Part I. Alternatives to Pilot Plant Studies for Membrane Technologies

FINAL Report

by
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Texas Water Development Board
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1 Executive summary

The Texas Water Development Board (TWDB) estimates that an additional 8.3 million acre-feet of water will be needed in Texas by 2060 if new water supplies are not developed to offset population growth and existing water supply reduction due to drought. By 2060, the Texas population is projected to be 46.3 million people, almost twice the 2010 population of approximately 25.4 million people. Development of alternative and new water resources is critical to sustainable growth of the State of Texas, and the use of reliable membrane water treatment systems will likely play an important role in developing these sustainable water resources.

Membrane technologies are applied for either particle filtration or removal of dissolved constituents. The technologies used for these applications have very different capabilities. Microfiltration and ultrafiltration membranes are low-pressure filtration processes that are principally designed to remove physical and microbiological contamination. For treatment systems designed to remove microbiological contamination, the Log Removal Value of a membrane system is a critical design parameter. Commercial microfiltration/ultrafiltration membrane systems include proprietary membrane materials and a range of hydraulic configurations. These characteristics influence performance of a particular membrane based on given feed water, making design criteria vendor-specific. Innovations in products over time to improve performance further complicate efforts to generically predict design criteria across the industry. As a result, design criteria are typically based on proprietary empirical models developed by the manufacturer or some form of testing on the actual source water with a specific model or prototype.

Nanofiltration and reverse osmosis membrane systems are typically used for desalting brackish groundwater and surface water. They are generally configured in spiral wound configurations, with membrane materials and system designs focused on dissolved salt rejection and energy efficiency (among other factors). These systems are designed with pretreatment filtration of raw waters because desalting membranes cannot be backwashed. Pretreatment filtration minimizes particle content and variability in the desalting feed, so design criteria is often established with models available from the membrane manufacturers that focus on predicting salt rejection and avoiding precipitation.

The regulatory requirements for approving construction of a membrane system for drinking water treatment vary from one State to the next. In general, these regulations are consistent with the federal requirements for groundwater and surface waters. For surface water treatment, membrane systems are categorized as “alternative filtration technologies,” typically, requiring performance demonstration to meet the requirements of the surface water treatment rules. Groundwater treatment is typically not subject to the same demonstration requirements as surface waters because the membranes (especially desalting membranes used to treat brackish groundwater) are not being used for pathogen removal. The design of these treatment systems is left to the judgment of the professional engineer.

Under the current Texas Administrative Code, membranes (both low-pressure and desalting) are considered “innovative technologies” for water treatment. To implement membrane treatment for drinking water, municipalities and water districts are required to perform demonstration-scale pilot testing for permitting approval by the Texas Commission on Environmental Quality, regardless of whether groundwater or surface water are used.

Texas Commission on Environmental Quality has a defined process for approving membrane technologies, which is intended to provide consistency in the design and piloting of membrane treatment facilities in Texas. This process is intended to bolster the reliability of the treatment plant's ability to produce the desired flow and product water quality. The principal disadvantage of this approach is that the requirement for piloting may, in some cases, be unnecessarily slow, and thereby delay or deter the construction process for communities in desperate need of new drinking water sources. As a result, the extra time, cost, and exception process steps required for the use of membrane technologies in water treatment facilities can deter owners and public water systems from developing new and much needed water supplies.

Another disadvantage of the current Texas Commission on Environmental Quality exception process for membrane treatment systems is that the requirement for demonstration piloting may unnecessarily encumber significant financial costs for the design of membrane treatment of typical waters where the performance of membrane systems can be well predicted. Nationally, the total cost of piloting a membrane system may range from $50,000 to $100,000. Based on recent projects in Texas that are ongoing with TWDB, the cost of pilot testing ranges from $75,000 to $2,690,945, and the ratio of the pilot cost to total cost ranges from less than one percent to as high as fourteen percent.

While the objective of Texas Commission on Environmental Quality's extensive pilot testing requirement is to protect public health and safety by demonstrating the reliability of membrane treatment processes, public health and safety may actually be at risk by the requirement if water supplies become inadequate to meet the needs of the community due to the time and cost of developing new water supplies that require membrane treatment. The design of reliable membrane treatment systems (especially brackish groundwater desalination) can be executed with proper engineering consideration without demonstration pilot testing, as in other states. Nevertheless, Texas Commission on Environmental Quality's rules are flexible to allow consideration of emergency situations and seek to have alternatives to pilot studies clearly defined.

2 Introduction

2.1 Background

The TWDB estimates that an additional 8.3 million acre-feet of water will be needed in Texas by 2060 if new water supplies are not developed to offset population growth and a reduction in existing water supplies due to drought (TWDB, 2012a). By 2060, the Texas population is projected to be 46.3 million people compared to the 2010 population of approximately 25.4 million people (TWDB, 2012a). Development of alternative and new water resources is critical to sustainable growth of the State of Texas, and the use of reliable membrane water treatment systems (both low-pressure filtration systems and desalination systems) will likely play an important role in developing these sustainable water resources.

Low-pressure membrane treatment processes (such as microfiltration and ultrafiltration) are alternatives to conventional granular media filtration for turbidity and pathogen removal, and may require a smaller land area footprint. Low-pressure membrane systems are quite robust with respect to variations in source water quality (such as seasonal effects on rivers and lakes).

Desalinated water is expected to be an increasingly important water supply to fill this water demand, with an estimated 310,000 acre-feet per year by 2060 (TWDB, 2011). Seawater and brackish water contain dissolved solids (salts) that need to be removed (a process called "desalination") to produce potable water. Desalting membrane systems such as nanofiltration, reverse osmosis, and electrodialysis are typically used for this purpose. Seawater desalination is available along the Gulf Coast, and there is an estimated 2.7 billion acre-feet of brackish water available statewide (TWDB, 2007).The majority of the new desalination capacity is expected to come from 60 percent brackish desalination and the rest from seawater desalination (TWDB, 2011). Currently in Texas, there is no seawater desalination and the brackish desalination capacity installed is 134,500 acre-feet per year (Shirazi and Arroyo, 2011). The two brackish desalination water sources are approximately 60 percent groundwater and 40 percent surface water (Arroyo, 2011). Reverse osmosis is the primary desalination technology utilized in Texas to generate drinking water.

Unfortunately, misconceptions about membrane technologies exist in part by regulators, decision makers, and the general public, which have impacted the industry by limiting the growth of application of membranes for water treatment (Mickley, 2001).Under the current Texas Administrative Code, membranes (both low-pressure and desalting) are considered "innovative technologies" for water treatment. To implement membrane treatment for drinking water, municipalities and water districts are required to perform demonstration-scale pilot testing for permitting approval by the Texas Commission on Environmental Quality.

Demonstration-scale pilot testing is costly for water systems and can be a significant fraction of the total cost of the full-scale treatment system. As a result, pilot testing can be a deterrent for the use of membrane technologies. In certain situations, such as brackish water desalination, pilot testing may not be necessary for full-scale technical design. Therefore, review of the current Texas Commission on Environmental Quality membrane permitting procedure is imperative for potential revision, in light of Texas future water demands, the current state of membrane technologies, and membrane performance evaluation methods. A revised permitting process that reduces or avoids pilot testing requirements could facilitate more rapid and less costly implementation of membrane technologies for meeting current and future water demands.

2.2 Project goals

The goal of this project is to develop a guidance document for more efficient pathways to safely approve desalting membrane systems in the State of Texas. The objectives of this project are (1) to perform a review of membrane performance evaluation methods (especially alternatives to demonstration-scale pilot testing) for predicting full-scale performance and (2) to collect data from past piloting alternative approaches and analyze these data to establish confidence for predicting full-scale performance and (3) to prepare a guidance document on alternatives to membrane pilot studies for Texas Commission on Environmental Quality acceptance and outreach.

The accuracy in predicting the performance of full-scale membrane treatment systems by alternative means than demonstration-scale piloting (Phase 2) may help Texas agencies approve membranes without the need of expensive demonstration-scale pilot testing. A summary of the results from the piloting alternatives data analysis is presented in *Part II. Performance Evaluation of Reverse Osmosis Membrane Computer Models.*

2.3 Literature review objectives

The first phase of this project is a literature review of membrane technology, methods for predicting performance of full-scale systems, and state permitting approaches of membrane technologies. The objectives of the literature review are as follows:

1. Evaluate the current state of low-pressure and desalting membrane technologies;
2. Summarize the alternative approaches to demonstration-scale pilot testing, such as computer models and bench-scale testing; and
3. Evaluate other states' approaches for approving membrane technologies for drinking water treatment.

The assessment of membrane technology (Chapter 3) begins with a background on membrane classifications and development. Then membrane technologies are reviewed separately as low-pressure and desalting systems, each with respect to system design, membrane composition, and system operation and maintenance.

Methods for performance evaluation and full-scale prediction (Chapter 4) begin with an overview of the input and output parameters and primary function of the methods in general. The types of methods identified are computer model, bench-scale, and pilot-scale tests, and each section includes a summary of the objectives and qualitative and quantitative results for each test. The low-pressure membrane methods examined are filtration models, bench-scale hollow-fiber and flat-sheet testing, single-element testing, and demonstration-scale testing. Similarly, the same four categories of tests are discussed for application to desalting membranes.

In Chapter 5, a review of the regulatory requirements for pilot testing for membrane treatment with groundwater and surface water sources are examined at the federal level. Next, Texas's approach on regulations, permitting, and piloting requirements is detailed. Then a comparison of federal and state membrane treatment regulations is provided for the following eight states: Arizona, California, Florida, Illinois, New Mexico, South Carolina, Virginia, and Wisconsin.

3 Membrane technology

3.1 Background

3.1.1 Membrane development

The membrane industry has advanced dramatically over the past century, as shown in Figure 3-1. Membrane technology was developed in the mid-1800s; the first "reverse osmosis" nitrocellulose synthetic membrane was created by Adolph Fick in 1855. The first desalination plant was installed in 1888 in Tas-Miela, Malta, a small island located in Mediterranean Sea. In 1937, Sartorius GmbH commercially manufactured nitrocellulose membranes, and subsequent researchers developed cellulose acetate membranes in the mid-1950s (Binnie, 2002). The first spiral wound module was created by General Atomics in 1967, and the development of the composite membrane was one of the greatest achievements in reducing energy consumption in membrane treatment systems. With the development of automated membrane synthesis, the membrane market has become quite competitive, and the cost of consistent and reliable membranes has decreased dramatically in recent years.

A significant part of the state of membrane technology is the number and capacity of membrane plants currently being used in the world. Low-pressure membrane plants in 2007 had global installed capacity of about 3,600 million gallons per day (National Water Research Institute, 2008). The world production of desalinated water is approximately 0.6 percent of total global water supply, which equates to 17,225 million gallons per day (IEA-ETSAP, 2012). Globally approximately 15,000 desalination plants exist with 18,915 million gallons per day design capacity (IEA-ETSAP, 2012). The main technology utilized for global production of desalinated water is reverse osmosis and accounts for 60 percent (IEA-ESTAP, 2012).

Nationwide surveys were conducted by Mickley and Associates to identify municipal water treatment plants with membrane filtration for the periods prior to 1992, 1999 to 2002, and 2002 to 2010 (Mickley, 1993, Mickley, 2006, Mickley, 2011). The last survey from 2002 to 2010 only updated the data for desalting membrane plants. These surveys examined treatment plants by size, type, and location. The most recent study identifies a total of 422 low pressure and desalting membrane water and wastewater treatment plants with a capacity of 25,000 gallons per day (0.025 million gallons per day) or greater (Mickley, 2006).

Low-pressure membrane plants (microfiltration and ultrafiltration) multiplied from 1 to 188 in the period from 1992 to 2002 (Mickley, 2006).The first microfiltration and ultrafiltration plants were installed in the United States in 1980 and 1993, respectively. Of the 188 low-pressure plants in 2002, 155 (82 percent) were microfiltration and 33 (18 percent) were ultrafiltration. Microfiltration plants are predominately located in California (22 percent), Colorado (12 percent), and Virginia (10 percent) (Mickley, 2006). For ultrafiltration plants, there is not a predominant location since the number of plants is small and spread out throughout the United States. (The state with the largest number of ultrafiltration plants is California with four plants.) Memcor, now a subsidiary of Siemens, is the predominant provider for microfiltration plants, followed by Pall. The primary providers for ultrafiltration systems are AquaSource, Koch, and Zenon.

Desalting plants, including reverse osmosis, nanofiltration, and electrodialysis, were also surveyed. These surveys revealed that desalting plants increased from 133 in 1993 to 324 in 2010, and these desalting plants are located primarily in Florida (45 percent), California (14 percent), and Texas (9 percent) (Mickley, 2011). The first reverse osmosis plant identified in the study was installed in 1966, and by 2010, the total number of reverse osmosis plants had grown to 260. The first nanofiltration plant was installed in 1999, and by 2010, a total of 43 nanofiltration plants existed. As of 2010, the distribution of desalting plants by type was 73 percent brackish reverse osmosis, 3 percent Seawater reverse osmosis, 13 percent nanofiltration, 6 percent electrodialysis/electrodialysis reversal, 3 percent microfiltration with reverse osmosis, and 1 percent microfiltration with nanofiltration.

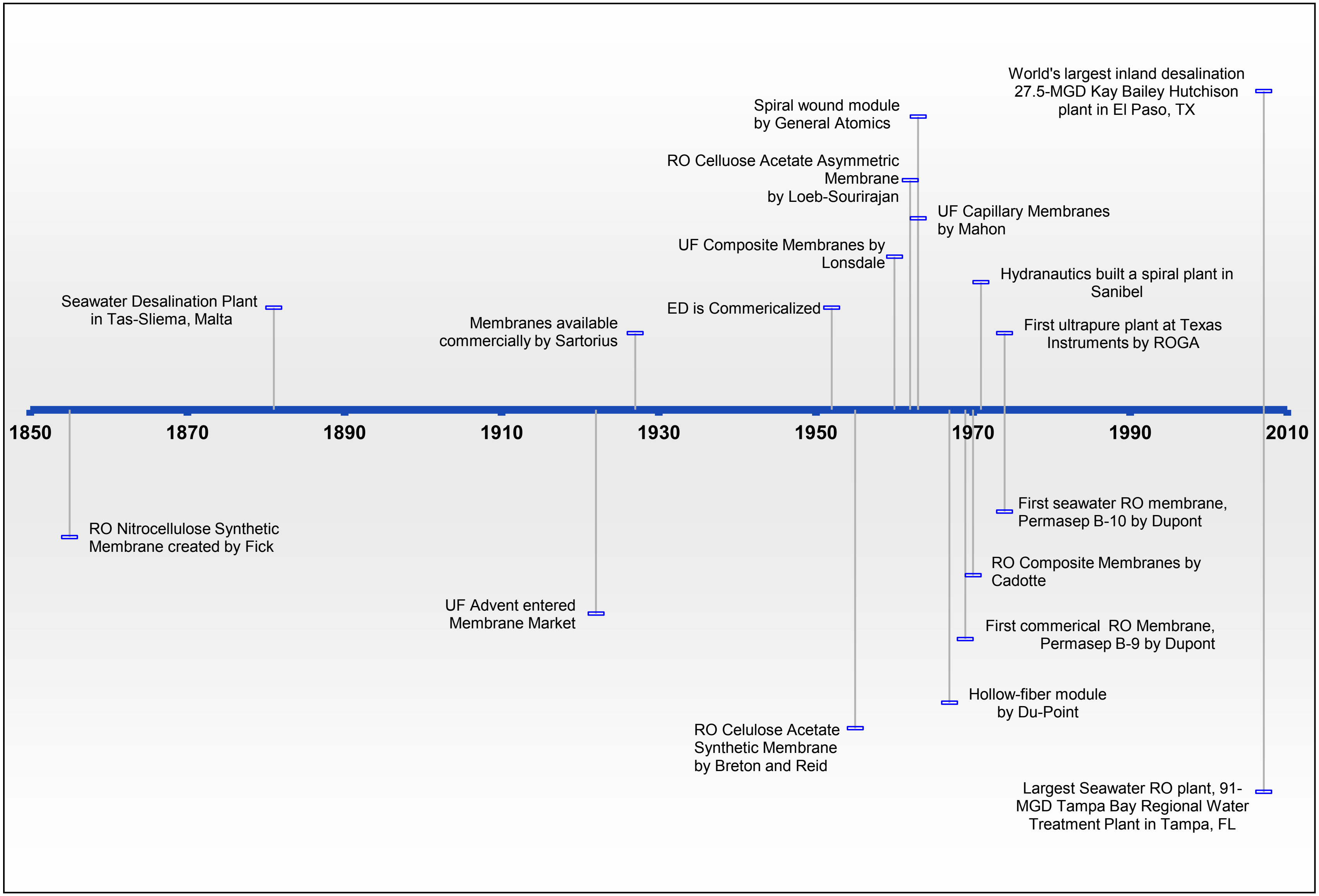


Figure 3-1. Membrane technology developments (1850-2010).

Texas membrane plants represent only a small portion of the total world and nationwide capacity. Water production and water treatment plants for low pressure and desalting membranes has approximately 181 million gallons per day (25 plants as of 2006) and 121 million gallons per day (44 plants as of 2010), respectively (South Central Membrane Association, 2006, TWDB, 2012b). In 1993, the first low pressure membrane plant in Texas was constructed in Sherman with a 10 million gallons per day capacity. In 2006, the Upper Trinity River Authority Harpool water treatment plant with a capacity of 20 million gallons per day became the largest low-pressure membrane plant in Texas. Several small desalting membrane plants originated back in 1990. In 2007, the largest inland brackish groundwater reverse osmosis plant in Texas and the nation, the Kay Bailey Hutchison plant was constructed with a design capacity of 27.5 million gallons per day in El Paso, Texas.

The use of membranes for water and wastewater treatment has grown significantly in recent years. Drivers for this growth include increasingly stringent water quality regulations, decreasing water supply, decreasing available land for conventional treatment systems, ability to remove multiple pathogens and contaminants, and decreasing membrane capital costs.

3.1.2 Membrane classifications

Membrane treatment systems for producing drinking water are well studied and documented (American Water Works Association, 2011; Davis, 2010; Greenlee *et al*, 2009; Kucera, 2010; Benjamin and Lawler, 2013; Howe *et al*, 2012). Pressure-driven membrane filtration[1] typically operates by forcing a pressurized feed stream through a microporous or semipermeable membrane, as shown in Figure 3-2. Depending on the type of membrane, certain contaminants will be rejected from passing through the filter, so that the water will be filtered as it passes through the membrane. In the "cross-flow" configuration (as shown), a concentrate stream is continuously sweeping away rejected contaminants. However, in the "dead-end" configuration (not shown), no concentrate stream exists, and all of the rejected contaminants accumulate on the feed-side of the membrane.

Two of the most important parameters for characterizing the performance of membrane treatment systems are *recovery* and *removal* (sometimes used synonymously with *rejection*, though others may draw a distinction). Recovery (r) is the water production efficiency of the treatment stage or system, which is defined as the fraction of permeate flow (Q_p) to feed flow (Q_f), as in Equation 3-1.

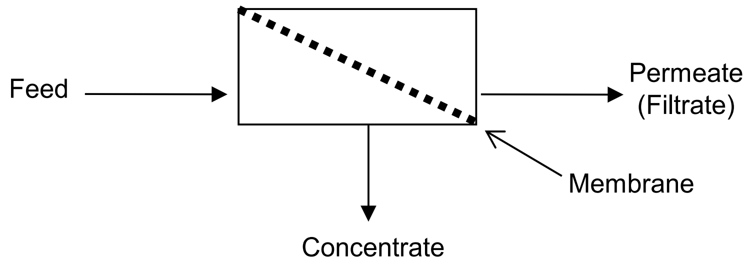
$$r = Q_p/Q_f \qquad \text{Equation 3-1}$$

Removal (R) is the contaminant removal efficiency, which is defined by the concentration (c) of each contaminant ($_i$) in the permeate ($_p$), relative to the feed concentration (c_f), as defined in Equation 3-2.

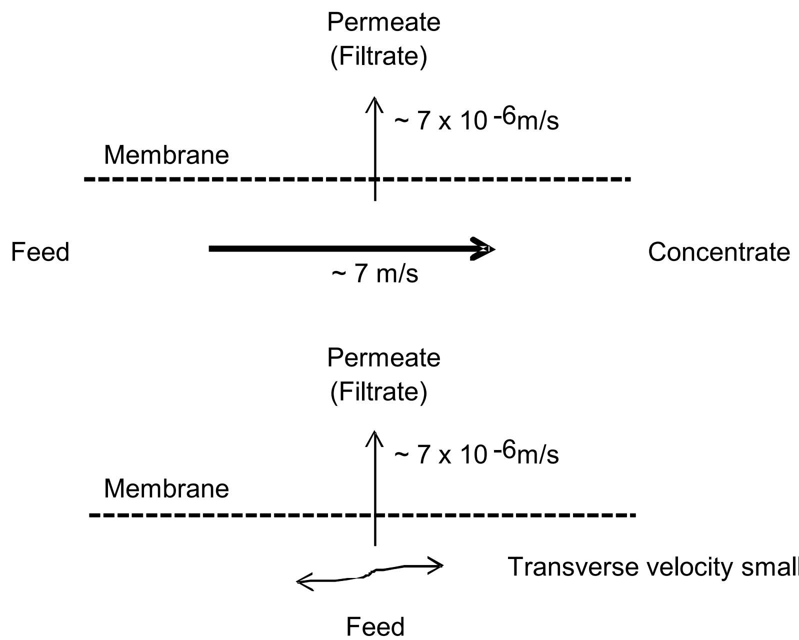
$$R_i = 1 - (c_p/c_f) \qquad \text{Equation 3-2}$$

Generally, "better" performance is associated with higher system recovery (*i.e.*, more water production) and higher contaminant removal (*i.e.*, cleaner water).

[1] Terminology regarding membrane treatment has been standardized (ASTM, 2010b).



(a)



(b)

Figure 3-2. Typical (cross-flow) membrane filtration configuration.

Water treatment membranes can be classified into two categories: low-pressure filtration and desalting[2]. Low-pressure membranes, such as microfiltration and ultrafiltration, are used to remove pathogens such as protozoa, bacteria, and viruses, as well as particulate turbidity and natural organic matter from surface and ground waters. Desalting membranes, such as nanofiltration, reverse osmosis, and electrodialysis, are typically used to remove dissolved organic and inorganic contaminants such as pharmaceutical compounds and salts. Table 3-1 displays the approximate size distributions of water contaminants and pressure-driven membrane processes. Table 3-1 provides a summary of key parameters of low pressure and desalting membranes.

[2]The term "low-pressure" developed in contrast with the relatively higher pressures required for desalting seawater by reverse osmosis. However, current desalting membrane technology now requires much lower pressures for effective treatment of brackish water compared to original seawater desalination.

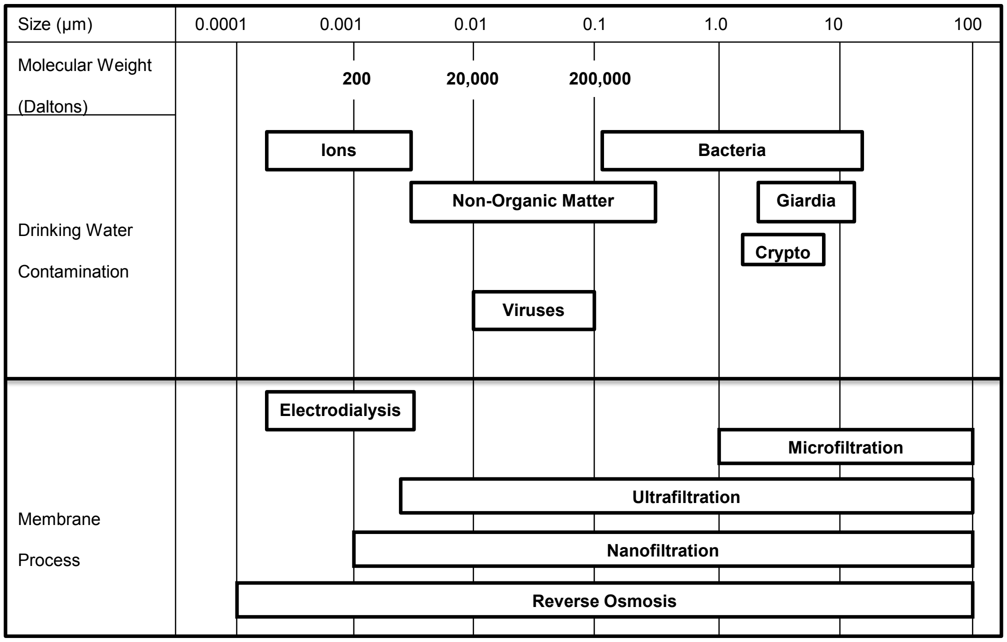


Figure 3-3. Classification of membrane by particle-size removal (Adapted from Davis, 2010).

Table 3-1: Comparison of low pressure and desalting membranes.

Membrane Types	Low Pressure (microfiltration and ultrafiltration)		Desalting (nanofiltration and reverse osmosis)	
Particle size	~0.1 µm	~0.01 µm	~0.001 µm	non-porous
Targeted Contaminants	bacteria, protozoa, algae	viruses, NOM	dissolved organic matter, divalent ions	monovalent ions
Pressure Range	5-20 psi		>40 psi	
Membrane Modules	usually hollow fiber		usually spiral	
Operation Mode	pressure and vacuum		pressure only	
Flux Range	15-100 GFD		8-15 GFD	

3.2 Current state of low-pressure filtration membrane technologies

Microfiltration and ultrafiltration membranes are frequently used for particle and pathogen filtration and typically operate with relatively low differential pressures (*i.e.*, the difference in pressure between the feed and filtrate sides of the membrane). Membrane equipment is quite durable with a design life of several decades, but the membrane replacement frequency is typically five to ten years. A chronological summary of large low-pressure membrane filtration plants in Texas is provided in Figure 3-4.

