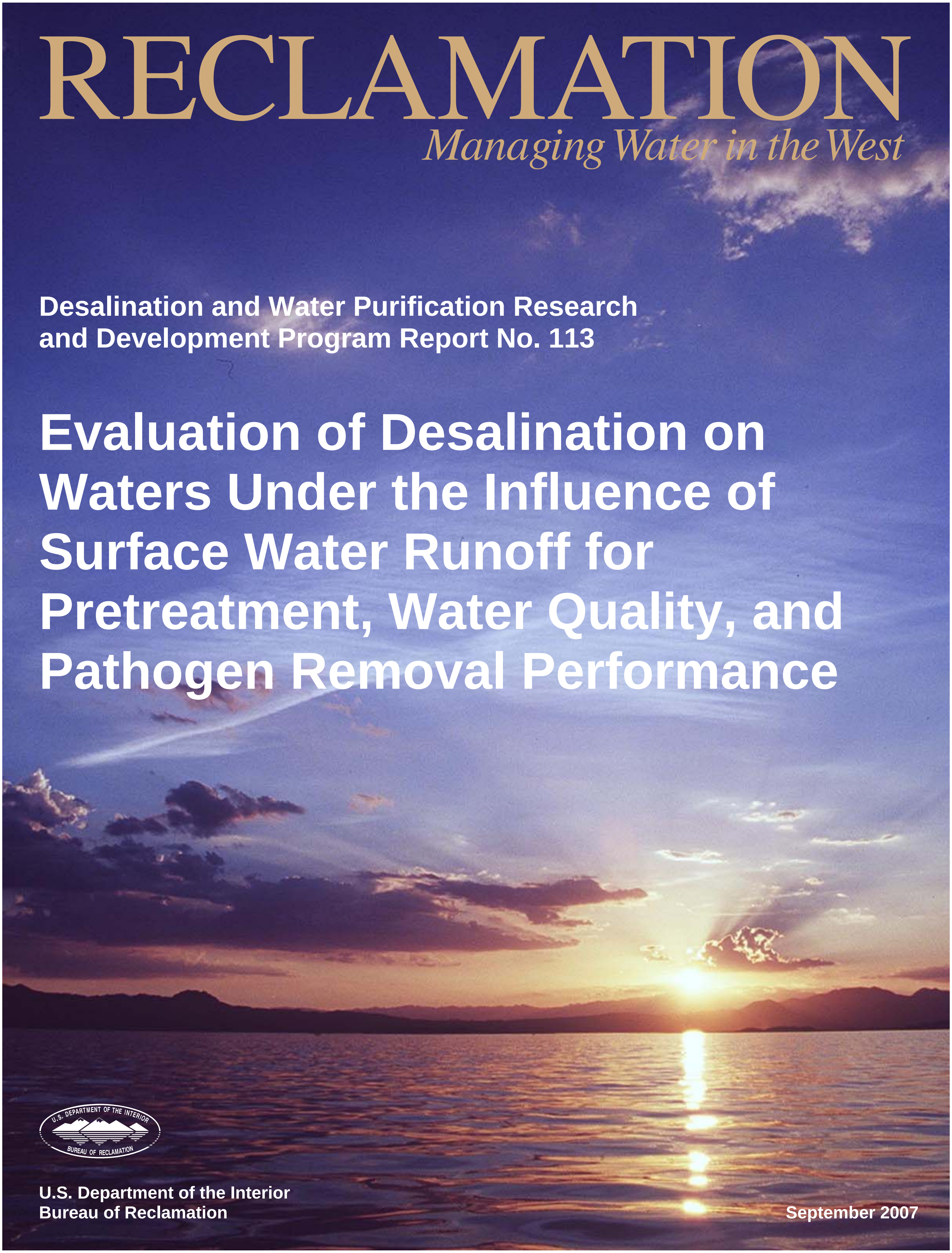

RECLAMATION
Managing Water in the West

Desalination and Water Purification Research and Development Program Report No. 113

Evaluation of Desalination on Waters Under the Influence of Surface Water Runoff for Pretreatment, Water Quality, and Pathogen Removal Performance

U.S. Department of the Interior
Bureau of Reclamation

September 2007

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Final report presents the desktop assessment and pilot scale studies for the purpose of evaluating water quality and pretreatment conditions for seawater reverse osmosis (SWRO) using seawaters under the influence (SWUI) of freshwater runoff. One of the objectives was to evaluate and compare the performances of a SWRO system when using two different pretreatment systems at pilot scale: conventional multi-media filtration (MMF) and ultrafiltration (UF). The pilot study demonstrated that UF pretreatment led to better performances of the SWRO than the MMF pretreatment. The second objective was to evaluate the pathogen rejections of each treatment process (SWRO, MMF and UF processes) and ensure that the processes would meet pathogen related regulations. This objective was performed spiking pathogen surrogates to the pilot plants and the results showed that the process trains MMF-SWRO and UF-SWRO met and exceeded the pathogen related regulations. The last objective was to identify, evaluate, and compare at desktop level the available treatment options (e.g., second pass, ion exchange, or others) for removal of Low Molecular Weight Contaminants to achieve standards set by the Safe Drinking Water Act, World Health Organization, and goals commonly set by the municipal utilities.

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Prepared for Reclamation Under Agreement No. 01-FC-81-0829

by

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Technical Service Center
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Denver, Colorado

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The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

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Abbreviations and Acronyms

ASTM	American Society for Testing and Materials
AWWARF	American Water Works Association Research Foundation
$B(OH)_3$	borate
BV	bed volume
°C	degrees Celsius
Ca	calcium
$CaCO_3$	calcium carbonate
CEB	chemically enhanced backwash
CCL	Candidate Contaminant List
Cl	chloride
cm	centimeter
DO	dissolved oxygen
DOC	dissolved organic carbon
EPA	United States Environmental Protection Agency
FP&L Cape Canaveral	Florida Power and Light Cape Canaveral Power Station
Fe	iron
ft^2	square feet
gfd	gallons per square foot per day
gpm	gallons per minute
gpm/ft^2	gallons per minute per square foot
H_3BO_3	boric acid
HCl	hydrochloric acid
HPC	Heterotrophic Plate Count
hr	hour
IESWTR	Interim Enhanced Surface Water Treatment Rule
LT2SWTR	Long Term 2 Surface Water Treatment Rule
LPRO	low-pressure reverse osmosis
MF	microfiltration
MGD	million gallons per day
mm	millimeter
mg/L	milligrams per liter
mL/min	milliliter per minute
MMF	multimedia filtration
MTC	mass transfer coefficients

Abbreviations and Acronyms (continued)

N	nitrogen
NDP	Net Driving Pressure
NF	nanofiltration
NTU	nephelometric turbidity unit
NWRI	National Water Research Institute
O&M	operation and maintenance
PBS	phosphate buffer solution
PE Anclote River	Progress Energy Anclote River Power Station
pfu	plaque forming units
psi	pounds per square inch
PV	pressure vessel
Reclamation	Bureau of Reclamation
REI	Reiss Environmental, Inc.
RO	reverse osmosis
SDI	silt density index
SDWA	Safe Drinking Water Act
SWRO	seawater reverse osmosis
SWTR	Surface Water Treatment Rule
SWUI	seawaters under the influence
SU	standard unit
TCR	Total Coliform Rule
TDS	total dissolved solids
TOC	total organic carbon
UF	ultrafiltration
WQS	water quality specifications
WHO	World Health Organization
Workshop	2001 Desalination Research and Development Workshop
>	greater than
/1,000 gal	per 1,000 gallons
/gal/day	per gallon per day
%	percent
µg/L	micrograms per liter
µm	micrometers
µS/cm	microsiemens per centimeter

1. Executive Summary

Using reverse osmosis (RO) for demineralization of seawater has been practiced world wide for decades, with a limited number of potable water applications within the United States. While costs have always been key in the development of seawater treatment facilities, many applications were in areas of the world with no other potable water alternative. As a result, costs were absorbed based on the absence of other alternatives. However, at this time in the United States, seawater reverse osmosis facilities are being evaluated with an extremely critical eye toward optimizing science and technology to minimize cost and comply with increasingly stringent finished water regulatory requirements. Therefore, optimization of cost and design considerations for seawater demineralization facilities is of critical importance now and into the future. Issues that have not been fully explored but are being addressed through this project are presented in the following subsections with the associated significant results.

1.1 Topic 1 – Evaluation of Seawater RO Pretreatment Alternatives

Research to date on pretreatment alternatives for seawater sources under the influence of freshwater runoff has been lacking due to one or both of two factors: using an open ocean intake and/or assessing the pretreatment systems without using a seawater reverse osmosis (SWRO) system to evaluate the specific benefit gained by the RO system. The purpose of this pilot testing was to assess pretreatment to the SWRO system. SWRO performance was evaluated in two process trains at two different sites in Florida. The two process trains tested were multi-media filtration (MMF)-SWRO and ultrafiltration (UF)-SWRO. The Cape Canaveral location represented a Florida east coast site (Atlantic Ocean). The Anclote/Tampa location represented a Florida west coast site (Gulf of Mexico). The purpose of testing two different source waters was to sufficiently demonstrate water quality and pretreatment conditions for SWRO using seawater under the influence of surface water runoff. Performance of the systems was assessed by evaluating the fouling of the cartridge filters and SWRO membranes.

The results of this pilot study illustrates that the SWRO system showed better performance in terms of productivity while using a UF system as pretreatment to SWRO than using conventional filtration pretreatment. The SWRO system did not show any fouling when using UF as pretreatment, whereas it showed a slight fouling when the conventional filtration process was used as pretreatment on the east coast site. No conclusions could be drawn on the west coast site regarding fouling of SWRO system due to poor performances of the pretreatments, either in terms of productivity or water quality. Production of high pretreatment water quality is a key parameter in the implementation of a seawater treatment plant. Poor pretreatment water quality would result in high cartridge filter replacement frequency and SWRO membrane cleaning and, therefore, high operation and maintenance (O&M) costs.

In addition, the pretreatment assessment shows that seawater treatment is site specific and that processes that could be operated on one site could not be operated on another. Therefore, implementation of a seawater treatment plant would require a pilot study to define pretreatment technology and operating conditions and to assess SWRO membrane fouling.

1.2 Topic 2 – Pathogen Removal by Seawater Reverse Osmosis

Due to the limited data on removal of pathogens by SWRO, a challenge test was developed to quantify log removal of pathogen surrogates. This information would support development of log removal credits by regulatory agencies and compliment the body of knowledge already in existence relative to freshwater sources and lower pressure reverse osmosis systems. Viral phages were selected as the organisms of choice, given their small size, and were used to determine the rejection potential of each of the three treatment processes associated with this pilot project. The three systems were ultrafiltration, conventional media filtration, and a seawater reverse osmosis system. The rejection capabilities of the two process trains (UF-SWRO and MMF-SWRO) were then assessed and compared to current and proposed pathogen-related water quality regulations.

The two process trains showed at least 8-log rejection of viruses; then, they would achieve 8-log removal of protozoa. Therefore, both process trains would meet the Interim Enhanced Surface Water Treatment Rule (IESWTR) requirement of 2-log *Giardia* removal and the maximum Long Term 2 Surface Water Treatment Rule (LT2SWTR) requirement of 5.5-log *Cryptosporidium* removal.

The significance of the virus challenge testing is that it will benefit the U.S. Environmental Protection Agency (EPA) and State regulatory agencies by providing needed research on pathogen removal to support assigning of removal credits to SWRO systems. The results showed and support the fact that UF and SWRO (12-log) achieve higher pathogen rejection than conventional filtration (8-log), as it has been shown in previous studies. Although conventional filtration receives 2.0-log credit for virus and 0.5-log credit for *Giardia*, UF and SWRO have not been assigned any log credit by EPA.

1.3 Topic 3 – Optimization of RO for Removal of Low Molecular Weight Inorganic Contaminants

The assessment was developed to quantify the impact different finished water quality specifications have on the design and costs of SWRO treatment plants. While every project is unique, the intent of this assessment is to illustrate the relationship between finished water quality and costs, using selected design variables.

The design and cost analysis was performed first by establishing a series of finished water quality specifications (WQS) that bracket a range that might reasonably be required by municipalities in the United States. Based on these specifications, a number of design criteria were identified that could be varied as necessary to meet water quality goals. Each finished water quality specification was then reviewed and a design developed that minimized the complexity and cost of the SWRO system while meeting the specification. Life-cycle costs for a 25-MGD SWRO plant were then developed for each alternative design. Results were then analyzed and interpreted to determine design direction(s) that may be useful for municipalities to consider as part of conceptual design and process design efforts.

The three WQS, in order of least to most difficult to meet, were: (1) total dissolved solids (TDS) = 400 milligrams per liter (mg/L), (2) chloride = 100 mg/L, and (3) boron = 0.5 mg/L. While the first WQS was achieved using a single pass SWRO system, additional treatment was necessary to meet the chloride and boron limit. The additional treatment for chloride or boron increased capital costs by 7 to 36 percent which corresponds to an increase in capital and construction costs by $6 to $28 million. Using a boron selective ion exchange resin was the most cost-effective alternative for reducing boron, saving approximately $3 million in annual amortized costs ($0.33 per kilogallon) compared to the second pass RO alternatives. Although boron is not currently regulated under the Safe Drinking Water Act, it is listed under the Candidate Contaminant List and may be regulated in the future. This assessment shows the potential costs of treating boron to a finished water standard of 0.5 mg/L.

From a more fundamental standpoint, this assessment shows how a SWRO design can be tailored to achieve a defined WQS; and based on this design, costs for capital, construction, and O&M can be readily determined and evaluated. Unlike the design of traditional freshwater conventional treatment plants, the modeling software that is available from the RO manufacturers coupled with the WTCost® program provides design teams the ability to evaluate design alternatives that achieve specific WQS and to estimate costs. This gives the designer the ability to estimate a dollar value for incremental improvements in finished water quality, which can be a valuable tool for a utility considering desalination.

2. Introduction

Using reverse osmosis (RO) for demineralization of seawater has been practiced world wide for decades, with a limited number of potable water applications within the United States. While costs have always been key in the development of seawater treatment facilities, many applications were in areas of the world with no other potable water alternative. As a result, costs were absorbed based on the absence of other alternatives. However, at this time in the United States, seawater reverse osmosis facilities are being evaluated with an extremely critical eye toward optimizing science and technology to minimize cost and comply with increasingly stringent finished water regulatory requirements. As a result, costs for RO have dropped, and the need for alternative water supplies has increased with first using brackish ground water and now seawater. In the past several years, an unprecedented number of seawater RO feasibility studies have been conducted, many in response to the costs developed for the Tampa Bay Desal I project. Therefore, optimization of cost and design considerations for seawater demineralization facilities is of critical importance now and into the future.

Specifically, issues that have not been fully explored but are being addressed through this project are as follows:

1. Pretreatment alternatives when utilizing seawater under the influence of freshwater (i.e., seawater/surface water mixes such as Tampa Bay Desal I and II),
2. Pathogen protection, and
3. Design and cost considerations associated with removal of low molecular weight constituents.

Regarding pretreatment, conventional multimedia filtration has been the standard for seawater pretreatment, a variant of which is currently being used at the Tampa Bay Desal I project. While multimedia filtration (MMF) is utilized world wide for pretreatment of seawater RO systems, this pretreatment can be the most difficult operational aspect of seawater facilities due to the vigilance needed to maintain adequate RO feed water quality (Ionics, 1999). Major issues regarding conventional media filtration for pretreatment of RO processes include: reliability of suspended solids removal—effluent quality depends on optimizing coagulant dose, surface loading rates, backwashing frequency and methods, ripening, media, and influent quality. Failure can lead to breakthrough and particle plugging of downstream membranes. Particle plugging can sometimes be irreversible and result in RO membrane replacement.

Microfiltration (MF) and ultrafiltration (UF) conversely can provide reliable suspended solids removal. Effluent quality is very consistent and relatively independent of operational setting upsets. While many studies have been performed on the use of MF/UF on seawater, most studies were limited to the reduction in silt density index (SDI) values of the MF/UF effluent and did not incorporate a seawater reverse osmosis (SWRO) skid to evaluate the true impact on the RO process. Norit membranes, a hollow fiber UF manufacturer, piloted UF on open intake seawater and found that the SDI values of the effluent were typically between 1 and 2 units, while that required for RO pretreatment is less than 3 units (S.C.J.M. van Hoof, 1999 and 2001). This study, while promising in nature, did not incorporate a SWRO skid to see the effects of this pretreatment.

Zenon Environmental has developed the ZeeWeed 1000 with one of its primary applications deemed to be pretreatment of SWRO and is said to provide "higher sustainable flux, smaller system size, lower cleaning frequency and longer membrane life" (P. Cote, 2001). Aquasource, a French UF manufacturer, did incorporate a SWRO skid behind their UF system and found that, in general, the water quality produced by the integrated membrane system was generally better than that of the conventional system (A. Brehant, 2002). Despite all of these promising pilot results, a large-scale MF or UF system has yet to be placed in operation pretreating seawater.

In the end, the increased capital and operation and maintenance (O&M) costs of MF or UF pretreatment must be justified via benefits such as a net reduction in life cycle costs or increased plant reliability. Both the Tampa Bay Desal I and the Ionics Trinidad seawater facilities have experienced issues with adequacy of the conventional pretreatment. Morro Bay, California, fast-tracked installation of iron removal filtration equipment due to the inability of the seawater well design to provide acceptable pretreatment. Clearly, the pretreatment issue reigns center.

In summary, the importance of pretreatment is a well-known fact for SWRO systems but can be more critical when the seawater is influenced by fresh surface water runoff from coastal sources. The Tampa Bay Desal I facility consists of a mixed seawater/surface water source with total dissolved solids (TDS) that varies from 19,000 milligrams per liter (mg/L) in the wet season to 33,000 mg/L in the dry season. While these waters may provide the benefit of lowering TDS, thus improving on energy costs for pumping, reducing transmission lines and other capital costs, the inherent variability in water quality from these sources may require increased pretreatment efficiency. Rain or storm events, which can elevate suspended solids in coastal water runoffs by a factor of 10 or more, can severely plug RO membranes without proper pretreatment. Therefore, meaningful research on pretreatment to SWRO facilities must be combined with the expected source water quality.

An additional area of concern is the removal of pathogens. While it is assumed by many that SWRO systems are capable of rejecting pathogens due to the large size of such microorganisms, the very high removal necessary to ensure protection of public health must be fully appreciated. For example, reduction of TDS from 30,000 mg/L to 300 mg/L represents only a 2-log reduction; whereas, log removals of pathogens on the order of 4+ are typically desired by the United States Environmental Protection Agency (EPA) in its current rule making efforts. A 2-log reduction in TDS cannot be equated to a 4+ log reduction in pathogens. While the inorganic ions that are removed are vastly smaller than pathogenic organisms, the potential exists for unacceptably low pathogen rejection. In the absence of research specific to seawater membrane elements, extrapolation of data from other freshwater studies is necessary. Given the smaller size of seawater microorganisms, data on the rejection of freshwater microorganisms by nanofiltration (NF) (the primary research to date) must be viewed with caution.

Lastly, rejection of low molecular weight constituents, such as boron or chloride, may be such that finished water quality goals are not met in the first pass of the RO system. This can necessitate design of a second pass (Tampa Bay Desal I), ion exchange, reductions in recovery, and reductions in the number of elements in series or other process modifications to ensure compliance with finished water quality goals. An assessment of the most cost-efficient method of meeting various final finished water quality goals would be of tremendous benefit to the industry and support development of accurate cost estimates when planning future facilities.

Each of these three problem areas (i.e., pretreatment alternatives, pathogen protection, and removal of low molecular weight constituents) is consistent with the priority categories previously identified by the Bureau of Reclamation (Reclamation) and the National Water Research Institute (NWRI) at the 2001 Desalination Research and Development Workshop. Therefore, Reclamation contracted under Financial Assistance Agreement No. 02-FC-81-0829, the services of Reiss Environmental, Inc. to conduct desktop assessments and pilot-scale studies to evaluate water quality and pretreat conditions for SWRO using seawaters under the influence of freshwater runoff (SWUI). The project background, objectives, and results are presented in this final report.

2.1 Background

While using RO for demineralizing seawater has been practiced for decades, potable applications within the United States have been limited in number. As costs for RO treatment have dropped and the need for alternative water supplies have increased, using first brackish ground water demineralization and now seawater demineralization has increased. In the past several years, an unprecedented number of seawater demineralization feasibility studies have been conducted, many in response to the costs developed for the Tampa Bay Desal I project.

Concurrent with this increased interest in seawater desalination is the need for additional research to support the advancement and application of desalination technology, and seawater desalination in particular. Reclamation has been at the forefront of this effort with a national research and development program. This has included developing needs assessments. The 2001 Desalination Research and Development Workshop (Workshop), conducted by Reclamation and NWRI, ranked ***"Additional Advancement of Membrane Technology"*** as **"Priority 1**," over 18 other issues. Within this category were several issues including advancement of pretreatment methods such as microfiltration. This project has identified the following research needs with regards to this priority:

- **Topic 1 - Pretreatment for Seawater Sources Under the Influence of Freshwater Runoff**: While research is ongoing in the field of open intake seawater integrated membrane systems, to date, limited research exists on the comparison of conventional versus MF/UF pretreatment for SWUI source waters.
- **Topic 2 - Pathogen Removal:** Significant research in the field of pathogen removal for NF and low-pressure reverse osmosis (LPRO) elements on fresh surface water has been published; however, there is extremely limited data on the log reduction capabilities of seawater elements.
- **Topic 3 - Removal of Low Molecular Weight Constituents:** Different techniques (second pass RO, ion exchange, reduced recovery, reduced elements per vessel) for the removal of low molecular weight compounds have been applied throughout the world; however, no compilation and cost comparison of these techniques to meet water quality goals has been performed.

As a result, the Evaluation of Desalination on Waters Under the Influence of Surface Water Runoff for Pretreatment, Water Quality and Pathogen Removal Performance project was developed to specifically address Priority 1 as defined by the Bureau of Reclamations 2001 Workshop and based on the experiences of the Reiss Environmental Project Team on Tampa Bay Desal I and other projects. This project team, consisting of Reiss Environmental, Inc. (REI), Norit Americas, Tampa Bay Water, and the University of South Florida has crafted this project to meet industry needs through a literature review, Tampa Bay Desal I project experience, and discussions with other researchers.

2.2 Purpose

This report presents the findings of the desktop assessment and pilot-scale studies performed to evaluate water quality and pretreatment conditions for SWRO using seawater under the influence of surface water runoff.

2.3 Objectives

Project objectives were divided into the following three major topics:

- **Topic 1 -** ***Evaluation of Pretreatment Alternatives for Seawater Under the Influence of Freshwater Runoff.*** Quantify relative rates of fouling for RO systems and associated costs when using conventional media filtration versus ultrafiltration (UF) as pretreatment for SWUI.
- **Topic 2 -** ***Pathogen Removal***. Quantify rejection capabilities of conventional media filtration, UF and RO systems (independent of each other) to reject pathogen-sized contaminants and then compare results with other freshwater NF and LPRO research.
- **Topic 3 -** ***Optimization of Designs for Removal of Low Molecular Weight Contaminants.*** Identify, evaluate, and compare available treatment options (e.g., second pass, ion exchange, or others) for removal of low molecular weight contaminants to achieve standards set by the Safe Drinking Water Act, World Health Organization (WHO), and goals commonly set by the municipal utilities.

Each topic is presented in the next three sections.

2.4 Significance

This project will benefit the following organizations, agencies, and people:

- Utilities, regulators, and developers by increasing the reliability and effectiveness of projects that are implemented by providing better design information and an increased understanding of design requirements to meet regulatory requirements and the accuracy of cost estimates for SWRO.
- EPA by providing needed research on pathogen removal to support assigning removal credits to SWRO systems.
- Consumers of future desalinated water with added confidence by demonstrating compliance with United States and world water quality standards.

- The membrane industry by increasing the existing knowledge base regarding pretreatment for SWRO and potentially improve SWRO system designs to meet short- and long-term regulatory requirements.

3. Evaluation of Seawater RO Pretreatment Alternatives

The importance of pretreatment is a well-known fact for SWRO systems and can be more critical when seawater is influenced by fresh surface water runoff from coastal sources. This is due to potential wide variations in water quality that need to be mitigated by the pretreatment process prior to reverse osmosis. Research to date on pretreatment alternatives for seawater sources under the influence of freshwater runoff has been lacking due to one or both of two factors: using an open ocean intake and/or assessing the pretreatment systems without using a SWRO system to evaluate the specific benefit gained by the RO system. As means of addressing these issues, this assessment has been developed to quantify relative rates of fouling for RO systems and associated costs when using conventional media filtration versus UF as pretreatment for SWUI of surface water.

3.1 Methodology

The purpose of this pilot testing was to assess pretreatment to the SWRO system. SWRO performance was evaluated in two process trains at two different sites in Florida. The Cape Canaveral location represented a Florida east coast site (Atlantic Ocean). The Anclote/Tampa location represented a Florida west coast site (Gulf of Mexico).

The two process trains tested were MMF-SWRO and UF-SWRO. Process Train 1 (figure 3-1) consisted of raw water screening via strainers (200 micrometers [µm] on the East Coast Site, 300 µm on the West Coast Site), in-line coagulation using ferric sulfate coagulant, two-stage conventional multimedia filtration (roughing and polishing filter), static filtration through cartridge filters, booster pump, and then seawater reverse osmosis. Process Train 2 (figure 3-2) consisted of raw water screening via basket strainer (200 µm), in-line coagulation using ferric sulfate coagulant, ultrafiltration, static filtration through cartridge filters, booster pump, and then seawater reverse osmosis.

Performance of the systems was assessed by evaluating the fouling of the cartridge filters and SWRO membranes. Fouling was assessed for each experiment based on declines in mass transfer coefficients (MTC) and increases in headloss along the feed side of the RO membrane. MTC is represented by the flux and net driving pressure (NDP) ratio. NDP is the average feed pressure minus permeate pressure and osmotic pressure. The MTC would show a decrease when fouling occurs during piloting. A chemical cleaning is usually necessary to

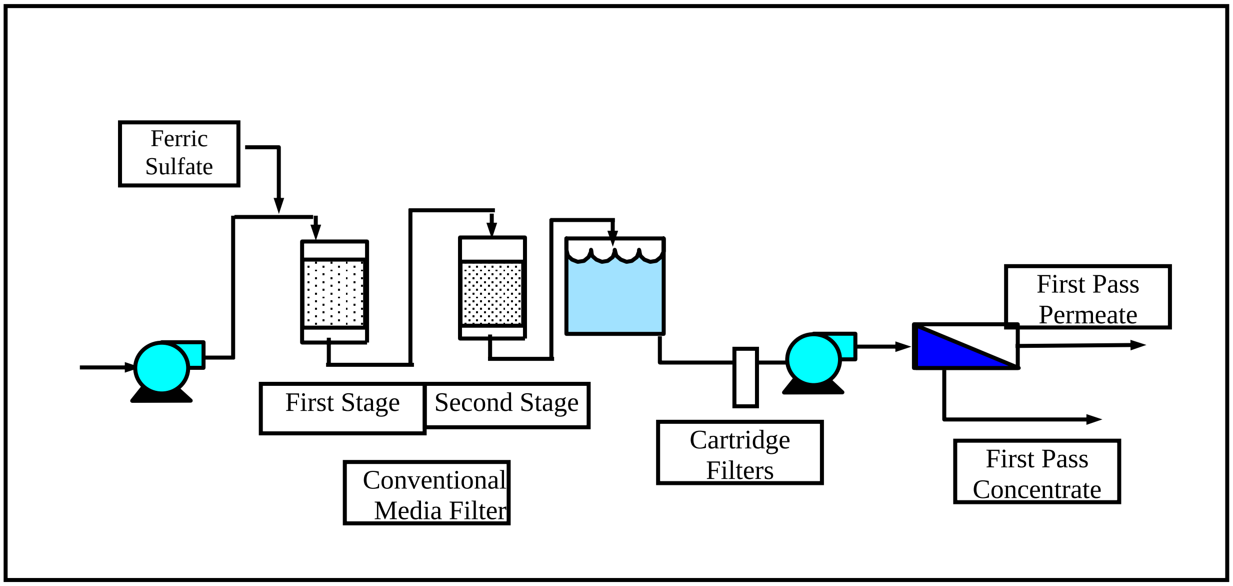


Figure 3-1. MMF-SWRO Process Train.

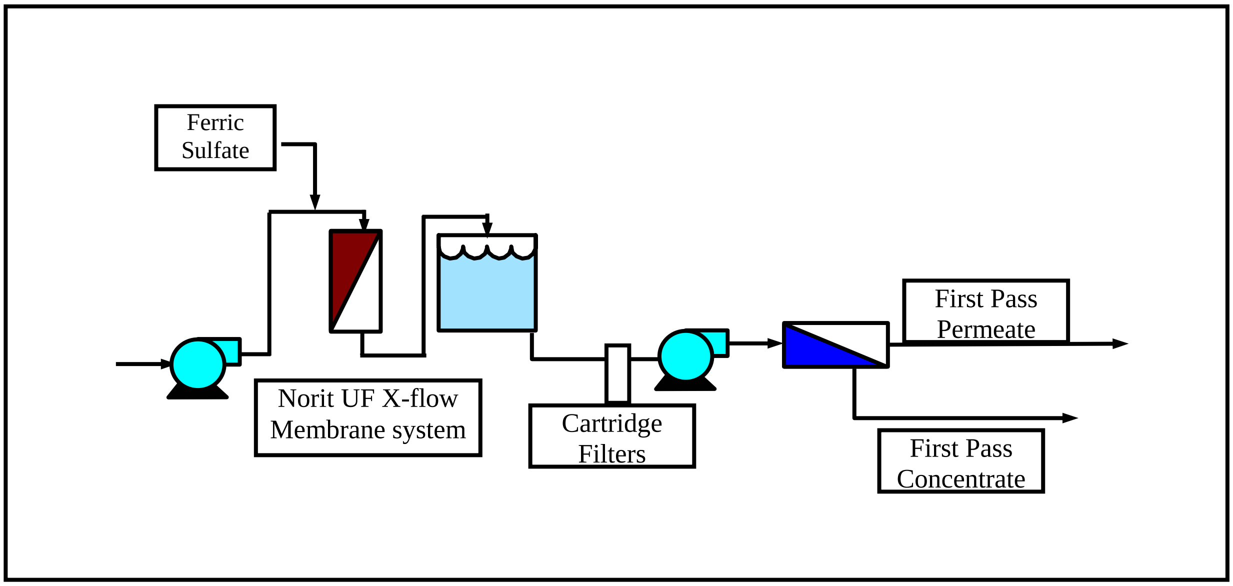


Figure 3-2. UF-SWRO Process Train.

improve the membrane performance when a MTC decrease of 10-20 percent (%) is observed. The runtime between chemical cleanings was calculated for each experiment and compared to one another to assess performance of each alternative. Feed side headloss or delta pressure increases indicate membrane particle plugging or feed spacer blockage. In addition, the replacement of the cartridge filters prior to SWRO membranes was evaluated based on the differential pressure.

Operating conditions such as flow rates and pressures as well as the water quality were monitored during the study to assess the performance of the SWRO membranes. The details of the monitoring are presented in the pilot protocols attached in Appendices A and B for the East and West Coast Sites, respectively.

3.1.1 Test Sites

Two sites were selected for testing, each located on the east and west coasts of Florida. The East Coast Site was colocated with an existing powerplant at Cape Canaveral in Titusville, known as the Florida Power and Light Cape Canaveral Power Station (FP&L Cape Canaveral). The West Coast Site was also co-located with a powerplant, the Progress Energy Anclote River Power Station (PE Anclote River) and is near the discharge of the Anclote River to the Gulf of Mexico. This site is also the proposed location for the Tampa Bay Water Gulf Coast Desalination Project. Both East and West Coast Sites have similar characteristics in that each source water is under the influence of freshwater runoff.

3.1.2 Pilot Equipment

The pilot equipment consisted of a conventional multimedia filtration pilot, ultrafiltration pilot and SWRO pilot for evaluating the objectives of this study. Norit Americas supplied the ultrafiltration pilot. The University of South Florida supplied the conventional MMF pilot used on the east coast. Tampa Bay Water provided the MMF pilot used on the West Coast Site. Reiss Environmental provided the SWRO system. This pilot equipment is described in more detail in the following subsections.

3.1.2.1 Conventional Multimedia Filtration Pilot – East Coast Site

A dual multimedia filter was used in conjunction with ferric sulfate coagulant as the conventional pretreatment method in the East Coast Site. This conventional media filtration pilot consists of two roughing filter units operating in parallel followed by two polishing filters operating in lead and lag. The filter was capable of producing 15 gallons per minute (gpm) of filtered effluent water that will be used as feed water to the SWRO pilot plant. The conventional media filtration pilot units for the East Coast Site are shown in figure 3-3

3.1.2.2 Multimedia Filtration Pilot – West Coast Site

The multimedia filtration pretreatment system utilized on the East Coast Site was eventually found to be inadequate to perform sufficient pretreatment of the raw water source on a continuous basis, without extensive labor requirements. Therefore, a new two-pass multimedia filtration system was designed to complete the west coast portion of the work. After completion of construction (2 months), the system was delivered to the Anclote, Florida, site on March 4, 2004. The pretreatment system was to pretreat seawater prior to the SWRO system after optimization of the system to meet filtrate adequate quality to feed RO membranes.

Figure 3-3. Multimedia Filtration Pilot Unit – East Coast Site.

The dual multimedia filter was used in conjunction with ferric sulfate coagulant as the conventional pretreatment method in the West Coast Site. This multimedia filtration pilot consisted of one roughing filter followed by one polishing filter. The filter system was capable of producing 20 gpm of filtered effluent water. The MMF pilot unit is shown in figure 3-4.

Figure 3-4. Multimedia Filtration Pilot Unit – West Coast Site.

3.1.2.3 Ultrafiltration Pilot

Norit Americas pilot unit (figure 3-5) was designed to provide up to 0.07-million gallon-per-day (MGD) water treatment capacity in a compact and fully equipped pilot system. Operating with two standard (8-inch-diameter, 60-inch-long) membrane modules, the pilot system can operate at flows from approximately 15 to 47 gpm. The membranes used during piloting are the same type, size, and orientation (horizontal) as those used in a full-scale system.

3.1.2.4 Seawater Reverse Osmosis Pilot

The Reiss Environmental RO Pilot Plant shown in figure 3-6 was mobilized to produce approximately 8 gpm of potable water. The seawater system consists of a single-pass system with 7–4,040 seawater membrane elements (TM810 membrane from Toray) in Pass 1. This pilot trailer was utilized to treat the MMF and UF filtrate waters.

Figure 3-5. Norit Americas Trailer-Mounted UF Pilot Plant.

Figure 3-6. Reiss Environmental Trailer-Mounted SWRO Pilot Plant.

Two sets of Toray membranes were used during the study. One set was used for the East Coast Site UF pretreatment, and a brand new set was installed to perform the East Coast Site MMF pretreatment and West Coast Site testing.

