Final Report

Establishing Correlations Between Membrane Fouling and Water Composition

Submitted by:
Jana Safarik and Don Phipps
Orange County Water District
10500 Ellis Ave.
Fountain Valley, CA 92708-8300

And

University of California, Riverside
Riverside, CA 92521

Project Manager: Shahid Chaudhry, California Energy Commission

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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What follows is a final report for the Improving Energy Usage, Water Supply Reliability and Water Quality Using Advanced Water Treatment Processes, contract number 400-00-013, conducted by the Orange County Water District and University of California, Riverside. The report is entitled "Establishing Correlations between Membrane Fouling and Water Composition." This project contributes to the Industrial/Agricultural/Water End-Use Energy Efficiency program.

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EXECUTIVE SUMMARY

Introduction

As the population in southern California continues to expand, local water utilities must deal with increased demand for limited water supplies and treatment to meet more stringent water quality requirements. Advances and improved cost effectiveness of membrane processes (i.e., ultra-low-pressure reverse osmosis (RO), microfiltration (MF) and nanofiltration (NF)) and the continued emergence of more stringent water quality regulations have continued to drive extensive research into these advanced water treatment technologies. However, all membrane processes are prone to various types of fouling (e.g., biological, colloidal, organic, and precipitative) that limit membrane applications. This project will develop standard methods and equipment to characterize the type and extent of membrane fouling under well-controlled operating conditions. The overall purpose of this project is to correlate observed membrane fouling with measured components in the source water and chemical and physical properties of the membranes with the aim to identify causal relationships between selected test parameters and membrane performance.

Background

A host of high-performance reverse osmosis (RO) membranes are currently employed in water purification applications. Membrane materials range from common substituted cellulose derivatives such as cellulose acetate or cellulose nitrate to more complex polymers with highly specialized properties such as aromatic cross-linked polyamides, polyether ureas, and polyethyleneamines. RO membranes used for treatment of industrial and municipal process waters often become biologically and/or chemically fouled as a result of complex interactions between membrane properties and source water quality. During operation, feed water is forced into the element under sufficient pressure to overcome the osmotic pressure of the dissolved solutes. The membrane barrier preferentially rejects the solutes and suspended solids, including bacteria, viruses and other microorganisms. Approximately 90 percent of the flow in RO systems is tangential to the membrane surface in order to prevent a buildup of solutes at the membrane interface; however, as the remainder passes through the membrane as permeate, a proportion of the feed water colloids and microorganisms entering the element are transported to the membrane surface where they adsorb, forming a fouling layer. The development of a fouling layer on the membrane surface results in gradual deterioration of function performance (i.e., decline in membrane water flux, decrease in water permeability, increase in transmembrane operating pressure and reduction in membrane mineral solute rejection). The deterioration of RO membrane performance is determined by complex interactions resulting from process operating conditions, membrane properties, and source water quality. Because fouling necessitates application of greater pressure to maintain product flow, it requires the expenditure of more energy to produce the same amount of water, and thus can dramatically diminish process efficiency and cost efficiency in a water processing (purification) system.

Project Objectives

1) To develop a bench-scale RO test unit to characterize the type and extent of membrane fouling under well-controlled operating conditions.
2) The secondary objective of this work was to provide water agency professionals with relevant data with respect to fouling potential of selected membranes and source waters that are applicable to ongoing and future research efforts conducted by water agencies.

Project Approach

Analytical methods and equipment were developed to correlate membrane fouling with feed water quality parameters under controlled operating conditions.

A self-contained, portable bench-scale RO test unit was fabricated and installed at locations with source waters including surface water, lime-clarified and microfiltered secondary treated wastewater, tertiary treated wastewater, and agricultural drainage water. Four commercially available membranes were tested: three polyamide membranes and one cellulose acetate membrane. Membranes were operated in a single-pass configuration, each at a constant flux of 10 gfd and 4 percent recovery. Typical duration of each run was 8 to 12 weeks or until the feed pressure to any polyamide membrane exceeded 200 psi. Membrane operating parameters (transmembrane pressure and water flux) were measured daily and water quality grab samples were collected weekly. Water quality analyses included general minerals, microbial analysis by heterotrophic plate counts and epifluorescence microscopy (total bacteria). At the end of each test, membranes were autopsied to determine both the nature of the biological material accumulated on the membrane surface (protein, carbohydrate, microbiological analysis by heterotrophic plate counts and epifluorescence microscopy). Collected data were compiled in a database. Chemical, physical, and biological characteristics of the source waters, membranes and fouling layers were measured and used to develop relationships between source water quality, membrane composition, and membrane fouling using artificial neural net analysis. A genetic algorithm (GA) was used to select specific molecular descriptors affecting specific water flux and percent rejection and an artificial neural network (ANN) was used to develop relationships between source water quality, membrane composition and membrane fouling. A polyamide "universal Model" including specific membrane characteristics (specific water flux, zeta potential, contact angle, membrane roughness, and indices of crosslinking) was also constructed.

Project Outcomes

Test #1: Surface Water with Conventional Treatment

The first test unit was delivered to Metropolitan Water District of Southern California (MWD), F.E. Weymouth Filtration Plant in La Verne, California. This unit remained in continuous operation for 1,872 hours. ESPA-1 membrane appeared to be the best performer at this site with the best overall percent rejection and steady specific water flux performance throughout the test.

Test #2: Secondary Treated Wastewater with Lime Clarification (#1)

Second unit was delivered to West Basin Municipal Water District, Carson, California. The unit remained in operation for 1,032 hours. The feed water tank to the unit became contaminated with algae which resulted in pressure increases above 200 psi (the predetermined experimental termination point). Membrane failure was attributed to algal contamination. Due to the unforeseen contamination only 840 hours of membrane performance data (before algal contamination) was used in the final analysis. The best performing membrane at this site before the contamination was ESPA-1. This membrane modeled the best in both the individual membrane models and the "universal" model.

Test #3: Secondary Treated Wastewater with Microfiltration (#1)

The third test site was Orange County Water District (OCWD), Fountain Valley, California. At the time of this test the plant's treatment train received secondary treated wastewater from Orange County Sanitation Department, Fountain Valley, California, which underwent chemical clarification, recarbonation, and multimedia filtration.
The OCWD RO test unit operated for 1,032 hours. All membranes at this site, using this feed water, showed a steady decline in performance over time.

Test #4: Secondary Treated Wastewater with Lime Clarification (#2)

Following OCWD the RO test unit was delivered to Santa Clara Valley Water District (SCVWD) located in San Jose California. The District's conventionally treated wastewater was used as the feed water for this test. RO test unit remained in operation for 1,272 hours. The experiment was terminated when the pressure in ESPA-1 reached 200 psi (the predetermined experimental cut off point). TW-30 appeared to be the best performing membrane using SCWD feed water.

Test #5: Secondary Treated Wastewater with Microfiltration (#2)

For the fifth location the RO test unit was returned to OCWD. The conventional wastewater treatment was replaced with MF. The second test performed at Orange OCWD used MF treated secondary treated wastewater. This unit remained in operation for 1,800 hours. Polyamide membranes using MF treated wastewater exhibited better percent rejection and specific flux performance. MC-2514 (CA) was the exception. MC-2514 performance in regards to percent rejection was equal for both feed waters.

Test #6: Agricultural Drainage Water Treated with Lime Clarification

The last test site was located in Yuma Arizona using treated agricultural drainage water as the feed to the RO test unit. This water was treated using conventional filtration processes that include lime clarification, coagulation using ferric chloride (dose) followed by dual media filtration. This unit remained in operation for 842 hours. TW-30 and MT-2514 membranes continuously performed at or above 98% rejection ESPA-1 did not perform as well as the other membranes at the onset of the experiment but within 48 hours started to improve and continued to improve (in regards to rejection) for the duration of the experiment

Membrane Performance Comparison by Feed Water Type

TW-30 Polyamide Membrane

TW-30 performed the best on Yuma source water. The poorest performance was associated with high fouling feed waters (OCWD and SCWD). TW-30 appeared to perform well on feed water with lower biological (total and viable) activity such as MF treated wastewater.

ESPA-1 Polyamide Membrane

The poorest performance was on conventional treated wastewater (OCWD and SCWD). ESPA-1 performed best on surface water (MWD) with high flux and consistent percent rejection. The fact ESPA-1 is a high specific water flux membrane may influence bacterial loading at the membrane surface. Increased water permeability increases movement and deposition of dissolved and suspended solids from the feed water, which may increase bacterial fouling (by deposition and growth), resulting in decreased membrane performance. In general ESPA-1 performed the best on MF treated feed waters (OCWD_MF and WB).

MT-2514 Polyamide Membrane

MT-2514 performed similarly to the other two polyamide membranes in the study and performed the best on feed water with lower microbial loads. Its performance on conventionally treated wastewater (OCWD and SCWD) was the poorest. MT-2514 appeared to accumulate bacteria at the membrane surface consistently no matter the feed water type, but it appeared to bind proteins and carbohydrates at faster rates. Like the other polyamide membranes, MT-2514 performed better on lower fouling feed waters such as MF, surface water and agricultural drainage water.

MC-2514 Cellulose Acetate Membrane

MC-2514 was the poorest performer of all membranes tested on all feed waters used in the study, and in addition exhibited the highest bacterial, protein and carbohydrate accumulation. MC-2514 was the only membrane tested in the study that maintained its flux and rejection using conventionally treated wastewater. Generally, high biological loads did not affect MC-2514 performance, which was the opposite for all three polyamide membranes.

ATR/FTIR Analysis of Clean and Fouled Polymer Membranes

As expected, each membrane type exhibited different membrane properties. TW-30 has a higher OH/Amide I Ratio, COO/Amide I and COO/Amide II Ratios meaning it is a less cross-linked membrane. The largest differences were observed with the OH/Amide I Ratio. ESPA-1 has the thickest polyamide layer as demonstrated by the higher polyamide thickness ratio. According to PCA analysis sites separated indicating organic constituents on membrane surfaces are different. Each water source has a unique signature on each membrane.

Membrane Biofilm and Feed Water Community Analysis

There does not appear to be a relationship between membrane chemistries because microbial communities on polyamide membranes are not consistently clustering into related groups. These data suggests there are several factors such as feed water chemistry, membrane surface chemistry and bacterial diversity influence microbial community structure on RO membrane surfaces.

Relationship between Source Water Composition and Membrane Performance

Databases relating source water quality parameters (physicochemical and biological) from all of the study sites to membrane performance (water flux and solute rejection) at each weekly time point were constructed for each of the test membranes. Each line of data in these databases provided the exemplars that were used in the construction of ANN models describing membrane performance. In addition, the databases for the polyamide membranes were combined into a single database, and the polyamide membrane parameters were included as independent input variables to produce the database used to create a "universal" polyamide model.

Individual membrane Performance Models

The ability of the ANN to capture behavior of the system is evidenced by both the relatively close agreement between the actual data and that predicted by the models, and by the close agreement between the Pearson correlation coefficients of the training and test sets, indicating that models were generally able to predict membrane behavior well. The same results were generally observed with models of membrane solute rejection, where there was fairly good agreement between the actual rejection observed in the field and that predicted by the models for each of the test membranes.

Specific Water Flux Models: Influential Source Water Parameters

Typically 6-7 parameters defined each of the water flux models. There was no absolute agreement between membrane models with respect to influential parameters; each membrane appeared to exhibit particular sensitivities with respect to chemical species or biological parameters in the source water. However, if the specific parameters are grouped into broader categories, some trends appear across membrane types. For MT-2414, specific water flux was negatively related to time and monavalent cations (potassium) but was positively related to monovalent anions (bromine) and strongly related to trivalent anions (phosphate-phosphorous). It was also positively related to bacterial load (bact/mL and CFU/100 mL). Among the polyamide membranes, the ESPA-1 membrane model for specific water flux indicated a negative relationship with time, boron, calcium bicarbonate, trivalent anions (phosphate-phosphorous) and the strongest negative relationship was with bacterial loading as viable bacteria (CFU/100 mL). TW-30 specific water flux was negatively related to time, monovalent cation (K) and trivalent anion (phosphate-phosphorous) but was positively related to total alkalinity and to the presence of monovalent anions (Cl and Br). For the cellulose acetate membrane (MC-25140 the specific water flux was negatively related to time, TDS, total hardness, monovalent anions (Cl), and strongly negatively related to bacterial loading in the feed (bact/mL and CFU/100mL). Specific water flux was positively related to monovalent cation (K).

Percent Rejection Models: Influential Source Water Parameters

Rejection was described using only 4 – 7 input parameters. As with the flux models, there was no absolute agreement between the membrane models with respect to the specific parameters deemed influential by the ANNs. For the polyamide membranes the MT-2514 model indicated rejection was negatively related to time and monovalent cation (k) but was positively related to divalent cation (Mg) and monvalent anion (Cl). For the ESPA-1 model, rejection was negatively related to time and to total hardness in the source water as well to bacterial load (bact/mL)but was positively related to divalent cation (Ca). TW-30 membrane model indicated that rejection was slightly positively related to time, to divalent cations (Mg), monovalent anions (NO2-N, Br) and to microbial load (CFU/100 mL), but was slightly negatively related to the monovalent anion (Cl) and strongly negatively related to trivalent anions (PO3-P). For the CA membrane MC-2514 rejection was negatively related to time, to monvalent anion (Br), to trivalent anion (PO3-P) but was positively related to divalent cation (K), strongly positively related to monovalent anion (NO2-N) and also to the divalent anion (NO3-N). The model indicated rejection was positively related to viable bacterial load in the source water (CFU/100 mL).

"Universal" Polyamide Model

The database for the "universal" polyamide model was constructed by combining the databases for all three polyamide membranes (MT-2514, ESPA-1 and TW-30), and adding a set of input parameters containing membrane physicochemical parameters measured by OCWD.

A total of six input parameters were required to construct both flux and rejection "universal" models. The "universal" model for polyamide membranes indicated that specific water flux was negatively related to time, strongly negatively related to total ion concentration (EC) in the feed water, and negatively related to monovalent cation (K), but was positively related to boron concentration, monvalent anion (Cl) and trivalent anion (PO3-P). The "universal' model for polyamide membranes indicated percent rejection was negatively related to time, total hardness, trivalent anion (PO3-P) and very strongly negatively related to the total bacterial concentration in the feed (bact/mL).

Measured membrane properties including roughness, contact angle, specific water flux, zeta potential, slope of zeta potential from pH5-7, membrane crosslinking and thickness were not deemed significantly influential to be included in either specific water flux or rejection models.

Conclusions and Benefits

Conclusions

- Analysis of membranes shows a considerable difference in surface properties.
- When membranes were exposed to different feed waters they behaved differently with respect to accumulation of biological material and performance (percent rejection and specific water flux).
- Microbial communities developed on membranes exposed to same feed water were different from the feed water community structure and different from each

other's community structures. The community structures were unique. Each membrane was keying in on different elements of the feed water and developed its own population community.

- In general, the degree of microbial fouling was related to the concentration of bacteria present in source waters.
- Generally, protein and carbohydrate loads were related to bacterial load in source water.
- Data suggest high flux membranes such as ESPA-1 will be poor performers on high fouling feed waters such as conventionally treated wastewaters.
- Generally, reduction of microbial particulates by MF resulted in improved membrane performance.
- Treatments that tended to reduce microbial loads in the source water (e.g., MF pretreatment) in general improved membrane performance.
- The water sources that lead to most rapid performance decline were characterized by high biological load.
- It was possible to describe membrane performance in terms of source water physicochemical and biological parameters using Artificial Neural Network modeling approach.
- According to the models, ionic composition of source water influenced membrane performance as much as biological loading.
- Models suggested that the effects that water physicochemical and biological properties exerted on membranes performance was membrane specific.
- For polyamide membranes it was possible to construct a model of general membrane performance. In this case, models suggested that membrane performance was most strongly influenced by biological loading, and TDS most strongly affected water flux.
- These results may be generalizable beyond this study but further data would be required to validate the models (different water sources and more membranes).

Benefits to California

California relies on many means to enhance the operations and cost effectiveness of water reuse. Using membrane processes benefits the region of southern California. Educated and well-informed selection of water treatment processes can translate into dollars saved. Using predictive tools such as ANN modeling will help water professionals to make appropriate membrane selections for specific source waters that will save time, money and energy.

ABSTRACT

The deterioration of RO membrane performance is determined by complex interactions resulting from process operating conditions, membrane properties, and source water quality. Because fouling necessitates application of greater pressure to maintain product flow, it requires the expenditure of more energy to produce the same amount of water, and thus can dramatically diminish process efficiency and cost efficiency in a water processing (purification) system. Analytical methods and equipment were developed to correlate membrane fouling with feed water quality parameters under controlled operating conditions. A self-contained, portable bench-scale RO test unit was fabricated and installed at locations with source waters including surface water, lime-clarified and microfiltered secondary treated wastewater, tertiary treated wastewater, and agricultural drainage water. Four commercially available membranes were tested: three polyamide membranes and one cellulose acetate membrane. Membranes were operated in a single-pass configuration, each at a constant flux of 10 gfd and 4 percent recovery. Water quality analyses included general minerals, microbial analysis by heterotrophic plate counts and epifluorescence microscopy. At the end of each test, membranes were autopsied to determine the nature of the biological material accumulated on the membrane surface (protein, carbohydrate, microbiological analysis by heterotrophic plate counts and epifluorescence microscopy, community analysis by 16S rRNA). Collected data were compiled in a database. Chemical, physical, and biological characteristics of the source waters, membranes and fouling layers were measured and used to develop relationships between source water quality, membrane composition, and membrane fouling (loss of water flux and rejection) using artificial neural net analysis. Using the

generated models it was possible to explain variations in data and their affect on specific water flux and percent rejection.

Report Organization

The report starts with discussing the project approach followed by a discussion on experimental and laboratory test methods and procedures. Each water agency's RO test unit results are discussed and analyzed. The process of ANN model building is explained followed by model results and conclusions.

1.0 INTRODUCTION

As the population in southern California continues to expand, local water utilities must deal with increased demand for limited water supplies and treatment to meet more stringent water quality requirements. Advances and improved cost effectiveness of membrane processes (i.e., ultra-low-pressure reverse osmosis (RO), microfiltration (MF) and nanofiltration (NF)) and the continued emergence of more stringent water quality regulations have continued to drive extensive research into these advanced water treatment technologies. However, all membrane processes are prone to various types of fouling (e.g., biological, colloidal, organic, and precipitative) that limit membrane applications. This project will develop standard methods and equipment to characterize the type and extent of membrane fouling under well-controlled operating conditions. The overall purpose of this project is to correlate observed membrane fouling with measured components in the source water and chemical and physical properties of the membranes with the aim to identify causal relationships between selected test parameters and membrane performance.

1.1 Background

RO membranes are employed in diverse applications such as seawater and brackish water desalination, removal of trace organic and inorganic constituents, and reclamation of municipal and agricultural wastewaters. Membranes are now one of the most important and versatile technologies currently available for environmental quality control [1,2]. The RO process results in the best overall removal of TDS and organic compounds. RO technology also has a high potential for removal of all classes of pathogens [3,4,5].

A host of high-performance RO membranes are currently employed in water purification applications. The membrane materials range from common substituted cellulose derivatives such as cellulose acetate or cellulose nitrate to more complex polymers with highly specialized properties such as aromatic cross-linked polyamides, polyether ureas, and polyethyleneamines. Sheets of these membranes are commonly wound into spiral-wrapped reverse osmosis membrane elements. During operation, feed water is forced into the element under sufficient pressure to overcome the osmotic pressure of the dissolved solutes. The membrane barrier preferentially rejects the solutes and suspended solids, including bacteria, viruses and other microorganisms. Approximately 90 percent of the flow in RO systems is tangential to the membrane surface in order to prevent a buildup of solutes at the membrane interface; however, as the remainder passes through the membrane as permeate, a proportion of the feed water colloids, precipitates and microorganisms entering the element are transported to the membrane surface where they adsorb, forming a fouling layer. The fouling layer can be chemical (calcium carbonate scale, calcium sulfate scale, metal oxides scale, silica coating, etc.), organic, and biological in composition. Membrane fouling is the main operational problem that limits the use of membranes in desalting. The composition and rate of fouling is a complex function of the composition of the feed water and the composition of the membrane surface. Prevention of these effects requires significant financial investment in membrane pretreatment measures such as flocculation/clarification, sedimentation, disinfection, pre-filtration, etc. Because fouling necessitates application of greater pressure to maintain product flow, it requires the expenditure of more energy to produce the same amount of water, and thus can dramatically diminish process efficiency and cost efficiency in a water processing (purification) system. Fouling also leads to added facility downtime to implement repairs, membrane cleaning procedures, and replacement of damaged or worn out membrane modules [6,7,8,9].

Feed water composition has a great influence on membrane fouling, as does the modification of the feed water composition by chemical additives such as detergents and biocidal agents. Each feed water type is complex mixture of dissolved and suspended chemical species along with a variety of microorganisms. Optimization of membrane systems for treatment of different types of feed waters involves careful consideration of feed water quality, membrane polymer type selection and operating conditions.

After analysis of feed water quality and membrane selection, the most applicable pretreatment technique can be chosen. Choosing adequate pretreatment technology is an important constituent of the RO process. Lack of or poor pretreatment can lead to increased fouling of RO membranes which results in reduced productivity and increased operating costs.

The foregoing examples suggest it is theoretically possible to predict membrane flux and rejection behavior of specific source waters from the knowledge of their chemical and biological attributes. However, since more than one chemical or biological parameter may influence membrane performance, multivariate statistical procedures such as multiple linear regression analysis or artificial neural network (ANN) analyses are required to accurately model the phenomenon.

We proposed to apply multivariate (ANN-based) techniques to create models that could describe and predict the rejection and flux of commercially available RO membranes based on several different types of source waters. The project focused on the source waters most commonly available in California (surface water, lime-clarified and microfiltered secondary treated wastewater, and agricultural drainage water).

ANNs are a useful tool for providing explanatory models of myriad and diverse systems, from industrial processes control to stock market forecasting. In the last few years ANN models have been utilized to predict organic compound toxicity organic compound interactions with RO membranes [10,11]. For their usefulness, ANN models do have shortcomings. For accuracy the models depend on sufficient exemplars to adequately define the nature of the system being modeled. If the system being modeled composed of explained by a small collection of continuous functions, a small number of exemplars may be used to construct an adequate model, provided the chosen exemplars represent the vertices of the system. If the system being described is highly complex, hundreds to thousands of exemplars are required to construct an adequate ANN models. ANN models may predict behavior of the system very well within the range of the input parameters provided by the exemplars used in their construction but typically can not adequately extrapolate beyond the range of the exemplars (especially in complex systems). Therefore, it is important to define the input data well before attempting to construct the predictive models using this technique.

1.2 Project Objectives

The primary objectives of this project were:

1. To develop a bench-scale RO test unit to characterize the type and extent of membrane fouling under well-controlled operating conditions.
2. The secondary objective of this work was to provide water agency professionals with relevant data with respect to fouling potential of selected membranes and source waters that are applicable to ongoing and future research efforts conducted by water agencies.

2.0 PROJECT APPROACH

This project was performed in collaboration between the Orange County Water District (OCWD) and the University of California, Riverside (UCR), with the cooperation and assistance of several water agencies (Table 1). OCWD and UCR were jointly responsible for integrating data obtained from their respective analysis and data obtained from the various membrane pilot systems into a single database. OCWD oversaw all RO unit operations, sample retrieval, general water quality testing, and biological analysis of water and membrane samples. UCR was responsible for conducting a suite of uniform analytical experiments on membrane and water samples focusing on chemical/physical properties. In the original test plan, OCWD and UCR were jointly responsible for the development, maintenance and analysis of the membrane fouling database to identify significant correlations among all the measured parameters obtained for each test site. Due to a change in UCR staffing during tenure of the study, OCWD became the lead and sole database manager and analyst. Also due to UCR's staffing changes particle analysis and zeta potential analysis of feed water and membrane permeates, that were slated to be performed by UCR, were not completed and therefore could not be used in the final analysis and modeling tasks

The project objectives were met by conducting the following tasks:

Task 1. Design and construct a self-contained, portable bench scale RO test unit to be installed at locations with varying source waters, including surface water, lime-clarified and microfiltered secondary treated wastewater, and agricultural drainage water. Bench-scale units contained four commercially available RO membranes: three polyamide membranes and one cellulose acetate membrane;

Task 2. Conduct suite of uniform analytical tests on the water samples provided by each water agency focusing on general minerals and biological properties. Use these data to construct a database for analysis and interpretation; and

Task 3. Identify relationships between source water quality, membrane composition, and membrane fouling.

2.1 Task 1. Design and construction and field operation of self-contained, portable bench-scale RO test units

Two RO bench-scale test units were designed and constructed at OCWD (Figure 1). Each unit was designed to operate four RO membrane elements in single pass configuration. Four RO membranes (with nominal size of 2.5 inches by 14 inches) were selected (Table 2). Membranes were selected according to commercial availability and membrane polymer type. All membranes were operated at a constant flux of 10 gfd (197 mL/min) and 4% recovery. Testing was conducted at participating water agencies using their respective source waters (Table 1). A standardized protocol was developed to operate the test units, and this protocol was strictly adhered to by each agency. Membranes were operated for 8-12 weeks and membrane performance was assessed in the absence of cleaning.

Membrane performance was evaluated in terms of salt rejection, flux, and operating pressure. Operating data was manually collected daily and water samples collected and analyzed weekly. Membranes were autopsied at the conclusion of the test period and compared with unexposed material.

2.2 Task 2. Water Quality and Membrane Characterization

Specific operations parameters were measured daily as an integral part of each agency's bench study. These included analysis of feed and permeate water, conductivity, measurement of inlet and outlet pressures and influent feed and permeate flow rates. Water quality grab samples were collected on a weekly basis by the participating agency and shipped to OCWD/UCR for analysis. In order to insure consistency in the sampling, prior to the start of the experiment, each agency was provided with sample bottles, labels, shipping containers and a set of detailed instructions for the collection, handling and shipment of samples. To maintain sample integrity, samples were cooled to 4° C and shipped immediately upon collection to OCWD/UCR for analysis. Chemical analysis of feed and permeate water was conducted per *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA, and WEF, 1998). Analyzed water quality parameters and average feed water results are presented in Table 3. Membrane flux and salt rejection were normalized to 25° C per ASTM method D 4516-85 (ASTM, 1989).

In addition to the chemical analysis, OCWD performed biological testing consisting of heterotrophic plate counts, total cell count (epifluorescent analysis) and microbial community analysis on each feed water.

Membranes were characterized in the laboratory to determine both the properties of the membrane and the nature of the biological material amassed on the membrane surface. Membrane characterization methods developed by OCWD were employed to examine the properties of virgin membrane materials, including ATR-FTIR spectrometry, atomic force microscopy (AFM), and captive (air) bubble contact angle analysis. Microbial community analysis and ATR-FTIR were performed on the fouled membranes submitted to OCWD upon completion of testing.

2.2.1 Membrane Autopsy

Membrane autopsy is a technique used to identify the cause of poor membrane performance. It involves the dissection of a fouled membrane element after removal from the plant or RO test unit for destructive analysis. The membrane element is unrolled to reveal the membrane leaves and plastic spacer material. A sample of the fouling layer is obtained from the membrane surface for chemical and microbiological analysis. Analytical techniques such as assay of protein [12], carbohydrate [13], heterotrophic plate counts (viable cell counts), epifluorescence analysis (total cell counts), community analysis and ATR/FTIR analysis are used to determine the nature of membrane fouling.

The fouled membranes were removed from the test unit at participating water agencies and transported to OCWD laboratory where they were dissected under aseptic conditions. Fouling material was scraped from the membrane surfaces using a sterile single-edge razor blade and placed into sterile vials. Scrapings were resuspended by vortexing in sterile R2A (Difco, Inc., Detroit, MI) growth medium (for bacterial enumeration) or sterile DI H_2O (for protein and carbohydrate assays). For bacterial enumeration serial dilutions were plated onto R2A medium. Plates were incubated up to two weeks at 28ºC after which the colony forming units (CFU) were counted and CFU/cm^2 were calculated. A known weight of biofilm was resuspended in DI H_2O by vortexing and sonication. Appropriate dilutions were made and carbohydrate assay and protein assays performed. The microbial community profile was also determined from the membrane scrapings. 2 x 3 cm of the fouled membrane were cut and stored in sterile plastic petri dishes for ATR/FTIR analysis.

2.2.2 ATR-FTIR Spectrometry

Absorption in the mid-infrared (IR) region (4000 – 500 cm^{-1}) was employed to acquire spectroscopic 'fingerprints' of clean and fouled membranes used in the study. The IR absorption spectra provided information on specific polymer functional groups (e.g., carbonyl, sulfonate, or amine groups) exposed at the membrane surface and were characteristic of the specific polymer surface chemistries employed.

The membranes were cut into small strips (~ 1 x 4 cm) and dried in a glove box purged with compressed air passed through a dryer (Balston, Havenhill, MA). A piece of membrane was pressed against each side of a 45°, 50 x10 x 2 mm zinc selenide internal reflection element (IRE). A torque of 10 oz-in. was applied to the bolt of the pressure plates of the attenuated total reflectance accessory (Harrick Scientific, Ossining, NY). Sample spectra consisted of 256 co-added scans collected at 4-cm^{-1} resolution with a Magna 550 FTIR spectrometer (Thermo Nicolet, Madison, WI). The single-beam spectra were (1) ratioed against a bare IRE background spectrum, (2) converted to absorbance, (3) corrected for the wavelength dependence of internal reflection and (4) baseline-corrected utilizing GRAMS/32 (Version AI 7.01) software (Thermo Galactic, Salem, NH).

Principal Component Analysis (PCA) was used to relate fouled membranes to specific feed water chemistries. PCA is a data reduction technique often used to relate spectroscopic data. The PCA turns training set spectra into mathematical spectra (loading vectors) which represent the most common loading variations to all the data. A set of scores for each factor is calculated for every spectrum in the training set. When the scores are multiplied by the loading vectors, and the results summed, the original spectra are reconstructed. ATR/FTIR spectra (15) were collected from each fouled membrane for a total of 60 spectra. PCA was performed with PLSplus IQ, Version 5.20 (Thermo Galactic, Salem, NH). The full spectrum from 4000 cm-1 to 650 cm-1 was used and the spectra were manually baseline corrected and mean centered prior to analysis.

2.2.3 Microbial Community Analysis

A microbial community analysis was performed on all feed water samples received from each participating water agency. A rapid method developed at OCWD was used in lieu of the commonly used but longer and more tedious culture and biochemical reaction method. This alternative, culture independent approach is based on polymerase chain reaction (PCR) amplification of the hypervariable region of the 16s ribosomal RNA (16s rRNA) gene. The 16s rRNA gene is used for characterization of microbial communities because it is ubiquitous amongst eubacteria. This method involves extracting total DNA from the sample, then amplifying only the hypervariable region of the 16s rRNA gene using a set of primers that bind specifically to the 16s rRNA hypervariable region. The amplified products (amplicons) are then rapidly separated on a capillary electrophoresis system (310 Genetic Analyzer) based on size. This instrument provides high sensitivity (up to one base pair resolution) with rapid analysis, and a typical separation run on this polymer based system is approximately ten minutes. The distribution of amplicon sizes provides a "fingerprint" describing the genetic diversity of the sample.

2.2.4 Atomic Force Microscopy

AFM provides essential information about the sub-micron surface topography and fundamental materials properties of RO membranes. Such information has been correlated with the performance (flux and solute rejection) and fouling potentials of separation membranes and therefore is critical in optimizing function and designing novel antifouling surfaces [14]. The AFM is an excellent tool for examining topography of polymer membrane surfaces in air-dried as well as fully hydrated forms.

The AFM used in this study was the CP AutoProbe (Park Scientific Instruments, Sunnyvale, CA) equipped with a non-contact/contact head and a 100 µm scanner operated in a constant force mode. Membrane coupons were attached to a circular stainless-steel sample holder using 12-mm carbon conductive tape (Ted Pella, Inc., Redding, CA). The holder with the attached membrane was mounted on the piezo scanner of the AFM. Images were acquired using silicon Ultralevers (force constant = 0.24 N/m; Park Scientific Instruments, Sunnyvale, CA), which were gold-coated cantilevers with integrated height-aspect ratio silicon nitride conical tips designed for maximum penetration into pores and other surface irregularities frequently encountered on polymer membranes. Tapping mode AFM (similar to non-contact mode AFM) was generally employed to minimize translational forces between the AFM tip and polymer membrane surface. In the taping mode, the AFM cantilever was maintained at some distance from the membrane surface (on the order of 1000 Å) and oscillated at a relatively high amplitude at or near its resonant frequency. The vibrating cantilever/tip was then moved closer to the sample surface until it just touched ('tapped') the sample once during each oscillation. AFM images were acquired at a scan rate of 1.0 – 2.0 kHz with a minimum information density of 256 x 256 pixels.

The root mean square roughness (RMS roughness) was calculated for membranes using Park Scientific software. For a transect containing N data points, the RMS roughness was given by the standard deviation of the heights:

$$R_{rms} = \sqrt{\frac{\sum_{n=1}^{n}(z_n - \bar{z})^2}{N-1}}, where\ \bar{z} = mean\ z\ height$$

2.2.5 Captive (Air) Bubble Contact Angle Measurement

The hydrophobicities of cells and inanimate substrata influence the strength and kinetics of microbial adhesion and early biofouling [15]. Therefore, the relative hydrophobicities of polymer membrane materials represent an important surface parameter in biofouling studies. The surface hydrophobicity of polymer membranes was determined by captive (air) bubble contact angle measurements [16]. A captive bubble contact angle apparatus constructed by OCWD staff was used in determining the contact angle of RO membranes used in this study [17]. This apparatus consists of a clear Plexiglass liquid reservoir, aluminum sample support stage, charge-coupled device (CCD) camera, imaging lens, x-y-z camera mount and an illumination source. The components are mounted on a flat sheet aluminum equipped with treaded legs to maintain a level plane. The specimen mounting stage consists of a ~10 x 10 x 2.5 cm block of aluminum with a ~ 1.0 cm wide slot cut 3.8 cm deep down the middle. The sample stage is placed in a ~10.2 x 10.2 x 10.2 cm clear Plexiglass reservoir filled with 18-megohm-cm DI water. A thread-feed syringe with Luerlock needle connection is angle-mounted on the side of the reservoir. The syringe is equipped with a 7.62-cm, 22-gauge stainless steel needle with a 90-degree bevel (Hamilton Co.). Air bubbles discharged from the syringe were an estimated ~10 μL. The syringe needle was reamed with 0.25 mm nickel wire prior to the day's measurements to insure needle diameter. A glass (microscope slide) window was mounted in the wall of the reservoir, opposite the syringe, to enable capture of images of air bubbles against the membrane sample. The CCD camera (COHU, Model 48155000AL2D) was equipped with a 0.75X to 3.0X objective (Edmund Scientific) and mounted on the x-y-z positioning stage. Images were captured and processed using Image-Pro Plus software (Media Cybernetics, Silver Springs, MD). A Sobell filter was used to outline the bubble's circular perimeter and the contact baseline. The Image-Pro program generated the bubble height and diameter data for calculation of the height diameter (H:D) aspect ratio. Departure of the air bubble from a perfect sphere with an aspect (height/diameter) ratio of 1.0 was related to the degree of spreading of the bubble over the membrane surface. Smaller aspect ratios (<<1.0) corresponded to greater bubble spreading and a more hydrophobic surface (larger contact angel), i.e., water was excluded from the bubble-membrane interface. Aspect ratios approaching 1.0 indicated a more hydrophilic membrane surface and smaller contact angle. Aspect ratio values were converted to contact angles according to the expressions (Druss, Inc. Charlotte, NC):

- Contact angle = 2 arctan (2h/d) for angles <90º
- Contact angle = 2 arctan [(2d/h –1)] for angles >90º where h = the bubble height and d = the bubble diameter.

A polymethylmethacrylate (PMMA), non-porous (i.e. dense) polypropylene, and glass microscope slides were analyzed as quality controls.

2.2.6 Membrane Zeta Potential Determination

The Zeta Potential was determined from streaming potential measurements using an Electro-Kinetic Analyzer (EKA, Anton Paar, Graz, Austria). This instrument utilizes silver/silver chloride electrode to measure the streaming potential that develops along a conduit with stationary charged walls (i.e., a thin rectangular channel with membranes lining opposing walls). A newly developed clamping cell was used to perform the streaming potential measurements [18]. 0.1N hydrochloric acid and 0.1N sodium hydroxide (ACS grade, Fisher Scientific) were used for pH adjustment to study the variation of zeta potential with different solution pH.

Conductivity and pH electrodes were calibrated before starting the zeta potential measurement for each membrane sample. A thermostatic water bath (Daigger, IL) was used to maintain a constant temperature of 25^{o}C for the electrolyte solution. Following parameters need to be entered to EKA software to obtain optimal performance during the measurements:

- Rinse time (s): 20, -20, 20,-20
- Max Pressure (mbar): 200
- Pressure Ramp (mbar): 800, -800, 800,-800

- pH change: 0.2 units between pH levels

Zeta potentials were determined for both fouled and clean pieces of membrane. These measurements were conducted using different types of pH adjustment techniques depending on the type of membrane. For the unused membrane pieces, streaming potential measurements were taken throughout the pH range from 3 to 9 in 0.2 pH unit increments and for the used membrane pieces streaming potential was measured at the pH value determined in the field for the feed conditions of the RO process.

2.2.6.1 Zeta Potential - New Membranes

Clean membranes were tested for their streaming potential. Prior to the zeta potential measurement, the membranes were stored in deionized water at approximately 4°C and rinsed thoroughly with deionized water. Before loading the sample into clamping cell, EKA was flushed with deionized water for 20 minutes. PMMA was cleaned by rinsing with Ethanol (100%) fallowed by deionized water. A clean membrane (2.5 x 2.5 inch) sample was loaded into clamping cell, the EKA system was filled with 9mM NaCl and this was circulated for 20 minutes until equilibrium conditions were achieved (including conductivity, pH, and electrolyte solution temperature). Schematic of the experimental run was given as below:

a. *First run, Acid adjustment*; Electrolyte solution was adjusted with 0.1N Hydrochloric acid to achieve pH range ~5 to 3 by using automatic titration unit in 0.2 pH increment.

	First Run		Second Run	
pH 3	←	Unadjusted pH	→	pH 9
	0.1 N HCl in 0.2 intervals		0.1 N NaOH 0.2 invervals	

b. *Second run, Basic adjustment*; Electrolyte solution was adjusted with 0.1N Sodium Hydroxide to achieve pH range ~5 to 9 by using automatic titration unit in 0.2 pH increment.

2.3 Database Construction

Operational, water quality, and membrane characterization data from each test were collected and integrated into a functional database managed by OCWD staff. Data included in the database consist of: 1) water quality analysis data of source waters at the participating water agency facilities, 2) results from characterization of membrane surfaces, and 3) operational data from dedicated bench units from each participating water agency, e.g. of salt rejection and specific water flux.

2.4 Task 3. Construction of Artificial Neural Network Models Describing the Association of Water Quality with RO Membrane Performance

All numerical operations were carried out using Microsoft Excel (Microsoft Corp., Redmond, WA). Exemplars were constructed for each site and membrane by combining all feed water quality parameters (independent input parameters) corresponding to the measured specific water flux (gfd/psi) or percent rejection (dependent output parameters). The order of exemplars was always randomized prior to modeling as a precaution to insure that the order in which data were presented did not influence the final results.

2.3.1 Identification of Subsets of Influential Descriptors Using a Genetic Algorithm

Input parameters were selected using a genetic algorithm (GA) (Neural Works Predict, Neuralware, Carnegie, PA). A logistic multiple linear regression fitness evaluation was utilized in this analysis and in addition a “Cascaded Variable Selection” was employed to rapidly eliminate inputs with a low probability of inclusion in the optimum input set. Inclusion of inputs by the GA was detected by construction of a single neural network and performing a sensitivity analysis to detect influential inputs. The GA eliminated descriptors that did not predict compound-membrane interactions, and reduced the initial 21 descriptor set down to subsets of 2 to 4 descriptors. Because the membrane fouling was time – dependent (not at equilibrium) time was forced into each input set.

2.3.2 Identification of Most Common Influential Descriptors

The GA converges on an optimum fit between the input parameters and the output parameter, but it does not necessarily predict a globally optimum input set; more than one combination may lead to an acceptable solution. However, statistically, it was expected that the GA should choose the most highly influential inputs most frequently. A histogram was constructed for each model by operating the GA on each data set for ten (10) iterations. Inputs selected by the GA were used to construct the histogram. Inputs selected ≥ 50% of the time were retained to construct the model.

2.3.3 Construction of the Artificial Neural Network (ANN) Models

The design of ANN models for this study was a three-layered network consisting of an input layer, a "hidden" processing layer and an output layer (a single output perceptron). The relationship between inputs and outputs were embossed upon the network by "training" it using exemplars from the real world. During the training process, perceptrons were added and the values of the weighting factors were adjusted until the behavior of the network converged on the behavior of the real system as determined by one or more correlative comparisons. At this point, the network had "learned" to recognize patterns in the input data that predict the output data. Challenging the network with a "test" set of exemplars evaluated the predictive ability of the network. Test data consisted of 10% to 20% of the exemplars that were not present during training. A well trained network predicted behavior of the test exemplars as well as it did the training exemplars. Models were constructed for each membrane describing the relationship between the feed water quality and both specific water flux and percent rejection. In addition, a set of "universal" models were constructed utilizing all of the polyamide membrane parameters as well as the feed water quality parameters.

3.0 PROJECT OUTCOMES.

3.1 Test #1: Surface Water with Conventional Treatment

3.1.1 Site Description

The first test unit was delivered to Metropolitan Water District of Southern California (MWD), F.E. Weymouth Filtration Plant in La Verne, California. The plant receives a blend of Colorado River water and California State project water, via the District's 242-mile Colorado River Aqueduct and the 444-mile State Water Project California Aqueduct, respectively. This water is then treated using conventional filtration (rapid mix, coagulation, flocculation, followed by dual media (anthracite/sand) filtration. Chemical additions included 10 mg/L ferric chloride, 3.0 mg/L cationic polymer, and post-disinfection with 3.0 mg/L monochloramines. The product water from this process was used as the feed water for the RO test unit installed at the La Verne facility.

3.1.2 Comparison of Membrane Performance

Feed water and membrane permeate water quality (general minerals) were analyzed on a weekly basis. All membranes improved water quality as expected (Table 4). ESPA-1 started out with a highest specific water flux but percent rejection was similar to the other polyamide membranes. In this test the TW-30 polyamide membrane had a slow start; it did not reach its optimum percent rejection until 168 hours into the experiment, after which, the membrane performance remained consistent and within experimental parameters (Figure 2). The initial poor performance may have been due to a bad seal that may have corrected itself with time. This phenomenon was only seen with the TW-30 membrane at the MWD facility. The cellulose acetate (CA) membrane, MC-2514, was the lowest performer of the membranes tested using MWD surface water.