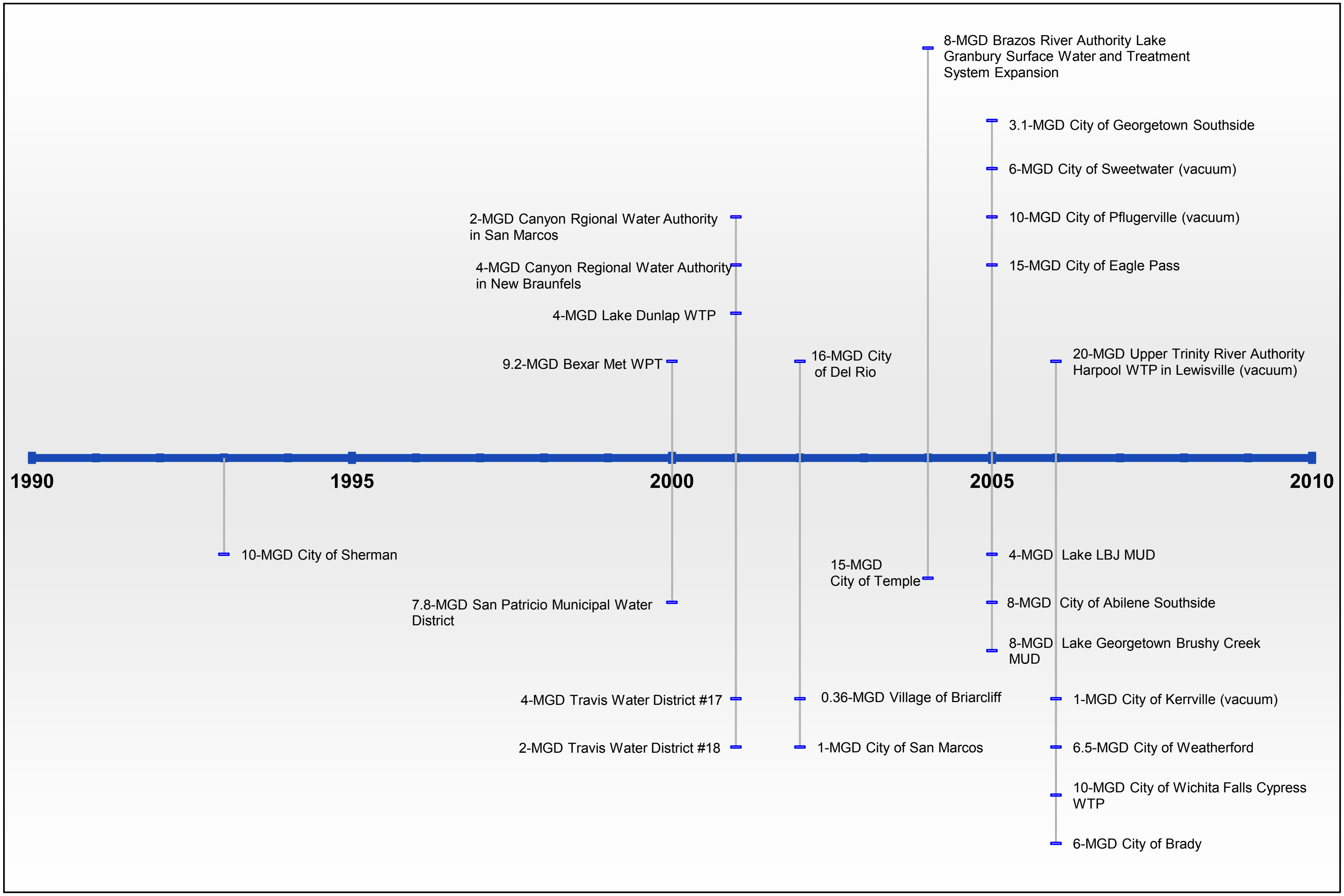


Figure 3-4. Low pressure membrane installations in Texas (1990-2010)

3.2.1 Membrane composition

Microfiltration membranes are microporous and isotropic with a nominal pore size range of 0.1 to 1.0 microns; microfiltration membranes remove turbidity and most bacteria but do not remove viruses (see Figure 3-3). Early microfiltration membranes were composed of cellulose acetate and nitrocellulose (Nyer, 2009), but now polymer microfiltration membranes can also be made of polyvinylidenedifluoride, polyamides, polyolefins, polysulfones, and polytetrafluoroethylene. Cellulose acetate is a relatively inexpensive material and has a working pH range between 5 and 8, but disadvantages include inferior thermal stability, mechanical stability and chemical tolerance. Polyvinylidenedifluoride has a superior resistance to solvents but is available only in larger pore sizes. Polyamides can be operated with lower pressure loss, at temperatures above 50 degrees Celsius, and working pH levels between 3 and 11, but polyamides are not tolerant of chlorine, which is a popular preventative measure against biofouling. Polysulfone membrane material operates at pH of 2 to 13 and has a good fouling resistance. Polytetrafluoroethylene membranes are hydrophobic with a wide operating temperature range (-100 to 260 degrees Celsius, beyond drinking water applications) and are generally resistant to fouling from organics, but they are relatively expensive, limited to 0.1 micrometer pore size. (Water Environmental Federation, 2006).

Ceramic microfiltration membranes can be made of alumina, glass, and carbon-coated zirconia. Ceramic membranes are available but not frequently used due to their typically higher cost and lower packing density (Lozier, 2005). Advantages of ceramic membranes are that they have longer life (up to 20 years) and are more durable, physically and chemically. Ceramic membranes can typically operate at a higher flux with a lower differential pressure, but typically have a higher capital cost than polymer-based low-pressure membranes. However, over the life of a membrane system, the net present value of a ceramic system may be lower (Gilbert *et al*, 2011).

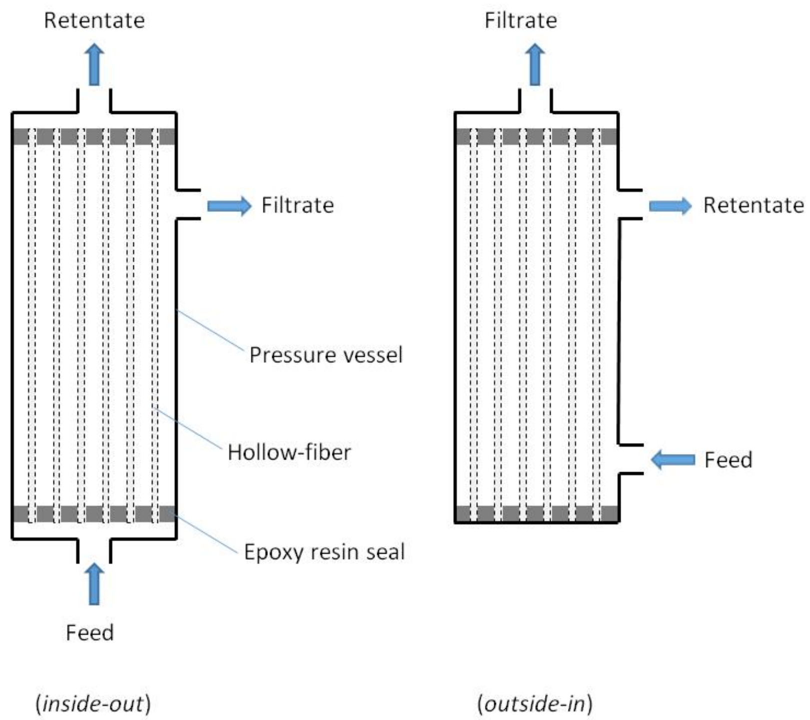
Ultrafiltration membranes are useful for filtering particles greater than their pore size of 0.005 to 0.1 μm, which includes water contaminants such as natural organic matter and viruses, as shown in Figure 3-3. Ultrafiltration membranes are typically classified by the molecular weight cut-off of rejected materials, which can range in mass from 1 to 1000 kilodaltons (Millipore, 2011). Early ultrafiltration membranes were composed of nitrocellulose (Nyer, 2009), but now ultrafiltration membranes can be manufactured from cellulose acetate, polyacrylonitrile copolymers, aromatic polyamides, polysulfone, polyvinylidenedifluoride, polytetrafluoroethylene, and nylon.

3.2.2 System design and operation

Low-pressure membrane filtration systems are designed based on source water quality, finished water quality goals, and nominal membrane ratings. The size and number of membrane modules and racks are based on the desired system flow rate, the membrane flux rating, and the backwash frequency.

Membrane modules are the smallest unit that contains the membrane and supporting structure, which typically contain, on an order of magnitude, 100 to 1000 square feet (10 to 100 square meters) per module. Membrane racks may contain only a few modules up to several hundred modules. Low-pressure membrane modules predominately include hollow fiber module that can be in a pressure vessel or submerged configuration. Membrane flux is the amount of permeate flow that can be transported through a membrane per unit area per time. Membrane flux typical ranges are 18 to 100 gallons per square feet per day (30 to 170 liters per square meters per hour) for pressurized systems and 15 to 45 gallons per square feet per day (25 to 75 liters per square meters per hour) for vacuum systems, and the typical feed pressures are 6 to 15 pounds per square inch (40 to 100 kilopascals) for pressurized systems and 3 to 6 pounds per square inch (20 to 40 kilopascal) for vacuum systems (American Water Works Association, 2011).

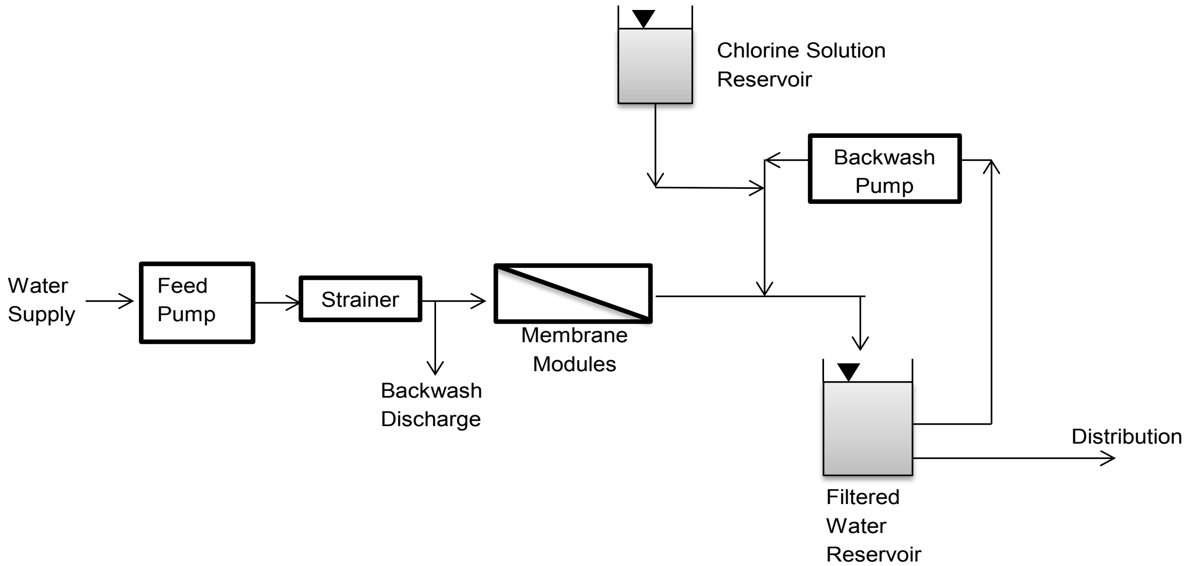
Microfiltration and ultrafiltration treatment systems are frequently designed with hollow-fiber modules, which contain many hollow-fiber (straw like) strands that may be bundled in a U-shape or suspended linearly between two manifolds. For hollow-fiber membranes, the flow direction can be “inside-out” (where feed water enters the interior of the fiber and is filtered as it passes through the wall to the outside) or “outside-in” (where water is fed to the exterior surface of the fiber and is filtered as it passes through the fiber wall to the interior axis of the fiber) as shown in Figure 3-5. Hollow fiber membranes can be confined in pressure vessels or submerged in basins, where flow is typically driven by vacuum (Davis, 2010). In a pressure vessel with hollow-fiber membranes, the flow direction may be either inside-out or outside-in, but in a submerged vacuum system, the flow direction is only outside-in.



Source: Adapted from Howe et al., 2012

Figure 3-5. Simplified diagram of inside-out and outside-in hollow fiber membrane modules.

A simplified schematic diagram for a typical low-pressure filtration system is shown in Figure 3-6. Feed water is typically passed through a strainer or cartridge filter before entering an microfiltration or ultrafiltration system, and an automated backwash system uses a filtered water reservoir (clearwell) for cyclical cleaning of the membranes.

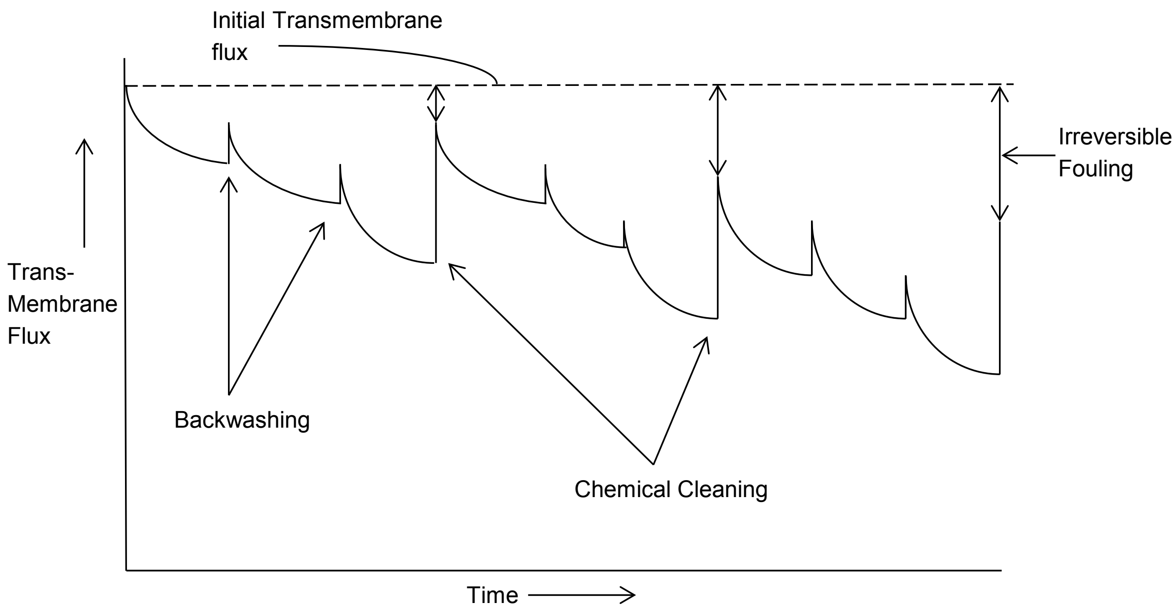


*Source:*Adapted from Davis, 2010.

Figure 3-6. Typical low-pressure membrane filtration process schematic.

For a new or freshly cleaned membrane, the predominant mechanism for particle rejection is sieving (size exclusion), whereby the rejected particles are too large to pass through the membrane pores. As rejected particles accumulate on the membrane surface (in dead-end mode), a "gel" layer begins to form, which may enmesh and capture additional particles, and as more particles accumulate, a denser "cake" layer may form. This accumulation of particles on the membrane surface (and within the membrane pores) creates resistance to the flux of water through the membrane. Thus, for a constant feed pressure, flux of water through the membrane declines, as shown in Figure 3-7. Backwashing is used at regular intervals (30 to 90 minute), where filtered water is reversed through the membrane to expel accumulated particles in the pores and remove the gel or cake on the surface. Typically, low-pressure membranes are operated in constant flux mode in which the feed pressure is increased to counter an increase in transmembrane pressure to maintain a constant flow rate.

Typically, backwashes are not effective at removing *all* of the accumulated particles, so the flux after a backwash is slightly less than the initial flux. After many backwash cycles, a chemical cleaning (*e.g.,* a chemically-enhanced backwash or a clean-in-place, typically using an acid or base) is required to remove accumulated particles not removed by the backwash. The frequency of chemical cleaning is dependent on the source water quality, but ranges from weekly to monthly. Unfortunately, chemical cleanings are usually not able to recover the flux to that of new membrane, and this flux difference is associated with "irreversible fouling" of the membrane. Fortunately, with regular backwashing and chemical cleaning, the irreversible fouling is minimized, and membranes can be used effectively for five to ten years. However, backwashing and chemical cleanings use filtered water, which decrease the overall system recovery, so a practical optimization lies between frequent backwashing/cleaning (significantly lowering the system recovery) and infrequent (irreversibly fouling the membranes). Some membrane compositions are tolerant of continuous application of a low dose of chlorine, which is used to minimize fouling by biological growth on membrane surfaces. Alternatively, shock treatments with a high dose of chlorine for a short duration may be used periodically.

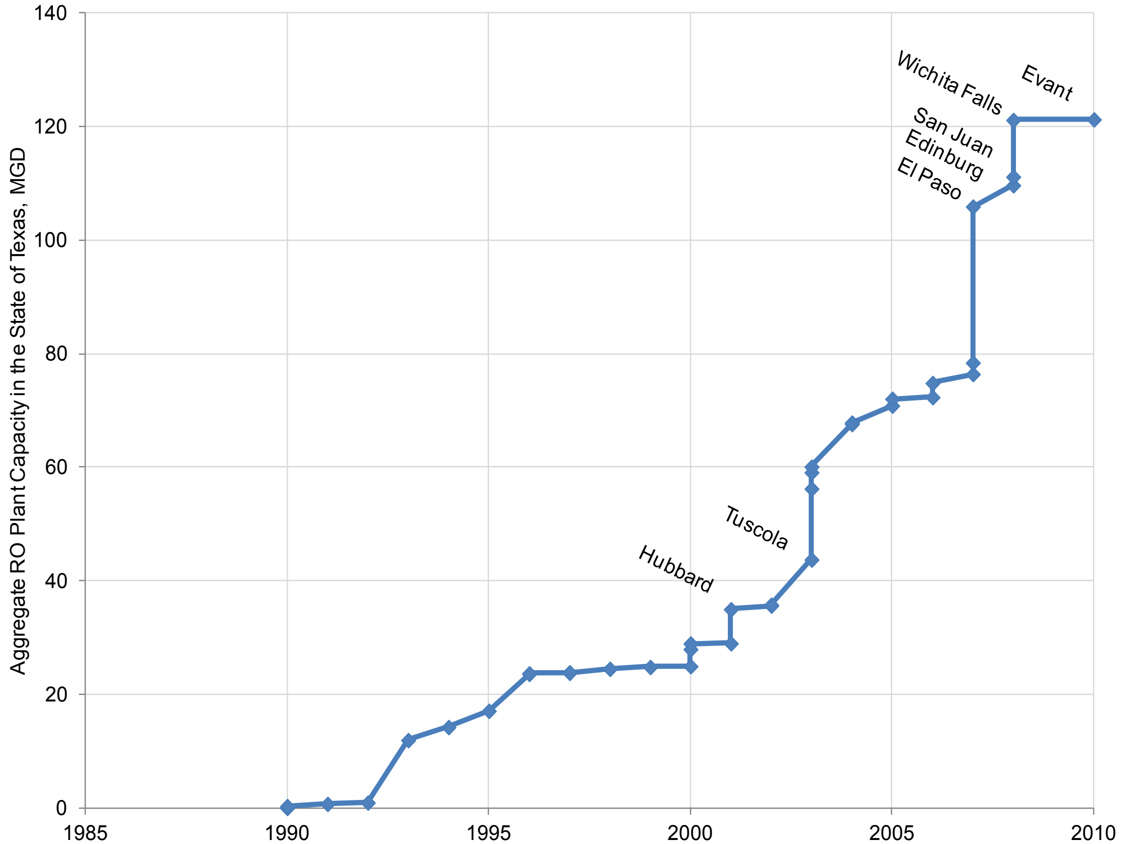


*Source:*Adapted from Howe *et al*, 2012.

Figure 3-7. Typical flux cycles for constant pressure operation and maintenance of membrane filtration.

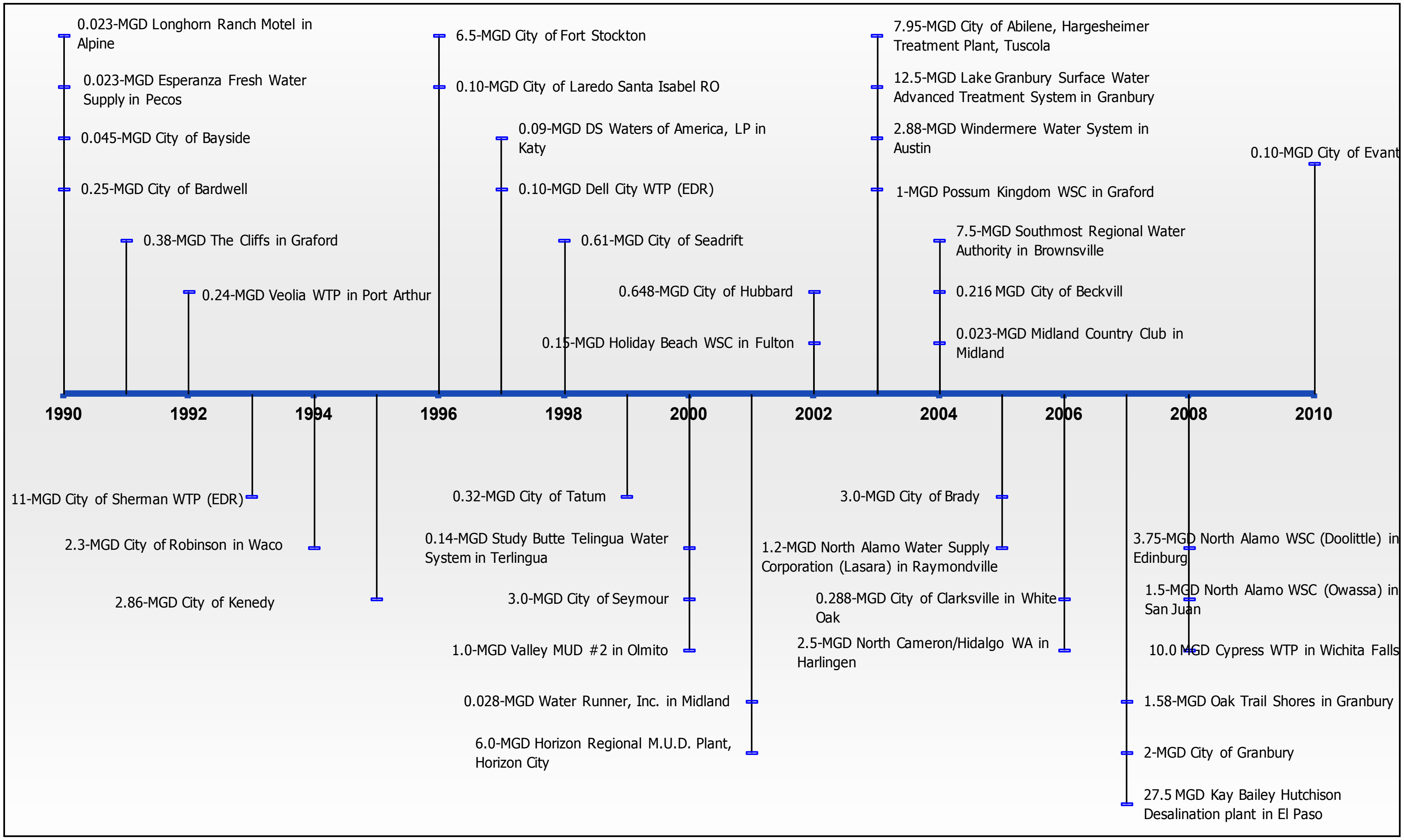
3.3 Current state of desalting membrane technologies

Membrane technologies for potable desalination of brackish, saline, and sea waters include nanofiltration, reverse osmosis, and electrodialysis. The salinity of “brackish” water is loosely defined as having a concentration of 1,000 to 10,000 milligrams per liter of total dissolved solids. (For comparison, the United Stated Environmental Protection Agency and Texas Commission on Environmental Quality Secondary Standard for total dissolved solids is 500 milligrams per liter and 1,000 milligrams per liter, respectively, and the average salinity of seawater is nearly 35,000 milligrams per liter). Nanofiltration and reverse osmosis are pressure-driven processes where the transmembrane pressure must overcome the natural osmotic pressure of the feed water to force water through semi-permeable membranes. Electrodialysis represents a family of electrically-driven separation processes where an electric voltage is used to draw ions through ion-exchange membranes. Over the past two decades, desalting membrane systems have increased in number and grown in plant capacity in the State of Texas, as shown in Figure 3-8. TWDB has created a desalination plant database that includes information existing desalination plants in Texas (TWDB, 2012b). The database provides a desalination plant report with information on the location, water production, and membrane system of the plant.



Aggregate RO Plant Capacity in the State of Texas, MGD
0
20
40
60
80
100
120
140
1985
1990
1995
2000
2005
2010
Hubbard
Tuscola
El Paso
Edinburg
San Juan
Wichita Falls
Evant

(a)



(b)

Figure 3-8. Desalting membrane applications in Texas (1990-2010).