3.2 Source Water Quality

Two different source waters were tested during this pilot study, Indian River Lagoon at the FP&L Cape Canaveral location and the Anclote River/Gulf of Mexico at the Anclote Power Station site. The purpose of testing two different source waters was to sufficiently demonstrate water quality and pretreatment conditions for SWRO using seawater under the influence of surface water runoff. The water quality of the two water sources is presented in table 2-1. The water quality represents the average of different sampling events in 2002 and 2003. The results of each sampling event are presented in appendix C. TDS are

Table 3-1. Source Water Quality

Parameter	Unit	East Coast Site Intake	West Coast Site Intake
Alkalinity, Total (as $CaCO_3$)	mg/L	133	120
Aluminum	mg/L	0.3	0.13
Barium	mg/L	0.02	0.02
Boron	mg/L	2.6	3.0
Bromide	mg/L	50	53
Calcium	mg/L	350	350
Cesium	mg/L	< 0.04	< 0.04
Chloride	mg/L	13,333	16,333
Chromium	mg/L	0.27	< 0.01
Color	CPU	10	20
Copper	ug/L	3	3.6
Dissolved Organic Carbon	mg/L	NA	4.3
Dissolved Oxygen (DO)	mg/L	8.8	5.9
Field pH	units	8.4	8
Fluoride	mg/L	0.84	0.9
Hardness, Total (as $CaCO_3$)	mg/L	4,467	5,233
Heterotrophic Plate Count (HPC)	Cfu/mL	NA	100
Iron (dissolved)	mg/L	0.06	< 0.02
Iron (total)	mg/L	0.16	0.14
Lead	mg/L	0.1	< 0.005
Magnesium	mg/L	877	1,057
Manganese	mg/L	0.02	< 0.01
Mercury	mg/L	< 0.0002	< 0.0002
Nitrate (as N)	mg/L	0.02	0.04
Nitrogen (as Ammonia)	mg/L	0.037	0.02
Phosphorus, Total	mg/L	0.04	0.04
Silica Dioxide	mg/L	1.02	0.9
Silica Dioxide (Colloidal)	mg/L	1.32	7
Silt Density Index (SDI)	–	> 6.67	> 6.67
Sodium	mg/L	7,600	8,800
Specific Conductivity	uohms/cm	37,000	36,955
Strontium	mg/L	5.0	6.0
Sulfate	mg/L	1,900	2,200
Temperature	^oC		28.3
Tin	mg/L	< 0.1	< 0.1
Total Dissolved Solids (Gravimetric)	mg/L	24,133	29,667
Total Organic Carbon	mg/L	7.8	4.5
TSS	mg/L	NA	27
Turbidity	NTU	3.7	7
Zinc	mg/L	0.02	< 0.01

NA: not available.

approximately 24,200 mg/L and 30,000 mg/L for the Indian River and Anclote River, respectively. In addition, wide variations of TDS were observed on the Anclote River (28,000 to 36,000 mg/L), whereas minor variations (24,000 to 24,400 mg/L) were observed on the Indian River. These water quality results show that both source waters are under the influence of fresh surface water since seawater has as TDS of approximately 34,000 to 36,000 mg/L.

Both source waters pose different treatment challenges. The Anclote River cooling water has higher concentrations for most of the other water quality parameters detected than the Indian River. Only total organic carbon (TOC) concentrations were higher for the Indian River intake water measured as 7.1 to 8.6 mg/L as compared with the Anclote River cooling water varying from 2.6 to 5.4 mg/L. It should be noted that source water analyses were performed on samples taken during the dry season at the beginning of 2003.

3.3 Operating Conditions

The conditions under which the two process trains were operated at the East and West Coast Sites are presented in tables 3-2 and 3-3, respectively. The seawater reverse osmosis system was conducted under the same conditions while using both pretreatment systems at both test sites with the exception of the MMF-SWRO on the West Coast Site.

The duration and dates of the pilot tests are presented in table 3-4. The pretreatment unit operating settings were optimized to supply filtrate water to the seawater system with turbidity lower than 0.3 nephelometric turbidity unit (NTU) and SDI less than 5. Each test was conducted for a period of 21 days (with the mentioned exception).

The SWRO system was operated at a flux of 10 gallons per square foot per day (gfd) and a recovery of 50% using seven elements in the pressure vessel. No acid or antiscalant were added to the feed water of the SWRO system to replicate the common pretreatment practice for seawater membrane system. The cartridge filter used as static filters prior to SWRO membranes was 2.5-inch wound string filters. In addition, the loading rate on these filters was approximately 2.5 gpm per 10 inches. This represents the low end of the loading rate range used in the membrane industry, the typical range being 2.5 to 5 gpm per 10-inch cartridge.

It is important to note that the SWRO system was not operated on the West Coast Site for the MMF system test. The MMF system could not produce water with SDI less than 4 on a consistent basis to supply water to the SWRO system.

Table 3-2. Piloting Test for East Coast Site

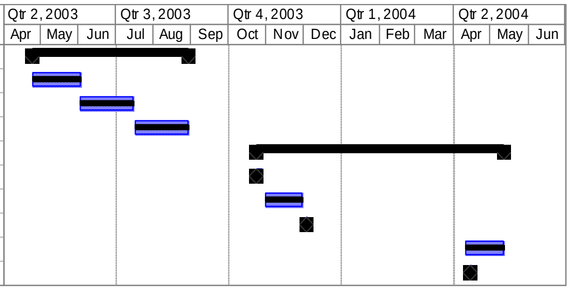
Parameters	Units	Settings
UF – SWRO Process Train		
Coagulant Dose to UF Unit (Ferric Sulfate)	mg/L as Fe	1.5
UF Flux	gfd	36
UF BW Frequency	min	30
Chemical Enhanced Backwash Frequency	day	1
SWRO 1st Pass Flux	gfd	10
SWRO 1st Pass Recovery	%	50
Acid Dose	mg/L	0
Antiscalant Dose	mg/L	0
MMF – SWRO Process Train		
Acid Addition		None
Coagulant Addition	mg/L as Fe	0.5
MMF 1st Pass Loading Rate	gpm/ft^2	4
MMF 1st Pass Backwash Frequency	hr	12
MMF 2nd Pass Loading Rate	gpm/ft^2	8
MMF 2nd Pass Backwash Frequency	hr	24
SWRO 1st Pass Flux	gfd	10
SWRO 1st Pass Recovery	%	50
Acid Dose	mg/L	0
Antiscalant Dose	mg/L	0

Table 3-3. Piloting Test for West Coast Site

Parameters	Units	Settings
UF – SWRO Process Train		
Coagulant Dose to UF Unit (Ferric Sulfate)	mg/L as Fe	1.5
UF Flux	gfd	36
UF BW Frequency	min	20
Chemical Enhanced Backwash Frequency	hr	18
SWRO 1st Pass Flux	gfd	10
SWRO 1st Pass Recovery	%	50
MMF – SWRO Process Train		
Acid Addition	–	variable
Coagulant Addition	mg/L	variable
MMF 1st Pass Loading Rate	gpm/ft^2	2
MMF 1st Pass Backwash Frequency	hr	variable
MMF 2nd Pass Loading Rate	gpm/ft^2	4
MMF 2nd Pass Backwash Frequency	hr	variable
SWRO 1st Pass Flux	gfd	Not tested
SWRO 1st Pass Recovery	%	Not tested

Table 3-4. East and West Coast Pilot Test Durations

ID	Task Name	Start	Finish
1	**East Coast Pilot**	**Thu 4/24/03**	**Thu 8/28/03**
2	Shakedown / Startup	Thu 4/24/03	Mon 6/2/03
3	UF - SWRO Pilot	Mon 6/2/03	Tue 7/15/03
4	MMF - SWRO Pilot	Thu 7/17/03	Thu 8/28/03
5	**West Coast Pilot**	**Thu 10/23/03**	**Tue 5/11/04**
6	Shakedown / Startup	Thu 10/23/03	Mon 10/27/03
7	UF - SWRO Pilot	Fri 10/31/03	Sat 11/29/03
8	Pathogen Challenge (UF/ SWRO)	Wed 12/3/03	Wed 12/3/03
9	MMF Pilot	Sat 4/10/04	Tue 5/11/04
10	Pathogen Challenge (MMF)	Wed 4/14/04	Wed 4/14/04



Additionally, the SWRO system was only operated on the UF system for 330 hours as the UF system could not produce water after this point of the test on a continuous basis without extensive labor cleaning requirement to correct the UF membrane fouling.

It is important to note that the SWRO system was not operated on the West Coast Site for the MMF system test. The MMF system could not produce water with SDI less than 4 on a consistent basis to supply water to the SWRO system. Additionally, the SWRO system was only operated on the UF system for 330 hours as the UF system could not produce water after this point of the test on a continuous basis without extensive labor cleaning requirement to correct the UF membrane fouling.

The UF pretreatment system was operated at a flux of 36 gfd and a recovery of 80% after optimization of the unit. The UF pretreatment was used in conjunction with ferric sulfate, a coagulant to minimize fouling of the UF membranes. The dose was approximately 1.5 mg/L as Fe. A chemical enhanced backwash was performed every day using muriatic acid.

The MMF systems tested were used in conjunction with ferric sulfate coagulant as the conventional pretreatment method in both test sites. The MMF first stage roughing filter was operated at a surface loading rate of 4 gallons per minute per square foot (gpm/ft^2), and the second stage polishing filter was operated at surface loading rate of 8 gpm/ft^2 on the East Coast Site; whereas, the MMF first stage roughing filters were operated at a surface loading rate of 2 gpm/ft^2, and the second stage polishing filter was operated at surface loading rate of 4 gpm/ft^2 on the West Coast Site. On the East Coast Site, the automatic backwash was set at once a day in the first half of the test and twice a day for the second half of the test on the East Coast Site. On the West Coast Site, the automatic backwash was set when the differential pressure reached 10 psi.

3.4 Results

The performances of the SWRO system are presented herein for both the East and West Coast Sites. The results for each site are presented individually for clarity, and due to the fact that the water quality of the source water is significantly different from each other, therefore leading to different results.

3.4.1 East Coast Site Results

The water productivity results as well as the water quality of the SWRO system on the East Coast Site are presented in this section. As described previously, the pilot test primary objective was to focus on fouling potential for MMF versus UF pretreatment for SWUI.

3.4.1.1 UF Results

Performance of the UF system was evaluated on the East Coast Site between June 20, 2003, and July 15, 2003. The performance evaluation was possible following 60 days of intermittent operation of the UF system to test several varied operational regimes to prevent UF membrane fouling and optimize performance. Based on the results of this testing, the operating condition presented in table 3-5 was determined to evaluate the fouling potential for the UF-SWRO process train.

Table 3-5. East Coast Site UF Operating Conditions

Period	Flux (gfd)	BW Frequency (min)	CEB[1] Frequency (hours)	Chemical
6/20/03 – 7/16/03	36	20 (45-second duration)	CEB #1 - every 6 hours CEB #2 - every 18 hours	CEB #1 - No chemical CEB #2 - Sodium hypochlorite

[1] CEB = chemically enhanced backwash.

The backwash frequency was every 20 minutes with duration of 45 seconds. A chemically enhanced backwash (CEB #2) was performed every 18 hours using sodium hypochlorite. During the chemically enhanced backwash, the membrane was soaked for 10 minutes and followed by an air integrity test. Also, every 6 hours, a chemically enhanced backwash (CEB #1) was performed in which no chemicals were injected and the membrane was soaked for 5 minutes followed by an air integrity test. The CEB #1 provided additional physical agitation to the membrane to assist removal of foulant particles. In addition to the normal backwashes and the chemically enhanced backwashes, the UF pretreatment system required a low pH and sodium meta-bisulfite cleaning and soak after 9 to 10 days of operation to lower transmembrane pressure and restore system permeability.

UF system productivity results are presented in appendix G. The transmembrane pressure of the UF system was consistently less than 3 psi during the pilot study and, therefore, showing no membrane fouling. These results show that the productivity could be sustained under the operating conditions set during the pilot study. Continuous operation of the UF pretreatment system was achieved for 25 days allowing for evaluation of water quality for the SWRO feed. SDI data for the UF filtrate water is presented in figure 3-7. Turbidity results for the UF filtrate are presented in figure 3-8. While the low results for the UF filtrate SDI indicate a high quality effluent (typically less than 1.0), subsequent investigation of the data indicates that the SDI analysis was flawed by a mechanical defect in the SDI device, and the results should be substantially higher. Higher SDI results would be expected based on the turbidity results reported (0.10 NTU to 0.40 NTU) in figure 3-8. Turbidity results greater than 0.20 observed on Tampa Bay Desal I pretreated seawater typically indicated an SDI in excess of 3.0. For these reasons, the East Coast Site SDI data is presumed to be inaccurate for comparative purposes to other projects. The SDI data is included in this discussion for comparative purposes with the MMF SDI data collected on the East Coast Site only.

The results appear to indicate that this UF pretreatment system performance produced a marginal water quality for pretreatment for SWRO (see section 3.4.1.3). A couple of potential causes may explain the marginal performance observed. Biogrowth observed within holding tanks in the UF and SWRO feed system likely contributed to fouling and water quality issues.

Barnacle growth was observed downstream of the 200-µm prescreen in the UF system feed tank during the East Coast Site study. As response to the observed growth, feed and holding tanks upstream of the UF pretreatment system were periodically dosed with sodium hypochlorite. Additionally, a gelatinous biogrowth developed in the holding tank downstream of the UF pretreatment system after 3 to 4 weeks of operation. As a response to this, the tank was dosed within sodium hypochlorite and flushed to remove biogrowth in the tank.

UF pretreatment system performance was hindered during the testing by intermittent failures of the air integrity test. Several membrane filaments were plugged to restore air integrity performance during the study. After the East Coast Site study was completed, the UF membranes were autopsied; and damaged fibers were found (see report in appendix I). These slices and punctures may explain filtrate water quality issues. This type of damage to fibers has been observed in other MF and UF pilot systems treating seawater and may be due to barnacle shards that pass through the screening process and into the UF module.

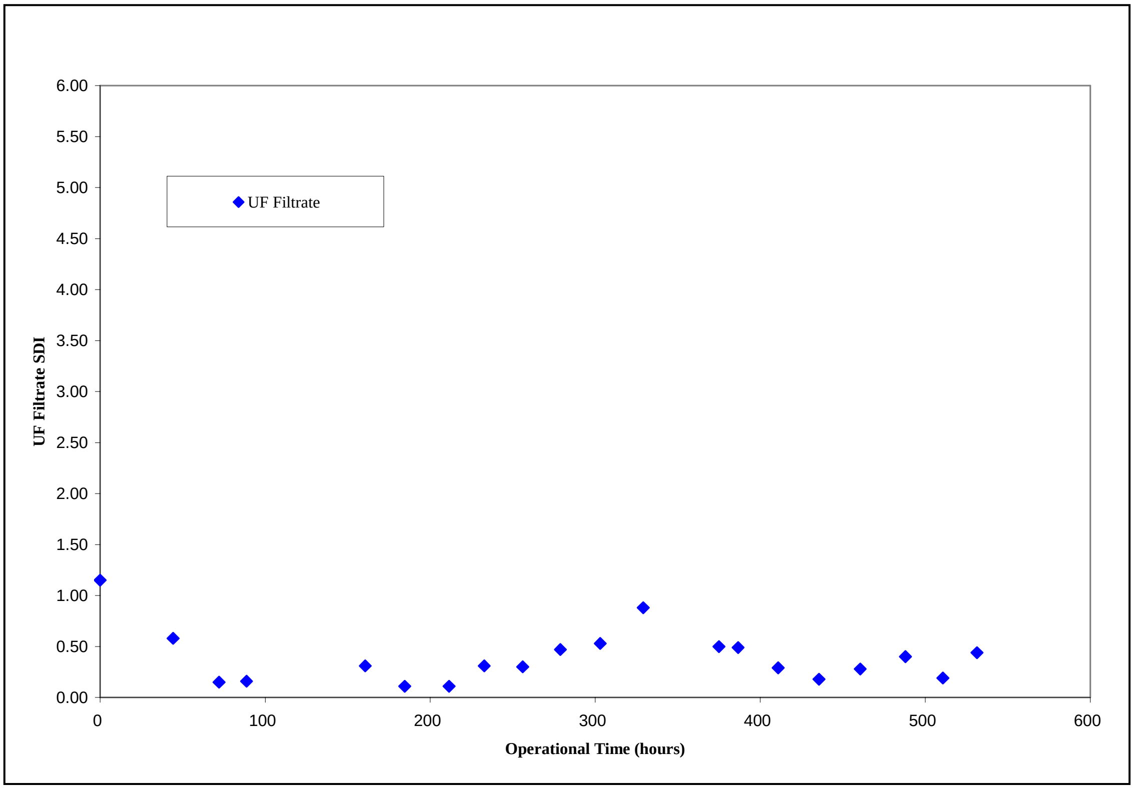


Figure 3-7. East Coast Site UF Filtrate SDI_{15}.

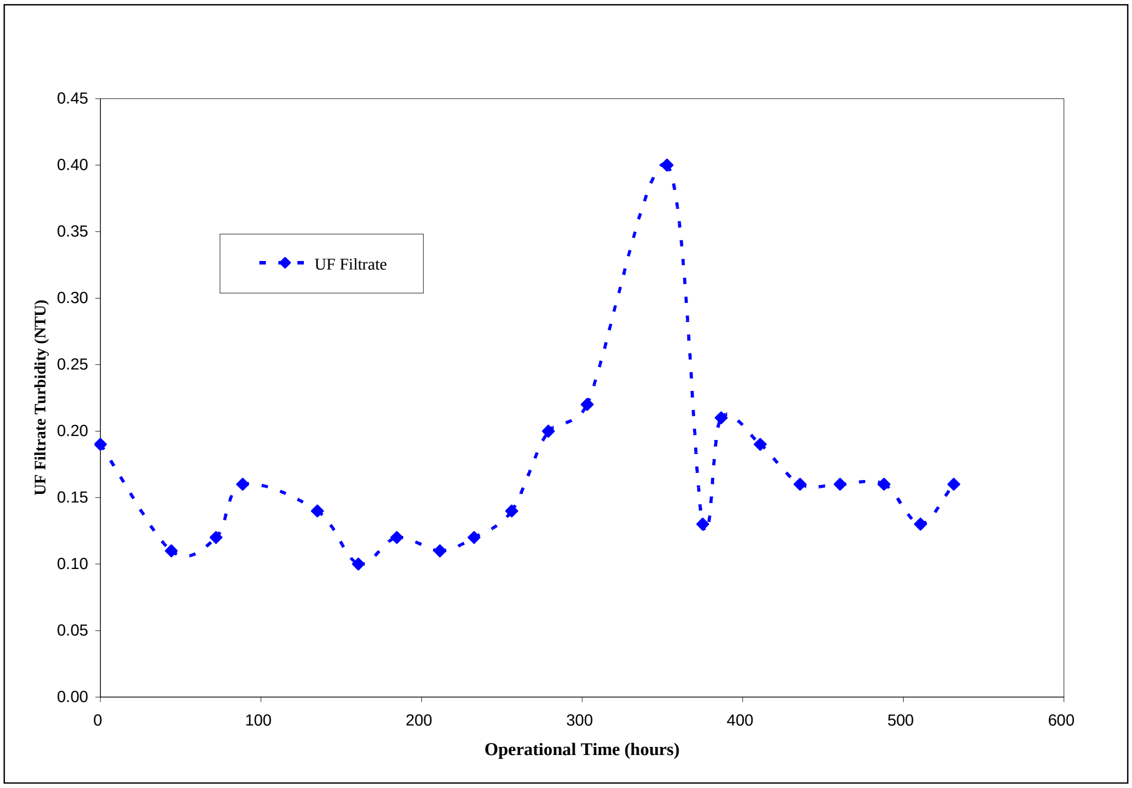


Figure 3-8. East Coast Site UF Filtrate Turbidity.

UF membrane operational experience from both the East and West Coasts Sites studies provide strong support for maintaining continuous chlorine residual through the pretreatment systems to address the high biological activity present in Florida SWUI.

3.4.1.2 MMF Results

Performance of the MMF system was evaluated for the East Coast Site. The performance evaluation focused on the acceptability of the filtrate water quality, relative to feeding a SWRO system.

As mentioned in table 3-2, the MMF was operated at 4 gpm/ft^2 and 8 gpm/ft^2 in the roughing and polishing filters, respectively. Backwashes were performed once every 12 hours on the roughing filters and once every 24 hours on the polishing filter.

The first pass (roughing) filter media consisted of 19 inches of anthracite (1.0-millimeter [mm] effective size with a 1.5 uniformity coefficient), 9 inches of 30-40 sieve size garnet, 9 inches of #12 garnet, and 9 inches of #8 garnet. The second pass (polishing) filter media consisted of 6 inches of anthracite (1.0-mm effective size with a 1.5 uniformity coefficient), 13 inches of filter sand (0.35- to 0.45-mm effective size with a 1.5 uniformity coefficient), 9 inches of 30-40 sieve size garnet, 9 inches of #12 garnet, and 9 inches of #8 garnet.

Ferric sulfate was utilized as a coagulant and injected upstream of the roughing filter. Initial operation of the MMF indicated acceptable water quality could be achieved with a ferric sulfate coagulant dose of 0.5 mg/L as iron (Fe). A target SDI of 4 and a turbidity of 0.5 NTU were the water quality goals set for the MMF system filtrate. These goals were conservative compared to the SWRO membrane manufacturer (Toray) warranty stipulation of SDI less than 5 and turbidity less than 1.0 NTU.

The MMF pretreatment system utilized on the East Coast Site pilot was plagued by mechanical problems and provided little flexibility for optimization of backwash parameters. These factors led to an ineffective backwash regimen that led to failure of the pretreatment system approximately 400 hours into the MMF-SWRO process train test.

SDI data for the MMF filtrate water is presented in figure 3-9. Turbidity results for the MMF filtrate are presented in figure 3-10. As with the East Coast Site UF testing, SDI results on the MMF filtrate water are suspected to be lower than the actual values due to a defective part on the SDI measuring device. For the first 300 hours of MMF operation, filtrate SDI ranged between 1.5 and 2.5, substantially higher than the UF filtrate results indicating the water quality of this MMF system was relatively poor as compared to the UF system tested. After

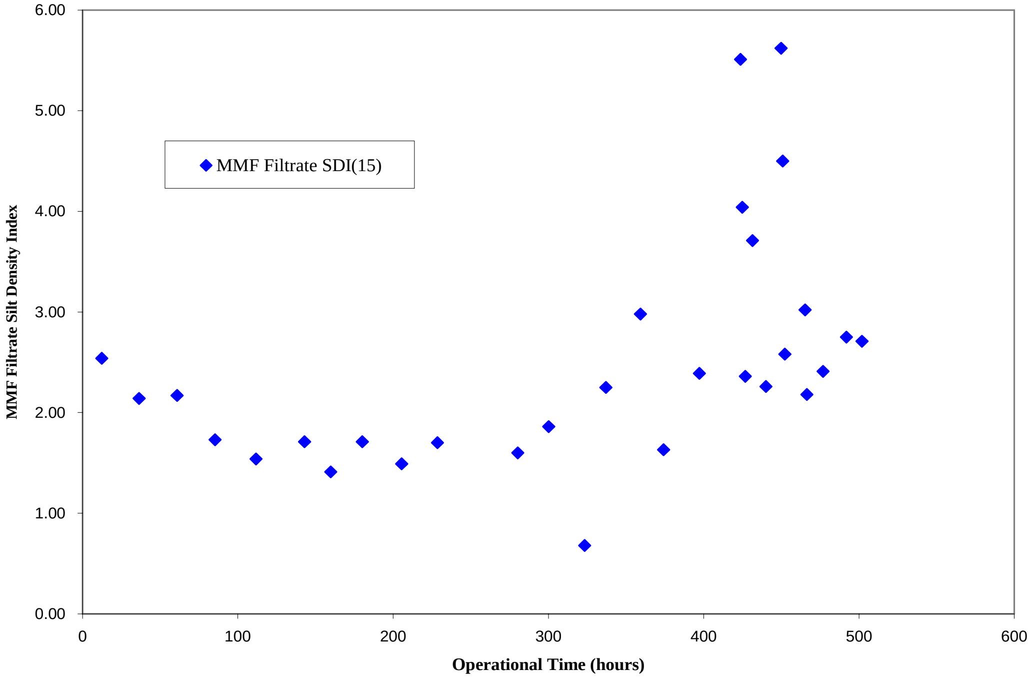


Figure 3-9. East Coast Site MMF Filtrate SDI_{15}.

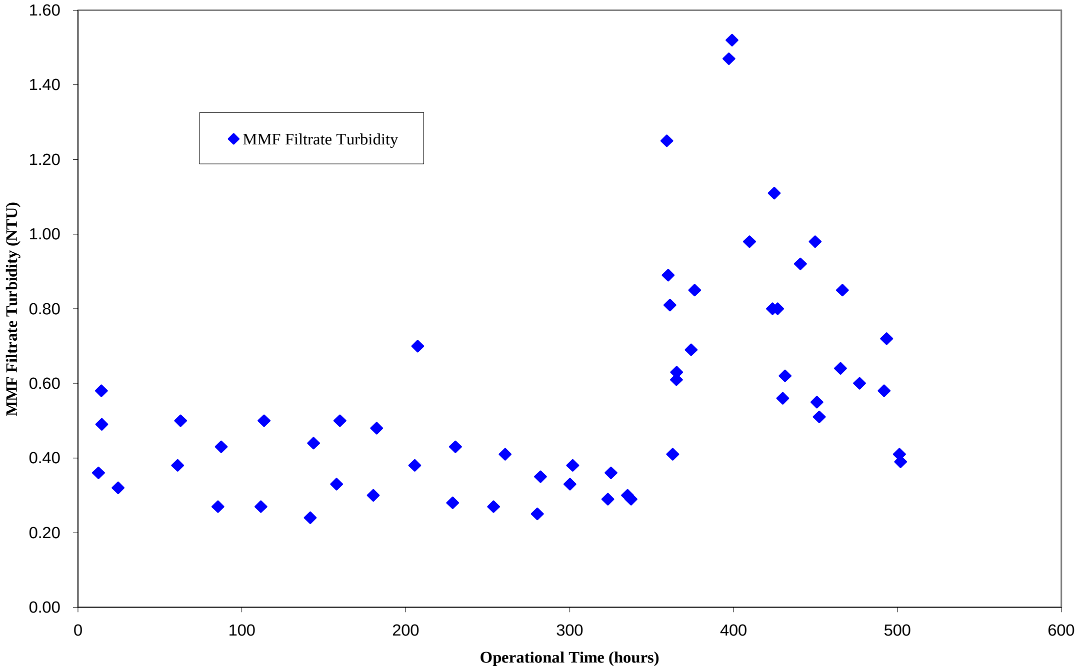


Figure 3-10. East Coast Site MMF MMF Filtrate Turbidity.

300 hours of operation, the performance of the MMF system declined with progressively higher SDI measured on the MMF filtrate. Ferric colored deposits were also noted on the SDI filters during the same period indicating significant breakthrough was occurring with the MMF system. Repeated backwashes and chemical cleanings after the 300-hour point were unable to restore system performance to the initial levels. The turbidity results confirm that the water quality of the MMF filtrate was much lower than that observed on the UF filtrate, even at the start of the testing. MMF turbidity ranged between 0.2 and 0.6 NTU during the first 300 hours of operation.

After approximately 400 hours of operation, the MMF system performance was unable to be recovered for any length of time to meet the performance goals of the system (filtrate water turbidity less than 0.5 NTU and SDI less than 4). Failure to recover MMF pilot system performance was determined to be associated with the limited backwash capabilities of this MMF system. The system utilized did not permit air agitation of the filter bed to assist removal of retained solids. Backwash operations additionally required increasing the roughing filter loading rate by 100% during the backwash cycle. Additionally, the automatic backwashing functions proved to be unreliable and required extensive operator intervention to ensure proper operation. Due to the limitations of this MMF system, an alternative system was selected for performance of the West Coast Site test.

3.4.1.3 SWRO Productivity

A SWRO system may experience a decline in productivity over time due to deposition of foulants such as particles, precipitants or biological material. Productivity is defined by the amount of treated water produced for a given pressure and is presented as the mass transfer coefficient. The MTC of the seawater reverse osmosis membrane was calculated based on the flux and net driving pressure of the system, consistent with American Society for Testing and Materials (ASTM) Standard D4516. This calculated MTC of the SWRO membrane using both pretreatments is presented in figure 3-11. As shown in figure 3-11, the SWRO MTC was more consistent when using UF as pretreatment than using the MMF pretreatment. Fouling is indicated by a decline in MTC or an increase in pressure differential across the feed side of the membrane. It is also seen that the mass transfer coefficients decreased after 230 hours of operation while using the MMF pretreatment, representing a 5–10% decline in performance. No appreciable decline in MTC was noted for the SWRO system using UF pretreatment.

Cleaning frequency was calculated based on a 20% decline in the mass transfer coefficient. Typically, a cleaning frequency is performed following a 10–20% decline in MTC or a 50% increase in feed side pressure differential. The

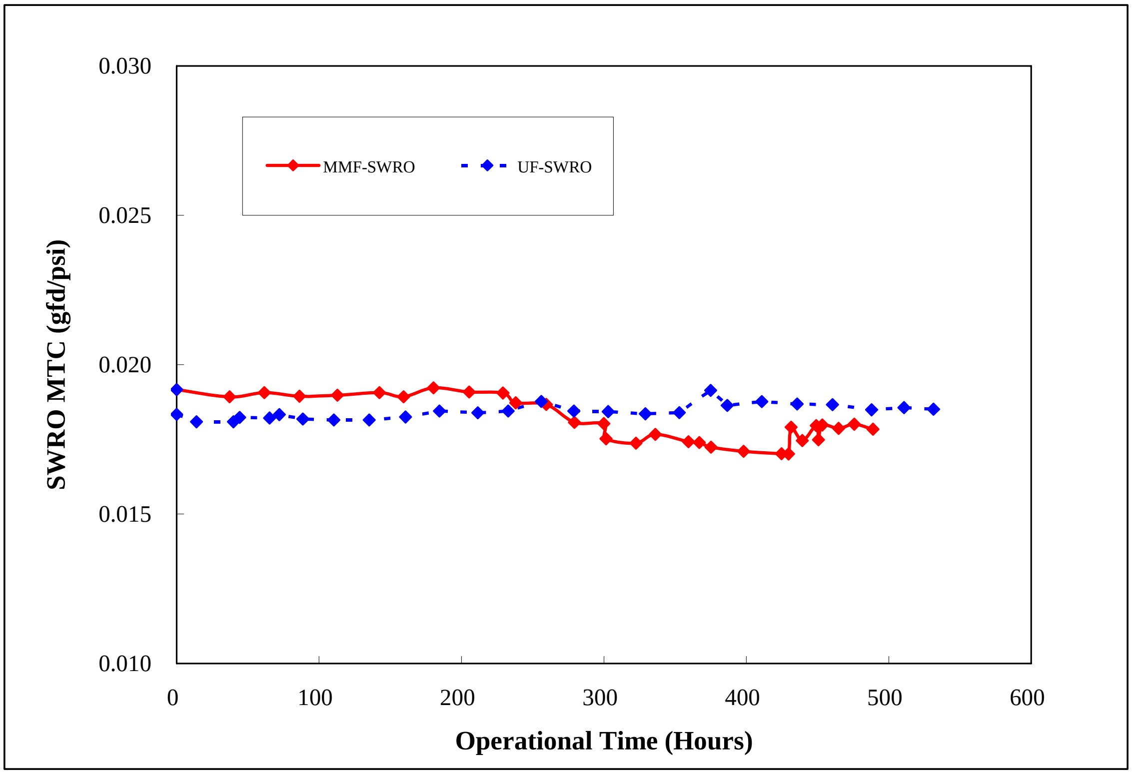


Figure 3-11. SWRO MTC for Both Process Trains UF-SWRO and MMF-SWRO.

calculated cleaning frequency for the MMF-SWRO system was 2 months. No cleaning of the SWRO membranes would be theoretically required when using UF pretreatment; however, typically; a cleaning every 6-18 months would be recommended.

The differential pressure along the feed side of the membrane (figure 3-12) supports the fact that SWRO membrane fouling was observed when using this MMF system for pretreatment. The differential pressure slightly increased after 230 hours; it was observed that the MTC decreased after 230 hours. The differential pressure averaged 5 psi for the first 230 hours and then averaged 9 psi the remaining of the 500-hour testing. This increase in differential pressure shows that particle fouling likely occurred on the SWRO membranes. The differential pressure using UF pretreatment was more consistent averaging 5 psi and varied only from 2 to 9 psi over the 21-day testing.

As presented previously, design criteria for the SWRO were 10 gfd flux and 50% recovery. In addition, there were no acid and/or antiscalant additions. Based on the performance results for the SWRO, these criteria are considered adequate for treatment of the Indian River Lagoon, for either process train.

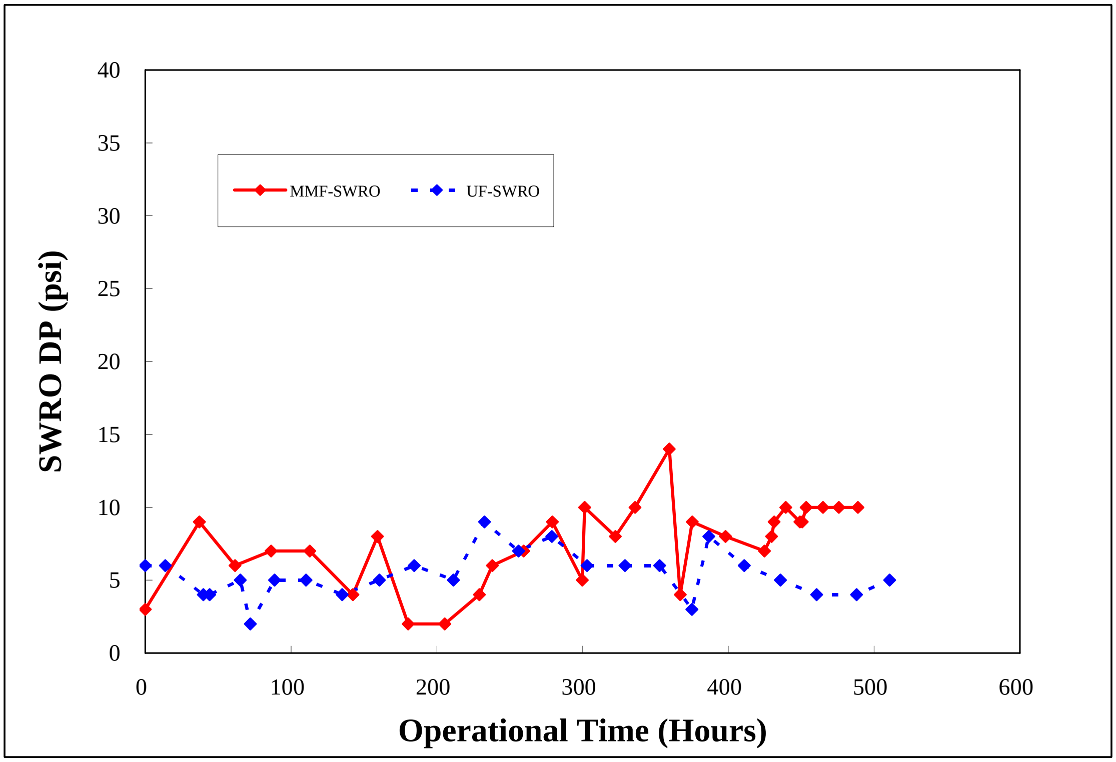


Figure 3-12. SWRO Feed Side Differential Pressure for Both Process Trains UF-SWRO and MMF-SWRO.

The differential pressure on the cartridge filter was also a design criterion that was considered for SWRO plant design. The cartridge filter differential pressure is shown in figure 3-13. In addition, filter replacement is represented on figure 3-13 for both pretreatments. As shown, the differential pressure on the cartridge filter began to increase after 200 hours of operation with the UF pretreatment. Over the length of the UF test, the differential pressure increased from 0.3 to 4 psi. It should be noted that only one set of cartridge filters was used during the 21-day UF testing. On the other hand, cartridge filters were changed three times during the 21-day testing while using MMF pretreatment, and the differential pressure reached 8 psi within a week. Typically, cartridge filters are replaced when the differential pressure reaches 10 to 15 psi, depending on the specifications of the cartridge filter manufacturers. The target replacement frequency in a full-scale facility is no more than once every 3 months. The loading rate of 2.5 gpm per 10 inches on the cartridge filter was lower than the loading rate designed at full-scale plant (2.5 to 5 gpm per 10 inches of cartridge filter), nevertheless, the trend is that the UF pretreatment led to better cartridge filter life expectancy. However, the cartridge filter life expectancy for even the UF system was well below the target.