The feed water was low in total and viable bacterial counts (Figure 3). For the duration of the experiment the total bacteria averaged 5.37 x 10^4/mL with the viable bacteria averaging 17.91 bacteria/100mL. Microbial concentration in the feed water varied over time. After several weeks of operation the membrane permeates began to yield higher bacterial counts. Since RO membranes are not produced in a sterile environments bacteria are present inside the membrane elements. Viable and total bacteria were detected after 48 hours of operation (Figure 4). The increase in permeate biological activity may be the result of bacterial growth on the back side of the membrane (permeate side). The membrane permeate may contain sufficient amount of activated organic carbon to promote bacterial growth and colonization and as the membrane ages resulting in increased bacterial counts.

3.1.3 Membrane Autopsy

The experiment was stopped and membranes were removed after 1,872 hours of continuous operation. The fouled membranes were placed into clean plastic bags and shipped to OCWD for analysis. Membranes were autopsied (section 2.1). All 4 membrane surfaces were covered with a rusty colored fouling layer (Figure 5) which was due to the ferric chloride addition during the coagulation treatment process.

3.1.3.1 Bacterial, Protein and Carbohydrate Results

The presence of carbohydrate and protein on the membrane surface indicates the presence of biological fouling. MT-2514 and ESPA-1 demonstrated the highest carbohydrate and protein loads as compared to TW-30 and MC-2514 (Figure 6). Due to contamination problems heterotrophic plate counts are not available for the membrane autopsies. Epifluorescent images showed the presence of bacteria and particulate debris (Figure 7).

3.2 Test #2: Secondary Treated Wastewater with Microfiltration (#1)

3.2.1 Site Description

Second unit was delivered to West Basin Municipal Water District, Carson, California. West Basin (WB) wholesales imported water to cities, municipal water companies, investor-owned utilities and private companies in southwest Los Angeles County. The feed water used in this experiment was microfiltration treated wastewater.

3.2.2 Comparison of Membrane Performance

Feed water and membrane permeate water quality (general minerals) were analyzed on a weekly basis. All membranes improved water quality as expected (Table 5). After 1,032 hours of operation the polyamide membrane pressures began to climb above 200 psi (the predetermined experimental termination point). Specific water flux dropped below 0.05 gfd/psi and percent rejection also began to deteriorate. All membrane elements began to fail simultaneously (Figure 8). The sudden increase in pressure and poor performance was attributed to algal contamination of the RO feed water tank (Figure 9). The algal contamination was noticed by WB staff 864 hours into the RO unit operation. The occurrence of the algal growth was not communicated to OCWD staff; hence the unit remained in operation for additional 168 hours. Due to the unforeseen contamination only 840 hours of membrane performance data, chemical and biological data was used in the project final analysis. After 1,032 hours of operation membranes were removed from the unit and delivered to OCWD for analysis.

3.2.3 Membrane Autopsy

An orange fouling layer was present on all 4 membranes (Figure 10). The large quantity of fouling material present on the membrane surfaces was the result of feed water contamination. Membrane failure due to algal contamination has been reported in previous studies performed at MWD [19]. Membrane scrapings were not analyzed for bacterial content due to the system's contamination.

3.2.3.1 Bacterial, Protein and Carbohydrate Results

Total bacterial loads increased from 10^4 bacteria/mL to 10^6 bacteria/mL in week 6 and 7 (Figure 12), algae were not enumerated. All 4 membranes, polyamides and cellulose acetate, had similar carbohydrate and protein loads (Figure 11). This may be the direct result of the feed water contamination that carried heavier algal and bacterial loads to the membrane surfaces, which in turned resulted in membrane performance failure.

3.3 Test #3: Secondary Treated Wastewater with Lime Clarification (#1)

3.3.1 Site Description

The third test site was Orange County Water District (OCWD), Fountain Valley, California. At the time of this test the plant's treatment train received secondary treated wastewater from Orange County Sanitation Department, Fountain Valley, California, which underwent chemical clarification, recarbonation, and multimedia filtration. The product from this treatment was used as feed water for the third RO test unit experiment.

3.3.2 Comparison of Membrane Performance

Feed water and membrane permeate water quality (general minerals) were analyzed on a weekly basis. All membranes improved water quality as expected (Table 6). The OCWD RO test unit operated for 1,032 hours. Within the first 120 hours the polyamide membrane percent rejection decreased from 98% for all three membranes to 97% for TW-30, 97% for MT-2514 and 96% for ESPA-1. After 120 hours all polyamide membranes' performance began to improve but never attained the initial start-up rejection of 98%. The polyamide membranes at this site, using this feed water, showed a steady decline in performance over time (Figure 13). Even though there was a steady decline there were periods through out the test when the performance improved and again decreased. This wave affect was observed in all three polyamides with the most pronounced effect observed in ESPA-1. The up and down affect in membrane performance was correlated with weekends when membrane monitoring was not as diligent due to reduced weekend operation's staff. MC-2514 continued to reject at 94% for 384 hours. After 384 hours the CA element began to follow a similar performance, upward/downward, as its polyamide counter parts. The total bacterial load at this site remained fairly constant at 3 x 10^6 bacteria/mL. The viable bacteria entering the membrane elements varied during the test from 10^3 to 10^5 bacteria/mL. Inoculating the membrane surfaces with viable bacteria may increase biofilm growth which will affect membrane performance. Viable bacteria in the permeate remained low, 1 CFU/100 mL (Figure 15).

3.3.3 Membrane Autopsy

Test was completed after 8 weeks of membrane operation. Membranes were removed and autopsied (section 2.1). The fouling layers appeared to be fairly thick and easy to scrape off the membrane surface. Photographs of these autopsies are not available.

3.3.3.1 Bacterial, Protein and Carbohydrate Results

Out of the 4 membranes ESPA-1 had the lowest viable bacterial load, 3.56 x 10^7 CFU/cm^2, MC-2514 had the highest, 3.51 x 10^{10} CFU/cm^2, TW-30 was 1.05 x 10^{10} CFU/cm^2 and MT-2514 at 1.92 x 10^{10} (Figure 16). MC-2514, the membrane with the lowest performance and highest bacterial counts also had the heaviest carbohydrate load

193.60 μg/cm^2 (Figure 17). Membrane scrapings had clumps of bacteria and other particulates making enumeration difficult, leading to large standard deviations among replicates (Figure 18).

3.4 Test #4: Secondary Treated Wastewater with Lime Clarification (#2)

3.4.1 Site Description

Following OCWD the RO test unit was delivered to Santa Clara Valley Water District (SCVWD) located in San Jose California. The District's wastewater is collected at the South County Regional Wastewater Treatment Plant located in Gilroy California where it undergoes conventional tertiary treatment. The treated water is then transferred to water ponds where it is allowed to soak into the soil and eventually added to the underground aquifer. The RO test unit was installed at the Gilroy treatment plant and operated using the plant's tertiary treated wastewater.

3.4.2 Comparison of Membrane Performance

Feed water and membrane permeate water quality (general minerals) were analyzed on a weekly basis. All membranes improved water quality as expected (Table 8). The SCWD RO test unit remained in operation for 1,272 hours. The experiment was terminated when the pressure in ESPA-1 reached 200 psi (the predetermined experimental cut off). Initially, the percent rejection for the polyamide membranes remained above 96%, TW-30 at 99.4%, MT-2514 at 98.9%, ESPA-1 at 96.7% and MC-2514 (CA membrane) at 92%. The percent rejection started out high and remained constant for all 3 polyamide membranes for 528 hours. After 528 hours changes in performance started to occur (Figure 19). Membranes began to reject less salts and membrane pressure was increased to maintain constant flux of 10gfd. After 500 hours of operation the total and viable bacteria in the membrane permeates increased (Figure 20, Figure 21). Feed bacteria remained constant (Figure 22).

3.4.3 Membrane Autopsy

After 1,272 hours membranes were removed from the RO unit and delivered to OCWD for analysis. These membranes appeared to have a very thin fouling layer (Figure 23). The fouling layer on each membrane was thin, wet and very loose which made it difficult to scrape off into sterile containers. ESPA-1 membrane appeared to have a thicker layer of fouling as compared to the other 3 membranes.

3.4.3.1 Bacterial, Protein and Carbohydrate Results

The appearance of a thicker fouling layer on ESPA-1 did not result in higher CFU/cm^2. All membranes had a similar viable bacterial load of 10^{10} CFU/cm^2 (Figure 25). ESPA-1 had the highest protein (70.76 µm/cm^2) and carbohydrate loads (56.56 µm/cm^2) (Figure 24). The combination of the membrane polymer chemistry and the feed water chemistry resulted in a high attenuation of protein and carbohydrate. TW-30, MT-2514 and MC-2514 did not exhibit this affect.

3.5 Test #5: Secondary Treated Wastewater with Microfiltration (#2)

3.5.1 Site Description

For the fifth location the RO test unit was returned to OCWD. The conventional wastewater treatment was replaced with MF. The second test performed at Orange OCWD used MF treated secondary treated wastewater.

3.5.2 Comparison of Membrane Performance

Feed water and membrane permeate water quality (general minerals) were analyzed on a weekly basis. All membranes improved water quality as expected (Table 7). The polyamide membranes continuously performed at a rejection of 97% or better (Figure 26). As in previous tests the CA membrane started at a lower rejection, 92%. Percent rejection remained high for all membranes during operation. The test was terminated due to time constraints, not membrane failure. The total bacterial load to the membranes remained constant (10^6 bacteria/L) during the test cycle (Figure 27). As seen in previous test systems the viable bacteria were a very small portion of the total, 10^1 to 10^2 CFU/100 mL. Bacteria were detected in first 500 mL of permeate generated after initial start up (10^3 total bacteria/mL, 10^1 CFU/100 mL) (Figure 28). Permeate total bacteria concentrations remained constant but viable bacteria concentrations increased with time, which is evidence of bacterial growth on the permeate side of the membrane elements.

3.5.3 Membrane Autopsy

After 1,800 hours of operation membranes were removed and autopsied (section 2.1). The fouling layers from OCWD_MF feed water were visibly different from OCWD (conventional treatment) membranes (Figure 29). All fouling layers were composed of bacterial cell and debris as seen in previous autopsies. Because the fouling layers from this unit were lighter and the membranes didn't show a significant decrease in performance it was postulated the biological component of the fouling layer would be smaller then seen on previous membrane surfaces which had visibly thicker fouling layers (MWD, WB and OCWD).

3.5.3.1 Bacterial Protein and Carbohydrate Results

The CFU's for the membrane fouling layers were 5.2 x 10^8 CFU/cm^2 for TW-30, 1.3 x 10^{10}CFU/ cm^2 for MT-2514, 1.3 x 10^{10}CFU/ cm^2 for MC-2514 and 3.62 x 10^9 for ESPA-1 (Figure 30). Even though the fouling layer on the membrane surfaces was light in appearance the viable bacterial counts were similar to other sites with thicker fouling layers (MWD, WB, and OCWD). The light appearance of the fouling layer may be related to protein and carbohydrate loads. Protein and carbohydrate concentrations were much lower for this site were in comparison to other sites tested, 0.02 $\mu g/cm^2$.

3.6 Test #6: Agricultural Drainage Water Treated with Lime Clarification

3.6.1 Site Description

The last test site was located in Yuma Arizona using treated agricultural drainage water as the feed to the RO test unit. This water was treated using conventional filtration processes that include lime clarification, coagulation using ferric chloride (dose) followed by dual media filtration.

3.6.2 Comparison of Membrane Performance

Feed water and membrane permeate water quality (general minerals) were analyzed on a weekly basis. All membranes improved water quality as expected (Table 9). This unit remained in operation for 842 hours. TW-30 and MT-2514 membranes continuously performed at or above 98% rejection (Figure 31). ESPA-1 did not perform as well as the other membranes at the onset of the experiment, but within 48 hours started to improve and continued to improve (in regards to rejection) for the duration of the experiment. As seen in previous tests, MC-2514 operated at a lower rejection (83.7%) and required higher pressure to maintain constant flux. As membrane pressure increased specific water flux decreased. Membrane performance with respect to specific water flux began to decrease for all membranes after 310 hours. Another significant decrease in specific water flux occurred between 498 and 510 hours followed by another decrease in 798 hours of operation. Total bacterial load in the feed water averaged 10^5 bacteria/mL with a small portion of the total load being due to viable bacteria (10^1 CFU/100 mL) (Figure 32). Permeate bacteria slightly increased as membranes aged (Figure 33).

3.6.3 Membrane Autopsy

The test was ended after 842 hours due to time constraints of the project (not membrane failure) and membrane were autopsied. The fouling layer in this case was thinner and difficult to scrape off the membrane surface into sterile vials. This maybe attributed to the shorter test duration or differences in microbial community or water chemistry. Unfortunately no photographs are available of these membranes due to a camera malfunction on the day of the autopsy. Visually these fouling layers were similar to the OCWD_MF fouling layers. All 4 membrane fouling layers were orange in color from the addition of ferric chloride during the treatment process.

3.6.3.1 Bacterial, Protein and Carbohydrate Results

The concentration of viable bacteria present in the membrane scrapings was lower in comparison to previous sites tested (Figure 34). MT-2514 and MC-25514 had the highest biological activity of 2.5×10^8 and 2.5×10^8 CFU/cm^2, respectively. MT-2514 also had a highest concentration of protein, 84.77 µg/ cm^2 which was not shared by MC-2514. MC-

2514 protein concentration was much lower, 10.39 µg/cm^2 (Figure 35). TW-30 having the lowest biological activity also had the lowest protein concentration, 3.98 µg/cm^2. ESPA-1 protein concentration was 21.23 µg/cm^2. The carbohydrate concentrations for all membranes were below 10µg/cm^2.

All polyamide membranes performance on the OCWD conventional treatment feed water deteriorated much faster than on the OCWD_MF feed water. MC-2514 percent rejection was equal for both feed waters.

3.7 Membrane Performance Comparison by Feed Water Type

3.7.1 TW-30 Polyamide Membrane

3.7.1.1 Water Flux and Percent Rejection

TW-30 performed best on agricultural drainage feed water (Yuma) consistently maintaining percent rejection above 99%. Specific water flux also remained consistent through out the Yuma test. The poorest performance was associated with high fouling feed waters (OCWD conventionally treated wastewater and SCWD conventionally treated wastewater). TW-30 percent rejection and specific water flux at these sites dropped within hours of start up and continued to decrease during the test period suggesting there is something in these feed waters that affect membrane performance from time zero. Rejection performance on the MF treated wastewaters (OCWD_MF and WB) and agricultural drainage was similar, at or above 97%. Percent rejection using surface water (MWD) was not as stable as the other sites in the study.

3.7.1.2 Biological Fouling

TW-30 performed the best on agricultural drainage water (Yuma). Fouling layer protein, carbohydrate and viable bacteria loads at this site were low compared to other sites tested. Total bacteria present in Yuma feed water was similar to other sites tested but the viable bacterial load was the lowest among the sites in the study. The lower biological presence on the membrane surface is also due to the shorter term of operation, 841 hours, which was significantly lower compared to other sites. TW-30 appears to perform well on feed waters with lower biological (total and viable) activity such as MF treated wastewater. TW-30 is classified as a low fouling membrane which would make it an ideal candidate for high fouling feed waters such as OCWD and SCWD. In this study TW30 performance steadily decreased on OCWD and SCWD feed waters but was the best performer on these feed waters among the membranes tested.

3.7.2 ESPA-1 Polyamide Membrane

3.7.2.2 Water Flux and Percent Rejection

The poorest performance for ESPA-1 was on conventional treated wastewater (OCWD and SCWD). ESPA-1 performed best on MF treated feed waters (OCWD_MF and WB). Percent rejection using MF treated wastewater remained consistent for the duration of the tests at both locations. At WB the specific water flux started to decline after initial start up and continued to slowly decrease over time. A much slower flux decline was observed on OCWD_MF feed water. ESPA-1 performed best on surface water (MWD) with high flux and consistent percent rejection. Agricultural drainage water did not seem to affect the membrane performance adversely in regards to percent rejection or specific water flux.

3.7.2.1 Biological Fouling

ESPA-1 performed equally well on surface water, agricultural drainage water and MF treated wastewater. Protein and carbohydrate were the lowest for this membrane using OCWD_MF feed water. WB, the other MF site, had the highest protein and carbohydrate loads which may be the result of the algal contamination which occurred during the test. Membranes were autopsied after they were exposed to algae for several days. It may be postulated if the membranes were removed sooner and the algal contamination did not occur the protein and carbohydrate loads would be closer to the OCWD_MF results. MF, agricultural drainage and surface feed waters had lower total bacteria (on average 10^4 bact/mL) then conventional treated feed waters (on average 10^6 bact/mL). ESPA-1 using OCWD conventional treated feed water demonstrated a rapid decrease in percent rejection and specific water flux. On conventional treated wastewater the membrane flux started above 0.4 gfd/psi and within 200 hours dramatically dropped to 0.1 gfd/psi as on OCWD_MF feed water the flux started low at 0.1 gfd/psi. The difference in starting flux may be due to biological differences and chemical differences in the feed waters. Interestingly, the conventional and MF feed waters at OCWD are very similar in water quality (Table 3) but different in biological content (Figure 42). The fact ESPA-1 is a high specific water flux membrane may influence bacterial loading at the membrane surface. Increased water permeability increases movement and deposition of solids present in the feed water which may increase bacterial adhesion resulting in increased biofouling and decreased membrane performance.

3.7.3 MT-2514 Polyamide Membrane

3.7.3.1 Water Flux and Percent Rejection

MT-2514 performed similar to the other two polyamide membranes in the study. It performed the best feed waters with lower microbial loads. MT-2514 performance on conventional treated wastewater (OCWD and SCWD) was the poorest. Percent rejection on MF treated wastewater remained consistent over time at both OCWD_MF and WB sites. Specific water flux decreased from initial start up at WB from 0.25 gfd/psi to 0.15 gfd/psi after 200 hours of operation. On OCWD_MF feed water the flux remained fairly constant with a small decrease over time. Using surface water (MWD) MT-2514 specific water flux remained constant over time. A small decrease in percent rejection started to occur around 750 hours of operation. Agricultural drainage water did not appear to have an adverse affect on MT-2514 performance for the duration of the experiment.

3.7.3.2 Biological Fouling

MT-2514 performance was similar to the other polyamide membranes at the same sites. It had very high rejection using agricultural drainage water and surface water. However, MT-2514 had a more protein associated with the membrane fouling layer (84.77µm/cm^2) than ESPA-1 (21.23µm/cm^2) and TW-30 (3.97µm/cm^2). Carbohydrate concentration was also higher for MT-2514 on agricultural drainage water but in the middle for surface water. OCWD_MF feed water generated the lowest protein and carbohydrate concentrations as seen with ESPA-1 and TW-30. Viable bacteria found in the fouling layer for MT-2514 was similar from site to site. MT-2514 appeared to accumulate bacteria at the membrane surface consistently no matter the feed water type but it appeared to bind proteins and carbohydrates at faster rates. This may be due to the polymer chemistry or feed water chemistry.

3.7.4 MC-2514 Cellulose Acetate Membrane

3.7.4.1 Water Flux and Percent Rejection

MC-2514 was poorest performer of all membranes tested on all feed waters tested in the study. Percent rejection was below 95% at all sites tested and a decline in specific water flux was observed on all feed waters except agricultural drainage water (Yuma). At Yuma the flux remained constant with a slight increase after 800 hours of operation. Percent rejection at Yuma also remained consistent over time but low, 85%, compared to high nineties observed with polyamide membranes. MC-2514 performed the best on MF feed water at OCWD and OCWD conventional treated wastewater. Percent rejection on SCWD feed water at the start was at 92% which was maintained for 600 hours after which the percent rejection began to decrease. Specific water flux at 600 hours also started to decline which may be related to a build up of a fouling layer at the membrane surface.

3.7.4.2 Biological Fouling

Viable bacteria present in MC-2514 fouling layer at all sites ranged between 10^8 bact/mL on agricultural drainage water to 10^{10} bact/mL on MF and conventional treated wastewaters (bacterial autopsy data for surface water is not available) . Protein load was lowest for MF treated wastewater at OCWD and surface water (MWD) and highest protein concentration was found on OCWD conventional treated feed water. Carbohydrate concentrations were highest on both conventional treated feed waters and lowest for OCWD_MF and agricultural drainage water (Yuma). The lowest performing membranes also had the highest bacterial, protein and carbohydrate loads. MC-2514 appeared to be dependent on bacterial fouling. More bacteria and bacterial debris resulted in lower percent rejection and specific water flux.

3.8 ATR/FTIR Analysis of Clean and Fouled Polymer Membranes

3.8.1 Analysis of Virgin Membrane Samples

ATR/FTIR spectrometry was utilized to characterized surface structure and chemistry of dried virgin polyamide membrane samples. This analysis was used to determine the degree of crosslinking and polyamide thickness. Each membrane type exhibited different degrees of crosslinking and thickness (Table 10). MT-2514 was the least crosslinked membrane by this determination and TW-30 was the most crosslinked membrane, with the COO/AMID I ratio, the COO/AMID II ratio and the OH/AMID I ratio two to four times the other membranes. The ESPA-1 membrane had the thickest polyamide layer as demonstrated by the higher polyamide thickness ratio, although there were not great differences between the polyamide membranes in general with respect to this parameter.

3.8.2 Analysis of Fouled Membrane Samples

For each membrane, the chemical signatures of the fouled surfaces at each site were compared using PCA (Figure 36 through Figure 39). Clustering of the spectra in these analyses show that the different membrane chemistries attracted different foulants from each of the sites. The data suggest that the nature of foulants accumulated on membranes is very highly influenced by the differences in the feed water constituents from site to site.

3.9 Membrane Biofilm and Feed Water Community Analysis

Microbial community analysis provides a sensitive measurement of differences in microbial community structures using dendritic cluster analysis. This analysis was performed on OCWD_MF and Yuma membrane scrapings and all feed waters. This analysis shows feed water microbial communities are different from each other and membranes are selecting different organisms from individual feed waters (Figure 40 through Figure 42). Membranes do not equally attract the same type of bacteria. If the same bacteria were consistently singled out, the microbial community patterns would be the same. Differences between the membranes microbial communities may be due to differential bacterial adsorption differences in membrane surface coatings used by manufacturers as well as bacterial growth at the membrane surface. These data suggests several factors such as feed water chemistry, membrane surface chemistry and bacterial diversity influence microbial community structure on RO membrane surfaces.

3.10 Relationships Between Source Water Composition and Membrane Performance

3.9.1 Construction of Databases Relating Source Water Parameters to Membrane Performance

Databases relating source water quality parameters (physicochemical and biological) from all of the study sites to membrane performance (water flux and solute rejection) at each weekly time point were constructed for each of the test membranes (APPENDIX 1). Each line of data in these databases provided the exemplars that were used in the construction of ANN models describing membrane performance. In addition, the databases for the polyamide membranes were combined into a single database, and the polyamide membrane parameters (Table 10) were included as independent input variables to produce the database used to create a "universal" polyamide model.

3.9.2 Application of ANN Modeling to Determine Relationships between Source Water Composition and RO Performance

Membrane performance (specific water flux and rejection) at the test sites was a non-equilibrium function (varied with time), and thus required time as an integral input in the constructing the models. In addition, the relatively small number of sites (only 6 in all) presented a further challenge in limiting the scope of variations observed amongst the physicochemical and biological parameters available for model construction. Typically, under these circumstances where there are many potential inputs, it is possible that more than one combination of input parameters may yield an acceptable "local" solution. The first priority of model construction was thus to identify the most influential physicochemical and biological input parameters that yielded a more "global" solution. To this end, iterative applications of the GA was employed during the initial screening to identify the most statistically common influential input parameters prior to ANN model construction. This gambit ensured that only inputs that were most commonly identified by the GA would be used for model construction, and tended to eliminate those included by noise in the GA. In addition, the number of degrees of freedom for model inputs were constrained during the initial input parameter screening by restricting the number of potential transformation functions (mathematical relationships feeding real world data into the ANN) to only a single function per real world input. Later, during ANN construction, this restraint was relaxed in order to give the ANN construction algorithm more degrees of freedom in feeding input data into the model.

3.9.2.1 Individual Membrane Performance Models

3.9.2.1.1 Overall Model Fitness

Results of attempts to construct ANN Models describing changes in the specific water flux (gfd/psi) of individual test membranes as a function of time and source water parameters are shown in Figure 43. The ability of the ANN to capture behavior of the system is evidenced by both the relatively close agreement between the actual data and that predicted by the models, and by the close agreement between the Pearson correlation coefficients of the training and test sets, indicating that models were generally able to predict membrane behavior well. The same results were generally observed with models of membrane solute rejection (Figure 44), where there was fairly good agreement between the actual rejection observed in the field and that predicted by the models for each of the test membranes.

In order to more clearly demonstrate the goodness of fit between the ANN models and the observed membrane performance in the field, Actual data were compared directly with the modeled performance for the cellulose acetate membrane MC-2514 (specific water flux; Figure 46, rejection), and for the polyamide membranes TW-30 (Figure 47, specific water flux; Figure 48, rejection), ESPA-1 (Figure 49, specific water flux; Figure 50, rejection), and MT-2514 (Figure 51, specific water flux; Figure 52, rejection).

It may be observed that the temporal changes in membrane performance (both specific water flux and rejection), though generally negative, often varied considerably from site to site. Moreover, the kinetics describing membrane performance in the field could not be generally represented by any simple mathematical decay curve, and thus it was not possible to generate simple rate constants with which to describe membrane behavior. For this reason, we chose to apply ANNs, a highly nonlinear approach, in order to describe membrane behavior.

In nearly all cases, the ANN models generated in this study were in very good agreement with the observed performance behavior of all the membranes used in the study at all of the sites. These results indicate that sufficient information existed in the measured source water quality parameters at the sites to describe the vast majority of the variations in membrane performance observed during the course of this study for all for the membranes tested.

3.10.2.1.2 Identification of Source Water Parameters Influencing Membrane Performance

Although ANN models cannot be easily dissected in the way that multiple linear regression models can, yielding slopes relating the individual independent variables to the dependent variable, it is possible to identify the influential inputs in the ANN models, and to assess their relative direction of influence by via performance of a "sensitivity analysis". This yields an index value related to the overall direction of influence of the model input and the magnitude of the influence relative to the other inputs in the model. It is similar in some ways to performing and derivative analysis in which the direction and acceleration of the dependent variable is expressed as a function of each independent variable. The danger of interpretation here is that with a complex multivariate system, local effects of the input may be vastly different from the overall effect (imagine the relationship between x and y with a sine function, e.g.). However, bearing that in mind, it is possible to extract useful information from a sensitivity analysis of an ANN model, and to use this to gain some insight as to the potential interactions between source water physiochemical parameters and membrane performance.

3.10.2.1.2.1 Specific Water Flux Models: Influential Source Water Parameters

The source water parameters deemed most influential on specific water flux for each of the test membranes are indicated in Table 11. Parameters included in the models are indicated in the table. Blank spaces indicate the parameter was not used in construction of a particular model.

Time was universally included by constraint; however, the sensitivity index indicates it was universally negative. This is not a surprising result, as it indicates that as the membranes were exposed to the source waters for increasing periods of time, their specific water flux on the overall tended to decline.

Typically, only 6 – 7 parameters were required to define each of the water flux models. There was no absolute agreement between membrane models with respect to influential parameters; each membrane appeared to exhibit particular sensitivities with respect to chemical species or biological parameters in the source water. However, if the specific parameters are grouped into broader categories, some trends appear across membrane types.

Microbiological fouling is known to result in a decline in specific water flux, and should be expected to appear as an influential parameter. In many cases this was noted; in the case of ESPA-1 and MC-2514 bacterial loading in the source water was strongly negatively related to specific water flux, and in the case of ESPA-1 this proved to be the most highly influential parameter in the specific water flux model. However, in the case of the other membranes, the effect was not so strong (MT-2514) or negative, and in the case of TW-30 there was no inclusion of microbial parameters in the model at all. ESPA-1 membranes in particular are high water flux membranes; for this reason it isn't particularly surprising to see such a strong negative effect of microbial concentration in the feed water.

Influence of ionic species suggested by the models may be related to the interactions of the ions with the charged membrane surfaces (mostly negatively charged at the pH of the source waters used in the study). For the polyamide membranes, in general monovalent cations (Na, K) exhibited a slight negative influence on specific water flux (the higher their concentration, the lesser the specific water flux) and monovalent anions exhibited a positive influence (the higher the concentration of monovalent anions, the greater the specific water flux). Although it is not possible with these experiments to establish a direct cause and effect relationship, it may be that these species in solution interfered with association of charged foulants (microbial, nanoparticulate or dissolved) with the membrane surfaces, or by associating with the membrane chemistry (surface or internal), influenced membrane permeability. In the case of the polyamide membranes, phosphate-phosphorus was very strongly related to specific water flux, but the direction of the relationship was variable. In the case of MT-2514 the effect was strongly positively associated with specific water flux (in fact, it was the most influential parameter in the model), indicating that increasing -phosphorus in the feed water generally favored improved water flux, while in the case of ESPA-1 and TW-30, the opposite case was observed. Differences in the membrane surface chemistry may be responsible for the observed variation in this influence of phosphate.

The cellulose acetate membrane model (MC-2514), behaved differently than the polyamide membrane models with respect to the influence of anions and cations. In this case, the total ionic strength (as TDS) was negatively influential, as might be generally expected by osmotic considerations. However, the influence of monovalent cations and ions in the MC-2514 model are exactly opposite of those generally observed for the polyamide membranes. This may be due to both differences in surface chemistry (which is unknown) and to differences in the membrane polymer chemistry as well.

The observed negative influence of boron in the ESPA-1 specific water flux model is notable, but may prove more difficult to explain. There is a variable effect of water hardness and alkalinity as well; in the case of the polyamide membrane ESPA-1 there was a negative influence of calcium bicarbonate in the specific water flux model, while total alkalinity exhibited a positive influence on specific water flux in the BW-30 model.

Notably, some source water components were not included in the specific water flux models. The source water pH was universally excluded, for instance. This was surprising, as pH certainly influences membrane surface charge and should have an effect on the binding of many species to the membranes. Apparently, the ranges of pH in the feed waters were not sufficient to make it as effective a driver in this study as were other water chemistry parameters. Likewise, electrical conductivity was excluded, and TDS only included in the cellulose acetate membrane model, and not in the polyamide membrane models. The ranges of dissolved ionic species in the source waters apparently also were also not sufficient to drive any interaction to the point that these parameters dominated the specific water flux of the polyamide membranes.

3.10.2.1.2.2 Percent Rejection Models: Influential Source Water Parameters

The source water parameters deemed most influential on percent rejection for each of the test membranes are indicated in Table 12. Parameters included in the models are indicated in the table. As before, blank spaces indicate the parameter was not used in construction of a particular model.

As with the specific water flux models, time was included by constraint. With the exception of TW-30, the sensitivity index indicates it was universally negative, and as with the specific water flux models this is not surprising, as the membranes generally exhibited a decline in rejection with exposure to the source waters for increasing periods of time.

As with the specific water flux models, rejection was described using only 4 – 7 input parameters. As with the water flux models, there was no absolute agreement between the membrane models with respect to the specific parameters deemed influential by the ANNs. However, as before, certain general observations may be made with regards to the types of parameters that the models indicated were predictors of solute rejection.

Microbial load in the source water was identified as negatively influential in the case of the ESPA-1 model. This is not surprising, as the ESPA-1 specific water flux model was also strongly influenced by the presence of bacteria in the source water. However, the microbial loading parameters were either not influential (MT-2514) or were positively influential (TW-30) with the other polyamide membrane models. In the case of cellulose acetate, a positive influence was noted. Both cases in which microbial influences were positive involved viable bacteria in the source water rather than total bacteria. It would appear that the relationship between bacteria in the source water and rejection as described by the models is not a direct interaction, as one would expect that to be negative. As viable bacteria are involved in both the case of TW-30 and MC-2514, perhaps microbial metabolic reduction of a physicochemical parameter that negatively influenced rejection, such as phosphate-phosphorus or nitrate-nitrogen (see below), may explain the relationship.

Divalent cations were included in all of the models describing membrane rejection, both polyamide (MT-2514, ESPA-1 and TW-30) and cellulose acetate (MC-2514). The direction of influence was universally positive. In the case of MT-2514, the rejection model identified the Mg concentration in the source water as the most positively influential parameter. Whether this effect represents a direct influence on the membrane chemistry or an indirect one is unknown. Certainly these chemical species can associate with the surface of the membrane, possibly competing with foulants for negatively charged groups on the membrane surfaces.

Monovalent anions were included in the rejection models, and in general were positively associated with rejection as they were with specific water flux. The cellulose acetate rejection model showed a very strong positive association with nitrite-nitrogen (it was the principal driver in that model), but bromine ion exhibited a negative influence. Chloride was positively associated with rejection with the MT-2514 model.

Divalent and trivalent anions were also included in the rejection models as they were in the specific water flux models. Phosphate-phosphorus was negatively influential in the TW-30 rejection model as it was in the specific water flux model. It was also negatively influential in the cellulose acetate membrane rejection model (MC-2514). Nitrate-nitrogen was found to be positively influential in this model, however.

It is notable that none of the rejection models included the general determinants of ionic strength (EC or TDS), pH or TOC (unfiltered, which might represent both microbial, nanoparticulate and dissolved organic species) any of which might be expected to be influential. As with the specific water flux models, it would appear that the variations observed between the source waters at the test sites were not enough to male these inputs significant drivers for rejection kinetics compared to other water chemistry parameters

In conclusion, the ANN rejection models more often exhibited an influence of water chemistry parameters than biological parameters, and principally by the concentrations of specific anions and cations. As with the specific water flux models, it would appear that differences in the surface chemistry (in the case of the polyamide membranes) or differences in the membrane chemistry (in the case of polyamide vs. cellulose acetate) strongly impacted which source water parameters most influenced rejection kinetics.

3.10.2.2 "Universal" Polyamide Model

Although each membrane apparently behaved in a manner specific for it's unique physiochemical makeup with respect to specific water flux and rejection, an attempt was made to identify interactions between the polyamide membranes and source water physicochemical and biological parameters based on common physicochemical properties of the membranes, and to identify, if possible, unique membrane properties that influenced the behavior of each membrane in the various source waters. The database for this "universal" polyamide model was constructed by combining the databases for all three polyamide membranes (MT-2514, ESPA-1 and TW-30), and adding a set of input parameters containing membrane physicochemical parameters measured by OCWD (Table 10).

3.10.2.1.2.2 Overall Model Fitness

Results of attempts to construct a "universal" polyamide ANN models describing changes in the specific water flux (gfd/psi) as a function of time and source water parameters are shown in Figure 53. The fitness of this model is significantly less that that of the individual polyamide models, as evidenced by the lower R-value (0.82 as opposed to >0.9). However, predictive ability (represented by the similarity between the R-values of the training and test sets) is still good. This ANN model, then, should represent the patterns of behavior common to all of the polyamide membranes, and thus should react to the more underlying principals affecting polyamide water flux as opposed to issues related to the specific properties of any one of the polyamide test membranes.

The ability of the "universal" polyamide specific water flux model to describe membrane behavior at each of the test sites is shown in Figure 54, Figure 55 and Figure 56. In this case, ability to predict the precise kinetics of water flux changes observed by the individual membranes at each site is noticeably less accurate than were the individual ANN models for specific water flux, but nonetheless, for the most part the fundamental relationships have been preserved. The greatest deviations occurred with the most rapid fouling source waters with regards to membrane failure (OCWD conventional treated wastewater and SCWD conventionally treated wastewater).

The properties of the "universal" polyamide model used to describe rejection are shown in Figure 57. As with the specific water flux model, the overall predictive ability of this model is less than that of the individual polyamide models describing rejection (overall R-value of 0.79 as opposed to R-values >0.9). In this case, two outlying points skewed the results, such that were they excluded from the analysis, the correlation coefficient would probably have been much higher. In general, there was a much better agreement between the actual rejection and the predicted values generated by the model. In general, the "universal" polyamide rejection model agreed well with the field observations for all three of the polyamide membranes at the majority of the sites. The exception was with ESPA-1 at the SCWD site, also more poorly predicted by the "universal" polyamide specific water flux model.

3.10.2.2.2.1 "Universal" Polyamide Models for Specific Water Flux and Rejection: Influential Source Water Parameters

Table 13 shows the specific source water physiochemical parameters that were selected by both the "universal" polyamdie specific water flux model and the "universal" polyamide rejection model. A total of six input parameters were required to construct both models. In this case the membrane parameters were included in the list of potential inputs, but in neither case were the membrane parameters determined to be influential in either of the ANN models. This does not mean that differences in membrane properties are not involved in modulating either specific water flux or rejection, but it does suggest that the particular membrane properties that were measured, which include surface roughness, hydrophobicity (contact angle), degree of internal crosslinking (the COO/Amide and OH/Amide ratios), the relative thickness of the polyamide layer, and the membrane surface charge (zeta potential) and ease of deprotonation (Zeta potential slope from pH 5 to pH 7) were not the particular membrane properties giving rise to the specific membrane behaviors noted in the other models. In this case, water physicochemical and biological parameters were greater drivers in determining model behavior.

In the case of both "universal" models, time once again appeared to be negatively related to both specific water flux and to rejection. This is as expected, as membrane performance generally deteriorated with respect to time during exposure to the source waters.

In this case, the specific water model now showed a negative response to EC (which is a general measure of total ionic species in solution); in fact, this was the most influential parameter in the model. This is not an unexpected result, as increasing the total ions in solution would result in a loss of driving force as a result of osmotic pressure in the feed water, and possibly a "tightening" of the membrane in response to increasing salinity (such an effect was demonstrated on polyamide membranes in this laboratory; and was predicted by monovalent ion inclusion in a trimesoyl chloride (TMP) – *meta*-

phenylenediamine (MPD) polyamide structure by molecular modeling) (Dr. Harry F. Ridgway, pers. com.).

Monovalent ions (K ion) exhibited a negative influence on specific water flux, as it did in both the MT-2514 and TW-30 membrane models. Potassium is a small ion with a high charge density, and also carried a larger entourage of water molecules in its sphere of hydration. The ion would certainly strongly associate with free carboxylate groups on the membrane surface or inside the permselective layer charges at the membrane surface, and may possibly interact with the polyamide to reduce water permeability.

Monovalent anions (chloride) exhibited a positive influence in this model. The mode of action of this ion is less clear; the effect may represent competition with membrane negative charges for potassium at the membrane surface, which would reduce its association with membrane carboxylate groups and (if the above hypothesis regarding potassium action is correct) should reduce the effects of potassium on the membrane.

Phosphate-phosphorus was also shown in the model to exhibit a positive influence on polyamide specific water flux. It could act in a fashion similar to chloride ion, competing for cations with the carboxylate groups on the membrane surface, or via an entirely different mechanism.

Finally, boron was observed to exhibit a fairly strong negative relationship with specific water flux. Boron is poorly rejected by polyamide membranes (50% - 70%, http://www.pwgazette.com/tfc.htm), and this would easily enter the polymer matrix. It possibly could facilitate water flux by opening the membrane structure, but it did so in general it might be expected to increase solute flux as well as water flux, in which case the rejection should suffer. As the rejection model does not indicate that boron exhibits a significant negative influence, either boron acts to improve water passage alone, or the action is by a different mechanism altogether.

The "universal" polyamide model for rejection also was influenced by phosphate-phosphorus, but in the opposite direction as was water flux. This might imply that the presence of phosphate-phosphorus increases membrane water flux and solute flux simultaneously, possibly by opening the membrane structure. The individual membrane models showed that this ion negatively affected the TW-30 rejection membrane model most; however, the though it also was negatively influential in the specific water flux model for that membrane, the effect was negative and not positive, as with the "universal" water flux model.

Total hardness also was negatively associated with rejection in the "universal" polyamide model. This could be related to the potential for forming chemical scale on the membrane surface during membrane operation. However, rejection was also positively associated with magnesium ion, which would not support that hypothesis. Magnesium would probably mainly associate with the negative charges at the membrane surface, as it is very well rejected by polyamide membranes, but it could also affect the internal structure of the membrane, possibly by bridging free carboxylate groups inside the polymer structure – a mechanism that should increase rigidity within the polymer structure and decrease the diffusion rate of solute molecules.

Finally, bacterial loading in the feed water (as total bacteria) exhibited the greatest negative influence on rejection in the "universal" polyamide model. This is certainly an expected result, as direct deposition of bacteria on the surface (and later growth of the adhering organisms) is known to be a principal cause of membrane failure. Although not the greatest factor in the individual membrane rejection models, (presumably because factors particular to the specific membrane chemistry had masked it), in a composite model expressing rejection of all three polyamide membranes, the level of bacteria in the feed water became a very prominent driver.

4.0 CONCLUSIONS AND BENEFITS

4.0.1 Conclusions

- Analysis of membranes shows a considerable difference in surface properties.

- When membranes were exposed to different feed waters they behaved differently with respect to accumulation of biological material and performance (percent rejection and specific water flux).
- Microbial communities developed on membranes exposed to same feed water were different from the feed water community structure and different from each others community structures. The community structures were unique. Each membrane was keying in on different elements of the feed water and developed its own population community.
- In general the degree of microbial fouling was related to the concentration of bacteria present in source waters.
- Generally protein and carbohydrate loads were related to bacterial load in source water.
- Data suggest high flux membranes such as ESPA-1 will be poor performers on high fouling feed waters such as conventionally treated wastewaters.
- Generally reduction of microbial particulates by MF resulted in improved membrane performance.
- Treatments that tended to reduce microbial loads in the source water (e.g., MF pretreatment) in general improved membrane performance.
- The water sources that lead to most rapid performance decline were characterized by high biologically loading source waters.
- It was possible to describe membrane performance in terms of source water physicochemical and biological parameters using Artificial Neural Network modeling approach.
- According to the models ionic composition of source water influenced membrane performance as much as biological loading.
- Models suggested that the effects that water physicochemical and biological properties exerted on membranes performance was membrane specific.
- For polyamide membranes it was possible to construct a model of general membrane performance. In this case models suggested that membrane performance was most strongly influenced by biological loading, and TDS most strongly affected water flux.

- These results may be generalizable beyond this study but further data would be required to validate the models (different water sources and more membranes).

It was possible to utilize the databases of source water properties and membrane performance gleaned from each of the participating agencies to successfully construct artificial neural networks with which the performance of the individual RO membranes (both polyamide and cellulose acetate) could be mimicked and investigated. These models indicated that although classical feed water parameters known to affect membrane performance (such as ionic strength and bacterial loading) were certainly factors, in many cases more subtle effects from the interplay of water chemistry parameters had significant influence on membrane performance. Moreover, differences in the individual membrane physicochemical properties led to differences in overall response to many of these feed water physicochemical parameters, such that the best predictions of membrane performance were obtained when each membrane was considered as an individual. Nonetheless, it was also possible in the case of the three polyamide membranes to consider broader behaviors by combining all of the polyamide membrane data into a model that smoothed away much of the individual differences in membrane response.