3.3.1 Membrane composition

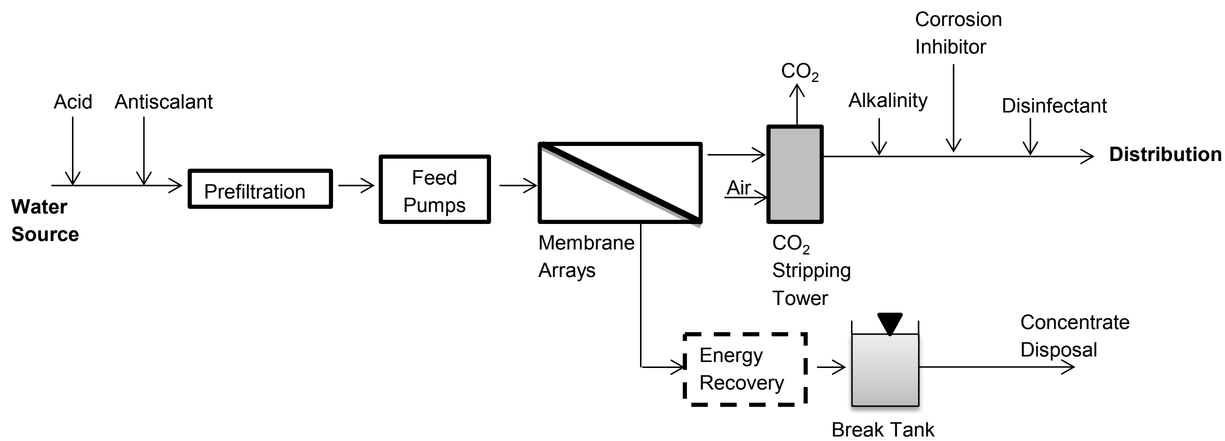
Nanofiltration and reverse osmosis membranes are frequently polymer-based thin-film composite membranes, which are constructed by bonding a very thin (*ca*. 0.1 micrometer) active layer to a thicker (*ca*. 0.2 millimeter), porous support layer (Water Environmental Federation, 2006). Cellulose acetate reverse osmosis membranes were initially developed in the 1950s and 1960s, and thin film-composite membranes were developed in the 1970s, as shown in Figure 3-1. Two common thin-film composite membranes are (1) a cellulose acetate active layer on a polyester fabric and (2) a polyamide active layer with a polysulfone support layer on a polyester fabric (Hydranautics, 2001). Nanofiltration membranes have pore sizes on the order of a nanometer (0.001 micrometer) and reject dissolved substances as small as divalent ions such as calcium and sulfate (Sarai, 2006). Reverse osmosis membranes are semi-permeable and non-porous, so they allow water to permeate but reject most dissolved substances (Sarai, 2006). Any dissolved organic or salt transport through a reverse osmosis membrane is based upon diffusion, not size exclusion.

Electrodialysis membranes are ion exchange membranes, which selectively permit or reject the transport of ions based on charge. Cation-exchange membranes permit cation transport but reject anion transport, and the reverse is true for anion-exchange membranes. Ion exchange membranes are typically composed of hydrophobic polymers (such as polystyrene, polyethylene, or polysulfone) that have been modified to include “fixed” ions of one type of charge (Strathmann, 2004). Most commercial cation-exchange membranes have sulfonate or carboxylfixed ions, and most commercial anion-exchange membranes have quaternary ammonium ions (Strathmann, 2004).

Nanofiltration and reverse osmosis membranes have been developed for a wide range of applications. For example, among the many membrane manufacturers, there exist multiple membrane types within each of the following categories: brackish water, fouling resistant, low energy, industrial grade brackish water, nanofiltration, sanitary/medical, seawater, semiconductor, and tap water (DOW, 2012a; General Electric, 2012a; Hydranautics, 2012a; KOCH, 2012a; Toray, 2012a). These membranes are tested on industry standard synthetic waters (specific to each category) using a method described by ASTM (2010a) (which defines the standardization of permeate flow, temperature correction factors, and concentration of salt “as mg/L NaCl”) so that individual membrane models are comparable between different manufacturers (DOW, 2012b) based on contaminant rejection, design flux, membrane surface area, and design pressure.

3.3.2 System design and operation

Desalting membrane systems are designed based on source water quality, membrane specifications, and desired product water characteristics, and the fundamentals of these designs have been standardized (ANSI-AWWA, 2010). A simplified example diagram of a membrane desalination system is shown in Figure 3-9. For pretreatment, acid and antiscalant may be added before the membrane treatment system, and the concentration of acid and antiscalant added is calculated based on the feed water quality and predictions for supersaturation of sparingly-soluble salts, based on the expected membrane rejections and system recovery. The necessary screening and prefiltration required for the treatment system is determined based on the feed water turbidity and measure of capacity for fouling known as silt density index. Additionally, PHREEQC (USGS, 2014) and Visual MINTEQ (KTH, 2013) are chemical solubility/equilibrium modeling software packages available at no cost. The required pressure and horsepower of the feed pumps are determined based on the osmotic pressure of the feed water and concentrate wastes, as well as hydraulic headlosses. The configuration of the membrane arrays (*i.e.*, number of vessels per stage) are optimized for economic value while still meeting minimum and maximum concentrate and feed flows, respectively, out of and into the vessels. The choice of membrane types are determined based on specific feed water quality and desired product water quality (using the methods described in the next chapter of this report).



Source: Adapted from Davis, 2010.

Figure 3-9. Typical membrane desalination process schematic.

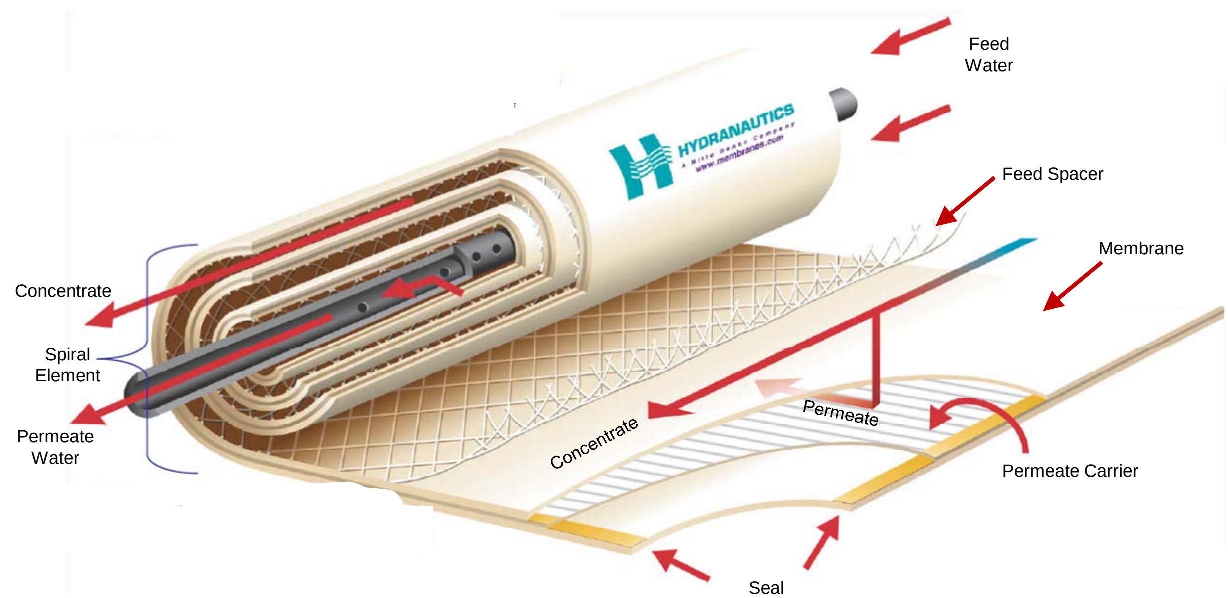
Carbon dioxide is not typically rejected by desalting membranes, so the permeate (product) is typically supersaturated with carbon dioxide and may require air stripping for removal. In general, the hardness and alkalinity of the permeate are too low to distribute to customers, causing corrosion in distribution pipes. The permeate will typically need to be stabilized by either blending some of the feed water back into the permeate and/or adding chemicals, such as lime, caustic soda, or calcite. A corrosion inhibitor may also be added to minimize aggressive behavior in metal pipes. Alternatively, the carbon dioxide in the RO permeate can be supplemented and reacted with natural calcite mineral to dissolve calcium and carbonate for stabilization through upflow calcite contactors. Finally, a disinfectant is added prior to distribution.

If the concentrate waste stream retains significant pressure relative to the feed stream, then an energy recovery device may be used to reduce energy costs. Common disposal options for inland desalination include discharge to the local wastewater sewer system, deep-well injection, evaporation ponds, and zero liquid discharge treatment. Discharge to a sewer system is feasible if conveniently located in proximity to the sewer collection system and if the mass flow of salt will not appreciably increase the salinity of the wastewater effluent. Deep-well injection typically uses a 1,000 to 5,000 feet deep well to dispose of concentrate waste into an aquifer that is typically more saline than the concentrate waste and has been determined by professional geologists to be confined from other fresh water aquifers that may be used for drinking water. Evaporation ponds, typically limited to arid climates, are constructed to provide a shallow pond (*e.g.,* less than one meter deep) where the water contained in the concentrate can be evaporated, leaving solid salts behind. Zero liquid discharge options are typically more expensive and require more energy to crystallize the concentrate waste, usually by thermal processes.

Nanofiltration and reverse osmosis systems are typically designed with spiral-wound modules. The orientation of the repeating group in a spiral wound element has four items: feed spacer, membrane (with dense side facing feed spacer), permeate flow spacer, and membrane (with support side facing permeate flow spacer). The layers are rolled around a central pipe which serves as the permeate collector, as illustrated in Figure 3-10. Pumps are used to pressurize the feed channel such that transmembrane pressure (*i.e.*, the difference in pressure between the feed side and permeate side of the membrane) exceeds the natural osmotic pressure associated with the salinity of the feed. Osmotic pressure (Π) is approximately proportional to the concentration of salt ions (c) in solution and can be approximated for brackish solutions by the following equation:

$$\Pi = c\,R\,T \qquad \text{Equation 3-3}$$

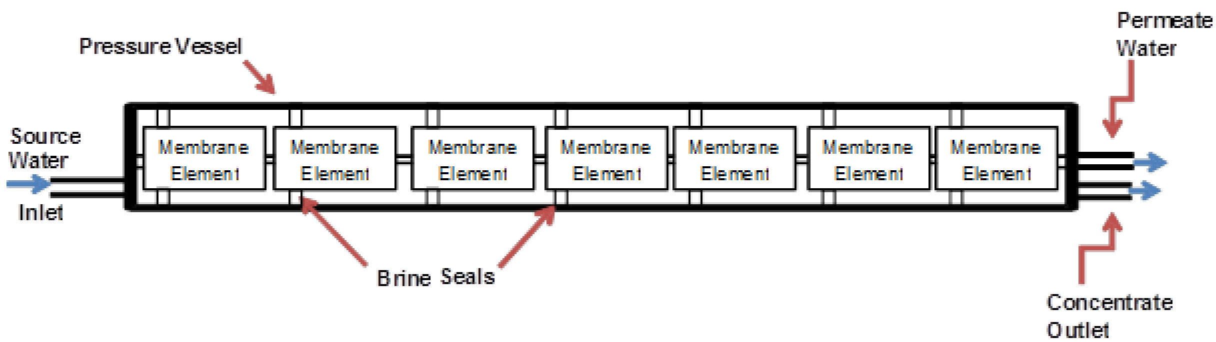
where R is the universal gas constant (8.314 J/mol-K), and T is the absolute temperature (in Kelvin). For example, the osmotic pressure of a solution of 2,000 milligrams per liter of sodium chloride is approximately 25 pounds per square inch (170 kilopascal). Nanofiltration systems typically operate at 50 to 150 pounds per square inch for softening, while pressure ranges for reverse osmosis treatment of brackish water and seawater are 100 to 600 pounds per square inch and 1,000 to 1,500 psi, respectively (Kucera, 2010). With a transmembrane pressure greater than the osmotic pressure of the feed, water is forced to permeate through the desalting membrane, but salt ions (and other molecules) are largely rejected.



Source: Courtesy of Hydranautics

Figure 3-10. Cutaway of a typical spiral-wound module.

For improved recovery, multiple elements are installed in series within a *pressure vessel* such that the concentrate leaving the first element becomes the feed to the next element in the pressure vessel, as shown in Figure 3-11. Typical nanofiltration and brackish reverse osmosis pressure vessels contain six or seven membrane elements, and some seawater pressure vessels are designed with eight membrane elements. The standard length for spiral-wound membrane elements is 40 inches, and typical diameters are 4 or 8 inches. A 40-inch long element is typically operated in the range of 8 percent to 15 percent recovery.

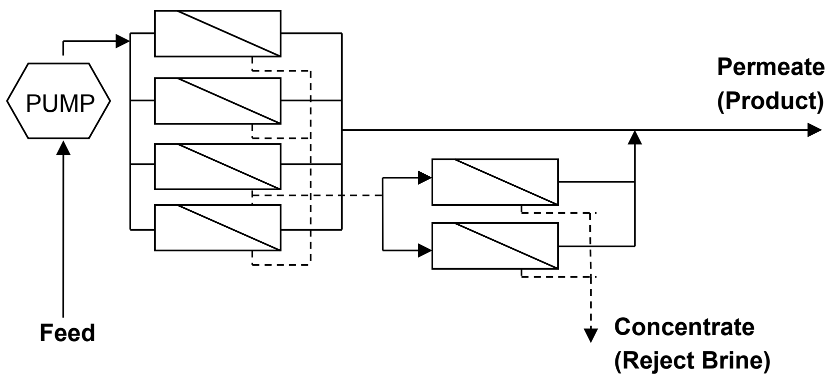


Source: Adpated from Davis, 2010.

Figure 3-11. Seven-element nanofiltration or reverse osmosis membrane pressure vessel.

Some manufacturers have developed 16-inch or 18-inch diameter vessels for large flow capacity plants. In 2003, the U.S. Department of the Interior, Bureau of Reclamation formed a consortium of membrane manufactures to evaluate the economics, benefits, and disadvantage of creating a larger diameter element. The consortium selected a 16-inch diameter as the recommended larger diameter industry standard and concluded that the use of large diameter elements has the greatest impact for brackish groundwaters with cost savings from 18.5 to 27 percent (Bartels, 2005). Membrane manufactures such as Dow FilmTec, Toray, and Hydranautics offer a 16-inch diameter element with membrane area of 1,600 to 1,760 square-feet and permeate flow rates of 34,000 to 41,000 gallons per day.

Multiple nanofiltration or reverse osmosis pressure vessels combined in parallel constitute a *stage*, and multiple stages constitute an array; for example, a two-stage, four-by-two array is shown in Figure 3-12. Multiple stages are employed for increased recovery. The combined concentrate waste from the first stage becomes the feed to the second stage. For example, with individual stage recoveries of 50 percent for each of the first and second stages, the overall system recovery would be 75 percent.



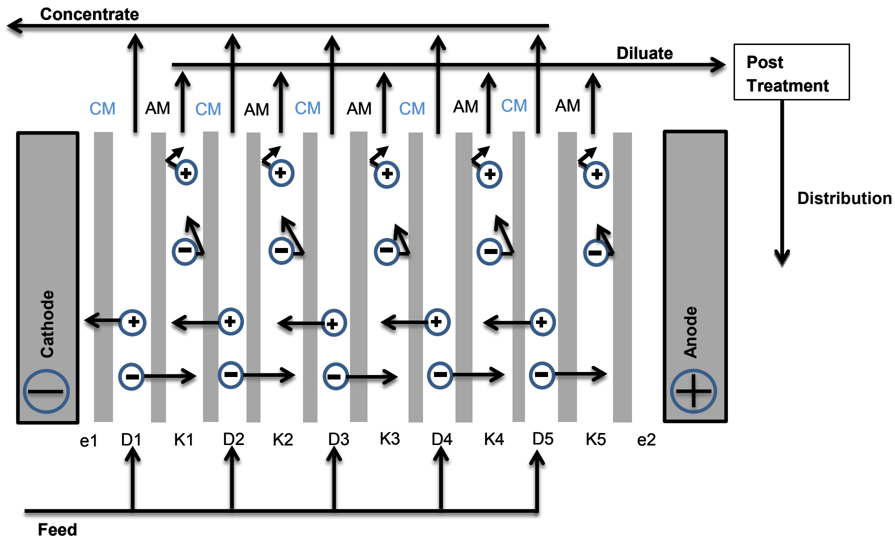
*Source:*Adapted from Howe *et al.*, 2012 and Davis, 2010.

Figure 3-12. Two-stage, four-by-two membrane array.

The concentration of particles and salts in the concentrate stream increases with each successive membrane element within a pressure vessel, as well as with each successive stage in the process array. Fouling or scaling of the membrane may occur as a result of accumulation of colloidal particles and/or solubility issues at the membrane surface, which limits the flux of water through the membrane. Backwashing is not feasible with non-porous membranes, and membrane replacement is relatively expensive, so particle fouling and mineral scaling are extremely undesirable in desalting. Preventative maintenance against mineral scaling often includes the addition of acid to the feed water to lower the pH to prevent membrane scaling by calcium carbonate. In many cases, addition of antiscalant compounds (such as polyphosphonates or acrylates) are also applied to feed water to prevent membrane scaling by sulfate or silica salts (ASTM 2008e, 2010d). The addition of acid and antiscalant compounds to the feed water can allow desalting systems to operate at significantly higher recoveries than without these additions.

In contrast to low-pressure membranes, which operate dynamically with rapid fouling and frequent backwashes, desalting membrane systems typically operate at steady-state. Stable and consistent operation involves regular record keeping (ASTM, 2008d), testing (ASTM, 2008b), and water analysis (ASTM, 2008c). In the case of unexplainable increase in permeate conductivity, checking for leaks (ASTM, 2008a) or integrity testing (ASTM, 2010c) may be performed. In the event of increased feed pressures due to membrane particle fouling or mineral scaling, restorative maintenance of membranes includes periodic (*e.g.,* quarterly to annually) rinsing of the feed and concentrate channels with permeate or chemically cleaning membranes (typically with acid, base, or other proprietary cleaners). This is referred to as a clean-in-place.

Electrodialysis and electrodialysis reversal desalting systems typically employ a *stack*, plate-and-frame geometry (shown in Figure 3-12). Repeating units of flat-sheet membranes and flow spacers are sandwiched between flat end-plates. An imposed electric field compels cations to move toward the cathode and anions to move toward the anode. As the feed water flows parallel (between) alternating anion and cation exchange membranes, anion exchange membranes allow anions to be transported from the diluate cell to the concentrate cell, and cation exchange membranes allow cations to be transported from the diluate cell to the concentrate cell. Electrodeionization systems are similar except that they use ion exchange resin in the flow channels to reduce electrical resistance and are more frequently constructed in a spiral-wound geometry and used for producing very low conductivity water.



Source: Adapted from MEGA, 2012.

Figure 3-13. Typical electrodialysis stack geometry.

3.4 Pending advances in membrane technologies

Membrane technology is continuously being improved. New products may be available to new and existing plants that provide opportunities to reduce pumping pressures, decrease clean-in-place intervals, and increase membrane life. All of these operational improvements will lead to a reduction of water production costs and a savings to the water utility without sacrificing the quality of treated water. Research and development in geometries, materials, and processes are briefly described here.

3.4.1 Geometries

Manufacturers of microfiltration and ultrafiltration systems typically have proprietary module designs, which preclude the interchangeability of components of membrane treatment systems (as compared to nanofiltration and reverse osmosis modules, which have industry standard designs). Significant economical efficiencies may be gained if the industry would adopt standards for membrane module, pressure vessel, and rack geometries. With respect to spiral-wound module design, improvements in energy efficiency and plant footprint could theoretically be achieved with spacerless membrane modules. Recent product releases by membrane manufacturers have included a 34-mil feed channel spacer element, which reduces the differential pressure in the feed channel and, as a result, also reduces the feed pressures. In a 2-stage brackish water reverse osmosis system, this may save as much as 30 psi in feed pressure.

3.4.2 Membrane materials and surface modifications

Several researchers are developing new membrane compositions for improved operation. In an invited review on the status and future of desalination, Elimelech and Phillip (2011) suggested that in the past several decades, the membrane materials and energy recovery devices have been developed to nearly minimize the energy required for desalination, and thus, the most strategic advancements in the near future will focus on minimizing or eliminating membrane fouling and biofouling. Several researchers focus on membrane material modification for improved performance, such as organic fouling resistant membranes (Ju and Freeman, 2006), chlorine resistant membranes (Freeman, 2007), scale/fouling monitoring (Uchymiach *et al*, 2007), and membrane surface treatments such as silver nanoparticles (Basri *et al*, 2010) or single-walled nanotubes (Kang *et al*, 2008). These technologies are in various stages of commercialization by existing membrane manufacturers (Toray, Dow FilmTec, Hydranautics, etc.) or by start-up companies (NanoH_2O).

In the State of Texas, "unconventional" water treatment processes must submit an exception request to the Texas Commission on Environmental Quality for approval (as described in Section 5.2 of this report). If Texas Commission on Environmental Quality develops an alternative approval process for brackish groundwater reverse osmosis treatment systems, then it would likely be beneficial to include criteria for review and approval of new membranes for use in those treatment systems.

3.4.3 Tandem and alternative treatment processes

Concentrate management continues to be a project-defining component in the development of inland desalination systems. A wide range of research around the world continues to investigate more effective concentrate treatment options with proper environmental care and energetic and economic efficiency (Pérez-González *et al*, 2011). Research topics include coupling of membrane and thermal treatment processes, and recovery of valuable minerals from concentrate, as well as improved regulatory permitting for deep-well injection and evaporation ponds (TWDB, 2004).

Membrane desalting technologies such as forward osmosis, membrane distillation, and capacitive deionization are being researched as alternatives to the conventional membrane technologies of nanofiltration, reverse osmosis, and electrodialysis. These technologies have been demonstrated at the lab and pilot level and are in the process of commercialization for full-scale use.

Forward osmosis is the process where osmotic pressure is used to diffuse water from high concentration to low concentration. A strategically chosen "draw solution" with a greater osmotic pressure than the raw feed is used to draw water across the membrane. Then another process is used to remove the components of the draw solution from the water and reconstitute the draw solution. Potential advantages of forward osmosis include lower energy consumption, higher contaminant rejection, and less membrane fouling. Expected applications of forward osmosis are in desalination and wastewater treatment. Major limitations for implementing forward osmosis are draw solute regeneration (which requires energy) and a lack of membrane development. A recent research study identifies the advantages, applications, and future opportunities for forward osmosis encircled by the following identified five challenges: concentration polarization, membrane fouling, reverse solute diffusion, membrane development, and draw solute design (Zhao *et al*, 2012): Additional research includes the study of biofouling of forward osmosis membranes (Liu and Mi, 2011) and identification of areas where solute regeneration is not required when combined with a reverse osmosis process (Hoover *et al*, 2011).

Membrane distillation is another emerging technology with limited current application. Membrane distillation uses a difference in vapor pressure between two streams (typically maintained by a difference in temperature) to drive water vapor through a hydrophobic membrane. Four configurations of membrane distillation include direct-contact, air-gap, sweep-gas, and vacuum. Membrane distillation shows promise to be able to use low-grade waste heat to drive desalination and produce high quality distillate, operating at low temperatures and requiring less extensive pretreatment (Walton, 1994). Multiple-effect distillation is a relatively new concept derived from membrane distillation that recycles the energy in the distillation process (Nyer, 2009). Advantages of membrane distillation consist of low temperature and pressure operation with renewable energy sources and treatment of highly saline waters (*e.g.*, greater than 100,000 milligrams per liter total dissolved solids) with very low salinity product water (*e.g.*, less than 100 milligrams per liter total dissolved solids). Limitations of membrane distillation include higher specific energy consumption, lower fluxes, higher capital costs, membrane conductive heat losses, and membrane scaling (Cath, 2010).

Capacitive deionization is an electrically-driven desalination technology, similar to electrodialysis, except that capacitive deionization systems typically operate in a batch mode. Compared to electrodialysis systems, capacitive deionization systems contain more electrodes and may not necessarily contain membranes. As a brackish feed flows through the capacitive deionization unit, ions are attracted and temporarily detained by charged electrodes. When the capacitance limit is reached, the electrodes are uncharged, and captured ions are dumped into a small quantity of wastewater. Limitations of capacitive deionization process are lower system recoveries, plant efficiencies, and high carbon costs (Anderson *et al*, 2010). Major advantages of the technology are low energy consumption and control of product water quality.

3.4.4 Implications regarding permitting

Most technologies, including conventional water treatment (coagulation, flocculation, sedimentation, and filtration) are not designed to remove *all* drinking water contaminants, so effective water treatment systems often incorporate multiple technologies or processes. For example, reverse osmosis membranes are designed to remove salinity, but reverse osmosis treatment systems are typically designed with straining or low-pressure membrane pretreatment to remove particles, as well as post-treatment for disinfection residual. In essence, engineers design membrane treatment systems to comply with state drinking water quality standards, and the design choices of treatment technology and recommended operational parameters are strategically selected based on source water quality, economics, and acceptable maintenance regimen to maintain a reliable treatment plant production flow rate to meet maximum day potable water and fire flow demands.

As conventional membrane technology improvements and alternative membrane technologies are commercialized, engineers consider the application of these new options within their ethical responsibility to “hold paramount the safety, health, and welfare of the public” (National Society of Professional Engineers, 2012). The engineer is ethically bound to use his or her learned judgment to determine what level of performance validation is necessary to confidently certify the engineering design as safe and appropriate for the public. Therefore, source waters that are not within a set of known water quality parameters may require a more comprehensive evaluation. Ultimately, the burden of the effectiveness of any water treatment system, conventional or innovative, lies upon the licensed professional engineer who stamps/seals the design. However, engineers without prior membrane filtration design experience may rely on the membrane manufacturer for the actual design, which may or may not be provided by a licensed professional engineer. In addition to professional engineers, the effectiveness of any water treatment system also depends on the manufacturer of the equipment, the builder of the facility, plant operation staff, and the regulatory agency. Thus, the design engineer uses whatever methods necessary to assess membrane performance and predict the performance of the full-scale treatment system. These assessment and prediction measures include computer modeling, membrane sample testing, single element/module testing, and demonstration-scale testing, and the details of these measures are discussed in the following chapter.