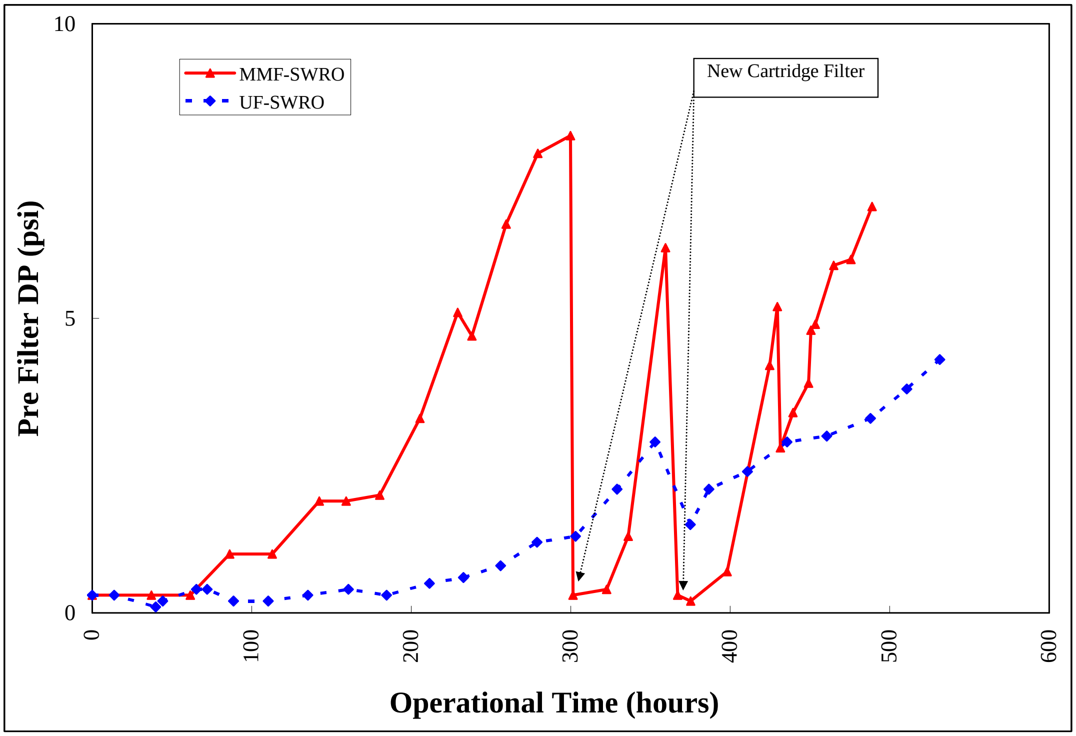


Figure 3-13. Cartridge Filter Differential Pressure for Both Process Trains.

The frequent change of cartridge filters using conventional filtration compared to UF can be explained by the better water quality of the UF system filtrate. The average turbidity of the UF filtrate was less than 0.2 NTU, whereas the average turbidity of the MMF filtrate was 0.56 NTU. In addition, the SDI of the UF filtrate was approximately 1.0 on average compared to approximately 2.5 for the MMF filtrate. This shows the importance of producing high quality water to feed the SWRO system. Even though the MMF filtrate water with a turbidity of 0.56 NTU and a SDI of 2.5 could be considered high quality water in applications other than membrane applications, this water does not have a high enough water quality to result in cost-effective membrane seawater treatment. This filtrate would result in frequent cartridge filter changes and, therefore, high O&M costs. As an example, a 10-MGD water treatment plant operating at 50% recovery would require installation of approximately 4,600 10-inch cartridge filters (20 MGD of feed water and a design criterion of 3 gpm per 10 inches of cartridge filter). At $2.50 per filter and replacement every 2 weeks, the cost in cartridge filters would be $300,000 per year, and this cost does not include labor and shut downs of the SWRO system, when the plant does not produce water.

3.4.1.4 Summary

A flux of 10 gfd and a recovery of 50% with seven elements per pressure vessel appear to be acceptable design criteria for a SWRO plant as demonstrated by the pilot studies on the East Coast Site. There was no need to add acid and/or antiscalant to control fouling of the SWRO system. Further long-term pilot testing at 10 gfd flux is recommended before finalization at this level, particularly if MMF pretreatment is utilized.

Fouling was not observed on the SWRO membranes using UF as pretreatment, whereas fouling was observed using conventional filtration pretreatment. It is likely that particle fouling occurred on the SWRO membranes while using conventional pretreatment. In addition, cartridge filter replacement frequency was higher using conventional pretreatment than using ultrafiltration pretreatment. Ultrafiltration pretreatment was, therefore, more effective than conventional filtration pretreatment in terms of SWRO performance and cartridge replacement. This higher performance using UF is most likely due to the higher water quality of the filtrate from the UF system. Turbidity and SDI were both lower in the UF filtrate than in the MMF filtrate.

During the short duration of the East Coast Site pilot testing, MMF pretreatment system was not able to produce a water quality that could be considered acceptable for SWRO pretreatment. Excessive cartridge filter replacement (at least once every 2 weeks) was needed during the MMF-SWRO pilot test. The UF pretreatment system produced a water quality acceptable for SWRO treatment; however, the cartridge filter replacement frequency appeared to be higher than desirable (approximately once a month). The target cartridge filter replacement frequency in a full-scale facility is no more than once every 3 months.

Additionally, performance was significantly hindered by biogrowth observed in the feed and pretreatment systems during the East Coast Site pilot testing. The short nature of this study allowed for an abbreviated optimization of each system prior to the test performance. Further pilot testing to optimize operational parameters and/or testing additional pretreatments of the feed water can be expected to improve either or both the UF and MMF pretreatment system performance.

3.4.2 West Coast Site Results

The SWRO system was not continuously operated on the West Coast Site due to the poor performance of the pretreatment processes. The ultrafiltration system could not sustain productivity over a long enough period of time without shutting down due to high transmembrane pressure, therefore requiring chemical cleaning. Due to the repeated fouling of the UF system, only limited SWRO system operation could be achieved with the UF pretreatment system. The ultrafiltration system was able to produce good water quality with turbidity less than 0.1 NTU and SDI less than 4. The conventional MMF filtration system could sustain productivity; however, it could only produce an SDI of less than 4 after approximately 50 hours of ripening and under the best scenario (see section 3.4.2.2). For these reasons, the SWRO system was not operated in conjunction with the MMF pretreatment system. The results of the UF and MMF systems are presented in the following subsections.

3.4.2.1 UF Results

Performance of the UF system was evaluated on the West Coast Site. The performance evaluation is focusing on the productivity of the system, since this was the main issue encountered during optimization of the system.

Different operating conditions on the UF system tested on the West Coast Site are presented in table 3-6, and the corresponding UF productivity results are presented in appendix H. The performance of the ultrafiltration pretreatment system was hindered by increasingly frequent fouling problems that have required chemical cleanings of the Norit Americas-supplied UF membrane. In addition, the effectiveness of the chemical cleanings degraded during the course of this study. Different chemical cleaning regimens were tested to restore the initial transmembrane pressure with limited success. By November 25, 2003, chemical cleaning frequency had increased to being required after 8 to 12 hours of operation; therefore, no tests could be effectively run. Results of the chemical cleanings showed permeability was not being restored to normal specifications.

Table 3-6. West Coast Site UF Operating Conditions

Period	Flux (gfd)	BW Frequency (min)	CEB Frequency (hours)	Chemical
11/02/03 – 11/06/03	36	20 (45-second duration)	1 CEB/16 hours 2 CEB/16 hours	Hydrochloric acid (HCl) and sodium hypochlorite (NaOCL)
11/07/03 – 11/09/03	36	20 (45-second duration)	2 CEB/8 hours	HCl/NaOCl
11/09/03 – 11/11/03	36	15 (45-second duration)	6	HCl/NaOCl
11/12/03 – 11/14/03	36	20 (60-second duration)	6	HCl/NaOCl
11/14/03 – 11/18/03	36	20 (60-second duration)	4	HCl/NaOCl
11/18/03 – 11/20/03	36	20 (60-second duration)	1 CEB/8 hours 2 CEB/8 hours	HCl

Several backwash and chemically enhanced backwash regimens (table 3-6) were attempted with varying degrees of effectiveness, but none were found to be successful.

The backwash frequency varied from 15 to 20 minutes with a duration from 45 to 60 seconds, depending on the test (table 3-6). The chemically enhanced backwash frequency varied from once every 4 hours to once every 16 hours using different chemicals. These tested regimes result in low recovery for the pretreatment system and high consumption of chemicals that would not be practical at full-scale and would result in high O&M costs.

Because the UF system could not sustain productivity over extended periods of time, there was insufficient flow available to feed the SWRO system continuously. Due to the repeated shutdowns from UF membrane fouling and the final fouling event which prevented further UF pretreatment operation, the SWRO system was only able to be operated intermittently for 330 hours.

The reasons for the severe fouling of the UF pretreatment system may include biological fouling, particle plugging and/or iron fouling, improper backwash, and/or chemical procedures. Extensive evaluations of cleaning methods to restore performance were conducted. The manufacturer, Norit Americas, was consulted and co-participated in evaluating fouling mechanisms. No definitive cause for poor UF performance was determined. It should be noted that the when the membranes were taken out of the pressure vessel on the East Coast Site, red coloration was observed on the feed side of the module suggesting iron plugging. A “slimy” layer was also observed in the pressure vessel suggesting that microorganisms could have caused fouling of the membranes.

The membranes were also autopsied, and damaged fibers were found (appendix I). These slices and punctures may explain filtrate water quality issues but do not explain the high observed rates of fouling. This type of damage to fibers has been observed in other MF and UF pilot systems treating seawater and may be due to barnacle shards that pass through the screening process and into the UF module. For this reason, a finer mesh screen was used during the second phase of this project (i.e., at the West Coast Site).

SDI data for the UF filtrate water on the West Coast Site is presented in figure 3-14. Turbidity results for the UF filtrate water on the West Coast Site are presented in figure 3-15. The SDI results for UF filtrate on the West Coast Site pilot varied between 0.2 and 4 and were substantially higher than results measured on the East Coast Site. The UF filtrate water turbidity results on the West Coast Site are comparable to the East Coast Site results (typically between 0.1 and 0.2 NTU). This further supports the conclusion that SDI values measured on the East Coast Site were lower than the actual values. Based on the turbidity

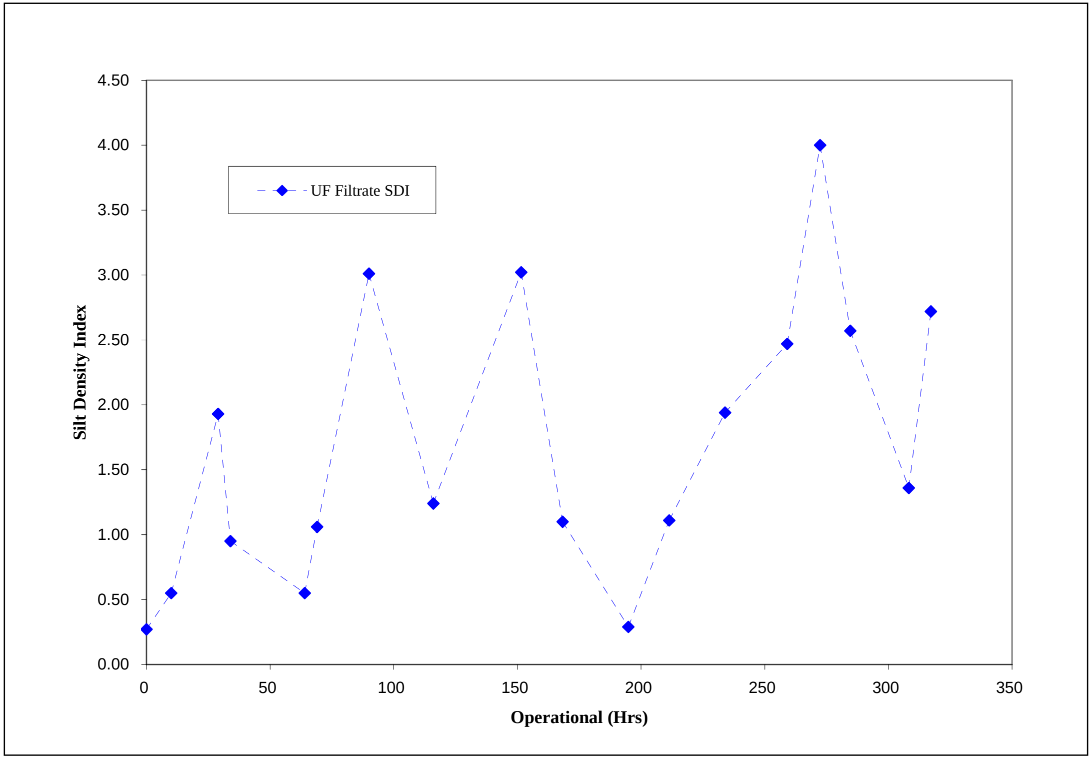


Figure 3-14. West Coast Site UF Filtrate SDI$_{15}$.

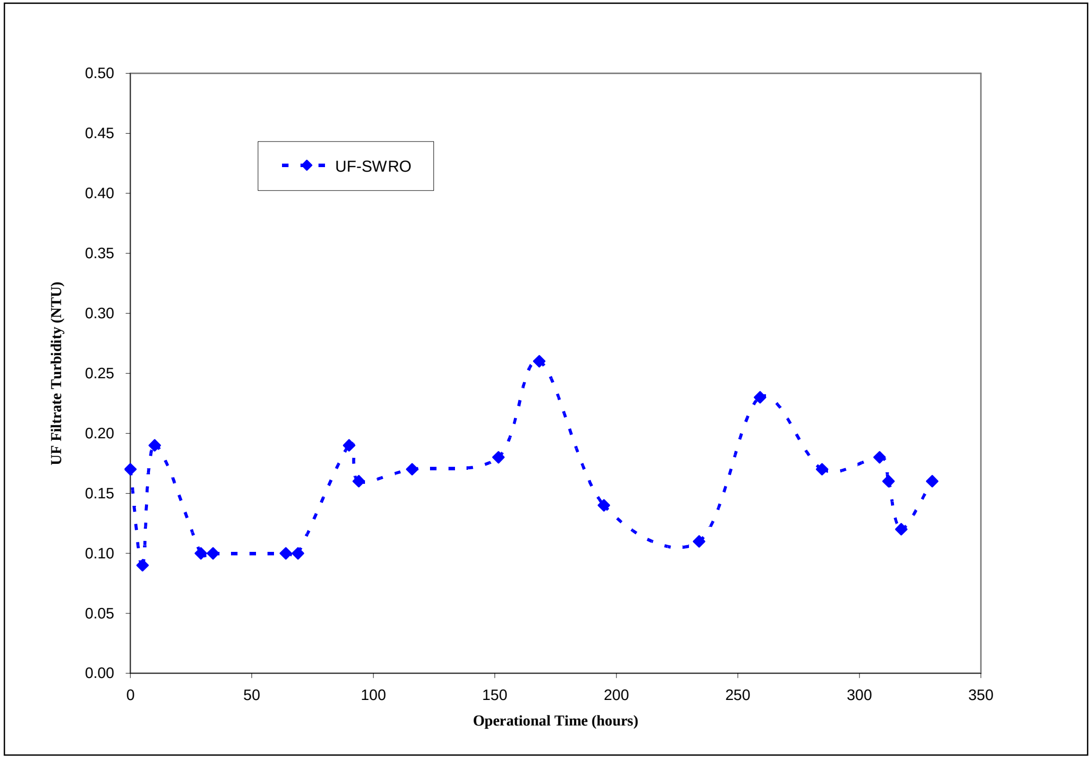


Figure 3-15. West Coast Site UF Filtrate Turbidity Results.

results, the performance of the UF membrane from a water quality perspective were relatively similar on both the East and West Coast Site pilot.

Performance of the MMF system was evaluated for the West Coast Site. The performance evaluation focused on the acceptability of the filtrate water quality, relative to feeding a SWRO system. Key parameters were turbidity and SDI, since these were the main issues encountered during optimization of the system.

As mentioned in table 3-3, the conventional filter was operated at 2 gpm/ft^2 and 4 gpm/ft^2 in the roughing and polishing filters, respectively. A backwash was performed each time the differential pressure reached 10 psi or after 100 hours of operation. The media consisted of 40 inches of sand (0.6-mm effective size with a 1.5 uniformity coefficient) in the first pass (roughing filter) and 20 inches of sand (0.6-mm effective size with a 1.5 uniformity coefficient) and 20 inches of anthracite (0.9-mm effective size with a 1.5 uniformity coefficient) in the second pass (polishing filter).

3.4.2.2 MMF Results

An Amiad strainer was installed prior to the roughing filter to sieve all large particles, shells, vegetation and debris from the seawater to protect the sand filter. A 200-µm strainer mesh size was used initially. The 200-µm mesh size resulted in a fouling rate that required excessive backwashing (twice a day) and maintenance. The size of the mesh was then changed to 300 µm and required approximately one backwash a day to maintain adequate operation.

The different operating conditions for the 16 runs completed during optimization are presented in table 3-7. The optimization of the conventional filter was performed to produce filtered water with a SDI of less than 4 and a turbidity of less than 0.3 NTU. The SDI goal was conservative compared to the SWRO membrane manufacturer (Toray) warranty stipulation of SDI less than 5. The turbidity goal was set at 0.3 NTU, which is below the membrane manufacturer recommendation (<1 NTU). Based on the results of the East Coast Site MMF pretreatment testing, these goals were determined to be the minimum required to warrant testing of the MMF filtrate on a SWRO system. Figure 3-16 shows the SDI of the polishing filtrate, and figure 3-17 shows the turbidity of the raw water, feed water, roughing filtrate, and polishing filtrate.

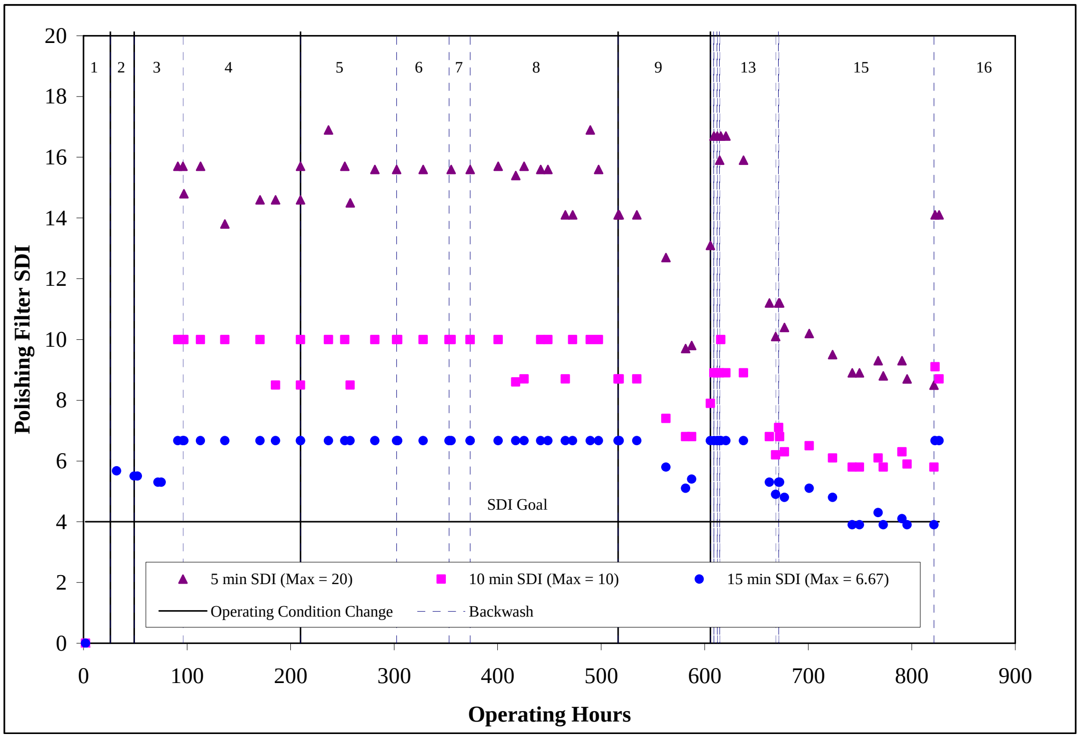


Figure 3-16. West Coast Site SDI of Polishing Filtrate (5-minute, 10-minute, and 15-minute SDIs.

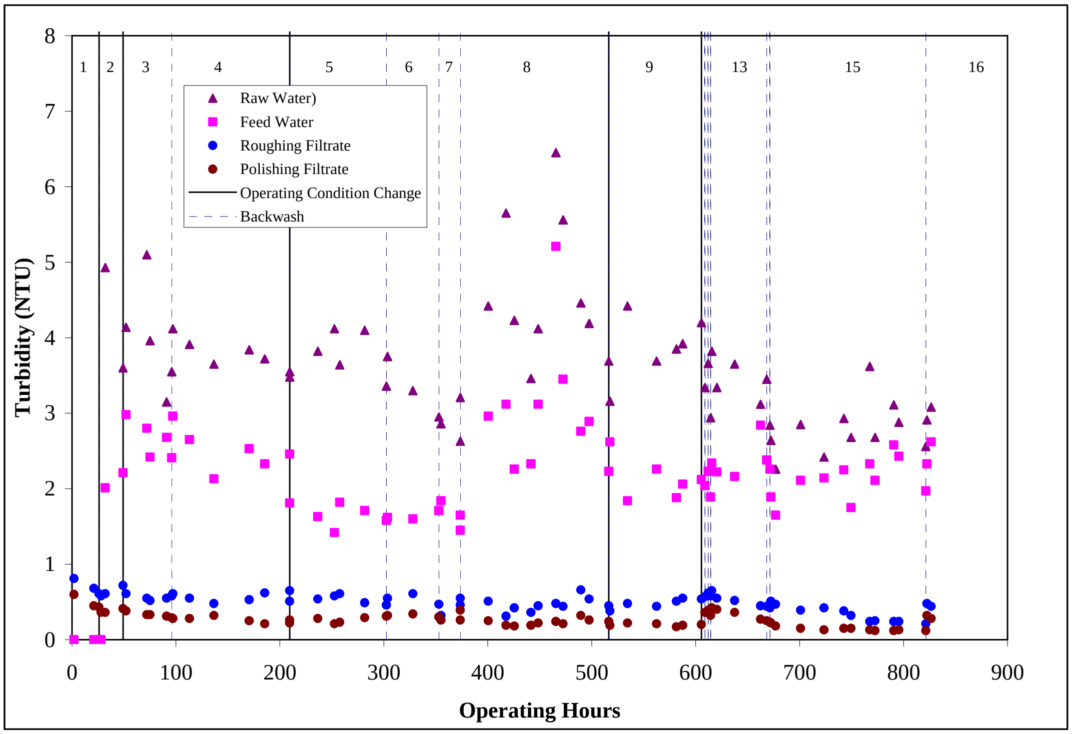


Figure 3-17. West Coast Site Turbidity of Raw Water, Feed Water, Roughing Filtrate, and Polishing Filtrate.

Table 3-7. Operating Conditions of the MMF System

Run	Acid Addition	Coagulant Dose (mg/L)	Operation Time (hours)
1	No Acid	0	26
2	pH 6.8	1.5	23
3	pH 7.2	1.5	47
4	pH 7.2	1.5	113
5	pH 7.2	0.8	93
6	pH 7.2	0.8	50
7	pH 7.2	0.8	20
8	pH 7.2	0.8	143
9	No Acid	0.4	89
10	No Acid	0.6	3
11	No Acid	0.6	3
12	No Acid	0.6	2
13	No Acid	0.6	54
14	No Acid	0.6	3
15	No Acid	0.6	150

It was observed that the 15-minute SDI was >6.67 most of the time (figure 3-16), which is the maximum value for a 15-minute SDI test, for the first eight runs when the pH was lowered to 6.8 or 7.2 units and when the coagulant dose was higher than 0.8 mg/L. Once no acid was added and the coagulant dose was lowered to 0.6 mg/L or 0.4 mg/L, the 15-minute SDI was then measurable and lower than 6.67. However, the SDI did not reach a value of less than 4 after 50 hours of operation as shown in run 15.

The turbidity of polishing filtrate averaged 0.26 NTU and varied from 0.12 to 0.45 NTU (figure 3-17). The observed turbidity in the polishing filtrate is consistent with membrane manufacturer recommendations. Membrane manufacturers typically recommend a turbidity of less than 1 NTU in the feed water of a reverse osmosis system. In addition, the turbidity was also below the goal of 0.3 NTU. It should be noted that the SDI was lower than 4.0 only when the turbidity was lower than 0.20 NTU.

Due to the high SDI, higher than the goal for this study (<4) and the membrane manufacturer recommendations (<5), the filtrate water quality was, therefore, not deemed adequate to feed the SWRO system. Feeding this filtrate with this low water quality to the SWRO system would have likely led to rapid fouling of the cartridge filters and potentially fouling of the SWRO membranes.

3.4.2.3 SWRO Productivity

Due to the high SDI during MMF pretreatment testing, higher than the goal for this study (<4) and the membrane manufacturer recommendations (<5), the filtrate water quality from the MMF was not deemed adequate to feed the SWRO system. Feeding the MMF filtrate with this low water quality to the SWRO system would have likely led to rapid fouling of the cartridge filters and potentially fouling of the SWRO membranes. No comparative performance analysis of SWRO fouling potential between the MMF-SWRO process train and UF-SWRO process train could be made from the West Coast Site pilot results.

Additionally, the UF system could not sustain productivity over extended periods of time; there was insufficient flow available to feed the SWRO system continuously. Due to the repeated shutdowns from UF membrane fouling and the final fouling event which prevented further UF pretreatment operation, the SWRO system did not operate long enough to provide an acceptable evaluation of the filtrate water quality for RO treatment. Repeated shutdowns interfered with sampling, monitoring, and data collection on the SWRO system during the abbreviated testing with the UF pretreatment. For these reasons, the limited data presented in this section does not provide an acceptable evaluation of the UF filtrate water suitability for RO treatment.

As presented previously, design criteria for the SWRO were 10-gfd flux and 50% recovery. In addition, there were no acid and/or antiscalant additions. A SWRO system may experience a decline in productivity over time due to deposition of foulants such as particles, precipitants, or biological material. Productivity is defined by the amount of treated water produced for a given pressure and is presented as the mass transfer coefficient. The MTC of the seawater reverse osmosis membrane was calculated based on the flux and net driving pressure of the system, consistent with ASTM Standard D4516. This calculated MTC of the SWRO membrane for the UF pretreatment is presented in figure 3-18. As shown in figure 3-18, the SWRO MTC appeared to be decreasing during the 330 hours of UF-SWRO process train operation; however, the limited duration of the test did not provide sufficient data to calculate a cleaning frequency.

As shown in figure 3-19, differential pressure along the feed side of the membrane did not appear to increase during the 330 hours of UF-SWRO process train operation; however, the limited duration of the test did not provide sufficient data to calculate a cleaning frequency. The differential pressure across the feed side of the membrane averaged 7 psi during the 330 hours of testing.

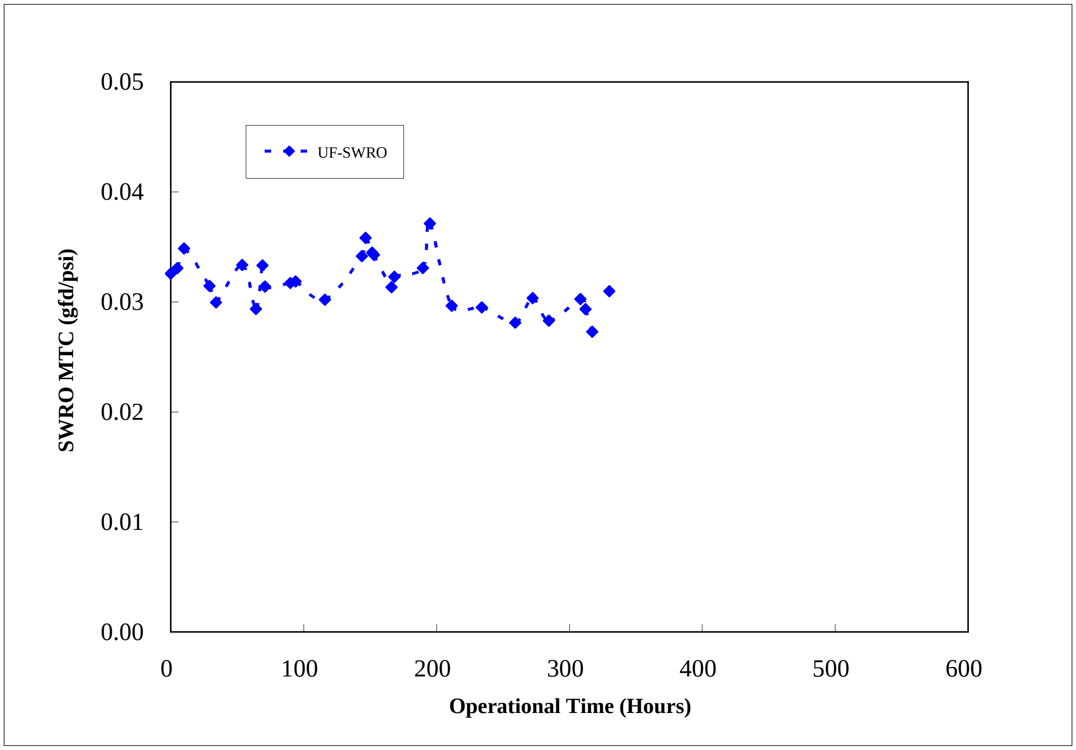


Figure 3-18. MTC for the UF-SWRO Process Train.

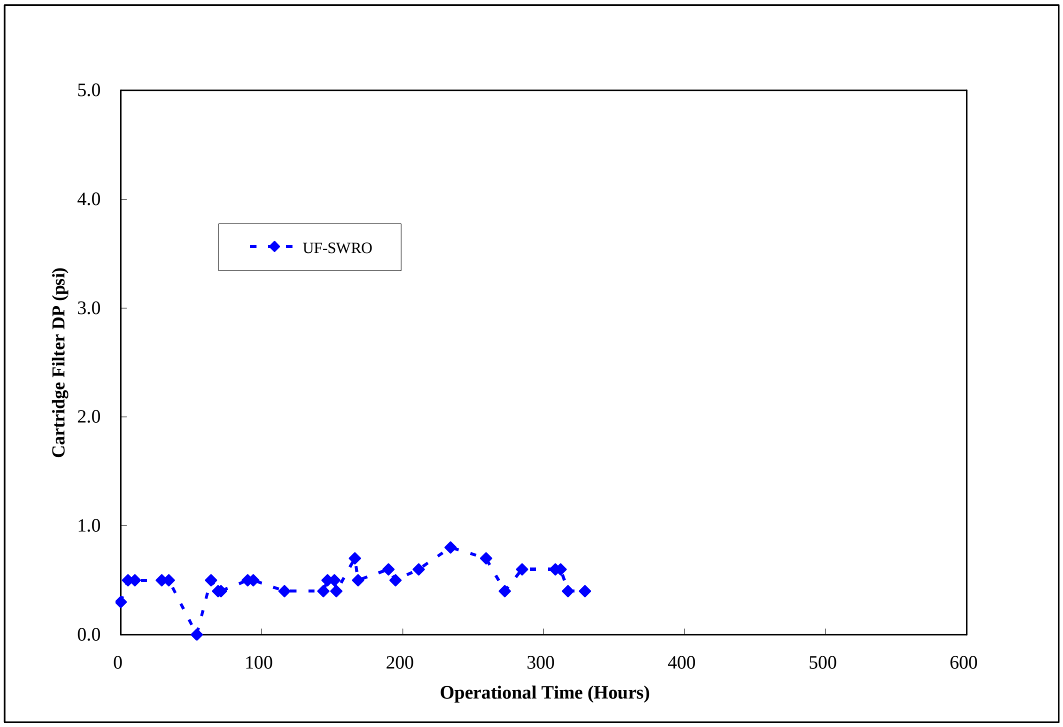


Figure 3-19. Cartridge Filter Differential Pressure for UF-SWRO Process Train.

The differential pressure on the cartridge filter was also a design criterion that was considered for SWRO plant design. The cartridge filter differential pressure is shown in figure 3-20. As on the East Coast Site, the cartridge filter differential pressure remained relatively constant during the first 200 to 300 hours of operation. However, severe fouling of the UF membrane cut short the testing before a determination could be made if operational techniques to reduce biogrowth produced longer cartridge filter replacement time.

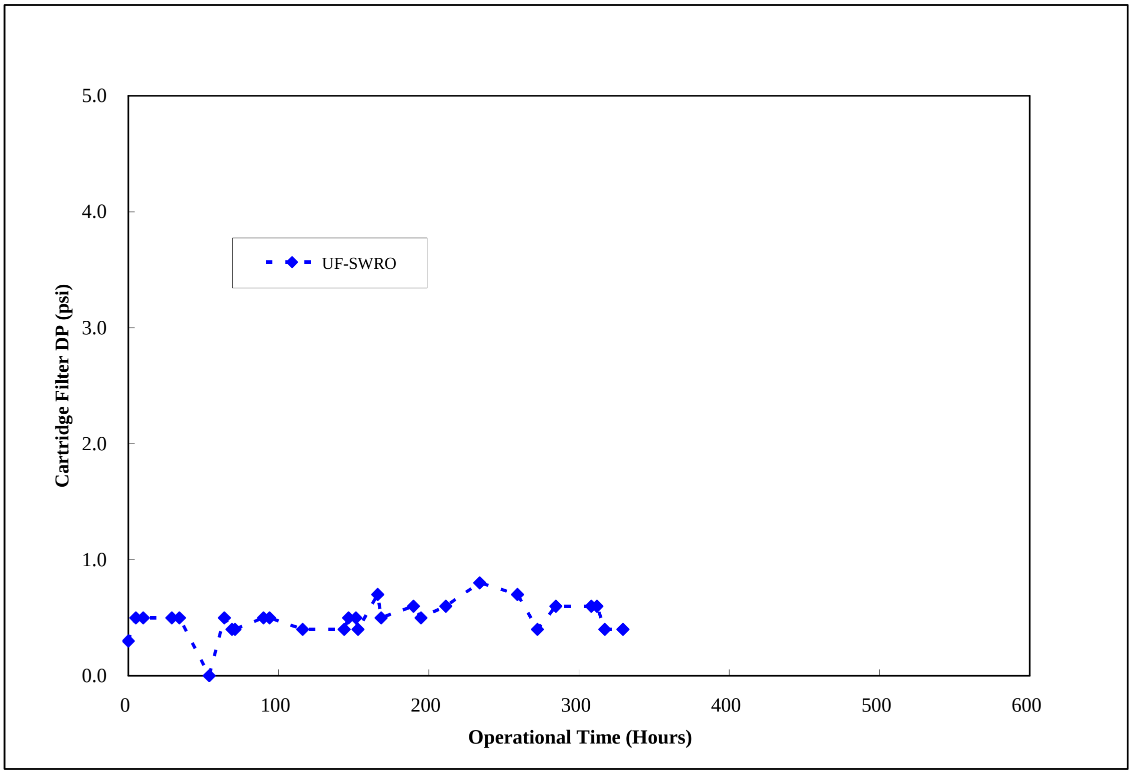


Figure 3-20. Cartridge Filter Differential Pressure for UF-SWRO Process Train.