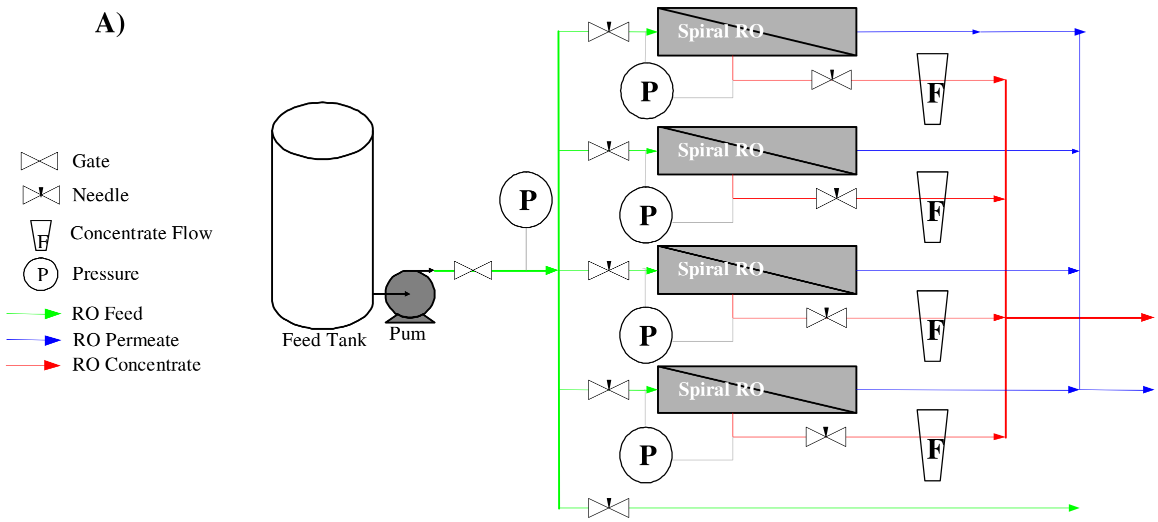
Although it is tempting to offer these models as a solution to predict membrane performance in general, it is prudent to note that they are based on a very limited field experience (six sites) and a rather small number of membranes (three polyamide and one CA membrane). Certainly within this realm of experience the models are valid; however, validity outside remains to be proven. Nonetheless, this study does suggest that performance of reverse osmosis membranes depends on a complex interplay of membrane properties and source water factors, and provides some insight as to the nature of that interplay. Furthermore, the study offers a method by which membrane performance may be analyzed and predicted with respect to easily quantifiable field parameters.

4.0.2 Benefits to California

It is increasingly more difficult to ensure reliable and adequate water supplies due to environmental constraints and rapid population growth. Southern California being a semi-arid region which is prone to prolong droughts must increase its conservation through water recycling, eliminating groundwater contamination, researching new technologies, and developing alternative water sources.

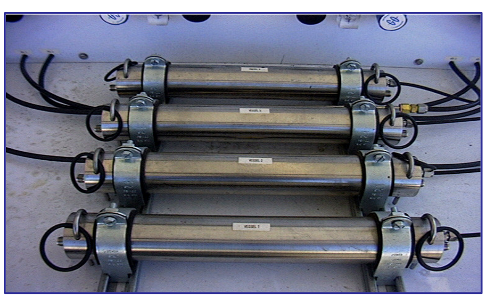
California relies on many means to enhance the operations and cost effectiveness of water reuse. Using membrane process would benefit the region of southern California. Educated and well informed selection of water treatment processes can translate into dollars saved. Techniques that help select the appropriate membranes for specific source waters will save time, money and energy.

A)



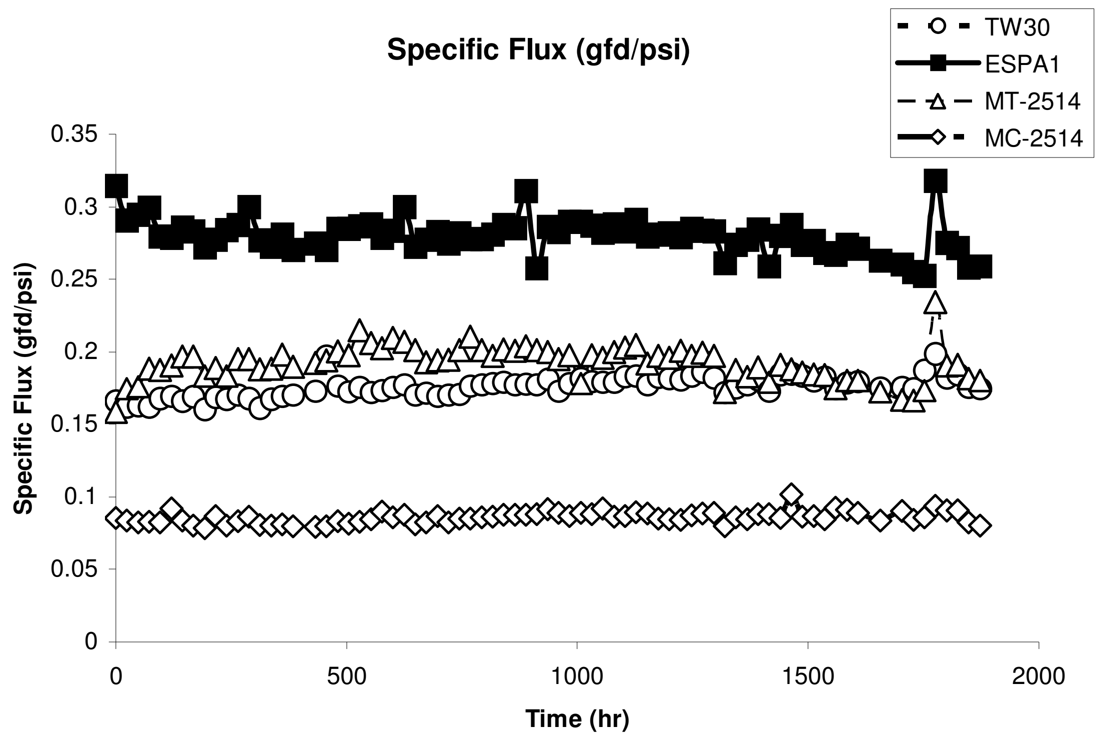
B)

Multi-Stage



Membrane

Figure 1. A) Portable bench-scale RO test unit. Schematic, B) portable bench-scale RO test unit in the field.



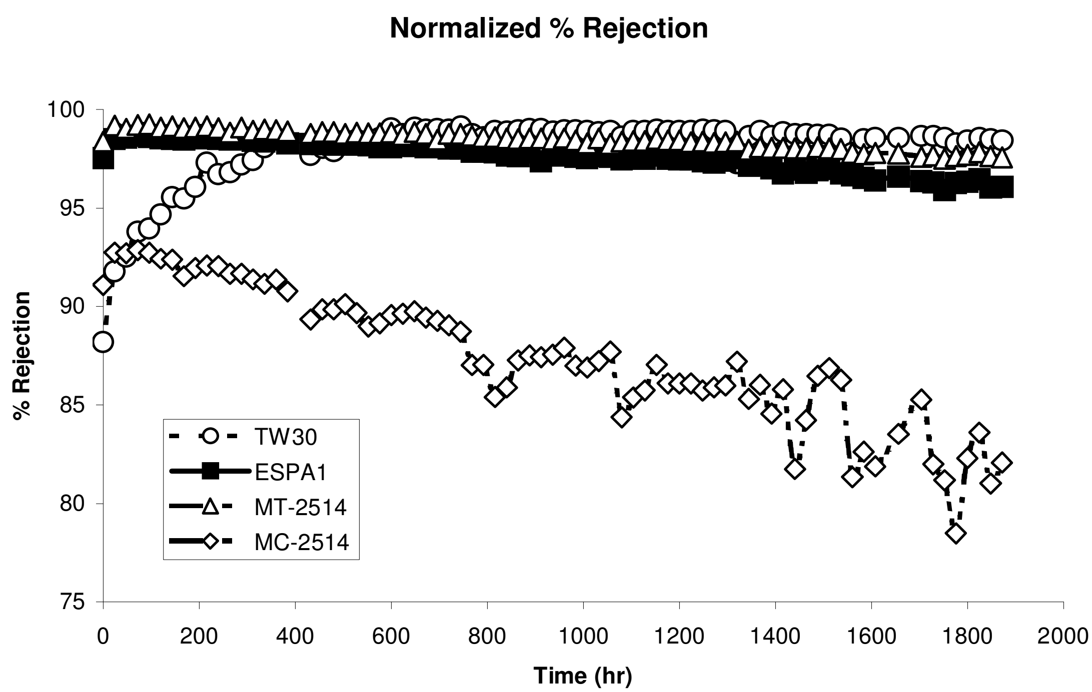


Figure 2. MWD RO Test Unit Performance Data.

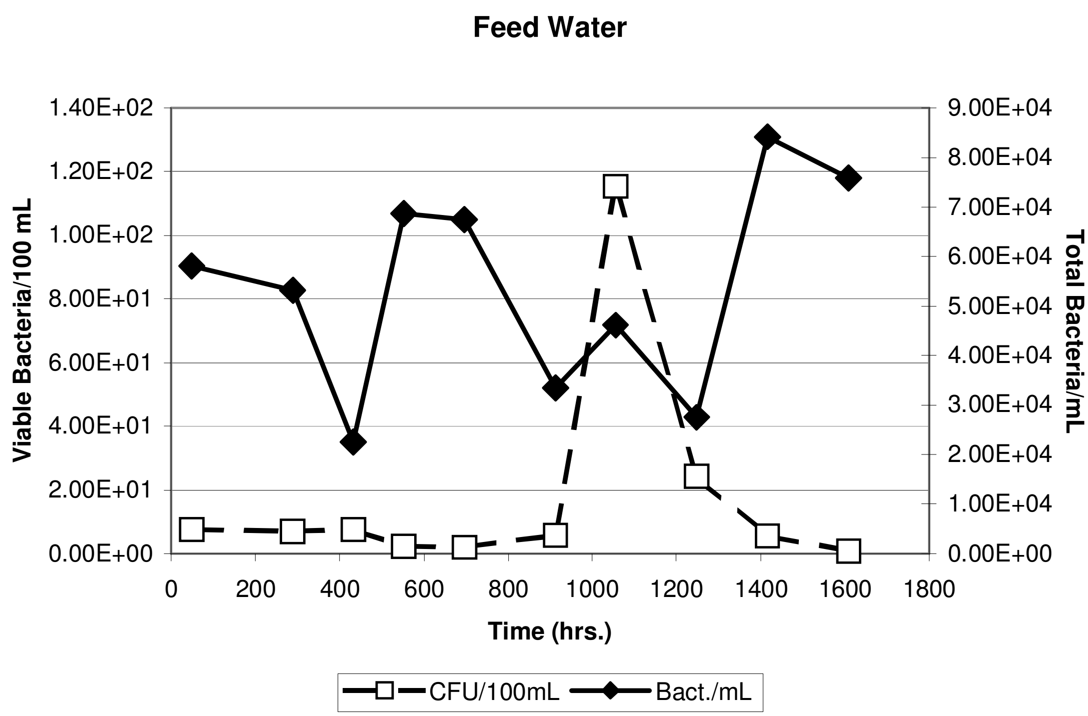
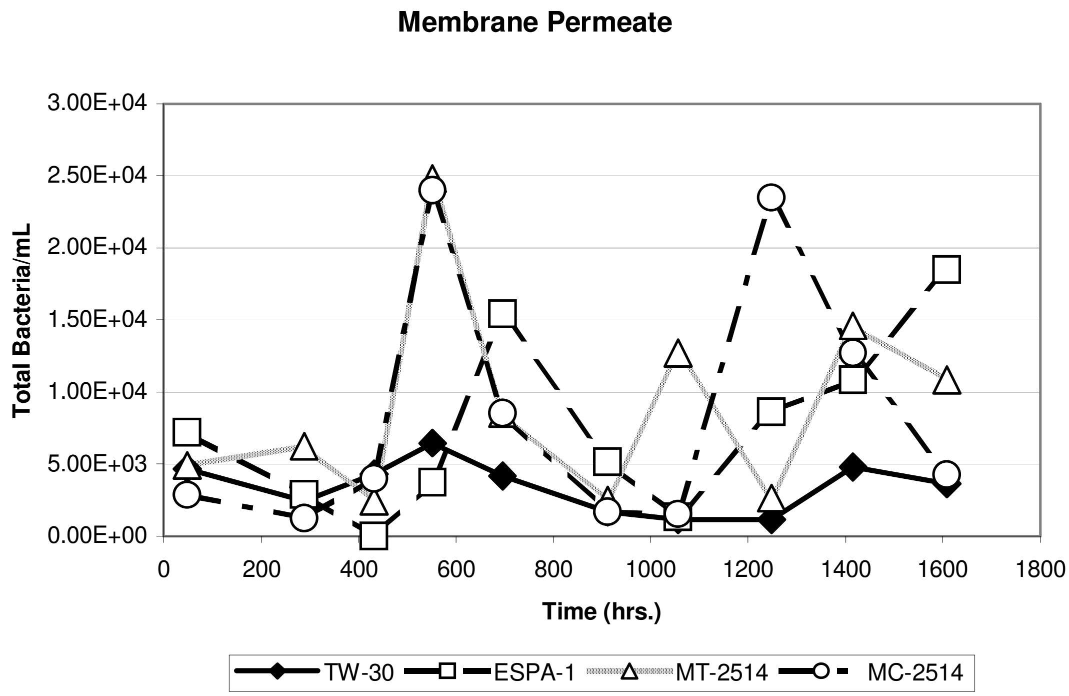


Figure 3. Total and viable bacterial load in MWD feed water.



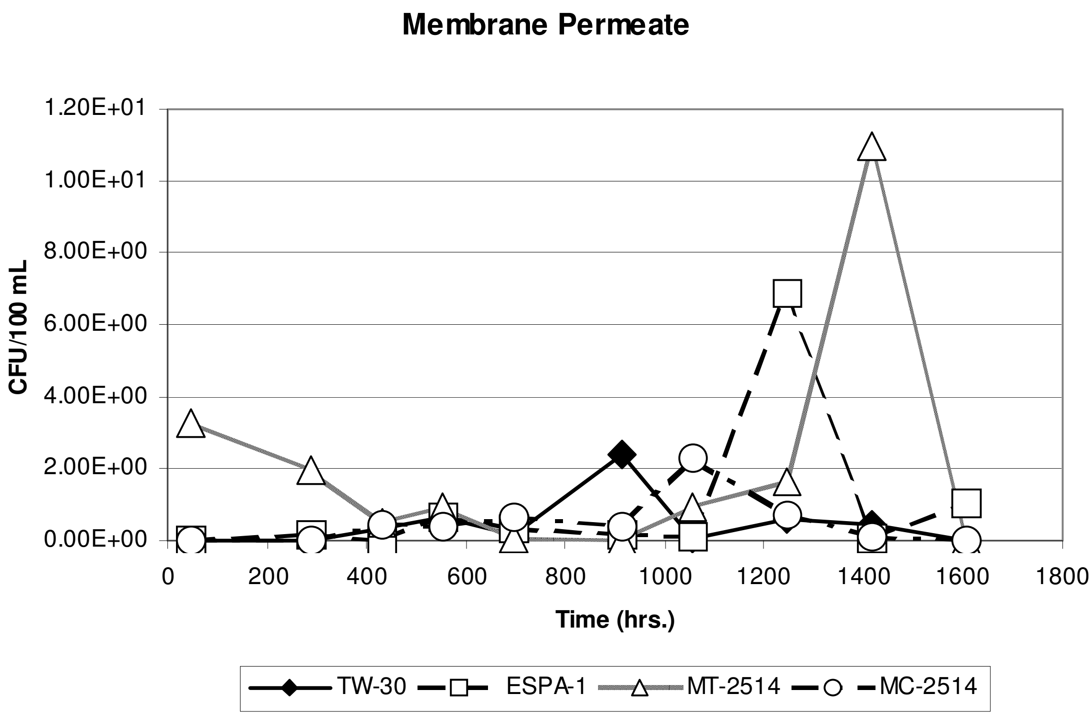
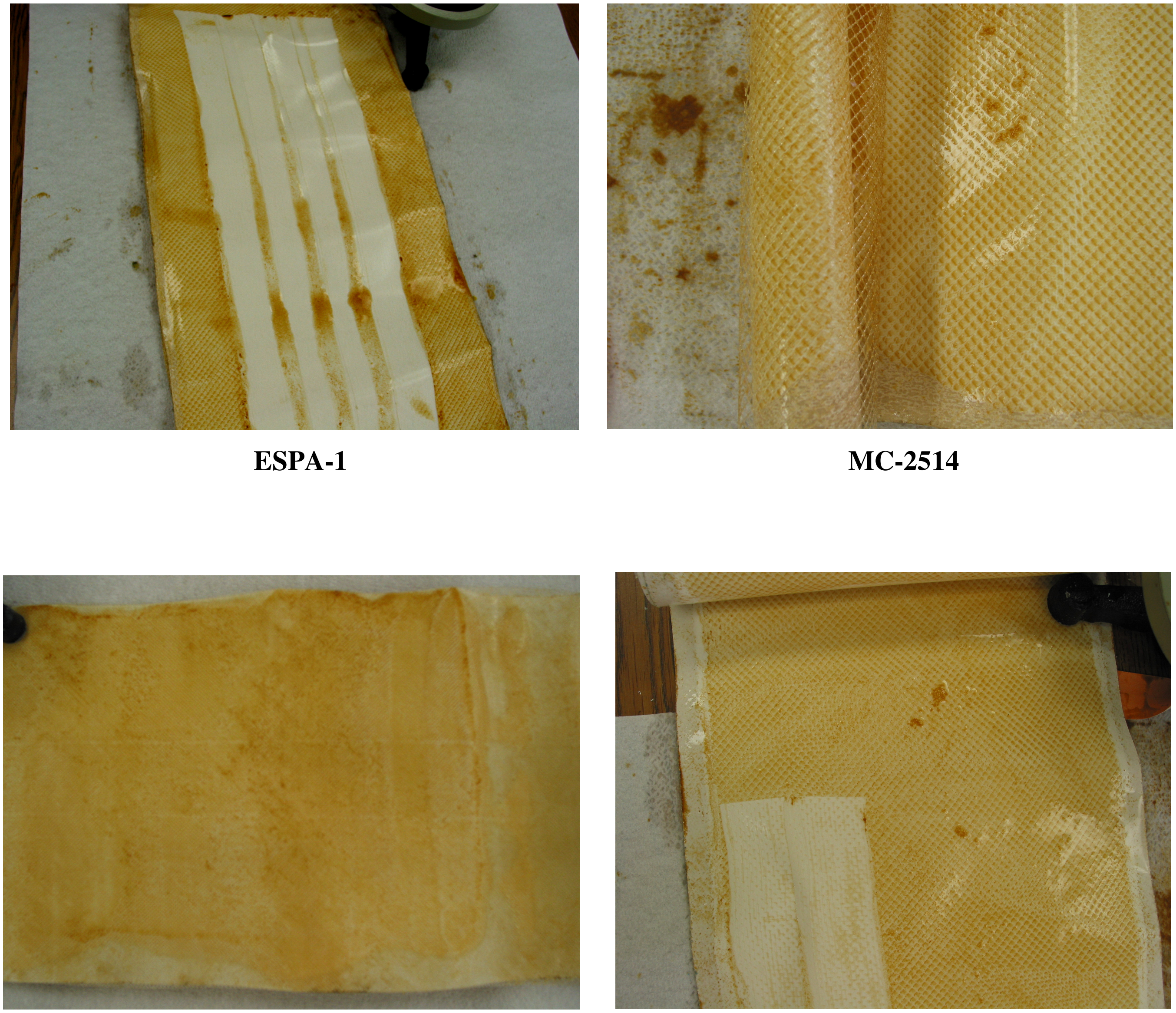


Figure 4. Total and viable bacteria in MWD RO test unit permeates. Bacteria were detected within 48 hours of operation.



ESPA-1 **MC-2514**

TW-30 **MT-2514**

Figure 5. Fouled RO membranes removed from MWD test unit after 1872 hours of operation.

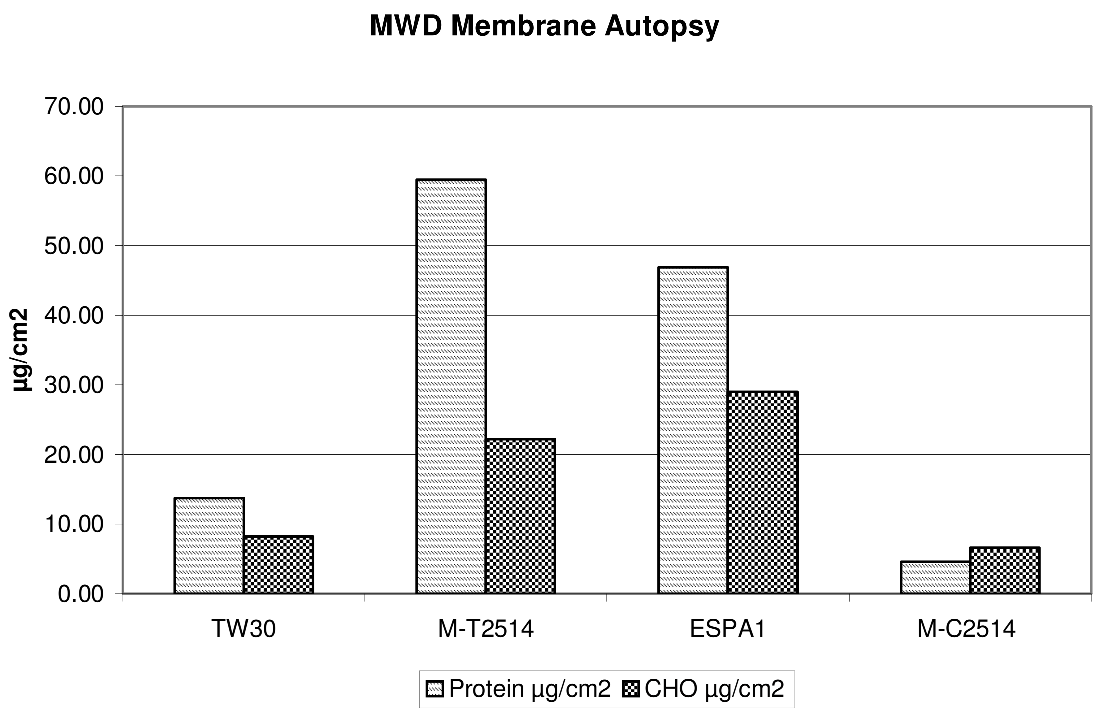


Figure 6. Fouled MWD membrane protein and carbohydrate loads.

(1) (2) (3) (4)

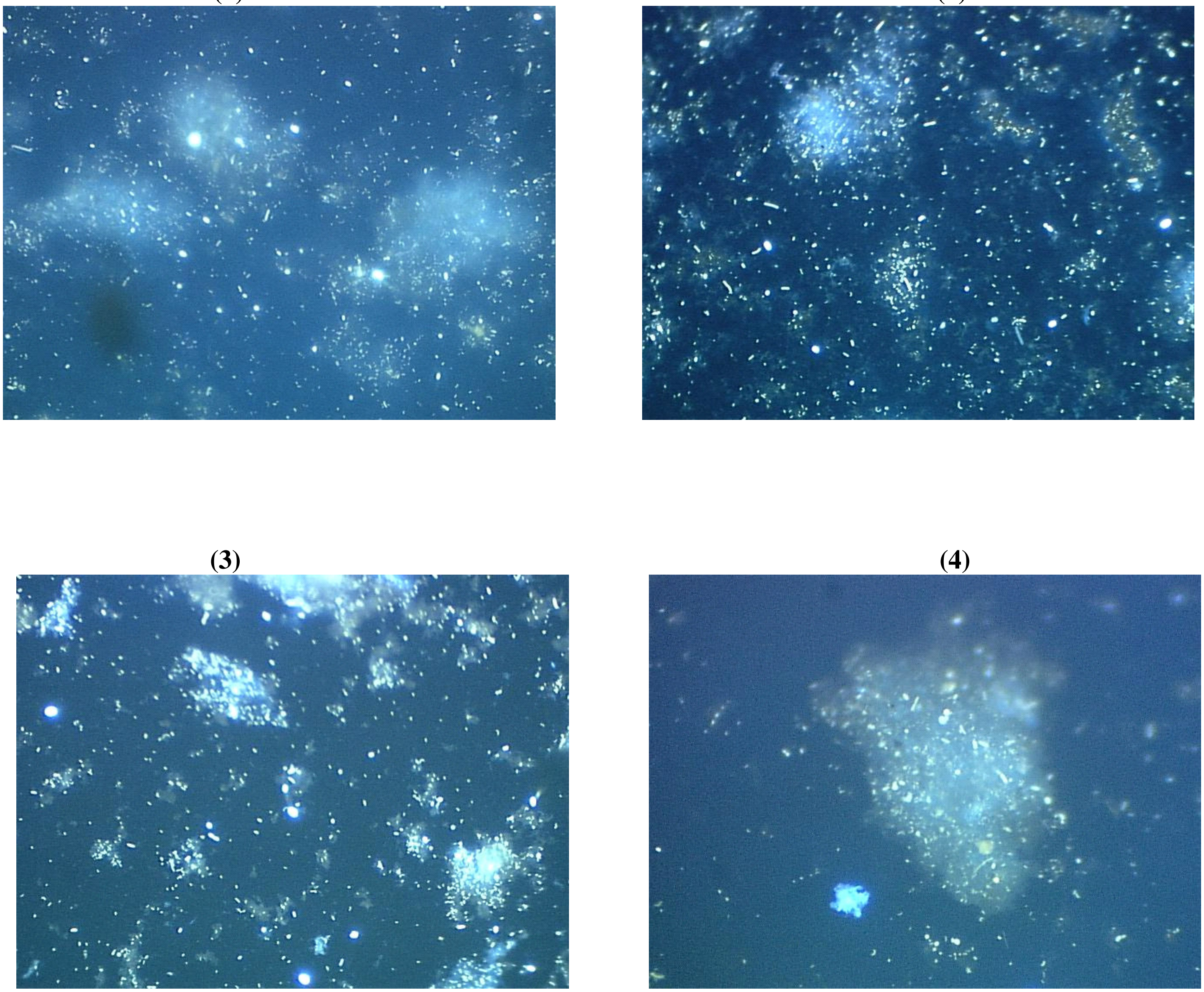
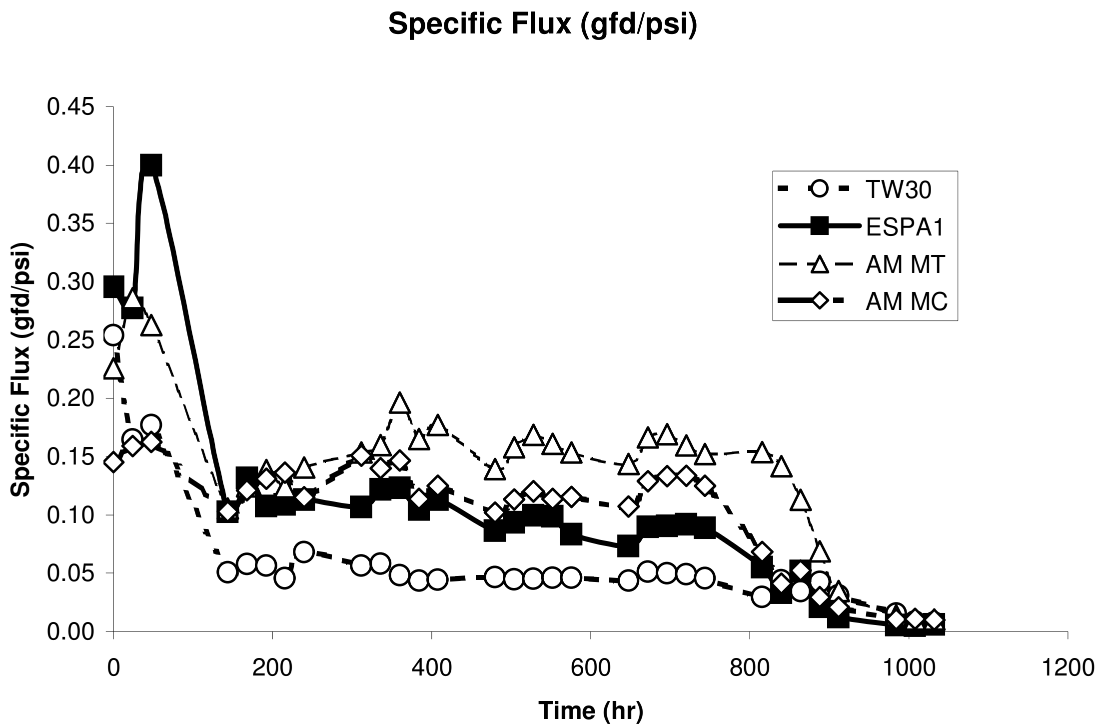


Figure 7. DAPI stained MWD membrane scrapings. Epifluorescent microscopy (Olympus IX 70, 100X objective). (1) ESPA-1 (2) MT-2514 (3) MC-2514 (4) TW-30.



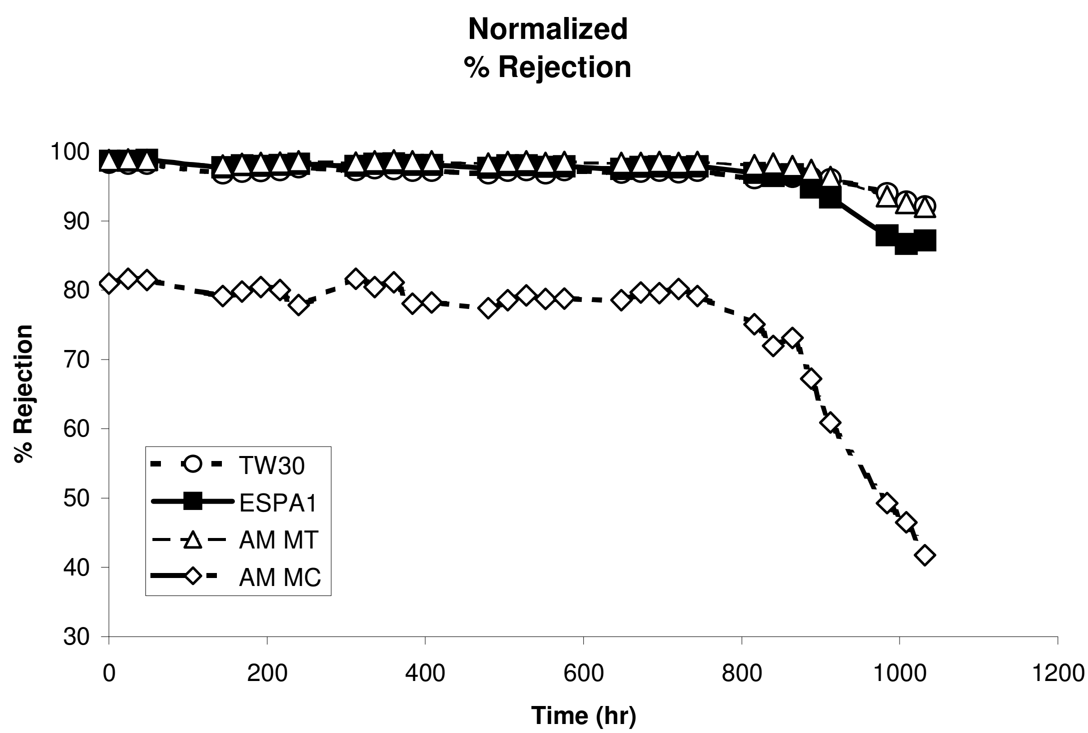
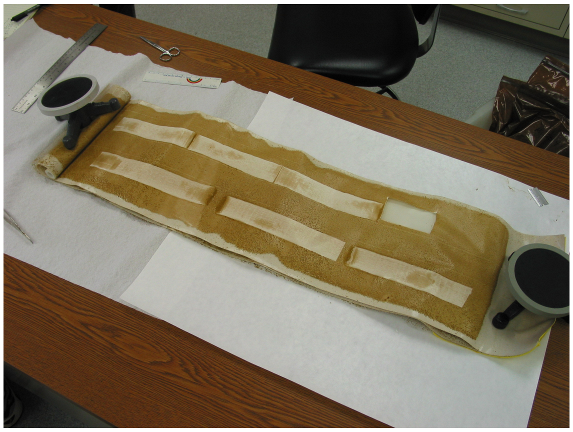
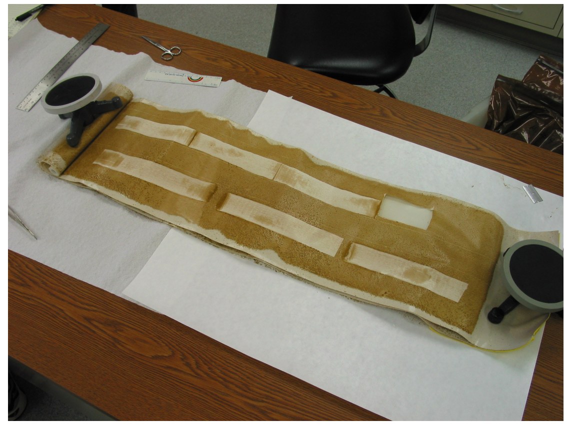


Figure 8. WB test unit performance data.

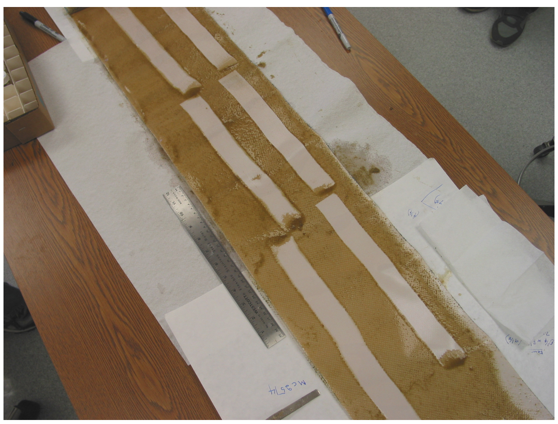
Figure 9. WB test unit feed water tank. 1032 hours of operation. Green color is the result of algae contamination.



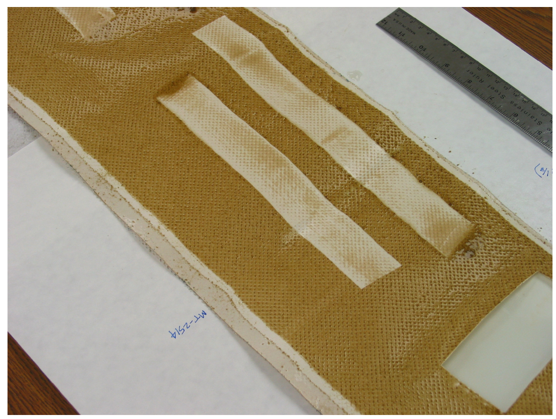
ESPA-1



TW-30



MC-2514



MT-2514

Figure 10. Fouled membranes removed from WB RO test unit after 1032 hours of operation.

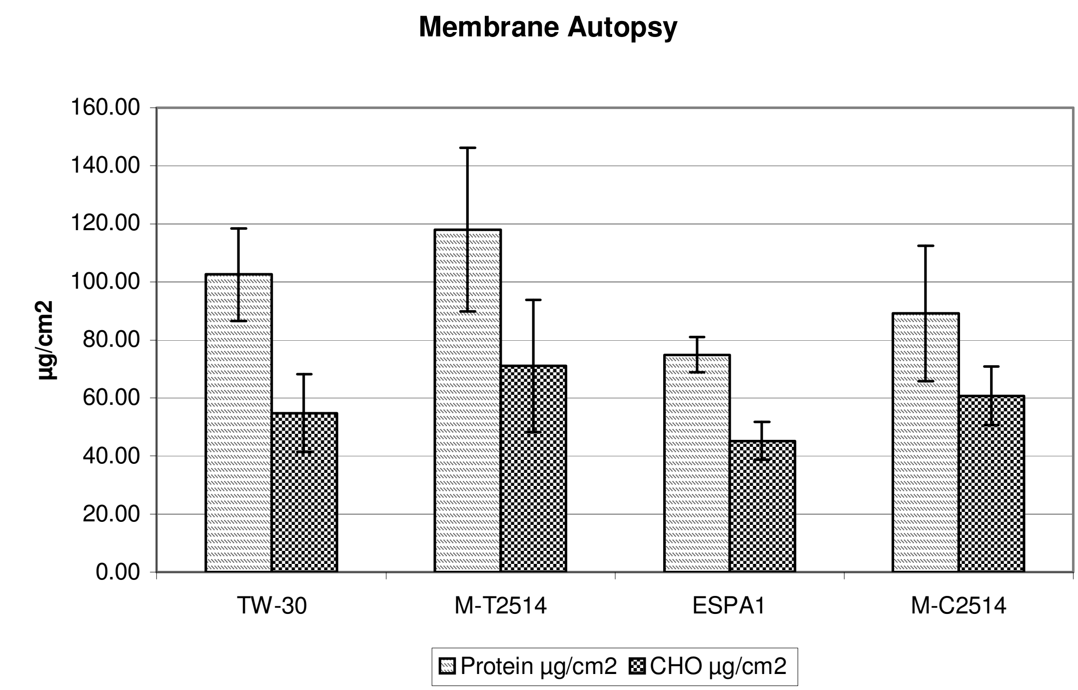


Figure 11. WB membrane protein and carbohydrate loads.

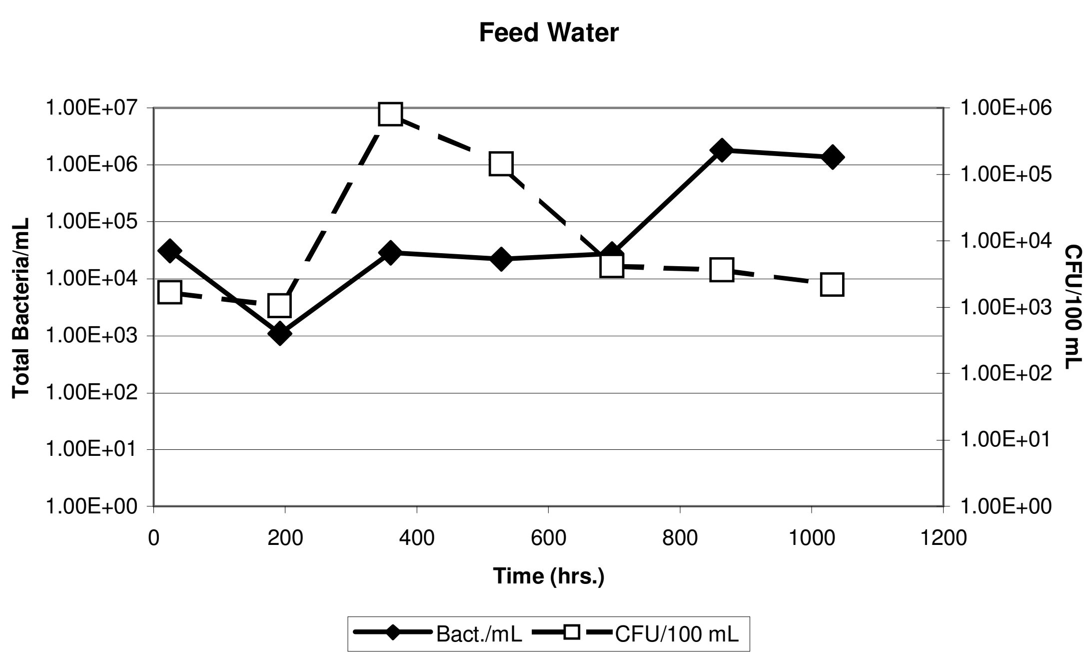
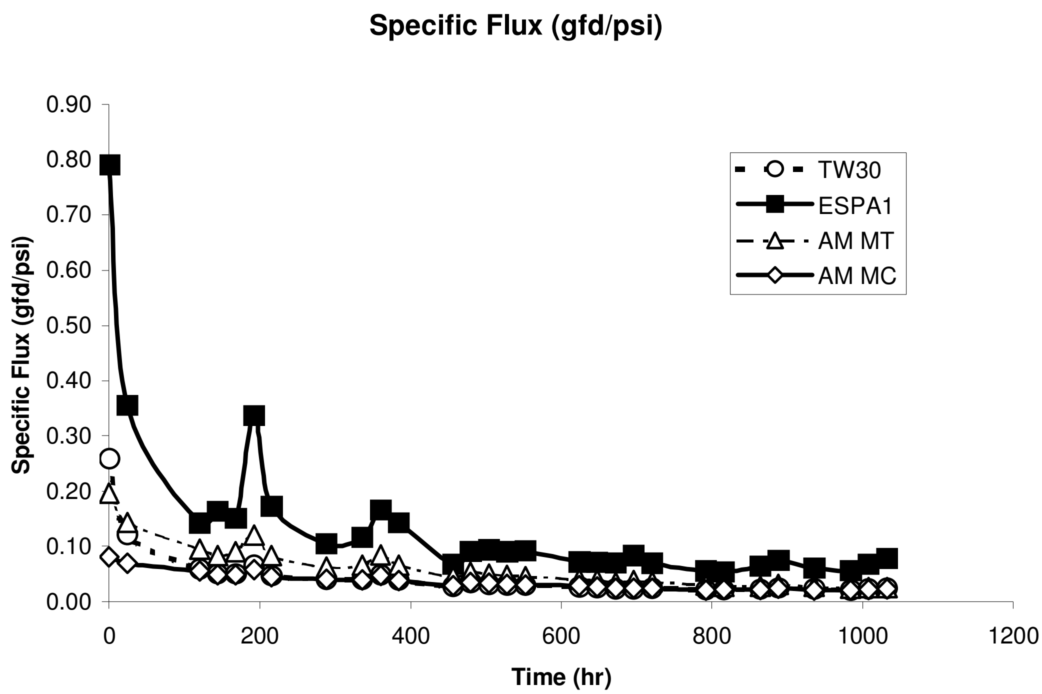


Figure 12. Total and viable bacterial loads in WB feed water.