4 Membrane performance evaluation and full-scale prediction methods

4.1 Overview

Treatment process selection is based on source water quality and product water quality goals. The analysis of raw and desired finished water qualities is focused on establishing treatment goals. Membrane processes may be selected as a part of a treatment train designed to meet finished water goals (*e.g.,* filtration/solids removal, salt removal, removal of a specific contaminant), that in most cases includes pretreatment (conditioning feed water for membrane filtration) and post treatment (*e.g.,* disinfection, corrosion control).

Should a membrane treatment process be selected, there are two main tools available to the engineer to develop design criteria: evaluating data from existing installations and membrane testing. There are several testing categories that engineers, utilities, and manufactures may use to predict full-scale performance, which, in turn, may be used by state regulators to review the design. Prior to testing, data from the following three aspects of a system are needed: raw water quality, permeate/filtrate quality goals, and project specific constraints (*e.g.,* space, residuals handling limitations, owner preferences).

Raw water quality parameters may be grouped into three categories: physical, chemical, and microbiological. Physical quality parameters may include temperature, turbidity, silt density index, electrical conductivity, color, *etc*. Chemical quality parameters may include: pH, alkalinity, hardness, total organic carbon, dissolved organic carbon, total dissolved solids, predominant ion or mineral composition, and specific contaminants of interest (*e.g.,* ammonia, silica, arsenic). Microbiological quality parameters may include concentrations of helminthes (worms), algae, protozoa (*e.g., Giardia* or *Cryptosporidium*), bacteria (*e.g.,* total coliforms or *E coli*), and viruses. Not all of these parameters impact low-pressure and desalting membranes alike, therefore, characterization of feed water quality is specific to the type of membrane technology selected (*i.e.*, particle filtration versus desalting membranes).

Membrane technologies have very different capabilities depending on whether they are applied for either particle filtration or removal of dissolved constituents. Microfiltration and ultrafiltration membranes are specifically designed to remove particles and pathogens. These systems are designed with capability for reverse flow (backwashing) and compatibility with cleaning chemicals necessary for removing organic materials, coagulants, and other precipitated metals that are present in unfiltered feed waters. Critical design criteria include number of filtration units, flux, recovery, backwash, and chemical cleaning intervals. Microfiltration and ultrafiltration membrane systems are based on range of proprietary membrane materials and hydraulic configurations. These characteristics influence performance of a particular membrane based on a given feedwater, making design criteria vendor-specific. Innovations to improve performance in low-pressure membranes further complicate efforts to generically predict design criteria across the industry. As a result, design criteria are typically based on proprietary testing on actual source water developed by the manufacturer.

For treatment systems designed to remove microbiological contamination, the log removal value of a membrane system is determined for meeting disinfection regulations. The log removal value of membranes based on the 40 CFR 141.719 (b)(2)(v) is determined by the following equation:

$$\textit{Log Removal Value} = \mathrm{Log}_{10}\,[C_f] - \mathrm{Log}_{10}\,[C_p] \qquad \text{Equation 4-1}$$

where C_f is the feed concentration of microorganisms and C_p is the product water concentration of microorganisms measured during challenge testing.

Nanofiltration and reverse osmosis membranes systems are typically used for desalting brackish groundwater and surface water. Generally, pressure-driven desalting membranes are configured in spiral wound elements, with membrane materials and system designs focused on dissolved salt rejection and energy efficiency (among other factors). These systems are designed with pretreatment filtration of raw waters because desalting membranes cannot be backwashed. Pretreatment filtration minimizes particle content and variability in the desalting feed, so design criteria is often established with models available from the membrane manufacturers that focus on predicting salt rejection and avoiding precipitation.

Desalting membrane systems may be used to remove multiple chemical contaminants or groups of ions from the source water. Pretreatment for desalting membrane systems, such as cartridge filters, and microfiltration or ultrafiltration are used to remove physical and microbiological contaminants. Pretreatment helps reduce the fouling of the membranes caused by organic and inorganic particulate material. Engineers and manufacturers generally do not seek to obtain microbiological log removal credits for desalting membrane systems since these membranes are used mainly for the purpose of removing dissolved salts. However, for those that do seek log-removal credits from desalting membranes, most state agencies have granted up to 2-log removal for *Giardia* and *Cryptosporidium* using conductivity profiling as a both a direct and indirect integrity test (United States Environmental Protection Agency, 2005b). The direct integrity testing needs to meet a resolution of 3 microns, sensitivity of log-removal credit granted, and frequency of once per day (United States Environmental Protection Agency, 2005b). While these membranes are capable of greater removals, a tracer that can be "discretely quantified" to the log-removal value has not yet been developed.

4.2 Methods for predicting full-scale treatment system operation

The performance of membranes in full-scale water treatment plants may be evaluated and predicted by several methods. Described here are four categories of performance prediction and testing: (1) computer modeling, (2) hollow-fiber testing (for low-pressure) or flat-sheet testing (for low-pressure or desalting), (3) single-element testing, and (4) demonstration-scale pilot testing. These methods are used (often in combination) to aid in design and operation of full-scale membrane water treatment plants. Each method is uniquely valuable for predicting aspects of full-scale performance (*e.g.,* product water quality or hydraulic characteristics), with tradeoffs in the investment of design time and financial cost, as shown in Table 4-1.

Table 4-1. Membrane performance prediction methods, sensitivities, and design costs for low-pressure and desalting membranes.

Predictive method	Product water quality characteristics	Hydraulic characteristics	Time	Financial
Computer Modeling	**Desalting:** Quantitative for bulk salinity (total dissolved solids) and major ion rejection	**Desalting:** Quantitative for bulk parameters such as pressures and fluxes	Minimal (hours)	Minimal
Bench-Scale Testing (Hollow-Fiber or Flat Sheet)	**Microfiltration/ultrafiltration:** Quantitative for bulk (turbidity and TSS) and individual contaminant (*e.g.*, protozoa, bacteria, or virus) rejection **Desalting:** Quantitative approximation for individual contaminant rejection at individual points in the membrane vessel.	Qualitative for typical hydraulic operation (e.g., in desalting membranes, increased rejection with higher fluxes)	Brief (hours to days)	Small
Single Element Testing	**Microfiltration/ultrafiltration:** Quantitative for bulk and individual contaminant rejection **Desalting:** Qualitative approximation for bulk and individual contaminant rejection at individual points in the membrane vessel.	**Microfiltration/ultrafiltration:** Quantitative for simulating individual element performance **Desalting:** Quantitative for simulating lead-element (or other individual element)performance	Moderate (days to weeks)	Moderate
Demonstration-Scale Pilot Testing	**Microfiltration/ultrafiltration:** Quantitative **Desalting:** Quantitative for systems with multiple stages	**Microfiltration/ultrafiltration:** Quantitative **Desalting:** Quantitative for systems with multiple stages	High (weeks to months)	High

For desalting processes, computer models have been developed to predict full-scale water treatment performance based on engineering design criteria and empirical operation. Most computer models for predicting the performance of commercial membranes have been calibrated by empirical data from the other three methods listed here and full-scale operation data. The models are similar, but not identical. Unfortunately, the technical details of commercial models are proprietary and not typically available for review. However, computer models are not entirely “black boxes” because output parameters such as recovery, flux, rejections are based on basic permeability and solubility equations that can be verified (approximately) by hand calculation. A benefit of computer models is their ability to perform iterations for multiple discrete units within a membrane element for permeate flux and concentrations within a matter of seconds. Calculating by hand the quantity and quality of water produced in a membrane element is a long process where one element is sectioned into ten discrete units along the flowpath. Approximately 20 calculations are performed to calculate water and salt fluxes for each discrete section of the element, for a total of 200 calculations per element. An example of this is shown elsewhere (Howe et al., 2012). The importance of desalting models is to provide a conceptual and predictive understanding of the transfer of water and solutes through reverse osmosis (Howe et al., 2012). Computer models are frequently used in the design of desalting membrane systems to predict bulk operation parameters, and they are generally useful for predicting the rejection of common contaminants.

Hollow-fiber or flat-sheet testing is a relatively simple laboratory method of analyzing a small sample of membranes for basic contaminant rejection. Hollow-fiber and flat-sheet tests of low-pressure membranes are frequently operated in a dead-end filtration mode, whereas flat sheet tests of desalting membranes are frequently operated with cross-flow in a system called Rapid Bench-Scale Membrane Testing. These flat sheet tests are relatively brief and inexpensive compared to the other membrane testing methods, and they are frequently used to determine the rejection of individual contaminants specific to the project source water. For example, if a brackish source water is influenced by agricultural drainage, then flat sheet testing may be used to determine the rejection of herbicides such as 2,4-D or atrazine, which are not typically included in commercial computer models. However, the sensitivity of performance prediction to hydraulic conditions is typically only qualitative. That is, Rapid Bench-Scale Membrane Testing operation is intended to simulate typical hydraulic conditions such as flux and cross-flow velocity, but the flat sheet geometry is significantly different than the full-scale spiral-wound geometry and representative full-scale operating conditions cannot be reproduced. When bench-scale data is allowed in lieu of a demonstration pilot, Texas Commission on Environmental Quality will specify the limiting conditions for the use of the data. For example, the restriction can state that bench-scale data cannot be used to support the hydraulics of an array or project recovery after a clean-in-place.

Single-element testing is quite valuable for demonstrating water quality and hydraulic performance of actual commercial membrane elements. Single-element pilot units are typically very mobile, and at relatively low flow rates compared to demonstration-scale piloting, single-element piloting can usually be performed on actual project source water at significantly lower cost than demonstration scale piloting. However, for desalting membranes, predicting the variations of water quality and hydraulic performance within a multiple-element vessel and multiple vessel/stage are not necessarily available through single-element testing. The data from a desalting membrane single-element pilot test may be used to calibrate the respective computer model for a membrane to evaluate multiple-element vessel and/or to determine particulate removal pretreatment needs.

Demonstration-scale piloting is the largest-scale and most expensive of the methods discussed here, but it is able to provide design engineers valuable performance data with respect to multiple element and multiple stage operation. System water quality data can be demonstrated for steady-state blending of product from multiple stages as a function of operational parameters such as flux and overall system recovery.

4.3 Low-pressure membrane testing

4.3.1 Filtration models

Filtration models have been proposed and used by various researchers to model the cumulative effects of cake formation and pore size on low-pressure membranes. The objective of a filtration model is to predict the fouling potential of a membrane by natural organic matter. Various low-pressure membrane filtration models have been developed.

Flux models for clean low-pressure membrane are based on the Poiseuille Equation of flow of through a small tube, while also accounting for the surface density (ρ, number of pores per unit area of membrane surface) and tortuosity (τ, a dimensionless value between zero and unity) of membrane pores, as shown in the following equation (Davis, 2010):

$$J = \rho_{pores} \tau \frac{\pi r^4}{8 \mu t_{mem}} \Delta P = \frac{\Delta P}{\mu R_m} \qquad \text{Equation 4-2}$$

where r is the radius of the pores, μ is the viscosity of the fluid, t_{mem} is the thickness of the membrane, and ΔP is the transmembrane pressure. Alternatively, the flux can be modeled similarly to Darcy's law, which consolidates the geometric parameters into a single parameter indicating the "resistance" (R_m) of the membrane. Tortuosity is a porous-media transport parameter that quantifies the nonlinearity of the pathway through the membrane pores; that is, tortuosity is the total tortuous path length traveled by a water molecule through a membrane divided by the thickness of the membrane. Aside from membranes containing non-interconnected pores of uniform size and length, tortuosity is a random variable that is a function of the probability distributions of pore size, length, and interconnectivity. Turbidity can be characterized through three-dimensional scanning/imagery techniques.

Time dependent flux model equations for low pressure membranes consist of the following phenomena: pore sealing, internal pore constriction, pore sealing with superposition, cake filtration. Corresponding flux equations, major features, and assumptions for these models can be found in water treatment references (e.g., Davis, 2010 and Howe et al., 2012).

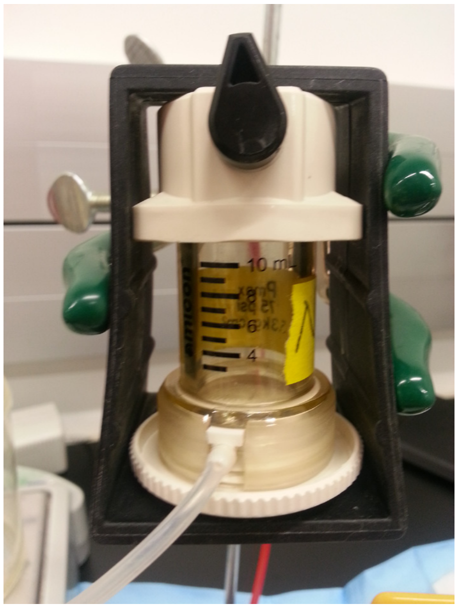
Filtration models require fairly detailed calibration by empirical testing with site-specific water quality. Input parameters for models are obtained from bench-scale tests. Testing of individual waters is required because organic fouling is highly dependent on the specific types and concentrations of organic material present in the raw water. Low-pressure filtration systems are typically operated in a dynamic (non-steady state) batch mode which requires cyclic backwashing/cleaning. As a result, a generic and universally applicable, mechanistic and time-dependent, low-pressure flux model has not been adopted for low-pressure filtration performance.

Filtration models have not been able to adequately explain fouling behavior of membranes because fouling can be attributed to various fouling mechanisms. Fouling and flux are impacted by the membrane pore sizes, the fouling cake layer on the surface of the membrane, and the adsorption of fouling particles within the membrane pores. As a result, fouling of membranes may be explained by one, two, or a combination of filtration models. In addition microfiltration and ultrafiltration membrane systems are proprietary and vary among manufactures, thus making it difficult to create and apply a standardize computer model.

4.3.2 Bench-scale hollow-fiber and flat-sheet testing

Bench-scale tests for low-pressure membranes may be used by manufacturers for quality management of their product and by researchers and engineers to economically screen several membranes or pretreatment alternatives in a short period of time (hours to days). The objective of performing bench tests for low-pressure membranes is to obtain log-removal and fouling potential of the membranes for raw water based on selected operating conditions (pressure and flux).

Bench-scale tests have historically included testing with a single hollow fiber, a bundle of hollow fibers, and flat sheets to evaluate the removal of microorganisms and particulate matter under various operating conditions (Nguyen, 2010, Marwah *et al* 2006, Chiu *et al* 2006). In hollow-fiber testing, a 0.5 to 1-inch diameter module with fiber(s) approximately one foot in length have been used in dead-end or cross-filtration modes. For flat sheet testing, two types of cells have been used in dead-end mode for testing: small unstirred cells that use a 55 millimeter diameter membrane sheet and the Sepa CF Membrane Element Cell that use a 19 centimeter by 14 centimeter membrane sheet (Figure 4-1 and 4-2).

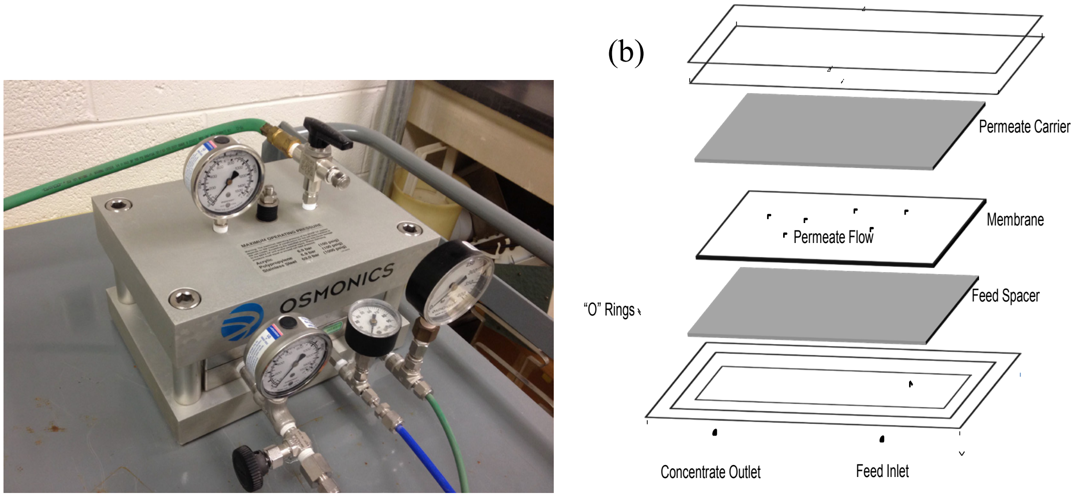


Source: Courtesy of Lauren Greenlee, NIST.

Figure 4-1. Example of unstirred cell used for flat sheet membrane testing.

(a)

(b)



Source:(a) Courtesy of W. Shane Walker, UTEP and (b) adapted from United States Environmental Protection Agency, 1996b

Figure 4-2. Osmonics Sepa™ CF II flat sheet membrane testing apparatus.

Despite the variety of approaches to bench-scale testing of low-pressure membranes, the results of some of these studies are for relative comparison of operating conditions and do not adequately characterize full-scale operation. For example, Marwah et al. (2006) used flat sheet and hollow fiber membranes operated at constant pressure (declining flux) in their bench tests to evaluate the impact of source water quality and pretreatment on microfiltration and ultrafiltration membranes. The results of the testing provided some guidance for membrane selection and pretreatment, but were not directly comparable to a full-scale system that use hollow fibers operated at constant flux.

In contrast, Nguyen (2010) evaluated the fouling characteristics of organic nitrogen compounds on two commercially available hollow-fiber poly (vinylidene-fluoroethylene) (PVDF) membranes, using 0.5-inch diameter by one-foot long module operated at a constant flux in dead-end mode. The testing was done to validate the development of three new fouling indices for low-pressure membranes (total fouling index, hydraulic irreversible fouling index, and chemical irreversible fouling index). The fouling indices calculated from the bench-scale results were compared to data from full-scale plants operated under similar raw water, flux, and pressure conditions. The researcher found that bench-scale fouling indices were representative of the full-scale as long as the test was done for 3 to 4 days. Future use of these indices is meant to provide a standard, non-proprietary, assessment for comparing the fouling potential of various low-pressure membranes.

In general, the use of bench-testing of low pressure membranes has declined in recent years as state regulations have required pilot test data for their implementation at full-scale. Nevertheless, it has been and continues to be an important tool in the development of low-pressure membranes.

4.3.3 Single-element testing

A single-element pilot-scale test assesses a single-membrane pressure vessel. The purpose of single-element testing is to examine the impact of recovery, flux, and operating pressures on the quality of filtrate and determine the required cleaning frequencies of the membrane.

The single-element pilot-scale unit is operated with a continuous feed water source and a concentrate recycle loop for a period of days or weeks. For spiral wound elements, a minimum 2.5-inch diameter pressure vessel may be used for single-element pilot-scale testing, but larger diameter, such as 4-inch and 8-inch, an also be used. Many low-pressure systems are operated with hollow-fibers, so a single module may be tested for evaluating performance. Since the geometry and operation of low-pressure hollow-fiber membrane filtration systems are not standardized across the industry, side-by-side comparison of particular membrane systems may be performed with single-elements for narrowing the selection of systems for demonstration- and full-scale.

Single-element testing allows examination additional parameters compared to bench-scale test. Biofouling and scaling effects on the membrane can be observed because of the longer testing periods and recycle loop control.

4.3.4 Demonstration-scale pilot testing

A demonstration-scale pilot test is generally considered to be the most representative of a full-scale water treatment process because it incorporates essentially all of the operational details of a full-scale system, only at a smaller scale. The objective of pilot testing is for an engineer to gather data on water quality and operation parameters to assist in the design of water treatment facility. Furthermore, pilot testing helps establish, maximize, and validate performance parameters, which in return provide insight on element and stage relationships and membrane area requirements. In contrast, challenge testing (as defined by the Long Term 2 Enhanced Surface Water Treatment Rule) is not the same as pilot testing. For challenge testing, the objective is to determine the log-removal credit for a specific membrane product.

The United States Environmental Protection Agency created a *Membrane Filtration Guidance Manual* to assist state agencies, engineers, and utilities with the use of membrane filtration in water treatment plants to meet the Long Term 2 Enhanced Surface Water Treatment Rule (United States Environmental Protection Agency, 2005b). States are allowed to pick their own regulations, whether the regulations follow Environmental Protection Agency manuals or industry practice, as long as minimum national requirements are met. However, as the manual notes in the piloting chapter, "the Long Term 2 Enhanced Surface Water Treatment Rule does not contain any requirements for pilot testing membrane filtration systems; thus, this chapter is simply intended to provide general guidance in terms of widely recognized industry practices" (United States Environmental Protection Agency, 2005b).

Similar to bench-scale testing, source water quality parameters are necessary inputs for the selection and evaluation of water treatment systems. Prior to conducting a demonstration-scale pilot test, a selection must be made of low-pressure membrane filtration systems for evaluation as they vary from manufacture to manufacture. The engineer has to select the membrane material, driving force (pressure or vacuum), and filtration direction (inside-out or outside-in). Engineers may use bench-scale and single-element tests to determine pretreatment and membrane system needs. They can also approximate the optimal membrane flux and backwash frequency with water quality parameters (United States Environmental Protection Agency, 2005b).

Pilot study protocols are required by some states agencies to be submitted prior to conducting pilot tests. Submitting a protocol allows the states to provide input that can be integrated into the pilot study before beginning testing rather than after testing and having to repeat the tests. Pilot studies are typically conducted on-site near the water source. The *Membrane Filtration Guidance Manual* recommends, at a minimum, conducting three 30-day operational cycles to establish, optimize, and validate the system (United States Environmental Protection Agency, 2005b). Furthermore, four to seven months of pilot operation is recommended in the guidance manual. Other industry guidance suggests that pilot test periods can be significantly shorter if conducted in periods of worst-case water quality (American Water Works Association, 2005).

4.4 Desalting membranes

A comparison of performance predicting methods for desalting systems is shown in Table 4-2. A more detailed review of each method is presented below.

Table 4-2. Comparison of predictive methods for desalting membranes.

Predictive method	Primary Use	Size of Membrane	Feed Flow Rate	Advantages	Limitations
Computer Modeling	Predict the hydraulic and water quality performance of a membrane system	Simulates 4 inch, 8 inch, and 16 inch models; quantitative for multiple stages	Simulates single-element, demonstration-scale, and full-scale	• Minimal time, cost • Several manufacturer models available for performance comparison • Simulates hydraulics and water quality produced from a full-scale system	• No observation of site-specific fouling and scaling • Does not incorporate physical pretreatment
Bench-Scale Testing (Flat Sheet)	Test rejection, fouling of particular ions or compounds	19 cm x 14 cm (*e.g.*, Osmonics)	~ 0.45 gal/min	• Economically compare rejection characteristics of several membranes	• Does not provide hydraulic data useful for design • Only an approximate representation of water quality from a full-scale system
Single- Element Testing	Simulate basic hydraulic, rejection, fouling, and cleaning performance; evaluate pretreatment	2.5 inch, 4 inch diameter	~ 4 - 10 gal/min	• Demonstrates element hydraulics and rejection for a source water • Demonstrates effectiveness of pretreatment • Data may be used to validate computer models	• Observation of scaling is by batch-recycle • Moderately expensive • May be time consuming
Demonstration-Scale Pilot Testing	Simulate short-term quasi-steady performance of treatment process train	4 inch, 8 inch; quantitative for systems with multiple stages	~ 20-200 gal/min	• Simulates hydraulics and water quality produced from a full-scale system • Hydraulic and water quality data are directly applicable to treatment train design	• May be expensive • May be time consuming

4.4.1 Models

Desalting membrane software models are theoretically-based, empirically-calibrated membrane models created by manufactures which are frequently used by engineers for the design of water treatment plant. When accurate water quality data is available, an engineer can design a treatment process solely based on the computer model. Engineers are also able to use the membrane system design software to compare the performance of different membranes and manufacturers and select several membranes for design or further evaluation. In general, the objective of a software model is to predict full-scale membrane performance.

In industry practice, the flux of water through the membrane is typically calculated by projection software as a function of the mass transfer coefficient of the membrane (k_w), the transmembrane pressure (ΔP), the difference in osmotic pressure between the feed and permeate ($\Delta\pi$), as shown in the following equation:

$$J = k_w(\Delta P - \Delta\pi) \qquad \text{Equation 4-3}$$

Thus, applying a greater feed pressure results in a greater flux of water through the membrane, but requires more electrical power to supply the higher pressure and flow. Solute rejection and transport is modeled in commercial membrane software as a mathematic function of solute diffusivity in the membrane, and the difference in concentration of the solute between the feed and permeate.

Membrane manufacturers perform in-house flat-sheet testing and single-element testing and use these water quality and flux data (in combination with pilot study data) to calibrate their models for membrane performance on various water qualities. Several membrane manufacturers have produced commercial design software which models the performance of pilot and full-scale systems of their nanofiltration and reverse osmosis membranes (DOW, 2012c; General Electric, 2012b; Hydranautics, 2012b; KOCH, 2012b; Toray, 2012b). These commercial software models are very similar and have similar input and output components.

Initial input data required for the use of computer models are water quality characteristics, pretreatment options, and membrane system configuration. More specifically the commercial software requires the user to input parameters for:

- Influent water quality (*e.g.,* temperature; pH; total dissolved solids; concentrations of individual ions such as sodium, magnesium, calcium, chloride, nitrate, sulfate, carbonate, boron, and silica; etc.).
- Scaling control options such as acid or antiscalant dosing.
- Operating parameters such as flux, flow, feed pressure, backpressure, system recovery.
- Membrane selection.
- Process configuration such as number of passes, number of stages per pass, number of pressure vessels per stage, and number of elements per vessel (DOW, 2012d).