3.4.2.4 Summary

Due to extensive shut downs of the UF system and the impracticability of cleaning it every day, the UF system could not sustain productivity over extended periods of time on the West Coast Site; there was insufficient flow available to feed the SWRO system continuously. Due to the repeated shutdowns from UF membrane fouling and the final fouling event which prevented further UF pretreatment operation, the SWRO system did not operate long enough to provide an acceptable evaluation of the UF filtrate water quality for RO treatment.

The SWRO system could not be operated on the West Coast Site with the MMF system, due to the poor water quality of the conventional MMF filtrate. After over 16 filtration runs and 800 hours of operation of the MMF system, SDI goals were not met. The filtrate quality from the multimedia filtration system was not adequate to operate an RO system and allow completion of a 30-day SWRO pilot experiment as originally planned. The quality of the filtrate from the multimedia filter system could be optimized so that the water quality goals are achieved. This would require more extensive studies using different combinations of pH, coagulants, and possibly polymers to shorten the ripening stage after backwash and to be able to operate a SWRO system continuously.

Even though the Norit UF system was not successful at completing the pilot test, the potential of this technology, and the Norit UF system in particular, cannot be adequately judged given the time constraints of this study. A full-fledged pilot study with adequate time to perform system optimization and evaluation of additional pretreatment processes can be expected to improve the system performance over the observed data. In addition, the performance of UF/MF systems vary by vendor technologies and site specific conditions, so the performance of this UF system may not be indicative of the general performance of this technology on the West Coast Site SWUI water.

3.5 Significance to Water Industry

The assessment presented in this section illustrates that the SWRO system showed better performance in terms of productivity while using a UF system as pretreatment to SWRO than using conventional filtration pretreatment. The SWRO system did not show any fouling when using UF as pretreatment, whereas it showed a slight fouling when the conventional filtration process was used as pretreatment. Production of high pretreatment water quality is a key parameter in the implementation of a seawater treatment plant. Poor pretreatment water quality would result in high cartridge filter replacement frequency and SWRO membrane cleaning and, therefore, high O&M costs.

In addition, the pretreatment assessment shows that seawater treatment is site specific and that processes that could be operated on one site could not be operated on another. Therefore, implementation of a seawater treatment plant would require a pilot study to define pretreatment technology and operating conditions and to assess SWRO membrane fouling.

4.0 Pathogen Removal by Seawater Reverse Osmosis

Due to the limited data on removal of pathogens by SWRO, a challenge test was developed to quantify log removal of pathogen surrogates. This information would support development of log removal credits by regulatory agencies and compliment the body of knowledge already in existence relative to freshwater sources and lower pressure RO systems. Viral phages were selected as the organisms of choice given their small size and were used to determine the rejection potential of each of the three treatment processes associated with this pilot project. These three systems included two pretreatment systems prior to a seawater reverse osmosis system, ultrafiltration and conventional media filtration, and a seawater reverse osmosis system. The virus challenge was performed utilizing three different viral phages, representing seawater pathogen surrogates.

The goal of the virus challenge was to quantify the capabilities of UF, conventional media filtration, and RO systems (independent of each other) to reject pathogen-sized contaminants. The rejection capabilities of the two process trains (UF-SWRO and MMF-SWRO) were then assessed and compared to current and proposed pathogen-related water quality regulations. The goal of this virus challenge test was also to demonstrate the significance of these results to the water industry.

This section of the report presents the pathogen removal capabilities of UF conventional media filtration and seawater reverse osmosis processes along with the project goals set forth, the methodologies applied in performing test, the results, and the significance of the results to the water industry.

4.1 Methodology

To achieve the project goals, viral challenge tests were performed to assess the log removal capabilities for the UF, MMF, and SWRO systems. First, a pH tracer study was performed on each system to determine the residence time of each system and how frequently samples should be collected for virus analysis. Then, the actual virus challenge test was performed on each system.

4.1.1 pH Tracer Study

The pH tracer test was performed by injecting 33% HCl acid into the feed water of each system and monitoring pH in the feed water and the filtrate for the two pretreatment processes and the permeate of SWRO system every 15 seconds. Monitoring pH was stopped when the pH in the filtrates and the permeate dropped and reached steady state. Upon completion of the acid pH tracer test, timing, and frequency of feed water, filtrate waters and permeate water were determined. Further details on the pH trace test protocol are presented in appendix E.

4.1.2 Virus Challenge Testing

For the virus challenge, three virus phages were selected: MS-2 (30 nm RNA virus specific for *Escherichia coli*, C3000: MS-2 is a pathogen to *E. coli* C3000 but harmless to the human being), Fr (28 nm RNA virus specific for *Escherichia coli* Migula: Fr is a pathogen to E.Coli Migula but harmless to the human being), and PRD-1 (68 nm DS DNA virus specific for *Salmonella typhimurium*: PRD-1 is a pathogen to *Salmonella* but harmless to the human being).

These viruses were grown up to 10^{+9} – 10^{+10} plaque forming units (pfu)/mL in the laboratory prior to the day of the challenge (Snustad and Dean, 1971). The stocks were kept at 4 degrees Celsius (°C) until use. On the challenge day, 300 mL of each phage stock was mixed together in a sterile 1,000-mL container. A sample of this solution was taken as diluted with feed and labeled as "Diluted Feed." This sample was further diluted to 1/100 in phosphate buffer solution (PBS) and labeled as "Experimental Initial." Sample was also taken prior to the virus spike and labeled as "Background" to check if there are any naturally occurring bacteriophages in feed water. The bacteriophages were then injected into the systems at the rate of 120 milliliters per minute (mL/min) for a 5:00-minute duration for the UF and SWRO systems. Ten-mL samples for the influent (raw feed) were taken for times T = 1, 2, 3, 4, and 5 minutes. The UF filtrate and permeate samples were taken at T = 1, 2, 3, 4, 5, 6, 7, and 8 minutes. Ten-mL samples for the MMF feed water were taken at times T =1, 2, 4, 5, and 6 minutes., whereas the MMF first stage filtrate were taken at times T = 15, 25, 32, 42, 52, 6,2 and 72:00 minutes, and the MMF second stage filtrate were taken at times T = 25:00, 35:00, 45:00, 55, 65, 75, and 85 minutes. Finally, another sample was taken from the "Diluted feed," diluted 1/100 in PBS and labeled "Experimental Final." The samples were preserved, stored at 4 °C, and transported to the laboratory for analysis. Further details on the virus challenge protocol are presented in appendix E.

4.1.3 Operating Conditions

Operating conditions for the UF, MMF, and SWRO systems during the virus challenge are shown in table 4-1. These operating conditions are representative of the operating conditions that would be implemented in a full-scale seawater membrane treatment plant. A constant flux of 37 gfd was maintained throughout the entirety of the virus challenge test on the UF system, and loading rates of 2 gpm/ft^2 and 4 gpm/ft^2 were maintained on the first stage and the second stage of the MMF system, respectively. The SWRO system was operated at a flux of 10 gfd and a recovery of 50%. The specifications of each system were presented earlier in section 2 of this report. No coagulant or other chemicals were added in the feed water to the UF system and MMF system to determine log rejection of the membrane or the media. No acid and antiscalant were added to the feed water of the SWRO system to obtain true log rejection of the seawater membrane. In addition, the cartridge filters before the seawater membranes were also removed before completing the virus challenge testing.

Table 4-1. Operating Conditions of the Three Systems During Virus Challenge Testing

	UF	MMF	SWRO
Filtrate and Permeate Flow (gpm)	19	18	3.7
Flux (gfd)	37	NA	10
Surface loading rate (gpm/sqft)	NA	2 (first stage) 4 (second stage)	NA
Recovery (%)	80	90	50
Pressure (psi)	5	28	645

4.2 Results

This section of the report presents the data from the pH tracer test and the virus challenge test. Both tests were performed following the methodology as mentioned in appendix E.

4.2.1 pH Tracer Study

As mentioned previously, the pH tracer study was to determine the timing and frequency of sampling during the virus challenge test. The results of the pH tracer study are presented in figures 4-1 and 4-2. As shown in figures 4-1 and 4-2, acid was added in the feed water so that the pH dropped to approximately 6.9. The residence time was defined for the purpose of this virus challenge test as the time it takes to reach the same pH of 6.9 in the filtrate and permeate. As seen in figures 4-1 and 4-2, the residence time in the UF and MMF systems operated in

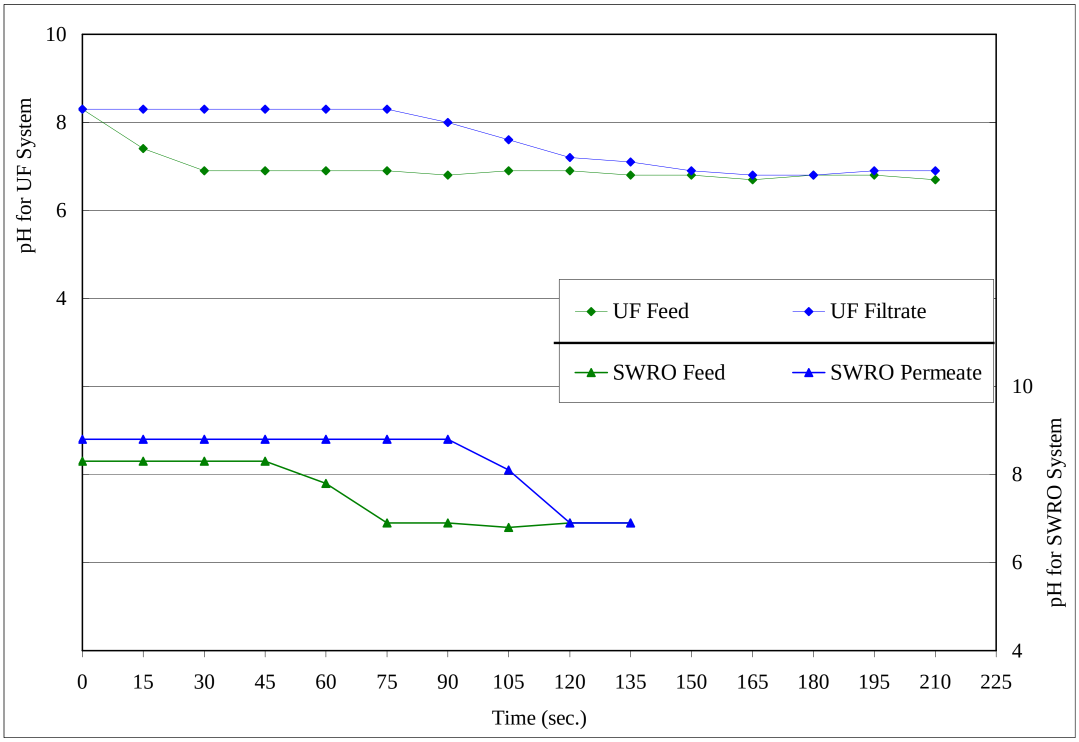


Figure 4-1. pH Tracer Result for the UF and SWRO Systems.

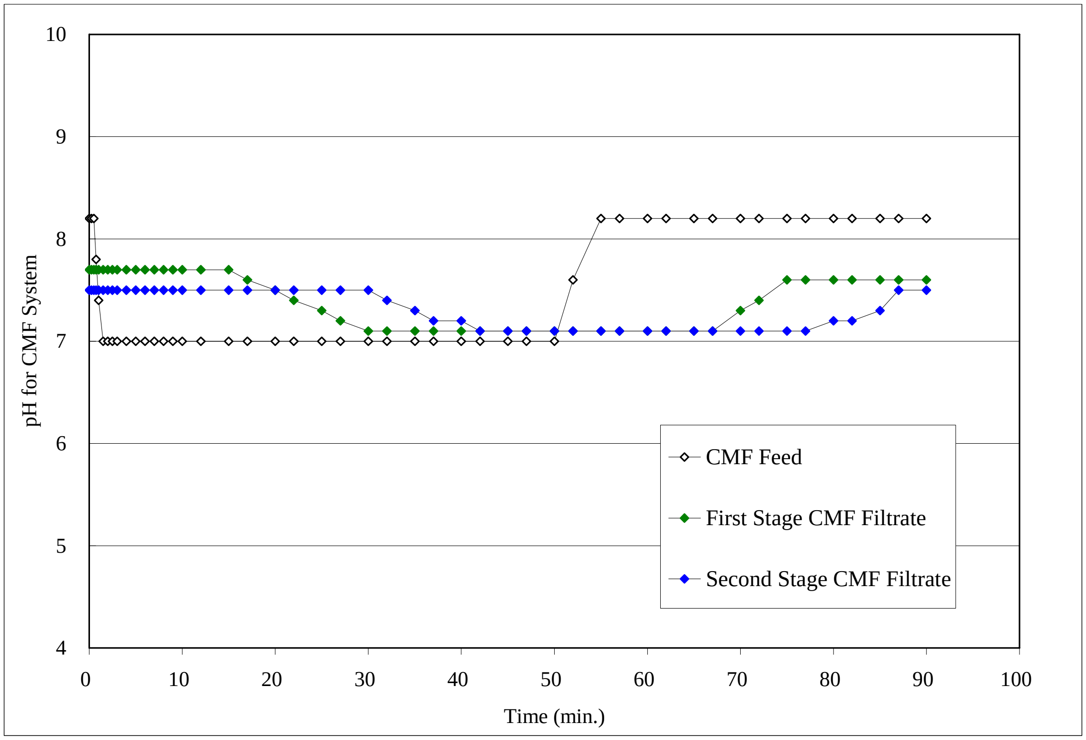


Figure 4-2. pH Tracer Result for the MMF System.

the conditions described in the previous section are approximately 2 minutes and 40 minutes, respectively. The residence time for the SWRO system was found to be 2 minutes.

Based on this pH tracer study, it was decided to analyze the feed water every minute for 5 minutes for the UF and SWRO systems. It was also established that UF filtrate and SWRO permeate would be sampled and analyzed for the virus challenge test every minute for 8 minutes. Regarding the MMF system, the feed water was analyzed every minute for 6 minutes, and the filtrate every 10 minutes for 80 minutes.

4.2.2 Virus Challenge Test Results

The results of the virus challenge test performed on the three process systems using three bacteriophages: MS-2 (30 nm RNA virus specific for *Escherichia coli* C3000), Fr (28 nm RNA virus specific for *Escherichia coli* Migula), and PRD-1 (68 nm DS DNA virus specific for *Salmonella typhimurium*) are presented within this subsection. Figures 4-3, 4-4, and 4-5 present the log rejection results of the UF system, the MMF system, and the SWRO system, respectively. All detailed results of the virus challenge tests are presented in appendix F.

The UF system showed a rejection consistently higher than 6-log for the three viruses spiked in the feed water of the system. The log rejection varied from 6.4 to 7.3 for the three viruses demonstrating a very consistent rejection. In addition, the UF showed a slightly higher rejection, approximately 0.5-log, for MS-2 and Fr than for PRD-1. It should be noted that these rejections are minimum rejections since the virus concentrations in the filtrate were below the detection limit (0.5 pfu/mL) of each virus. Therefore, higher log rejections could have been observed if the concentrations in the feed water were higher. Even though the three viruses have different sizes, there is no relationship between the virus log rejection by the UF membrane and the virus size. The virus size of the Fr, MS-2, and PRD-1 are 28, 30, and 64 nm, respectively, and therefore at least twice the size of the UF pores (10 nm). The fact that no viruses were detected in the filtrate indicates that the pore size distribution of the UF membrane is relatively narrow and that there are virtually no pores with a size larger than 0.02 µm (20 nm).

The MMF system showed varying rejection capabilities between 1.5- and 3.1-log for the three viruses. The log rejection of the MMF system was calculated using the virus concentration in the second stage filtrate at T = 45 minutes with virus

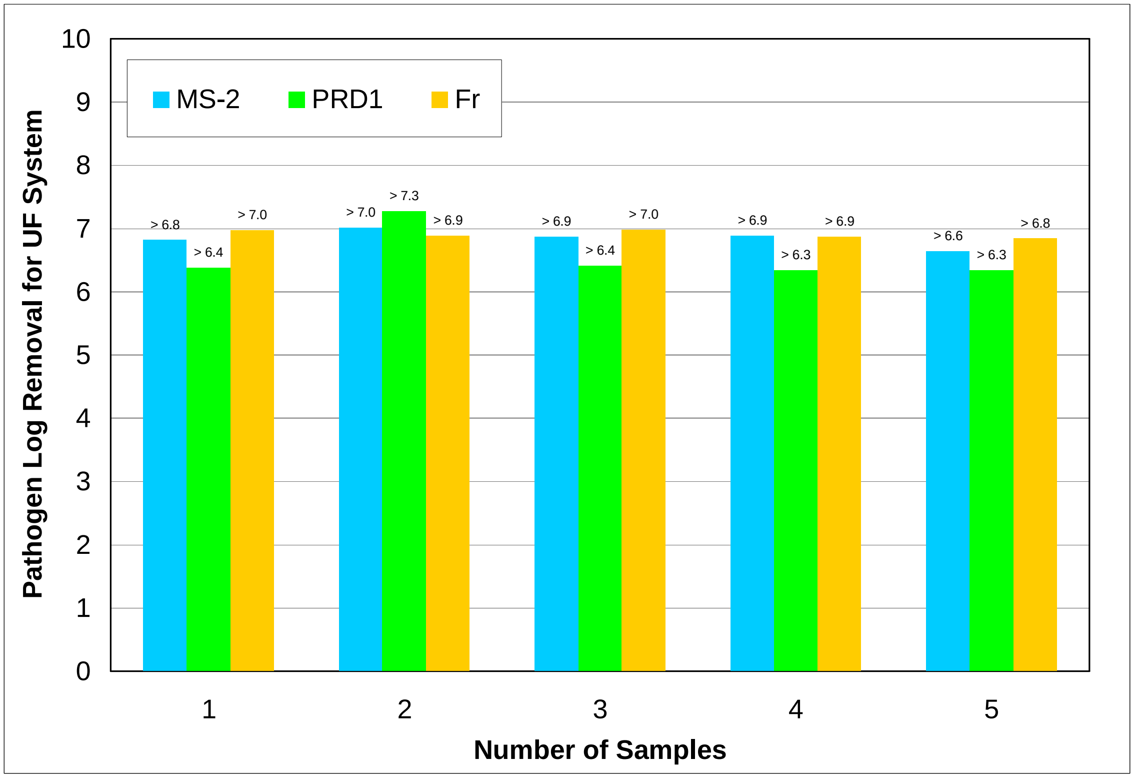


Figure 4-3. Log Rejection of the UF System.

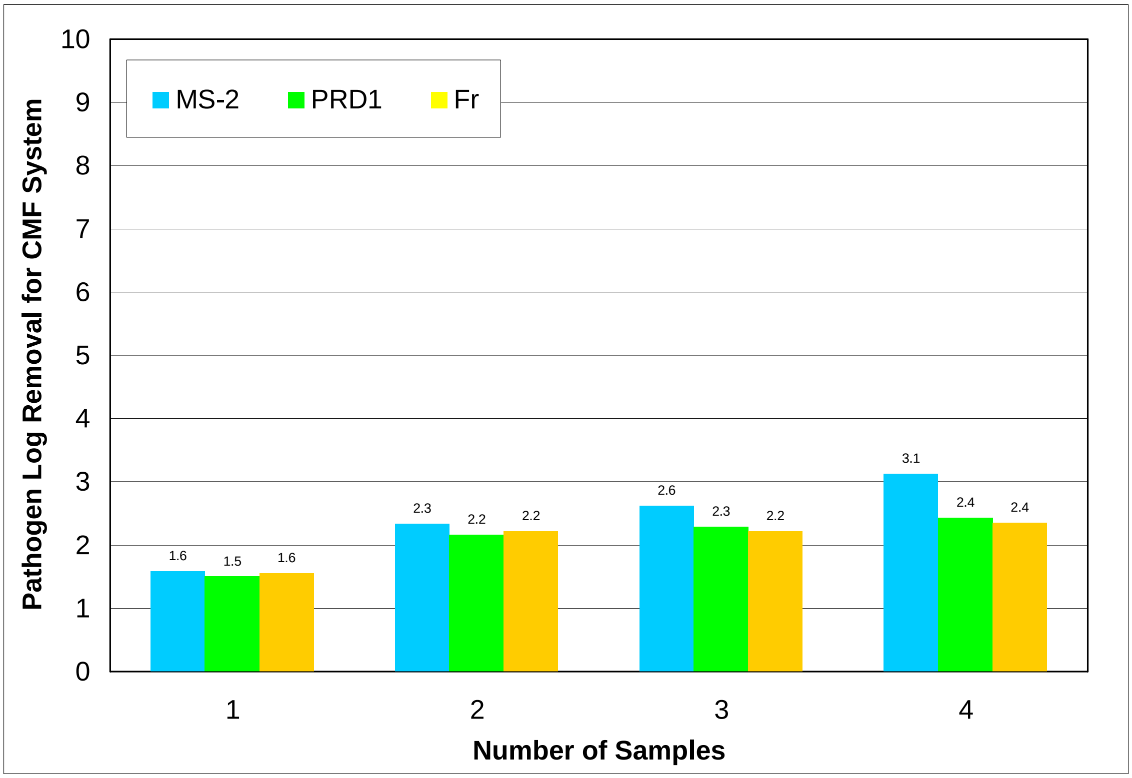


Figure 4-4. Log Rejection of the MMF System.

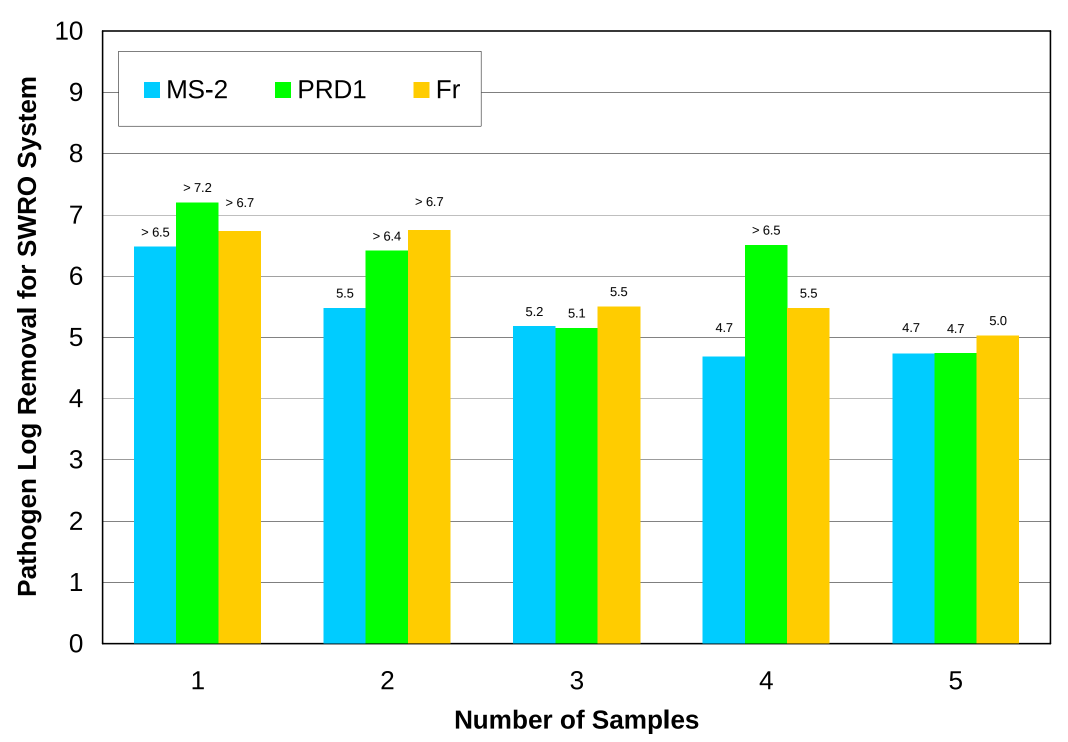


Figure 4-5. Log Rejection of the SWRO System.

concentration in the feed water at T= 2, 4, 5, 6 minutes, since the residence time of the system is approximately 40 minutes. These log rejections would, therefore, be for residence times of 43, 41, 40, and 39 minutes. The rejection of MS-2 was higher than PRD-1 and Fr rejections; on the other hand, the rejections of PRD-1 and Fr were very similar. These system log rejections are 0.5 to 2.0 more logs than the 1.0-log credit for virus received by direct filtration process under the Surface Water Treatment Rule.

The SWRO system showed virus rejection varying from 4.7- to 7.2-log for the three viruses. Viruses were detected in the permeate stream. The presence of viruses in the permeate stream could be explained by pinhole defects on the membrane or leakage from the raw water side to the permeate water side through defective seals between the membrane module and end cap. Even though the three viruses have different sizes, there is no relationship between the virus log rejection by the SWRO membrane and the virus size, as with the UF membrane. This less-than-absolute removal by RO systems has been documented previously and is not unexpected.

The virus log removal of the UF pretreatment is higher than the log removal of the conventional media filtration pretreatment. The UF system showed more than 3.0-log virus removal than the conventional filtration system. This higher rejection for the UF system is because the UF membrane has a specific pore size distribution with a nominal pore size of 0.01 µm, whereas media filtration is subject to breakthrough and preferential paths where pathogens could bleed through. It should be noted that the virus concentration in the UF filtrate was below detection limit, whereas high virus concentrations (more than 2 logs) were observed in the MMF system for the same virus concentration in the feed waters.

The UF pretreatment system showed higher virus rejections than the SWRO system. Even though seawater membranes have higher potential rejection than UF membranes due to the smaller pore size of seawater membrane, the lowest rejection was observed for the seawater system. This might be due to the membrane configuration difference between the two systems. The SWRO membrane system consists of a series of membrane elements and is susceptible to leakage of raw water to permeate between membrane and pressure vessels end caps. The UF system consists of fibers that are sealed in the lumen of the pressure vessel with an epoxy resin, therefore, minimizing leakage of the raw water side to the filtrate water side. More importantly, the fabrication of the active film of RO membranes can lead to imperfections due to inconsistent film layers on the surface of the supporting structure. These can result in areas of bulk convective transport of material through the membrane. Given that typical log removal of TDS needs only to be 2-log (i.e., reduction of TDS from 30,000 mg/L to 300 mg/L), a higher log removal has not typically been an area of focus for manufacturing considerations.

4.2.3 Process Trains Virus Removal

The log removal of the two process trains UF-SWRO and MMF-SWRO were computed by adding the log average of each individual process forming the two process trains and are shown in figure 4-6 as well as the log rejection of the individual processes. Since higher rejections were observed for the UF system compared to the MMF system, the UF-SWRO process train has consequently higher rejection potential than the MMF-SWRO process train. The UF-SWRO could achieve up to 14-log removal of viruses whereas the MMF-SWRO could achieve up to 13-log removal. Even though these high removals (13 to 14 logs) are potential removals, removal at full-scale could be less. The reason is that the pathogen concentration in the feed will be lower and the pretreatment will remove most of the pathogens; and therefore, the SWRO system will not likely receive 5 or 7 logs of pathogens.

Taylor et al., 1999, studied the capabilities of UF and RO membranes to reject pathogens. Feed water was spiked with *Giardia* and *Cryptosporidium*, and UF showed higher log removal of pathogens than RO membranes as it was observed

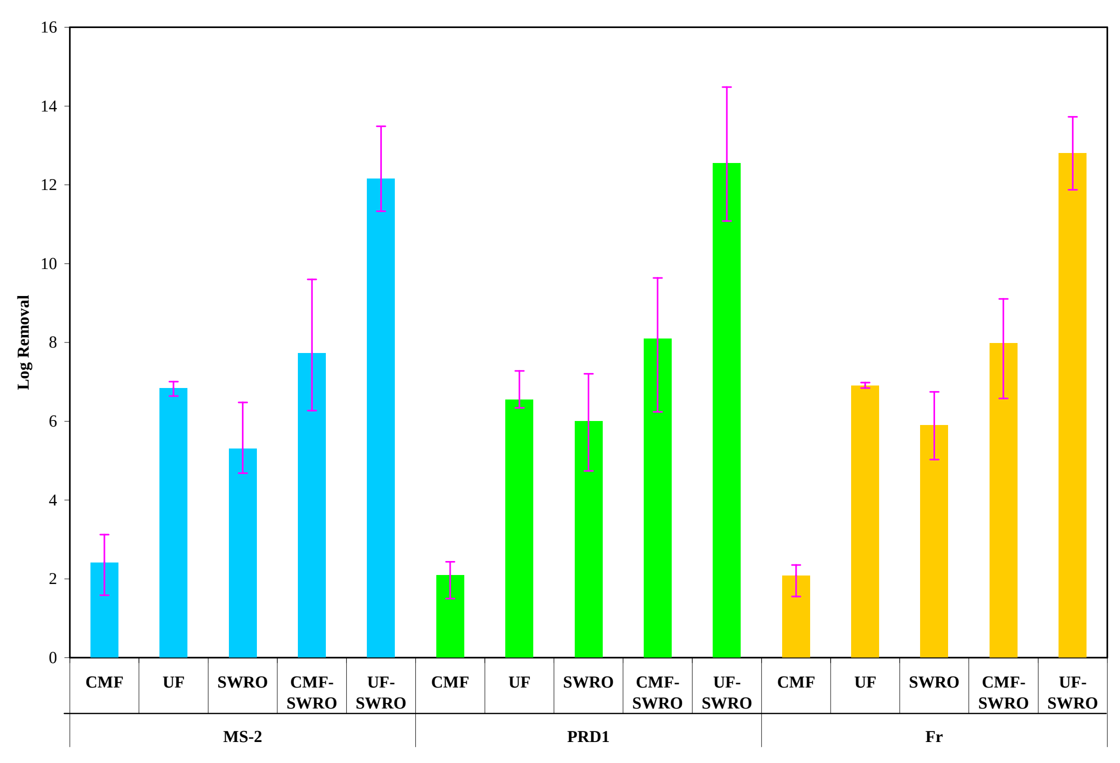


Figure 4-6. Log Removal of the Three Process Systems and the Two Process Trains.

in this study. UF showed removal of 4 to 8 logs whereas RO showed removal of 1 to 7 logs. In addition, the American Water Works Association Research Foundation (AWWARF) project titled “Application of Membrane Filtration Techniques for Compliance with the Surface Water and Groundwater Treatment Rules” showed that MF and UF were capable of removing more than 6.0-log of *Cryptosporidium* and *Giardia* under worst-case conditions, which support the results and findings of this virus challenge study.

4.2.4 Turbidity and Conductivity Results

Turbidity and conductivity were analyzed during the challenge study to confirm that the three units operated as they should in terms of water quality. As seen in table 4-2, the turbidity and conductivity are representative of the performances of the units quality wise.

It should be noted that coagulation was used in conjunction with UF or MMF to represent operation of these units at full-scale.

Table 4-2. Turbidity and Conductivity Results During Virus Challenge Study

UF Feed	UF Filtrate	MMF Feed	MMF 1st Stage	MMF 2nd Stage	SWRO Permeate
Turbidity (NTU)					
2.7	0.14	5.57	0.45	0.23	0.09
Conductivity (micro-ohms per centimeter [uohms/cm])					
38,900	38,900	43,275	43,050	42,875	345

4.3 Regulatory Compliance

The log removal of the two process trains tested (UF-SWRO and MMF-SWRO) were compared to the log removal requirements set by the existing and proposed pathogen regulations.

The Total Coliform Rule (TCR), the Surface Water Treatment Rule (SWTR) and the Interim Enhanced Surface Treatment Rule (IESWTR) are the two main existing rules that described pathogen removal requirements for all community water systems using surface water as source water. These two rules focused on bacteria, virus, and protozoa removal requirements. The Long Term 2 Surface Water Treatment Rule (LT2SWTR) is the proposed rule that is to focus on the protozoa *Cryptosporidium* removal requirement.

The SWTR states that all water treatment systems must achieve 4-log virus removal and 3-log *Giardia* removal, whereas the IESWTR states that a water treatment system must achieve 2-log *Cryptosporidium* removal. This log *Cryptosporidium* removal requirement will be modified under the LT2SWTR. The log removal requirement will not be a fixed log removal but will be a function of the *Cryptosporidium* concentration in the surface water used as source water. The log removal for any water system using filtration technology different from conventional filtration (coagulation/sedimentation/media filtration) and direct filtration is proposed to vary from 3- to 5.5-log as shown in table 4-3. The log rejection requirement for a seawater system would fall in the last column of table 4-3.

The virus challenge testing showed that both process trains achieved more than 12-log virus rejection and, therefore, met the SWTR requirements of 4-log virus removal/inactivation. The log rejection of protozoa would be at least the log virus rejections observed during the virus challenge since the protozoa are 2- to 3-log larger than viruses. The size of viruses is typically between 0.01 and 0.1 µm, whereas the size of protozoa such as *Giardia* and *Cryptosporidium* varies between 4-20 µm (the typical size of *Giardia* and *Cryptosporidium* is 4-6 µm and 7-15 µm,

Table 4-3. *Cryptosporidium* Treatment Requirement per LT2ESWTR Bin Classification

	Crypto per Liter in Source Water	Total Treatment Required (log removal)	Additional Treatment Required			
			Conventional Treatment	Direct Filtration	Slow Sand or Diatomaceous Earth Filtration	Alternative Filtration Technology
Bin 1	< 0.075	3.0	No additional treatment	No additional treatment	No additional treatment	No additional treatment
Bin 2	> 0.075 < 1	4.0	1.0-log treatment[1]	1.5-log treatment[1]	1.0-log treatment[1]	Determined by State[1,3]
Bin 3	> 1 < 3	5.0	2.0-log treatment[2]	2.5-log treatment[2]	2.0-log treatment[2]	Determined by State[1,4]
Bin 4	> 3	5.5	2.5-log treatment[2]	3.0-log treatment[2]	2.5-log treatment[2]	Determined by State[1,5]

[1] System may use any technology or combination of technologies from the microbial toolbox.

[2] Systems must achieve at least 1.0-log of the required treatment using ozone, chlorine dioxide, ultraviolet, membranes, bag/cartridge filters, or bank filtration.

[3] Total *Cryptosporidium* removal and inactivation must be at least 4.0-log.

[4] Total *Cryptosporidium* removal and inactivation must be at least 5.0-log.

[5] Total *Cryptosporidium* removal and inactivation must be at least 5.5-log.

respectively). The two process trains showed at least 12-log rejection of viruses; then, they would achieve 12-log removal of protozoa. Therefore, both process trains would meet the IESWTR requirement of 2-log *Giardia* removal and the maximum LT2SWTR requirement of 5.5-log *Cryptosporidium* removal.

4.4 Significance to Water Industry

The significance of the virus challenge testing is that it will benefit EPA and state regulatory agencies by providing needed research on pathogen removal to support assigning of removal credits to SWRO systems. The results showed and support the fact that UF and SWRO achieve higher pathogen rejection than conventional filtration, as it has been shown in previous studies. Although conventional filtration receives 2.0-log credit for virus and 0.5-log credit for *Giardia*, UF and SWRO have not been assigned any log credit by EPA.

This virus challenge testing program will also benefit the consumers of future desalinated water with added confidence by demonstrating compliance with United States and world water quality standards in terms of pathogen protection. This challenge testing also showed that SWRO systems provide higher pathogen protection than conventional treatment.

5. Optimization of RO for Removal of Low Molecular Weight Inorganic Contaminants

Design of SWRO systems involves consideration of numerous factors to achieve the desired finished water quality while minimizing life-cycle costs. Typical systems utilize a single pass array configuration. However, as finished water quality goals become more stringent, additional treatment may be necessary. This is especially true for low molecular weight inorganic constituents such as boron and chloride. Boron levels in seawater, which typically average 4.5 mg/L, may exceed World Health Organization guideline values of 0.5 mg/L after single pass SWRO. This is particularly true for systems operating at high recoveries or using warm source waters. In addition, utilities may select treatment standards that are more stringent than regulatory requirements and may result in a need for additional treatment. This was the case in the Tampa Bay Desal I project where Tampa Bay Water lowered the acceptable chloride concentration from 250 mg/L as recommended by the Safe Drinking Water Act to less than 100 mg/L to reduce the risk of corrosion. This requirement resulted in the design of a second pass RO system to further reduce chloride concentration to the specified 100-mg/L level.