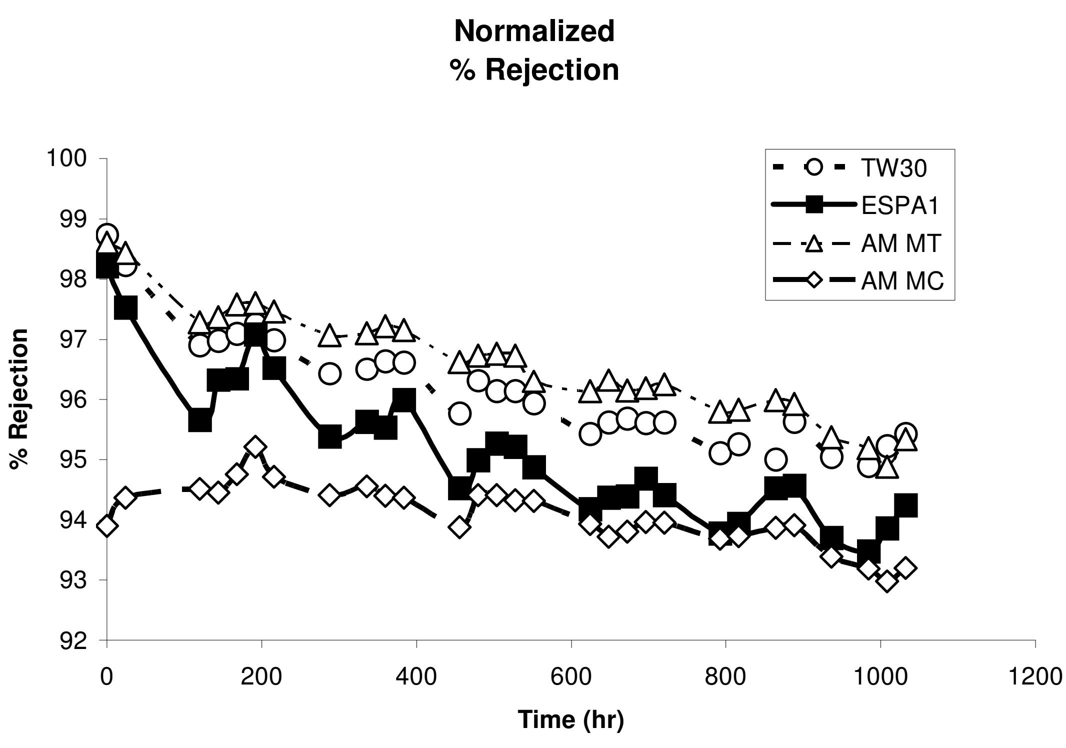


Figure 13. OCWD RO test unit (conventional treatment) performance data.

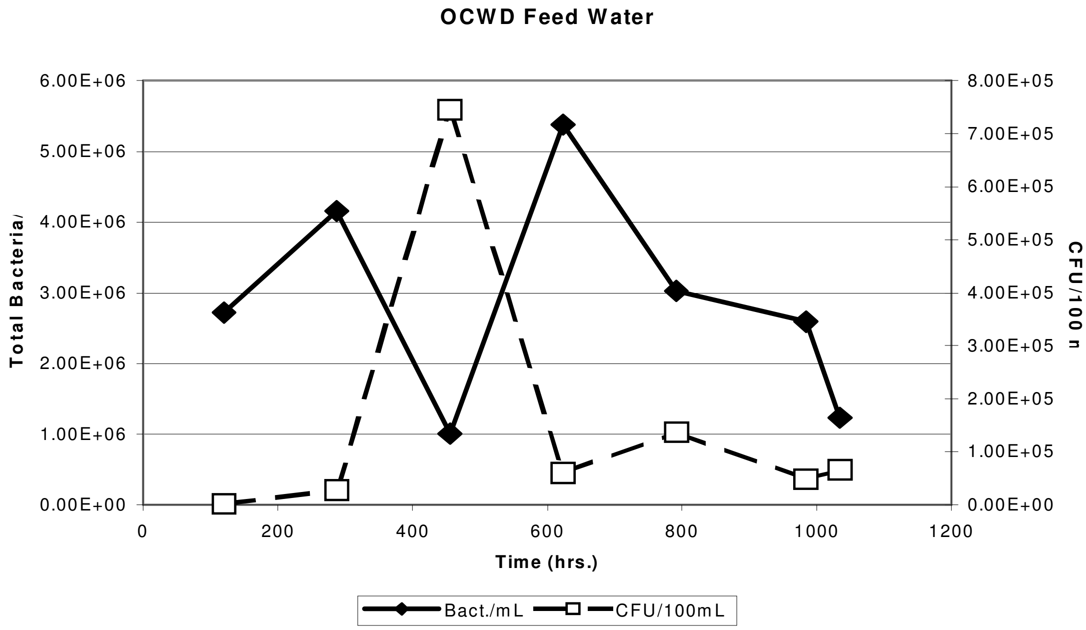


Figure 14. Total and viable bacterial loads into OCWD RO test unit.

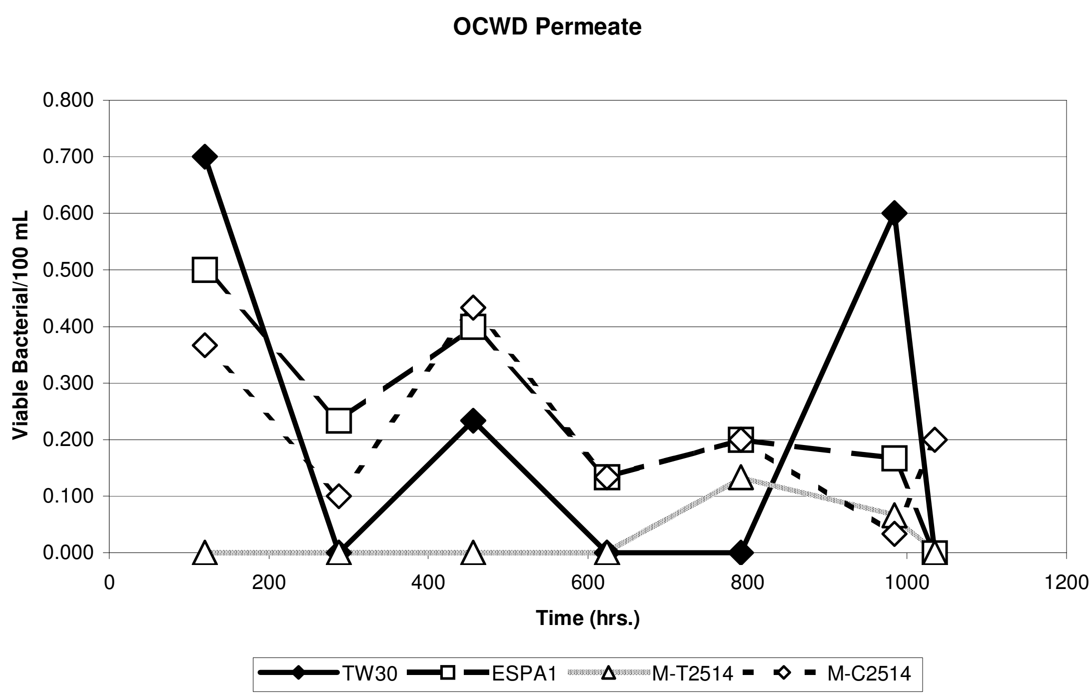


Figure 15. OCWD RO test unit viable bacteria in membrane permeate.

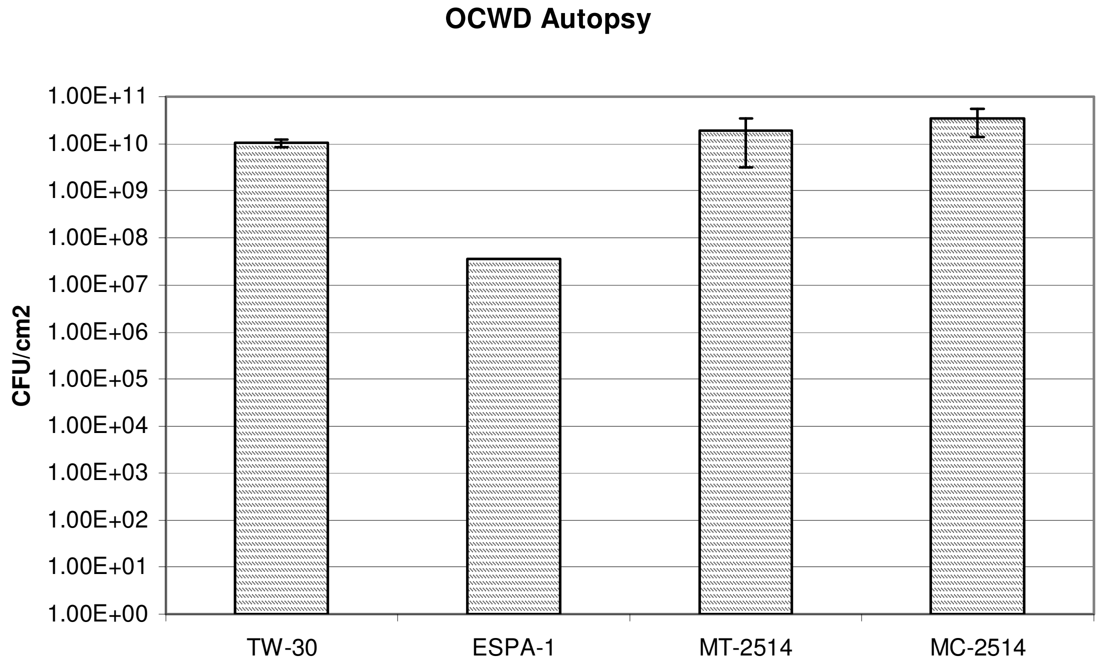


Figure 16. OCWD fouled membrane autopsy.

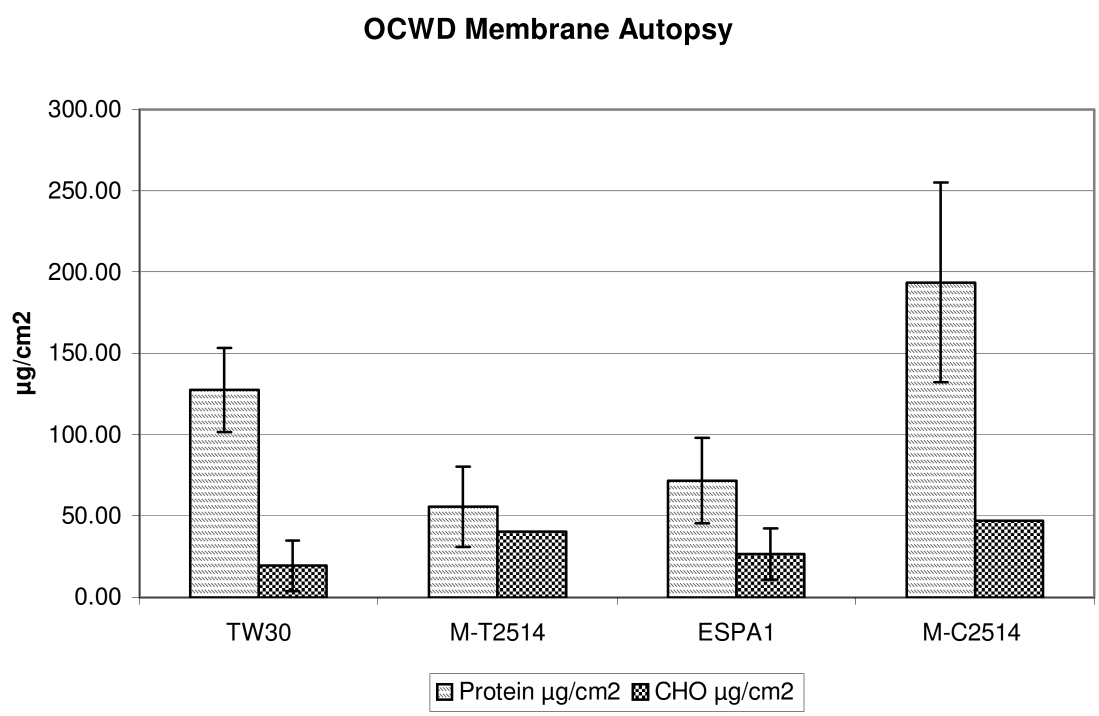


Figure 17. OCWD RO test unit fouled membrane scrapings, protein and carbohydrate.

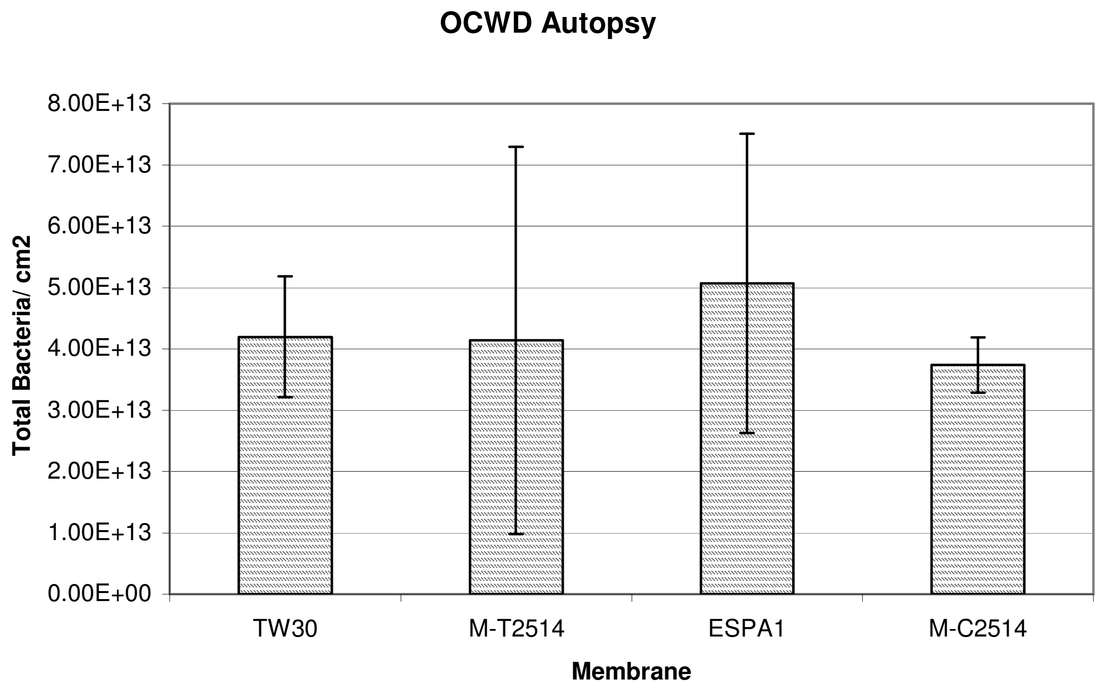
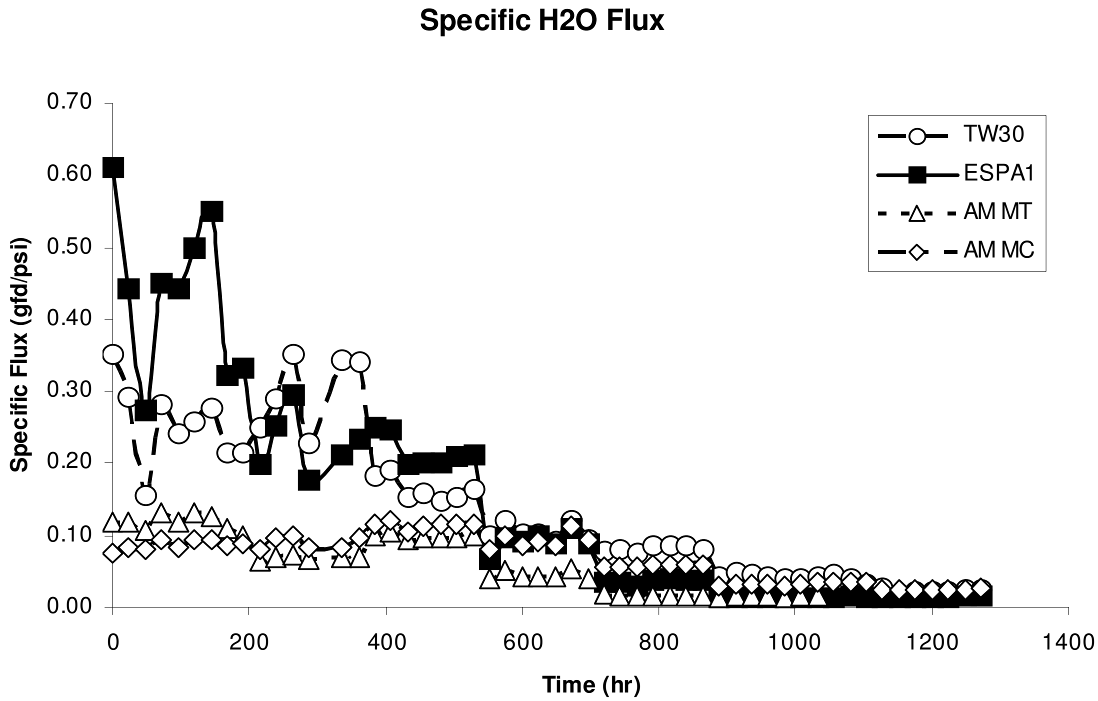


Figure 18 . OCWD fouled membrane autopsy, total bacteria. Samples contained bacteria and other particulates which made enumeration difficult resulting in large standard deviations.



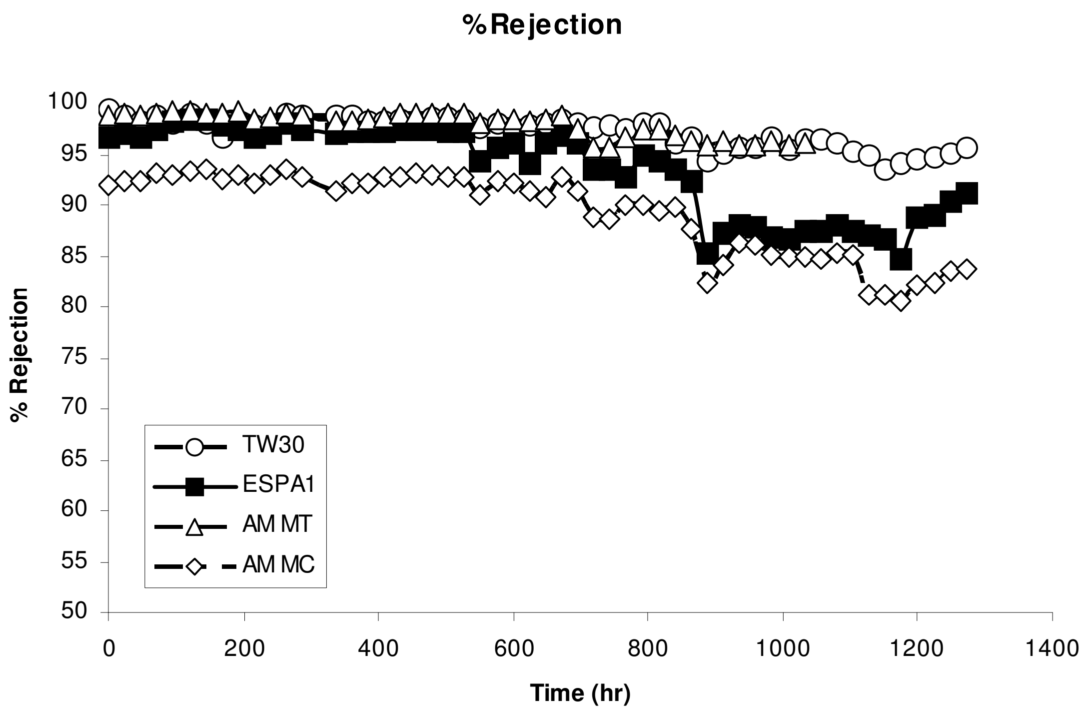


Figure 19. OCWD RO test unit fouled membrane scrapings, protein and carbohydrate.

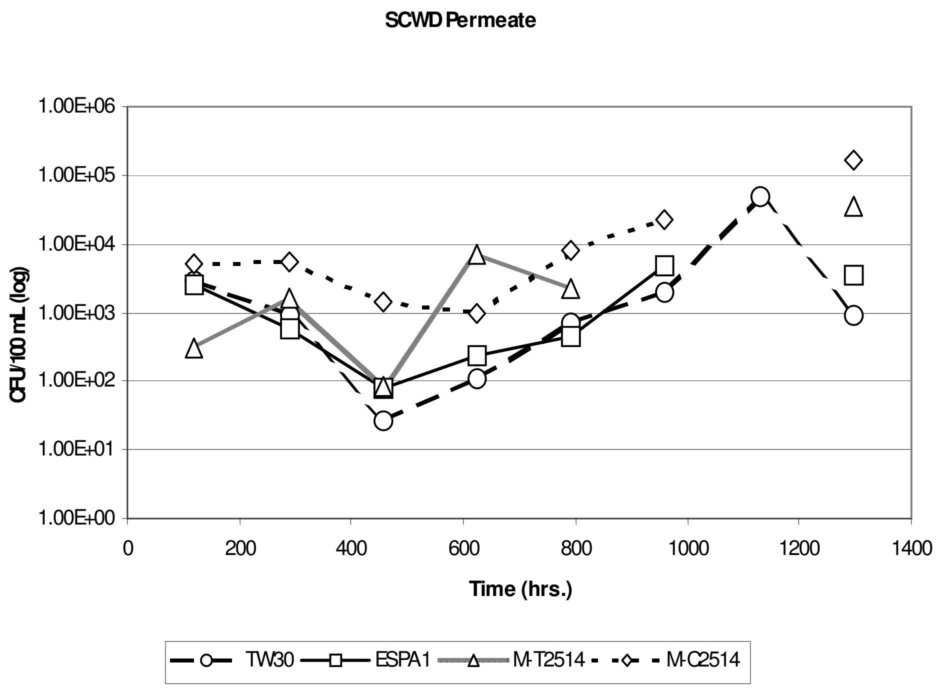


Figure 20. SCWD test unit. Total bacteria in membrane permeate.

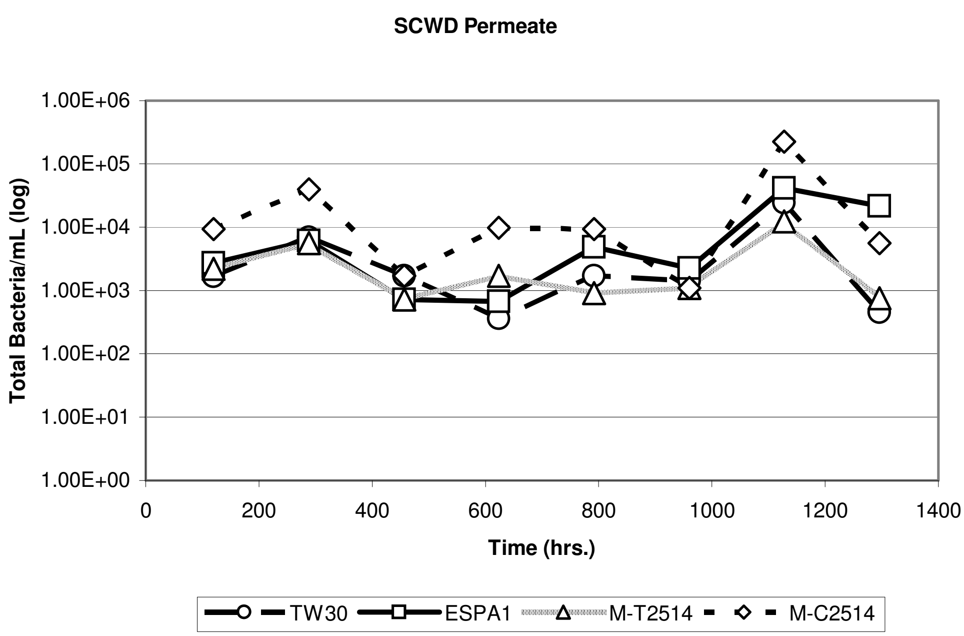


Figure 21. SCWD test unit. Viable bacteria in membrane permeate.

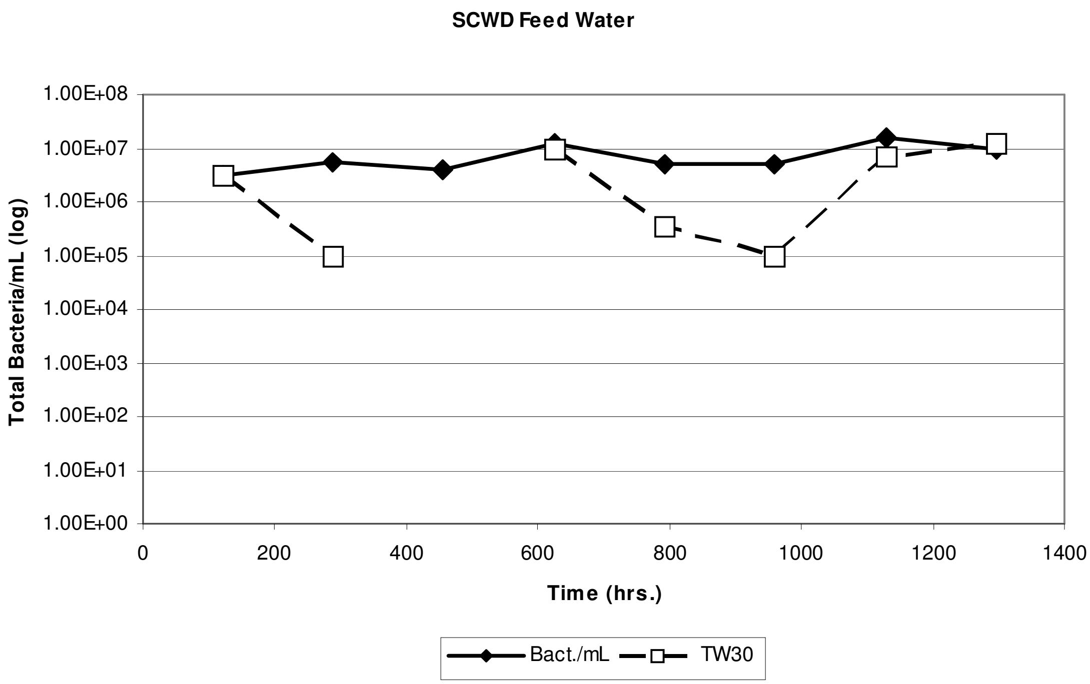
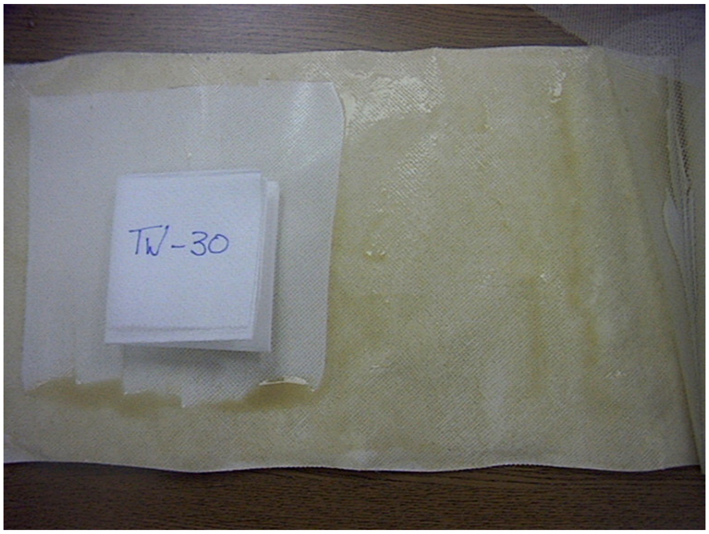
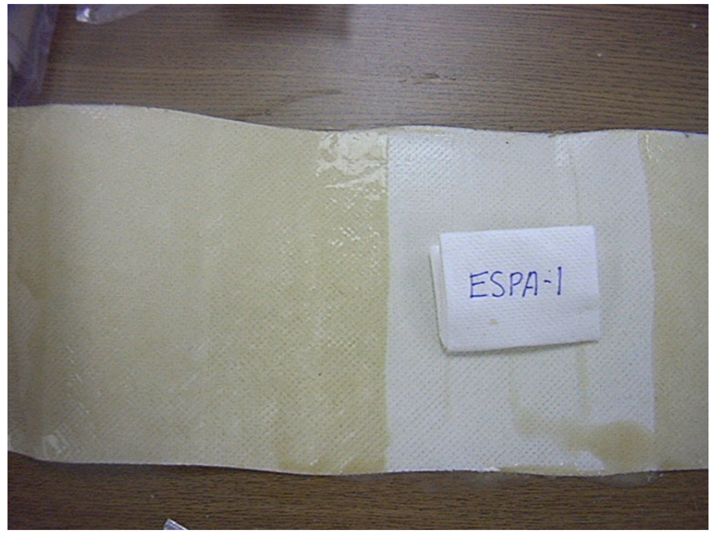


Figure 22. SCWD RO test unit total bacteria in feed water.



TW-30



ESPA-1

MT-2514

MC-2514

Figure 23. Fouled membranes from SCWD RO test unit.

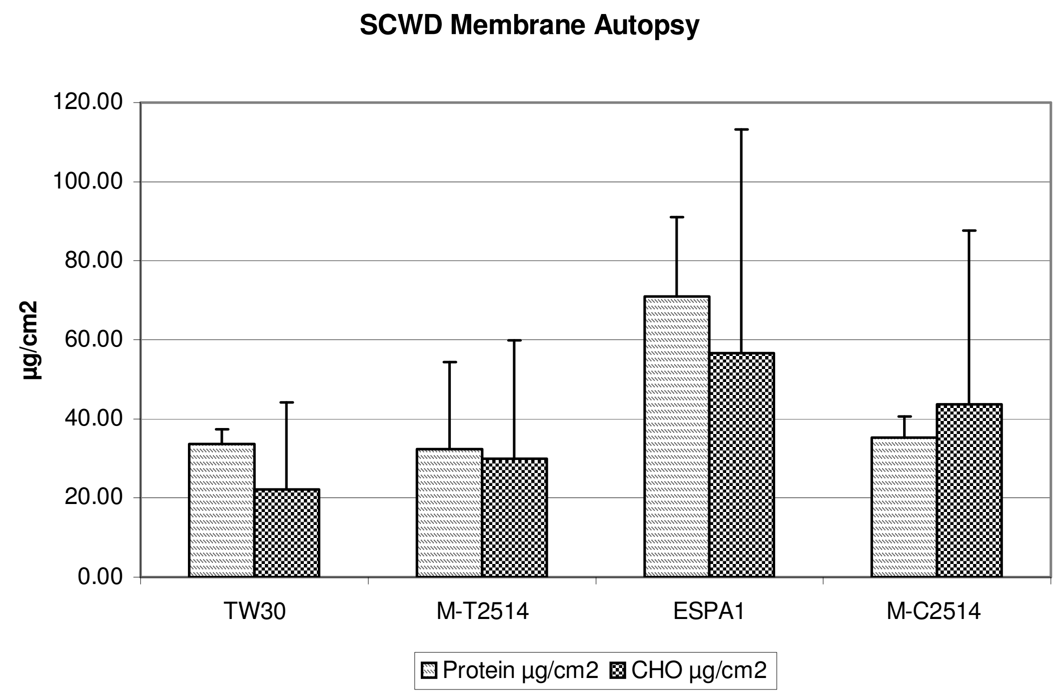


Figure 24. SCWD RO test unit fouled membrane scrapings.

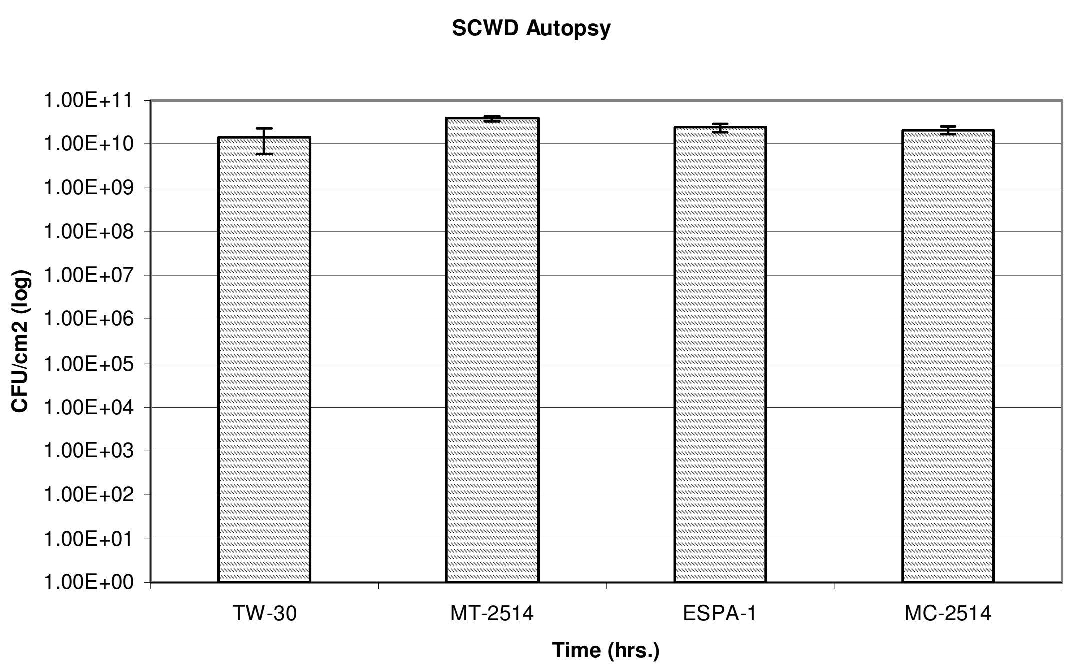
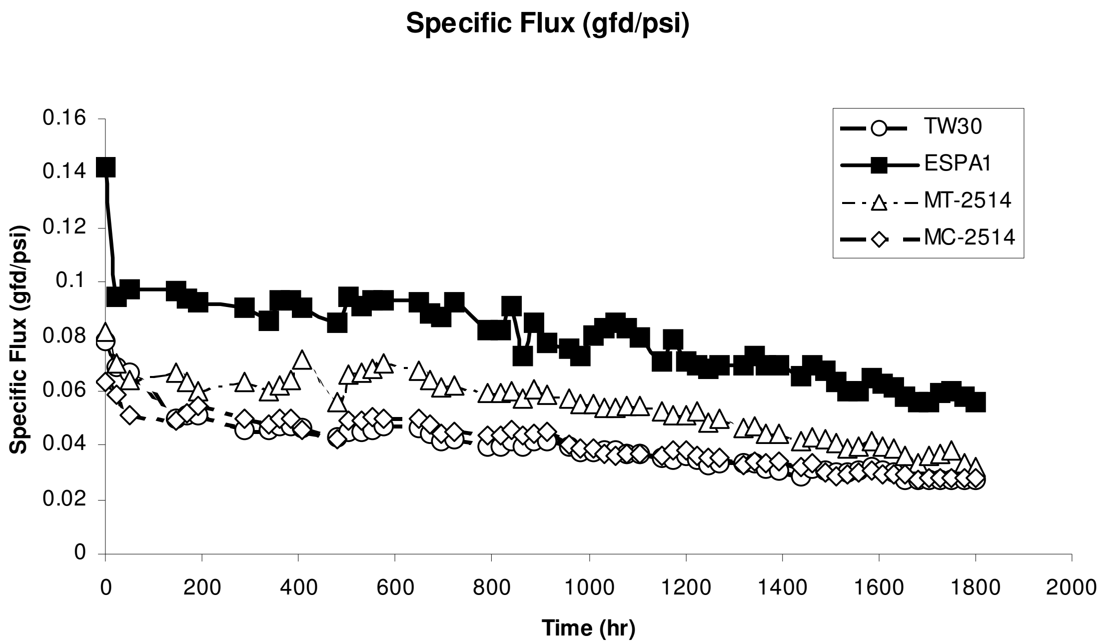


Figure 25. SCWD Membrane Autopsy. Viable bacteria in membrane scrapings. CFUs found on membrane surfaces were similar for all membranes.



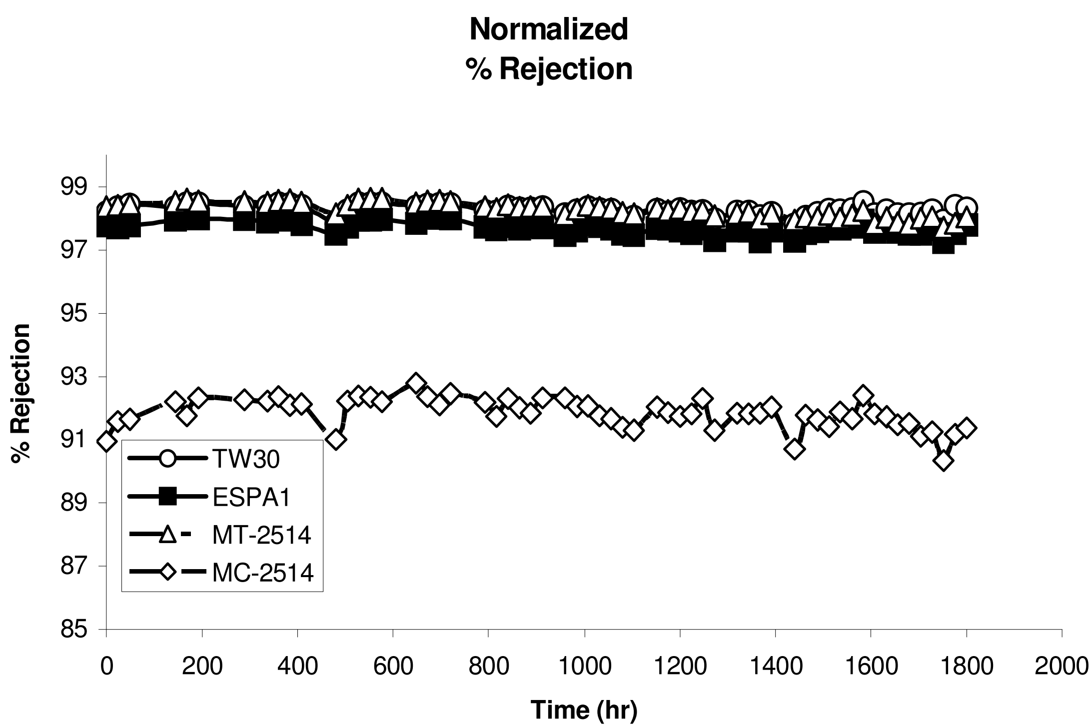
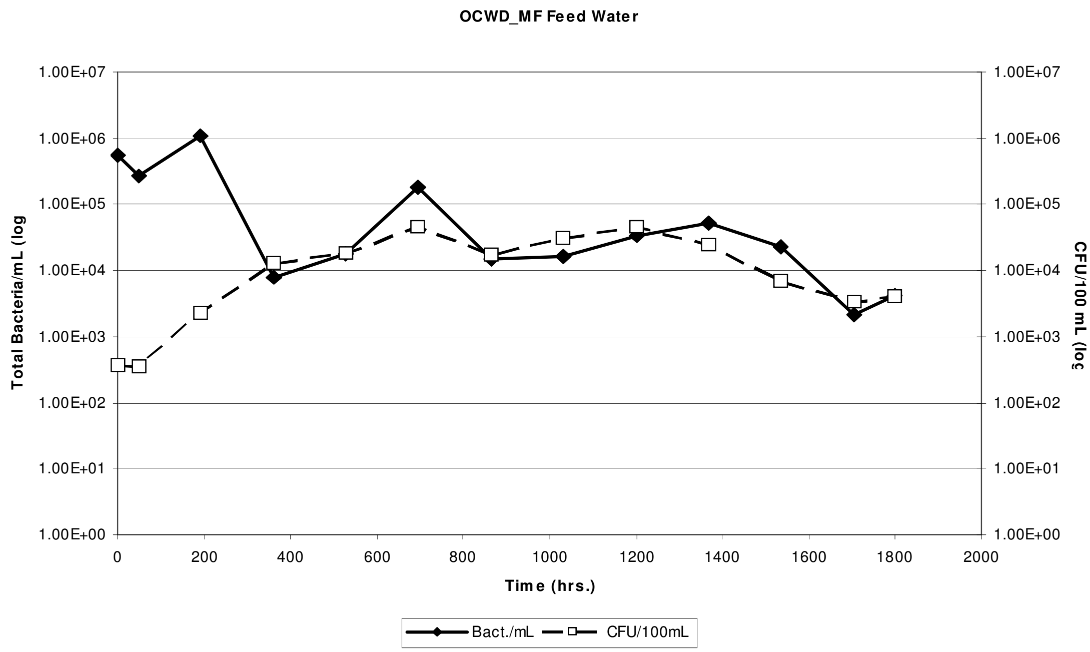


Figure 26. OCWD_MF Performance Data.