Typically, manufactures specify allowable feedwater quality with respect to silt density index. However, some manufactures provide examples of brackish water composition for wells (DOW, 2012e), and others provide design guidelines. The computer model then calculates permeate and concentrate water qualities and checks the process configuration for infeasibilities. The computer models outcomes notifies the user whether water quality standards are met and identifies potential problems such as low pressure, high flux, scaling potential, and low/high flow rates.

Notifications in a model are typically given as design and saturation limitation warnings. A predominate limitation of computer models is that they only predict precipitation scaling potential by equilibrium (saturation) comparisons. Another model constraint is the use of waters with extreme high and low temperatures and total dissolved solids. Further research is required to specify quantitative limitations of the models.

Computer models for electrically-driven desalting membrane systems such as electrodialysis reversal are very similar with respect to input and output water quality parameters, except that electrically-driven computer models simulate the transport of ions through membranes (compared to the transport of water through membranes in pressure-driven membrane systems). These models are used to calculate the number of stacks and the electrical power requirements. Currently, GE has an electrodialysis design software called Watsys, but it is not available to the public.

4.4.2 Bench-scale membrane testing

Desalting membrane bench-scale test are conducted using a small sheet of membrane and small volume of water for a period of hours or days. Manufactures use bench-scale membrane test, along with other types of testing and operating data, to calibrate their computer models. Similar to low pressure bench-scale membrane tests, engineers use desalting membrane bench-scale test to inexpensively compare performance of various membranes. The primary value of bench-scale tests is to evaluate membrane performance with respect to rejection of water quality parameters not typically considered by commercial software models. Even with the relatively successful characterization, bench-scale testing results of desalting membranes do not characterize the hydraulics and long-term performance of full-scale operations.

The Information Collection Rule required public water systems serving more than 100,000 people to submit water quality data for 18 months (United States Environmental Protection Agency, 1996a). The Information Collection Rule Manual for Bench and Pilot Studies (United States Environmental Protection Agency, 1996b) is a guidance document created by the Environmental Protection Agency to assist engineers and utilities required to complete studies and submit data reports. The manual provides guidance for bench- and pilot-scale studies for membrane filtration primarily applicable to desalting membranes within the Information Collection Rule context.

Desalting membrane bench-scale test consist of flat sheet testing. Similar to low pressure flat sheet membrane testing, two types of cells have been used in dead-end mode for testing: small unstirred cells that use a 55-millimeter diameter membrane sheet and the Sepa CF Membrane Element Cell that use a 19 cm by 14 cm membrane sheet. Figure 4-2 illustrates a cross-flow membrane cell typically used in bench-scale tests. Information Collection Rule guidance manual suggests performing Rapid Bench-Scale Membrane Tests on two membranes with the following four recoveries: final stage average (90 percent), conservative average (70 percent), average (50 percent), and first stage average (30 percent).

The output parameters obtained from bench-scale tests are general impacts on flux, pressure, and recovery on permeate quality and membrane performance. Bench-scale tests are used to aide in the process of narrowing or selecting the best membrane for rejecting solutes that cannot be predicted using computer models. The Information Collection Rule manual reports that Rapid Bench-Scale Membrane Tests can predict full-scale performance with the following accuracies:

1. Initial membrane productivity within 10 percent of the initial productivity observed in pilot studies.
2. Solute rejections within 2 percent to 20 percent of rejections observed in pilot studies.
3. Cleaning frequencies within 40 percent of those observed on the pilot-scale.
4. The potential for severe and rapid membrane fouling.
5. Concentrate water quality

Grooters (2006) conducted a four hour membrane screening test and five day Rapid Bench-Scale Membrane Tests using Sepa CF Membrane Cell and then compared the results to pilot tests to evaluate the performance of nanofiltration membranes on Colorado River water. A membrane screening test is a shorter-duration rapid bench-scale test. Similar performance resulted for all three types of test. More specifically the observed percent difference between membrane screening tests and rapid bench-scale membrane tests for rejection and bulk rejection in this study were 4 percent and 2 percent, respectively. The conductivity and hardness data for feed and bulk rejection differed by no more than 4 percent and 2 percent, respectively. In comparison of the rapid bench-scale membrane tests and pilot test, the bulk rejection differed by approximately 10 percent. The team concluded that membrane-screening tests could be used to predict membrane rejection at pilot scale and to select a membrane based on constituent rejection (Grooters et al, 2006).

Allgeier and Summers (1995) investigated flux and rejection of thin composite nanofiltration membranes for surface water (pretreated) and groundwater (untreated) using rapid bench-scale membrane tests. The results of the study indicated that the pressure, flux, and rejection values obtained for the nanofiltration membrane are similar to the values reported by manufacturer and indicative of short-term performance.

4.4.3 Single-element pilot testing

A single element pilot-scale test is a test conducted on-site in continuous-flow mode using a single-element pressure vessel with a minimum size of 2.5-inch diameter and 40-inch length (United States Environmental Protection Agency, 1996b). A photograph of an actual single-element test unit is provided in Figure 4-3.

A single-element test can be operated as if the membrane were a lead element in a pressure vessel for the first stage of a full-scale system. The flux data from test may be used to validate the modeling software for total dissolved solids rejection. The test data can also be used to determine particle removal needs for pretreatment. Lead elements in the first stage are the most informative because they are the most challenged by particle fouling. The next most informative element is the last element in the last stage, because scaling is first noticed at that location. The salt concentration increases as water passes through the feed or reject channel, and the outlet is the last element.

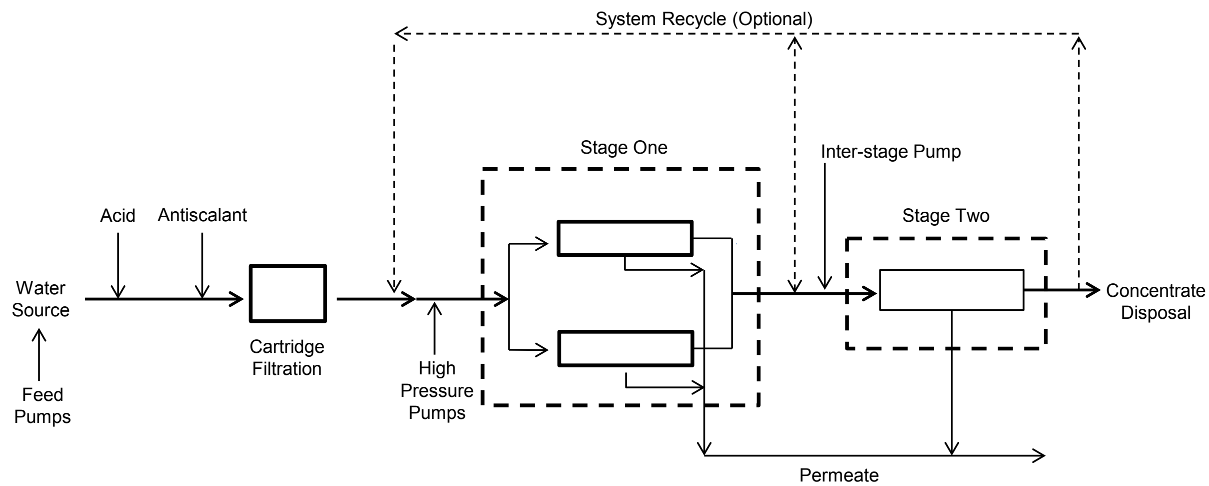
Manufacturers routinely use single-element testing with 4-inch diameter membranes to develop permeate flow and membrane rejection data for their product specifications. This testing is conducted using standard conditions (for example, 2,000 mg/L sodium chloride solution, 225 pounds per square inch, 25 degree Celsius, pH 8, and 15 percent recovery) by many manufacturers, allowing comparison of nanofiltration and reverse osmosis membrane products.

Source: Courtesy of Anthony Tarquin, UTEP.

Figure 4-3. Example of a single element test unit.

4.4.4 Demonstration-scale pilot testing

A demonstration-scale pilot test is designed to more accurately simulate the hydraulics and operation of a full-scale system compared to rapid bench-scale membrane testing and single-element testing. A true demonstration-scale pilot plant requires at least two stages, with element, vessel, and array staging similar to full-scale design. The system is operated at the same pressure, flux, and recovery as the proposed full-scale system, which provides the best indicator of overall full-scale performance in terms of pretreatment needs, fouling, and permeate water quality. Raw water flow rates for demonstration-scale pilot testing may range from 15 to 240 gallons per minute, depending on the size of the membranes used and the number of treatment trains tested in parallel.



Source: Adapted from United States Environmental Protection Agency, 1996b.

Figure 4-4. Schematic of a two-stage pilot system.

Pilot testing may include membrane elements with 8-, 4-, and 2.5-inch diameters to develop membrane flux criteria. Typically, 8- or 4-inch diameter elements are used in the first two stages of an array and 2.5-inch diameter elements may be used if a third stage is needed. Membrane and pretreatment compatibility with the proposed raw water, flux, and recovery may be screened using computer modeling and flat-sheet testing.

The duration of a pilot study may be 2 to several months of operational time, depending on the project objectives, regulatory requirements, and variability of raw water quality. The additional time needed for site preparation before the pilot will depend on its complexity. Site preparation will require considerations for raw water supply and pumping, effluent discharge, power supply, equipment shelter, process piping and tanks, and availability of labor. If no infrastructure previously exists (as with some new groundwater treatment plants) site preparation may be costly and require several months to complete.

McCurday (2006) performed a five-month pilot study on a reverse osmosis membrane for a groundwater source to evaluate pretreatment, particle fouling, and mineral scaling and compare performance from the pilot study to computer model projections. Groundwater quality for Beebe Draw aquifer consisted of sodium, chloride, magnesium, silica, calcium, and other major ions. All three membranes had salt rejections of roughly 99 percent, which were within 0.2 percent of the manufacturer's specifications. The computer model calculations were very similar to the data collected during the pilot study (concentrate, permeate, and salt rejections).

5 Review of regulatory requirements for pilot testing

5.1 United States federal regulations for membrane treatment

5.1.1 Background

Since 1986, the United States Environmental Protection Agency has promulgated increasingly higher standards for the filtration of surface waters. Additionally, in 2006, the United States Environmental Protection Agency required increased protection to groundwater sources against microbial pathogen contamination. A summary of the key provisions of these rules is presented in Table 5-1.

Table 5-1. Summary of United States Federal Water Treatment Rules

Rule	Code of Federal Regulations	Key filtration provisions
Surface Water Treatment Rule	Subpart H 40 CFR §141.70-76	Surface water systems must provide treatment equivalent of 3-log *Giardia* and 4-log virus
Interim Enhanced Surface Water Treatment Rule	Subpart P 40 CFR §141.170-175	Combined filter effluent turbidity limit of 0.3 Nephelometric Turbidity Unit (NTU) Requires individual filter monitoring Requires 2-log *Cryptosporidium* removal
Long Term 1 Enhanced Surface Water Treatment Rule	Subpart T 40 CFR §141.500-571	Systems serving less than 10,000 must meet same standards as IESWTR
Long Term 2 Enhanced Surface Water Treatment Rule	Subpart W 40 CFR §141.700-723	Requires additional removal of *Cryptosporidium* in system with elevated influent concentrations Identified several "toolbox" technologies to achieve additional *Cryptosporidium* removal
Ground Water Rule	Subpart S 40 CFR §141.400-405	Requires monitoring for fecal indicators in groundwater sources May require 4-log virus removal and/or inactivation depending on risk

Until promulgation of the Long Term 2 Enhanced Surface Water Treatment Rule, membrane technology was not specifically addressed by the surface water treatment rules. It was considered an alternative filtration technology by federal and state regulators. In the Long Term 2 Enhanced Surface Water Treatment Rule, membrane technology is presented as a distinct technology for compliance with the rule. The *Membrane Filtration Guidance Manual* (United States Environmental Protection Agency, 2005b) was developed to aid state regulators with the use of membrane technology for compliance, including requirements for challenge testing, direct integrity testing, and continuous indirect integrity monitoring and recommended practices for pilot testing and implementation considerations. Nevertheless, the regulatory framework of the Long Term 2 Enhanced Surface Water Treatment Rule and *Guidance Manual* only apply to membrane systems used to achieve *Cryptosporidium* removal (predominantly low-pressure membrane filtration systems). The use of membrane technology for *Giardia* and virus removal may be regulated under the other surface water treatment rules at the states' discretion.

The Ground Water Rule may require 4-log virus removal and/or inactivation in a groundwater source depending on a state's trigger level for fecal indicators. A groundwater source that requires corrective action under this rule will typically use chemical disinfection, but may use membrane filtration to comply with the rule. Membranes used for this purpose are required to be characterized by a molecular weight cutoff or equivalent parameter. Similar to requirements for surface water, membranes may be subject to challenge or demonstration studies to receive log-removal credit for viruses and direct integrity monitoring (United States Environmental Protection Agency, 2008). Other than the need to remove viruses in some groundwater sources, the federal regulations do not have specific requirements for treatment and technology testing to meet drinking water standards. Rather, they provide lists of best available technologies, which may include membrane technologies, to meet the maximum contaminant level for specific contaminants.

Based on the federal regulations, states have some flexibility in how they implement the testing and approval of membrane technologies. The following sections include a detailed description of the current requirements for membrane technology testing and approval in Texas and a comparison of membrane technology testing and approval in other states for surface- and ground-waters.

5.2 Texas approach

5.2.1 Membrane technologies in the Texas Administrative Code

Texas Commission on Environmental Quality has been delegated authority by the United States Environmental Protection Agency to administer the state's drinking water program and enforces Rules and Regulations for Public Waters Systems found in the Texas Administrative Code. In the Texas Administrative Code, an "innovative/alternate treatment" is defined as any treatment process that does not have design requirements specified in other sections of the Texas Administrative Code, which includes both membrane filtration and demineralization (30 Texas Administrative Code § 290.38). Unlike many other states, Texas Commission on Environmental Quality does not differentiate between the use of innovative technologies on groundwaters and surface waters. In this regard, Texas Commission on Environmental Quality exceeds the federal requirements.

The implementation of innovative/alternate treatment systems requires pilot test data (30 Texas Administrative Code §290.42(g)). The Texas Administrative Code language is similar to the language in 40 Code of Federal Regulations §141.73 (d). In the Code of Federal Regulations, pilot studies or other means are considered acceptable for use to demonstrate performance. The Texas Administrative Code is more specific in requiring the use of pilot test data or data collected at similar full-scale operations for this purpose. The Texas Administrative Code specifies that pilot test data must be representative of actual operating conditions, a pilot study protocol may be required, and a one-year manufacturer's performance warranty may also be required (Appendix A).

Membrane filtration systems are specifically addressed in 30 Texas Administrative Code §290.42(g) (3), and a copy of the code is included in Appendix Aof this report. The membrane requirements for challenge testing, direct integrity testing, and indirect integrity monitoring were adopted from federal regulations and applied for removal of *Giardia,* in addition to *Cryptosporidium*.

5.2.2 Texas Commission on Environmental Quality Approval Process

New water systems and major improvements to existing systems are subject to a plan approval process prior to construction and operational monitoring after construction (30 Texas Administrative Code §290.39).The agency has 60 days to complete the review of the plans and specifications of the project, but typically their review time is less. All materials submitted for review must be signed and sealed by a registered Texas Professional Engineer. Materials required for submittal include, but are not limited to, a plan review form, engineering reports, technical plans, specifications, legal documents, and business plans.

The engineering report, in general, includes a project description, calculations, and figures. The following is a list of items the engineering report should incorporate based on Rule 30 Texas Administrative Code §290.39(e) (1):

- Project description of proposed site and surroundings
- Population data of present and future areas to be served
- Quantity and quality of water source
- Maximum and minimum water demands of present and future
- Design data; pumping, water storage, delivery, and pressure capacities
- Type of treatment and equipment

All items submitted for review such as reports, plans, specifications, and business plan must be approved prior to starting construction. If changes are made to approved design, plans, and specifications of the water system, Texas Commission on Environmental Quality needs to be notified in writing and they will determine if a resubmission is required. The changes to the water system cannot be applied in the field until approved. A list of changes that are considered significant are listed in 30 TAC §290.39(j) (1). The agency has the authority to stop the construction and operation of a water system if it is a danger to the public. Once the water treatment plant is operating, plant and membrane performance is tracked using monthly operation reports.

5.2.3 Demonstration piloting requirements for membrane performance verification

The use of innovative technologies used to treat groundwater or surface water is considered upon submittal of pilot data. To generate new data, there is a need for a pilot study to demonstrate the performance of the proposed membrane system. The pilot requirements, such as duration of study and objectives, are very similar to the recommendations in the piloting section of the *Membrane Filtration Guidance Manual* for surface water treatment. However, here Texas Commission on Environmental Quality exceeds the federal mandate and has applied similar requirements to groundwater and surface water. Otherwise, the piloting requirements found in the Texas Commission on Environmental Quality staff guidance documents provides additional detail not found in the national regulations or guidance manuals, including provisions for the removal of dissolved solids using nanofiltration and reverse osmosis.

The specific requirements, such as the duration of the study and parameters to be measured during the pilot study, are not addressed in the state regulations. However, staff guidance documents exist, which Texas Commission on Environmental Quality reviewers use and are available to the public on their website (Texas Commission on Environmental Quality, 2004a-d). Texas Commission on Environmental Quality regulations state that a protocol may be required to be reviewed and approved prior to commencing the pilot study (30 Texas Administrative Code §290.42(g)). Even though a protocol is not mandated in state code, in *practice*, a protocol is always required. The review of the protocol is beneficial to both parties as the agency may identify items lacking in the study prior to conducting the study, which may expedite the approval process. The staff guidance documents also imply the non-official requirement of a pilot study protocol.

The piloting process consists of submitting a protocol of the pilot study, conducting the pilot study, and presenting the results of the study and recommendations for the full-scale design in a report. The pilot study is expected to be representative of full-scale plant operation conditions. This includes water characteristics such as salinity, turbidity, and temperature, in addition to using a membrane of the same material and construction as the full-scale system. The water treatment process of the full-scale plant will be simulated in the pilot study, and the study should include disinfection, pretreatment, and other processes. In addition, a one-year manufacturer's performance warranty for the membrane may be required. Modifications made to the pilot study made during stage 2 or 3 may require repeating the study. Modifications are allowed in stage 1 where the treatment process is being optimized.

The pilot study is performed for a minimum period of 90 days in three stages. Stage 2 and 3 must have a testing period of at least 30 and 10 days, respectively. The study should be performed during the season with the most difficult water quality and operation conditions. The first stage is to determine and establish performance parameters such as backwash, flux, recovery, and clean-in-place rates. The second stage is to improve or optimize the efficiency of the parameters established in the first stage and to demonstrate continuous consistent performance. The final stage is to validate the performance of the prior stages and note any decline in effectiveness. Particularly, the third stage is to demonstrate specific flux recovery following a clean-in-place procedure and the effectiveness of the cleaning procedure. After each stage and prior to beginning the next stage, a clean-in-place and direct integrity test needs to be performed. Direct integrity testing must be conducted at least once every seven days, or daily for systems in Bin 1, 2, 3, or 4. The parameters to be monitored and the frequency of data records vary between stages. Greater details of what is anticipated to be in the protocol can be found in Texas Commission on Environmental Quality's guidance document titled, "Review of Pilot Study Protocols for Membrane Filtration" (Texas Commission on Environmental Quality, 2004c).

Results of the study are compiled in a report and presented to Texas Commission on Environmental Quality. A separate Texas Commission on Environmental Quality guidance document titled, "Review of Pilot Study Reports for Membrane Filtration" (Texas Commission on Environmental Quality 2004d), details the items that are expected to be in the pilot study report. In general, the report should include the methods and equipment utilized, equipment calibrations performed, rainfall data collected, and test values gathered.

Membrane filtration without pretreatment can receive a 2.0-log removal credit for *Cryptosporidium* and 3.0-log removal credit for *Giardia* (regardless of the actual pathogen removal efficiencies). For membrane filtration with coagulation and flocculation, the log removal credit is the same for *Cryptosporidium* and *Giardia* with addition of receiving 1.0-log removal for viruses (Texas Commission on Environmental Quality, Weddell). With coagulation, flocculation, and clarification, and membrane filtration, the log removal credit for virus increases to 2.0 and the other credits are the same.

A disadvantage of the current Texas Commission on Environmental Quality approval process for membrane treatment systems is that the requirement for demonstration piloting may encumber significant financial costs for the design of a membrane water treatment plant. Pilot testing costs vary from project to project. Parameters that affect pilot costs include availability of appropriate facilities, laboratory analysis costs, size and number of processes in the treatment train, and testing schedule. Including the setup, labor, supplies, and water quality testing, the total cost of piloting a membrane system ranges from $50,000 to $100,000 (Vickers, 2005). Based on recent projects in Texas and tracked by TWDB, the cost of pilot testing ranges from $75,000 to $2,690,945 (Table 5-2).

5.3 Comparison of regulations with other states

A comparison of the Texas approach with eight key states was conducted to evaluate how membrane filtration is addressed in state code and practice and to identify national trends. States were chosen for comparison based on historical and recent development of membrane treatment. Information regarding regulations and practices for the eight states was collected by searching each state's administrative code, guidance documents, and enforcement agency website. Plan reviewers of public water systems for various states were contacted via email and telephone to verify and expand on the information from the initial search and gain responses to any unanswered questions. Each state's section includes an analysis of state regulations, permitting requirements, and pilot requirements for water treatment facilities with groundwater and surface water sources.

Normally, membrane technologies are approved if the proposed treatment system meets national and state drinking water regulations. However, the flexibility and strictness of the approval process typically depends on practices internal to each state regulatory agency. The internal agency practices are an accumulation of engineering experience, the state's project experience, and the philosophy towards either the engineer's or the state drinking water program's responsibility to protect the public. A summary of certain aspects of regulatory requirements and practices in eight select states (in comparison with Texas) is provided in Table 5-3. Permitting codes are listed in the first column, and aspects of these codes are summarized with respect to the level of performance demonstration required, design and performance data approval, and manufacturing and engineering responsibilities.

When submitting a permit to construct a membrane treatment plant, the states surveyed require the engineer to submit a report detailing the technical basis of the treatment plant's design. The design parameters of the full-scale design and components of the engineer's report are typically rule-based requirements. This type of report is an industry standard and generally follows the criteria presented in Recommended Standards for Water Works (Great Lakes-Upper Mississippi River Board, 2007). At times, a state may also issue guidance documents that may include instructions, a checklist, and an application, created by the regulatory department to assist the applicant in the permitting process. These guidance documents may also include instructions on the technical report.

For the states examined, pilot testing requirements were commonly included in internal staff guidance documents created to aide employees in permit reviews. These guidance documents consequently serve as supplements to state regulations because of the lack of detail in the state code. Permit submittal requirements are defined by state code. However, once an initial permit application and attachments are submitted, the department may request additional information that is not identified in the state code. The basis for the request for additional information may be due to internal office practices or guidance documents.

Table 5-2. Pilot cost and membrane filtration method for projects in Texas.

Project name	Source[1]	Feed total dissolved solids (mg/L)	Pilot cost (US $)	Membrane system process train	Design capacity (MGD)	Project cost (US $M)
Brazos River WTP	SW	1800	75,000	microfiltration/ultrafiltration	1.0	$5.0 M
Colorado River Metro Water District Big Spring Water Reclamation Plant	RWW	2700-2800	750,000	microfiltration/ultrafiltration and reverse osmosis	2.5	$13.5 M
Fort Hancock	GW	1600-2400	-	reverse osmosis	0.4	$3.9 M
Hickory Aquifer Well Field	GW	<1000	750,000	reverse osmosis		$122 M
Kay Bailey Hutchison	GW	4300-4400	-	reverse osmosis	27.5 (15)	$87 M
Parker County SUD	-	-	-	microfiltration and reverse osmosis		
Roscoe Reverse Osmosis WTP	-	800-1000	75,000	reverse osmosis	0.43	$1.77 M
San Antonio Water Systems	GW	1,300 – 1,600	2,690,945	reverse osmosis (4 treatment trains tested)		$341 M
Southernmost Regional Water Authority	-	3500	0			$23 M
Walden Conjunctive Use WTP	RWW & GW		760,000	microfiltration, nanofiltration, and reverse osmosis		>$5.45 M

Note: [1] SW: Surface Water; RWW: Reclaimed Wastewater; GW: Groundwater

Table 5-3. State regulations for membrane permitting and performance demonstration.