Other alternatives that could be implemented in lieu of second pass RO include reducing first pass recovery, adjusting the number of first pass elements used per pressure vessel, and using ion exchange. The first two alternatives have the potential of improving finished water quality by limiting the diffusion of concentrated contaminants into the permeate water near the tail end of the pressure vessel. Anion and cation exchange resins can also be used individually or in mixed beds to reduce a variety of inorganic contaminants, and select ion exchange resins can be used to reduce specific contaminants such as boron, leaving the concentrations of the other ions unchanged.

While the design of SWRO systems will continue to evolve, the key unit processes have remained unchanged for some time and will most likely remain unchanged in the near future as a number of seawater desalination projects are implemented in the United States. Using available technologies, municipalities and their design teams are tasked with developing process designs that meet finished water quality goals while minimizing costs. The differing finished water quality goals associated with these projects should naturally result in differing process designs and life cycle costs.

The assessment described in this section was developed to quantify the impact different finished water quality specifications have on the design and costs of

SWRO treatment plants. While every project is unique, the intent of this assessment is to illustrate the relationship between finished water quality and costs, using selected design variables. The impact of a more stringent finished water quality specification on costs is an important consideration that is difficult to capture using historical project costs. Large (> 5 MGD) seawater desalination projects have primarily been constructed overseas. The costs associated with these projects can have limited pertinence to pending United States projects for a number of reasons, with just one being that finished water quality requirements were likely different than those that may be required in future United States seawater projects.

5.1 Methodology

The design and cost analysis was performed first by establishing a series of finished water quality specifications that bracket a range that might reasonably be required by municipalities in the United States. Based on these specifications, a number of design criteria were identified that could be varied as necessary to meet water quality goals. Each finished water quality specification was then reviewed and a design developed that minimized the complexity and cost of the SWRO system while meeting the specification. A plant capacity of 25 MGD was used as the basis of design, given that the majority of SWRO systems under consideration in the United States are of similar size. Life-cycle costs were then developed for each alternative design. Results were then analyzed and interpreted to determine design direction(s) that may be useful for municipalities to consider as part of conceptual design and process design efforts. Note that this effort was ‘desktop’ in nature and did not involve pilot testing. The following sections describe each component of this comparative analysis.

5.2 Finished Water Quality Goals

Three finished water quality specifications (WQS) were established to represent a range of potential municipal requirements. The least stringent and likely the most common finished water quality goal is a TDS concentrate of 400 mg/L or less. This is a common objective in the Caribbean and other areas of the world utilizing seawater desalination. In addition, this is slightly less than the secondary standard for TDS of 500 mg/L set by the SDWA. This limit is commonly selected since it ensures a nonsaline finished water that will not result in “salt water” complaints from customers.

The second, more stringent specification is a chloride level of 100 mg/L or less. This represents the water quality requirement of Tampa Bay Water for their 25-MGD SWRO system commissioned in 2003. This criterion was established to minimize corrosion on a regional distribution system that has historically received low chloride ground water. Other regional water providers may also be faced with a similar situation, given that most seawater projects being considered in the United States will serve large populations through existing distribution systems. Given the rejection characteristics of SWRO membranes, it is expected that a system meeting the 100-mg/L chloride limit would more than meet the 400-mg/L TDS requirement of WQS No. 1, making chloride concentration of 100 mg/L the contaminant that drives the design.

The third and most stringent specification is the WHO boron standard of 0.5 mg/L. While the SDWA does not currently list a standard for boron, boron is listed on EPA's Candidate Contaminant List meaning a maximum contaminant level for boron may be established by EPA in the future. For these reasons, boron could potentially be considered important to certain municipalities. Given the rejection characteristics of SWRO membranes, it is expected that a system meeting a 0.5-mg/L boron limit would more than meet the WQS of 100 mg/L of chloride and 400 mg/L of TDS, making a boron limit of 0.5 mg/L the factor that would drive the design.

The three WQS used for this comparative analysis are listed in table 5-1. Note that only the primary contaminant is presented for each specification. While the concentration of all three contaminants will vary with variations in SWRO system design, computer models or field data using a specific membrane element are necessary to determine the resulting concentration of the other two contaminants when complying with the limit for a given contaminant. However, the level of treatment necessary will follow the order of the WQS, regardless of the membrane selected.

Table 5-1. Selected Finish Water Quality Specifications

Constituent	Specification No. 1 (Least Stringent)	Specification No. 2 (More Stringent)	Specification No. 3 (Most Stringent)
TDS	400	–	–
Chloride	–	100	–
Boron	–	–	0.5

5.3 Design Factors

To meet the three WQS, alternate SWRO designs were developed. A single pass SWRO system was developed as a "Base Design" treatment system and is shown in figure 5-1. A single pass system represents the least complex design and was used as a building block for evaluation of more complex designs that were needed to achieve more stringent WQS as defined in table 5-1.

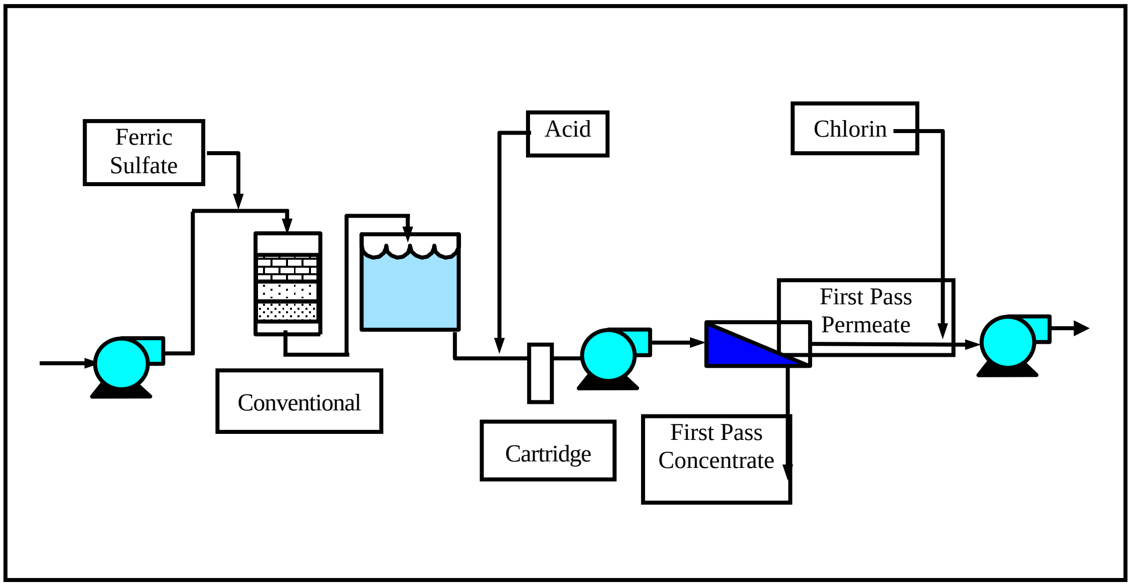


Figure 5-1. Single Pass SWRO Process Diagram.

The design variables that were assessed are as follows:

1. Second pass RO
2. Second pass RO with pH adjustment
3. Ion exchange
4. Reduced first pass recovery
5. Adjusting number of first pass elements per pressure vessel

Alternatives 1-3 represent installation of an additional unit process following the single pass system, to further treat the permeate (finished water) from the first pass system. Process flow diagrams for these systems are presented in figures 5-2 and 5-3. Alternatives 4 and 5 represent variations internal to the first pass system that may have value in meeting finished water quality standards without the need for additional treatment such as a second pass RO system.

To compare the cost of each alternative, all unit processes for an operable SWRO facility were defined and included intake and outfall structures, multimedia filtration and chemical pretreatment, single pass RO, chemical stabilization and disinfection, raw water pumps, high-pressure pumps, transfer pumps (if needed), finished water pumps, and above ground steel storage tanks. Costs could then be developed that provided an appropriate sensitivity assessment that encompassed the overall facility costs. Costs for concentrate or brine disposal were not included in the cost analyses, since they are site specific and common to all alternatives.

The ability of the alternative designs to meet the three finished WQS was assessed using a computer model that simulates a membrane system. While the

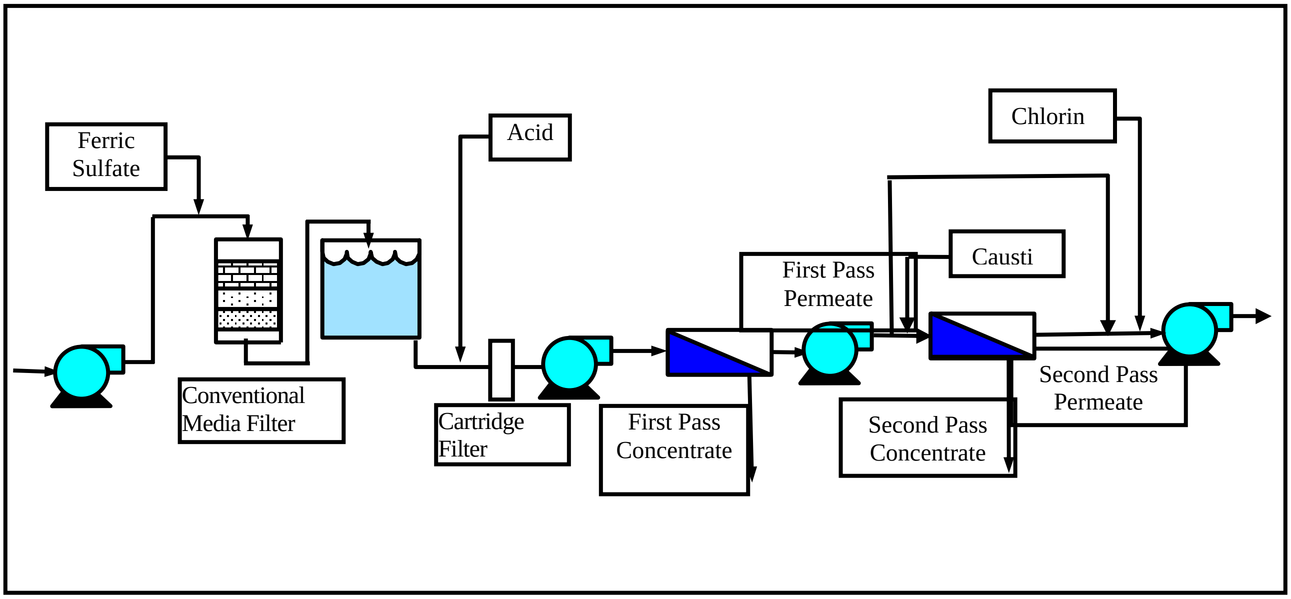


Figure 5.2 First and Second Pass SWRO Process Flow Diagram.

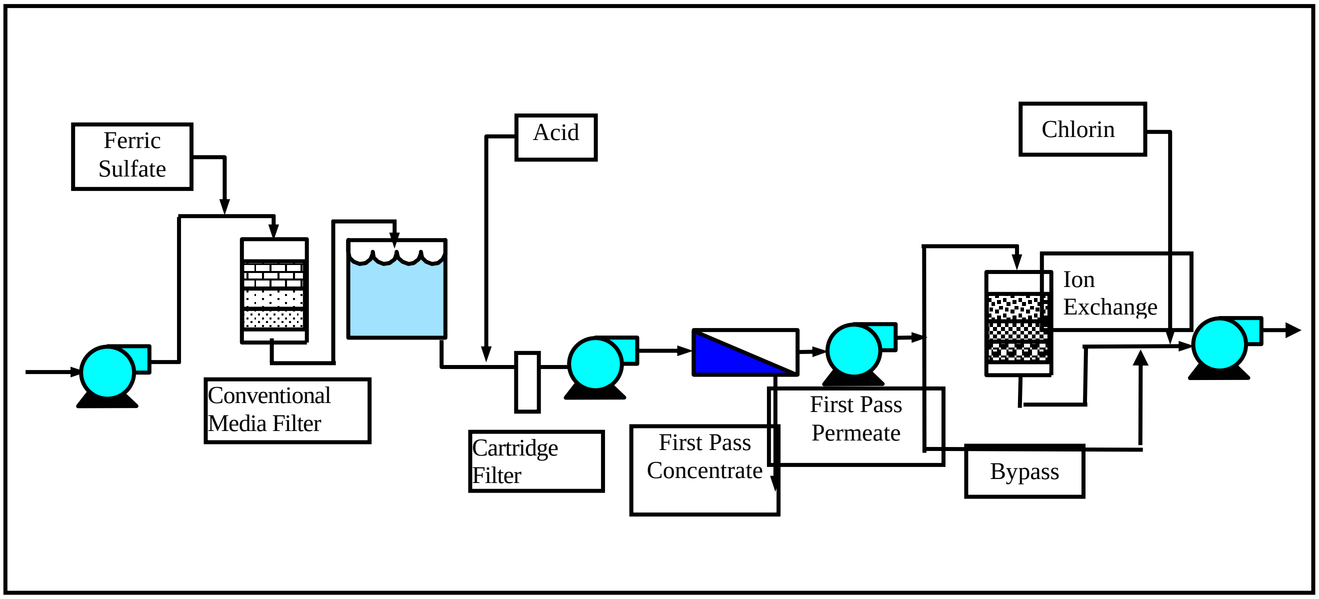


Figure 5-3. First Pass SWRO and Second Pass Ion Exchange Process Flow Diagram.

performance of membrane elements varies, each of the major membrane element manufacturers offers one or more seawater membrane elements that behave in a relatively similar manner in terms of inorganic ion rejection. Therefore, a computer model from a single manufacturer, Toray Membrane America, was selected for this analysis. The TorayRO Design Software (Version 2.02, Toray Membrane America) was considered representative of the general behavior of seawater membrane elements. In addition, the TorayRO software was valuable in its ability to predict boron concentrations in the finished water, which was not found in other manufacturer models at the time this work was completed.

5.4 Source Water Quality

For the purposes of this assessment, typical seawater quality was selected as source water for treatment. Table 5-2 lists the parameters and corresponding values used for each as input to the membrane modeling software. Although seawater quality can vary throughout the world, these were selected as average conditions that might occur in the Atlantic Ocean on the east coast of Florida. Since increased temperatures can increase the diffusion of contaminants through the membrane, thus increasing their concentrations in the finished water, a relatively high seawater temperature of 25 ºC was selected as worst case scenario. It is important to note that SWRO facilities utilizing cooling water discharges from powerplants may have feed temperatures as high as 40 ºC, and this alone will result in lesser quality finished water, for a given set of design and operating conditions.

Table 5-2. Seawater Quality (Stumm and Morgan, 1981)

Parameter	Value (mg/L)[1]
Temperature	25 °C
pH	8.1 Standard Units
Calcium	410
Magnesium	1,290
Sodium	10,770
Potassium	400
Strontium	7.9
Bicarbonate	140
Chloride	19,350
Sulfate	2,710
Fluoride	1.3
Boron	4.5
Silica Dioxide	2.5
Phosphate	0.5
Carbonate	4.47
Carbon Dioxide	1.18
Total Dissolved Solids	35,108

[1] Unless otherwise noted.

5.5 Cost Estimating

Cost estimating was performed using the WTCost© Water Treatment Cost Estimation Program (Version 1.0.0) sponsored by The American Membrane Technology Association and developed by I. Moch and Associates, Inc. and Boulder Research Enterprises with Reclamation. The WTCost© Program is based on a cost model developed by Reclamation in the 1990s and has been updated and expanded by a number of collaborators over the years to its current version, representing a state-of-the-art cost estimating program. The WTCost© Program was used in estimating capital/construction and annual operating costs for the SWRO alternatives as well as the ancillary equipment needed for ion exchange. Costs for the ion exchange vessels, ion exchange resin, and regenerative costs were provided by an ion exchange manufacturer and incorporated in the overall costs.

The WTCost© Program is comprehensive in that it allows not only for capital and construction costs to be estimated but also provides estimates for annual O&M costs that include usage and associated costs for electricity, chemicals, labor, maintenance, and equipment replacement. Using the same base rate for each of these costs (i.e., $0.09/KwH), an annual operational and maintenance cost estimate was calculated by the WTCost© Program that was specific to each alternative design and process equipment selected. Capital and construction costs for each alternative were amortized over a 20-year period at a 6-percent interest rate to determine an equivalent annual payment amount. The equivalent annual payment was then added to the annual O&M cost for each alternative design to provide a total annual facility cost that incorporates capital, construction and O&M. It should be noted that the costs associated with disposal of concentrate of the reverse osmosis system or the brine of the ion exchange process were not included in the costs estimates due to their high variability and because they are mostly site specific depending on the disposal method selected.

5.6 Results

SWRO designs were developed using the TorayRO Design Software that achieves each water quality specification. Cost estimates for capital, construction, and O&M were determined based on these designs using the WTCost© Software Program. Because the WQS dictates the design, the discussion of the results from this assessment has been divided according to each WQS.

5.6.1 Water Quality Specification No. 1 – TDS of 400 mg/L

To meet the 400-mg/L requirement of WQS No. 1, the single pass SWRO system Base Design was evaluated. This design represents the simplest, most cost-effective design. Specifications are summarized in table 5-3. This system was designed based on 10 banks of 2.5 MGD each, achieving a total finished water capacity of 25 MGD. This base SWRO system was designed at 50% recovery, seven elements per pressure vessel, and an average flux of 10 gfd. The beta factor was limited to 1.2 or less. The Toray TM820-400 seawater RO membrane was used. Chemical pretreatment consisting of sulfuric acid was used to lower the pH of the feed water to 6.0 standard units (SU) to minimize scaling by calcium carbonate ($CaCO_3$) as predicted by the TorayRO Design Program. Even though in most seawater treatment plant, there is no addition of acid, this assumption represents the worst case scenario in terms of water quality, since sulfate (via sulfuric acid) will be added in the feed water.

Table 5-3. WQS No. 1 – Specifications and Finished Water Quality

System	Units	Base Design
		Single-pass
First Pass		
Flux	gfd	10
Recovery	%	50%
Elements/Pressure Vessel	#	7
Number of Pressure Vessels	#	890
Pressure	psi	860
Acid	–	H_2SO_4
pH	Units	6
TDS (Water Quality Goal)	mg/L	400
Finished Water Quality		
TDS	mg/L	**216**
Chloride	mg/L	124
Boron	mg/L	1.1
Flows		
Finished Water Flow	MGD	**25**
First Pass Feed Flow	MGD	**50.0**
Costs		
Capital/Construction	$ 1,000	**$77,300**
Annual Operating Costs	$ 1,000	**$15,400**
Annualized Total Costs[1]	$ 1,000	**$22,141**
Annualized Total Costs[1]	$/1,000 gal	**$2.43**

[1] Capital/construction costs were amortized over a period of 20 years at 6% interest rate.

Utilizing this Base Design, computer projections of finished water quality were estimated. As shown in table 5-3, an operating pressure of 860 psi is necessary to meet the flux and recovery specifications of 10 gfd and 50%, respectively. More importantly, results show that the Base Design meets the 400-mg/L TDS requirement. This precludes the need for additional treatment to meet WQS No. 1; and thus, no additional assessment of compliance with WQS No. 1 was needed or performed. Costs were developed for this Base Design based on the specifications in table 5-3. It is important to note that the Base Design does not meet the WQS No. 2 chloride limit of 100 mg/L nor the WQS No. 3 boron limit of 0.5 mg/L. Capital/construction costs were estimated to be $77.3 million or $3.09 per gallon per day (/gal/day). Annual O&M costs were estimated at $15.4 million or $1.68/1,000 gal. Amortizing capital/construction costs over a 20-year period at a 6-percent interest rate and adding the resulting annual payment to the annual operating costs results in an annualized cost of $22.1 million or $2.43/1,000 gal treated. This cost falls within the range of $1.38 to $5.97/1,000 gal reported by others for potential desalination facilities to be located in Texas using the Gulf of Mexico as a source water (HDR, 2000). It should be noted that these costs are estimates of the cost to construct and operate the treatment process identified and are not an attempt to develop total project costs for specific sites, which would include assessing land costs, permitting costs, and other factors that vary by State and site.

5.6.2 Water Quality Specification No. 2 – Chloride of 100 mg/L

The 100-mg/L chloride limit of WQS No. 2 was developed to represent a municipality concerned with corrosion resulting from addition of desalinated seawater into an existing distribution system. As presented previously, the Base Design results in a finished water chloride concentration of 124 mg/L, thereby requiring additional treatment to achieve the 100-mg/L chloride limit. To meet this requirement, only the second pass alternative was evaluated. Use of an ion exchange resin was considered most appropriate for removing boron and, thus, was not considered for removing chloride. Demineralization (i.e., removing chloride) in a split-stream scenario to trim the chloride level down to less than 100 mg/L in the finished water is prohibitively expensive on an operations basis due to the cost of regenerant versus comparable cost of power to a second pass system.

The design specifications, finished water quality, and cost summaries for the WQS No. 2 are presented in table 5-4. As shown, a second pass system sized to produce 22% of the overall 25-MGD flow would be required to dilute the overall chloride concentrate to 100 mg/L. Capital/construction costs were estimated to be $89.2 million or $3.57/gal/day. Annual O&M costs were estimated at $16.2 million or $1.77/1,000 gal. Amortizing capital/construction costs over a

Table 5-4. WQS No. 2 – Specifications and Finished Water Quality

System	Units	Base Design	Alternative 1
		Single-pass	**Two-pass**
First Pass			
Flux	gfd	10	10
Recovery	%	50%	50%
Elements/Pressure Vessel (PV)	#	7	7
Number of Pressure Vessels	#	890	890
Pressure	psi	860	860
Acid	–	H_2SO_4	H_2SO_4
pH	Units	6	6
Chlorides (Water Quality Goal)	mg/L	100	100
Second Pass			
Flux	gfd	–	20
Recovery	%	–	90%
Configuration	–	–	24-12
Number of Pressure Vessels	#	–	33
Pressure	psi	–	108
Elements/PV	#	–	7
TDS	mg/L	–	17
Chloride	mg/L	–	7
Boron	mg/L	–	0.9
Bypass to Reach 100 mg/L Clorlide	%	–	78%
Finished Water Quality			
TDS	mg/L	216	175
Chloride	mg/L	**124**	**100**
Boron	mg/L	1.1	0.9
Flows			
Finished Water Flow	MGD	**25**	**25**
First Pass Feed Flow	MGD	**50.0**	**51.1**
Costs			
Capital/Construction	$ 1,000	**$77,300**	**$89,200**
Annual Operating Costs	$ 1,000	**$15,400**	**$16,200**
Annualized Total Costs[1]	$ 1,000	**$22,141**	**$23,978**
Annualized Total Costs[1]	$1,000/gal	**$2.43**	**$2.63**

[1] Capital/construction costs were amortized over a period of 20 years at 6% interest rate.

20-year period at a 6-percent interest rate and adding the resulting annual payment to the annual operating costs results in an annualized cost of $24.0 million or $2.63/1,000 gal treated.

5.6.3 Water Quality Specification No. 3 – Boron of 0.5 mg/L

The 0.5-mg/L boron limit of WQS No. 3 was developed to represent a municipality complying with the WHO boron standard. As presented previously, the Base Design resulted in a finished water boron concentration of 1.1 mg/L, thereby requiring additional treatment to achieve the WHO standard. To meet this requirement, a total of three alternatives were evaluated:

Alternative 1	Second pass RO treatment
Alternative 2	Second pass RO treatment with pH adjustment
Alternative 3	Ion exchange

Design specifications as well as modeling results are presented in table 5-5. The second pass RO systems (i.e., Alternatives 1 and 2) were evaluated using a 90% recovery, 20-gfd flux, a 2-1 array configuration, and seven elements per pressure vessel. The ion exchange system was designed with six 11.5-foot diameter vessels (five operating and one in regeneration), a 30-bed volume (BV) per hour (which represents a surface loading rate of 18 gpm/ft^2) and is based on use of Amberlite IRA743 boron selective resin manufactured by Rohm Haas. The capacity of the resin is 0.8 equivalent per liter (eq/L) and is specific to borate.

Boron in water exists in two forms: boric acid (H_3BO_3) and borate ($B(OH)_3$). The amount of either species is dependent on the pH of the water with boric acid favored at a low pH and borate favored at a high pH. Of the two, borate is the species removed by second pass RO. Increasing the pH of permeate water increases the amount of borate and, subsequently, the amount of boron removed. Therefore, to reduce boron using the second pass RO system, the pH of the first pass RO permeate was increased from 9.0 to 11.0. Boron was subsequently reduced from a feed concentration of 1.8 mg/L to less than 0.2 mg/L in the permeate under this scenario.

As shown, all three systems (i.e., Alternatives 1, 2, and 3) can achieve the boron limit. Note that use of second pass with caustic addition still requires full treatment of feedwater from the first pass system permeate. This requires a first pass system capable of producing 27.8 MGD, to be used as feed to second pass. When caustic is used to increase the pH of the second pass feed to a pH of 11, only 59% of first pass water requires additional treatment. In addition, the first pass system is only designed to produce 26.6 MGD.

Table 5-5. WQS No. 3 (and Alternatives) – Specifications and Finished Water Quality

System	Units	Base Design	Alternative		
			1	2	3
		Single-pass	Two-pass	Two-pass	Single-pass + IX
First Pass					
Flux	gfd	10	10	10	10
Recovery	%	50%	50%	50%	50%
Elements/PV	#	7	7	7	7
Number of Pressure Vessels	#	890	960	950	890
Pressure	psi	860	860	860	860
Acid	–	H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
pH	Units	6	6	6	6
TDS	mg/L	216	216	216	216
Chlorides	mg/L	124	124	124	124
Boron	mg/L	1.1	1.1	1.1	1.1
Second Pass		**None**			**None**
Flux	gfd	–	20	20	–
Recovery	%	–	90%	90%	–
Configuration	–	–	24-12	16-8	–
Number of Pressure Vessels	#	–	330	240	–
Pressure	psi	–	108	114	–
Elements/PV	#	–	7	7	–
Base	–	–	NaOH	NaOH	–
Antiscalant		–	Yes	Yes	–
pH	SU	–	9	11	–
TDS	mg/L	–	17	33	–
Chlorides	mg/L	–	7	14	–
Boron	mg/L	–	0.5	0.07	–
Bypass to Reach 0.5 mg/L B	%	–	0%	41%	–
Ion Exchange		**None**	**None**	**None**	
Bed Volume/hr		–	–	–	30
Resin Capacity	eq/L	–	–	–	0.8
Number of Vessels	#	–	–	–	6
Regenerants	–	–	–	–	Acid and caustic
Assumed TDS conc after IX	mg/L	–	–	–	216
Assumed Cl conc after IX	mg/L	–	–	–	124
Assumed B conc after IX	mg/L	–	–	–	0.01
Bypass	%	–	–	–	47%
Finished Water Quality					
Boron (Water Quality Goal)	mg/L	0.5	0.5	0.5	0.5
TDS	mg/L	216	17.0	85	216
Chloride	mg/L	124	7.0	44	124
Boron	mg/L	**1.1**	**0.5**	**0.5**	**0.5**
Flows					
Finished Water Flow	MGD	**25**	**25**	**25**	**25**
Second Pass Feed Flow	MGD	NA	**27.78**	**15.71**	NA
IX Feed Flow	MGD	NA	NA	NA	**13.33**
First Pass Feed Flow	MGD	**50.0**	**55.6**	**53.1**	**50.0**
Costs					
Capital/Construction	$ 1,000	**$77,300**	**$105,000**	**$97,500**	**$81,200**
Annual Operating Costs	$ 1,000	**$15,400**	**$17,800**	**$18,000**	**$16,500**
Annualized Total Costs[1]	$ 1,000	**$22,141**	**$26,956**	**$26,502**	**$23,581**
Annualized Total Costs[1]	$/1,000 gal	**$2.43**	**$2.95**	**$2.90**	**$2.58**

[1] Capital/construction costs were amortized over a period of 20 years at 6% interest rate.

Capital costs range from $81 to $105 million ($3.25 to $4.23/gal/day), representing a minimum of $5 million ($0.20/gal/day) over the cost of the single pass Base Design to achieve the boron standard. Operating costs ranged from $16.5 to $18 million per year, representing an increase of at least $1.1 million per year over the Base Design. On an annualized cost basis, costs range between $23.7 to $26.9 million per year ($2.58 to $2.95/1,000 gal), representing an annual increase of at least $1.6 million ($0.17/1,000 gal). The capital/construction and O&M costs for ion exchange (i.e., Alternative 3) were lower than either of the second pass RO alternatives (i.e., Alternatives 1 and 2). Therefore, ion exchange appears to be the most cost-effective alternative for this application. Note that boron removal using the selected ion exchange resin may not remove chloride ions to any significant degree; and, therefore, chloride levels could be as high as the first pass RO permeate levels (124 mg/L). In the event lower chloride levels are desired, a second pass RO system would provide the necessary multicontaminant removal capabilities.

5.6.4 Other Design Considerations

Other alternatives that could also be considered in lieu of second pass RO or ion exchange include reducing first pass recovery, adjusting the number of first pass elements used per pressure vessel, and using higher rejection first pass membranes. The first two alternatives have the potential of improving finished water quality by limiting the diffusion of inorganic ions from passing through the membrane. Both of these alternatives were modeled using the TorayRO Program. Figures 5-4 and 5-5 show the influence these alternatives have on first pass permeate water boron concentrations, respectively, with a feed boron concentration of 4.5 mg/L.

Between the two design criteria, reducing the recovery has the greatest effect. Reducing the recovery from 60 to 50 to 40 percent results in corresponding boron concentrations of 1.24, 1.06, and 0.94 mg/L, respectively, in the first pass permeate. Although this is still above the WHO standard of 0.5 mg/L, it does show that permeate water quality can be improved by lowering the recovery and in some limited cases could be used to adjust a design that may not meet finished water quality standards or goals.

This is in contrast with reducing the number of first pass elements as shown in figure 5-5 which has little effect on permeate water quality. Varying the number of elements from 8 to 7 to 6 per pressure vessel results in corresponding boron concentrations of 1.07, 1.06, and 1.07 mg/L, respectively, in the first pass permeate. It is noted that the permeate water quality on the latter elements degrades as more elements are added inside the pressure vessel. However, as a result of the higher pressures needed to drive these latter elements, flux rates for the leading elements are higher. Because the water quality from the leading

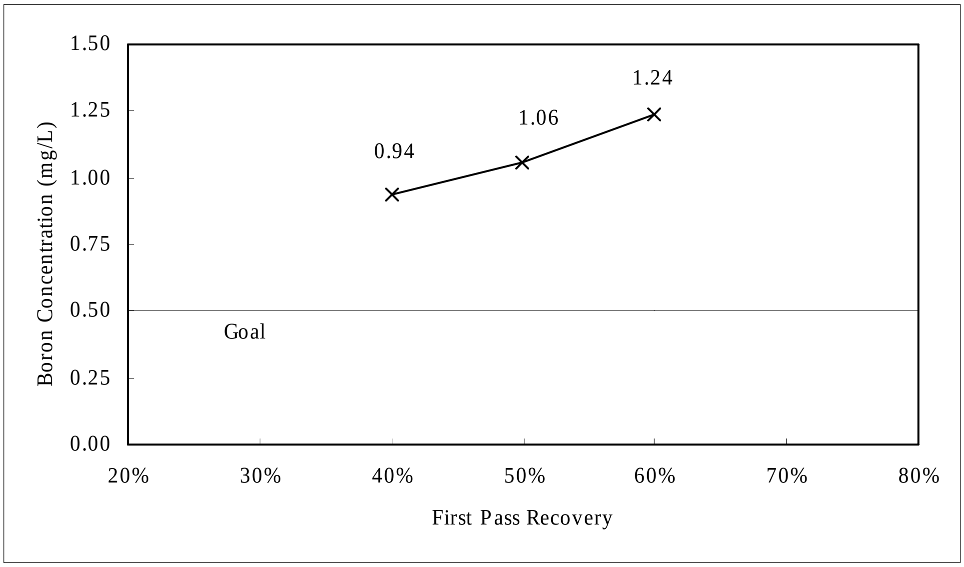


Figure 5-4. Boron Concentration as a Function of Varying Permeate Water Recovery (Feed B conc. = 4.5 mg/L).

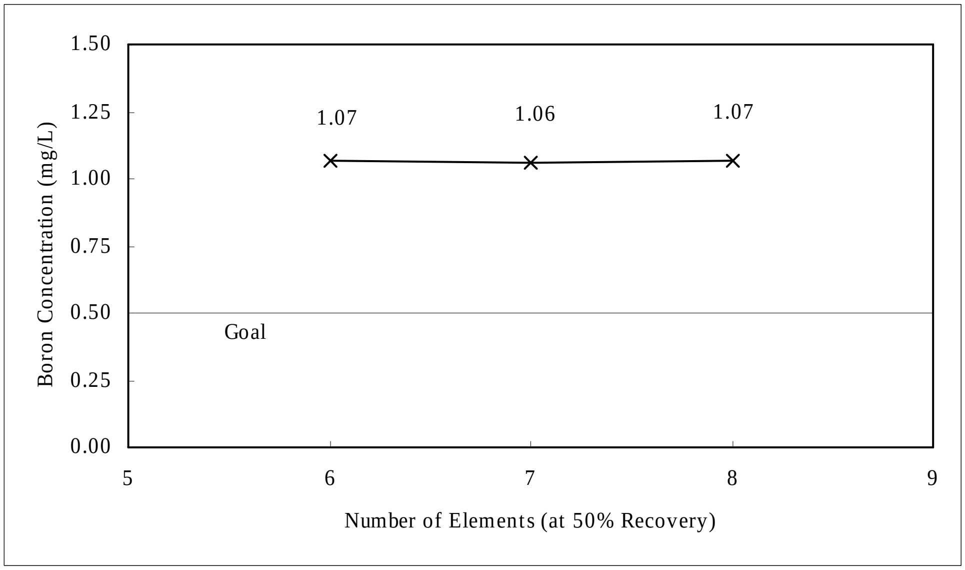


Figure 5-5. Boron Concentration as a Function of Number of First Pass Membrane Elements (Feed B conc. = 4.5 mg/L).

elements is better, this compensates for the poorer water quality produced from the latter elements, resulting in a similar water quality as compared with a design having fewer elements. Thus, the decision to have more or less elements within a pressure vessel is governed by the capital costs of the pressure vessels themselves (i.e., the more elements that can be added in a pressure vessel, the fewer pressure vessels that are needed for a given design) compared to the power costs needed to supply sufficient pressure to the latter elements and consideration of manufacturer-warranted, acceptable design conditions that may limit maximum flux rate in the leading elements.

Related to the use of a first pass membrane with higher rejection characteristics, Hydranautics has recently released data from a desalination pilot study treating water from the Mediterranean that demonstrated nearly 90-percent removal of boron using the SWC4 membrane (personal communication, Mark Wilf, Hydranautics, May 16, 2003). Given the feed water boron concentrations of 4.5 mg/L used in this desktop assessment, the resulting first pass boron concentration would be approximately 0.50 mg/L using this membrane. Because this concentration achieves the WHO standard of 0.5 mg/L, a second pass system may not be required assuming feed water concentrations and temperatures do not increase. However, feed pressure requirements are likely higher than a seawater membrane with lesser rejection. Therefore, the life cycle costs of operating a first pass system using higher rejection membranes would have to be compared with second pass system costs to determine which alternative would be more cost effective.