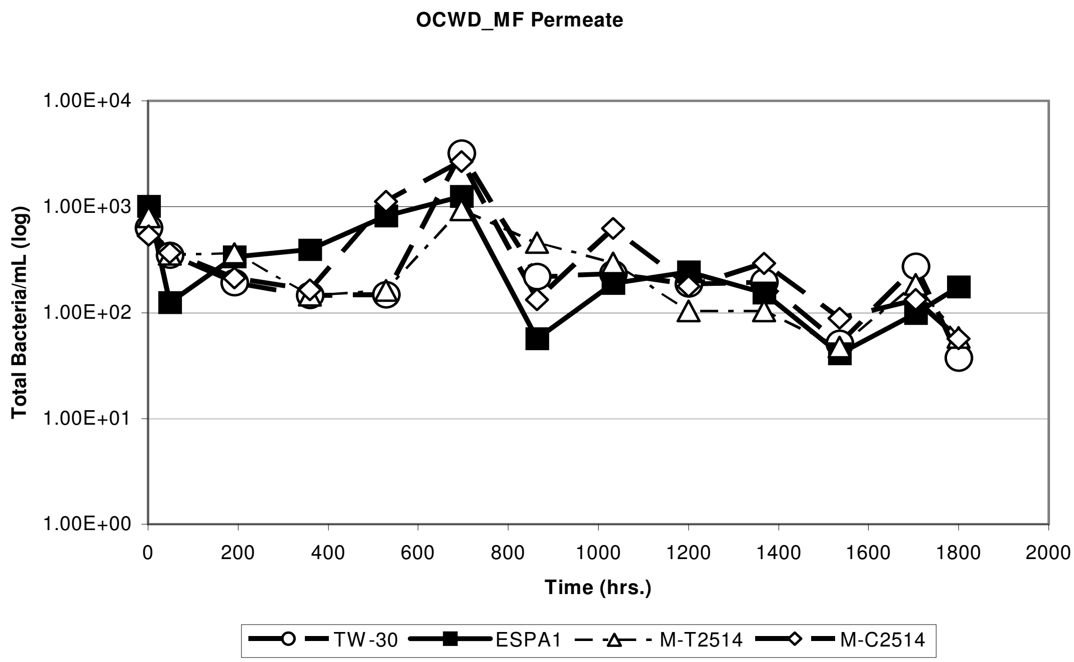


Figure 27. OCWD_MF feed water and permeate total and viable bacteria

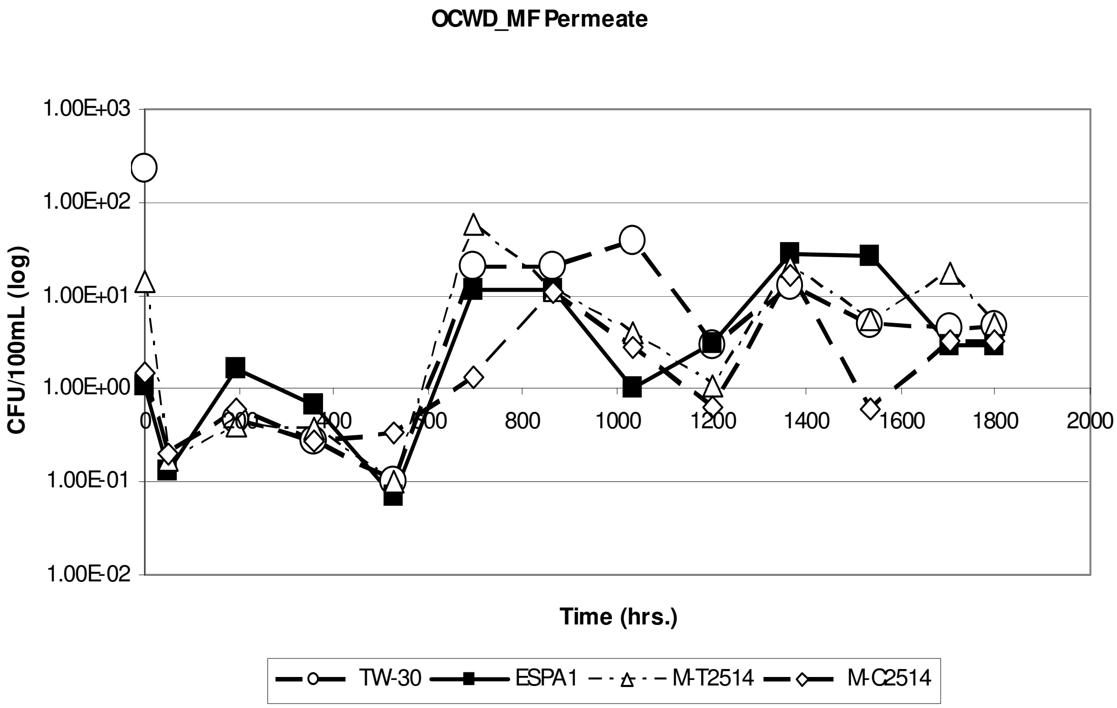
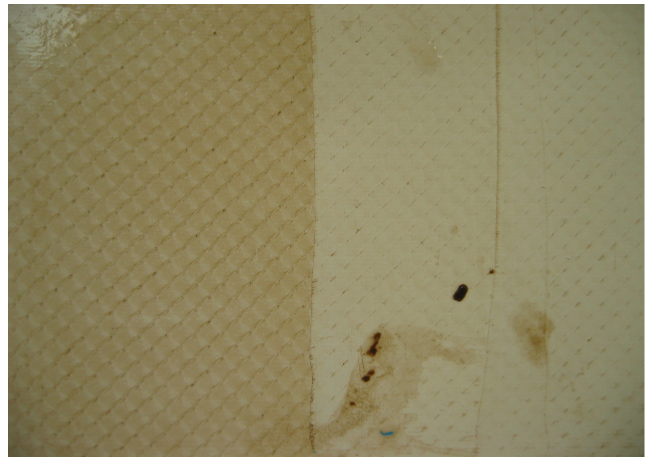


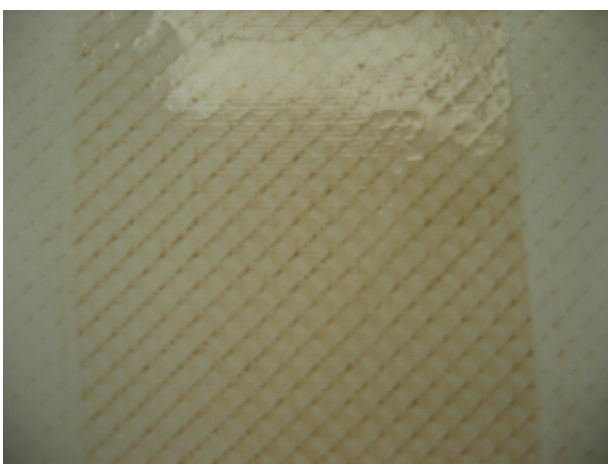
Figure 28. OCWD_MF Total Bacteria in Permeate.

Viable bacteria were detected at t=0 and continued to be detected throughout the experiment. Bacterial concentrations appeared to increase over time indicating growth on the permeate sides of the membrane elements.

ESPA-1



MC-2514



MT-2514

TW-30

Figure 29. Fouled Membrane from OCWD_MF Test Unit. Fouling layers were fairly thin and loose.

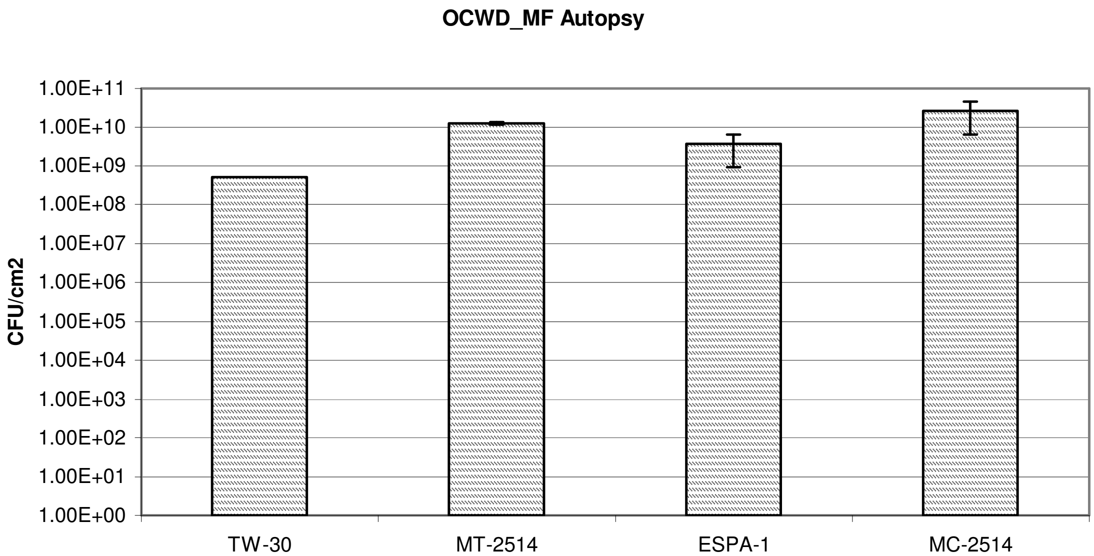
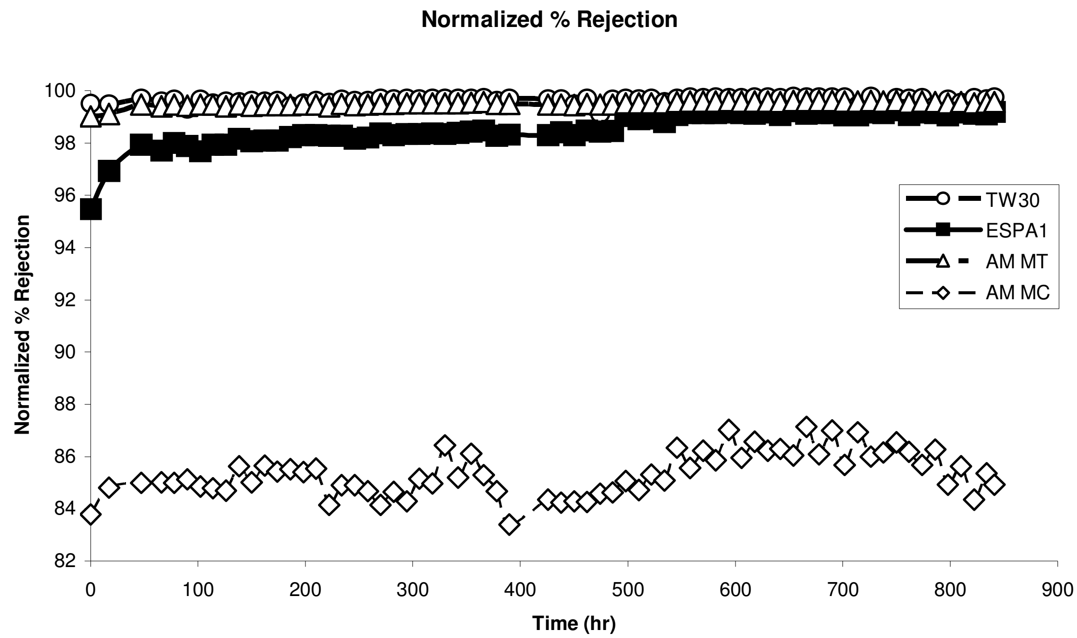


Figure 30. OCWD_MF Membrane Autopsy.



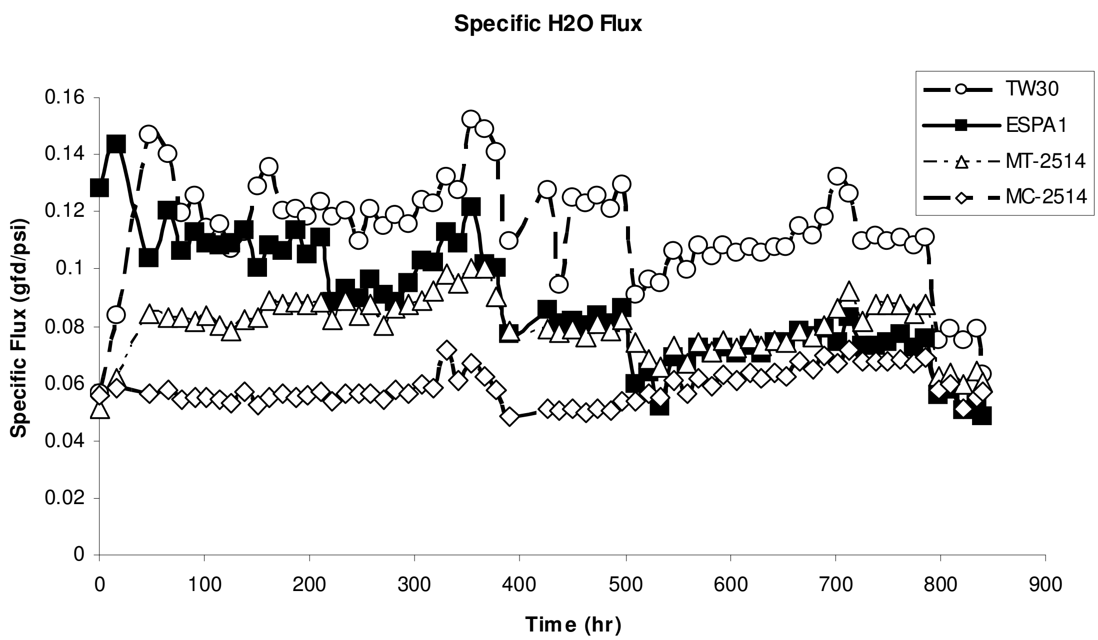


Figure 31. Yuma RO Test Unit Performance Data.

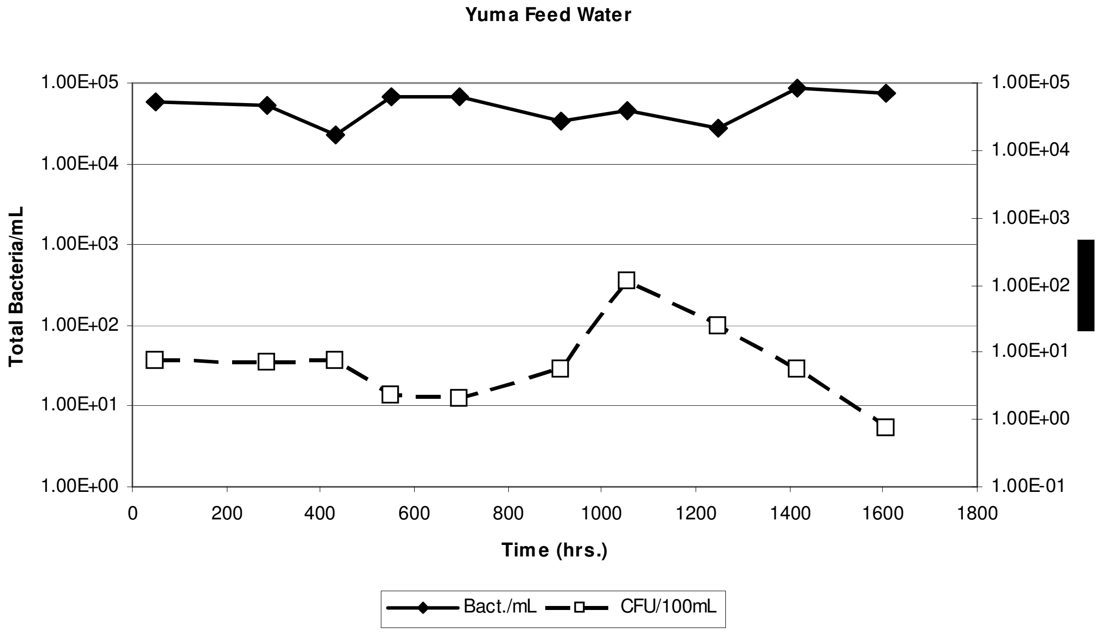
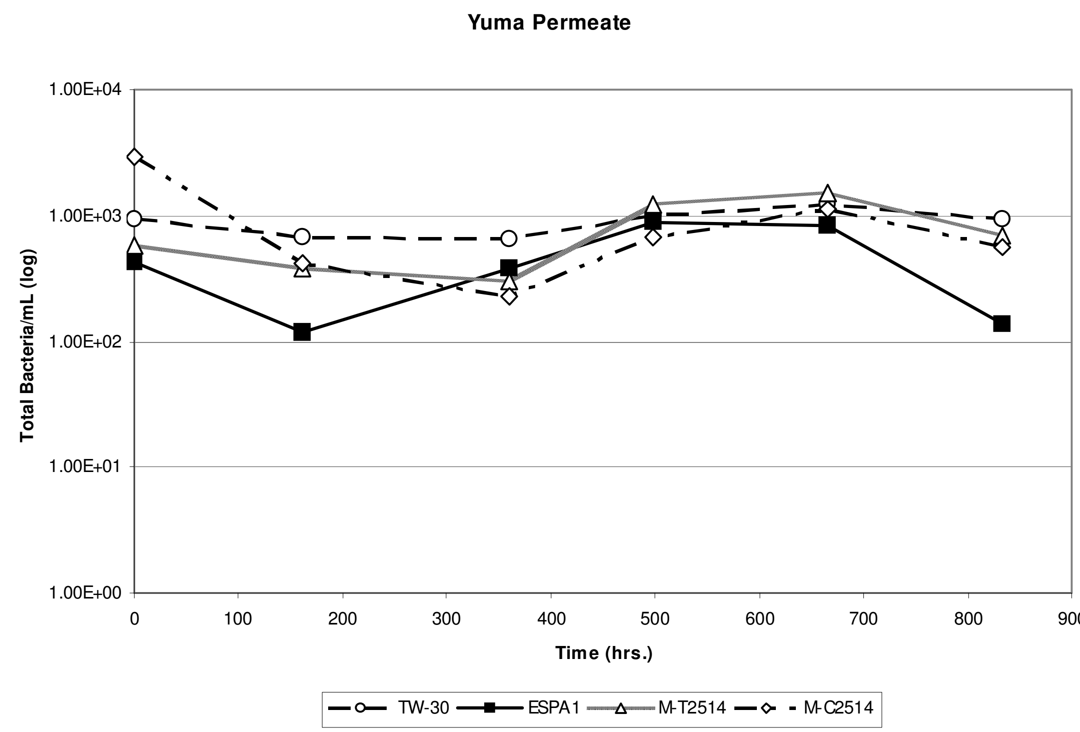


Figure 32. Yuma RO test unit feed water total and viable bacteria.



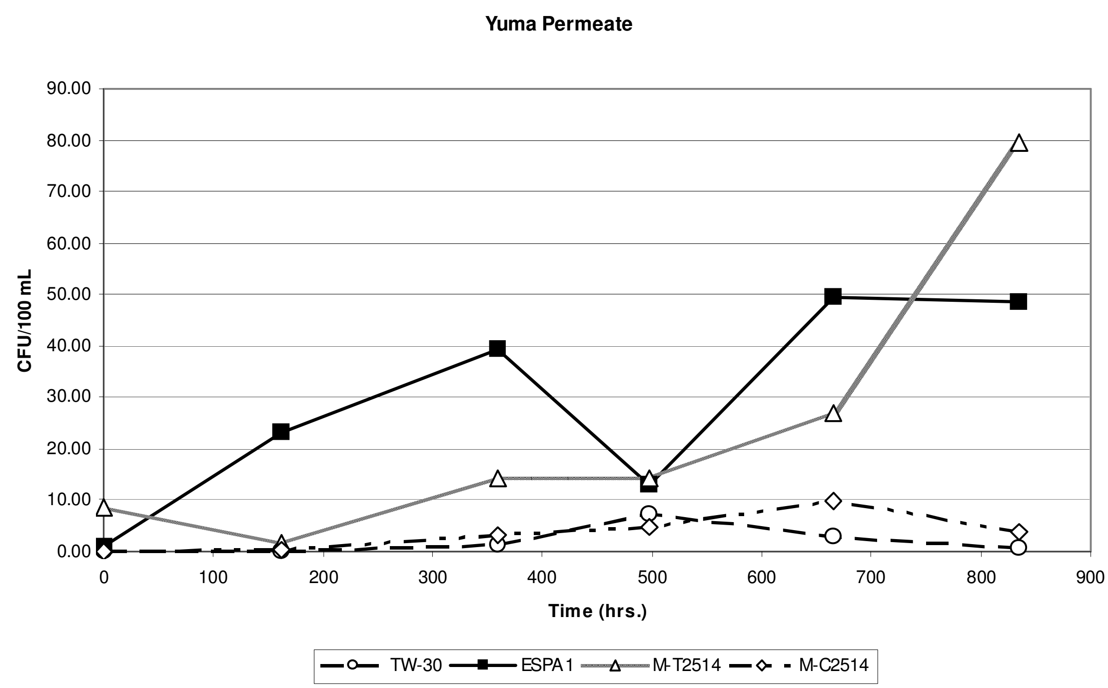


Figure 33. Yuma RO test unit permeate total and viable bacteria

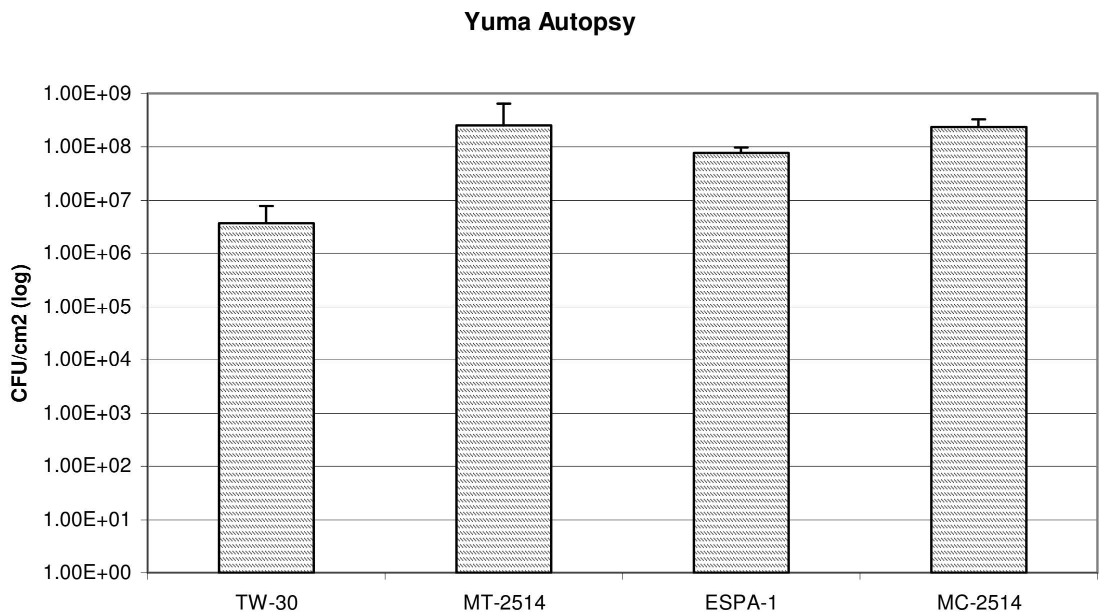


Figure 34. Yuma RO test unit viable bacteria in fouling layer.

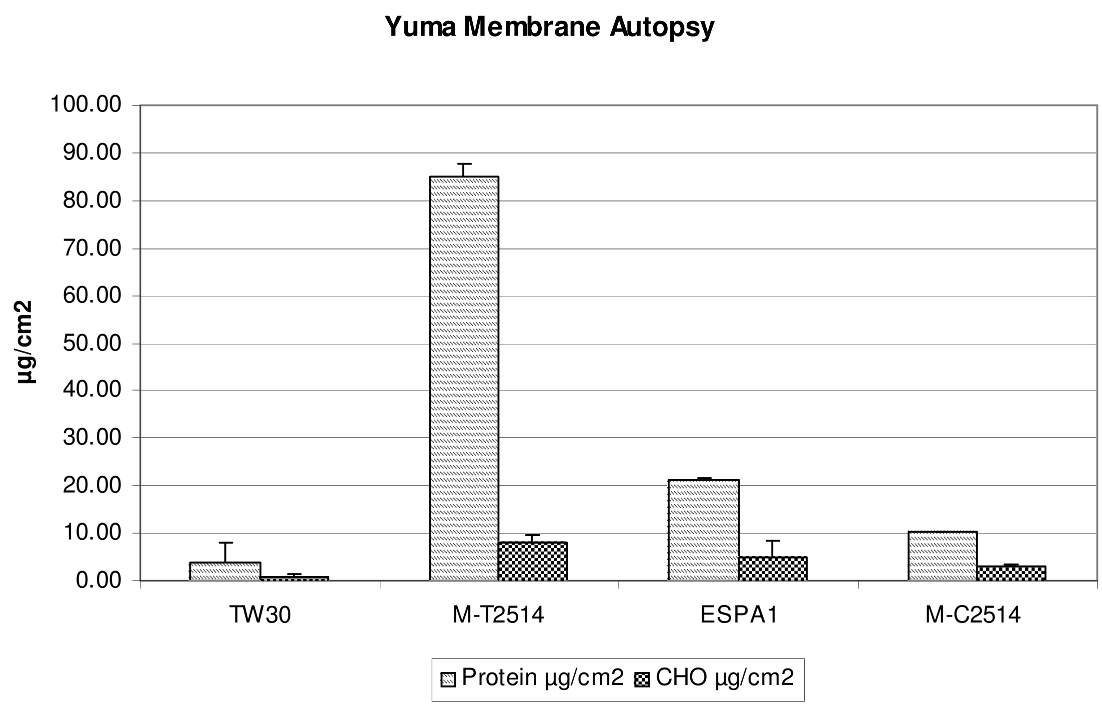


Figure 35. Yuma RO test unit membrane autopsy. Protein and carbohydrate present in fouling layer.

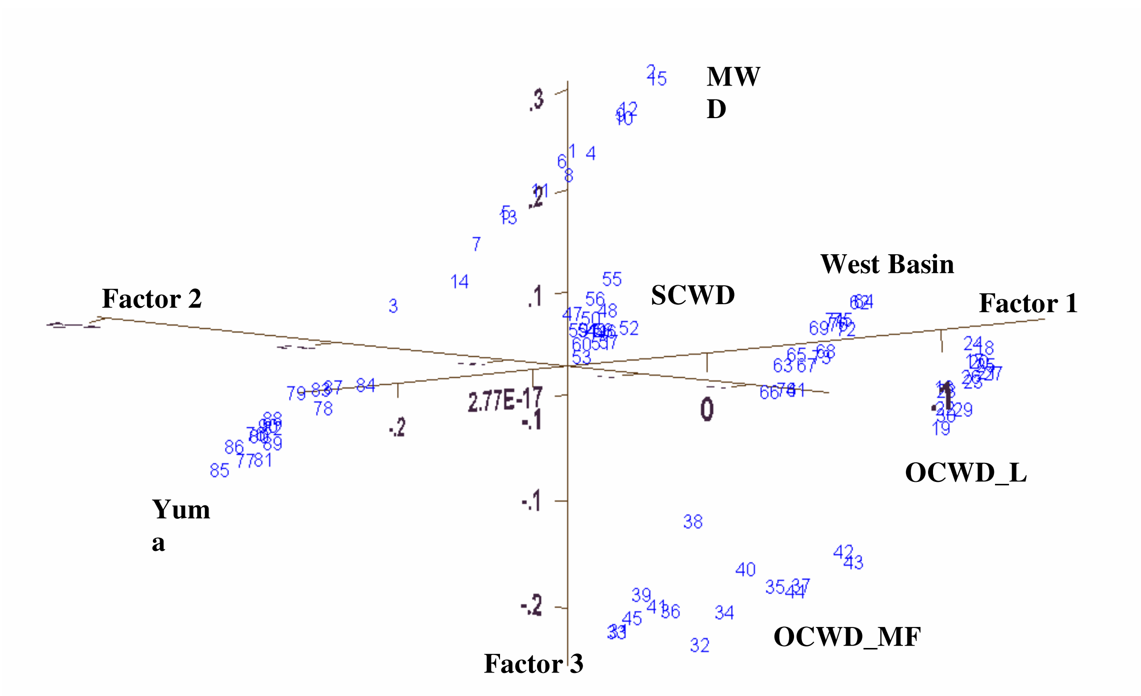


Figure 36. Principal components scores plot of factors 1, 2 and 3 using the entire spectral range from 4000 cm-1 to 650 cm-1 for M-C2514 operated on feed water from MWD, OCWD, OCWD_MF, SCWD, West Basin and Yuma.

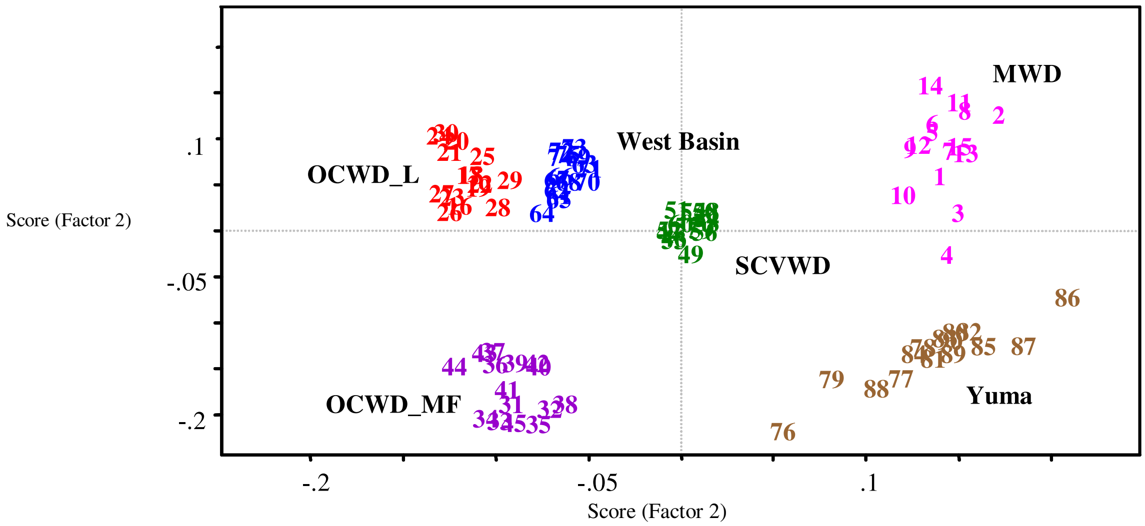


Figure 37. Principal components scores plot of factors 2 and 3 using the entire spectral range from 4000 cm-1 to 650 cm-1 for fouled TW-30 operated on MWD, OCWD, OCWD_MF, SCWD, West Basin and Yuma feed waters.

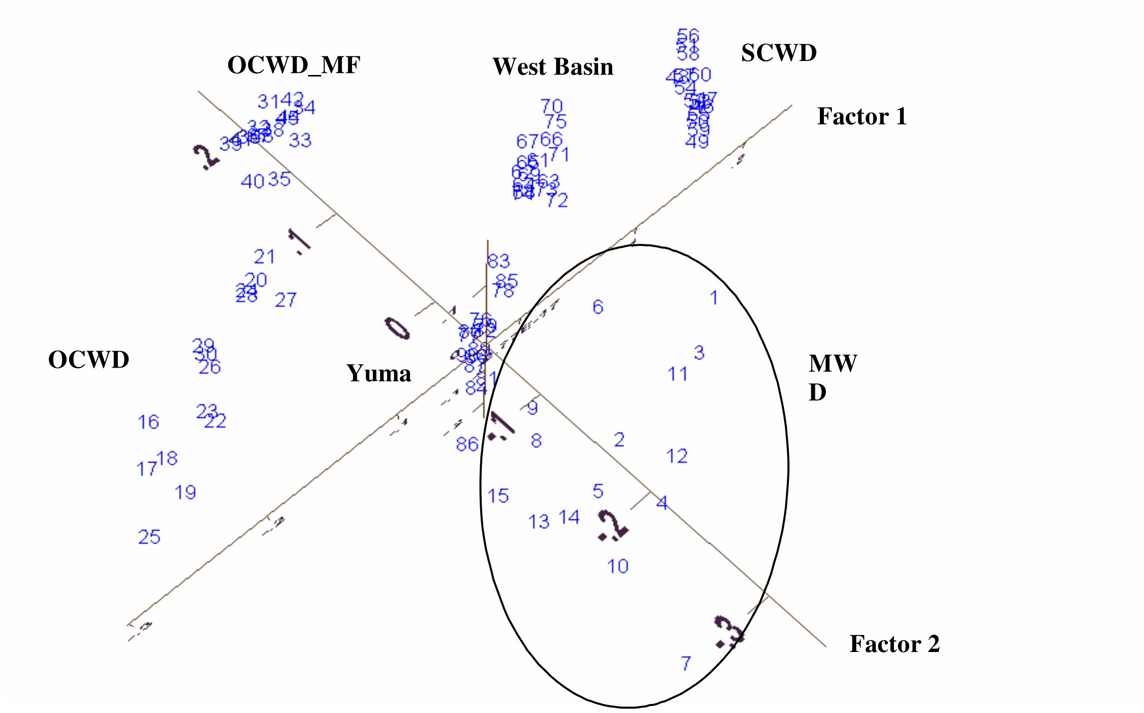


Figure 38. Principal components scores plot of factors 1, 2 and 3 (not labeled) using the entire spectral range from 4000 cm-1 to 650 cm-1 for fouled ESPA-1 reverse osmosis membranes operated on feed water from MWD, OCWD, OCWD_MF, SCWD, West Basin and Yuma.

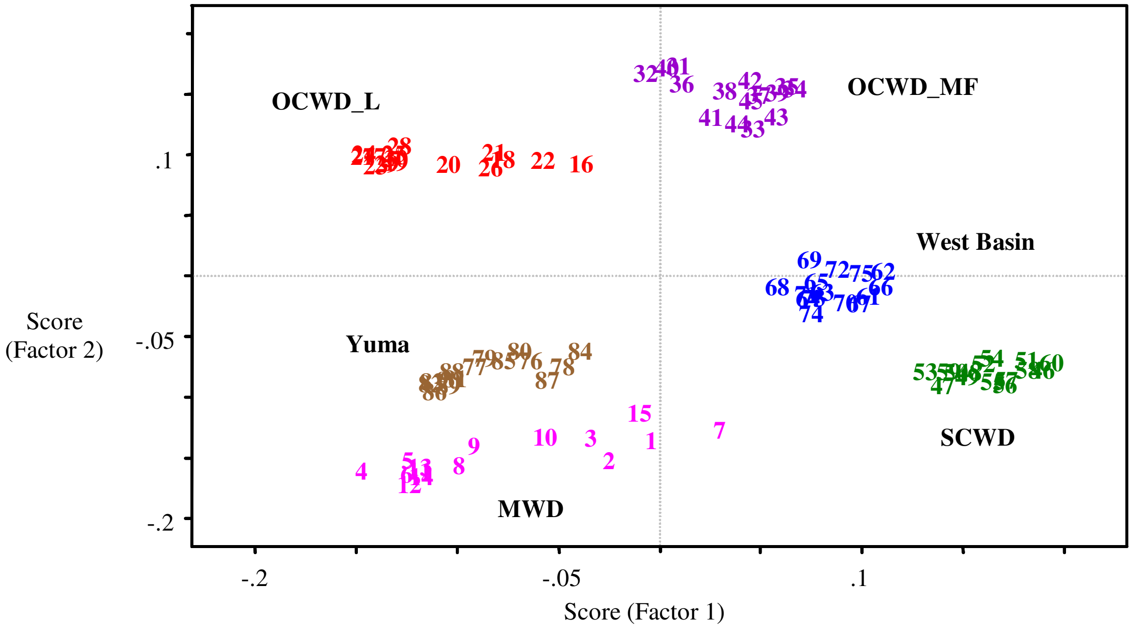


Figure 39. Principal components scores plot of factors 1and 2 using the entire spectral range from 4000 cm-1 to 650 cm-1 for fouled M-T2514 operated on feed water from MWD, OCWD, OCWD_MF, SCWD, West Basin and Yuma.

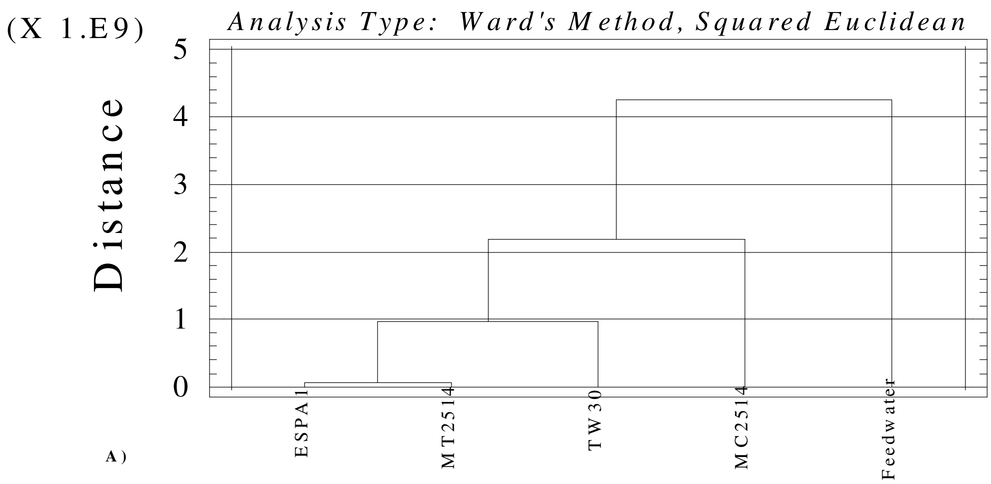


Figure 40. Dendritic comparison of microbial communities from biofilm scrapings from OCWD_MF.

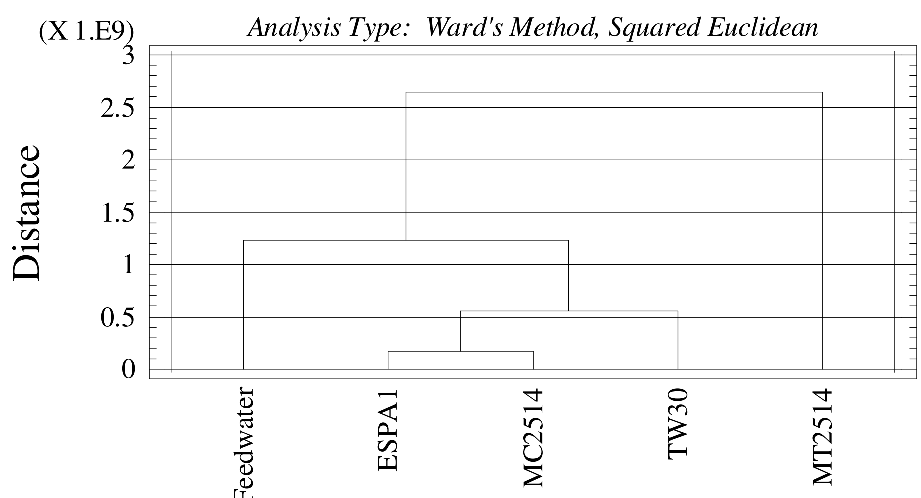


Figure 41. Dendritic comparison of microbial communities from biofilm scrapings from Yuma RO test unit.

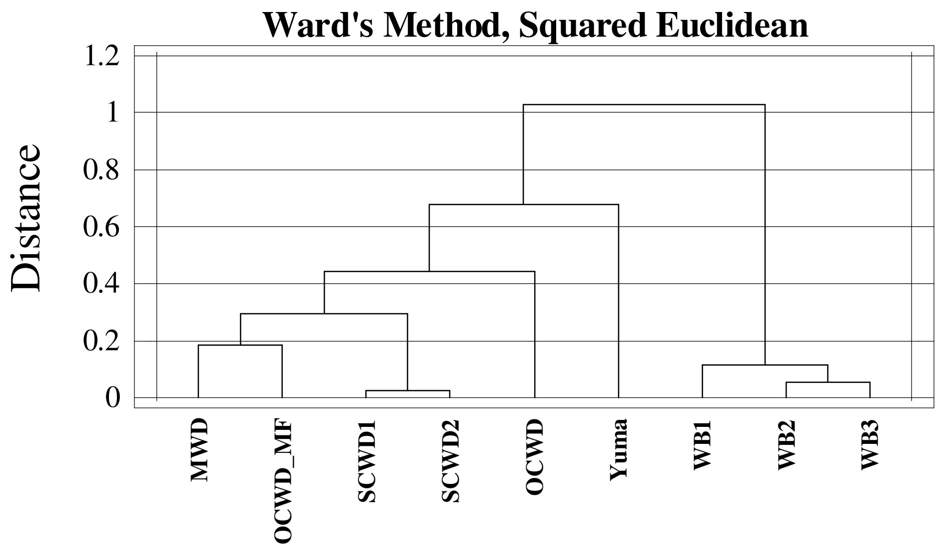
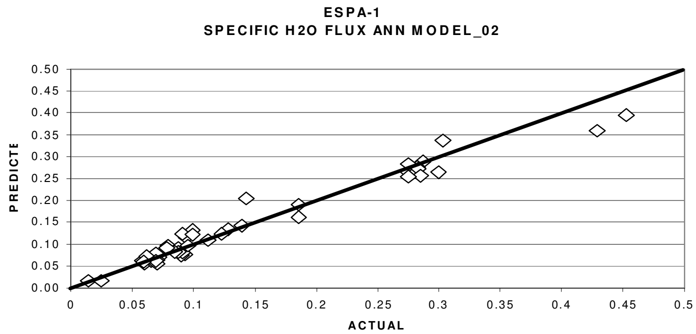
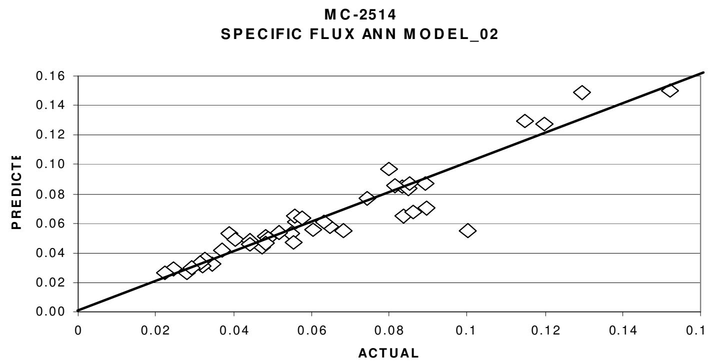


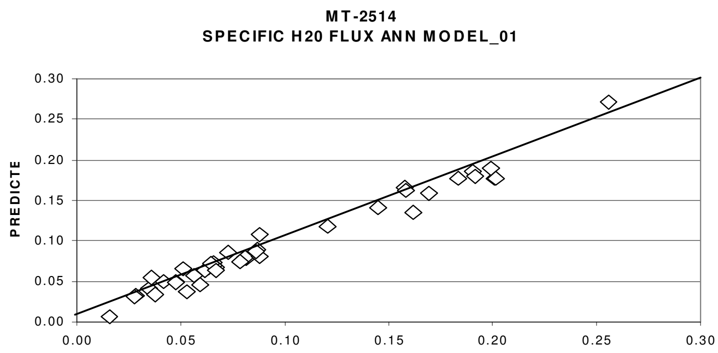
Figure 42. Dendritic comparison of microbial communities in feed waters tested in study. SCWD1 and SCWD2 were taken on different days but clustered together indicating microbial community similarities, WB1 – WB3 were taken on different days but clustered together indicating microbial community similarities. Microbial communities differed from site to site but remained similar within sites during test period.



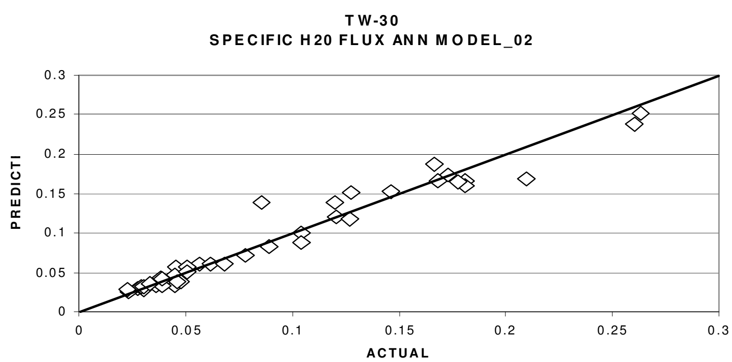
ESPA-1	R	Records
All	0.98	44
Train	0.99	30
Test	0.97	14



MC-2514	R	Records
All	0.94	42
Train	0.98	29
Test	0.90	13

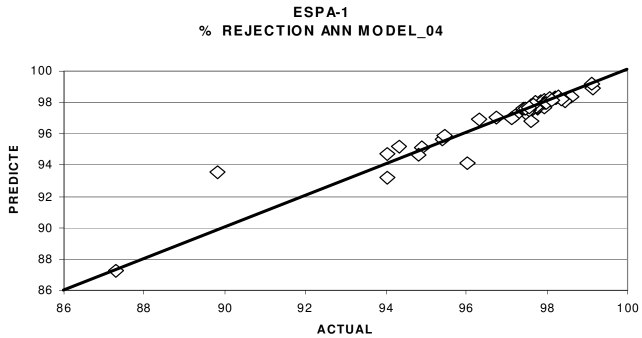


MT-2514	R	Records
All	0.99	41
Train	0.99	28
Test	0.99	13

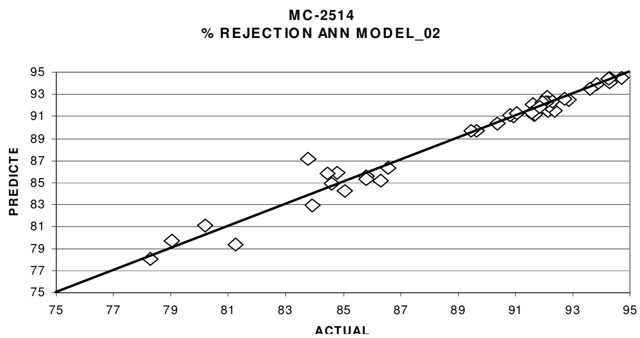


TW-30	R	Records
All	0.98	40
Train	0.99	27
Test	0.95	13

Figure 43. Specific Water Flux ANN Model Results The graphs show the accuracy of prediction. The overall R values are high and there is a good agreement between the test and the train values. The line indicates a perfect model.