State	Permitting Regulations	Full-Scale Plant Design Parameters and Performance Data Required by State Regulatory Code[1]	Level of Performance Demonstration Required by State Regulatory Code Before Full-Scale Design	Manufacturer's Performance Warranty As Required By State	Submittal Requirements from State Guidance Documents or Practice For Construction Plan Approval
Texas	Texas Administrative Code (TAC) Chapter 30, Subchapter D, Section 290, Section 290.42(g)	• Flux, recovery, pretreatment, blending & post- treatment (corrosion control) strategy • NSF 60/61 certification for chemicals & materials of construction • "may be required"	Ground- and Surface-Water: Demonstration-scale pilot test by professional engineer, or data from other utility with similar water quality.	• One-year manufacturer's performance warranty • Bond guarantee may be required from the manufacturer for technologies subject to probationary acceptance	Ground- and Surface-Water: • Demonstration test report must be prepared by a Professional Engineer • Engineering Report submitted with construction permit application • Design/Construction contract documents
Arizona	Arizona Administrative Code (AAC), R-18-4 (Department of Environmental Quality Safe Drinking Water) and R-18-5 (Department of Environmental Quality Environmental Reviews and Certifications)	• Design Standards based on Engineering Bulletin No. 10, Guidelines for the Construction of Water Systems (ADEQ, 1978) • Construction Plans • Construction Specifications • Project description • Calculations • System capacity • Fire flow analysis • Pressure analysis	Ground- and Surface-Water: Not Required, Engineer's Discretion	Informal Requirement, Manufacture's performance warranty	• Engineer Report • Design documents and application forms
California	Groundwater: Sections 64552 & 64560,Ch 16, Title 22 of the California Code of Regulations (CCR) Surface Water: Section 64653, Ch 17, Title22 of the CCR	• Process flow diagram indicating various process elements required to meet MCLs and points of chemical additions. • Design capacities. • Treatment chemicals dosage, feed methodology, meets NSF 60 requirements. • Operations plan	Groundwater: Not Required if the best available technology is used, Engineer's Discretion Surface Water: Pilot test, or demonstration test by manufacturer or other utility with similar water quality.	No Requirement	Groundwater: • "Technical Report" submitted with construction permit application • Design/Construction contract documents Surface Water: • Demonstration test reports for surface water must be prepared by a Professional Engineer • "Engineering Report" submitted with construction permit application • Design/Construction contract documents
Florida	Florida Administrative Code (FAC) 62-555.320(2) & FAC 62-555.330(3) which references *Recommended Standards for Water Works*	• Hydraulic profile and various design flow rates • Sizes, capacity, loading rates, and other design parameters • Chemical application points and doses • Residuals disposal • Backflow prevention	Groundwater: Not Required, Engineer's Discretion Surface water: • Manufacture technical information • Data and report from Pilot-scale study or Full-scale plant • Operation and maintenance requirements	No requirement	Groundwater: • Preliminary Design Report with construction permit application • Design/Construction contract documents Surface water: • Preliminary Design Report with construction permit application • Manufacture technical information • Data and report from Pilot-scale study or Full-scale plant • Operation and maintenance requirements • Design/Construction contract documents

Note:[1]MCL: Maximum Contaminant Level; NSF: National Sanitation Foundation

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State	Permitting Regulations	Full-Scale Plant Design Parameters and Performance Data Required by State Regulatory Code[1]	Level of Performance Demonstration Required by State Regulatory Code Before Full-Scale Design	Manufacturer's Performance Warranty As Required By State	Submittal Requirements from State Guidance Documents or Practice For Construction Plan Approval
Illinois	Illinois Administrative Code, Title 35, Subtitle F, Chapter I, Part 611, Section 743(b)	• Design basis • Operation requirements • General layout • Detailed plans • Specifications • Recommended Standards for Water Works • Interim Standard on Membrane Technologies	Groundwater: Up to 6 months of pilot testing Surface Water: 12 month Pilot test	No requirements	Surface water and groundwater: • Protocol • Completed study • Report with results of study • Design/construction contract documents
New Mexico	New Mexico Administrative Code (NMAC), Title 20, Chapter 7, Part 10 Recommended Standards for Water Supply Systems, Section 4.3 Filtration	• Pretreatment design • Cleaning system design • Plans • Specifications • Flux rates	Groundwater: Not Required, Engineer's Discretion Surface water: Pilot plant studies or other means	No requirements	• Application • Engineering report • Plans • Specifications
South Carolina	Primary Drinking Water Regulation R.61-58.D(10)	• Flux, recovery, pretreatment, blending & post-treatment (corrosion control) strategy • Concentrate and cleaning waste disposal plan • Flow meter, pressure instrument, and sample tap positions • Valves for membrane cleaning • Monitoring equipment for pH, conductivity, temperature, turbidity and any other parameters required by MCL • NSF 60/61 certification for chemicals & materials of construction • Disinfection required	Groundwater: Not Required, Engineer's Discretion Surface water: Pilot plant studies or other means	No requirements	Groundwater: • Engineer's Report with construction permit application • Design/Construction contract documents Surface water: • Engineer's Report with construction permit application • Plans, Specifications, and design data
Virginia	Virginia Administrative Code(VAC), 12VAC5-590-420 (B) (2) (d) 12VAC5-590-880	• Schematic flow diagrams • Hydraulic profiles • Points of chemical application • Capacities • Filtration rates • Backwash rate • Retention times	Groundwater: Not Required, Engineer's Discretion Surface Water: Pilot plant studies or other means	No requirements	Ground water and surface water: • Application • Preliminary Meeting • Engineer Report • Plans • Specifications • Business plan
Wisconsin	Wisconsin Administrative Code, Natural Resources (NR), NR811.50 NR 108Requirements for Plans and Specifications Submittal for Reviewable Projects and Operations of Community Water systems, Sewerage Systems and Industrial Wastewater Facilities NR 809Safe Drinking Water NR 811Requirements for the Operator and Design of Community Water Systems	• Recommended Standards for Water Works • Interim Standard on Membrane Technologies • Chemicals NSF/ANSI Standard 60 certified • Schematic flow diagram • Pipe layout • Hydraulic profile • Points of chemical application	Groundwater: Not Required, Engineer's Discretion Surface Water: Pilot Testing for 9-12 months for ultrafiltration/microfiltration	No requirements	Groundwater and surface water: • Engineering Report • Plans • Specifications • Results report of pilot study

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5.3.1 Arizona

The Arizona Department of Environmental Quality enforces environmental regulations of the Arizona Administrative Code, and drinking water regulations are included in 18 Arizona Administrative Code 4. Arizona's drinking water regulations are undergoing major revision, but the current regulations are brief and direct the reader to the Code of Federal Regulations (Arizona Department of Environmental Quality, 2008a). A draft of the revised drinking water regulations is available from the Arizona Department of Environmental Quality that shows the actual incorporation of the Code of Federal Regulations, but it is not final (Arizona Department of Environmental Quality, 2008b).

Early in a water treatment project (including the use of membrane technology), the project team is required to meet with Arizona Department of Environmental Quality to present preliminary drawings and data (for example, model projections for reverse osmosis systems) and discuss the need for testing of the proposed treatment system. Pilot studies are not required by rule for regulatory approval of membrane systems treating either surface- or ground-waters. Arizona Department of Environmental Quality may require pilot studies on a case-by-case basis, but this is rare. Pilot testing for surface waters is not required because the two main surface waters in Arizona are the Colorado River and Gila Salt River Basins, which are well-characterized water sources. Water quality parameters that have been more problematic are aesthetic issues such as color, taste, odor, and algal blooms.

The design of the membrane treatment system is left to the judgment of the professional engineer based on the design standards for water treatment and distribution systems as summarized in Engineering Bulletin No. 10, *Guidelines for the Construction of Water Systems*, issued by Arizona Department of Environmental Quality (1978). Approval of membrane systems by Arizona Department of Environmental Quality is based on internal practices established through accrual of state project experience. For cases in which a water source does not meet a specific maximum contaminant level, the state may recommend that the treatment system achieve 80 percent of the respective maximum contaminant level as a safety factor in the design.

Design and construction of drinking water systems are reviewed and approved by the Drinking Water Facilities Review Unit in the Safe Drinking Water Section, which is part of the Engineering Review Program in the Water Quality Division Program of Arizona Department of Environmental Quality. The permit review process consists of two stages. The first stage is a submittal for "approval to construct," in which an application, engineer's report, plans, and specifications are included. A manufacturer's warranty for the membrane utilized in the system is informally required. Most submissions for water treatment designs include product specifications and a membrane performance warranty. It is in the interest of the project's operating cost and reliability to use a membrane with a good life span. When reviewing the manufacturer information, the regulatory reviewer seeks for the manufacturer to have NSF International certification and a good reputation. This review period is 53 to 83 days, depending on the complexity of the project.

Once the water treatment plant is built, the second stage of the process includes an application for the "approval to operate" permit. The plant design must be built in accordance with the approved permit, otherwise the engineer is required to indicate any changes, and Arizona Department of Environmental Quality will decide whether a new permit or more information is required.

In addition, a new permit is required for a water treatment plant changing from conventional treatment to membrane filtration. In general any changes from the approved permit, requires a resubmittal. If a membrane is being replaced with the same membrane, it is not considered a deviation from the approved permit, but only maintenance. When changing manufacture and membrane material, it is left to the engineer's discretion to submit a letter of notification of this change.

The performance of water treatment plants is tracked by the compliance and analytical results from turbidity and chlorine residual measurements. Performance is also evaluated during review inspections as part of sanitary surveys.

5.3.2 California

The California Department of Public Health enforces environmental regulations of the California Code of Regulations, and drinking water regulations are included in California Code of Regulations 17 and California Code of Regulations 22. In July 2007, California Department of Health Services was restructured into the California Department of Public Health and the Department of Health Care Services. The California Regulation Related to Drinking Water manual was compiled to assist California Department of Public Health personnel when reviewing permits and needing a quick reference to regulations (California Department of Public Health, 2011). Treatment and pilot testing requirements for water treatment facilities are different if the source is groundwater or surface water. This is consistent with federal requirements.

Membrane systems are categorized as "alternative filtration technologies" for surface water treatment, requiring performance demonstration to meet the requirements of the surface water treatment rules (22 California Code of Regulations § 64653(f)).

Typically, the first step in evaluating the use of membrane treatment for a surface water source is to check the *California Surface Water Treatment Alternative Filtration Technology Demonstration Report.* This report summarizes a list of accepted membrane technologies, their corresponding log-removal credits, and reasoning behind the appointed removal credit for a surface water source (California Department of Health Services, 2001). The removal efficiency of alternative technologies is based on studies that follow the California Surface Water Treatment Rule. For each membrane approved, the report provides the following: manufacture information; name of the study and who conducted it; water source; log-removal credits for *Cryptosporidium*, *Giardia*, and virus; performance standards; and operation criteria. Additional topics discussed for each membrane are membrane integrity, filter backwash, and membrane cleaners. First-year operational reports that summarize the membrane performance and any deviations are attached as appendix. Since the "alternative to filtration" rule focuses on pathogen removal, the membranes approved in the Demonstration Report are predominantly low-pressure membranes. For membranes and/or water sources that are not listed in the *Demonstration Report*, a California Department of Public Health -approved challenge test will need to be conducted to receive log-removal credit for the membrane/source water combination.

Even with the log removal credit, California Department of Public Health strongly recommends pilot testing using the proposed treatment scheme and surface water for one year. The purpose of this testing is to evaluate the impact of seasonal water quality on membrane performance. This includes fouling characteristics and disinfection by-product formation that may occur from recycling maintenance backwashes, enhanced cleaning backwashes, and/or clean-in-place streams. Seawater reverse osmosis plants will require pilot testing, but are typically limited to 2-log removal credit for *Cryptosporidium* and *Giardia* because a tracer that can be "discretely quantified" (as required by the *Membrane Filtration Guidance Manual*) to the log-removal value being sought is currently unavailable for reverse osmosis membranes.

For groundwater sources, no pilot testing is required as long as the proposed treatment technology is a best available technology capable of meeting the respective maximum contaminant levels for the treated water. Primary constituents such as arsenic and radium have specified best available technologies (best available technologies) in the regulations (United States Environmental Protection Agency, 2007b). The removal technologies listed for arsenic removal are the following: activated alumina, anion exchange, mixed bed ion exchange, green sand filtration, oxidation/coagulation/filtration, lime softening, and reverse osmosis (United States Environmental Protection Agency, 2007b). These groundwater systems are not subject to the same piloting requirements as surface waters because the membranes (typically nanofiltration and reverse osmosis) are not being used for pathogen removal. The design of these treatment systems is therefore, left to the judgment of the professional engineer.

For technologies proposed for treating groundwater that are not designated as a best available technology, a pilot study will be required to demonstrate technology performance including removal efficiency. Non-BAT approvals are not site specific and the California Department of Public Health can use the pilot study data when reviewing another application using the same technology for similar water sources elsewhere in California.

District engineers in the California Department of Public Health, with the consultation of the California Department of Public Health's Water Treatment Committee, grant or deny permits. The permitting process begins with the manufacturer or the public water system interested in using the technology (for surface water or non-best available technology groundwaters) submitting a written request. Then a demonstration study protocol is developed with and approved by the district engineer and WTC. Finally, the study is conducted and the results are compiled in a report and submitted for review. If approved, a report is due after a year of operation summarizing the performance of the technology.

Regardless of the water source, a public water system is required to submit a domestic water supply permit for a new source or modification in treatment of an existing source. An application guidance document is available for this permit (California Department of Public Health, 2007). A major focus is on the preparation of the technical report. The following elements of the technical report addressed in the guidance document are general water system information, source water information, treatment and design information, operational plans, and environmental documentation. Permit requirements for domestic public water system are listed in 22 California Code of Regulations § 64552.

5.3.3 Florida

Florida Department of Environmental Protection enforces environmental regulations (Chapter 62-555 and 62-550) in the Florida Administrative Code. Treatment requirements for water treatment facilities are different for sources from groundwater and surface water. In general, the treatment requirements are not explicit in the state code, but the state regulations provide reference to the Code of Federal Regulations, 40 CFR141.

Treatment techniques for surface water sources are detailed in Florida Administrative Code Rule 62-550.817 and are similar to United States Environmental Protection Agency requirements for the surface water treatment rules. Although membrane filtration is not listed as a filtration method, the code states "systems providing reverse osmosis, ultrafiltration, or nanofiltration shall provide sufficient disinfection to achieve a minimum of 0.5-log *Giardia* lamblia cyst and 2-log virus inactivation to supplement membrane filtration treatment" (Florida Administrative Code Rule 62-550.817(2) (b) (4)(d)). Pilot testing is required for membrane treatment systems using a surface water source. Nevertheless, "well-operated" membrane filtration systems (including reverse osmosis, nanofiltration, and ultrafiltration) are granted 2.0 log-removal credit for *Cryptosporidium*, 2.0 log-removal credit for viruses, and a 2.5 log-removal credit for *Giardia* lamblia based on effluent turbidity standards. (Rule 62-550.817(9) (b), Florida Administrative Code). Disinfection is expected to be used to achieve the remaining log removal credit that may be required.

Groundwater classifications and standards are addressed in Florida Administrative Code Chapter 62-520. Pilot testing is not required for water treatment plants using these sources. Typical water quality issues that are addressed by groundwater treatment include elevated total dissolved solids, sulfate, and other secondary contaminants, but may include primary contaminants also. The design of a groundwater treatment system is left to the judgment of the professional engineer. If conducted, design reports for groundwater systems to Florida Department of Environmental Protection may include data and analysis from a manufacture and bench-scale tests.

In Florida, water treatment plants are classified into categories based on the treatment process, which is used to determine the permit fee. A water treatment plant that uses a membrane process such as electrodialysis, electrodialysis reversal, microfiltration, ultrafiltration, nanofiltration, or reverse osmosis is classified as Category II (Florida Administrative Code Section 62-699.310 (e)) (Florida Department of Environmental Protection, 2007). A "Specific Permit to Construct PWS Components" is required when constructing a water treatment facility (Florida Department of Environmental Protection, 2003). Together with the application, a design report is also submitted describing the following existing and post development conditions: location, costs, water source, impacts to public water system, design, and operating capacities, and the treatment process to be used. Projects that involve a new water source or new treatment facility require the following additional information: water quality data, chemical doses, residual quantities, schematic/flow diagram, hydraulic profile, and a discussion on techniques used to meet primary and secondary standards (Section 62-555.520, Florida Administrative Code). Membrane plant performance is tracked using monthly compliance reports and sanitary survey inspections every 3 years.

5.3.4 Illinois

The Illinois Environmental Protection Agency enforces Primary Drinking Water Standards (Title 35, Part 611) in the Illinois Administrative Code. Treatment requirements and pilot testing differ for public water systems with groundwater or surface water sources.

Public water systems with sources from surface water or groundwater under the influence of surface water have to meet requirements similar to the United States Environmental Protection Agency surface water treatment rules. Membrane technologies are categorized under "other filtration technologies" and also referred to as an "alternative filtration technology" (35 Illinois Administrative Code 611.250 (d)). Pilot testing of Membranes Filtration for Treating Surface Waters is an internal document that is used by staff in the permit section of the Division of

Public Water Supplies, which details the requirements for pilot testing for water facilities with surface water sources (Illinois Environmental Protection Agency, 2001). Pilot testing is required for one year using operating conditions representative of full-scale. Illinois Environmental Protection Agency requires a protocol of the pilot study to be submitted prior to beginning pilot testing. Additional requirements include conducting continuous monitoring for particle counts and turbidity. Chemicals and equipment used for the study must be NSF International Standard 61 certified and five years of raw water data should be reviewed (Illinois Environmental Protection Agency, 2001). Once the pilot study is complete, a report detailing the results is submitted along with a construction permit application.

For groundwater sources, six months of pilot testing is required, but the testing period can be shortened. The time frame may be shortened to depending on the availability of general raw water quality data (for example pH and hardness) for the source and recommendations by the responsible engineer for an appropriate testing period. The minimum testing requirements allow the use of a single-element pilot unit for testing reverse osmosis and nanofiltration membranes.

The permitting requirements for public water systems are detailed in Part 602 and 652. To construct a water treatment plant, a construction permit followed by operation permit upon completion of the facility is obtained from the Division of Public Water Supplies Permit Section. In conjunction with a *Division of Public Water Supplies Application for Construction* form, a design report, general layout, detailed plans, and specifications are submitted for review (Illinois Environmental Protection Agency, 2000). Performance of membrane systems is tracked using monthly reports and periodic inspections.

5.3.5 New Mexico

New Mexico Environmental Department enforces State and Federal Drinking Water Regulations in the New Mexico Administrative Code. General requirements for drinking water facilities are addressed in the 20.7.10 New Mexico Administrative Code (New Mexico Administrative Code, 2002). The requirements are not explicit but rather provide reference to adoptions of the Code of Federal Regulations and standard manuals. Several guidance documents used by the department are listed in 20.7.10.102 New Mexico Administrative Code. The manuals include, but are not limited to, American Water Works Association manuals, New Mexico Environmental Department manuals, and *Recommended Standards for Water Works* (Great Lake-Upper Mississippi River Board, 2007).

The *Recommended Standards for Water Supply Systems, Policies for the design, review, and approval of plans and specifications for water supply systems and treatment works* manual contains design standards for water facilities used by state employees as guidelines. For source development of surface waters (Section 3.1), minimum treatment requirements are determined by New Mexico Environmental Department and filtration should be provided to all surface water and groundwater under the direct influence of surface water .Membrane filtration is defined by New Mexico Environmental Department to include microfiltration, ultrafiltration, nanofiltration, reverse osmosis, electrodialysis, and electrodialysis reversal. Microfiltration and ultrafiltration membranes are granted log-removal credits for *Giardia*, *Cryptosporidium*, and viruses for a proposed full-scale system based on pilot- or full-scale removal data. In many cases, this data is well-established for the surface waters of New Mexico and pilot testing may not be required. Electrodialysis and electrodialysis reversal receive no log removal credit because the treated water is not passed through a membrane barrier with these technologies. No reference was made to the mechanism for granting nanofiltration and reverse osmosis log removal credit for surface waters.

New Mexico Environmental Department has indicated in Section 4.3.3 that a pilot study should investigate operational parameters such as, but not limited to, flux rates, pretreatments of source water, and membrane cleanings *(*New Mexico Environmental Department*,* 2006*)*. Prior to commencing a pilot study or the design of a water treatment system, the interested party should contact and schedule a meeting with New Mexico Environmental Department to discuss the proposed project and review available water quality data. Consent must be received from New Mexico Environmental Department before beginning the pilot study.

Under source development of groundwater (Section 3.2) in the *Recommended Standards for Water Supply Systems*, filtration requirements are not addressed. In practice, pilot testing is not required for groundwaters and treatment system design is left to the judgment of the professional engineer. This is consistent with federal requirements.

A review of the permitting process is found in 20.7.10.201 New Mexico Administrative Code. An *Application for Construction or Modification of a Public Water Supply System* must be submitted 30 days prior to advertising a project for bid or entering a construction contract (New Mexico Environmental Department, 2011). Along with the application, the following items need to be submitted: an engineering design summary, plans, specifications, disinfection system plan, and an inventory of existing or potential contamination within a 1,000-foot radius. Plans should include the layout of the water treatment facility with details such as elevations, sections, and diagrams. The disinfection plan should indicate sampling frequency, sampling location, and an emergency plan in case of contamination. If the water source is new, a nitrate sample also needs to be collected. In addition, "documents demonstrating that the public water system has sufficient technical, managerial, and financial capacity" are required to be submitted (20.7.10.201(D) (1)). The documentation and information required to prove the applicant's capacities are detailed in Appendix A of the application. Performance of membrane treatment systems are tracked by sanitary surveys every 3-years for community systems and 5-years for non-community systems and operation reports that detail turbidity and chlorine residual measurements.

5.3.6 South Carolina

South Carolina Department of Health and Environmental Control enforces State Primary Drinking Water Regulations (R.61-58) found in the South Carolina Administrative Code of Regulations. Treatment and filtration requirements are addressed separately for surface water (R.61-58.3) and groundwater sources (R.61-58.2).

Membrane technologies are considered an "innovative treatment technique" by South Carolina Department of Health and Environmental Control. Design requirements for surface water sources are in R.61-58.3. Pilot testing may be required to demonstrate performance of the filtration method for surface water sources. Typically, pilot testing is performed for one-year to evaluate seasonal variations in fouling characteristics of a membrane. Also, South Carolina Department of Health and Environmental Control may require a pilot test if an existing membrane is replace with one by a different manufacturer and/or material. To date, South Carolina Department of Health and Environmental Control has not had to review an application for membrane replacement.

Treatment requirements for groundwater sources are in R.61-58.2(D). Pilot testing is not required for approval of membrane treatment systems using these sources. This is consistent with federal requirements.

To permit a water facility, a *Construction Permit Application* is submitted to the Water Facilities Permitting Division of Bureau of Water (South Carolina Department of Health and Environmental Control, 2008). The agency has a maximum of 45 days to complete the technical review, but the average review period is 25 days. The review process is separated into two phases (South Carolina Department of Health and Environmental Control, 2004).

In the first phase a preliminary engineering report is submitted and reviewed before starting final design. The preliminary engineering report is prepared in accordance with Regulations 61-58.1(C) which include a description of the following: project area, water source, water treatment plant, waste disposal handling, and an alternative water source economic and engineering assessment. The water treatment plant description should include capacities, treatment method, and flow diagram.

In the second phase, final plans, specifications, and design calculations are presented for the construction of the water treatment plant. The submittal package consists of the following items: plans, specifications, design calculations, a location map, construction easements, a letter from the entity supplying the water, a letter from the entity accepting operation and maintenance responsibility, and a letter from the local government of that potable water planning authority. Plans should include a flow diagram, hydraulic profiles, as well as points of chemical application and sampling (R.61-58.1 (E)). Specifications should encompass construction and material (R.61-58.1(F)). Design data for the water treatment plan indicate retention times, velocities, filtration rates, overflow rates, and backwash rates (R.61-58(G)). Membrane plant performance is tracked by South Carolina Department of Health and Environmental Control with monthly operating reports that include turbidity and other measurements.

5.3.7 Virginia

The Virginia Department of Health enforces Water Works Regulations (Chapter 590) in the Virginia Administrative Code. The Water Works Regulations is separated further into three parts: General Framework for Waterworks Regulations (Part I), Operation Regulations for Waterworks (Part II), and Manual of Practice for Waterworks Design (Part III).

Treatment technique requirements for waterworks with sources from surface water or groundwater under the direct influence of surface water are found in Part II in 12VAC5-590-420. Membrane filtration is categorized under "other filtration technologies" (12VAC5-590-420 (B) (2) (d)). Pilot testing is required to establish that, in combination with disinfection, a membrane system can achieve 3-log inactivation of *Giardia lamblia,* 4-log inactivation of viruses, and 2-log inactivation of Cryptosporidium. Virginia Department of Health allows the use of a single membrane module (identical to the one proposed for the full-scale system) and a "smaller-scale" membrane module (identical in material and similar in construction to the proposed full-scale module).

For groundwater sources, Virginia Department of Health does not require pilot testing unless the water source(s) have "poor" quality where the state regulator and engineer define "poor" quality. In general, the design of these treatment systems is left to the judgment of the professional engineer.

The Division of Water Supply Engineering in Virginia Department of Health reviews the requests to construct water treatment plants. The permit process consists of five steps to obtain an operation and construction permit, which include the following: (1) submitting Water Works Application Form, (2) participating in a preliminary meeting, (3) developing a business plan, (4) submitting an engineering report, and (5) submitting plans and specification (Virginia Department of Health, 2007a-b). A preliminary meeting is held to discuss the proposed project and identify additional permits required from other agencies such as a permit from the Virginia Department of Environmental Quality for the withdrawal or discharge to a water system. A business plan is also required only for first time owners of a water treatment facility. The specifics of submittal items for obtaining a construction permit are located in 12VAC5-590-200.

Performance of all water treatment plants is tracked by monthly operating reports that provide the highest turbidity measurements and integrity testing results with log removals. Onsite inspections are also completed every six months.

5.3.8 Wisconsin

The Wisconsin Department of Natural Resources enforces drinking water regulations found in the Wisconsin Administrative Code. Wisconsin is part of the ten states that use the Recommended Standards for Water Works (Great Lakes-Upper Mississippi River Board, 2007). The Wisconsin administrative code was updated in December 2011 and all rules are effective January 2012. The applicable chapters related to drinking water are the following: Requirements for Plans and Specifications for Reviewable Projects and Operations of Community Water Systems, Sewerage Systems, and Industrial Wastewater Facilities (Chapter NR 108), Safe Drinking Water (Chapter NR 809), Requirements for the Operation and Maintenance of the Public Water Systems (Chapter NR 810), and Requirements for the Operation and Design of Community Water Systems (Chapter NR 811).

