	0.20	0.15	25.0
08/27/08; 13:15	0.19	0.18	5.3
08/27/08; 14:15	0.24	0.16	33.3
08/27/08; 14:50	0.18	0.17	5.6

Table A57: Operational Parameters for R3f System during Challenge 11

Date & Time	Pressure (Psi)					Flow (gpm)	Totalizer (gallon)	Flow (gallon)
	In	Out 1	Out 2	ΔP1	ΔP2			
08/27/08; 12:15	70	60	56	10	4	4.6	27376	0
08/27/08; 13:15	74	56	52	18	4	3.8	27597	221
08/27/08; 14:15	79	38	35	41	3	2.9	27805	208
08/27/08; 15:15	96	28	28	68	0	2.4	27948	143
							Total	572

Table A58: Operational Parameters for Multimedia System during Challenge 11

Time	Pressure (Psi)			Flow (gpm)
	In	Out	Δ P	
08/27/08; 15:00	6.2	5.0	1.2	3.0
08/27/08; 16:00	4.3	2.0	2.3	3.0
08/27/08; 17:00	8.6	7.0	1.6	3.0
08/27/08; 18:00	7.3	5.0	2.3	3.0

Table A59: HPC Results for R3f System during Challenge 11

Time	HPC/mL			% Removal		
	Influent	Effluent 1	Effluent 2	Filter 1	Filter 2	Overall
08/27/08; 14:15	1.9×10^5	5.7×10^4	2.6×10^4	70.0	54.4	86.3

Table A60: HPC Results for Multimedia System during Challenge 11

Time	HPC/mL		% Removal
	Influent	Effluent	
09/11/08; 16:20	1.41×10^5	2.2×10^4	84.4

Table A61: HPC Results for UF filter during Challenge 11

Time	HPC/mL		% Removal
	Influent	Effluent	
08/27/08; 14:15	2.6×10^4	2.1×10^3	91.9

Table A62: Particle Counts (2-5 µm) Results for R3f System during Challenge 11

Time	Particle Counts/mL			% Removal		
	Influent	Effl. 1	Effl. 2	Filter 1	Filter 2	Overall
08/27/08; 14:15	> 20000	840	520	>95.8	38.1	>97.4
08/27/08; 15:15	> 20000	800	450	>96.0	43.8	>97.8

Date: 09/11/08

Test ID: Turbidity Challenge 12

Filter Configuration: Garnet (33 µm) + Garnet (33 µm)

Target flow: 5 gpm for R3f and 3.0 gpm for Multimedia System

Target feed water turbidity: 5.0 NTU

Chemical Coagulant: 4 mg/L Alum

Table A63: Turbidity Results for R3f System during Challenge 12

Date & Time	Turbidity (NTU)				Overall % Removal
	Influent	Effl. 1	Effl. 2	Blank	
09/11/08; 13:45	4.80	0.24	0.21	0.16	95.6
09/11/08; 14:45	4.50	0.26	0.21		95.3
09/11/08; 15:45	4.0	0.26	0.20	0.16	95.0
09/11/08; 16:45	3.9	0.27	0.21		94.6
09/11/08; 16:45	3.9	0.33	0.28	0.16	94.6

Table A64: Turbidity Results for the Multimedia System during Challenge 12

Time	Turbidity (NTU)		% Removal
	Influent	Effluent	
09/11/08; 14:45	6.1	0.53	91.3
09/11/08; 15:45	6.0	0.35	94.2
09/11/08; 16:45	6.6	0.40	93.9
09/11/08; 17:45	6.6	0.40	93.9

Table A65: Turbidity Results for the UF system during Challenge 12

Time	Turbidity (NTU)		Overall % Removal
	Influent	Effluent	
09/11/08; 13:45	0.21	0.16	23.8
09/11/08; 14:45	0.21	0.17	19.0
09/11/08; 15:45	0.20	0.15	25.0
09/11/08; 16:45	0.21	0.17	19.0
09/11/08; 16:45	0.28	0.17	39.3

Table A66: Operational Parameters for R3f System during Challenge 12

Date & Time	Pressure (Psi)					Flow (gpm)	Totalizer (gallon)	Flow (gallon)
	In	Out 1	Out 2	ΔP1	ΔP2			
09/11/08; 13:30	60	50	45	10	5	5.2	28226	0
09/11/08; 14:30	72	57	52	15	5	4.6	28535	309
09/11/08; 15:30	75	58	58	17	0	4.0	28792	257
09/11/08; 16:30	84	63	62	21	1	3.8	29044	252
09/11/08; 17:45	90	62	62	28	0	3.4	29222	178
							Total	996

Table A67: Operational Parameters for Multimedia System during Challenge 12

Time	Pressure (Psi)			Flow (gpm)
	In	Out	Δ P	
09/11/08; 14:15	6.6	5.5	1.1	3.0
09/11/08; 15:45	9.1	7.0	2.1	3.0
09/11/08; 16:45	8.1	6.0	2.1	3.0
08/27/08; 17:45	8.0	6.0	2.0	3.0

Table A68: Operational Parameters for UF system during Challenge 12

Time	Pressure (Psi)			Flow (gpm)
	In	Out	Δ P	
09/11/08; 13:30	40	0	40	5.2
09/11/08; 14:30	50	0	50	4.6
09/11/08; 15:30	56	0	56	4.0
09/11/08; 16:30	62	0	62	3.8
09/11/08; 17:45	62	0	62	3.4

Table A69: HPC Results for R3f System during Challenge 12

Time	HPC/mL			% Removal		
	Influent	Effluent 1	Effluent 2	Filter 1	Filter 2	Overall
09/11/08; 16:20	9.9×10^4	7.7×10^4	5.1×10^4	22.2	33.8	48.5

Table A70: HPC Results for Multimedia System during Challenge 12

Time	HPC/mL		% Removal
	Influent	Effluent	
09/11/08; 16:20	3.0×10^4	2.1×10^4	30.0

Table A71: HPC Results for UF filter during Challenge 12

Time	HPC/mL		% Removal
	Influent	Effluent	
08/19/08; 16:20	5.1×10^4	5.7×10^3	88.9

Table A72: TOC/DOC Results for R3f System during Challenge 12

Time	Concentration (mg/L)			% Removal		
	Influent	Effl. 1	Effl. 2	Filter 1	Filter 2	Overall
Total Organic Carbon (TOC)						
09/11/08; 16:20	1.38	1.33	1.33	3.6	0	3.6
Dissolved Organic Carbon (DOC)						
09/11/08; 16:20	1.46	1.31	1.32	10.3	0	9.6

Table A73: TOC/DOC Results for Multimedia System during Challenge 12

Time	Concentration (mg/L)		% Removal
	Influent	Effluent	
Total Organic Carbon (TOC)			
09/11/08; 16:20	1.30	1.44	0
Dissolved Organic Carbon (DOC)			
09/11/08; 16:20	1.34	1.29	3.7

Table A74: TOC/DOC Results for Bag Filters during Challenge 12

Time	Concentration (mg/L)		% Removal
	Influent	Effluent	
Total Organic Carbon (TOC)			
09/11/08; 16:20	1.33	1.28	3.6
Dissolved Organic Carbon (DOC)			
09/11/08; 16:20	1.32	1.31	0.80