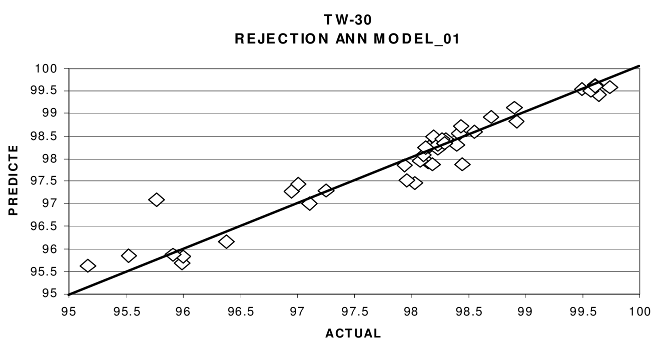


ESPA-1	R	Records
All	0.95	44
Train	0.96	30
Test	0.90	14



MC-2514	R	Records
All	0.98	42
Train	0.99	29
Test	0.98	13

MT-2514	R	Records
All	0.96	41
Train	0.96	28
Test	1.00	13



TW-30	R	Records
All	0.96	40
Train	0.96	27
Test	0.99	13

Figure 44. Percent Rejection ANN Model Results

The graphs show the accuracy of prediction. The overall R values are high and there is a good agreement between the test and the train values. The line indicates a perfect model.

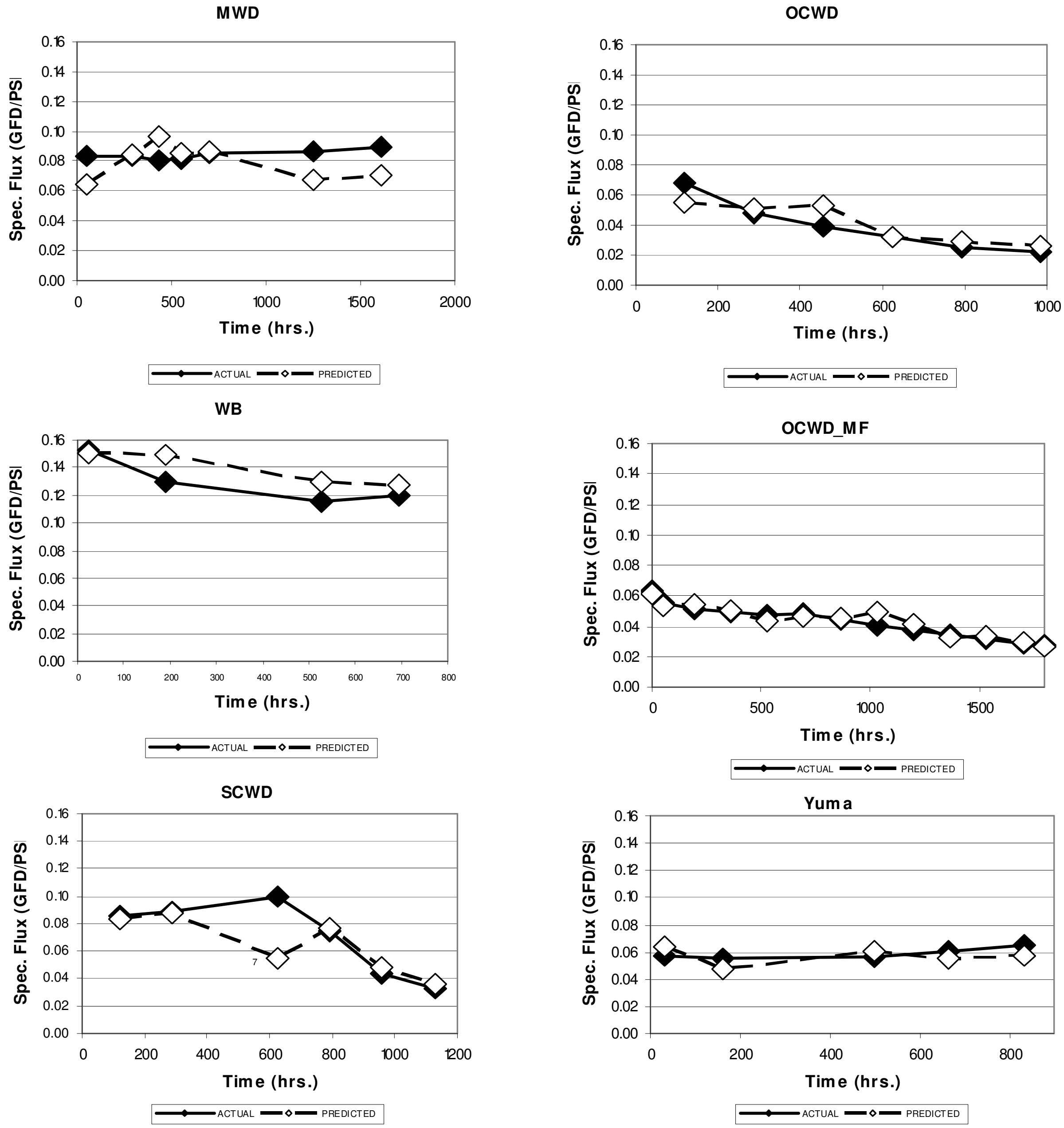


Figure 45. ANN Model for MC-2514 – Specific Water Flux

MWD and SCWD models have some variations but the generally the trend is evident. OCWD, OCWD_MF and Yuma generally track well. These models are capturing lot of variations in the data. Inputs are capable of predicting membrane performance on specific feed waters over time

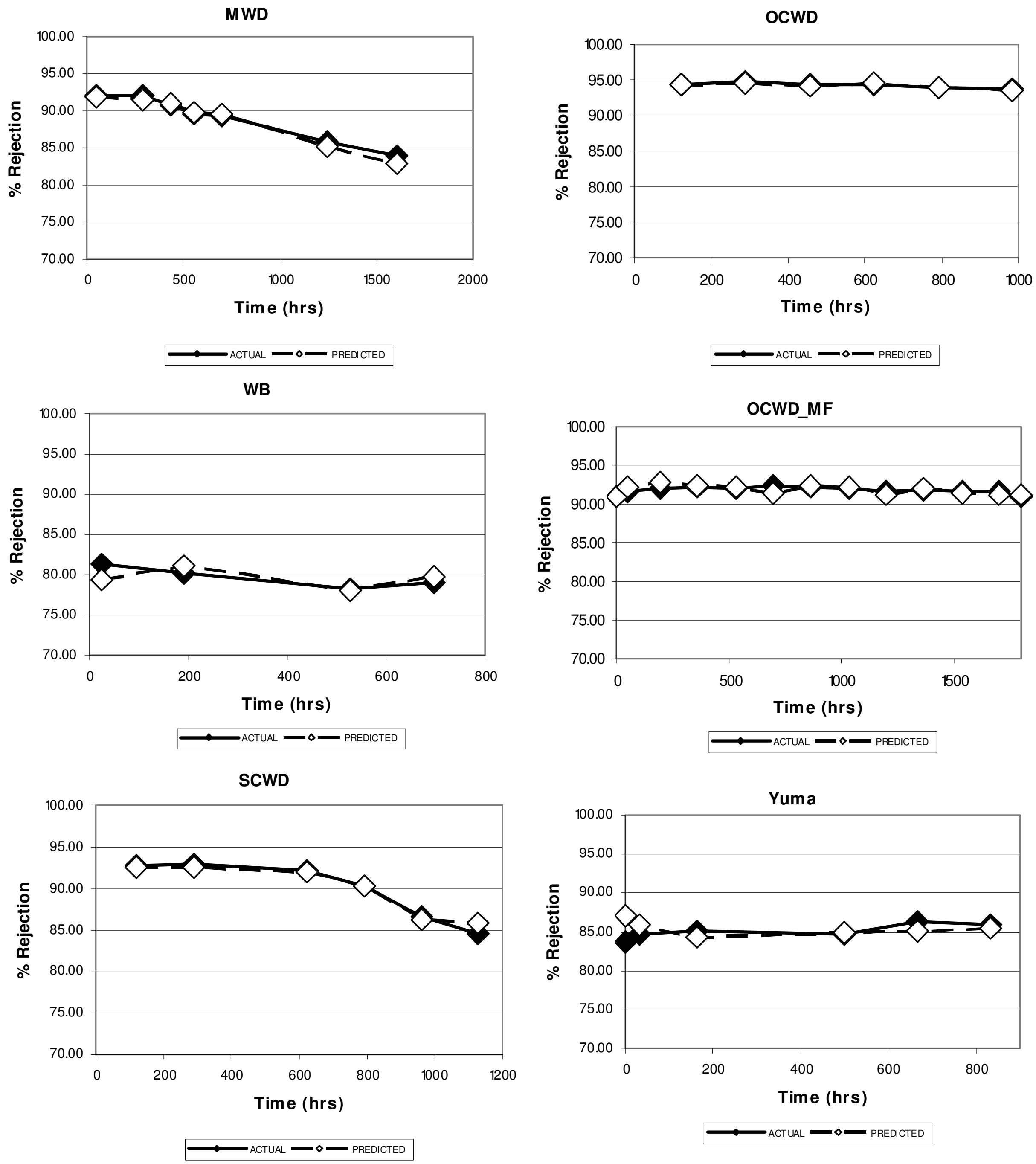


Figure 46. ANN Model for MC-2514 – Percent Rejection

The predicted agrees well with the actual data.

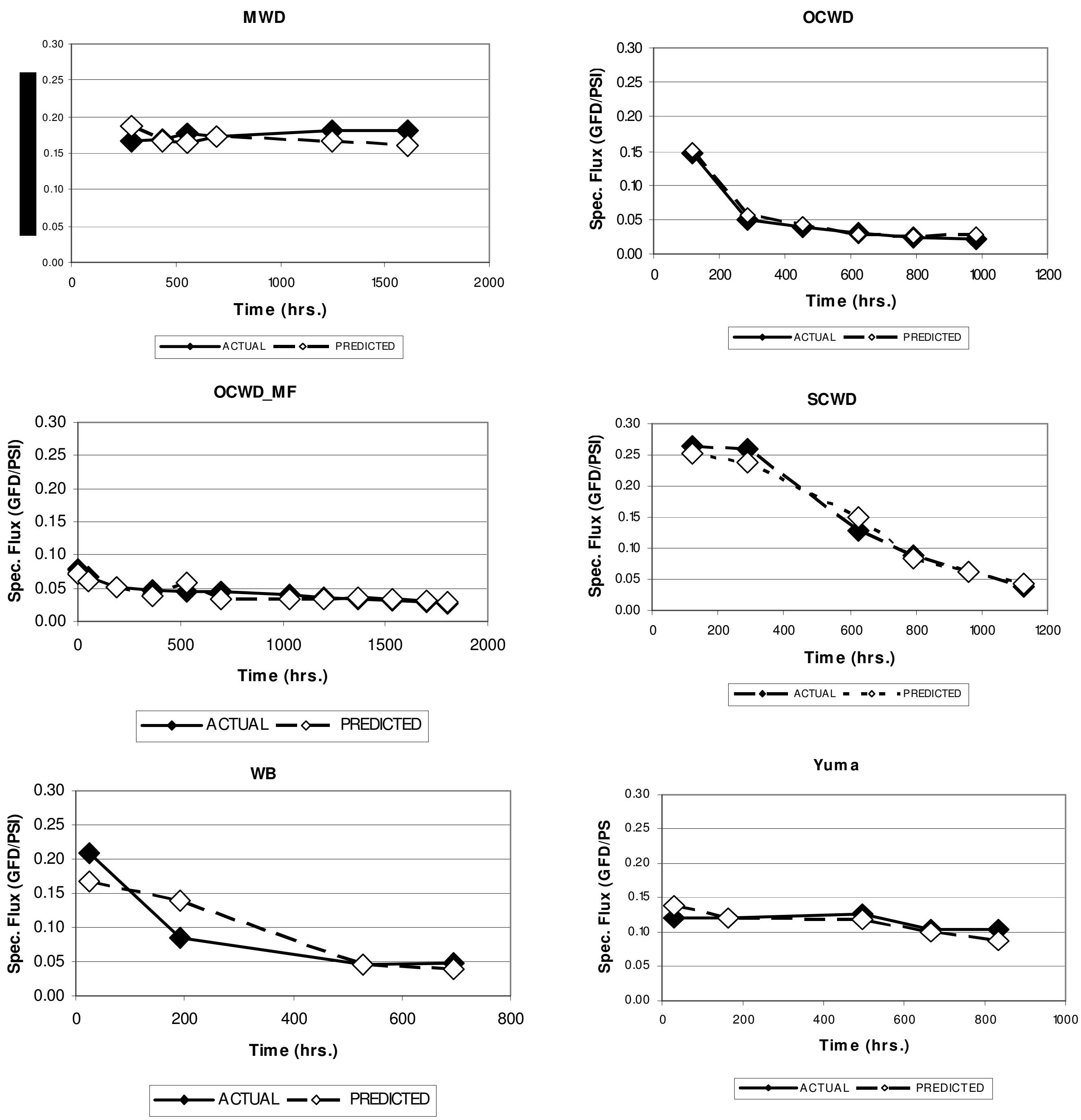


Figure 47. ANN Model for TW-30 – Specific Water Flux

The predicted models agree with the actual data. MWD tracked well but at end of the run the model detected some differences. WB model seem to be more optimistic but generally the trend is in the same direction. Yuma model at beginning has some variation but tracks well.

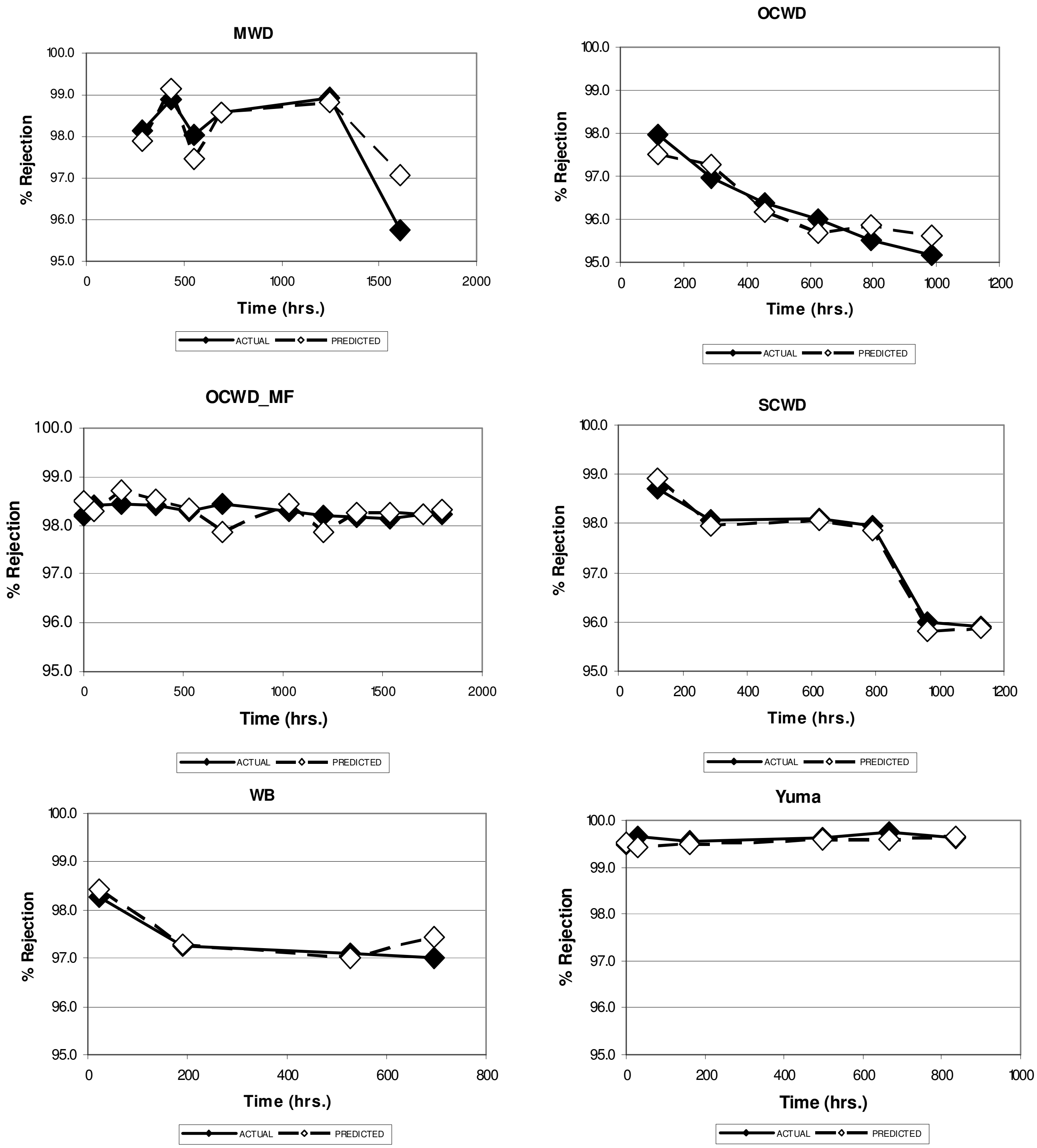


Figure 48. ANN Model for TW-30 – Percent Rejection

MWD and OCWD models have some variations at the ends but generally all models trend in the same direction as actual data.

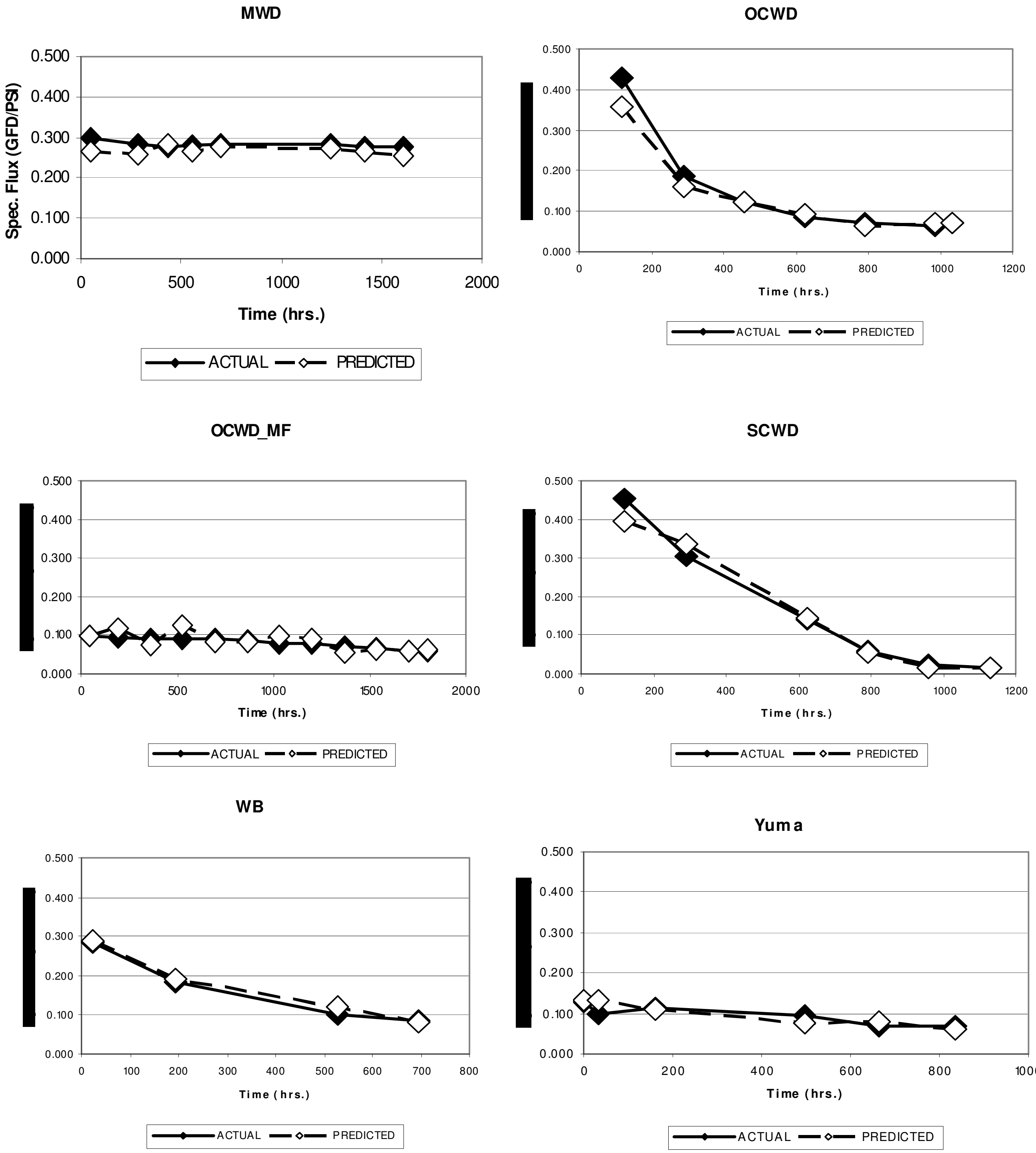


Figure 49. ANN Model for ESPA-1 – Specific Water Flux

Good models, predicted tracks actual in most instances. Inputs are capable of predicting membrane performance specific feed waters over time.

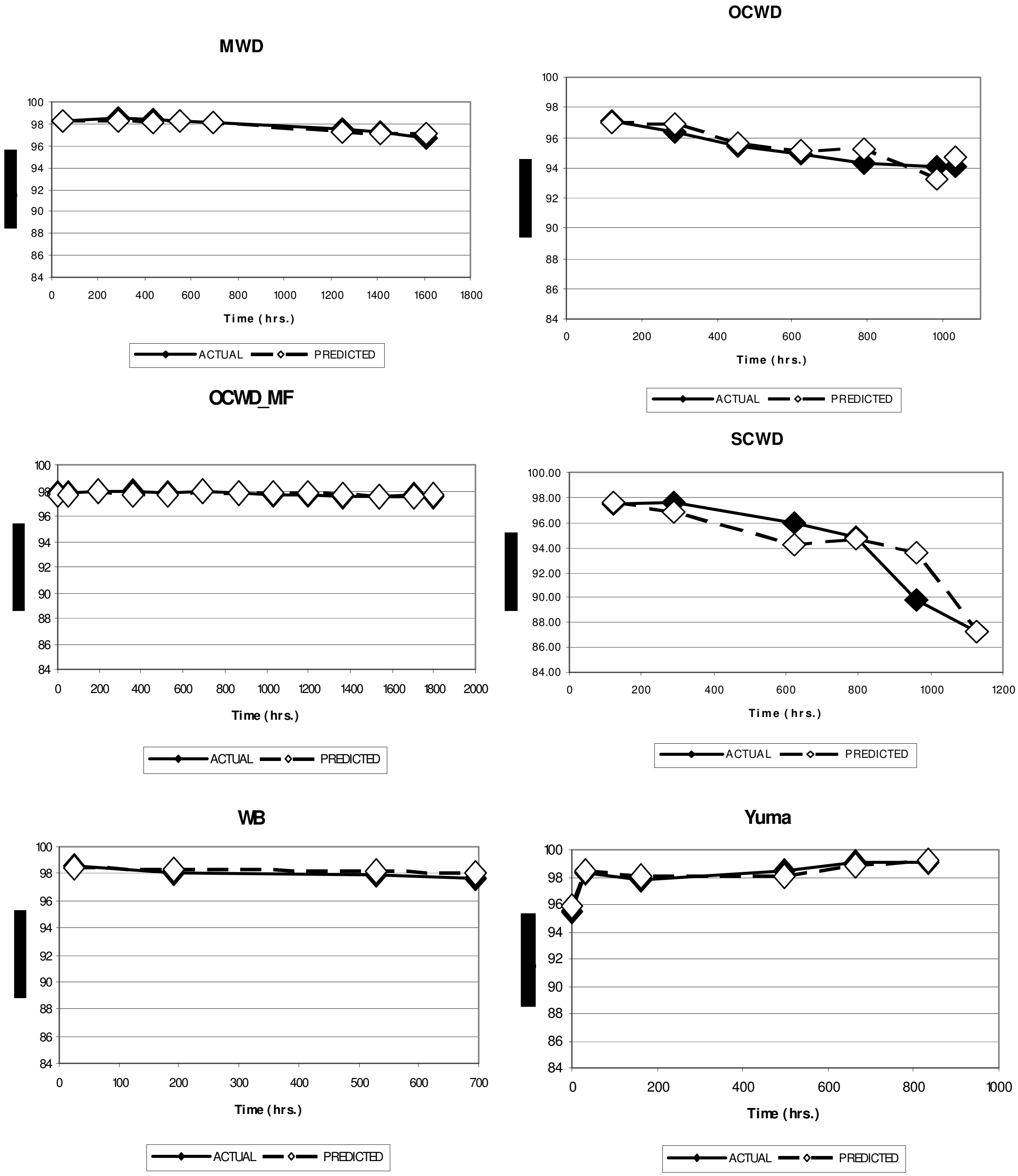


Figure 50. ANN Model for ESPA-1 – Percent Rejection

Good models, predicted tracks actual in most instances. Inputs are capable of predicting membrane performance on specific feed waters over time.

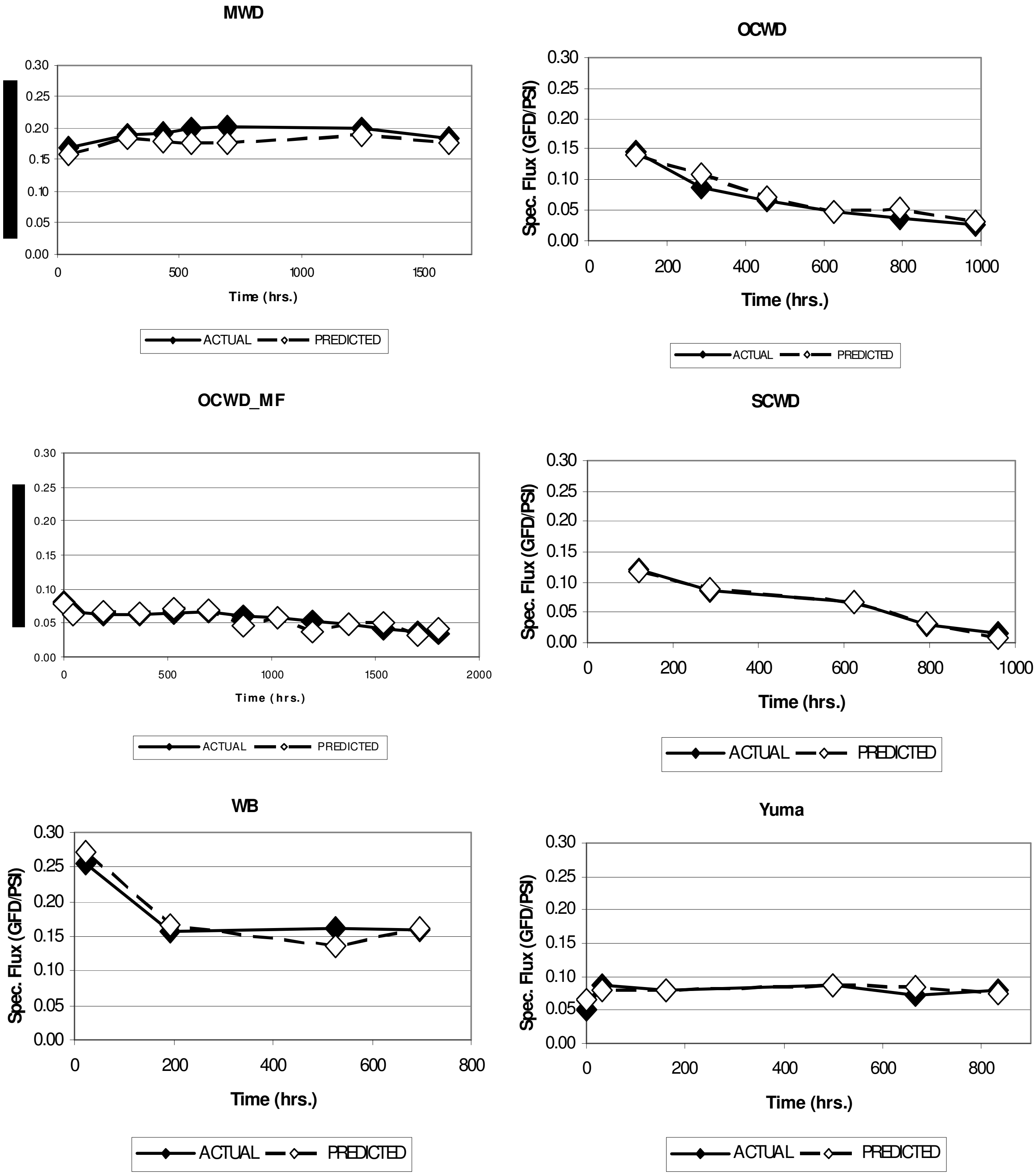


Figure 51. ANN Model for MT-2514 – Specific Water Flux. Good models, predicted tracks actual in most instances.

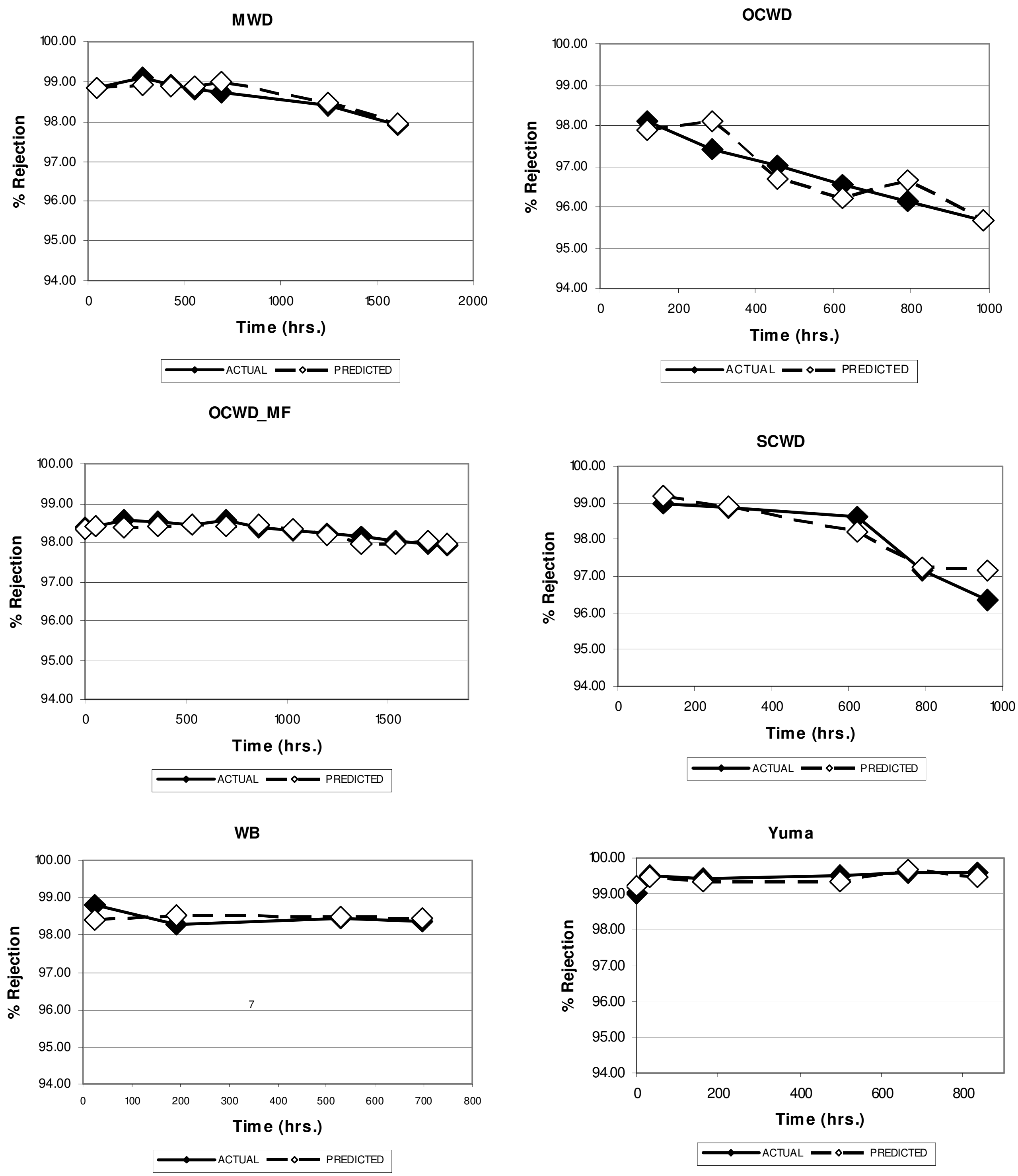
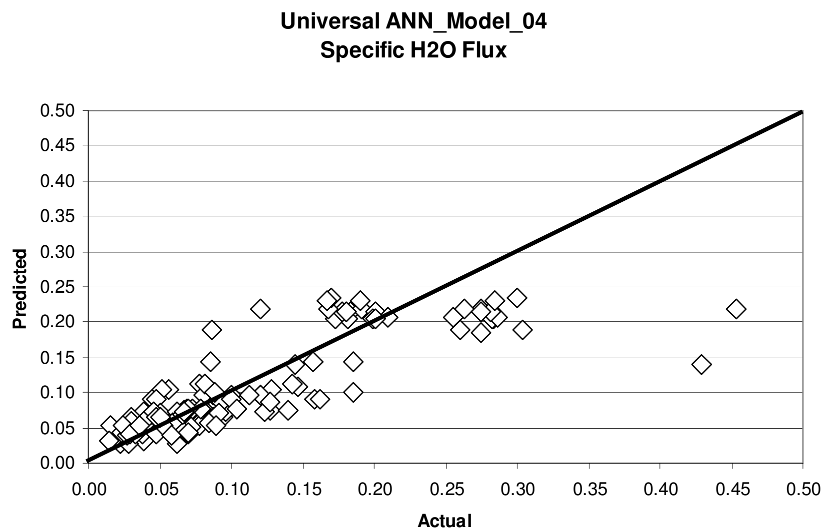


Figure 52. ANN Model for MT-2514 – Percent Rejection. SCWD has a small variation at end but the generally trend is followed.



Spec. Flux	R	Records
All	0.8201	125
Train	0.8286	87
Test	0.8016	38

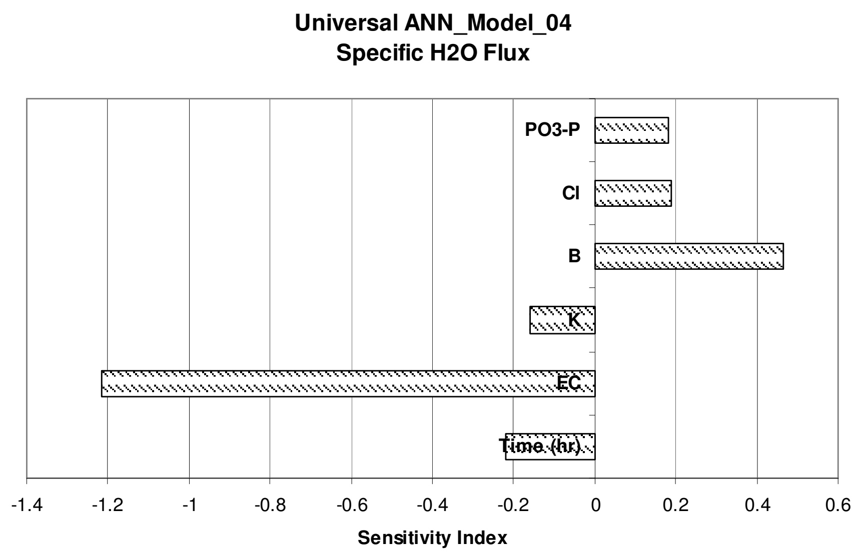


Figure 53. "Universal" ANN Model for Specific Flux

The graph shows the accuracy of prediction. The overall R values are in good agreement between test and the train values. The line indicates a good model. The sensitivity index lists the inputs to the model and indicates how sensitive the model output is to small changes in each input.

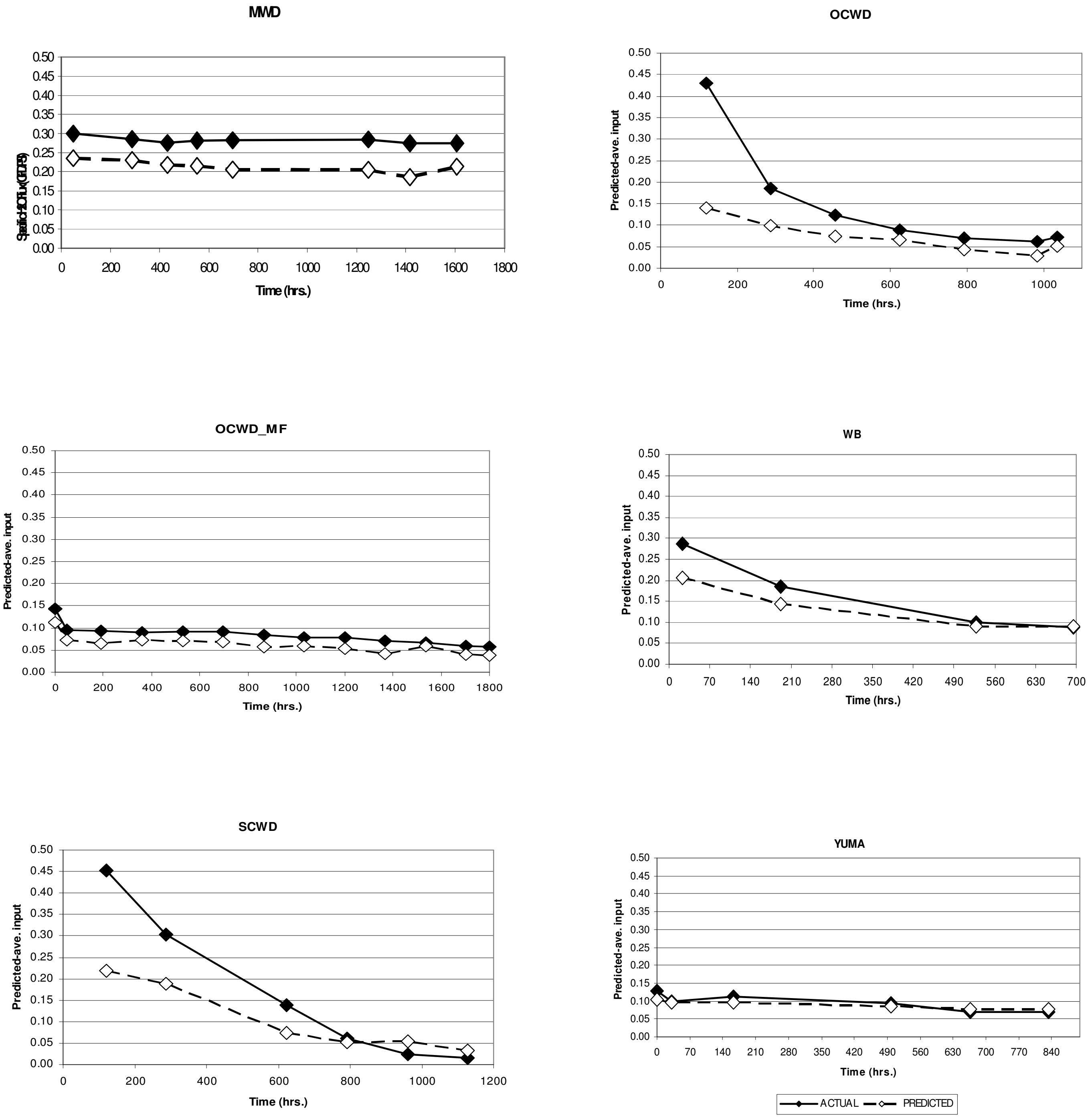


Figure 54. ESPA-1 ANN "Universal" Model – Specific Water Flux

Predicted and actual values are not exactly the same but the general trend is the same Models will not predict exact details at specific time points but general trends are represented.

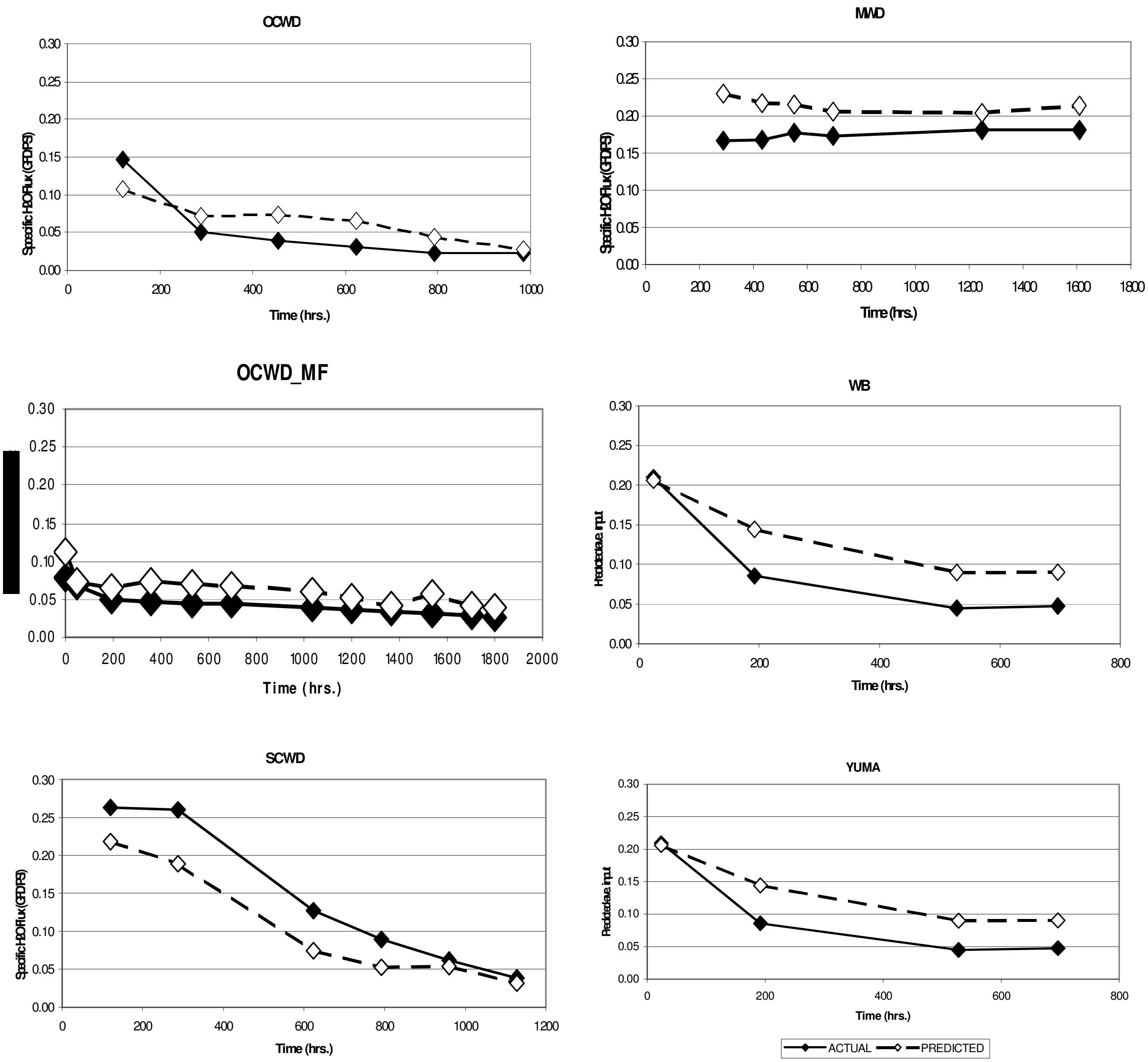


Figure 55. TW-30 ANN "Universal" Model – Specific Water Flux

Predicted and actual values are not exactly the same but the general trend is the same. Model will not predict exact details at specific time points but general trends are represented.