Water treatments requirements are different when public water systems use groundwater versus surface water and groundwater under the direct influence of surface water. However, Wisconsin Department of Natural Resources incorporates the requirements for testing membrane systems using surface- and ground-waters in one section (NR 811.50). The membrane filtration section covers water quality considerations, pilot testing, challenge testing, pretreatment, membrane materials, backwashing, membrane cleaning, membrane integrity testing, monitoring, and post treatment. This section is provided in Appendix 8.2 of this report.

Pilot testing membrane systems is required for surface water sources to establish the performance of the technology, but may be waived if the technology is being used in another facility and operating successfully. The plans, specifications, and engineering report should be submitted for review prior to beginning the testing. A pilot study protocol is an informal requirement and manufacture performance warranty is not required. Testing should last the time necessary to be able to establish the treatment efficiency and operation parameters. For microfiltration and ultrafiltration with a surface water source, pilot testing should be conducted for 9 to 12 months. In general, requirements should follow the United States Environmental Protection Agency Membrane Filtration Guidance Manual.

For groundwater sources, pilot testing is not required unless the water quality is “poor” where “poor” water quality is not defined in the Wisconsin regulations. When pilot testing is required, testing should be conducted for two to seven months for groundwater sources that use nanofiltration and reverse osmosis membranes.

Wisconsin Department of Natural Resources has a maximum of 90 days to review a permit, but they usually take 60 days for projects that are not water main extensions. New community water systems also have to acquire a capacity certification before initiating operation. For a permit submittal, an engineering report, plans, and specifications are required to submit for review and comment. The details of engineering report, plan, and specifications are addressed in NR108 and NR811.09 (Wisconsin Department of Natural Resources, 2011a and 2011b). Performance of the treatment facilities is completed thru the monthly reports and direct integrity testing (pressure decay) performed every eight hours for surface water systems.

6 Conclusions

The Texas Commission on Environmental Quality has a defined process for approving membrane technologies, which is intended to provide consistency in the design and piloting of membrane treatment facilities in Texas. When compared to federal and other state requirements, particularly as it applies to groundwater sources, the requirement to demonstrate membrane performance with pilot testing is a conservative requirement, which is intended to bolster the reliability of the treatment plant's capacity and filtered water quality. Texas Commission on Environmental Quality is open to reviewing details and requirements of the permitting process to consider improving it without jeopardizing the public's health. Texas Commission on Environmental Quality and TWDB are working together to identify areas for improvement and gather information on the state of the art and current practices. With continued coordination between Texas Commission on Environmental Quality and TWDB, the development of a more efficient and effective approval process for membrane treatment systems may be possible.

Membrane treatment systems may be categorized as low-pressure filtration or desalting. Low-pressure systems such as microfiltration and ultrafiltration are typically designed for particle and pathogen removal. Desalting systems such as nanofiltration, reverse osmosis, and electrodialysis are typically designed for dissolved solids (salinity) removal. While membrane technology continues to advance, the industry continues to move toward standardization, and membrane treatment systems are typically designed for decades of operation with very reliable capacity and water quality.

Treatment process selection is based on source water quality and product water quality goals. The analysis of raw and desired finished water qualities is focused on establishing treatment goals. Membrane processes may be selected as a part of a treatment train designed to meet finished water goals (*e.g.*, filtration/solids removal, salt removal, removal of a specific contaminant), that in most cases includes pretreatment (conditioning feed water for membrane filtration) and post treatment (*e.g.*, disinfection, corrosion control).

The performance of membranes in full-scale water treatment plants may be evaluated and predicted by several methods. Described here are four categories of performance prediction and testing: (1) computer modeling, (2) hollow-fiber testing (for low-pressure) or flat-sheet testing (for low-pressure or desalting), (3) single-element testing, and (4) demonstration-scale pilot testing. These methods are used (often in combination) to aid in design and operation of full-scale membrane water treatment plants. Each method is uniquely valuable for predicting aspects of full-scale performance (*e.g.*, product water quality or hydraulic characteristics), with tradeoffs in the investment of design time and financial cost. All four prediction methods mentioned above are not perfectly accurate and have certain limitations, which need to be considered when weighing the benefits of each testing methods.

A review of federal drinking water regulations for public water systems is important to understanding the hierarchy of the regulations and their implications on state code. Surface Water Treatment Rules and Ground Water Rule are subparts of the primary drinking water regulations and all have the same class level. Each rule has subset requirements that are at a lower hierarchy level. Pilot testing of membrane filtration is required under the Surface Water Treatment Rule. The Surface Water Treatment Rule did not specifically address membrane technologies because at the promulgation of the Surface Water Treatment Rule, membrane technology was a new concept in the application of surface water (United States Environmental Protection Agency, 2001b). An important observation from the review is that pilot testing is not required for groundwaters that use membrane filtration, even though the Ground Water Rule lists membrane filtration as an option to meet 4-log removal of viruses and compliance monitoring. Additional information on the use of nanofiltration and reverse osmosis for virus reduction credit may be found in Appendix E of the United States Environmental Protection Agency Membrane Filtration Guidance Manual.

National Secondary drinking water regulations are non-enforceable guidelines, except in a few states, including Texas. Total dissolved solids is a secondary drinking water regulation; however, requirements for primary drinking water regulations are being applied to secondary requirements. For example, the removal of total dissolved solids in a water source can be completed using desalting membranes. Nevertheless, Texas requires piloting testing since a membrane technology is being utilized. However, at the national level there are no pilot testing requirements for secondary drinking water regulations.

The principal disadvantage of the current Texas Commission on Environmental Quality exception approval process for membrane treatment systems is that the requirement for piloting may, in some cases, be unnecessarily slow, and thereby delay or deter the construction process for communities in desperate need of new drinking water sources. As a result, the extra time, cost and approval process steps required for the use of membrane technologies in water treatment facilities can deter owners and public water systems from developing new and much needed water supplies.

Another disadvantage of the current Texas Commission on Environmental Quality approval process for membrane treatment systems is that the requirement for demonstration piloting may unnecessarily encumber significant financial costs for the design of a membrane water treatment plant. Pilot testing cost varies from project to project. Components that affect pilot costs include availability of appropriate facilities, laboratory analysis costs, size, and number of processes in the treatment train, and testing schedule. Including the setup, labor, supplies, and water quality testing, the total cost of piloting a membrane system ranges from $50,000 to $100,000 (Vickers, 2005). Based on recent projects in Texas that are ongoing with TWDB, the cost of pilot testing ranges from $75,000 to $2,690,945.

While the objective of Texas Commission on Environmental Quality's pilot testing requirement is to protect public health and safety by demonstrating the reliability of membrane treatment processes, public health and safety may actually be at risk by the requirement if water supplies become inadequate to meet the needs of the community due to the time and cost of developing new water supplies that require membrane treatment. Texas Commission on Environmental Quality's requirements can provide some assurance to the water system that the purchased treatment process will be effective and the potential challenges to a treatment process will be effective. However, Texas Commission on Environmental Quality approval does not constitute a guarantee of the water treatment system.

Some are of the opinion that proper engineering consideration necessitates demonstration testing to prove process performance, and a pilot study can accomplish this objective. However, evaluation of membrane performance and the design of reliable membrane treatment systems (especially brackish water desalination) can be executed with proper engineering consideration, which may exclude demonstration-scale pilot testing (as in other States). Dialogue is occurring among engineers and state regulators to develop more streamlined procedures for developing key water treatment systems without comprising the safety and health of the public.

7 References

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8 Appendix A

8.1 Texas regulations for membrane treatment

8.1.1 Texas Administrative Code

In 30 TAC §290.42(g) addresses other treatment processes:

> *g) Other treatment processes. Innovative/alternate treatment processes will be considered on an individual basis, in accordance with §290.39(l) of this title. Where innovative/alternate treatment systems are proposed, the licensed professional engineer must provide pilot test data or data collected at similar full-scale operations demonstrating that the system will produce water that meets the requirements of Subchapter F of this chapter (relating to Drinking Water Standards Governing Drinking Water Quality and Reporting Requirements for Public Water Systems). Pilot test data must be representative of the actual operating conditions which can be expected over the course of the year. The executive director may require a pilot study protocol to be submitted for review and approval prior to conducting a pilot study to verify compliance with the requirements of §290.39(l) of this title and Subchapter F of this chapter. The executive director may require proof of a one-year manufacturer's performance warrantee or guarantee assuring that the plant will produce treated water which meets minimum state and federal standards for drinking water quality. (Texas Commission on Environmental Quality, 2011).*

In 30 TAC §290.42(g) (3), Paragraph (3) of Subsection (g) specifically addresses membrane filtration systems:

> *(3) Membrane filtration systems or modules installed or replaced after April 1, 2012 and used for microbiological treatment, can receive Cryptosporidium and Giardia removal credit for membrane filtration only if the systems or modules meet the criteria in subparagraphs (A) - (F) of this paragraph.*
>
> *(A) The membrane module used by the system must undergo challenge testing to evaluate removal efficiency. Challenge testing must be conducted according to the criteria established by 40 CFR §141.719(b)(2) and the executive director.*
>
> *(i) All membrane module challenge test protocols and results, the protocol for calculating the representative Log Removal Value (LRV) for each membrane module, the removal efficiency, calculated results of LRVC-Test , and the non-destructive performance test with its Quality Control Release Value (QCRV) must be submitted to the executive director for review and approval prior to beginning a membrane filtration pilot study at a public water system.*
>
> *(ii) Challenge testing must be conducted on either a full-scale membrane module identical in material and construction to the membrane modules to be used in the system's treatment facility, or a smaller-scale membrane module identical in material and similar in construction to the full-scale module if approved by the executive director.*

(iii) Systems may use data from challenge testing conducted prior to January 5, 2006, if prior testing was consistent with 40 CFR §141.719, submitted by the system's licensed professional engineer, and approved by the executive director.

(iv) If a previously tested membrane is modified in a manner that could change the removal efficiency of the membrane product line or the applicability of the non-destructive performance test and associated QCRV, additional challenge testing to demonstrate the removal efficiency of the modified membrane and determine a new QCRV for the modified membrane must be conducted and results submitted to the executive director for approval.

(B) The membrane system must be designed to conduct and record the results of direct integrity testing in a manner that demonstrates a removal efficiency equal to or greater than the removal credit awarded to the membrane filtration system approved by the executive director and meets the requirements in clauses (i) - (ii) of this subparagraph.

(i) The design must provide for direct integrity testing of each membrane unit.

(ii) The design must provide direct integrity testing that has a resolution of 3 micrometers or less.

(iii) The design must provide direct integrity testing with a sensitivity sufficient to verify the log removal credit approved by the executive director. Sensitivity is determined by the criteria in 40 CFR §141.719(b)(3)(iii).

(iv) The executive director may reduce the direct integrity testing requirements for membrane units.

(C) The membrane system must be designed to conduct and record continuous indirect integrity monitoring on each membrane unit. The turbidity of the water produced by each membrane unit must be measured using the Hach Filter Trak Method 10133. The executive director may approve the use of alternative technology to monitor the quality of the water produced by each membrane unit.

(D) The level of removal credit approved by the executive director shall not exceed the lower of:

(i) the removal efficiency demonstrated during challenge testing conducted under the conditions in subparagraph (A) of this paragraph, or

(ii) the maximum removal efficiency that can be verified through direct integrity testing used with the membrane filtration process under the conditions in subparagraph (B) of this paragraph.

(E) Pilot studies must be conducted using membrane modules that will meet the requirements of this section.

(F) Membrane systems must be designed so that membrane units' feed water, filtrate, backwash supply, waste and chemical cleaning piping shall have cross-connection protection to prevent chemicals from all chemical cleaning processes from contaminating other membrane units in other modes of operation. This may be accomplished by the installation of a double block and bleed valving arrangement, a removable spool system or other alternative methods approved by the executive director (TCEQ, 2011).

8.2 Wisconsin regulations

8.2.1 NR811.50 Membrane filtration.

(1) Treatment objectives. *The selection of the specific membrane process shall be matched to the desired treatment objectives. The department shall be contacted to determine inactivation/removal credits for the specific membrane and treatment objective membranes to be used in treatment of surface water or groundwater under the direct influence of surface water.*

(2) Water quality considerations. *A review of historical source raw water quality data, including turbidity or particle counts or both, seasonal changes, organic loading, microbial activity, and temperature differentials as well as other inorganic and physical parameters shall be conducted. The data shall be used to determine feasibility and cost of the system and the degree of pre-treatment. Design considerations and membrane selection at this phase shall also address the issue of target removal efficiencies and system recovery versus acceptable transmembrane pressure differentials. On surface water supplies, pre-screening or cartridge filtration may be required. The source water temperature shall be considered when establishing the design flux of the membrane under consideration and the number of treatment units to be installed. Seasonal variation of design flow rates may be based on documented lower demand during colder weather.*

(3) Pilot testing. *Prior to initiating the design of a membrane treatment facility, pilot testing shall be conducted. The pilot plant study shall be designed to identify the best membrane to use, need for pre- treatment, type of post- treatment, cold and warm water flux, backwash optimization, chemical cleaning optimization, fouling potential, operating and transmembrane pressure, integrity testing procedures, bypass ratio, amount of reject water, system recovery, process efficiency, particulate or organism removal efficiencies, and other design and monitoring considerations, each where applicable. The duration of the pilot testing shall be 9 to 12 months for microfiltration and ultrafiltration on surface water supplies and 2 to 7 months for reverse osmosis and nanofiltration on groundwaters. The general protocol and sampling schedule shall follow the US EPA Membrane Filtration Guidance Manual, EPA 815-R-06-009, November 2005.*

(4) Challenge Testing. *Membranes treating surface waters or groundwater under the direct influence of a surface water shall be challenge tested to establish a product specific maximum Cryptosporidium and Giardia Lamblia log removal credit. Challenge testing shall meet the requirements of* s. *NR 810.45 (2).*

(5) Pretreatment. *Pretreatment shall be as follows:*

(a) Microfiltration and ultrafiltration. *Pretreatment shall be designed to remove suspended solids and large particulate matter. The pretreatment may consist of a screen or strainer with a 200 to 500 micron rating. Chemicals used for pretreatment shall be certified for compliance with ANSI/NSF Standard 60.*

(b) Reverse osmosis and nanofiltration. *Pretreatment shall be provided where appropriate for turbidity reduction, iron or manganese removal, stabilization of the water to prevent scale formation, microbial control, chlorine removal for certain membrane types, and pH* *adjustment. At a minimum, cartridge filters shall be provided for the protection of the reverse osmosis or nanofiltration membranes against particulate matter.*

(6) Membrane materials. *Two types of membranes may be used for reverse osmosis and nanofiltration. These are cellulose acetate based and polyamide composites. Microfiltration and ultrafiltration membranes may be organic polymers such as: cellulose acetate, polysulfones, polyamides, polypropylene, polycarbonates or polyvinylidene. The physical configurations may include: hollow fiber, spiral wound or tubular. Membrane materials shall be compatible with any pre-oxidants.*

(7) Useful life of membranes. *The life expectancy of a particular membrane under consideration shall be evaluated during the pilot study or from other relevant available data.*

(8) Backwashing. *Automated periodic backwashing shall be provided for microfiltration and ultrafiltration on a timed basis or once a target transmembrane pressure differential or a high resistance have been reached. Back flushing volumes may range from 5 percent to 15 percent of the permeate flow depending upon the frequency of flushing or cleaning and the degree of fouling. The back flushing volumes shall be considered in the treatment system sizing and the capacity of the raw water source. For systems using pressurized air, the compressors shall utilize food grade oil and filters shall be provided to prevent oil from reaching the membranes. Chemically enhanced backwash systems shall be protected from cross connections and shall be followed by a regular backwash. Backwash wastes shall be disposed of in accordance with subch. XII.*

(9) Membrane cleaning. *A means shall be provided to allow for periodically cleaning the membrane. Cleaning shall include a soak type cleaning and may also include more frequent maintenance cleans. The cleaning process shall protect the raw and finished water from contamination. Cleaning chemicals, frequency and procedure should follow membrane manufacturer's guidelines. Some cleaning solutions require heated water. Cleaning chemicals shall be NSF/ANSI Standard 60 certified. Membrane cleaning shall be initiated by the operator. Waste streams from chemical cleaning shall be discharged to the sanitary sewer. Adequate space shall be provided for different or additional chemicals which may be required to adequately clean the membranes in the future.*

(10) Membrane integrity testing. *A means shall be provided to conduct direct and indirect integrity testing to routinely evaluate membrane and housing integrity and overall filtration performance. Direct integrity testing may include pressure and vacuum decay tests for microfiltration and ultrafiltration and marker-based tests for nanofiltration and reverse osmosis. The direct testing method shall allow for conducting tests at least once per day and may be required 3 times per day. Indirect monitoring options may include particle counters or turbidity monitors or both and shall allow for testing continuously. The testing methodology shall be approved by the department during startup procedures.*

(11) Monitoring. *Equipment shall be provided to monitor water quality, flow rates, and water pressure.*

(a) Water quality. *Sampling taps shall be provided to allow monitoring of water quality from the source water, from the water after any pretreatment, from the filtrate of each* *membrane unit, from the combined filtrate of all membranes, from the backwash, and prior to the entry to any clearwell.*

(b) Flow monitoring. *Water meters shall be provided to allow flow measurement from the source water, from the filtrate of each unit, from the combined filtrate of all units, from the backwash source, from any recirculation line, and from any waste line.*

(c) Pressure monitoring. *Pressure gauges shall be provided prior to the membrane units, after each membrane unit, and on the combined effluent of all membrane units.*

(d) Additional monitoring. *Additional monitoring points shall be provided as necessary to satisfy integrity testing requirements and operational reporting requirements of* sub. *(10) and* s. *NR 810.07.*

(12) Cross connection control. *Cross connection control considerations shall be incorporated into the system design, particularly with regard to chemical feeds and waste piping used for membrane cleaning, waste stream and concentrate. Protection may include block and bleed valves on the chemical cleaning lines and air gaps on the drain lines.*

(13) Redundancy of critical components. *Redundancy of critical control components including but not limited to pumps, valves, air supply, chemical feed equipment and computers shall be provided.*

(14) Post treatment. *Post treatment of water treated using reverse osmosis or nanofiltration shall be provided. Post treatment may consist of degasification for carbon dioxide, if excessive, and hydrogen sulfide removal, if present, pH and hardness adjustment for corrosion control, and disinfection as a secondary pathogen control and for distribution system protection.*

(15) Bypass water. *The design shall provide for a portion of the raw water to bypass the unit to maintain stable water within the distribution system and to improve process economics as long as the raw water does not contain unacceptable contaminants. Alternative filtration shall be provided for bypassed surface water or groundwater under the direct influence of surface water.*

(16) Reject water. *Reject volumes shall be evaluated in terms of the source availability and from the waste treatment availabilities. The amount of reject water from a unit may be reduced to a limited extent by increasing the feed pressure to the unit. Waste disposal from reverse osmosis or nanofiltration reject water shall discharge to a municipal sewer system, to waste treatment facilities, or to an evaporation pond.*

(17) Treatment efficiency. *The design treatment efficiency shall be determined by pilot testing.*

(18) Power consumption. *The power consumption of a particular membrane under consideration shall be evaluated during the pilot study or from other relevant data.*

(19) Control systems.

(a) Back-up systems. *Automated monitoring and control systems shall be provided with back-up power and operational control systems consisting of the following:*

1. *Dual running programmable logic controllers (PLCs) with synchronized programs and memory, or spare PLCs loaded with the most current program.*

2. *Spare input/output (I/O) cards of each type.*

3. *A minimum of 2 human machine interfaces (HMI).*

4. *Backup power supply including uninterruptible power supply (UPS).*

(b) Remote or unmanned operational control. *Systems designed for remote or unmanned control shall be provided alarms, communication systems, and automatic shutdown processes. The department shall be contacted to determine the extent of operational control required. At a minimum the following alarms shall be provided:*

1. *High raw or filtrate turbidity.*

2. *Pump failure.*

3. *High pressure decay test.*

4. *High transmembrane pressure.*

5. *PLC failure.*

6. *Membrane unit shutdown.*

7. *Clearwell level high or low.*

8. *Equipment failure.*

9. *High or low chlorine residual.*

10. *Low chemical level.*

11. *Power failure.*

12. *Building intrusion*

13. *Building low temperature. (WDNR, 2011b)*

8.2.2 NR 811.09- Specific requirements for waterworks, plans, specifications and engineering reports.

(1) Plans.

(a) General. The detailed construction plans shall contain appropriate plan and profile views, elevations, sections and supplemental views which together with the specifications provide all necessary information for construction of the improvements. The elevations shall be based on sea level datum or local datum when a conversion to sea level datum is provided. Manufacturer's drawings are not acceptable as construction plans and will not be approved. Other state and local codes, including those of the department of safety and professional services, the public service commission, and the department of health services, shall be consulted for other requirements where applicable.

(b) Wells.

1. A general plan shall be submitted which shows the location of the proposed well and its relation to proposed or existing water supply facilities. It shall show all features of *sanitary significance which could have an effect on water quality. A separate well site plan shall be submitted which shows the property lines, contours or an appropriate number of spot elevations so that drainage can be determined, surficial features, structures, and any other relevant data. The well site plan shall also show the locations of all the observation wells, monitoring wells, test wells, treatment wells, or other wells to be constructed in relation to the well site and all permanent supply wells to be constructed on the site. A detailed well cross-section shall be submitted which shows the size and depths of drill holes and casings, depth of grout, and geological formations to be penetrated.*

2. A copy of a well site investigation report shall be submitted as required in sub. (4) *prior to or along with the plans submitted to the department for all final wells or applicable test wells as described in s.* NR 811.12 (1) (g) 2. *Based upon a review of the submitted well site investigation report, the department may perform an on-site inspection of the well site. Wellhead protection criteria conforming to s.* NR 811.12 (6) *shall be considered when siting wells. In addition, drawdown effects from the pumping or test pumping of test wells and final wells shall be considered during well siting and design. Information on possible drawdown effects on nearby private wells, public wells, or surface water bodies from pumping test wells or final wells and the means to be provided for measuring the effects shall be included with all submittals to the department where significant drawdown may occur or when required by the department.*

3. Plans and specifications shall be submitted prior to the construction of any test well to be pumped at a rate of 70 gallons per minute or more for a duration of 72 hours or more. When it is known with reasonable certainty that any proposed test well will be converted to a final well the plans and specifications for the final well shall be submitted for department approval prior to construction of the test well.

(c) Surface water intakes.

1. `Location plan.' Plans shall show the location of the intake pipeline and crib relative to the low lift pumping facility. The pipeline shall be referenced by bearing and distance, and the crib location shall be defined by latitude and longitude.

2. `Detailed plans.' A profile of the proposed pipeline and crib shall be provided in addition to construction plans.

(d) Treatment plants.

1. `Location plan.' The location plan shall show the location of the treatment plant in relation to the remainder of the water system and the water source or intake.

2. `Layout.' The general layout plans shall include a contour map of the site, the site size, the size and location of plant structures, a schematic flow diagram indicating the various plant units, the piping layout, and a hydraulic profile at gravity plants.

3. `Detailed plans.' The detailed construction plans shall include the location, dimensions, elevations and details of all existing and proposed plant units or equipment.

(e) Chemical feed equipment. The plan shall include a layout of the waterworks structure and piping. All of the following locations and details of the proposed equipment shall be included:

1. Descriptions and specifications of feed equipment, including anti-siphon devices and feed ranges.

2. Location of feeders, piping layout and points of application.

3. Storage and handling facilities.

4. Specifications for chemicals to be used.

5. Operating and control procedures.

6. Description of testing equipment and procedures.

7. Well or booster pump discharge rates and pressures.

8. Emergency eyewash and shower units.

(f) Pumping facilities. The plan shall show a general layout of the pumping equipment, pump bases, suction and discharge lines and related appurtenances.

(g) Buildings. The plans shall show the locations of all buildings and other site improvements in relation to the site property boundaries. The following details shall be included, where applicable:

1. Building dimensions, profiles, elevations, architectural details, plumbing details, HVAC details, security details, and other building appurtenances.

2. Property site contours.

3. The diameter and locations of all water mains, water service laterals, and appurtenances such as valves and hydrants.

4. The diameters and locations of all floor drains, building drain, building sewer, and POWTS components.

5. The location, elevations, construction details, and appurtenances of any on-site storm water retention or detention ponds.

6. Construction details for any non-water system related improvements to be located or constructed on the property.

(h) Water mains.

1. `Location plan.' The plan shall show the proposed water main extensions in relation to existing facilities. A map, such as required by s. NR 810.26 (2)*, of the existing system or a portion thereof with the proposed extensions shown will satisfy this requirement.*

2. `Detailed plans.' The plans shall show the location of the proposed water main within the street right-of-way or easement; the location of other utilities, such as sanitary or storm sewers; elevations at intersections and hydrants or a profile of the proposed water main; location of proposed appurtenances; details or special features and connection to the existing system. Profiles showing the ground surface, the proposed water main, the proposed sanitary or storm sewer and rock depths are necessary when approval of a common trench is requested in high bedrock areas. The size of proposed and existing water mains shall also be shown.

3. `Worksheet submittal.' Complete information as requested on any required worksheet shall be provided. The forms shall be completed for all water main projects including revisions to existing projects, upgrading of existing mains and resubmittals of projects previously approved by the department.

(i) Storage facilities.

1. `Location plan.' The plan shall show the location of the proposed facility in relation to existing facilities.

2. `Detailed plans.' Plans shall show contour lines at the site and complete construction details. Overflow elevations for existing and proposed facilities shall be noted.