5.7 Significance to Water Industry

The assessment presented in this section illustrates the monetary significance of meeting three different WQS for a SWRO facility. The three WQS, in order of least to most stringent to meet, were:

(1) TDS = 400 mg/L

(2) Chloride = 100 mg/L

(3) Boron = 0.5 mg/L

While the first WQS was achieved using a single pass SWRO system, additional treatment was necessary to meet the chloride and boron limit. The additional treatment for chloride or boron increased capital costs by 7 to 36 percent which corresponds to an increase in capital and construction costs by \$6 to \$28 million. Using a boron selective ion exchange resin was the most cost-effective alternative for reducing boron, saving approximately \$3 million in annual amortized costs (\$0.33/1,000 gal) compared to the second pass RO alternatives. Although boron is not currently regulated under the SDWA, it is listed under the Candidate Contaminant List and may be regulated in the future. This assessment shows the potential costs of treating boron to a finished water standard of 0.5 mg/L.

From a more fundamental standpoint, this assessment shows how a SWRO design can be tailored to achieve a defined WQS; and based on this design, costs for capital, construction and O&M can be readily determined and evaluated. Unlike the design of traditional freshwater conventional treatment plants, the modeling software that is available from the RO manufacturers coupled with the WTCost® program provide design teams with the ability to evaluate design alternatives that achieve specific WQS and to estimate costs. This gives the designer the ability to estimate a dollar value for incremental improvements in finished water quality, which can be a valuable tool for a utility considering desalination.

6. Conclusions

1. MMF pretreatment conducted during the East and West Coast Sites pilots to treat seawater under the influence of surface water failed to produce a high quality treated filtrate water acceptable for subsequent SWRO treatment. Fouling was observed on SWRO membranes using MMF pretreatment during the East Coast Site test. Additionally, the use of the MMF pretreatment system on the East Coast Site resulted in high cartridge filter replacement frequency—the cartridge filters were replaced on a weekly basis. In comparison, the UF pretreatment system produced a higher quality filtrate with little to no fouling of the SWRO membrane and a reduced cartridge filter replacement frequency. The MMF pretreatment system filtrate on the West Coast Site consistently exceeded the treatment goals and was not suitable to allow performance of the SWRO test.

2. The results of the MMF testing point to a clear need to adequately pilot this technology to address site specific conditions for any SWRO pretreatment application. MMF systems require a full-fledged pilot with several months of operation at a SWRO pilot site to optimize system performance. This would require more extensive studies using different combinations of pH, coagulants, and possibly polymers to shorten the ripening stage after backwash and to be able to continuously operate a SWRO system.

3. Performances of pretreatment systems prior to seawater reverse osmosis to treat seawater under the influence of surface water are site specific. On the east coast of Florida, UF pretreatment was relatively successful at sustain productivity, whereas on the west coast of Florida the UF pretreatment was plagued with fouling issues that limited operation of the unit. The MMF pretreatment system performance was poor on both coasts. Although the change of MMF equipment for the West Coast Site testing appeared to correct the productivity problems that were encountered on the East Coast Site, both MMF systems were unable to achieve adequate water quality to be suitable for SWRO pretreatment. UF filtrate water quality appeared to be marginal during testing on the East Coast Site which produced substantial cartridge filter fouling.

4. The marginal performance results of the UF pretreatment system indicate that this technology also has limitations and requires adequate site specific pilot testing and optimization to determine its suitability and economic viability as a SWRO pretreatment system. The short duration of the pilot studies performed on the East and West Coast Sites did not provide an adequate amount of time to perform system optimization for either the MMF or UF systems, and the performance of these systems during this pilot may be substantially improved with further piloting to optimize system operating parameters and/or testing additional pretreatment processes to address site specific conditions.

5. Controlling biological activity within the feed and pretreatment system appears to be critical with Florida SWUI. Biological growth issues needed to be addressed on several occasions during the pilot study. In particular, a UF membrane autopsy confirmed the presence of slicing and puncturing of the membrane filaments during the East Coast Site testing.
6. The UF system showed consistently more than 6-log rejection of viruses without any viruses detected in the filtrate water. On the other hand, the MMF system showed rejection on the order of 2-log. In addition, viruses were detected in the filtrate. The SWRO system showed virus log rejection on the order to 4 to 6-log. As for the SWRO system, few viruses were detected in the permeate.
7. The process train using either ultrafiltration or multimedia filtration as pretreatment followed by SWRO treatment would meet and exceed all existing and proposed regulations related to pathogen removals and especially the upcoming Long Term 2 Surface Water Treatment Rule.
8. The study showed that, depending on the water quality goals set by a utility or a design team, further treatment in addition to a first pass SWRO system is necessary to meet the water quality goals. For example, with a TDS goal of 400 mg/L, there is no need to implement additional treatment. Alternatively, to meet a goal of 100-mg/L chloride or a goal of 0.5 mg/L of boron, further treatment would be required by either implementing a reverse osmosis membrane second pass or an ion exchange process.
9. The cost analyses showed that implementation of ion exchange would be less expensive than the implementation of a second pass RO to meet the goal of 0.5 mg/L of boron. Ion exchange would save approximately $3 million in annual amortized costs ($0.33/1,000 gal) compared to the RO alternatives for a 25-MGD seawater treatment plant.

7. References

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APPENDIX A
EAST COAST PILOT PROTOCOL

June 2003

Contents

1. Introduction

The U.S. Department of the Interior, Bureau of Reclamation (Reclamation) in collaboration with Reiss Environmental is conducting a research project to evaluate desalination of seawater that has been diluted with freshwater from coastal surface runoff. These waters which are less saline than seawater can be more economical to treat due to the lower operating pressures needed for desalination using technologies such as reverse osmosis (RO).

Problems occur, however, when the diluting surface water has contaminants from runoff such as particulate matter and organics. These contaminants, if not properly removed, can foul RO reducing their productivity while increasing operational costs. Therefore, the intent of this research project is to evaluate the performance and benefits of using conventional sand filters versus ultrafiltration, another membrane filtration technology, as pretreatment to RO.

2. Piloting Protocol

Two pretreatment processes (figure 1) will be tested prior to seawater reverse osmosis (SWRO) to treat seawater under the influence of freshwater runoffs in order to evaluate SWRO membrane fouling as a function of pretreatment. The two pretreatments are conventional media filtration using 2 passes (CF) and ultrafiltration (UF). The two resulting process trains are CF – SWRO and UF – SWRO.

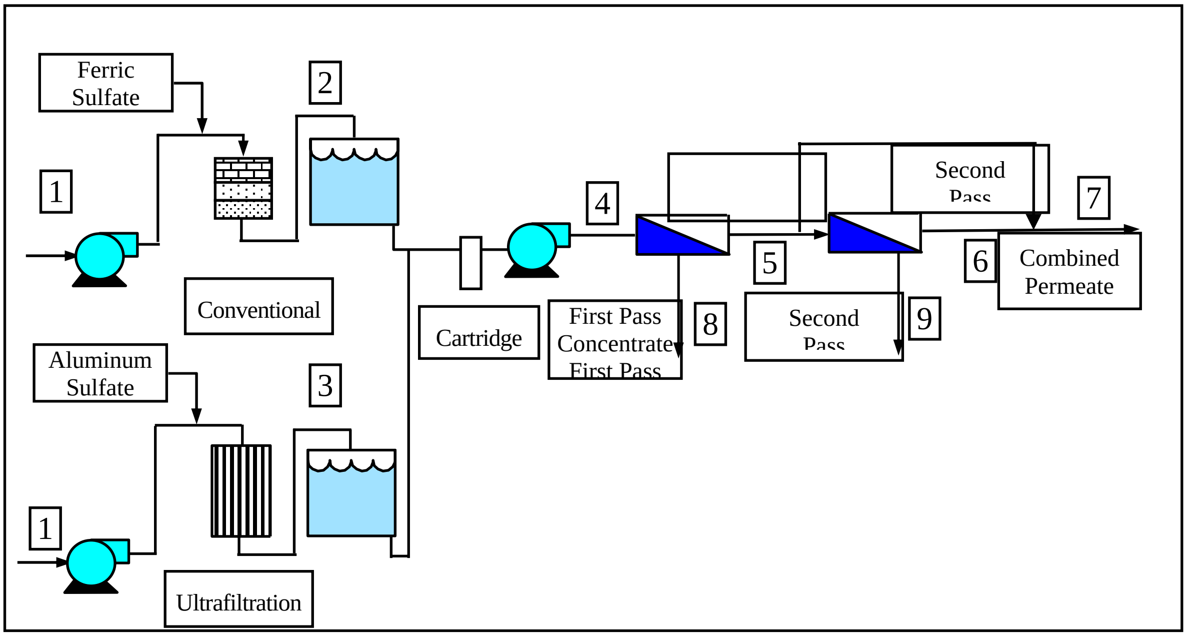

Figure 1. Treatment process diagram showing conventional media filtration and ultrafiltration pretreatment followed by first and second pass seawater reverse osmosis.

2.1 Site Layout

Site layout showing the locations of the pilot unit trailers, equipment, pumps, and tanks is presented in figure 2.

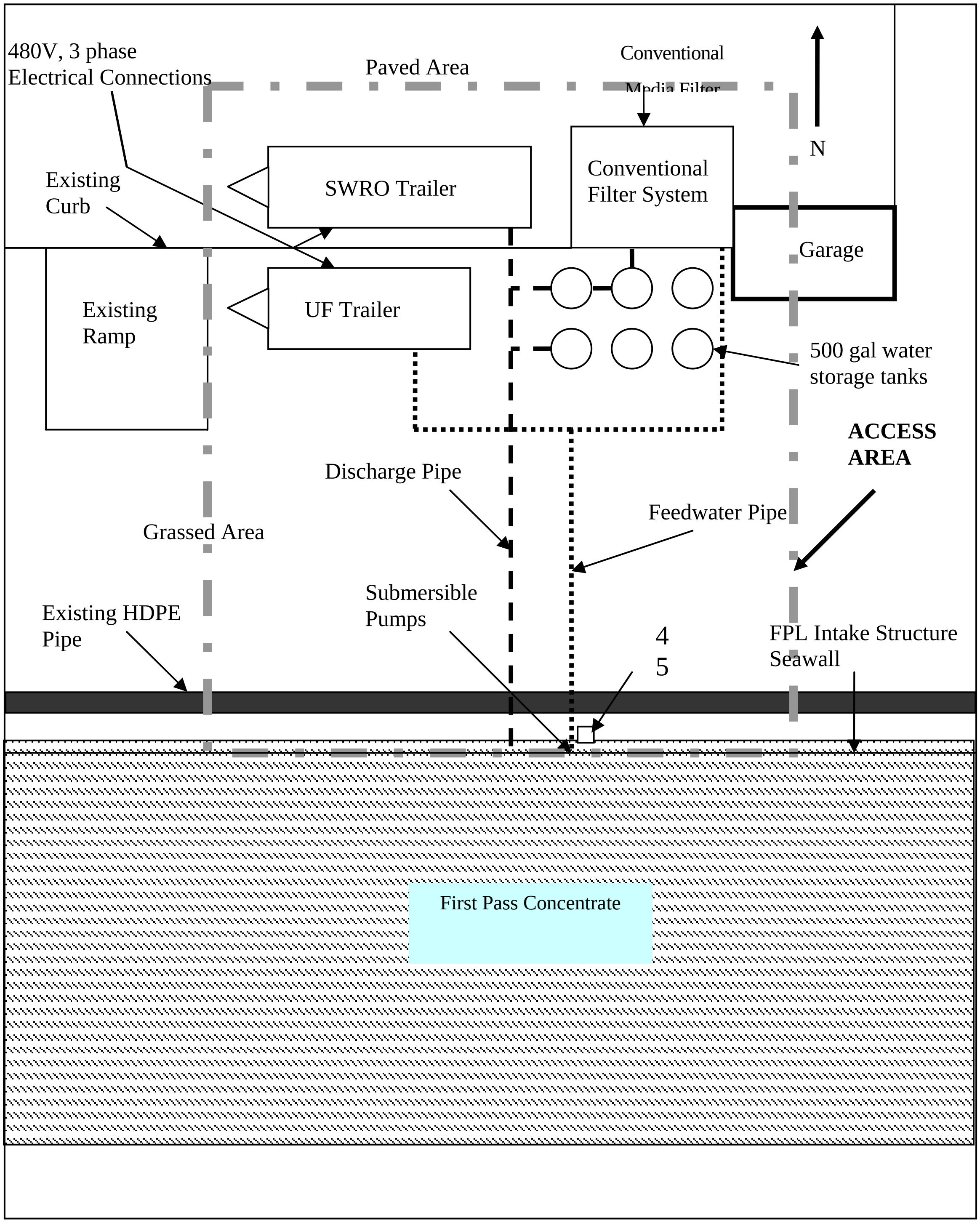

Figure 2. Proposed site layout for pilot units and equipment

2.2 Pilot Equipment

2.2.1 Pilot Units

Three pilot units described below will be transported and installed at each site.

1. Reiss Environmental will provide a conventional pretreatment multimedia filter and the desalination membrane pilot plant. The Seawater RO membrane pilot is a trailer mounted system (see photo 1). This pilot is capable of mirroring full-scale desalination plants (see photo 2) and is also self-contained with lab facilities. Trailer dimensions are 32 ft x 8.5 ft.

Photo 1 – Seawater RO Trailer.

Photo 2 – Seawater RO Membrane System.

2. Norit America will supply a UF pilot plant, as advanced pretreatment to the Seawater RO membrane process. As seen below, the 15+ gallons per minute (gpm) pilot is self-contained and all integral piping is already completed (see photos 3 and 4). Trailer dimensions are 24 ft. x 8.5 ft.

Photo 3 – Ultrafiltration Pretreatment Pilot Trailer.

Photo 4 – Ultrafiltration Pilot (rear view).

3. University of South Florida is to provide a conventional filter process pilot plant fabricated by Calgon. A dual multimedia filter implementing ferric chloride as a coagulant will be used as the conventional pretreatment method. It will be capable of producing 15 gallons per minute (gpm) of

effluent water. System is free standing in a 15 ft x 20 ft area. System will be covered in a tent. Photographs are not available.

2.2.2 Other Equipment

- Feed water and pilot discharge piping to and from the pilot units and source water.
- Two submersible pumps installed in the source water.
- Water storage tanks for feed water, permeate, and backwash storage.
- Various lab equipment: portable turbidimeter, portable conductivity meter, pH meter

2.3 Experimental Matrix

Table 1 below presents the conditions under which the two process trains will be operated. The seawater system will be conducted under the same conditions for both pretreatments. The pretreatment unit operating settings are optimized to supply filtrate water to the seawater system with turbidity lower than 0.3 NTU and SDI less than 5. Table 2 presents the flow conditions for the two process trains. Each test is to be conducted for a period of 21 days. No acid or antiscalant will be added to the feed water of the SWRO system to replicate the common pretreatment practice for seawater membrane system.

A flux of 36 gfd was selected for the ultrafiltration pretreatment as a conservative flux. However, changes can be made to reflect results of the optimization of the ultrafiltration system.

Table 1. Piloting test for East and West Coast Sites

Parameters	Units	Settings
Exp. 1 *(UF – SWRO Process Train)*		
UF flux	gfd	36
UF BW frequency	min	30
SWRO 1st pass flux	gfd	10
SWRO 1st pass recovery	%	50
SWRO 2nd pass flux	gfd	20
SWRO 2nd pass recovery	%	15
Exp. 2 *(CF – SWRO Process Train)*		
CF 1st pass loading rate	gpm/sqft	4
CF 1st pass backwash frequency	hr	24
CF 2nd pass loading rate	gpm/sqft	8
CF 2nd pass backwash frequency	hr	24
SWRO 1st pass flux	gfd	10
SWRO 1st pass recovery	%	50
SWRO 2nd pass flux	gfd	20
SWRO 2nd pass recovery	%	15

Table 2. Flow Settings

Parameters	Units	Settings
Exp. 1 *UF – SWRO Process Train*		
UF flow	gpm	18
SWRO 1st pass permeate flow	gpm	3.7
SWRO 1st pass concentrate flow	gpm	3.7
SWRO 2nd pass permeate flow	gpm	0.9
SWRO 2nd pass concentrate flow	gpm	0.2
Exp. 2 *CF – SWRO Process Train*		
CF 1st pass flow	gpm	8.7
CF 2nd pass flow	gpm	17.4
SWRO 1st pass permeate flow	gpm	3.7
SWRO 1st pass concentrate flow	gpm	3.7
SWRO 2nd pass permeate flow	gpm	0.9
SWRO 2nd pass concentrate flow	gpm	0.2

Fouling will be assessed for each experiment based on declines in mass transfer coefficients (MTC) and increases in headloss along the membranes feed side. MTC is represented by the flux and net driving pressure (NDP) ratio. NDP is the average feed pressure minus permeate pressure and osmotic pressure. The MTC will decrease when fouling occurs during piloting. A chemical cleaning is usually necessary when a MTC decrease of 15% is observed. The runtime between chemical cleanings will be calculated for each experiment and compared to one another to assess performance of each alternative. Feed side headloss or delta pressure increases indicate membrane particle plugging or feed spacer blockage.

2.4 Operational and Analytical Requirements

Flow diagram of the two process trains shown in figure 1 show the monitoring and/or sampling points as numbers as described in table 3. Data collection will consist of routine operational and analytical data as reported in data forms and non-routine data as reported in an operational log book.

Table 3. Pilot Plant Sampling and Monitoring Locations

Number	Description
1	Feed
2	CSF Filtrate
3	UF Filtrate
4	First Pass SWRO Feed
5	First Pass SWRO Permeate
6	Second Pass Permeate
7	Combined Permeate
8	First Pass Concentrate
9	Second Pass Concentrate

2.4.1 *Operational Data*

On-site data will be collected to monitor pilot settings and performance. Data Sheets 1 through 4 included at the end of this document have been prepared for use by the staff to assist in data collection (table 4). There is no datasheet for the UF unit since operational data for the UF unit will be downloaded from the PLC to the on-site computer. Operational data will be collected to determine fouling effects of the four primary RO fouling mechanisms (i.e., plugging, scaling, biological fouling, and organic adsorption). Operational data will be collected and plots of water mass transfer coefficient (specific flux) with time will be developed. Data will be plotted and interpreted as necessary to determine the effects of pretreatment on RO performance.

Table 4. Datasheets

Datasheet 1	Datasheet for CF pretreatment
Datasheet 2	Datasheet for SWRO system
Datasheet 3	Daily Water quality datasheet
Datasheet 4	Weekly Water quality datasheet

2.4.2 *Analytical Data*

Water quality measurements will be taken at regular intervals as indicated in table 5 to ensure proper operation and performance of the pilot plants.

Table 5. Parameters to be measured during pilot testing

		Location					
Parameter	Field or Lab	Raw	Pretreated[1]	First Pass Permeate	Second Pass Permeate	First Pass Concentrate	Second Pass Concentrate
Turbidity	Field	Daily	Daily	Daily		Daily	
TDS (probe)	Field	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly
pH	Field	Daily	Daily	Daily	Daily	Daily	
Conductivity	Field	Daily	Daily	Daily	Daily	Daily	Daily
Temperature	Field	Daily	Daily	Daily			
DO	Field	Weekly	Weekly	Weekly		Weekly	
SDI	Field	Weekly	Weekly				
TOC	Lab	Weekly	Weekly	Weekly	Weekly	Weekly	
DOC	Lab	Weekly	Weekly			Weekly	
HPC	Lab	Weekly	Weekly	Weekly	Weekly	Weekly	Weekly
Full Scan[2]	Lab	One per test run		One per test run			

[1] Testing of pretreatment alternatives will occur sequentially in time requiring that each be monitored while in operation.

[3] Full scan of analysis as defined in table 3-1.

To further evaluate performance, the analytical parameters listed in table 6 will also be measured on the raw and first pass permeate to determine their removals by SWRO. These samples will be collected once from each test run.

Table 6. List of parameters needed to characterize source waters for SWRO

Parameter	Field or Laboratory	Analytical Method
Alkalinity, Total (as $CaCO_3$)	Laboratory	EPA 310.1
Aluminum	Laboratory	SM3111D (EPA 202.1)
Barium	Laboratory	SM3111D (EPA 208.1)
Boron	Laboratory	SM4500B
Bromide	Laboratory	EPA 300.2
Calcium	Laboratory	EPA 215.1
Cesium	Laboratory	EPA 258.1
Chloride	Laboratory	EPA 300.0
Chromium	Laboratory	SM 3111 B
Color	Laboratory	SM 2120 C
Copper	Laboratory	SM 3111 B
Field Dissolved Oxygen	Field	SM 4500-O G
Field pH	Field	SM4500-H+B
Fluoride	Laboratory	EPA 300.0
Hardness, Total (as $CaCO_3$)	Laboratory	SM 2340 C
Heterotrophic Plate Count	Laboratory	SM 9215 D
Iron (dissolved)	Laboratory	SM3111B (EPA 236.1)
Iron (total)	Laboratory	SM 3111 B
Lead	Laboratory	SM 3111 B
Magnesium	Laboratory	EPA 242.1
Manganese	Laboratory	SM3111B (EPA 243.1)
Mercury	Laboratory	SM 3112 B
Nitrate (as N)	Laboratory	EPA 300.0
Nitrogen (as Ammonia)	Laboratory	EPA 350.1
Phosphorus, Total	Laboratory	EPA 365.4
Silica Dioxide	Laboratory	EPA 370.1
Silica Dioxide (Colloidal)	Laboratory	EPA 370.1
Silt Density Index (SDI)	Laboratory	ASTM D4189-95
Sodium	Laboratory	SM3111B (EPA 273.1)
Strontium	Laboratory	SM303A
Specific Conductivity	Field	SM2510B
Sulfate	Laboratory	EPA 300.0
Tin	Laboratory	SM 3111 B
Total Dissolved Solids (gravimetric)	Laboratory	SM2540C (EPA 160.1)
Total Organic Carbon	Laboratory	SM 5310B
Turbidity	Laboratory	SM2130
Zinc	Laboratory	SM3111B (EPA 289.1)

Abbreviations: SM – According Standard Methods for Examination of Water and Wastewater.
EPA – According to U.S. Environmental Protection Agency published methods

2.4.3 Operational Logbook

An Operational Logbook will also be maintained on-site to document non-routine occurrences such as the following:

- The date and time membranes are taken off-line and chemically cleaned along with a detailed description of the cleaning procedure (i.e., cleaning agent, volume of cleaning solution, duration of cleaning, etc.)
- Process upsets that could affect performance (e.g. pretreatment failure, a major change in water quality, operator error, etc.)
- Replacement and specification of membrane module or any other system components
- Any change in system operating parameters
- Any time the system is off

Staff will enter all activities in this logbook that might be considered of importance in interpretation of pilot results.

3. Site Requirements

3.1 Electrical Requirements

Table 6 presents the electrical requirements in order to implement the pilot study.

Table 6. Electrical Support Requirements

Location	Electrical Specifications	Notes
Seawater RO Pilot Unit Trailer	480 VAC, 3 phase, 80 Amps	Female Hubbell Connection
UF Pilot Unit Trailer	480 VAC, 3 phase, 60 Amps	Female Hubbell Connection
CMF Free Standing System	220 VAC, 1 phase, 50 Amps	2 outlets
CMF Free Standing System	115 VAC, 1 phase	6 outlets
Submersible Pumps	220 VAC, 1 phase, 20 Amps	2 outlets at intake seawall

Abbreviations: RO – Reverse Osmosis; UF – Ultrafiltration; CMF – Conventional Media Filtration

3.2 Feed and Discharge Streams

Pilot testing will result in four different process waters as listed below along with their estimated flows. Because all four waters will be combined and discharged together, the resulting water quality is expected to remain the same as the source water except for the resulting solids removed by the prefilters. These solids will be collected and discharged to nearest sanitary sewer system, pending approval by local governing agency.

1. Prefiltered water (~2 gpm for CMF and ~21 gpm for UF)
2. Clarified prefiltered backwash water (<1 gpm for CMF and ~2 gpm for UF)

3. First pass Seawater RO concentrate (~7 gpm) and permeate (~5.7 gpm)
4. Second pass Seawater RO concentrate (~0.2 gpm) and permeate (~1.1 gpm)

Prefiltered Water: To ensure that adequate feed water is available for the Seawater RO pilot system, excess filtered water from the prefilters will be generated requiring discharge. An estimated 2 gpm of filtered water from the conventional media filtration pilot unit and 21 gpm from the ultrafiltration pilot unit are expected to be discharged back to the source water downstream of the feed.

Clarified Prefiltered Backwash Water: Backwash water from the conventional filters or the ultrafiltration system will be collected in two 500-gallon storage tanks. These will be used in clarifying the backwash water prior to discharge to the source water. Discharge is expected occur over a 24-hour period resulting in a flow rate < 1 gpm from the conventional media filters and 2 gpm for the ultrafilters. Settled solids retained in each tank will be collected for discharge to the nearest sanitary sewer system. Approximately every 3 days, chlorine will be added to the backwash water used in backwashing the ultrafilters. A representative from Reiss Environmental will use a Hach Chlorine Field Test Kit to measure the chlorine levels in the resulting backwash water waste to insure residual chlorine levels are zero prior to discharge to the source water downstream of the feed.

First Pass Seawater RO Permeate and Concentrate: The estimated 14 gpm of prefiltered water entering the first pass Seawater RO system will generate approximately 7 gpm of permeate water and 7 gpm concentrate water, assuming a 50% recovery. Only an estimated 1.3 gpm of the permeate water from the first pass system will be treated by the second pass Seawater RO system. All other remaining process waters would need to be discharged. An estimated 5.7 gpm of permeate water and 7.0 gpm of concentrate is expected to be discharged back into the source water downstream of the feed.

Second Pass Seawater RO Permeate and Concentrate: The first pass permeate water entering the second pass Seawater RO system will generate approximately 1.1 gpm of permeate water and 0.2 gpm of concentrate water, assuming an 85-percent recovery. Both streams will need to be discharged back into the source water downstream of the feed.

3.3 Site Restoration

The pilot plants will be returned to the respective suppliers. Reiss Environmental with assistance from the site owner will return the site to as close to the original condition as possible. All piping and pumps not purchased by the site owner will be returned to Reiss Environmental. All other equipment will be left in place if the site owner believes it would be needed for future use.

Data Sheet 1. Datasheet for CF pretreatment

USBR - East Coast Site
Conventional Filtration Data Collection

			Twice a Day								
			Temperatur	Flow (gpm)				Pressure (psi)			
Day	Military Time	Init.	Feed	First pass feed	First pass filtrate	Second pass feed	Second pass filtrate	First pass feed	First pass filtrate	Second pass feed	Second pass filtrate
			1	4	5		6	4	5		6

Data Sheet 2. Datasheet for SWRO system

USBR - East Coast Site

Seawater Reverse Osmosis Operational Data Sheet

Page: ______________

			Twice a Day																		
Date, Time			Temp	Run Time (hrs)		Flow rate (gpm)					Pressure (psi)										
Date	Military Time	Initials	Feed Temp (oC)	Raw Water Pump	SWRO Pump	1st pass concentrate	1st pass permeate	1st pass bypass	2nd pass permeate	2nd pass concentrate	HPP discharge	1st pass feed	1st pass interstage	1st pass concentrate	1st pass permeate	Raw Feed Pressure	Cartridge Filter Upstream Pressure	Cartridge Filter Downstream Pressure	2nd pass feed	2nd pass concentrate	2nd pass permeate

Data Sheet 3. Daily water quality datasheet

USBR - East Coast Site
Daily Field Water Quality Monitoring Data Sheet

Page ____________

Day	Military Time	Initial	pH (daily)								Conductivity (daily)								Temperature (daily)			
			Feed	CMF Filtrate	UF Filtrate	First pass feed	First pass permeate	Second pass permeate	First pass concentrate	Second pass concentrate	Feed	CMF Filtrate	UF Filtrate	First pass feed	First pass permeate	Second pass permeate	First pass conentrate	Second pass concentrate	Feed	UF Filtrate	CMF Filtrate	First pass feed

Data Sheet 4. Weekly water quality datasheet

USBR - East Coast Site
Weekly Field Water Quality Monitoring Data Sheet

Page ______

Day	Military Time	Initial	Turbidity (weekly)							Dissolved Oxygen (weekly)					SDI (weekly)	
			Feed	Feed (Reading on 1720 D Turb.)	CMF Filtrate	UF Filtrate	UF Filtrate (Reading on 1720 D Turb.)	First pass permeate	Second pass permeate	Feed	CMF Filtrate	UF Filtrate	First Pass Permeate	First Pass Concentrate	CMF Filtrate	UF Filtrate

APPENDIX B
WEST COAST PILOT PROTOCOL

September 2003

Contents

Page

1. Introduction

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2. Piloting Protocol

Two pretreatment processes (figure 1) will be tested prior to seawater reverse osmosis (SWRO) to treat seawater under the influence of freshwater runoffs in order to evaluate SWRO membrane fouling as a function of pretreatment. The two pretreatments are conventional media filtration using 2 passes (CF) and ultrafiltration (UF). The two resulting process trains are CF – SWRO and UF – SWRO.

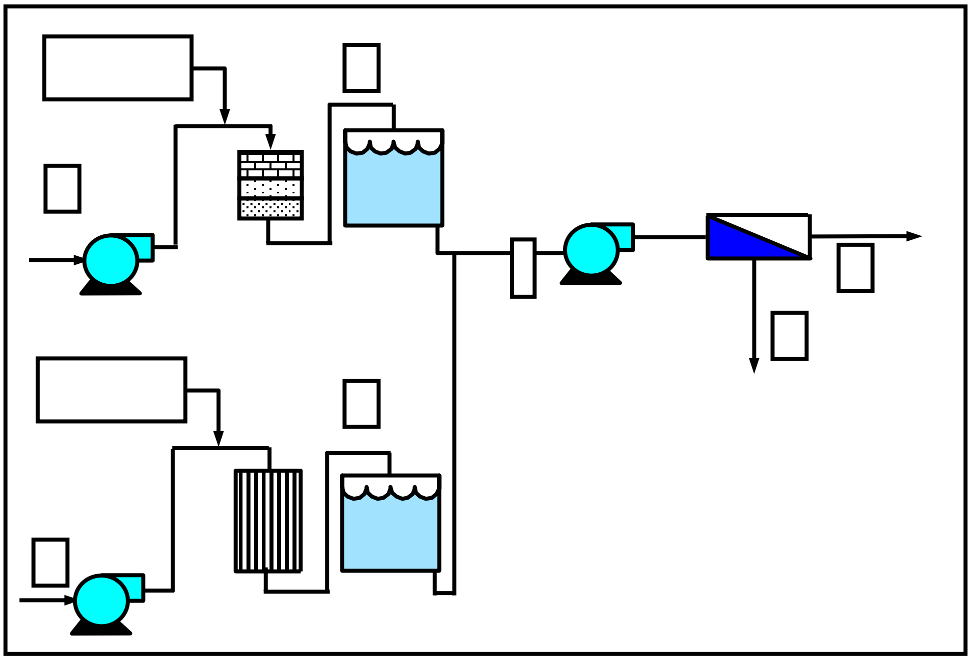


Figure 1. Treatment process diagram showing conventional media filtration and ultrafiltration pretreatment followed by first and second pass seawater reverse osmosis.

2.1 Pilot Equipment

2.1.1 Pilot Units

Three pilot units described below will be transported and installed at each site.

1. Reiss Environmental will provide a conventional pretreatment multimedia filter and the desalination membrane pilot plant. The Seawater RO membrane pilot is a trailer mounted system (see photo 1). This pilot is capable of mirroring full-scale desalination plants (see photo 2) and is also self-contained with lab facilities. Trailer dimensions are 32 ft x 8.5 ft.

Photo 1 – Seawater RO Trailer.

Photo 2 – Seawater RO membrane system.

2. Norit America will supply a UF pilot plant, as advanced pretreatment to the Seawater RO membrane process. As seen below, the 15+ gallons per minute (gpm) pilot is self-contained and all integral piping is already completed (see photos 3 and 4). Trailer dimensions are 24 ft x 8.5 ft.

Photo 3 – Ultrafiltration Pretreatment Pilot Trailer.

Photo 4 – Ultrafiltration Pilot (rear view)

3. University of South Florida is to provide a conventional filter process pilot plant fabricated by Culligan. A dual multimedia filter implementing ferric

chloride as a coagulant will be used as the conventional pretreatment method. It will be capable of producing 20 gallons per minute (gpm) of effluent water. System is free standing in a 15 ft x 20 ft area (see photos 4 and 5). Surface area of the first pass (two filters) is 10 square feet (sqft) whereas the surface area of the second pass is 5 sqft. One of two filters will be used during filtration (polishing filters are used alternatively after backwash).

Photo 5 – The two Roughing Filters (Right side).

Photo 6 – The two Polishing Filters.

2.1.2 Other Equipment

- Feed water and pilot discharge piping to and from the pilot units and source water.
- Two submersible pumps installed in the source water.
- Water storage tanks for feed water, permeate, and backwash storage.
- Various lab equipment: portable turbidimeter, portable conductivity meter, pH meter

2.2 Experimental Matrix

Table 1 below presents the conditions under which the two process trains will be operated. The seawater system will be conducted under the same conditions for both pretreatments. The pretreatment unit operating settings are optimized to supply filtrate water to the seawater system with turbidity lower than 0.3 NTU and SDI less than 5. Table 2 presents the flow conditions for the two process trains. Each test is to be conducted for a period of 30 days. No acid or antiscalant will be added to the feed water of the SWRO system to replicate the common pretreatment practice for seawater membrane system.

A flux of 36 gfd was selected for the ultrafiltration pretreatment based on the east coast study results. However, changes can be made to reflect results of the optimization of the ultrafiltration system using different source water.

Fouling will be assessed for each experiment based on declines in mass transfer coefficients (MTC) and increases in headloss along the membranes feed side. MTC is represented by the flux and net driving pressure (NDP) ratio. NDP is the average feed pressure minus permeate pressure and osmotic pressure. The MTC will decrease when fouling occurs during piloting. A chemical cleaning is usually necessary when a MTC decrease of 15% is observed. The runtime between chemical cleanings will be calculated for each experiment and compared to one another to assess performance of each alternative. Feed side headloss or delta pressure increases indicate membrane particle plugging or feed spacer blockage.

Table 1. Piloting test for West Coast Site

Parameters	Units	Settings
Exp. 1 *(UF – SWRO Process Train)*		
UF flux	gfd	36
UF BW frequency	min	30
SWRO 1st pass flux	gfd	10
SWRO 1st pass recovery	%	50
Exp. 2 *(CF – SWRO Process Train)*		
CF 1st pass loading rate	gpm/sqft	2
CF 1st pass backwash frequency	hr	12
CF 2nd pass loading rate	gpm/sqft	4
CF 2nd pass backwash frequency	hr	12
SWRO 1st pass flux	gfd	10
SWRO 1st pass recovery	%	50

Table 2. Flow Settings

Parameters	Units	Settings
Exp. 1 *UF – SWRO Process Train*		
UF flow	gpm	18
SWRO 1st pass permeate flow	gpm	3.7
SWRO 1st pass concentrate flow	gpm	3.7
Exp. 2 *CF – SWRO Process Train*		
CF 1st pass flow	gpm	20
CF 2nd pass flow	gpm	20
SWRO 1st pass permeate flow	gpm	3.7
SWRO 1st pass concentrate flow	gpm	3.7

2.3 Operational and Analytical Requirements

Flow diagram of the two process trains shown in figures 1 show the monitoring and/or sampling points as numbers as described in table 3. Data collection will consist of routine operational and analytical data as reported in data forms and non-routine data as reported in an operational log book.