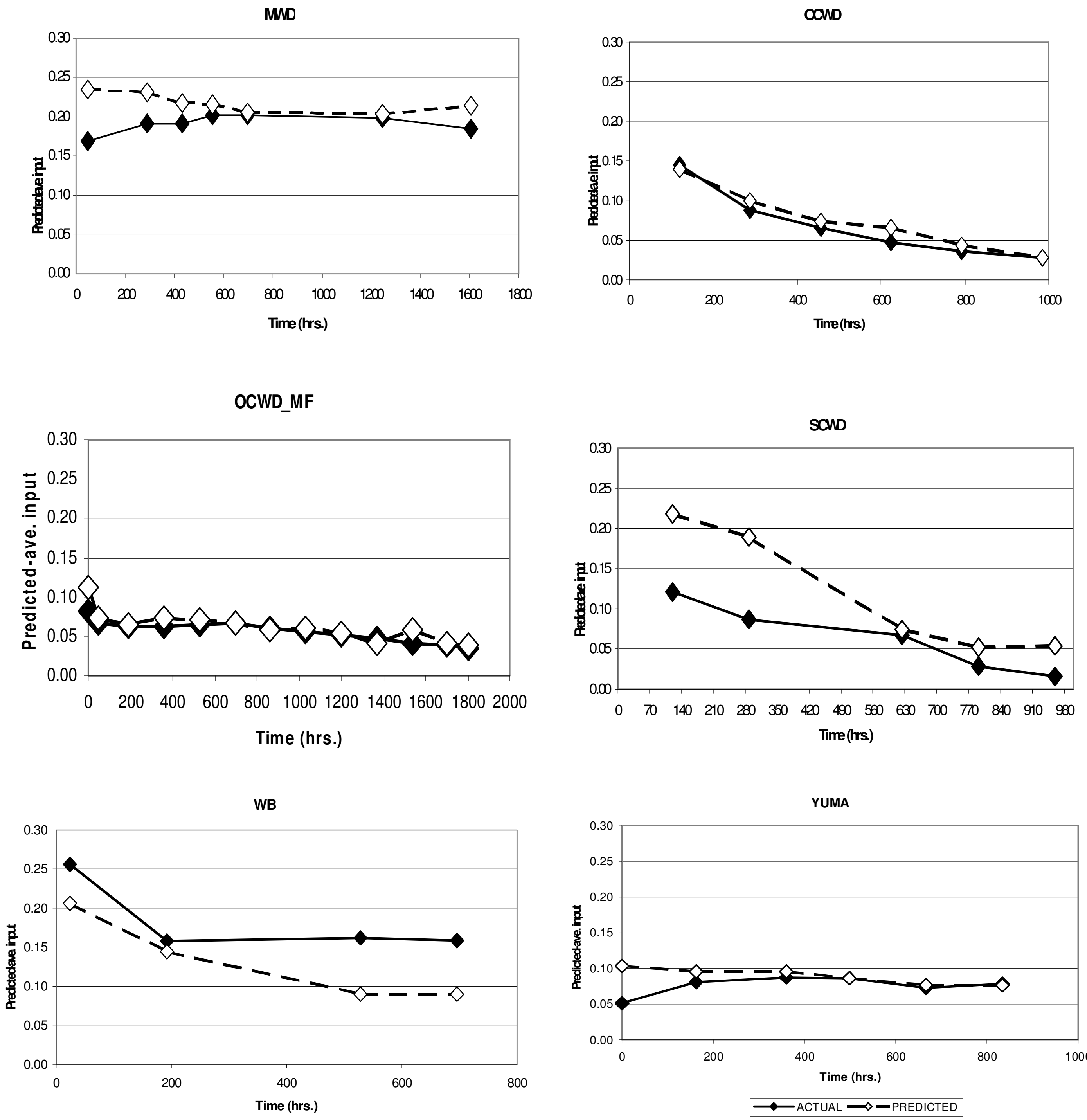
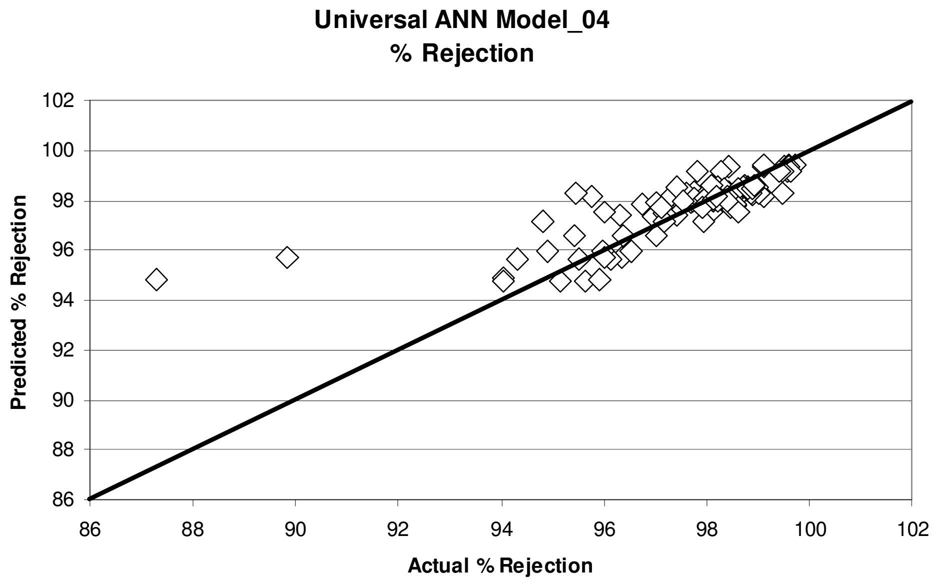


Figure 56. MT-2514 ANN "Universal" Model – Specific Water Flux

Predicted and actual values are not identical but the general trends observed. In this case MWD did not track very well at the start. Model will not predict exact details at specific time points but general trends are represented.



% rejection	R	Records
All	0.7862	125
Train	0.7843	100
Test	0.9108	25

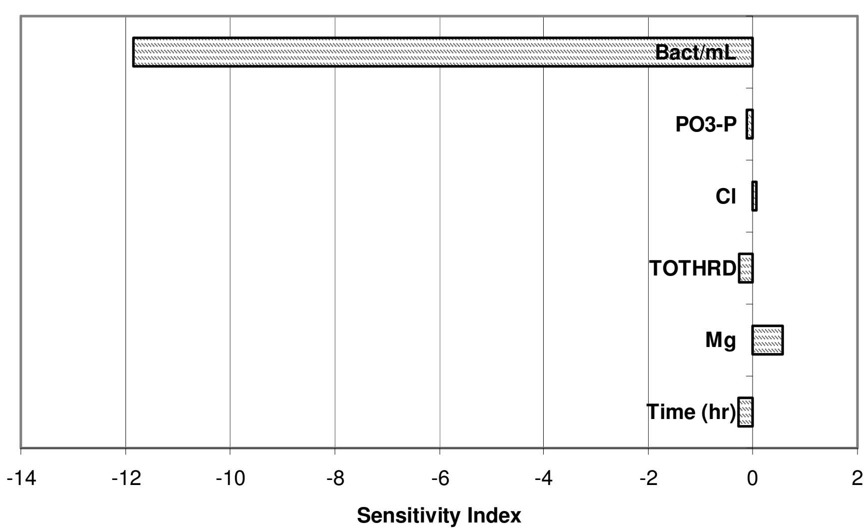


Figure 57. "Universal" ANN Model for Percent Rejection

The graph shows the accuracy of prediction. The overall R values are in good agreement between test and the train values. The line indicates a good model. The sensitivity index lists the inputs to the model and indicates how sensitive the model output is to small changes in each input.

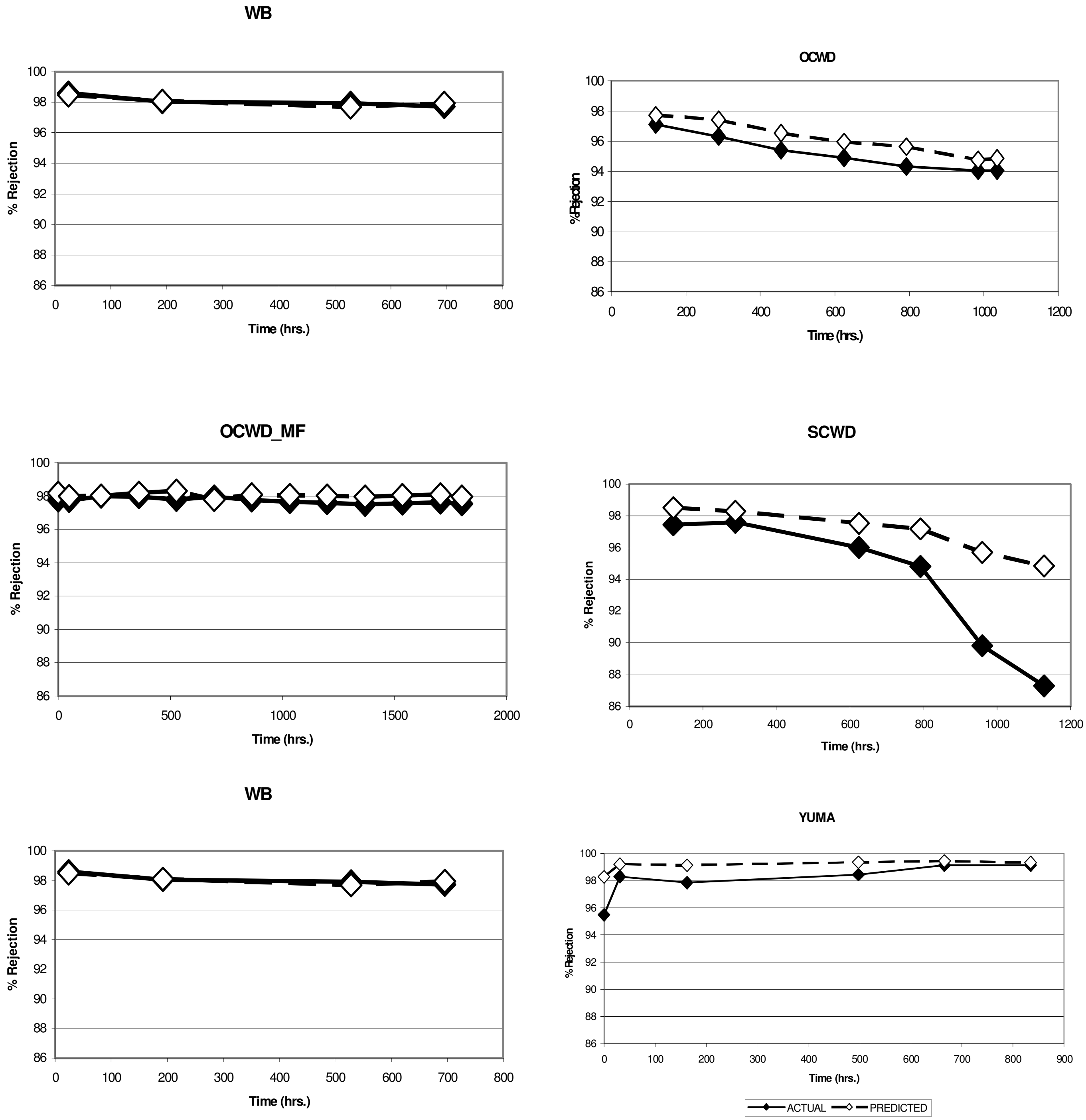


Figure 58. ESPA-1 ANN "Universal" Model – Percent Rejection

Predicted and actual values are not exactly the same but the general trend is the same. OCWD_MF predicted and actual values track very well as SCWD tracks the general trend.

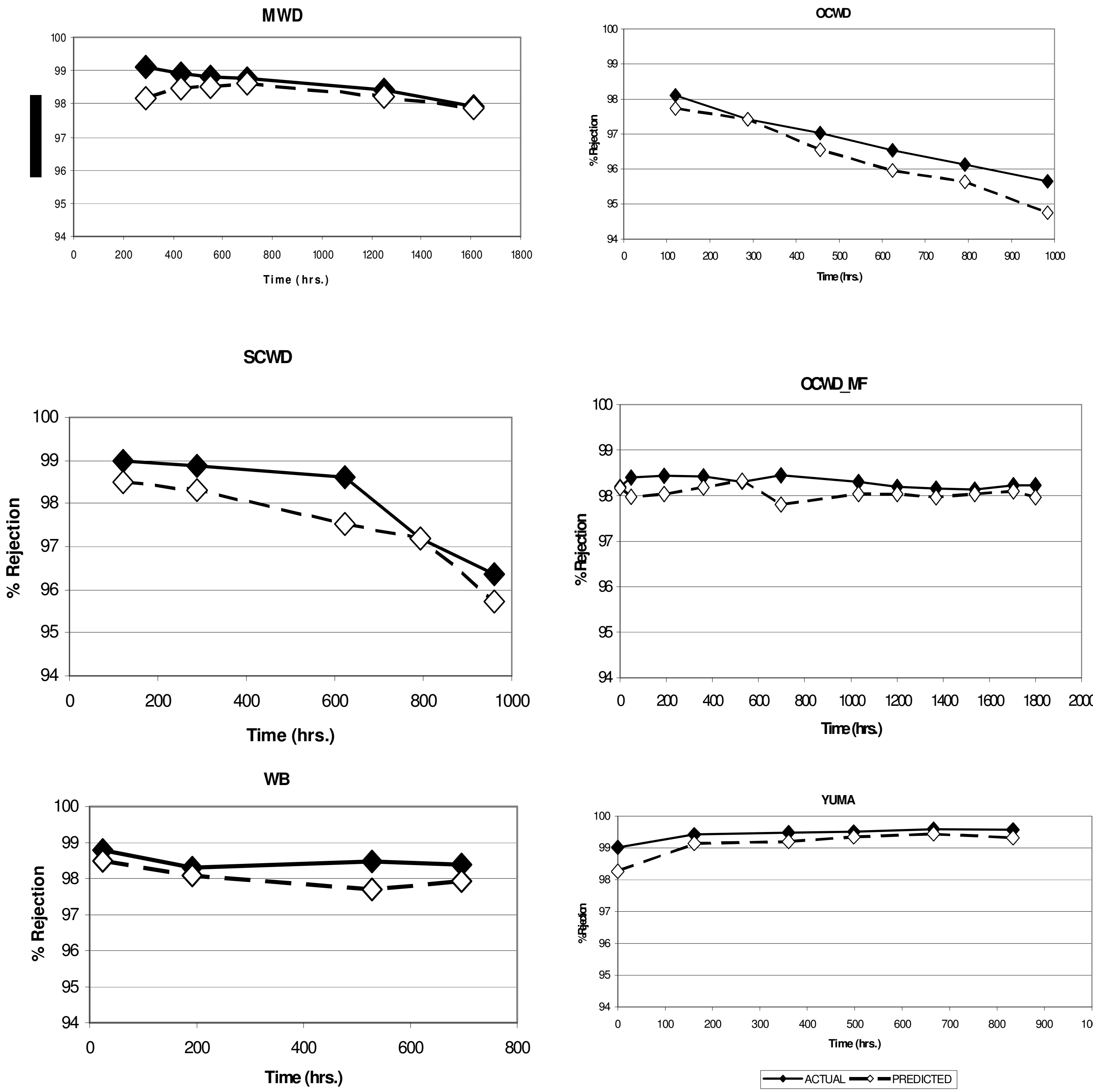


Figure 59. MT-2514 ANN "Universal" Model – Percent Rejection

Predicted and actual values are not exactly the same but the general trend is the same.

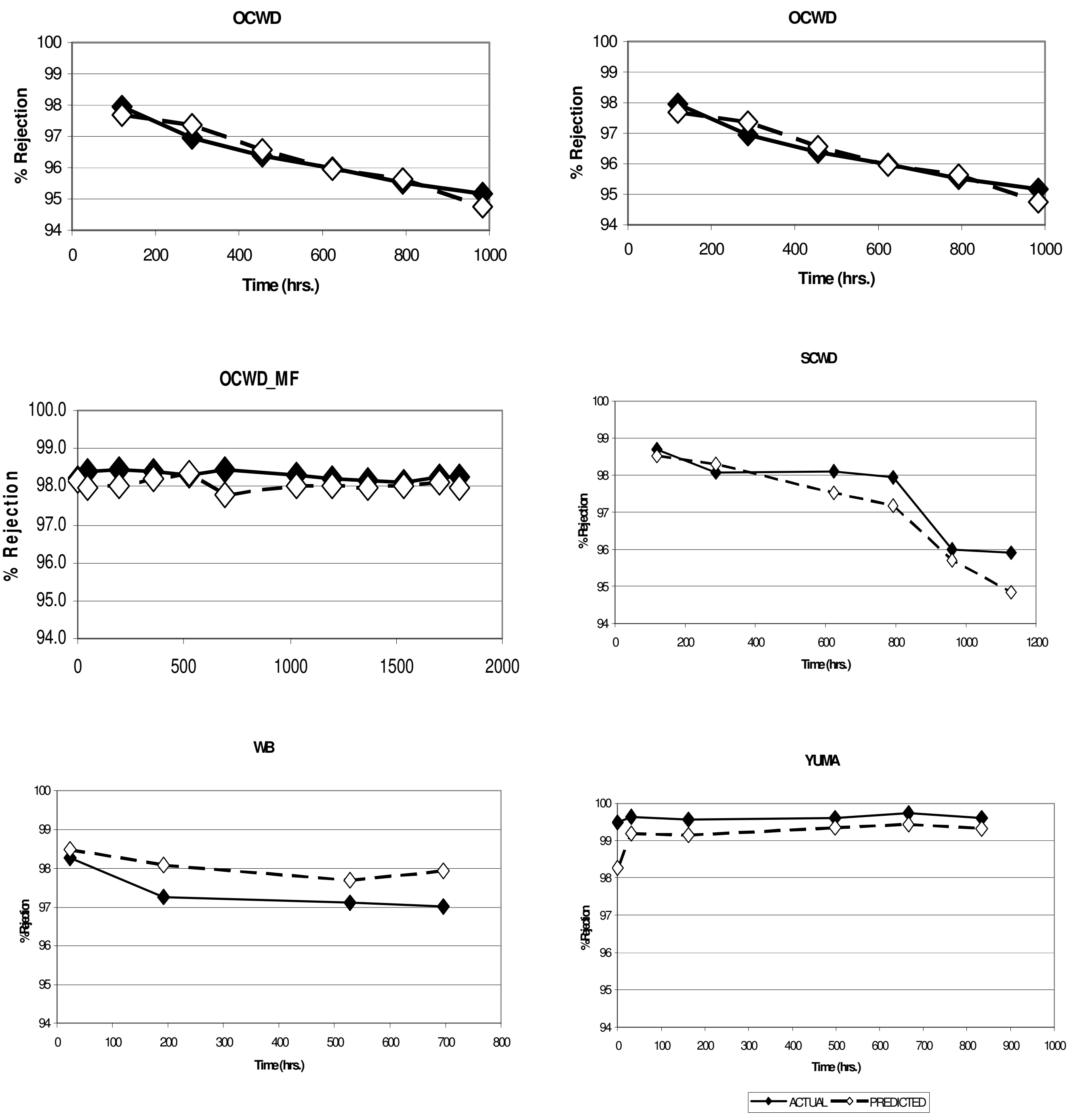


Figure 60. TW-30 ANN "Universal" Model – Percent Rejection

Predicted and actual values are not exactly the same but the general trend is the same.

Table 1. Participating Water Agencies and Source Water

Test #	Participating Agency	Water Source	Pretreatment
1	Metropolitan Water District of So. Cal.	Surface Water	Conventional (No Lime)
2	Orange County Water District	Secondary Treated Wastewater	Conventional with Lime Clarification
3	West Basin Municipal Water District	Secondary Treated Waste Water	Microfiltration
4	Santa Clara Valley Water District	Secondary Treated Wastewater	Conventional with Lime Clarification
5	Orange County Water District	Secondary Treated Wastewater	Microfiltration
6	University of California Riverside	Agricultural Drainage Water	Conventional with Lime Clarification

Table 2. Membranes and manufacturers used in this study.

Membrane	Polymer Chemistry	Manufacturer
MC-2514	Cellulose Acetate	Applied Membranes, San Marcos, CA
MT-2514	Polyamide	Applied Membranes, San Marcos, CA
ESPA-1	Polyamide	Hydranautics, Oceanside, CA
TW-30	Polyamide	Dow FilmTec, Midland, MI

Table 3. Water quality parameters measured for each feed water and membrane permeate also used as ANN independent variable inputs

Test Name/Model Inputs	Units	MWD	OCWD	WB	SCWD	OCWD_MF	Yuma
Electrical Conductivity (EC)	µm/cm	882.80	1550.00	1408.57	1145.56	1747.69	3790.00
Total Dissolved Solids (TDS)	mg/L	488.29	863.17	651.00	650.67	965.23	2324.67
pH	UNITS	7.43	6.19	7.69	7.94	6.97	5.83
Sodium (Na)	mg/L	91.33	191.00	171.00	119.33	208.23	602.17
Potassium (K)	mg/L	4.16	14.21	16.54	24.74	17.52	6.57
Magnesium (Mg)	mg/L	26.49	3.73	23.96	29.89	21.85	61.48
Calcium (Ca)	mg/L	60.77	79.44	49.47	48.19	70.42	80.27
Boron (B)	mg/L	0.14	0.34	0.59	0.38	0.43	1.03
Total Hardness (as CaCO3)	mg/L	253.40	213.71	222.14	243.44	276.77	453.83
Alkalinity-Phenolphtalein (ALKPHE)	mg/L	<1	<1	<1	<1	<1	<1
Total Alkalinity (TOTALK)	mg/L	114.80	38.33	304.57	240.67	120.61	4.55
Hydroxide (OHCa)	mg/L	<1	<1	<1	<1	<1	<1
Carbonate (CO3Ca)	mg/L	<1	<1	<1	<1	<1	<1
Bicarbonate (HCO3Ca)	mg/L	114.800	38.329	304.571	240.667	119.825	4.55
Nitrite Nitrogen (NO2-N)	mg/L	0.004	0.582	0.18	0.01	0.753	<0.002
Chloride (Cl)	mg/L	98.34	219.25	176.14	143.47	208.46	618.50
Bromide (Br)	mg/L	<0.1	0.23	0.39	0.12	0.28	0.14
Nitrate Nitrogen (NO3-N)	mg/L	0.50	0.75	0.38	1.76	1.01	4.00
Phosphate Phosphorus (orthophospahte) (PO3-P)	mg/L	<0.1	<0.1	1.53	2.15	0.24	<0.1
Sulfate (SO4)	mg/L	169.60	366.71	114.14	56.53	379.23	917.67
Total Organic Carbon (Unfiltered) (TOC)	mg/L	2.62	9.15	10.27	6.07	10.34	1.29

Table 4. MWD RO Test Unit Feedwater and Membrane Permeate General Minerals.

Test Name	Units	Feedwater	MT-2514	ESPA1-2514	TW30-2514	MC-2514
Electrical Conductivity (EC)	µm/cm	882.80	18.11	27.80	92.37	51.96
Total Dissolved Solids (TDS)	mg/L	488.29	8.80	10.29	16.00	23.14
pH	UNITS	7.43	6.16	6.21	6.17	6.30
Sodium (Na)	mg/L	91.33	2.14	5.21	5.68	7.46
Potassium (K)	mg/L	4.16	<0.1	0.16	0.20	0.26
Magnesium (Mg)	mg/L	26.49	0.60	0.61	2.14	0.79
Calcium (Ca)	mg/L	60.77	0.90	0.15	6.98	0.99
Boron (B)	mg/L	0.14	<0.1	0.12	<0.1	0.11
Total Hardness (as CaCO3)	mg/L	253.40	3.76	2.75	20.07	6.06
Alkalinity-Phenolphtalein (ALKPHE)	mg/L	<1	<1	<1	<1	<1
Total Alkalinity (TOTALK)	mg/L	114.80	4.86	5.82	4.53	7.01
Hydroxide (OHCa)	mg/L	<1	<1	<1	<1	<1
Carbonate (CO3Ca)	mg/L	<1	<1	<1	<1	<1
Bicarbonate (HCO3Ca)	mg/L	114.80	4.86	5.82	4.53	7.01
Nitrite Nitrogen (NO2-N)	mg/L	0.004	<0.002	<0.002	<0.002	<0.002
Chloride (Cl)	mg/L	98.34	4.13	6.54	4.84	10.94
Bromide (Br)	mg/L	<0.1	<0.1	<0.1	<0.1	<0.1
Nitrate Nitrogen (NO3-N)	mg/L	0.50	0.34	0.32	0.34	0.38
Phosphate Phosphorus (orthophospahte) (PO3-P)	mg/L	<0.1	<0.1	<0.1	<0.1	<0.1
Sulfate (SO4)	mg/L	169.60	4.12	2.79	3.91	3.47
Total Organic Carbon (Unfiltered) (TOC)	mg/L	2.62	0.24	0.28	0.23	0.26

Table 5. WB RO Test Unit Feedwater and Membrane Permeate General Minerals

Test Name	Units	Feedwater	M-T2514	ESPA1-2514	TW30-2514	M-C2514
Electrical Conductivity (EC)	µm/cm	1408.57	25.57	45.17	23.17	306.29
Total Dissolved Solids (TDS)	mg/L	651.00	18.00	28.67	19.67	120.00
pH	UNITS	7.69	6.34	6.49	6.36	7.07
Sodium (Na)	mg/L	171.00	2.96	3.14	1.94	39.63
Potassium (K)	mg/L	16.54	0.21	0.23	0.21	3.60
Magnesium (Mg)	mg/L	23.96	0.58	0.58	0.60	2.43
Calcium (Ca)	mg/L	49.47	2.05	17.80	0.85	5.74
Boron (B)	mg/L	0.59	0.19	0.26	0.16	0.48
Total Hardness (as CaCO3)	mg/L	222.14	3.51	16.35	2.75	24.36
Alkalinity-Phenolphtalein (ALKPHE)	mg/L	<1	<1	<1	<1	<1
Total Alkalinity (TOTALK)	mg/L	304.57	12.63	21.87	12.31	54.09
Hydroxide (OHCa)	mg/L	<1	<1	<1	<1	<1
Carbonate (CO3Ca)	mg/L	<1	<1	<1	<1	<1
Bicarbonate (HCO3Ca)	mg/L	304.57	12.63	21.87	12.31	54.09
Nitrite Nitrogen (NO2-N)	mg/L	0.180	<0.002	<0.002	<0.002	<0.002
Chloride (Cl)	mg/L	176.14	2.71	2.81	2.69	54.33
Bromide (Br)	mg/L	0.39	<0.1	<0.1	<0.1	0.26
Nitrate Nitrogen (NO3-N)	mg/L	0.38	0.32	0.32	0.32	0.43
Phosphate Phosphorus (orthophospahte) (PO3-P)	mg/L	1.53	<0.1	<0.1	<0.1	0.10
Sulfate (SO4)	mg/L	114.14	3.20	3.11	3.19	4.93
Total Organic Carbon (Unfiltered) (TOC)	mg/L	10.27	0.42	0.42	0.41	1.24

Table 6. OCWD RO Test Unit Feedwater and Membrane Permeate General Minerals

Test Name	Units	Feedwater	MT-2514	ESPA-1	TW-30	MC2-514
Electrical Conductivity (EC)	µm/cm	1550.00	31.23	32.70	29.81	74.07
Total Dissolved Solids (TDS)	mg/L	863.17	11.67	19.17	13.33	31.33
pH	UNITS	6.19	5.89	6.10	5.83	5.89
Sodium (Na)	mg/L	191.00	5.51	5.24	1.79	9.71
Potassium (K)	mg/L	14.21	0.53	0.33	0.32	0.83
Magnesium (Mg)	mg/L	3.73	1.63	1.63	2.45	1.63
Calcium (Ca)	mg/L	79.44	0.24	0.87	0.32	0.53
Boron (B)	mg/L	0.34	0.10	0.14	12.30	0.24
Total Hardness (as CaCO3)	mg/L	213.71	5.58	6.53	7.80	4.26
Alkalinity-Phenolphtalein (ALKPHE)	mg/L	<1	<1	<1	<1	<1
Total Alkalinity (TOTALK)	mg/L	38.33	13.97	14.39	36.47	14.80
Hydroxide (OHCa)	mg/L	<1	<1	<1	<1	<1
Carbonate (CO3Ca)	mg/L	<1	<1	<1	<1	<1
Bicarbonate (HCO3Ca)	mg/L	38.33	13.97	14.39	36.47	14.80
Nitrite Nitrogen (NO2-N)	mg/L	0.582	0.04	0.11	0.04	0.26
Chloride (Cl)	mg/L	219.25	2.56	2.80	2.54	11.11
Bromide (Br)	mg/L	0.23	<0.1	<0.1	<0.1	<0.1
Nitrate Nitrogen (NO3-N)	mg/L	0.75	0.38	0.36	0.38	0.47
Phosphate Phosphorus (orthophospahte) (PO3-P)	mg/L	<0.1	<0.1	<0.1	<0.1	<0.1
Sulfate (SO4)	mg/L	366.71	3.10	2.98	3.10	3.85
Total Organic Carbon (Unfiltered) (TOC)	mg/L	9.15	0.45	0.54	0.51	0.87

Table 7. SCWD RO Test Unit Feedwater and Membrane Permeate General Minerals

Test Name	Units	Feedwater	M-T2514	ESPA1-2514	TW30-2514	M-C2514
Electrical Conductivity (EC)	µm/cm	1145.56	25.07	20.89	14.61	129.89
Total Dissolved Solids (TDS)	mg/L	650.67	17.56	17.33	12.67	70.56
pH	UNITS	7.94	6.23	6.24	6.26	72.70
Sodium (Na)	mg/L	119.33	2.28	3.43	2.43	18.28
Potassium (K)	mg/L	24.74	0.37	0.51	0.44	6.51
Magnesium (Mg)	mg/L	29.89	0.20	0.20	0.23	0.97
Calcium (Ca)	mg/L	48.19	4.56	0.73	1.18	1.61
Boron (B)	mg/L	0.38	0.18	0.26	0.16	0.33
Total Hardness (as CaCO3)	mg/L	243.44	14.65	2.65	5.50	7.94
Alkalinity-Phenolphtalein (ALKPHE)	mg/L	<1	<1	<1	<1	<1
Total Alkalinity (TOTALK)	mg/L	240.67	11.39	6.83	7.14	15.20
Hydroxide (OHCa)	mg/L	<1	<1	<1	<1	<1
Carbonate (CO3Ca)	mg/L	<1	<1	<1	<1	<1
Bicarbonate (HCO3Ca)	mg/L	240.67	11.39	6.83	7.14	15.20
Nitrite Nitrogen (NO2-N)	mg/L	0.008	<0.002	<0.002	<0.002	<0.002
Chloride (Cl)	mg/L	143.47	2.51	3.49	2.33	24.91
Bromide (Br)	mg/L	0.12	<0.1	<0.1	<0.1	<0.1
Nitrate Nitrogen (NO3-N)	mg/L	1.76	0.35	0.41	0.36	1.17
Phosphate Phosphorus (orthophospahte) (PO3-P)	mg/L	2.15	<0.1	<0.1	<0.1	<0.1
Sulfate (SO4)	mg/L	56.53	2.73	2.67	2.73	2.88
Total Organic Carbon (Unfiltered) (TOC)	mg/L	6.07	0.28	0.29	0.31	0.41

Table 8. OCWD_MF RO Test Unit Feedwater and Membrane Permeate General Minerals

Test Name	Units	Feedwater	MT-2514	ESPA1--	TW-30-	MC-2514
Electrical Conductivity (EC)	µm/cm	1747.69	29.45	39.12	28.00	143.00
Total Dissolved Solids (TDS)	mg/L	965.23	15.78	20.77	13.15	64.46
pH	UNITS	6.97	6.30	6.15	6.10	6.22
Sodium (Na)	mg/L	208.23	4.96	6.10	3.47	20.08
Potassium (K)	mg/L	17.52	0.34	0.43	0.34	1.60
Magnesium (Mg)	mg/L	21.85	0.20	<0.1	0.10	0.24
Calcium (Ca)	mg/L	70.42	0.63	1.85	0.83	0.92
Boron (B)	mg/L	0.43	0.15	0.23	0.15	0.34
Total Hardness (as CaCO3)	mg/L	276.77	2.00	4.80	2.97	3.21
Alkalinity-Phenolphtalein (ALKPHE)	mg/L	<1	<1	<1	<1	<1
Total Alkalinity (TOTALK)	mg/L	120.61	15.12	15.37	13.95	18.71
Hydroxide (OHCa)	mg/L	<1	<1	<1	<1	<1
Carbonate (CO3Ca)	mg/L	<1	<1	<1	<1	<1
Bicarbonate (HCO3Ca)	mg/L	119.82	12.78	14.20	9.68	18.53
Nitrite Nitrogen (NO2-N)	mg/L	0.753	0.01	0.10	<0.002	0.52
Chloride (Cl)	mg/L	208.46	1.80	2.91	2.97	25.77
Bromide (Br)	mg/L	0.28	<0.1	<0.1	<0.1	0.15
Nitrate Nitrogen (NO3-N)	mg/L	1.01	0.18	0.37	0.45	0.43
Phosphate Phosphorus (orthophospahte) (PO3-P)	mg/L	0.24	<0.1	<0.1	<0.1	<0.1
Sulfate (SO4)	mg/L	379.23	2.85	2.83	2.25	2.81
Total Organic Carbon (Unfiltered) (TOC)	mg/L	10.34	0.88	0.92	0.76	1.25

Table 9. Yuma RO Test Unit Feedwater and Membrane Permeate General Minerals

Test Name	Units	Feedwater	M-T2514	ESPA1-2514	TW30-2514	M-C2514
Electrical Conductivity (EC)	μm/cm	3790.00	34.07	72.23	18.58	683.67
Total Dissolved Solids (TDS)	mg/L	2324.67	14.00	31.17	8.17	324.67
pH	UNITS	5.83	6.07	5.82	5.93	5.80
Sodium (Na)	mg/L	602.17	4.85	12.92	3.30	120.83
Potassium (K)	mg/L	6.57	0.10	0.40	<0.1	1.63
Magnesium (Mg)	mg/L	61.48	0.10	0.20	<0.1	1.45
Calcium (Ca)	mg/L	80.27	1.70	0.30	<0.1	2.12
Boron (B)	mg/L	1.03	0.33	0.70	0.28	0.94
Total Hardness (as CaCO3)	mg/L	453.83	8.10	1.70	<1	11.12
Alkalinity-Phenolphtalein (ALKPHE)	mg/L	<1	<1	<1	<1	<1
Total Alkalinity (TOTALK)	mg/L	4.55	3.63	1.52	1.88	2.58
Hydroxide (OHCa)	mg/L	<1	<1	<1	<1	<1
Carbonate (CO3Ca)	mg/L	<1	<1	<1	<1	<1
Bicarbonate (HCO3Ca)	mg/L	4.55	3.63	1.52	1.88	2.58
Nitrite Nitrogen (NO2-N)	mg/L	<0.002	<0.002	<0.002	<0.002	<0.002
Chloride (Cl)	mg/L	618.50	5.82	16.60	3.97	183.33
Bromide (Br)	mg/L	0.14	<0.1	0.15	<0.1	<0.1
Nitrate Nitrogen (NO3-N)	mg/L	4.00	0.39	0.76	0.35	2.88
Phosphate Phosphorus (orthophospahte) (PO3-P)	mg/L	<0.1	<0.1	<0.1	<0.1	<0.1
Sulfate (SO4)	mg/L	917.67	4.45	3.28	2.88	10.52
Total Organic Carbon (Unfiltered) (TOC)	mg/L	1.29	0.12	0.14	0.12	0.15

Table 10. Polyamide Membrane Properties. Membrane properties used as inputs in "Universal" polyamide model.

Membrane Properties	TW-30	MT-2514	ESPA-1
Roughness (nm)	58.94	81.44	83.95
Contact Angle	61.53	61.17	61.95
Specific Water Flux (gfd/psi)	0.11	0.14	0.24
Zeta Potential (mV)	-9.60	-20.84	-25.20
Zeta Potential Slope (pH 5-7)	-3.77	-4.11	-2.01
COO/AMID I Ratio	0.45	0.20	0.28
COO/AMID II Ratio	0.43	0.18	0.45
OH/Amide I Ratio	2.51	0.63	0.76
Polyamide Thickness	1.26	1.44	1.47

Table 11. ANN Specific Water Flux Model Influential Parameters. Sensitivity indices for each input, showing overall direction and magnitude of influence on specific water flux.

		Membrane Type			
	Parameter	**MT-2514**	**ESPA-1**	**TW-30**	**MC-2514**
	Time	**-0.350**	**-0.274**	**-0.821**	**-0.362**
Total Ions	**EC**				
	TDS				**-1.028**
Hydrogen Ions	**Ph**				
Monovalent Cations	**Na**				
	K	**-0.802**		**-0.517**	**0.248**
Divalent Cations	**Mg**				
	Ca				
	B		**-0.765**		
Hardness/Alkalinity	**TOTHRD**				**-0.500**
	ALKPHE				
	TOTALK			**0.617**	
	OHCa				
	CO3Ca				
	HCO3Ca		**-0.342**		
Monovalent Anions	**NO2-N**				
	Cl			**0.162**	**-0.048**
	Br	**0.042**		**0.106**	
Divalent/Trivelant Anions	**NO3-N**				
	PO3-P	**25.051**	**-18.268**	**-0.966**	
	SO4				
Organics	**TOC**				
Bacterial	**Bact/mL**	**0.272**			**-9.053**
	CFU/100mL	**0.519**	**-73.260**		**-16.927**

Table 12. ANN Percent Rejection Model Influential Parameters. Sensitivity indices for each input, showing overall direction and magnitude of influence on rejection in the models.

		Membrane Type			
	Parameter	MT-2514	ESPA-1	TW-30	MC-2514
	Time	-0.345	-0.621	0.129	-0.111
Total Ions	EC				
	TDS				
Hydrogen Ions	Ph				
Monovalent Cations	Na				
	K	-0.390			
Divalent Cations	Mg	0.805		1.226	
	Ca		0.114		0.623
	B				
Hardness/Alkalinity	TOTHRD		-0.159		
	ALKPHE				
	TOTALK				
	OHCa				
	CO3Ca				
	HCO3Ca				
Monovalent Anions	NO2-N			0.359	16.462
	Cl	0.216		-0.023	
	Br			0.446	-0.510
Divalent/Trivalent Anions	NO3-N				1.569
	PO3-P			-2.034	-0.697
	SO4				
Organics	TOC				
Bacterial	Bact/mL		-0.653		
	CFU/100mL			4.664	0.782

Table 13. ANN “Universal” Model Influential Parameters for Specific Water Flux and Percent Rejection. Sensitivity indices for each input showing overall direstion and magnitude of influence in models.

	Parameter	Specific H2O	% Rejection
	Time	-0.220	-0.269
Total Ions	EC	-1.216	
	TDS		
Hydrogen Ions	Ph		
Monovalent Cations	Na		
	K	-0.158	
Divalent Cations	Mg		0.572
	Ca		
	B	0.467	
Hardness/Alkalinity	TOTHRD		-0.266
	ALKPHE		
	TOTALK		
	OHCa		
	CO3Ca		
	HCO3Ca		
Monovalent Anions	NO2-N		
	Cl	0.188	0.069
	Br		
Divalent/Trivelant Anions	NO3-N		
	PO3-P	0.180	-0.114
	SO4		
Organics	TOC		
Bacterial	Bact/mL		-11.850
	CFU/100mL		
Membrane Properties	Roughness (nm)		
	Contact Angle		
	Specific Water Flux (GFD/PSI)		
	Zeta Potential (mV)		
	Zeta Potential Slope (pH 5-7)		
	COO/AMID I RATIO		
	COO/AMID II RATIO		
	OH/Amide I Ratio		
	"Polyamide Thickness"		

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GLOSSARY

Reverse osmosis membrane properties used as inputs in development ANN models.

Contact Angle (degrees) – The air bubble contact angle of the membrane, measured at the outside angle between the membrane surface and a line tangential to an air bubble trapped against the membrane surface (in 17 MOhm deionized water at 24ºC). The contact angle represents a measure of surface hydrophibicity; the smaller the angle, the greater the surface hydrophibicity.

COO/Amide I Ratio – A unitless relative index of membrane cross-link frequency derived from attenuated total internal reflection Fourier transform absorption at 1415cm^{-1} corresponding to the presence of free carboxylate groups and the absorption 1665 cm^{-1} corresponding to the amide I bonds in the membrane. The larger the ratio, the less cross-linked the membrane.

COO/Amide II Ratio - A unitless relative index of membrane cross-link frequency derived from ATR/FTIR absorption at 1415cm^{-1} corresponding to the presence of free carboxylate groups and the absorption 1542 cm^{-1} corresponding to the amide II bonds in the membrane. The larger the ratio, the less cross-linked the membrane.

OH/Amide I Ratio - A unitless relative index of membrane cross-link frequency derived from ATR/FTIR absorption at 3400 cm^{-1} corresponding to the presence of hydroxyl groups and the absorption 1665 cm^{-1} corresponding to the amide I bonds in the membrane. The larger the ratio, the less cross-linked the membrane.

Perceptron – Basic information processing element of neural network consisting of multiple input nodes with associated waiting functions that are summed internally to a single output node.

Polyamide Thickness – A unitless relative index derived from ATR/FTIR measurements based on the ratio of the strength of the 1665 cm^{-1} amide I absorption band of the polyamide layer and the 874 cm^{-1} absorption band of the polysulfone membrane support layer. The larger the ratio, the thicker the polyamide layer.

Roughness (nm) – A direct measurement by atomic force microscopy (AFM) of the rugosity of the membrane surface defined as the standard deviation of the height of features on the membrane, expressed in nanometers. The roughness of the membrane may reflect subtle differences in internal physicochemical properties. Interactions of nanoparticles with membrane surfaces are often positively related to surface roughness.

Specific Water Flux (gfd/psi) – Measurement of the membrane water flux per unit water pressure. Many membrane properties are represented by the specific water flux, including membrane density and intrinsic porosity, hydraulic conductivity, hydrogen bonding, charge interactions and many others.

Zeta Potential Slope (pH 5-7) – This is rate of change of the Zeta potential as the pH is shifted from 5 to 7. This index is inversely proportional to the ease with which membrane protons may be introduced or removed as the function of pH; the more negative the index, the more easily the merman may be protonated or deprotonated.

Å	Angstrom
AFM	Atomic Force Microscopy
ANN	Artificial Neural Network
ATR/FTIR	Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy
Bact.	Bacteria
CA	Cellulose Acetate
CCD	Charged-coupled Device
CFU	Colony Forming Unit
cm^2	centimeter squared
COO	Carboxylate
DI	Deionized
DNA	Deoxyribonucleic Acid
ESPA-1	Hydranautics reverse osmosis membrane
GA	Genetic Algorithm
gfd	gallon feet per day
HCl	Hydrochloric Acid
IR	mid-infrared
kHz	kilohertz
mL/min	milliliters per minute
mm	millimeter
N/m	Neuton per meter
MC-2514	Applied Membranes Cellulose Acetate Membrane
MF	Microfiltration
MWD	Metropolitan Water District
MT-2514	Applied Membranes Polyamide Membrane
N	Neuton
NaCl	Sodium Chloride
NF	Nanofiltration
NaOH	Sodium Hydroxide
OCWD	Orange County Water District
OCWD_MF	Orange County Water District_Microfiltration
OH	Hydroxide
PCA	Principal Component Analysis
psi	pound per square inch
rRNA	ribosomal ribonucleic acid
RO	Reverse Osmosis
R-value	Pierson Correlation Coefficient
SCWD	Santa Clara Water District
TW-30	Dow Film Tec Polyamide
UCR	University of California, Riverside

μL	microliter
μm	micron
WB	West Basin Municipal Water District

APPENDIX 1: MEMBRANE PERFORMANCE DATABASES

ESPA-1 Feed Water Quality Parameters and Membrane Performance at All Sites

Location	Time (hr)	EC	TDS	Ph	Na	K	Mg	Ca	B	TOTHRD	TOTALK	HCO3Ca	NO2-N	Cl	Br	NO3-N	PO3-P	SO4	TOC	Bact/mL	CFU/100 mL		spec. flux	% rejection
SCWD	120	1160	674	7.8	123	22.5	29.8	49.3	0.40	246	243	243	0.008	169	0.12	1.51	0.3	62.8	5.34	3.22E+06	2.98E+06		0.45	97.4
SCWD	288	1140	639	8.3	117	24.3	29.2	45.8	0.38	235	246	246	0.010	156	0.12	0.90	0.3	64.8	6.29	5.24E+06	9.42E+04		0.30	97.6
SCWD	624	1130	632	7.8	116	24.4	28.3	44.4	0.36	227	235	235	0.005	159	0.10	2.40	2.4	63.0	5.99	1.21E+07	9.70E+06		0.14	96.0
SCWD	792	1170	681	7.9	119	24.6	28.2	44.9	0.36	228	241	241	0.009	2.2	0.10	0.33	0.1	2.8	8.16	4.97E+06	3.45E+05		0.06	94.8
SCWD	960	1130	641	8	119	25.4	30.3	48.4	0.39	246	246	246	0.005	160	0.10	1.77	2.7	64.0	5.9	5.13E+06	9.33E+04		0.02	89.8
SCWD	1128	1150	657	7.7	116	23.9	28.8	47.5	0.36	237	244	244	0.007	162	0.10	0.29	3.4	62.2	5.80	1.61E+07	7.00E+06		0.01	87.3
MWD	48	910	NA	7.4	96	4.4	28.6	60.5	0.13	269	114	114	0.004	97.6	0.10	0.47	0.1	180.0	2.65	5.81E+04	7.67E+00		0.30	98.2
MWD	288	900	526	7.5	95	4.3	27.7	60.8	0.14	266	117	117	0.002	99.1	0.10	0.44	0.1	182.0	2.25	5.32E+04	7.00E+00		0.28	98.5
MWD	432	912	444	7.6	99	4.4	28.8	63.6	0.13	277	115	115	0.003	98.9	0.10	0.46	0.1	178.0	2.36	2.25E+04	7.67E+00		0.28	98.4
MWD	552	911	510	7.7	98	4.4	29.2	64.6	0.14	282	119	119	0.003	96.4	0.10	0.10	0.1	179.0	2.27	6.87E+04	2.33E+00		0.28	98.2
MWD	696	916	544	7.4	94	4.3	27.7	60.3	0.13	265	119	119	0.005	97.2	0.10	0.10	0.1	186.0	3.16	6.75E+04	2.10E+00		0.28	98.1
MWD	1248	837	460	7.2	83	3.6	23.1	51.2	0.14	223	108	108	0.003	101	1.00	0.51	0.1	152.0	3.35	2.75E+04	2.43E+01		0.28	97.5
MWD	1416	892	NA	7.4	90	4.2	26.6	91.7	0.14	264	118	118	0.003	94.6	1.00	0.58	0.1	179.0	3.13	8.42E+04	5.53E+00		0.27	97.2
MWD	1608	760	410	7.2	83	3.7	20.3	39.9	0.15	183	104	104	0.003	103	1.00	0.10	0.1	110.0	2.25	7.59E+04	7.67E-01		0.27	96.8
OCWD	120	1600	890	6.2	200	14.0	3.9	74.8	0.36	203	44	44	1.480	220	0.25	0.65	0.1	379.0	8.48	2.72E+06	1.57E+03		0.43	97.1
OCWD	288	1580	860	6.3	212	15.8	9.6	72.9	0.41	221	44	44	0.226	228	0.22	0.65	0.1	359.0	11.8	4.16E+06	2.80E+04		0.19	96.3
OCWD	456	1510	853	6.2	186	14.6	0.9	86.5	0.30	220	16	16	0.860	213	0.24	0.93	0.1	338.0	6.4	1.01E+06	7.45E+05		0.12	95.4
OCWD	624	1530	828	6.2	187	13.8	1.6	83.0	0.35	214	33	33	0.288	0.5	0.21	0.82	0.1	374.0	9.39	5.38E+06	6.00E+04		0.09	94.9
OCWD	792	1630	872	6.3	195	14.4	4	83.1	0.31	224	43	43	0.594	216	0.25	0.70	0.1	358.0	10.2	3.03E+06	1.37E+05		0.07	94.3
OCWD	984	1590	876	6.1	190	14.6	2.1	79.7	0.33	208	45	45	0.250	0.5	0.22	0.10	0.1	387.0	10.2	2.59E+06	4.87E+04		0.06	94.0
OCWD	1035	1410	NA	6	167	12.3	4	76.1	0.30	206	44	44	0.373	0.5	0.22	0.10	0.1	372.0	7.56	1.23E+06	6.53E+04		0.07	94.0
WB	24	1400	650	7.7	175	16.2	21.7	51.4	0.63	218	303	303	0.244	179	0.40	0.40	1.2	109.0	11.30	3.11E+04	1.67E+03		0.29	98.6
WB	192	1380	668	7.4	160	15.7	24.6	47.7	0.57	220	303	303	0.215	166	0.35	0.47	1.6	110.0	12.1	1.10E+03	1.05E+03		0.19	98.1
WB	528	1360	646	7.6	176	17.4	25.2	50.6	0.65	230	303	303	0.122	169	0.36	0.34	1.7	112.0	0.47	2.20E+04	1.44E+05		0.10	97.9
WB	696	1420	694	7.6	175	17.2	24.8	50.9	0.58	229	299	299	0.175	185	0.42	0.17	1.4	117.0	11.3	2.74E+04	4.15E+03		0.09	97.7
OCWD_MF	1	1640	878	6.5	175	15.5	21.2	18.5	0.36	276	87	87	0.530	190	0.18	1.16	0.1	371.0	11.9	5.44E+05	3.60E+02		0.14	97.8
OCWD_MF	48	1840	1030	7.6	222	17.5	22.1	76.2	0.41	281	98	98	0.019	220	0.26	0.55	0.2	428.0	14.3	2.73E+05	3.50E+02		0.10	97.7
OCWD_MF	192	1850	1010	7	222	17.2	22.1	78.6	0.41	287	155	155	0.080	223	0.25	0.41	0.2	373.0	12	1.10E+06	2.30E+03		0.09	98.0
OCWD_MF	360	1770	990	6.8	208	17.4	21.9	77.2	0.45	283	129	129	0.045	214	0.23	0.51	0.2	377.0	11.8	7.98E+03	1.30E+04		0.09	97.9
OCWD_MF	528	1800	1000	7.2	225	18.2	23.1	79.7	0.45	294	159	159	0.129	210	0.28	0.62	0.3	397.0	12.5	1.78E+04	1.80E+04		0.09	97.8
OCWD_MF	696	1820	1020	7	219	17.3	21.3	76.4	0.44	278	124	124	0.189	213	0.33	0.59	0.4	397.0	9.45	1.81E+05	4.40E+04		0.09	97.9
OCWD_MF	864	1820	948	7.7	209	18.6	22.2	82.2	0.44	297	130	na	1.270	220	0.26	0.47	0.3	362.0	8.35	1.46E+04	1.70E+04		0.08	97.8
OCWD_MF	1032	1700	964	6.8	188	18	21.3	78.1	0.46	283	100	100	1.470	203	0.38	0.21	0.2	381.0	10.5	1.61E+04	3.10E+04		0.08	97.7
OCWD_MF	1200	1730	960	6.6	212	17.6	21.2	72.1	0.42	267	113	113	0.732	202	0.29	0.34	0.3	378.0	11.7	3.33E+04	4.60E+04		0.08	97.6
OCWD_MF	1368	1650	920	6.6	207	17.3	20.2	71.9	0.44	263	112	112	2.510	205	0.31	6.32	0.1	380.0	7.81	5.20E+04	2.43E+04		0.07	97.5
OCWD_MF	1536	1520	822	7	175	16	21.6	71.6	0.41	268	111	111	1.790	183	0.24	0.37	0.2	308.0	11.6	2.27E+04	6.90E+03		0.07	97.6
OCWD_MF	1704	1770	986	6.9	220	19.7	22.2	67.6	0.46	260	129	129	0.170	204	0.28	0.82	0.3	389.0	11.8	2.13E+03	3.30E+03		0.06	97.6
OCWD_MF	1800	1810	1020	6.9	225	17.5	23.7	65.4	0.44	261	121	121	0.859	223	0.31	0.72	0.3	389.0	0.65	4.20E+03	4.10E+03		0.06	97.5
YUMA	0	3960	2470	5.7	639	6.9	66.8	95.2	1.15	513	1	1	0.002	654	0.10	4.33	0.1	975.0	1.32	1.83E+04	6.67		0.13	95.5
YUMA	162	3560	2180	6.3	589	6.8	60.7	76.0	1.03	440	7	7	0.002	571	0.10	3.83	0.1	882.0	1.36	1.63E+04	0.00		0.11	97.8
YUMA	31	3970	2440	5.9	599	6.4	59	70.0	1.01	418	2	2	0.002	621	0.10	4.43	0.1	916.0	1.18	1.20E+04	366.67		0.10	98.3
YUMA	498	3890	2370	6	622	6.8	67.2	86.3	1.05	492	4	4	0.002	651	0.10	3.92	0.1	941.0	1.31	1.23E+04	15.00		0.09	98.4
YUMA	666	3630	2180	4.8	547	6.1	52.9	74.0	0.92	403	2	2	0.002	595	0.14	3.72	0.1	877.0	1.32	1.13E+04	25.00		0.07	99.1
YUMA	834	3730	2308	6.3	617	6.4	62.3	80.1	1.02	457	12	12	0.002	619	0.14	3.79	0.1	915.0	1.24	1.32E+04	52.40		0.07	99.1

MT-2514 Water Quality Parameters and Membrane Performance at All Sites

Location	Time (hr)	EC	TDS	Ph	Na	K	Mg	Ca	B	TOTHRD	TOTALK	HCO3Ca	NO2-N	Cl	Br	NO3-N	PO3-P	SO4	TOC	Bact/mL	CFU/100 mL		spc. flux	% rejection
SCWD	120	1160	674	7.8	123	22.5	29.8	49.3	0.40	246	243	243	0.008	169	0.12	1.51	0.3	62.8	5.34	3.22E+06	2.98E+06		0.12	99.0
SCWD	288	1140	639	8.3	117	24.3	29.2	45.8	0.38	235	246	246	0.010	156	0.12	0.90	0.3	64.8	6.29	5.24E+06	9.42E+04		0.09	98.9
SCWD	624	1130	632	7.8	116	24.4	28.3	44.4	0.36	227	235	235	0.005	159	0.10	2.40	2.4	63.0	5.99	1.21E+07	9.70E+06		0.07	98.6
SCWD	792	1170	681	7.9	119	24.6	28.2	44.9	0.36	228	241	241	0.009	2	0.10	0.33	0.1	2.8	8.16	4.97E+06	3.45E+05		0.03	97.2
SCWD	960	1130	641	8.0	119	25.4	30.3	48.4	0.39	246	246	246	0.005	160	0.10	1.77	2.7	64.0	5.90	5.13E+06	9.33E+04		0.02	96.3
MWD	48	910	NA	7.4	96	4.4	28.6	60.5	0.13	269	114	114	0.004	98	0.10	0.47	0.1	180.0	2.65	5.81E+04	7.67E+00		0.17	98.9
MWD	288	900	526	7.5	95	4.3	27.7	60.8	0.14	266	117	117	0.002	99	0.10	0.44	0.1	182.0	2.25	5.32E+04	7.00E+00		0.19	99.1
MWD	432	912	444	7.6	99	4.4	28.8	63.6	0.13	277	115	115	0.003	99	0.10	0.46	0.1	178.0	2.36	2.25E+04	7.67E+00		0.19	98.9
MWD	552	911	510	7.7	98	4.4	29.2	64.6	0.14	282	119	119	0.003	96	0.10	0.10	0.1	179.0	2.27	6.87E+04	2.33E+00		0.20	98.8
MWD	696	916	544	7.4	94	4.3	27.7	60.3	0.13	265	119	119	0.005	97	0.10	0.10	0.1	186.0	3.16	6.75E+04	2.10E+00		0.20	98.7
MWD	1248	837	460	7.2	83	3.6	23.1	51.2	0.14	223	108	108	0.003	101	0.10	0.51	0.1	152.0	3.35	2.75E+04	2.43E+01		0.20	98.4
MWD	1608	760	410	7.2	83	3.7	20.3	39.9	0.15	183	104	104	0.003	103	0.10	0.10	0.1	110.0	2.25	7.59E+04	7.67E-01		0.18	97.9
OCWD	120	1600	890	6.2	200	14.0	3.9	74.8	0.36	203	44	44	1.480	220	0.25	0.65	0.1	379.0	8.48	2.72E+06	1.57E+03		0.15	98.1
OCWD	288	1580	860	6.3	212	15.8	9.6	72.9	0.41	221	44	44	0.226	228	0.22	0.65	0.1	359.0	11.80	4.16E+06	2.80E+04		0.09	97.4
OCWD	456	1510	853	6.2	186	14.6	0.9	86.5	0.30	220	16	16	0.860	213	0.24	0.93	0.1	338.0	6.40	1.01E+06	7.45E+05		0.07	97.0
OCWD	624	1530	828	6.2	187	13.8	1.6	83.0	0.35	214	33	33	0.288	1	0.21	0.82	0.1	374.0	9.39	5.38E+06	6.00E+04		0.05	96.5
OCWD	792	1630	872	6.3	195	14.4	4.0	83.1	0.31	224	43	43	0.594	216	0.25	0.70	0.1	358.0	10.20	3.03E+06	1.37E+05		0.04	96.1
OCWD	984	1590	876	6.1	190	14.6	2.1	79.7	0.33	208	45	45	0.250	1	0.22	0.10	0.1	387.0	10.20	2.59E+06	4.87E+04		0.03	95.7
WB	24	1400	650	7.7	175	16.2	21.7	51.4	0.63	218	303	303	0.244	179	0.40	0.40	1.2	109.0	11.30	3.11E+04	1.67E+03		0.26	98.8
WB	192	1380	668	7.4	160	15.7	24.6	47.7	0.57	220	303	303	0.215	166	0.35	0.47	1.6	110.0	12.10	1.10E+03	1.05E+03		0.16	98.3
WB	528	1360	646	7.6	176	17.4	25.2	50.6	0.65	230	303	303	0.122	169	0.36	0.34	1.7	112.0	0.47	2.20E+04	1.44E+05		0.16	98.5
WB	696	1420	694	7.6	175	17.2	24.8	50.9	0.58	229	299	299	0.175	185	0.42	0.17	1.4	117.0	11.30	2.74E+04	4.15E+03		0.16	98.4
OCWD_MF	1	1640	878	6.5	175	15.5	21.2	18.5	0.36	276	87	87	0.530	190	0.18	1.16	0.1	371.0	11.90	5.44E+05	3.60E+02		0.08	98.4
OCWD_MF	48	1840	1030	7.6	222	17.5	22.1	76.2	0.41	281	98	98	0.019	220	0.26	0.55	0.2	428.0	14.30	2.73E+05	3.50E+02		0.07	98.4
OCWD_MF	192	1850	1010	7.0	222	17.2	22.1	78.6	0.41	287	155	155	0.080	223	0.25	0.41	0.2	373.0	12.00	1.10E+06	2.30E+03		0.06	98.5
OCWD_MF	360	1770	990	6.8	208	17.4	21.9	77.2	0.45	283	129	129	0.045	214	0.23	0.51	0.2	377.0	11.80	7.98E+03	1.30E+04		0.06	98.5
OCWD_MF	528	1800	1000	7.2	225	18.2	23.1	79.7	0.45	294	159	159	0.129	210	0.28	0.62	0.3	397.0	12.50	1.78E+04	1.80E+04		0.06	98.4
OCWD_MF	696	1820	1020	7.0	219	17.3	21.3	76.4	0.44	278	124	124	0.189	213	0.33	0.59	0.4	397.0	9.45	1.81E+05	4.40E+04		0.07	98.6
OCWD_MF	864	1820	948	7.7	209	18.6	22.2	82.2	0.44	297	130	na	1.270	220	0.26	0.47	0.3	362.0	8.35	1.46E+04	1.70E+04		0.06	98.4
OCWD_MF	1032	1700	964	6.8	188	18.0	21.3	78.1	0.46	283	100	100	1.470	203	0.38	0.21	0.2	381.0	10.50	1.61E+04	3.10E+04		0.06	98.3
OCWD_MF	1200	1730	960	6.6	212	17.6	21.2	72.1	0.42	267	113	113	0.732	202	0.29	0.34	0.3	378.0	11.70	3.33E+04	4.60E+04		0.05	98.2
OCWD_MF	1368	1650	920	6.6	207	17.3	20.2	71.9	0.44	263	112	112	2.510	205	0.31	6.32	0.1	380.0	7.81	5.20E+04	2.43E+04		0.05	98.1
OCWD_MF	1536	1520	822	7.0	175	16.0	21.6	71.6	0.41	268	111	111	1.790	183	0.24	0.37	0.2	308.0	11.60	2.27E+04	6.90E+03		0.04	98.0
OCWD_MF	1704	1770	986	6.9	220	19.7	22.2	67.6	0.46	260	129	129	0.170	204	0.28	0.82	0.3	389.0	11.80	2.13E+03	3.30E+03		0.04	98.0
OCWD_MF	1800	1810	1020	6.9	225	17.5	23.7	65.4	0.44	261	121	121	0.859	223	0.31	0.72	0.3	389.0	0.65	4.20E+03	4.10E+03		0.04	97.9
YUMA	0	3960	2470	5.7	639	6.9	66.8	95.2	1.15	513	1	1	0.002	654	0.10	4.33	0.1	975.0	1.32	1.83E+04	6.67E+00		0.05	99.0
YUMA	162	3560	2180	6.3	589	6.8	60.7	76.0	1.03	440	7	7	0.002	571	0.10	3.83	0.1	882.0	1.36	1.63E+04	0.00E+00		0.08	99.4
YUMA	31	3970	2440	5.9	599	6.4	59.0	70.0	1.01	418	2	2	0.002	621	0.10	4.43	0.1	916.0	1.18	1.20E+04	3.67E+02		0.09	99.5
YUMA	498	3890	2370	6.0	622	6.8	67.2	86.3	1.05	492	4	4	0.002	651	0.10	3.92	0.1	941.0	1.31	1.23E+04	1.50E+01		0.09	99.5
YUMA	666	3630	2180	4.8	547	6.1	52.9	74.0	0.92	403	2	2	0.002	595	0.14	3.72	0.1	877.0	1.32	1.13E+04	2.50E+01		0.07	99.6
YUMA	834	3730	2308	6.3	617	6.4	62.3	80.1	1.02	457	12	12	0.002	619	0.14	3.79	0.1	915.0	1.24	1.32E+04	5.24E+01		0.08	99.6

TW-30 Water Quality Parameters and Membrane Performance at All Sites

Location	Time (hr)	EC	TDS	Ph	Na	K	Mg	Ca	B	TOTHRD	TOTALK	HCO3Ca	NO2-N	Cl	Br	NO3-N	PO3-P	SO4	TOC	Bact./mL	CFU/100mL		spec. flux	% rejection
SCWD	120	1160	674	7.8	123.0	22.5	29.8	49.3	0.40	246	243	243	0.008	169.0	0.12	1.51	0.3	62.8	5.34	3.22E+06	2.98E+06		0.26	98.7
SCWD	288	1140	639	8.3	117.0	24.3	29.2	45.8	0.38	235	246	246	0.010	156.0	0.12	0.90	0.3	64.8	6.29	5.24E+06	9.42E+04		0.26	98.1
SCWD	624	1130	632	7.8	116.0	24.4	28.3	44.4	0.36	227	235	235	0.005	159.0	0.10	2.40	2.4	63.0	5.99	1.21E+07	9.70E+06		0.13	98.1
SCWD	792	1170	681	7.9	119.0	24.6	28.2	44.9	0.36	228	241	241	0.009	2.2	0.10	0.33	0.1	2.8	8.16	4.97E+06	3.45E+05		0.09	97.9
SCWD	960	1130	641	8.0	119.0	25.4	30.3	48.4	0.39	246	246	246	0.005	160.0	0.10	1.77	2.7	64.0	5.9	5.13E+06	9.33E+04		0.06	96.0
SCWD	1128	1150	657	7.7	116.0	23.9	28.8	47.5	0.36	237	244	244	0.007	162.0	0.10	0.29	3.4	62.2	5.80	1.61E+07	7.00E+06		0.04	95.9
MWD	288	900	526	7.5	94.9	4.3	27.7	60.8	0.14	266	117	117	0.002	99.1	0.10	0.44	0.1	182.0	2.25	5.32E+04	7.00E+00		0.17	95.8
MWD	432	912	444	7.6	99.0	4.4	28.8	63.6	0.13	277	115	115	0.003	98.9	0.10	0.46	0.1	178.0	2.36	2.25E+04	7.67E+00		0.17	98.0
MWD	552	911	510	7.7	97.7	4.4	29.2	64.6	0.14	282	119	119	0.003	96.4	0.10	0.10	0.1	179.0	2.27	6.87E+04	2.33E+00		0.18	98.1
MWD	696	916	544	7.4	93.9	4.3	27.7	60.3	0.13	265	119	119	0.005	97.2	0.10	0.10	0.1	186.0	3.16	6.75E+04	2.10E+00		0.17	98.9
MWD	1248	837	460	7.2	82.9	3.6	23.1	51.2	0.14	223	108	108	0.003	101.0	0.10	0.51	0.1	152.0	3.35	2.75E+04	2.43E+01		0.18	98.9
MWD	1608	760	410	7.2	82.8	3.7	20.3	39.9	0.15	183	104	104	0.003	103.0	0.10	0.10	0.1	110.0	2.25	7.59E+04	7.67E-01		0.18	98.6
OCWD	120	1600	890	6.2	200.0	14.0	3.9	74.8	0.36	203	44	44	1.480	220.0	0.25	0.65	0.0	379.0	8.48	2.72E+06	1.57E+03		0.15	98.0
OCWD	288	1580	860	6.3	212.0	15.8	9.6	72.9	0.41	221	44	44	0.226	228.0	0.22	0.65	0.0	359.0	11.8	4.16E+06	2.80E+04		0.05	96.9
OCWD	456	1510	853	6.2	186.0	14.6	0.9	86.5	0.30	220	16	16	0.860	213.0	0.24	0.93	0.1	338.0	6.4	1.01E+06	7.45E+05		0.04	96.4
OCWD	624	1530	828	6.2	187.0	13.8	1.6	83.0	0.35	214	33	33	0.288	0.5	0.21	0.82	0.1	374.0	9.39	5.38E+06	6.00E+04		0.03	96.0
OCWD	792	1630	872	6.3	195.0	14.4	4.0	83.1	0.31	224	43	43	0.594	216.0	0.25	0.70	0.1	358.0	10.2	3.03E+06	1.37E+05		0.02	95.5
OCWD	984	1590	876	6.1	190.0	14.6	2.1	79.7	0.33	208	45	45	0.250	0.5	0.22	0.10	0.1	387.0	10.2	2.59E+06	4.87E+04		0.02	95.2
WB	24	1400	650	7.7	175.0	16.2	21.7	51.4	0.63	218	303	303	0.244	179.0	0.40	0.40	1.2	109.0	11.30	3.11E+04	1.67E+03		0.21	98.3
WB	192	1380	668	7.4	160.0	15.7	24.6	47.7	0.57	220	303	303	0.215	166.0	0.35	0.47	1.6	110.0	12.1	1.10E+03	1.05E+03		0.09	97.3
WB	528	1360	646	7.6	176.0	17.4	25.2	50.6	0.65	230	303	303	0.122	169.0	0.36	0.34	1.7	112.0	0.47	2.20E+04	1.44E+05		0.05	97.1
WB	696	1420	694	7.6	175.0	17.2	24.8	50.9	0.58	229	299	299	0.175	185.0	0.42	0.17	1.4	117.0	11.3	2.74E+04	4.15E+03		0.05	97.0
OCWD_MF	1	1640	878	6.5	175.0	15.5	21.2	18.5	0.36	276	87	87	0.530	190.0	0.18	1.16	0.1	371.0	11.9	5.44E+05	3.60E+02		0.08	98.2
OCWD_MF	48	1840	1030	7.6	222.0	17.5	22.1	76.2	0.41	281	98	98	0.019	220.0	0.26	0.55	0.2	428.0	14.3	2.73E+05	3.50E+02		0.07	98.4
OCWD_MF	192	1850	1010	7.0	222.0	17.2	22.1	78.6	0.41	287	155	155	0.080	223.0	0.25	0.41	0.2	373.0	12	1.10E+06	2.30E+03		0.05	98.4
OCWD_MF	360	1770	990	6.8	208.0	17.4	21.9	77.2	0.45	283	129	129	0.045	214.0	0.23	0.51	0.2	377.0	11.8	7.98E+03	1.30E+04		0.05	98.4
OCWD_MF	528	1800	1000	7.2	225.0	18.2	23.1	79.7	0.45	294	159	159	0.129	210.0	0.28	0.62	0.3	397.0	12.5	1.78E+04	1.80E+04		0.05	98.3
OCWD_MF	696	1820	1020	7.0	219.0	17.3	21.3	76.4	0.44	278	124	124	0.189	213.0	0.33	0.59	0.4	397.0	9.45	1.81E+05	4.40E+04		0.04	98.4
OCWD_MF	1032	1700	964	6.8	188.0	18.0	21.3	78.1	0.46	283	100	100	1.470	203.0	0.38	0.21	0.2	381.0	10.5	1.61E+04	3.10E+04		0.04	98.3
OCWD_MF	1200	1730	960	6.6	212.0	17.6	21.2	72.1	0.42	267	113	113	0.732	202.0	0.29	0.34	0.3	378.0	11.7	3.33E+04	4.60E+04		0.04	98.2
OCWD_MF	1368	1650	920	6.6	207.0	17.3	20.2	71.9	0.44	263	112	112	2.510	205.0	0.31	6.32	0.1	380.0	7.81	5.20E+04	2.43E+04		0.03	98.2
OCWD_MF	1536	1520	822	7.0	175.0	16.0	21.6	71.6	0.41	268	111	111	1.790	183.0	0.24	0.37	0.2	308.0	11.6	2.27E+04	6.90E+03		0.03	98.1
OCWD_MF	1704	1770	986	6.9	220.0	19.7	22.2	67.6	0.46	260	129	129	0.170	204.0	0.28	0.82	0.3	389.0	11.8	2.13E+03	3.30E+03		0.03	98.2
OCWD_MF	1800	1810	1020	6.9	225.0	17.5	23.7	65.4	0.44	261	121	121	0.859	223.0	0.31	0.72	0.3	389.0	0.65	4.20E+03	4.10E+03		0.03	98.2
Yuma	0	3960	2470	5.7	639.0	6.9	66.8	95.2	1.15	513	1	1	0.002	654.0	0.10	4.33	0.1	975.0	1.32	1.83E+04	6.67E+00		0.06	99.5
Yuma	162	3560	2180	6.3	589.0	6.8	60.7	76.0	1.03	440	7	7	0.002	571.0	0.10	3.83	0.1	882.0	1.36	1.63E+04	0.00E+00		0.12	99.6
Yuma	31	3970	2440	5.9	599.0	6.4	59.0	70.0	1.01	418	2	2	0.002	621.0	0.10	4.43	0.1	916.0	1.18	1.20E+04	3.67E+02		0.12	99.6
Yuma	498	3890	2370	6.0	622.0	6.8	67.2	86.3	1.05	492	4	4	0.002	651.0	0.10	3.92	0.1	941.0	1.31	1.23E+04	1.50E+01		0.13	99.6
Yuma	666	3630	2180	4.8	547.0	6.1	52.9	74.0	0.92	403	2	2	0.002	595.0	0.14	3.72	0.1	877.0	1.32	1.13E+04	2.50E+01		0.10	99.7
Yuma	834	3730	2308	6.3	617.0	6.4	62.3	80.1	1.02	457	12	12	0.002	619.0	0.14	3.79	0.1	915.0	1.24	1.32E+04	5.24E+01		0.10	99.6

MC-2514 Water Quality Parameters and Membrane Performance at All Sites

Location	Time (hr)	EC	TDS	Ph	Na	K	Mg	Ca	B	TOTHRD	TOTALK	HCO3Ca	NO2-N	Cl	Br	NO3-N	PO3-P	SO4	TOC	Bact/mL	CFU/100 mL		spc. flux	% rejection
SCWD	120	1160	674	7.8	123	22.5	29.8	49.3	0.40	246	243	243	0.008	169.0	0.12	1.51	0.3	62.8	5.34	3.22E+06	2.98E+06		0.08	92.6868
SCWD	288	1140	639	8.3	117	24.3	29.2	45.8	0.38	235	246	246	0.010	156.0	0.12	0.90	0.3	64.8	6.29	5.24E+06	9.42E+04		0.09	92.87
SCWD	624	1130	632	7.8	116	24.4	28.3	44.4	0.36	227	235	235	0.005	159.0	0.10	2.40	2.4	63.0	5.99	1.21E+07	9.70E+06		0.10	92.17
SCWD	792	1170	681	7.9	119	24.6	28.2	44.9	0.36	228	241	241	0.009	2.2	0.10	0.33	0.1	2.8	8.16	4.97E+06	3.45E+05		0.07	90.36
SCWD	960	1130	641	8.0	119	25.4	30.3	48.4	0.39	246	246	246	0.005	160.0	0.10	1.77	2.7	64.0	5.90	5.13E+06	9.33E+04		0.04	86.56
SCWD	1128	1150	657	7.7	116	23.9	28.8	47.5	0.36	237	244	244	0.007	162.0	0.10	0.29	3.4	62.2	5.80	1.61E+07	7.00E+06		0.03	84.47
MWD	48	910	NA	7.4	96	4.4	28.6	60.5	0.13	269	114	114	0.004	97.6	0.10	0.47	0.1	180.0	2.65	5.81E+04	7.67E+00		0.08	92.19
MWD	288	900	526	7.5	95	4.3	27.7	60.8	0.14	266	117	117	<.002	99.1	0.10	0.44	0.1	182.0	2.25	5.32E+04	7.00E+00		0.08	92.14
MWD	432	912	444	7.6	99	4.4	28.8	63.6	0.13	277	115	115	0.003	98.9	0.10	0.46	0.1	178.0	2.36	2.25E+04	7.67E+00		0.08	90.80
MWD	552	911	510	7.7	98	4.4	29.2	64.6	0.14	282	119	119	0.003	96.4	0.10	0.10	0.1	179.0	2.27	6.87E+04	2.33E+00		0.08	89.63
MWD	696	916	544	7.4	94	4.3	27.7	60.3	0.13	265	119	119	0.005	97.2	0.10	0.10	0.1	186.0	3.16	6.75E+04	2.10E+00		0.09	89.47
MWD	1248	837	460	7.2	83	3.6	23.1	51.2	0.14	223	108	108	0.003	101.0	0.10	0.51	0.1	152.0	3.35	2.75E+04	2.43E+01		0.09	85.82
MWD	1608	760	410	7.2	83	3.7	20.3	39.9	0.15	183	104	104	0.003	103.0	0.10	0.10	0.1	110.0	2.25	7.59E+04	7.67E-01		0.09	83.93
OCWD	120	1600	890	6.2	200	14.0	3.9	74.8	0.36	203	44	44	1.480	220.0	0.25	0.65	0.1	379.0	8.48	2.72E+06	1.57E+03		0.07	94.26
OCWD	288	1580	860	6.3	212	15.8	9.6	72.9	0.41	221	44	44	0.226	228.0	0.22	0.65	0.1	359.0	11.80	4.16E+06	2.80E+04		0.05	94.71
OCWD	456	1510	853	6.2	186	14.6	0.9	86.5	0.30	220	16	16	0.860	213.0	0.24	0.93	0.1	338.0	6.40	1.01E+06	7.45E+05		0.04	94.30
OCWD	624	1530	828	6.2	187	13.8	1.6	83.0	0.35	214	33	33	0.288	0.5	0.21	0.82	0.1	374.0	9.39	5.38E+06	6.00E+04		0.03	94.28
OCWD	792	1630	872	6.3	195	14.4	4.0	83.1	0.31	224	43	43	0.594	216.0	0.25	0.70	0.1	358.0	10.20	3.03E+06	1.37E+05		0.02	93.83
OCWD	984	1590	876	6.1	190	14.6	2.1	79.7	0.33	208	45	45	0.250	0.5	0.22	0.10	0.1	387.0	10.20	2.59E+06	4.87E+04		0.02	93.62
WB	24	1400	650	7.7	175	16.2	21.7	51.4	0.63	218	303	303	0.244	179.0	0.40	0.40	1.2	109.0	11.30	3.11E+04	1.67E+03		0.15	81.27
WB	192	1380	668	7.4	160	15.7	24.6	47.7	0.57	220	303	303	0.215	166.0	0.35	0.47	1.6	110.0	12.10	1.10E+03	1.05E+03		0.13	80.22
WB	528	1360	646	7.6	176	17.4	25.2	50.6	0.65	230	303	303	0.122	169.0	0.36	0.34	1.7	112.0	0.47	2.20E+04	1.44E+05		0.11	78.28
WB	696	1420	694	7.6	175	17.2	24.8	50.9	0.58	229	299	299	0.175	185.0	0.42	0.17	1.4	117.0	11.30	2.74E+04	4.15E+03		0.12	79.04
OCWD_MF	1	1640	878	6.5	175	15.5	21.2	18.5	0.36	276	87	87	0.530	190.0	0.18	1.16	0.1	371.0	11.90	5.44E+05	3.60E+02		0.06	90.95
OCWD_MF	48	1840	1030	7.6	222	17.5	22.1	76.2	0.41	281	98	98	0.019	220.0	0.26	0.55	0.2	428.0	14.30	2.73E+05	3.50E+02		0.05	91.61
OCWD_MF	192	1850	1010	7.0	222	17.2	22.1	78.6	0.41	287	155	155	0.080	223.0	0.25	0.41	0.2	373.0	12.00	1.10E+06	2.30E+03		0.05	92.09
OCWD_MF	360	1770	990	6.8	208	17.4	21.9	77.2	0.45	283	129	129	0.045	214.0	0.23	0.51	0.2	377.0	11.80	7.98E+03	1.30E+04		0.05	92.28
OCWD_MF	528	1800	1000	7.2	225	18.2	23.1	79.7	0.45	294	159	159	0.129	210.0	0.28	0.62	0.3	397.0	12.50	1.78E+04	1.80E+04		0.05	91.96
OCWD_MF	696	1820	1020	7.0	219	17.3	21.3	76.4	0.44	278	124	124	0.189	213.0	0.33	0.59	0.4	397.0	9.45	1.81E+05	4.40E+04		0.05	92.35
OCWD_MF	864	1820	948	7.7	209	18.6	22.2	82.2	0.44	297	130	na	1.270	220.0	0.26	0.47	0.3	362.0	8.35	1.46E+04	1.70E+04		0.04	92.14
OCWD_MF	1032	1700	964	6.8	188	18.0	21.3	78.1	0.46	283	100	100	1.470	203.0	0.38	0.21	0.2	381.0	10.50	1.61E+04	3.10E+04		0.04	92.06
OCWD_MF	1200	1730	960	6.6	212	17.6	21.2	72.1	0.42	267	113	113	0.732	202.0	0.29	0.34	0.3	378.0	11.70	3.33E+04	4.60E+04		0.04	91.66
OCWD_MF	1368	1650	920	6.6	207	17.3	20.2	71.9	0.44	263	112	112	2.510	205.0	0.31	6.32	0.1	380.0	7.81	5.20E+04	2.43E+04		0.03	91.82
OCWD_MF	1536	1520	822	7.0	175	16.0	21.6	71.6	0.41	268	111	111	1.790	183.0	0.24	0.37	0.2	308.0	11.60	2.27E+04	6.90E+03		0.03	91.57
OCWD_MF	1704	1770	986	6.9	220	19.7	22.2	67.6	0.46	260	129	129	0.170	204.0	0.28	0.82	0.3	389.0	11.80	2.13E+03	3.30E+03		0.03	91.67
OCWD_MF	1800	1810	1020	6.9	225	17.5	23.7	65.4	0.44	261	121	121	0.859	223.0	0.31	0.72	0.3	389.0	0.65	4.20E+03	4.10E+03		0.03	91.03
YUMA	0	3960	2470	5.7	639	6.9	66.8	95.2	1.15	513	1	1	0.002	654.0	0.10	4.33	0.1	975.0	1.32	1.83E+04	6.67E+00		0.06	83.79
YUMA	162	3560	2180	6.3	589	6.8	60.7	76.0	1.03	440	7	7	0.002	571.0	0.10	3.83	0.1	882.0	1.36	1.63E+04	0.00E+00		0.06	85.05
YUMA	31	3970	2440	5.9	599	6.4	59.0	70.0	1.01	418	2	2	0.002	621.0	0.10	4.43	0.1	916.0	1.18	1.20E+04	3.67E+02		0.06	84.80
YUMA	498	3890	2370	6.0	622	6.8	67.2	86.3	1.05	492	4	4	0.002	651.0	0.10	3.92	0.1	941.0	1.31	1.23E+04	1.50E+01		0.06	84.62
YUMA	666	3630	2180	4.8	547	6.1	52.9	74.0	0.92	403	2	2	0.002	595.0	0.14	3.72	0.1	877.0	1.32	1.13E+04	2.50E+01		0.06	86.28
YUMA	834	3730	2308	6.3	617	6.4	62.3	80.1	1.02	457	12	12	0.002	619.0	0.14	3.79	0.1	915.0	1.24	1.32E+04	5.24E+01		0.06	85.82

APPENDIX 2: RO TEST UNIT STANDARD OPERATING PROCEDURE

This test unit is designed as a single-pass system with 4 RO vessels arranged in parallel and fed by a common manifold. Each vessel (and its corresponding bank) is designed to run independently and is equipped with a pressure gauge to monitor feed and concentrate pressure as well as a flow meter to monitor the concentrate flow rate. The permeate flux must be measured by hand using a standard stopwatch and graduated cylinder. The permeate tubing is located on the right side of each vessel and collectively drain into a manifold, also located on the right side of the test unit. The direction of flow to each vessel is from left to right if standing in front of the unit. Each vessel contains 1 spiral wound element with the following dimensions: 2.5-in diameter and 14-in length. A temperature gauge has been mounted on the panel to measure the feed water temperature in the tank.

A 30-gallon feed tank and lid are mounted on the rear of the test unit. A spillway is inserted at the top of the tank to ensure that an optimal supply of water exists in the tank at all times. As a safety precaution, the tank is also equipped with a float level switch, which will automatically turn the system off in the event that the water supply to the tank is interrupted.

All membranes shall be operated at a constant flux throughout the duration of the test period. Membrane performance (measured in terms of flux and rejection) shall be monitored and recorded on a routine basis using the provided log sheets. Detailed water quality analysis shall be coordinated with the project coordinator.

The following pages provide detailed information regarding the operation of this RO test unit.

Start-Up Procedure

1. Open tank influent valve to fill tank and allow excess to spill over to drain.
2. Open priming vent plug (1) on the pump until a steady stream of airless water runs out the priming port.
3. Close the priming vent plug.
4. Insure that the following valves are fully open:
5. Bypass Valve (1)
6. Brine Flow Valve (4)
7. Close the GO pressure regulators (blue knob) (4) completely by turning counterclockwise (“decrease” as noted on the pressure regulator blue dial).
8. Switch system power on.
9. Slowly initiate flow to each bank/membrane vessel by opening the GO regulators (NOTE: Turn each GO regulator clockwise [“increase” as noted on the blue dial] 5-8 times until concentrate flow rate reads approximately 1.5 GPM on each flow meter).
10. Close the Bypass Valve completely.

11. Begin closing Brine Flow Valves (NOTE: Concentrate flow rate will begin to decrease while the pressure begins to increase). While doing this, proceed to step 10.
12. Continue to open the GO pressure regulators (clockwise turn [“increase” direction as noted on the blue dial]).
13. Toggle between adjusting GO pressure regulator and the Brine Flow Valve until the desired flow rates (concentrate and permeate) are achieved (see Membrane Operating Parameters for specifications). NOTE: During the first 2-3 days of operation, these parameters will continually change until the membranes stabilize. Once stabilized, these parameters should only need minor adjustments to maintain a constant permeate or flux.

<u>Shut-Down Procedure</u>

1. Completely Open Bypass Flow Valve.
2. Close GO pressure regulators (counterclockwise turn [“decrease” as noted on the pressure regulator blue dial]).
3. Switch system power off.
4. Drain water from feed tank.
5. Secure unit.