Table 3. Pilot Plant Sampling and Monitoring Locations

Number	Description
1	Feed
2	CSF Filtrate
3	UF Filtrate
4	First Pass SWRO Permeate
5	First Pass Concentrate

2.3.1 Operational Data

On-site data will be collected to monitor pilot settings and performance. Data Sheets 1 through 4 included at the end of this document have been prepared for use by the staff to assist in data collection (table 4). There is no datasheet for the UF unit since operational data for the UF unit will be downloaded from the PLC to the on-site computer. Operational data will be collected to determine fouling effects of the four primary RO fouling mechanisms (i.e., plugging, scaling, biological fouling, and organic adsorption). Operational data will be collected and plots of water mass transfer coefficient (specific flux) with time will be developed. Data will be plotted and interpreted as necessary to determine the effects of pretreatment on RO performance.

Table 4. Datasheets

Datasheet 1	Datasheet for CF pretreatment
Datasheet 2	Datasheet for SWRO system
Datasheet 3	Daily Water quality datasheet
Datasheet 4	Weekly Water quality datasheet

2.3.2 Analytical Data

Water quality measurements will be taken at regular intervals as indicated in table 5 to ensure proper operation and performance of the pilot plants.

To further evaluate performance, the analytical parameters listed in table 6 will also be measured on the raw and first pass permeate to determine their removals by SWRO. These samples will be collected once from each test run.

Table 5. Parameters to be measured during pilot testing

Parameter	Field or Lab	Location			
		Raw	Pretreated[1]	First Pass Permeate	First Pass Concentrate
Turbidity	Field	Daily	Daily	Daily	Daily
TDS (probe)	Field	Weekly	Weekly	Weekly	Weekly
pH	Field	Daily	Daily	Daily	Daily
Conductivity	Field	Daily	Daily	Daily	Daily
Temperature	Field	Daily	Daily	Daily	
DO	Field	Weekly	Weekly	Weekly	Weekly
SDI	Field	Weekly	Weekly		
TOC	Lab	Weekly	Weekly	Weekly	Weekly
DOC	Lab	Weekly	Weekly		Weekly
HPC	Lab	Weekly	Weekly	Weekly	Weekly
Full Scan[2]	Lab	One per test run		One per test run	

1. Testing of pretreatment alternatives will occur sequentially in time requiring that each be monitored while in operation
2. Full scan of analysis as defined in table 6.

Table 6. Full scan parameters

Parameter	Field or Laboratory	Analytical Method
Alkalinity, Total (as $CaCO_3$)	Laboratory	EPA 310.1
Aluminum	Laboratory	SM3111D (EPA 202.1)
Barium	Laboratory	SM3111D (EPA 208.1)
Boron	Laboratory	SM4500B
Bromide	Laboratory	EPA 300.2
Calcium	Laboratory	EPA 215.1
Cesium	Laboratory	EPA 258.1
Chloride	Laboratory	EPA 300.0
Chromium	Laboratory	SM 3111 B
Color	Laboratory	SM 2120 C
Copper	Laboratory	SM 3111 B
Field Dissolved Oxygen	Field	SM 4500-O G
Field pH	Field	SM4500-H+B
Fluoride	Laboratory	EPA 300.0
Hardness, Total (as $CaCO_3$)	Laboratory	SM 2340 C
Heterotrophic Plate Count	Laboratory	SM 9215 D
Iron (dissolved)	Laboratory	SM3111B (EPA 236.1)
Iron (total)	Laboratory	SM 3111 B
Lead	Laboratory	SM 3111 B
Magnesium	Laboratory	EPA 242.1
Manganese	Laboratory	SM3111B (EPA 243.1)
Mercury	Laboratory	SM 3112 B
Nitrate (as N)	Laboratory	EPA 300.0
Nitrogen (as Ammonia)	Laboratory	EPA 350.1
Phosphorus, Total	Laboratory	EPA 365.4
Silica Dioxide	Laboratory	EPA 370.1
Silica Dioxide (Colloidal)	Laboratory	EPA 370.1
Sodium	Laboratory	SM3111B (EPA 273.1)
Strontium	Laboratory	SM303A
Specific Conductivity	Field	SM2510B
Sulfate	Laboratory	EPA 300.0
Tin	Laboratory	SM 3111 B
Total Dissolved Solids (gravimetric)	Laboratory	SM2540C (EPA 160.1)
Total Organic Carbon	Laboratory	SM 5310B
Turbidity	Laboratory	SM2130
Zinc	Laboratory	SM3111B (EPA 289.1)

Abbreviations: SM – According Standard Methods for Examination of Water and Wastewater.
EPA – According to U.S. Environmental Protection Agency published methods

2.2.3 Operational Logbook

An Operational Logbook will also be maintained on-site to document non-routine occurrences such as the following:

- The date and time membranes are taken off-line and chemically cleaned along with a detailed description of the cleaning procedure (i.e., cleaning agent, volume of cleaning solution, duration of cleaning, etc.)
- Process upsets that could affect performance (e.g., pretreatment failure, a major change in water quality, operator error, etc.)
- Replacement and specification of membrane module or any other system components
- Any change in system operating parameters
- Any time the system is off

Staff will enter all activities in this logbook that might be considered of importance in interpretation of pilot results.

3. Site Requirements

3.1 Electrical Requirements

Table 7 presents the electrical requirements in order to implement the pilot study.

Table 7. Electrical Support Requirements

Location	Electrical Specifications	Notes
Seawater RO Pilot Unit Trailer	480 VAC, 3 phase, 80 Amps	Female Hubbell Connection
UF Pilot Unit Trailer	480 VAC, 3 phase, 60 Amps	Female Hubbell Connection
CMF Free Standing System	220 VAC, 1 phase, 50 Amps	2 outlets
CMF Free Standing System	115 VAC, 1 phase	6 outlets
Submersible Pumps	220 VAC, 1 phase, 20 Amps	2 outlets at intake seawall

Abbreviations: RO – Reverse Osmosis; UF – Ultrafiltration; CMF – Conventional Media Filtration

3.2 Feed and Discharge Streams

Pilot testing will result in four different process waters as listed below along with their estimated flows. Because all four waters will be combined and discharged together, the resulting water quality is expected to remain the same as the source water except for the resulting solids removed by the prefilters. These solids will be collected and discharged to nearest sanitary sewer system, pending approval by local governing agency.

1. Prefiltered water (~2 gpm for CMF and ~21 gpm for UF)
2. Clarified prefiltered backwash water (<1 gpm for CMF and ~2 gpm for UF)
3. First pass Seawater RO concentrate (~7 gpm) and permeate (~5.7 gpm)
4. Second pass Seawater RO concentrate (~0.2 gpm) and permeate (~1.1 gpm)

Prefiltered Water: To ensure that adequate feed water is available for the Seawater RO pilot system, excess filtered water from the prefilters will be generated requiring discharge. An estimated 2 gpm of filtered water from the conventional media filtration pilot unit and 21 gpm from the ultrafiltration pilot unit are expected to be discharged back to the source water downstream of the feed.

Clarified Prefiltered Backwash Water: Backwash water from the conventional filters or the ultrafiltration system will be collected in two 500-gallon storage tanks. These will be used in clarifying the backwash water prior to discharge to the source water. Discharge is expected occur over a 24-hour period resulting in a flow rate < 1 gpm from the conventional media filters and 2 gpm for the ultrafilters. Settled solids retained in each tank will be collected for discharge to the nearest sanitary sewer system. Approximately every 3 days, chlorine will be added to the backwash water used in backwashing the ultrafilters. A representative from Reiss Environmental will use a Hach Chlorine Field Test Kit to measure the chlorine levels in the resulting backwash water waste to insure residual chlorine levels are zero prior to discharge to the source water downstream of the feed.

First Pass Seawater RO Permeate and Concentrate: The estimated 14 gpm of prefiltered water entering the first pass Seawater RO system will generate approximately 7 gpm of permeate water and 7 gpm concentrate water, assuming a 50% recovery. Only an estimated 1.3 gpm of the permeate water from the first pass system will be treated by the second pass Seawater RO system. All other remaining process waters would need to be discharged. An estimated 5.7 gpm of permeate water and 7.0 gpm of concentrate is expected to be discharged back into the source water downstream of the feed.

Second Pass Seawater RO Permeate and Concentrate: The first pass permeate water entering the second pass Seawater RO system will generate approximately 1.1 gpm of permeate water and 0.2 gpm of concentrate water, assuming an 85-percent recovery. Both streams will need to be discharged back into the source water downstream of the feed.

3.3 Site Restoration

The pilot plants will be returned to the respective suppliers. Reiss Environmental with assistance from the site owner will return the site to as close to the original condition as possible. All piping and pumps not purchased by the site owner will be returned to Reiss Environmental. All other equipment will be left in place if the site owner believes it would be needed for future use.

Data Sheet 1. Datasheet for CF pretreatment

USBR - West Coast Site

Page No. ____________

Conventional Filtration Operational Data Sheet

			Twice a Day													
			Operating					Pressure (psi)								
Date	Military Time	Initials	Filter No. 1	Filter No. 2	Filter No. 3	Filter No. 4	Ferric Sulfate Tank Level (see footnotes)	Feed Filter No. 1	Feed Filter No. 2	Polishing No. 1	Polishing No. 2	Filtrate No. 1	Filtrate No. 2	Discharge water temperature (°C)	Discharge water flowrate (gpm)
							CMF 1	CMF 2	CMF 3	CMF 4	CMF 5	CMF 6	CMF 7	CMF 8	CMF 9

1. read and record level of drum **daily,**
2. read and record level of drum before switching to another drum
3. record date, time and level of new drum

Data Sheet 2. Datasheet for SWRO system

USBR - West Coast Site

Seawater Reverse Osmosis Operational Data Sheet

Page: __________

			Twice a Day																		
Date, Time			**Temp**	**Run Time (hrs)**		**Flow rate (gpm)**					**Pressure (psi)**										
Date	Military Time	Initials	Feed Temp (oC)	Raw Water Pump	SWRO Pump	1st pass concentrate	1st pass permeate	1st pass bypass	2nd pass permeate	2nd pass concentrate	HPP discharge	1st pass feed	1st pass interstage	1st pass concentrate	1st pass permeate	Raw Feed Pressure	Cartridge Filter Upstream Pressure	Cartridge Filter Downstream Pressure	2nd pass feed	2nd pass concentrate	2nd pass permeate

Data Sheet 3. Daily water quality datasheet

USBR - West Coast Site
Daily Field Water Quality Monitoring Data Sheet

Page ____________

Day	Military Time	Initial	pH (daily)								Conductivity (daily)								Temperature (daily)			
			Feed	CMF Filtrate	UF Filtrate	First pass feed	First pass permeate	Second pass permeate	First pass concentrate	Second pass concentrate	Feed	CMF Filtrate	UF Filtrate	First pass feed	First pass permeate	Second pass permeate	First pass conentrate	Second pass concentrate	Feed	UF Filtrate	CMF Filtrate	First pass feed

Data Sheet 4. Weekly water quality datasheet

USBR - West Coast Site
Weekly Field Water Quality Monitoring Data Sheet

Page ____________

Day	Military Time	Initial	Turbidity (weekly)							Dissolved Oxygen (weekly)					SDI (weekly)	
			Feed	Feed (Reading on 1720 D Turb.)	CMF Filtrate	UF Filtrate	UF Filtrate (Reading on 1720 D Turb.)	First pass permeate	Second pass permeate	Feed	CMF Filtrate	UF Filtrate	First Pass Permeate	First Pass Concentrate	CMF Filtrate	UF Filtrate

APPENDIX C
Source Water Quality

Table C-1. East Coast Site Raw Water Quality

Parameters	Unit	2/18/2003	2/24/2003	3/3/2003	Average
Alkalinity, Total (as $CaCO_3$)	mg/L	130	130	140	133
Aluminum	mg/L	0.3	0.51	0.2	0.34
Barium	mg/L	0.02	0.02	0.02	0.02
Boron	mg/L	2.7	2.7	2.4	2.6
Bromide	mg/L	50	49	51	50
Calcium	mg/L	300	340	410	350
Cesium	mg/L	<0.04	<0.04	<0.04	<0.04
Chloride	mg/L	13,000	14,000	13,000	13,333
Chromium	ug/L	< 0.01	<0.01	0.27	0.27
Color	CPU	10	10	10	10
Copper	mg/L	0.0029	0.0037	0.0027	0.0031
Dissolved Oxygen (DO)	mg/L	8	9.6	NA	8.8
Field pH	units	8.3	8.5	8.4	8.4
Fluoride	mg/L	0.98	0.62	0.92	0.84
Hardness, Total (as $CaCO_3$)	mg/L	4,100	4,300	5,000	4,467
Iron (dissolved)	mg/L	0.09	0.04	0.05	0.06
Iron (total)	mg/L	0.12	0.19	0.18	0.16
Lead	mg/L	< 0.05	<0.05	0.1	0.1
Magnesium	mg/L	820	840	970	877
Manganese	mg/L	< 0.01	<0.01	0.02	0.02
Mercury	mg/L	< 0.0002	0.0002	<0.0002	< 0.0002
Nitrate (as N)	mg/L	0.01	0.03	0.02	0.02
Nitrogen (as Ammonia)	mg/L	0.02	0.02	0.07	0.04
Phosphorus, Total	mg/L	< 0.03	<0.03	0.04	0.04
Silica Dioxide	mg/L	0.65	0.84	1.56	1.02
Silica Dioxide (Colloidal)	mg/L	0.55	1.8	1.6	1.32
Silt Density Index (SDI)		> 6.67	NA	NA	> 6.67
Sodium	mg/L	6,800	8,000	8,000	7,600
Specific Conductivity	uohms/cm	38,000	37,000	36,000	37,000
Strontium	mg/L	5.2	5.1	4.7	5.0
Sulfate	mg/L	1800	1900	2000	1,900
Tin	mg/L	< 0.1	<0.01	<0.01	<0.01
Total Dissolved Solids (gravimetric)	mg/L	24,400	24,000	24,000	24,133
Total Organic Carbon	mg/L	8.6	7.8	7.1	7.8
Turbidity	NTU	3	4.3	3.8	3.7
Zinc	mg/L	< 0.01	<0.01	0.02	0.02

Table C-2. West Coast Site Raw Water Quality

		3/31/2003	4/16/2003	5/28/2003	Average
Alkalinity, Total (as $CaCO_3$)	mg/L	120	120	120	120
Aluminum	mg/L	0.13	< 0.1	< 0.1	0.13
Barium	mg/L	0.01	0.02	< 0.01	0.02
Boron	mg/L	3.3	3.2	3.0	3
Bromide	mg/L	51	46	63	53
Calcium	mg/L	320	300	430	350
Cesium	mg/L	< 0.04	< 0.04	< 0.04	< 0.04
Chloride	mg/L	16,000	14,000	19,000	16,333
Chromium	mg/L	< 0.01	< 0.01	< 0.01	< 0.01
Color	CPU	30	20	10	20
Copper	ug/L	4.1	5.3	1.4	3.6
Dissolved Organic Carbon	mg/L	5.3	4.8	2.9	4.3
Fluoride	mg/L	0.61	0.98	1.2	0.9
Hardness, Total (as $CaCO_3$)	mg/L	4,800	4,500	6,400	5,233
Heterotrophic Plate Count (HPC)	cfu/ml	240	48	12	100
Iron (dissolved)	mg/L	< 0.02	< 0.02	< 0.02	< 0.02
Iron (total)	mg/L	0.33	0.08	0.02	0.14
Lead	mg/L	< 0.005	< 0.002	< 0.002	< 0.005
Magnesium	mg/L	960	910	1,300	1,057
Manganese	mg/L	< 0.01	< 0.01	< 0.01	< 0.01
Mercury	mg/L	< 0.0002	< 0.0002	< 0.0002	< 0.0002
Nitrate (as N)	mg/L	< 0.01 U	< 0.01 U	0.04	0.04
Nitrogen (as Ammonia)	mg/L	< 0.01	< 0.02	< 0.01	0.02
Phosphorus, Total (P)	mg/L	0.06	< 0.03	0.017	0.04
Silica Dioxide	mg/L	1.2	1.1	0.34	0.9
Silica Dioxide (Colloidal)	mg/L	17	4.5	0.11	7
Sodium	mg/L	7,900	7,500	11,000	8,800
Specific Conductivity	uohms/cm				
Strontium	mg/L	5	5.2	7.9	6.0
Sulfate	mg/L	2,100	1,900	2,600	2,200
Tin	mg/L	< 0.1	< 0.1	< 0.1	< 0.1
Total Dissolved Solids (gravimetric)	mg/L	27,000	26,000	36,000	29,667
Total Organic Carbon	mg/L	5.7	5.2	2.7	4.5
TSS	mg/L	55	11	16	27
Turbidity	NTU	18	1.7	1.6	7
Zinc	mg/L	< 0.01	< 0.01	< 0.01	< 0.01

APPENDIX D
Process Train Water Quality

Table D-1. East Coast Site Water Quality (Full-scan)

		UF Pretreatment (06/30/03)		MMF Pretreatment (07/22/03)	
Parameter	**Unit**	**Raw Water**	**Permeate**	**Raw Water**	**Permeate**
Alkalinity, Total (as CaCO3)	mg/L	140	< 2	150	< 11
Nitrogen (as Ammonia)	mg/L	0.02	0.04	0.03	< .1
Bromide	mg/L	43	0.84	42	0.36
Chloride	mg/L	12,000	210	12,000	86
Color	CPU	10	< 5	10	< 1
Specific Conductivity	umhos/cm	34,000	710	34,000	310
Fluoride	mg/L	2.2	0.014	2.9	< 0.02
Hardness, Total (as CaCO3)	mg/L	3,900	6.6	4,000	7.1
Nitrate (as N)	mg/L	0.02	< 0.01	0.71	0.02
Sulfate	mg/L	1,700	3.5	1,600	3.4
Total Dissolved Solids (gravimetric)	mg/L	21,000	360	22,616	200
Total Organic Carbon	mg/L	12	< 1	10	< 0.5
Phosphorus, Total	mg/L	< 0.03	< 0.03	< 0.04	< 0.03
Turbidity	NTU	5	< 0.05	9	< 0.02
Aluminum	mg/L	0.13	< 0.1	0.14	< 0.04
Barium	mg/L	< 0.01	< 0.01	0.026	< 0.1
Boron	mg/L	3	1.4	2	0.7
Calcium	mg/L	280	0.48	290	0.52
Cesium	mg/L	< 0.04	< 0.001	< 0.04	< 0.001
Chromium	mg/L	< 0.01	< 0.01	< 0.05	< 0.05
Copper	ug/L	2.3	< 0.005	1.4	< 0.02
Iron (total)	mg/L	0.15	< 0.02	0.13	< 0.03
Iron (dissolved)	mg/L	< 0.02	< 0.02	< 0.001	< 0.001
Lead	mg/L	< 0.002	< 0.001	0.002	< 0.1
Magnesium	mg/L	780	1.3	790	1.4
Manganese	mg/L	< 0.01	< 0.01	< 0.01	< 0.01
Mercury	mg/L	< 0.0002	< 0.0002	< 0.001	< 0.001
Silica Dioxide (Colloidal)	mg/L	0.3	< 0.1	0.3	< 0.1
Silica Dioxide	mg/L	1.2	< 0.1	2.9	< 0.1
Silicon as SiO2	mg/L	1.5	< 0.01	3.2	< 0.01
Sodium	mg/L	6,400	130	NA	54
Strontium	mg/L	6	0.01	6	0.01
Tin	mg/L	< 0.1	< 0.1	< 0.1	< 0.1
Zinc	mg/L	< 0.01	< 0.01	< 0.005	< 0.005

Table D-2. East Coast Site Water Quality (weekly TOC, DOC, and HPC)

Date	Raw	Pretreated	Permeate	Concentrate
TOC				
UF Pretreatment				
06/11/03	17	13	< 1	23
06/26/03	14	12	< 1	23
06/30/03	14	12	< 1	25
07/09/03	15	12	< 1	25
MMF Pretreatment				
07/22/03	15	12	< 1	25
07/29/03	13	10	< 1	21
08/05/03	13	12	< 1	22
DOC				
UF Pretreatment				
06/11/03	16	13	NA	25
06/26/03	13	12	NA	25
06/30/03	14	14	NA	25
07/09/03	14	14	NA	25
MMF Pretreatment				
07/22/03	13	13	NA	28
07/29/03	13	12	NA	24
08/05/03	13	12	NA	23
HPC				
UF Pretreatment				
06/11/03	40	20	120	80
06/26/03	60	16	12	176
06/30/03	4	< 4	< 4	8
07/09/03	280	< 10	30	110
MMF Pretreatment				
07/22/03	120	20	< 25	210
07/29/03	24	< 4	< 4	4
08/05/03	20	< 4	< 4	< 4

APPENDIX E
pH Tracer and Virus Challenge Test Protocol

pH Tracer Test Protocol

This test was specifically performed prior to the virus challenge test to optimize the time interval between each sample in the feed, influent and the effluent of the system under review. This would also provide the number of samples that would be required to be taken to get most accurate results of log removal of viruses. Prior to the start of the system, the following was confirmed:

a. Acid Dosing Pump: 3 GPD [2.083×10^{-3} GPM]

b. Flow Rate: 13 gpm RO system, 19 gpm UF system

c. 33% HCl Acid which is to be used as a tracer

Preparation

a. Assemble 3 GPD metering pump with proper piping and prime with first pass permeate water in 5 gallon bucket.

b. Using 33% HCl acid, mix a 10% solution in a 5 gallon bucket.

c. Estimate that 35% stroke rate and 35% stroke length will provide pH 5 or so in both the RO and UF tests (78 mg/L 33% HCl acid).

pH tracer for UF system

a. Injection point: Feed point upstream of Feed Pump after coagulation.

b. Sample points are sample port designated as post chemical feed for feed water and combined filtrate water for filtrate water.

c. Open both the post chemical feed and combined filtrate sample ports before acid injection begins. Use a gentle flow rate.

d. Measure pH using beaker as flow thru cell.

e. Turn on the acid metering pump and monitor the post chemical feed till pH drops to 6.0. Record time.

f. Start measuring the pH from the sample port designated as combined filtrate pH as in e.

g. Monitor till pH changes and record every 15 sec at 2 min + until pH is back to original value.

pH tracer for MMF system

a. Injection point: Feed point upstream of Feed Pump after coagulation.

b. Sample points are sample port designated as post chemical feed for feed water and first stage filtrate and second stage filtrate for filtrate waters.

c. Open both the post chemical feed and filtrate sample ports before acid injection begins. Use a gentle flow rate.

d. Measure pH using beaker as flow thru cell.

e. Turn on the acid metering pump and monitor the post chemical feed till pH drops to 6.0. Record time.

f. Start measuring the pH from the sample port designated as first stage and second stage filtrate pH as in e.

g. Monitor till pH changes and record approximately every minute until pH is back to original value.

pH tracer for RO system

a. Injection Point: Existing acid feed point downstream of Raw Water Pump and upstream of Cartridge Filter.

b. Remove cartridge filters out for pH Tracer test to mimic Virus challenge for the RO system.

c. Sample points will be post chemical feed sample point for feed water and permeate sample point for permeate water.

d. Open sample ports before the acid injection begin. Use a gentle flow rate.

e. Measure pH using beaker as flow thru cell.

f. Monitor till pH drops to 6.0 on the feed water. Record ambient pH at time 0. Note time and pH of initial pH decrease and time that pH reaches 6.0.

g. Start measuring first pass permeate pH as in f.

h. Monitor till pH changes and record every 15 sec at 2 min + until pH is back to original value.

Virus Challenge Test Protocol

The virus challenge test was performed upon completion of the acid pH tracer test and knowing residence time of the respective systems. The acid test also assists in knowing as to when the acid enters and exits the system on both the influent (feed) and the effluent (permeate) side helping decide on the number and time of sampling during the virus challenge test.

Preparation

a. Obtain the three bacteriophages used in the study: MS-2 (30 nm RNA virus specific for E.Coli C3000), Fr (28 nm RNA virus specific for E.Coli C), and PRD-1 (68 nm DS DNA virus specific for Salmonella typhimurium).

b. Grow these viruses upto 10^9 plaque forming units (pfu)/mL in the laboratory prior to the challenge day (Snustad and Dean, 1971) and then preserved in 4 °C till use.

c. On the challenge day, 300mL of each phage was mixed together in a sterile 1000 mL container.

d. Sterile 15 mL polypropylene tubes (Fisher Scientific) containing 0.5 mL of 10% Beef Extract to stabilize and preserve the viruses following collection should be used for sample collection.

Virus Challenge for UF System

a. 300 mL of each phage stock were mixed together in a sterile 1000 mL container.

b. 1 mL sample of this seed solution was removed and mixed with 49 mL of influent water and named “Diluted Seed.”

c. The above sample was further diluted 1/100, and labeled as “Experimental Initial” and used as a phage survival control.

d. 10 mL of sample of feed water prior to the spike was removed and labeled “Background” to determine the amount of naturally occurring bacteriophages in the feed water.

e. Virus injection point: Feed point upstream of Feed Pump after coagulation (same port as in pH tracer test).

f. Sample points will be post chemical feed sample point for feed water and combined filtrate sample point for filtrate water.

g. Open the post chemical feed and filtrate before virus injection begins. Use a gentle flow rate.

h. At time T=0, the viral mixture was injected (pre-pump) into the influent of the unit by a peristaltic pump at the rate of 120 ml/min for a 5:00 min duration.

i. Samples (10 ml) of the influent (post pump) will be taken from the feed sampling port at the following times T = 0:00, 2:00, 3:00, 4:00 and 5:00 minutes.

j. Samples (10 ml) of the effluent will be taken from the effluent sampling port at the following times T = 1:00, 2:00, 3:00, 4:00, 5:00, 6:00, 7:00 and 8:00 minutes.

k. At the end of the experiment, another sample of the seed solution will be removed from the "Diluted Seed," diluted 1/100 in PBS, labeled as "Final" and used as a phage survival control.

l. All samples collected should be placed in 4°C and transported to the laboratory for analysis. All effluent samples should be kept in a separate physical location than the influent or seed samples.

m. Phages would be enumerated by the double agar overlay procedure (Snustad and Dean, 1971) and reported as pfu/ml.

n. The following hosts should be used to enumerate the respective viruses:
Escherichia coli C-3000 (ATCC 15597) for bacteriophage MS2 (ATCC 15597-B1)
Escherichia coli Migula (ATCC 19853) for bacteriophage Fr (ATCC 15767-B1) and
Salmonella Typhimurium (ATCC 19585) for bacteriophage PRD-1.

Virus Challenge on the Conventional Treatment System

a. 1 mL sample of this seed solution was removed and mixed with 49 mL of influent water and named "Diluted Seed."

b. The above sample was further diluted 1/100, and labeled as "Experimental Initial" and used as a phage survival control.

c. 10 mL of sample of feed water prior to the spike was removed and labeled "Background" to determine the amount of naturally occurring bacteriophages in the feed water.

d. Injection Point: Feed point upstream of Feed Pump after coagulation (same port as in pH tracer test).

e. Sample points will be post chemical feed sample point for feed water, first stage filtrate and second stage filtrate sample points.

f. Open the sample ports before virus injection begins. Use a gentle flow rate.

g. At time T=0, the virus mix should be injected (pre-pump) into the influent of the unit by a peristaltic pump at the rate of 120 ml/min for a 5:00 min duration.

h. Samples (10 ml) of the influent (post pump) will be taken from the feed sampling port at the following times T = 0:00, 1:00, 2:00, 3:00, 4:00 5:00 and 6:00 minutes.

i. Samples (10 ml) of the first stage filtrate will be taken from the effluent sampling port at the following times T = 0:00, 15:00, 25:00, 32:00, 45:00, 52:00, 62:00 and 72:00 minutes.

j. Samples (10 ml) of the second stage filtrate will be taken from the effluent sampling port at the following times T = 0:00, 25:00, 35:00, 45:00, 55:00, 65:00, 75:00 and 85:00 minutes.

k. At the end of the experiment, another sample of the seed solution will be removed from the “Diluted Seed,” diluted 1/100 in PBS, labeled as “Final” and used as a phage survival control.

l. All samples collected should be placed in 4°C and transported to the laboratory for analysis. All effluent samples should be kept in a separate physical location than the influent or seed samples.

m. Phages would be enumerated by the double agar overlay procedure (Snustad and Dean, 1971) and reported as pfu/ml.

n. The following hosts should be used to enumerate the respective viruses:
Escherichia coli C-3000 (ATCC 15597) for bacteriophage MS2 (ATCC 15597-B1)
Escherichia coli Migula (ATCC 19853) for bacteriophage Fr (ATCC 15767-B1) and
Salmonella Typhimurium (ATCC 19585) for bacteriophage PRD-1.

Virus Challenge on the RO System

a. 1 mL sample of this seed solution was removed and mixed with 49 mL of influent water and named “Diluted Seed.”

b. The above sample was further diluted 1/100, and labeled as “Experimental Initial” and used as a phage survival control.

c. 10 mL of sample of feed water prior to the spike was removed and labeled “Background” to determine the amount of naturally occurring bacteriophages in the feed water.

d. Injection Point: Fabricated an injection port upstream of raw water pump and Cartridge Filter.

e. Remove cartridge filters out for virus challenge for the RO system.

f. Sample points will be post chemical feed sample point for feed water, permeate sample point for permeate water and concentrate sample point for concentrate water.

g. Open the sample ports before virus injection begins. Use a gentle flow rate.

h. At time T=0, the virus mix should be injected (pre-pump) into the influent of the unit by a peristaltic pump at the rate of 120 ml/min for a 5:00 min duration.

i. Samples (10 ml) of the influent (post pump) will be taken from the feed sampling port at the following times T = 0:00, 2:00, 3:00, 4:00 and 5:00 minutes.

j. Samples (10 ml) of the effluent will be taken from the effluent sampling port at the following times T = 1:00, 2:00, 3:00, 4:00, 5:00, 6:00, 7:00 and 8:00 minutes.

k. RO concentrate samples should be taken at the same time the effluent samples were taken.

l. At the end of the experiment, another sample of the seed solution will be removed from the “Diluted Seed,” diluted 1/100 in PBS, labeled as “Final” and used as a phage survival control.

m. All samples collected should be placed in 4°C and transported to the laboratory for analysis. All effluent samples should be kept in a separate physical location than the influent or seed samples.

n. Phages would be enumerated by the double agar overlay procedure (Snustad and Dean, 1971) and reported as pfu/ml.

o. The following hosts should be used to enumerate the respective viruses:
Escherichia coli C-3000 (ATCC 15597) for bacteriophage MS2 (ATCC 15597-B1)
Escherichia coli Migula (ATCC 19853) for bacteriophage Fr (ATCC 15767-B1) and
Salmonella Typhimurium (ATCC 19585) for bacteriophage PRD-1.

APPENDIX F
Virus Challenge Test Results

Table F-1. MMF Virus Challenge Test Results

Time (min)	Feed Bacteriophage Concentration (pfu/mL)			1st Stage Bacteriophage Concentration (pfu/mL)			2nd Stage Bacteriophage Concentration (pfu/mL)		
	MS-2	PRD1	Fr	MS-2	PRD1	Fr	MS-2	PRD1	Fr
0	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
1	< 0.5	< 0.5	< 0.5						
2	9.0E+04	2.1E+05	3.0E+05						
4	5.0E+05	9.7E+05	1.4E+06						
5	9.8E+05	1.3E+06	1.4E+06						
6	3.1E+06	1.8E+06	1.9E+06						
15				4.5E+04	6.6E+04	7.3E+04			
25				2.3E+04	1.4E+04	2.7E+04	5.3E+04	3.8E+04	2.7E+04
32				1.7E+04	1.6E+04	5.7E+03			
35							2.2E+04	1.8E+04	1.8E+04
42				3.9E+03	4.7E+03	7.6E+03			
45							2.3E+03	6.6E+03	8.4E+03
52				2.1E+03	2.5E+03	3.4E+03			
55							1.3E+03	2.5E+03	2.4E+03
62				1.4E+03	1.8E+03	2.0E+03			
65							9.4E+02	2.2E+03	2.3E+03
72				1.2E+03	1.3E+03	1.9E+03			
75							9.0E+02	1.5E+03	4.3E+03
85							8.7E+02	1.0E+03	1.5E+03

Table F-2. MMF First Stage Log Removals

Time (min)	Feed Bacteriophage Concentration (pfu/mL)			1st Stage Bacteriophage Concentration (pfu/mL)			1st Stage Bacteriophage Log Removal			Residence Time (min)
	MS-2	PRD1	Fr	MS-2	PRD1	Fr	MS-2	PRD1	Fr	
0	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5				
1	< 0.5	< 0.5	< 0.5							
2	9.0E+04	2.1E+05	3.0E+05							
4	5.0E+05	9.7E+05	1.4E+06							
32				1.7E+04	1.6E+04	5.7E+03	0.7	1.1	1.7	30
32				1.7E+04	1.6E+04	5.7E+03	1.5	1.8	2.4	28

Log removal calculation (app. 30 min detention time): T = 2 min for feed with T = 32 min for filtrate (yellow cells); T = 4 min for feed with T = 32 min for filtrate (green cells).

Table F-3. MMF Second Stage Log Removals

Time (min)	1st Stage Bacteriophage Concentration (pfu/mL)			2nd Stage Bacteriophage Concentration (pfu/mL)			2nd Stage Bacteriophage Log Removal			Residence Time (min)
	MS-2	PRD1	Fr	MS-2	PRD1	Fr	MS-2	PRD1	Fr	
0	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5				
15	4.5E+04	6.6E+04	7.3E+04							
25	2.3E+04	1.4E+04	2.7E+04	5.3E+04	3.8E+04	2.7E+04	NA	0.2	0.4	10
32	1.7E+04	1.6E+04	5.7E+03							
35				2.2E+04	1.8E+04	1.8E+04	0.0	NA	0.2	10
42	3.9E+03	4.7E+03	7.6E+03							
45				2.3E+03	6.6E+03	8.4E+03	0.9	0.4	NA	13
52	2.1E+03	2.5E+03	3.4E+03							
55				1.3E+03	2.5E+03	2.4E+03	0.5	0.3	0.5	13
62	1.4E+03	1.8E+03	2.0E+03							
65				9.4E+02	2.2E+03	2.3E+03	0.3	0.0	0.2	13
72	1.2E+03	1.3E+03	1.9E+03							
75				9.0E+02	1.5E+03	4.3E+03	0.2	0.1	NA	13
85				8.7E+02	1.0E+03	1.5E+03	0.1	0.1	0.1	13

Log removal calculation (app. 10 min detention time): T = 15 min for feed with T = 25 min for filtrate (yellow cells); T = 25 min for feed with T = 35 min for filtrate (green cells); etc…

Table F-4. MMF System Log Removals

Time (min)	Feed Bacteriophage Concentration (pfu/mL)			2nd Stage Bacteriophage Concentration (pfu/mL)			System Bacteriophage Log Removal			Residence Time (min)
	MS-2	PRD1	Fr	MS-2	PRD1	Fr	MS-2	PRD1	Fr	
0	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5				
1	< 0.5	< 0.5	< 0.5							
2	9.0E+04	2.1E+05	3.0E+05							
4	5.0E+05	9.7E+05	1.4E+06							
5	9.8E+05	1.3E+06	1.4E+06							
6	3.1E+06	1.8E+06	1.9E+06							
45				2.3E+03	6.6E+03	8.4E+03	1.6	1.5	1.6	43
45				2.3E+03	6.6E+03	8.4E+03	2.3	2.2	2.2	41
45				2.3E+03	6.6E+03	8.4E+03	2.6	2.3	2.2	40
45				2.3E+03	6.6E+03	8.4E+03	3.1	2.4	2.4	39

Log removal calculation (app. 40 min detention time): T = 2 min for feed with T = 45 min for filtrate (yellow cells); T = 4 min for feed with T = 45 min for filtrate (green cells); etc…

Table F-5. UF Virus Challenge Test Results

Time (min)	Feed Bacteriophage Concentration (pfu/mL)			Filtrate Bacteriophage Concentration (pfu/mL)			Bacteriophage Log Removal		
	MS-2	PRD1	Fr	MS-2	PRD1	Fr	MS-2	PRD1	Fr
0	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5			
1	3.3E+06	1.2E+06	4.7E+06	< 0.5	< 0.5	< 0.5			
2	5.1E+06	9.5E+06	3.9E+06	< 0.5	< 0.5	< 0.5			
3	3.7E+06	1.3E+06	4.8E+06	< 0.5	< 0.5	< 0.5	6.8	6.4	7.0
4	3.9E+06	1.1E+06	3.7E+06	< 0.5	< 0.5	< 0.5	7.0	7.3	6.9
5	2.2E+06	1.1E+06	3.5E+06	< 0.5	< 0.5	< 0.5	6.9	6.4	7.0
6	NA	NA	NA	< 0.5	< 0.5	< 0.5	6.9	6.3	6.9
7	NA	NA	NA	< 0.5	< 0.5	< 0.5	6.6	6.3	6.8
8	NA	NA	NA	< 0.5	< 0.5	< 0.5			

Log removal calculation (2 min detention time): T = 1 min for feed with T = 3 min for filtrate (yellow cells); T = 2 min for feed with T = 4 min for filtrate (green cells); etc.

Table F-6. SWRO Virus Challenge Test Results

Time (min)	Feed Bacteriophage Concentration (pfu/mL)			Permeate Bacteriophage Concentration (pfu/mL)			Bacteriophage Log Removal		
	MS-2	PRD1	Fr	MS-2	PRD1	Fr	MS-2	PRD1	Fr
0	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5			
1	1.5E+06	8.0E+06	2.7E+06	< 0.5	< 0.5	< 0.5			
2	3.0E+06	1.3E+06	2.8E+06	< 0.5	< 0.5	< 0.5			
3	4.5E+06	1.4E+06	3.2E+06	< 0.5	< 0.5	< 0.5	6.5	7.2	6.7
4	3.4E+06	1.6E+06	3.0E+06	1.E+01	< 0.5	< 0.5	5.5	6.4	6.7
5	3.8E+06	1.1E+06	3.2E+06	3.E+01	1.E+01	1.E+01	5.2	5.1	5.5
6	NA	NA	NA	7.E+01	< 0.5	1.E+01	4.7	6.5	5.5
7	NA	NA	NA	7.E+01	2.E+01	3.E+01	4.7	4.7	5.0
8	NA	NA	NA	3.E+01	< 0.5	7.E+01			

Log removal calculation (2 min detention time): T = 1 min for feed with T = 3 min for permeate (yellow cells); T = 2 min for feed with T = 4 min for permeate (green cells); etc.

APPENDIX G
East Coast Site
UF Pretreatment Productivity

Figure G-1. UF Pretreatment Productivity Results (6/18/03 to 6/27/03)

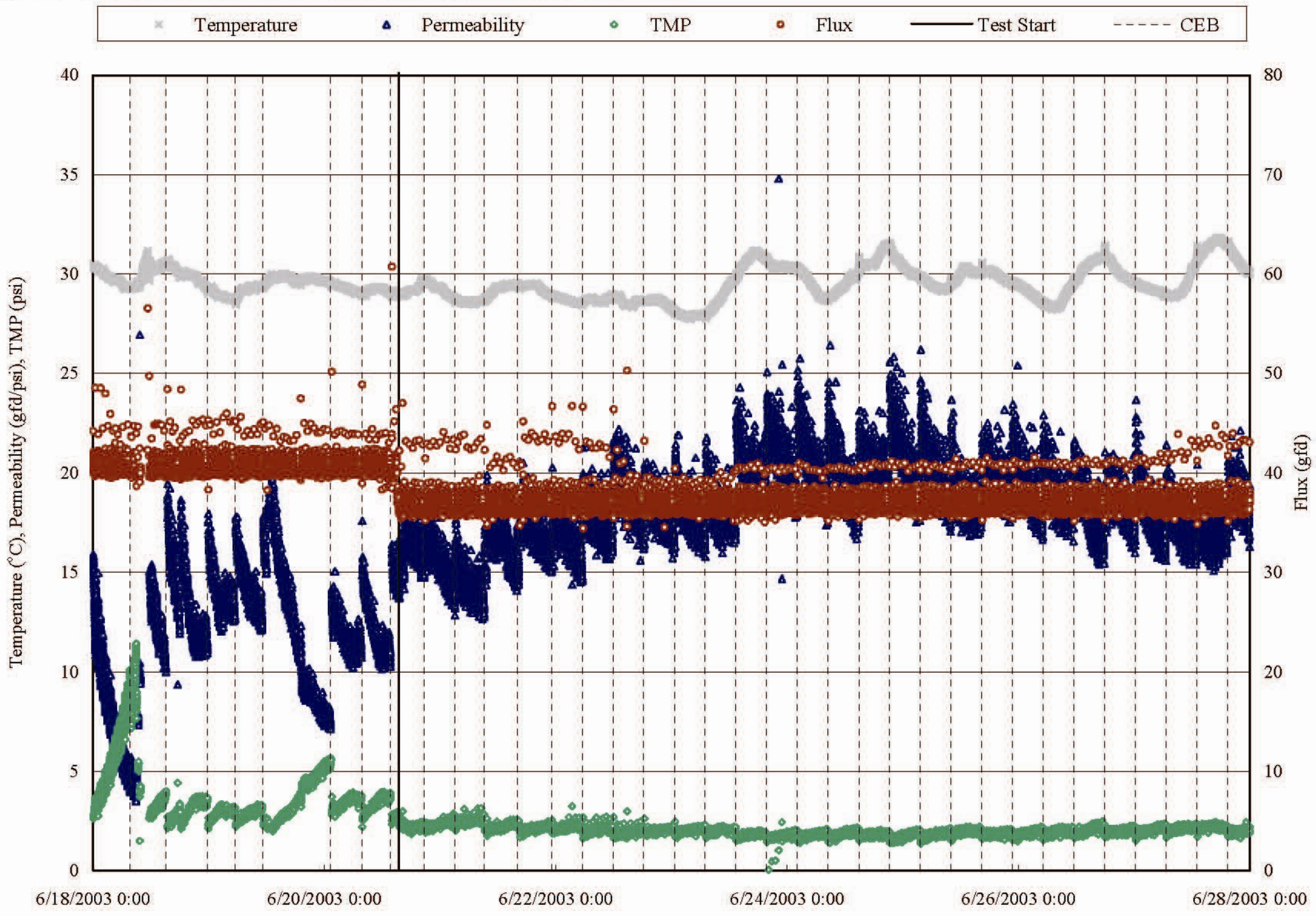


Figure G-1 (Cnt'd). UF Pretreatment Productivity Results (6/28/03 to 7/7/03)

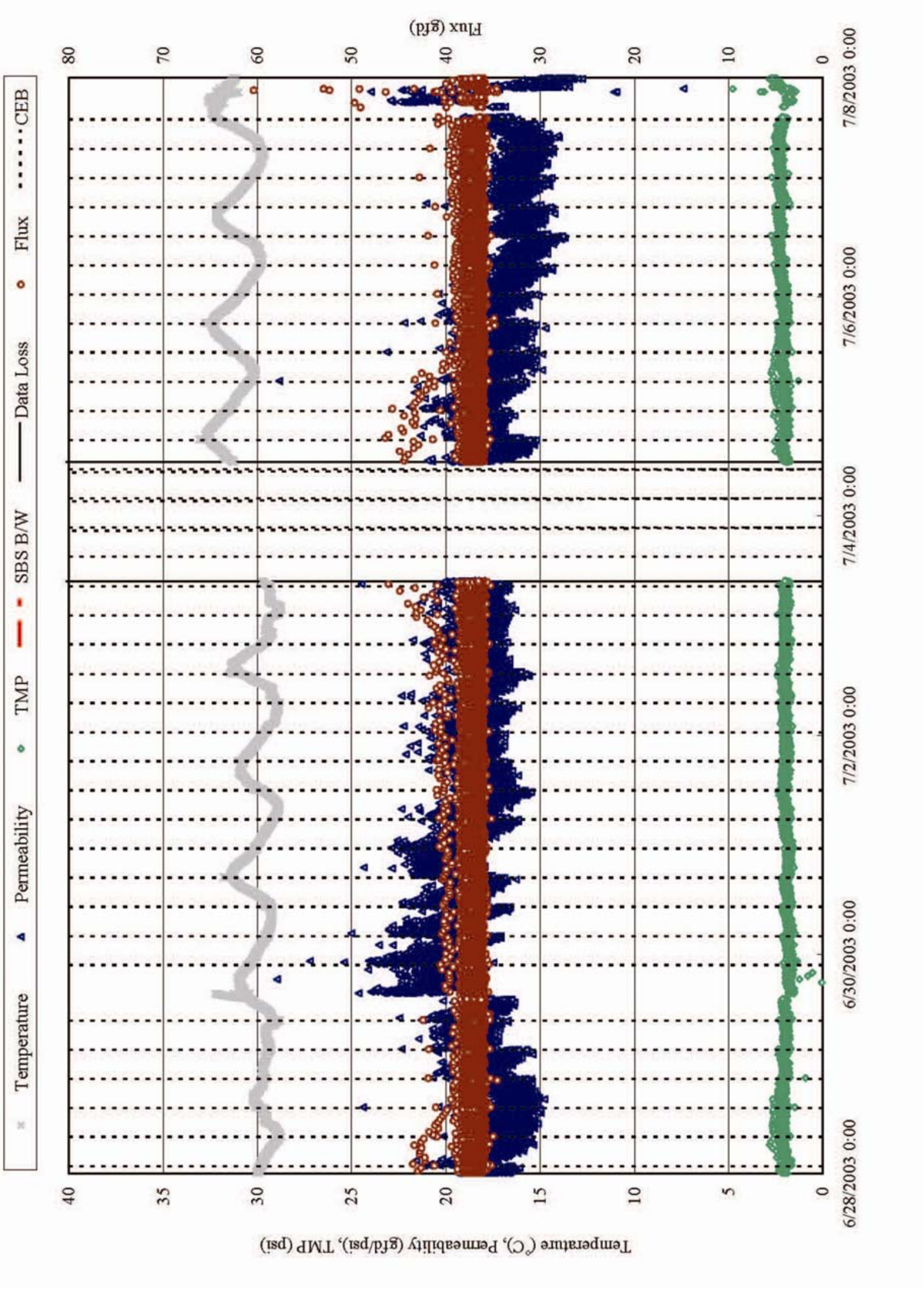
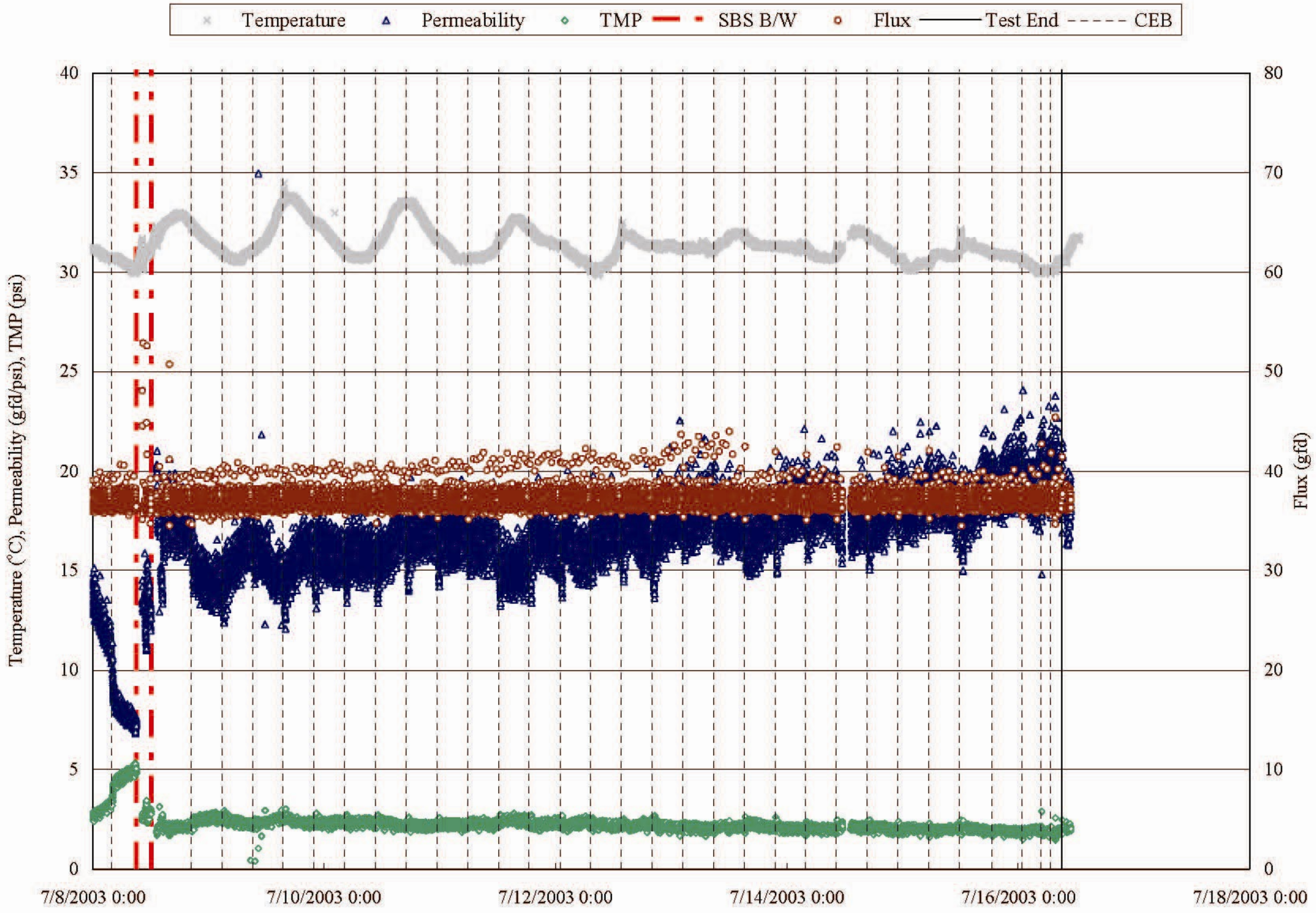


Figure G-1 (Cnt'd). UF Pretreatment Productivity Results (7/8/03 to 7/17/03)



APPENDIX H
West Coast Site
UF Pretreatment Productivity

Figure H-1. UF Pretreatment Productivity Results (10/31/03 to 11/10/03)

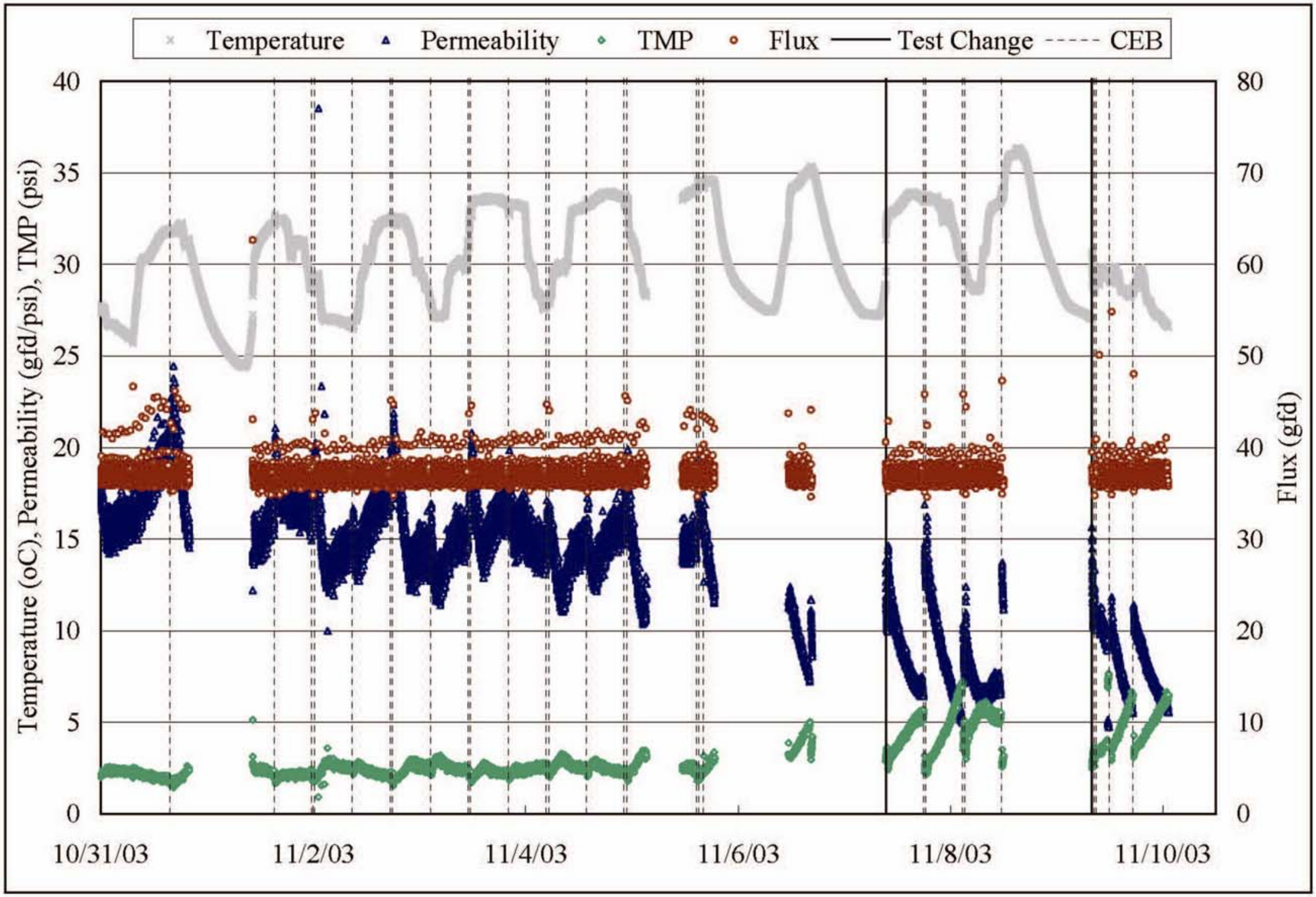


Figure H-1 (Cnt'd). UF Pretreatment Productivity Results (11/10/03 to 11/18/03)

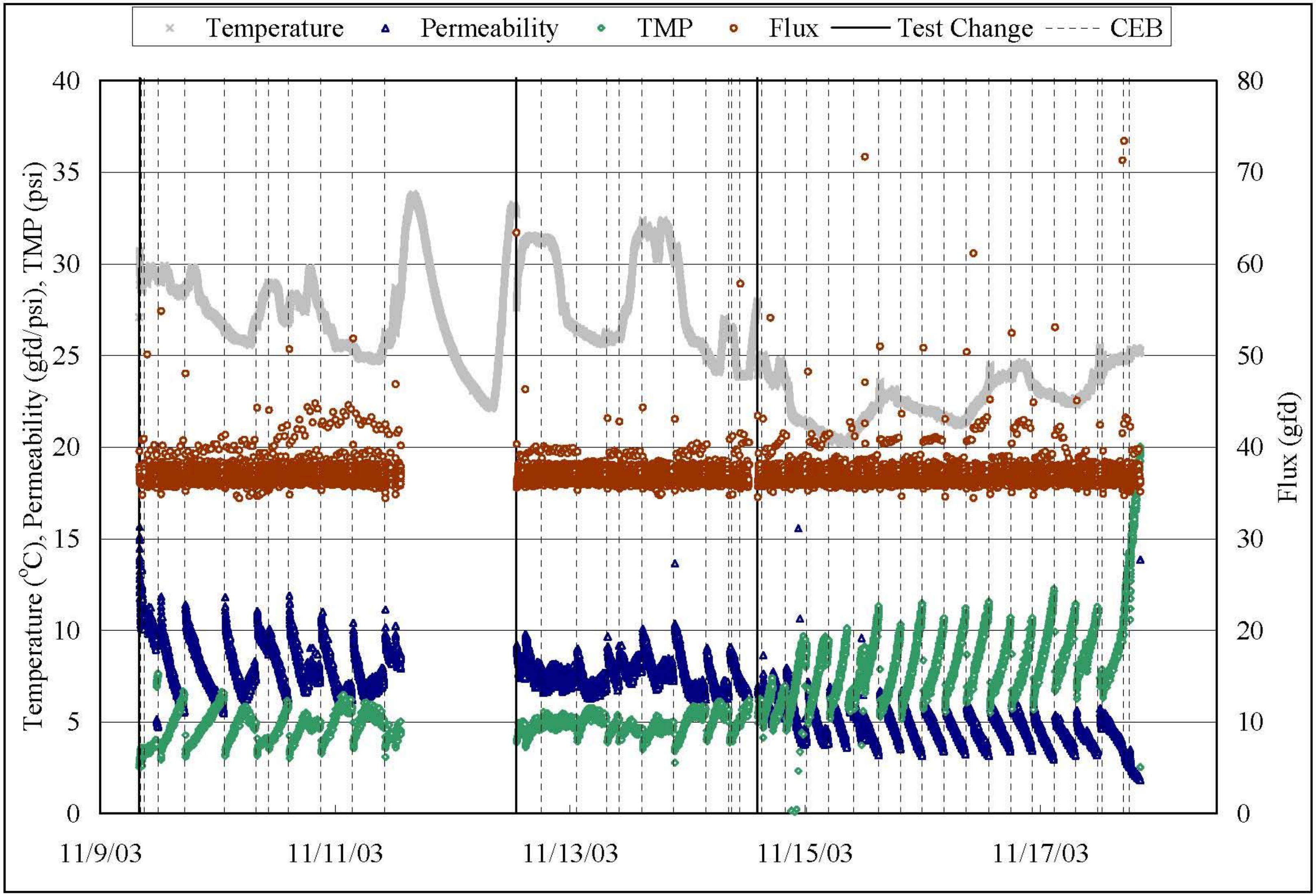
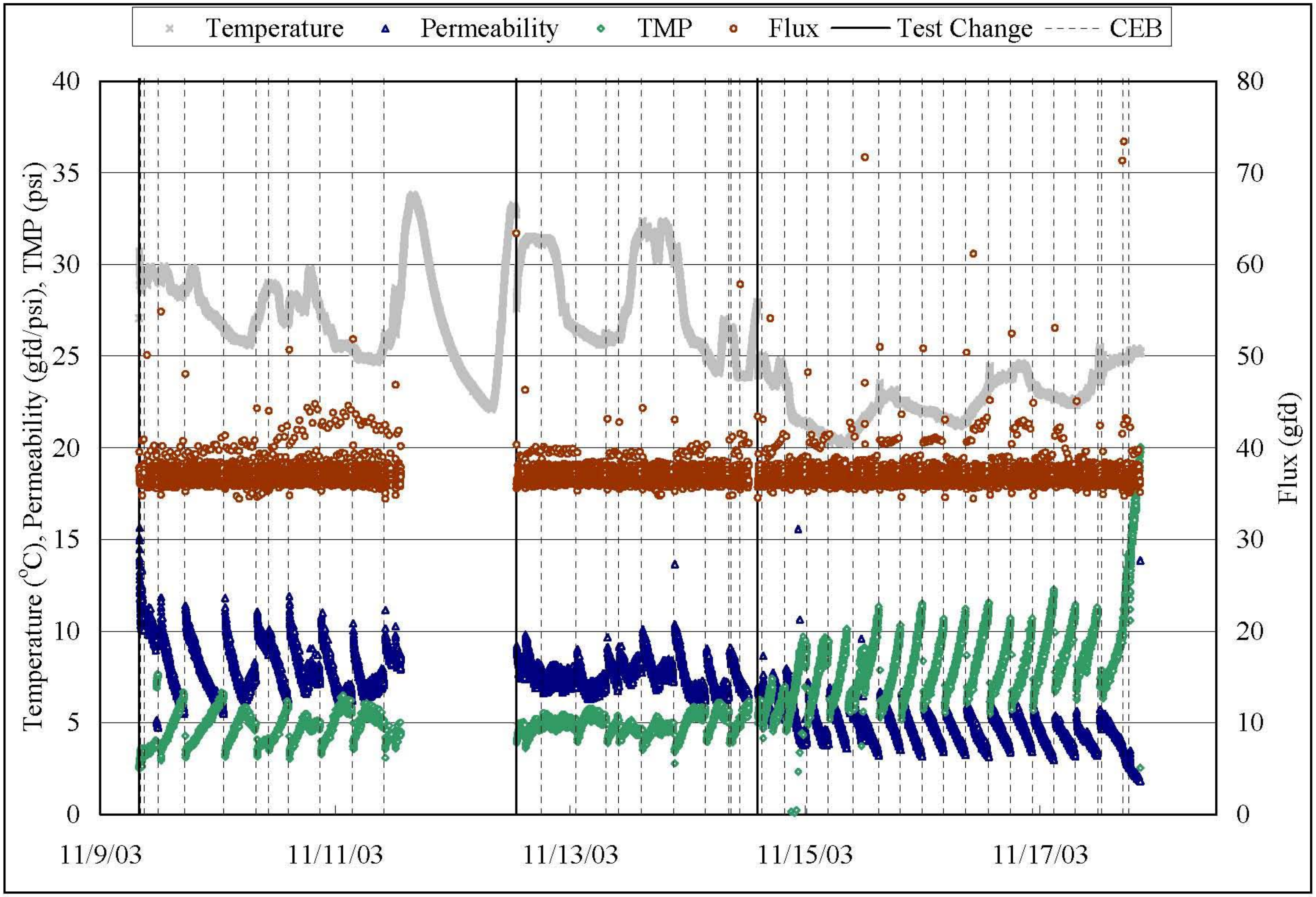


Figure H-1 (Cnt'd). UF Pretreatment Productivity Results (11/10/03 to 11/18/03)



APPENDIX I
UF Membrane Autopsy Report

X-FLOW

Investigation report

One S-225 0.8 UFC M5 element
from Norit Americas /
Pilot plant Florida

PRC number: PRC 10041
Date: 21-08-03
Author: Michaela Klotz

Short Conclusion

For the defects in the element no product related cause could be found. Probably the fouling within the coating layer in combination with the probably position of the element caused the defects.
Therefore the element will not be replaced by guarantee.

Introduction

The element comes from a pilot plant in Florida. It was one of two UF-elements which were used to pre-treat seawater prior to RO. The elements have been part of a study using air pressurization (10 psi) at the end of a CEB to check integrity and to assist in cleaning.
Operating conditions at the end of the study were:

- 62 l/m^2 h
- 20 min. filtration time
- 18 backwashes/CEB (= CEB every 6 h)
- 3 CEB1 / CEB 2
  - CEB1 = 5 min. soak with NO Chemicals, followed by air pressurization
  - CEB2 = 10 min. soak with Clorox
- Approximately every 9 days a manual CEB was conducted with Sodiumbisulfite and acid for a 1 hour soak
- As pre-treatment Ferric Sulfate was dosed with a concentration of approximately 2 ppm.

The element which was sent back had several fibre breakages on several occasions during the study. The second module in the pilot unit did not need any repair. Norit Americas would like to know what is in the fibres and what the reason is for the fibre breakages.

In addition it was mentioned that "barnacle growth" (expression from Chris White) in the feed tank was found, but that during removal of the element no growth was visible in the pressure vessel.

Element-No. 02I217 (S-225 0.8 UFC M5)

The element was produced in January 2002. It is filled with membrane batch 261101-III. When it left QC it had two closed fibres at side 1 and no closed fibre at side 2.

When the element came back it was really dirty from the outside. The PVC-housing was nearly completely covered with a black and brown fouling layer (this was also already stated by Norit Americas / they already gave away a sample of the "black growth" to Ionics). The two feed sides of the element were also fouled with red-brown and black stuff.
Please see the following pictures (which were taken after the bath test when most of the fouling was already removed):

Fig. 1: element 02A217 – side 1

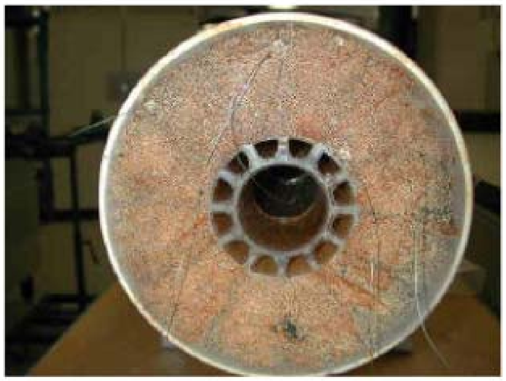


Fig. 2: element 02A217 – side 2

Bath Test

At side 1 of the element 6 already repaired fibres could be stated

- segment 1 – 2
- segment 3 – 1
- segment 5 – 1
- segment 6 – 1
- segment 8 – 1

At side 2 of the element 8 already repaired fibres could be stated

- segment 5 – 1
- segment 6 – 3
- segment 7 – 1
- segment 8 – 1
- segment 10 – 1
- segment 12 - 1

Within the bath test two more defective fibres could be stated at each side (side 1: one in segment 4 and 7 / side 2: one in segment 4 and 9).

Membrane Investigation

After the bath test the two new defective fibres were marked with fish wire at side 2 and another six old repair pins were drilled out and marked.
The element was opened between segment 4 and 9 (referring to side 1) by using the grinding tool.

The height of epoxy and coating was determined at both sides as follows:

- S1: Height of epoxy: approx. 3.5 cm
  Height of coating: approx. 8.0 cm
- S2: Height of Epoxy: approx. 4.0 cm
  Height of Coating: approx. 8.5 cm

From the outside the fibres were not completely clean any longer but it could not be stated a severe fouling layer. At several places red-brown spots can be seen, especially within and at the end of the coating layer. In addition within the coating height many membranes seem to be very dirty from inside. And at some places the membranes are somehow lightly yellow-coloured from the outside.

Please see the following pictures of the open element:

Fig. 3: element 02A217 – open

Fig. 4: element 02A217 – open side 1

Fig. 5: element 02A217 – open side 1

Fig. 6: element 02A217 – open side 2

Fig. 7: element 02A217 – open side 2

Two membrane bundles (4 and 6) were taken out of the element and the two defective fibres of these bundles were separated. But the defects could not be determined. Some fibres were cut to look at the inner side of the membranes and a lightly yellow fouling layer could be seen in every membrane. It might be assumed that this layer can be reduced to the pre-treatment of the water with Ferric Sulfate.

Please see the following pictures of one membrane bundle:

Fig. 8: element 02A217 – membrane bundle

Fig. 9: element 02A217 – membrane bundle

Fig. 10: element 02A217 – membranes (inner surface)

For the other marked defective fibres the place of the defect was determined in the wate bath.

- Segment 5 one defect closed to the epoxy of side 1
- Segment 7 two defects closed to the epoxy of side 1
- Segment 7 one defect 15 cm away from side 1
- Segment 8 one defect 35 cm away from side 2
- Segment 9 one defect closed to the epoxy of side 1

As the place of the defects in segments 4 and 6 could not be determined in the lose membrane, it can be assumed that these two defects were also placed closed to the epoxy of side 1.

SEM-pictures:
Please see the following SEM-pictures of two of the defects which could be determined.

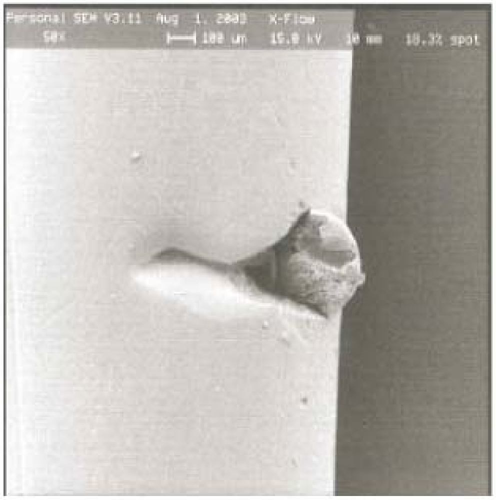


Fig. 11: element 02A217 – defect in segment 7
50 x

Fig. 12: element 02A217 – inner surface of defective membrane in segment 7
10.000 x

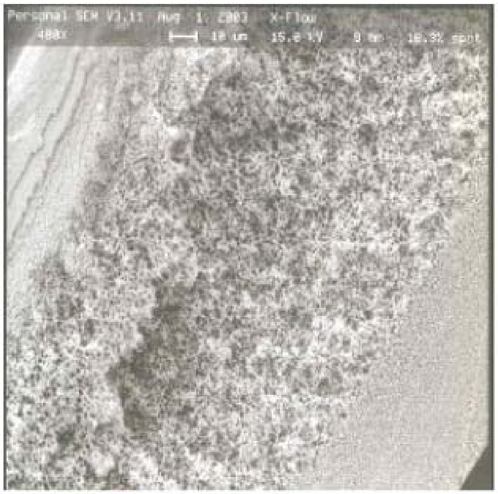


Fig. 13: element 02A217 – cross section of defective membrane in segment 7
400 x

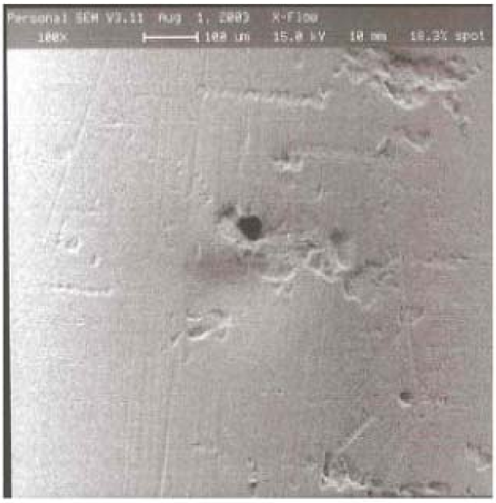


Fig. 14: element 02A217 – defect in segment 8
100 x

Fig. 15: element 02A217 – defect in segment 8
2.800 x

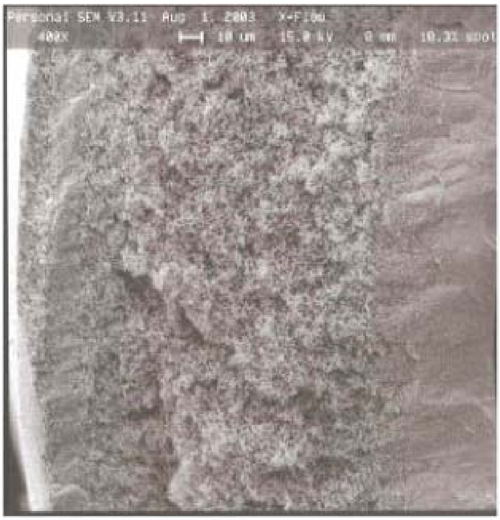


Fig. 16: element 02A217 – cross section of defective membrane in segment 8
400 x

Conclusion

The element was very dirty from outside and at the feed sides when it came back. This may point to the case that the pre-treatment of the seawater does not work properly or that the pre-treatment is not sufficient.
The light fouling layer on the inner membrane surface may also point to a not sufficient cleaning procedure.
Six of the eight determined defects are placed closed to the epoxy of side 1, two of these defects are placed somewhere else.
The last mentioned two defects look as if the outer membrane surface was somehow physically damaged. While the cause for the damage could not be determined.
For the higher amount of defects closed to side 1 which seem to be placed within the coating layer no obvious cause was found but it does not seem to be a production failure. It can be seen that especially within the coating layer of side 1 the membranes seem to be very dirty from inside. Looking at the membrane behaviour it can be assumed that side 1 of this element was placed at the feed side of the pressure vessel where the hydraulic power is the highest. The position of the element in connection with the fouling might be an explanation for the appeared defects within the coating layer.

As no product related cause for the defects could be found, this element will not be replaced by guarantee.