(2) Specifications. Complete, detailed material and construction specifications shall be supplied for all phases of the proposed project. Specifications shall contain a program for keeping existing waterworks facilities in operation during construction of additional facilities so as to minimize interruptions of service. Specifications shall be included for controlling erosion on the construction site as a result of construction activity as specified in subch. V of ch. NR 151.

Note: Department approved Construction Site Erosion and Sediment Control Technical Standards can be found on the department's internet web site.

(3) Engineering report. An engineering report shall be submitted with all reviewable projects with the exception of water main extensions. The engineering report, required by s. NR 108.04 (2) (a)*, shall contain the controlling assumptions made and the factors used in determining the functional design of the proposed waterworks improvements as a whole and of each of the component parts or units. Where applicable, the report shall make reference to available regional, metropolitan, county or local water supply or water quality management plans and shall clearly indicate whether the proposed project is in conformance with the plans.*

Note: It is recommended that the report also include an energy efficiency analysis.

(4) Engineering report requirements. The engineering report required under sub. (3) *shall, in all cases, indicate the basis of design and shall include the following specific data, if applicable:*

(a) Description. A brief description of the project and the need for improvements.

(b) Location. A description of the geographic location of the project, including reference to maps or exhibits and the location of existing facilities.

(c) Topography. A brief description of the topography of the general area and its relation to the area involved in the project.

(d) Population. Past census data and estimated future projection to the design year for the area involved in the project.

(e) Design period. The design period being used for sizing major system components, based on the population projection.

(f) Investigations. The results of any investigations, such as soil borings, test wells, pilot tests, water quality data, and fire flow tests.

(g) Flooding. Any areas of the project which are located within the floodway or floodplain as defined in ch.NR 116 shall conform to the requirements of that chapter.

(h) Wetlands. Any areas of the project which are to be located within a wetland, pass through a wetland or may impact a wetland shall be identified.

Note: Copies of the Wisconsin wetland inventory maps are available for inspection at the office of the department of natural resources and may be purchased through the department's internet web site. The department of natural resources is in the process of placing the wetland inventory maps on the department's internet web site.

(i) Recommendations. After discussion of alternatives, the recommendations for improvements shall be listed and a statement of the reasons for selection of the recommended alternative shall be provided. A discussion of estimated capital costs and estimated annual operation and maintenance costs shall be included.

(j) Specific information. The report shall, in addition, include specific information relevant to the type of project. The specific information required for each type of project is as follows:

1. `Groundwater sources — Well site investigation reports.' A copy of a well site investigation report shall be submitted for department review and approval prior to the department approving the construction of a permanent well as required in sub. (1) (b) 2., or where there is reasonable certainty that the location of any test well will be the location of the permanent well. If no test well is to be constructed, site approval may be obtained simultaneously with department approval of plans for the final well. The investigation shall include a field survey of the well site and the surrounding area. The investigation shall consist, at a minimum, of a map and report indicating:

a. The well location by quarter quarter section, township, range, county, latitude, and longitude.

b. The boundaries of the site and the location of the well on the site.

c. The topography of the site.

d. The regional flood elevation.

e. The past and present use of the proposed site.

f. The potential contamination sources within 1/2 mile of the well location summarized in a table or list including distance and direction from the well site and also shown on a map surrounding the well site. The table or list shall include an assessment of the potential for the contamination sources to impact a well constructed on the site and shall include information obtained by checking the department's database of contaminated properties, established in accordance with ss. 292.12 (3), 292.31 (1), and 292.57, Stats., and the department of safety and professional services Storage Tank Database.

Note: The department's database of contaminated properties, established in accordance with ss. 292.12 (3), 292.31 (1), and 292.57, Stats., can be found on the department's Bureau for Remediation and Redevelopment internet web site. The Bureau for Remediation and Redevelopment Tracking System (BRRTS) is an on-line database that provides information on areas of known contaminated soil or groundwater and tracks the status of *the cleanup actions. RR Sites Map is the program's geographic information system that provides a map-based system of contaminated properties in Wisconsin. Information that appears on the RR program's database and GIS applications can also be obtained by contacting the regional drinking water staff person responsible for the water system. The department can be contacted to obtain a copy of A Guide For Conducting Potential Contaminant Source Inventories For Wellhead Protection. The department of safety and professional services Storage Tank Database Information can be found on the department of safety and professional services internet web site.*

g. The specific geologic formation or formations from which water will be pumped or withdrawn.

h. The test or final well construction details, or both, including the descending order and depths of the specific geologic formations to be penetrated.

i. The proposed test or final well pumping capacity in gallons per minute, or both, as applicable.

j. The direction of groundwater flow in the specific geologic formation or formations from which water will be pumped or withdrawn.

k. The zone of influence of the proposed well consisting of the distance to one foot of aquifer drawdown at the anticipated final pumping rate when pumpage of the well is assumed to be continuous without recharge for 30 days. The zone of influence shall be calculated using the Theis Method with or without computer modeling unless another method is approved by the department. The aquifer transmissivity (T) and storage (S) coefficients used shall be provided.

L. The recharge area for the well. The recharge area shall be calculated using the Uniform Flow Equation or a computer generated groundwater model unless another method is approved by the department.

Note: A copy of A Template For Preparing Wellhead Protection Plans For Municipal Wells, in which use of the Uniform Flow Equation is discussed, may be obtained from the department.

m. The results from any previous test wells including details of test well location and construction, water quality, pumping conditions including drawdown effects, if applicable, on other nearby wells or surface water bodies, geologic borings, and seismic, resistivity or other groundwater investigations.

n. The anticipated annual volume of water to be withdrawn and the compatibility with the existing water supply facilities.

o. The location and data from any piezometers.

p. The location of any nearby wetlands.

q. The distance and direction from the proposed well to the nearest existing well serving another water utility.

r. The distance and direction from the proposed well to the nearest neighboring private wells within 1,200 feet of the well site.

s. The location and distance to surface water and springs.

t. The locations of alternate well sites for the proposed well and other information such as test pumping or modeling as requested by the department in order to conduct a review under ch.NR 820 to justify the proposed well location if the well will be pumped at a rate equal to or greater than 70 gallons per minute and the department determines that the proposed well will be located within a groundwater protection area as defined in s. 281.34 (1) (a), Stats., or that operation of the well could result in significant adverse impacts to springs as defined in s. 281.34 (1) (f), Stats.

u. A summary evaluation of the site including advantages and disadvantages and the need for any possible water treatment.

2. Surface water sources. To assess the water available at the source, the engineering report shall include a survey and study of the source, including obtaining samples from a number of locations and depths in order to select the best intake site. Sampling shall be sufficient to adequately determine the water quality characteristics. The report shall summarize information on hydrological data, such as safe yield, maximum and minimum water levels or flows, the quality of raw water with special emphasis on results of testing programs, fluctuation in water quality, including seasonal variations and effects, the presence of befouling organisms, and existing and future potential sources of contamination.

3. Water treatment or chemical addition processes. The engineering report shall include a summary establishing the adequacy of the proposed processes for the treatment of the specific water under consideration. The report shall include any data from pilot or full scale plant studies and describe the method of disposal of any wastes and any possible effects on the environment.

4. Pumping facilities. The engineering report shall include a description of the area to be served and the basis for design, including maximum and minimum discharge heads and flows, pump operational controls, and provisions for emergency operation.

5. Water storage facilities. The engineering report shall include a description of the high to low static pressure range which the proposed facility will provide for existing and future service areas and the volume of domestic and fire storage required within the design period. The report shall explain how the proposed and existing facilities will meet these requirements. The report shall also relate the compatibility of the proposed facilities with existing facilities and any changes that will have to be made to the existing facilities.

History: CR 09-073: cr. Register November 2010 No. 659, eff. 12-1-10; correction in (1) (a), (4) (j) 1. f. made under s. 13.92 (4) (b) 6., Stats., Register December 2011 No. 672.

9 Appendix B – Review Comments and Responses

Comments on Developing Practical Alternatives to Pilot Plant Studies for Innovative Water Technologies TWDB Contract #1148321310

General Comments

1. There are all kinds of pilot tests, particularly when piloting and demonstrating are mixed as they are in this document. In some cases, demonstration refers to a substantially larger-in-scale and longer-in-time application than a pilot test. Presumably, the capacity of the pilot unit and the duration of the testing will be discussed in some detail in the other components of this study; but, where possible, please specify the requirements of the various regulations in terms of capacity and duration. At the lower end of capacity, the pilot unit should at least operate at the recovery of a full-scale plant.
Where possible, flows and duration were included if the state regulations specified.

2. In the 'Membrane technology' section of the document, please include a discussion to reflect that a significant part of the state of membrane technology is the number and capacity of membrane plants currently being used in the world. The description of membrane process technology as "innovative" no longer seems valid when one looks at how much of it is currently employed. While the focus in this document appropriately is Texas, the use in Texas represents only a small portion of the total world capacity.
Text was added for global context. Indeed, while the use of membrane technology is becoming more conventional, the term "innovative" may reflect the perspective of regulation of membrane technology in comparison to traditional water treatment (*e.g.*, coagulation, flocculation, sedimentation, granular filtration, and chlorination).

3. Several figures in the report use the term, "Used without permission." Generally copyrighted information is the intellectual property of someone. The current form of reference far exceeds the bounds of fair use (www.copyright.gov/fls/fl102.html; www.techlearning.com/techlearning/pdf/events/techforum/tx05/TeacherCopyright_chart.pdf; http://guides.library.ucla.edu/content.php?pid=133097&sid=1141278).

Either get permission from the authors to use the figures in the report, and send copies of the permission to TWDB; or, please replace the figures with those prepared by report's authors.
All figures were recreated with a note indicating that they were adapted from the source.

4. This report contains a number of grammatical errors. Please review and fix these errors.

Grammar errors were corrected.

Specific Comments

1. **Executive Summary:**

   a. Page 1, first paragraph: Please use recent data from the 2012 State Water Plan.
   Data was updated.

   b. Page 1, third paragraph: The description after the first sentence is correct for nanofiltration and reverse osmosis, but not generally for electrodialysis. The same comment applies to this paragraph when it appears on page 23.
   Electrodialysis was removed from the sentences.

   c. Page 2, second paragraph, first sentence: Please replace the words "can be accurately calculated" with the words "can be well predicted".
   Replaced with "can be well predicted".

   d. Page 2, second paragraph, last sentence: Please replace the words "ranges from less than one percent to fourteen percent" with the words "ranges from less than one percent to <u>as high as</u> fourteen percent".
   Added "as high as".

   e. Page 2, last paragraph, last sentence: Please replace the words 'brackish water desalination' with the words 'brackish groundwater desalination'.
   Replaced "water" with "groundwater".

2.1 Background:

a. Page 3, first paragraph: Please use recent data from the 2012 State Water Plan.
Data was updated.

b. Page 3, third paragraph, last sentence: Please replace the word 'membrane' with the word 'desalination'.
Replaced "membrane" with "desalination".

2.2 Project Goals:

Please add the third goal of the project, "To prepare a guidance document on alternatives to membrane pilot studies for TCEQ acceptance and outreach."

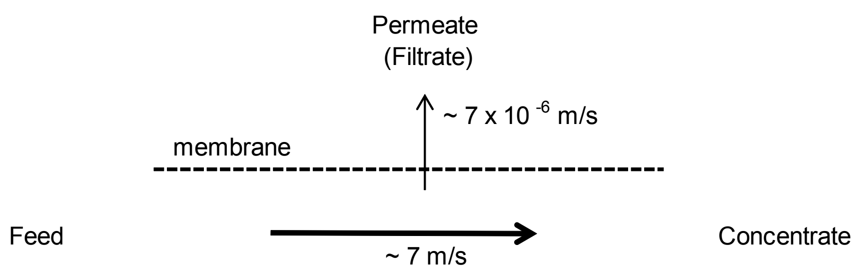
Added third goal.

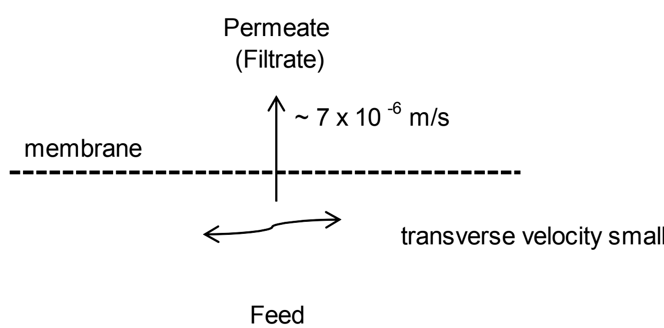
3.1.1 Membrane classifications:

a. Figure 3-1: The figure shows an RO unit as a rectangle with a diagonal line through it. While this shorthand is commonly used, it does not illustrate the concept of crossflow very well. Additionally, the report should focus on flow near the membrane, which is really the subject of the text, rather than on an element or a vessel. Please replace the figure with a figure similar to the first item below. An important feature of crossflow is

that the fluid velocity parallel to the membrane surface is high compared to the flow perpendicular to (i.e., through) the membrane. “Dead-end” could be shown by something similar to the second item below.
Figures included cross-flow and dead-end as part b of Figure 3-2. Please note that the order of Section 3.1.1 and 3.1.2 was switched.

b. Figure 3-2: Please show an operating pressure scale at the bottom of the figure.
An operating pressure scale was not added to the figure. However, we included Table 3-1, which provides ranges of pressures for low-pressure and desalting membranes.





3.1.2 Membrane development

a. Figure 3-3: Please correct the spelling of Loeb, Sourirajan and Lonsdale.
Corrected spelling on timelines.

b. The third paragraph of page 8 discusses the growth of desalination industry globally. Similar to the third paragraph of page 8, please include a paragraph focusing the development of the desalination industry in Texas.
Added development information for Texas.

3.2.1 System design

a. Section 3.2.1 discusses various parameters related to membrane technology including permeate flux, and membrane module. Please define the terms before using them. Additionally, please consider adding a paragraph with information on various membrane modules. It will help readers understand the various terminologies that are described in Section 3.2.2 (System operation and maintenance).
Defined permeate flux and membrane module. Membrane modules for low-pressure are detailed in corresponding section.

b. 'System design' section includes some of the features such as flux rate for pressure systems and vacuum systems, which are discussed in Section 3.2.2 (System operation and maintenance). Therefore, please consider combining Sections 3.2.1 (System design) and 3.2.2 (System operation and maintenance).
Combined Sections 3.2.1 and 3.2.3, now Section 3.2.2 System and Operation.

3.2.1 Membrane composition

a. Please correct the section number. Same section number (3.2.1) is provided to two different sections, system design, and membrane composition.
Corrected section numbers.

b. Page 10, first paragraph, last sentence: Please mention clearly that the temperature range for polytetrafluoroethylene membranes goes way beyond any possible use in water treatment.
Text modified.

c. To provide an overview on low pressure and high pressure membranes, please add a table at the end of this section. The table should summarize various parameters of low pressure and high pressure membranes. An example of such a table is shown below:
Added a table to section 3.1.2 since the table includes information for low-pressure and desalting membranes.

Membrane Types	Low pressure (MF and UF)	High pressure (NF and RO)
Particle size that is removed	~0.1 µm	~0.0001µm
Pressure range	5-20 psi	>80 psi
Membrane modules	Usually hollow fiber	Usually spiral wound
Operation mode	Pressure and vacuum	Pressure only
Flux range	15-100 GFD	8-15 GFD

3.2.2 System operation and maintenance

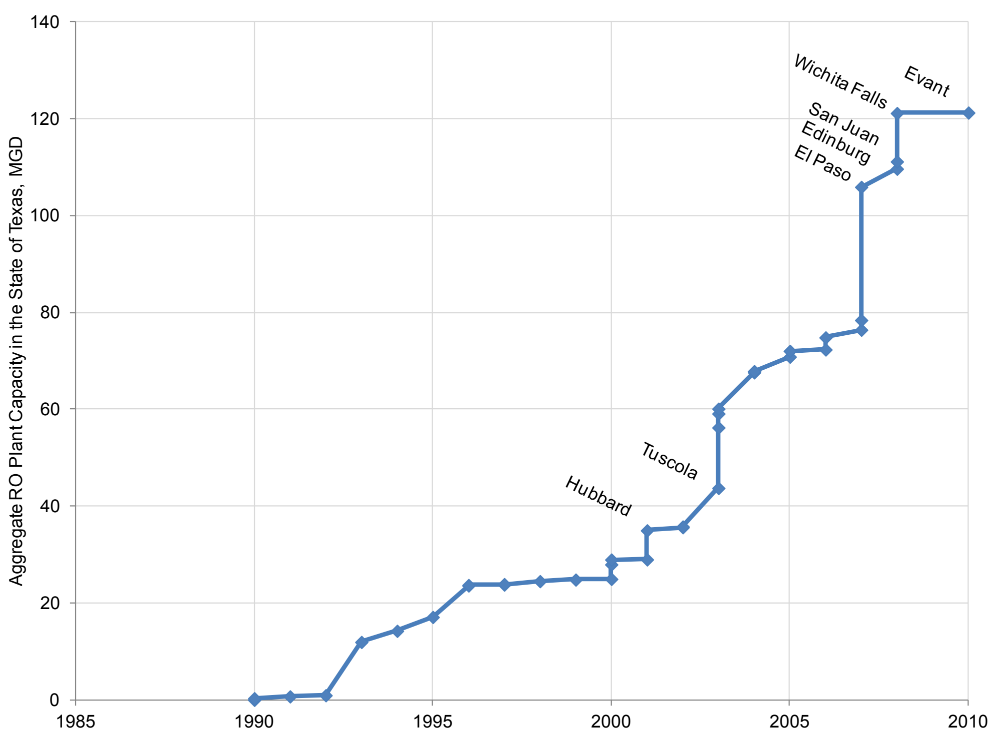
a. Please include a figure of a submerged membrane system.
Unfortunately, we did not have an image with permission rights to include in the report.

b. Page 12, second paragraph, line 8: Please delete the words ‘periodic time’.
Deleted words.

c. Page 13, first paragraph, second to last sentence: Please delete the word ‘organics’ as chlorine is used to minimize fouling only by biological growth.
Deleted words “organics and”.

3.3 Current state of desalting membrane technologies

To show the growth of desalination capacity in Texas, please provide a figure similar to the following figure. Additionally, please include a list of details for the plants.
Added figure as part (a) of Figure 3-8 and referred the reader to TWDB database of plants in Texas.



3.3.1 System design

a. ‘System design’ section includes some of the features such as osmotic pressure, which are discussed in Section 3.3.3 (System operation and maintenance). Therefore, please consider combining Sections 3.3.1 (System design) and 3.3.3 (System operation and maintenance).
Combined sections; now Section 3.3.2, “System design and operation”.

b. Please define ‘SDI’, before using it.
Defined SDI in sentence.

c. Page 15, second paragraph: While this discussion matches the diagram accompanying it, it is not consistent with the “Upflow Calcite Contactor” Study, written by some of the

present authors and currently being published by the TWDB. In that study, CO_2 was injected as part of stabilization of the product water. Since it is a part of the process that significantly affects the quality of the product water, please consider including a paragraph on water stabilization in this section.
There is no inconsistency with the referenced TWDB study. In the previous study, carbon dioxide was added to lower the pH upstream of the upflow calcite contactors. Carbon dioxide and calcite react to form calcium bicarbonate, which provides hardness and alkalinity to stabilize the permeate water quality. Text was added to explicitly state that upflow calcite contactors can be used to stabilize RO permeate.

d. Page 15, last paragraph, second sentence: The sentence does not make sense. Please clarify.
Deleted sentence.

e. Page 17, first paragraph: Please indicate clearly that the orientation of the repeating group in a spiral wound element has four items: feed spacer, membrane with dense side facing feed spacer, permeate flow spacer, and membrane with support side facing permeate flow spacer. This repeating group is shown in figure 3-10, although orientation of the membranes is not indicated there.
Deleted existing sentence and added sentence.

f. Page 18, first paragraph: Please consider introducing the discussion on recovery with a statement like "A 40-inch long element is typically run at about 10% recovery and rarely more than 15%."
Added sentence.

g. Page 18, first paragraph: Please provide a little more discussion on the size of elements and the development of the 16-inch element. Please consider using Reclamation's DWPR Report #114 as a reference for the discussion.
Added a paragraph on 16-inch elements with reference specified.

h. Page 19, last paragraph: Staging in ED is not done in the same way as it is in RO. Unlike RO, relatively little water is lost from the diluate channels in ED, so the stages have about the same flow capacity. One first stage stack feeds one second stage stack, which in turn feeds one third stage stack. It would be appropriate to separate the discussions on RO and ED. The last paragraph of page 18 discusses issues related to RO and NF. Therefore, please consider moving this paragraph below Figure 3-11 (before discussing electrodialysis).
Switched order of paragraphs.

i. Figure 3-11: The arrow pointing to the concentrate seal on the top is misplaced. Please correct.
Corrected figure.

3.4.3 Tandem and alternative treatment processes

a. Please include a paragraph describing major limitations for implementing FO as an alternative treatment process.
Added major limitations and research studies.

b. Please include a paragraph describing major advantages and limitations of membrane distillation.
Added major advantages and limitations.

c. Please add a paragraph describing major advantages and limitations of capacitive deionization process.
Added information.

d. Page 21, third paragraph, third sentence: Please revise the sentence to read "another process is used to remove the components of the draw solution from the water *and reconstitute the draw solution*."
Revised sentence.

e. Page 21, fifth paragraph: Please mention that compared to ED systems, capacitive deionization systems also contain a lot more electrodes and generally do not contain membranes.
Added sentence.

3.4.4 Implications regarding permitting

a. Page 21, last paragraph, first sentence: Please revise the sentence to read "Most technologies*, including conventional water treatment (coagulation, flocculation, sedimentation and filtration),* are not designed to …."
Revised sentence.

b. Page 22, second paragraph, fourth sentence: Please mention clearly that in addition to professional engineers, the effectiveness of any water treatment system also depends on the manufacturer of the equipment, the builder of the facility, plant operation staff, and the regulatory agency.
Added sentence.

4.1 Overview (Membrane performance evaluation and full-scale prediction methods)

Page 23, last paragraph of Section 4.1, third sentence: Because pretreatment helps reduce both organic and inorganic fouling, please replace the word 'organic' with 'organic and inorganic'.
Replaced words.

4.2 Methods for predicting full-scale treatment system operation

a. Table 4-1: Please consider removing the top row ('Predictive sensitivity to' and 'Design cost') from the table.
Removed top row of table.

b. Page 24, second paragraph (below Table 4-1): Please mention that not all models are identical. However, a great deal of information can be obtained by looking at the criteria for input data and requirement for outputs.
   Added sentence.

c. Table 4-2: Please add a third column in the table that shows the meaning of the symbols (e.g., J_t, J_0, R_m) used in flux equation column.
   The table was eliminated because it contained information beyond the scope of this project, and the reader is referred to two reference books that contain tables that detail equations, symbols, and explanations.

4.3.1 Filtration models

Page 25, fifth paragraph, first sentence: Poiseuille is misspelled. Please correct.
Corrected spelling.

4.3.4 Demonstration-scale pilot testing

Page 29: This page contains three references to EPA, 2005. However, they are not listed in the 'References' section (section 7).
References were listed as U.S. EPA; references were revised.

4.4.1 Models (Desalting membranes)

a. Please include a step-by-step process for selecting membrane type, membrane configuration, and system criteria for a desalting membrane process.
   Each membrane model has a slightly different user interface; user documents provide step-by-step instructions. A general step-by-step process is described in the data analysis and guidance document sections of this work.

b. Please mention the major limitations of computer models for accurately predicting the performance of a membrane system.
   Added limitations of models.

c. Page 31, first paragraph: Please mention the names of some of the major ED design programs.
   Currently, GE has an electrodialysis design software called Watsys, but it is not available to the public.

4.4.3 Single-element pilot testing

Second paragraph, Section 4.4.3: In this paragraph, please mention that after a lead element, the next most informative element is the last element in the last stage. Because of the increase in salt concentration as water passes through the feed/reject channel, the outlet of the last element is where scaling is first noticed.
Modified sentence.

4.4.4 Demonstration-scale pilot testing

To aid the readers, please summarize different approaches of desalting membrane testing in a tabular form. An example of the table is shown below:
Added table as Table 4-2 in desalting membranes overview, Section 4.4.

Parameters	**Computer Modeling**	**Single Element**	**Bench-scale Testing**	**Demonstration-scale Testing**
Primary Use	To predict the performance of a membrane system	To validate modeling software output	To calibrate the computer model	Accurately simulate the operation of a full-scale system
Size of Membrane	None	2.5" diameter	19 cm X 14 cm	
Flow Rate	None			15-240 gpm
Advantages	Least costly			
Limitations	Does not provide sufficient information for full-scale operation			Simulate hydraulics for full-scale operation

5.2 Texas approach

Please include a sub-section on the various exceptions that TCEQ presently approves for different membrane filtration or desalination projects in Texas.

To our knowledge there is no official list exceptions to pilot testing and may be done on a case-by-case basis.

5.2.3 Demonstration piloting requirements for membrane performance verification

The text says the cost of piloting ranges from \$75,000 to \$760,000; however, Table 5-2 shows \$2,690,945 for SAWS. The upper limit of \$760,000 also appears on pages 2 and 51. Please fix and clarify.

Corrected to reflect new amount.

5.3 Comparison of regulations with other states

Table 5-3, Row 3 (California), Column 4 (Level of Performance Demonstration Required by ---): In the <u>Groundwater</u> description, please mention clearly that performance demonstration is not required if the best available technology is used.

Added wording.

5.3.1 Arizona

Page 43, third paragraph, last sentence: The word "engineer" should be "engineer's".

Corrected grammar.

Appendix A
Comments from TCEQ

Specific Comments

1. Executive summary

a. Page 2, first paragraph, last sentence: Not really a permit, but an exception to TCEQ rules. Because the treatment requirements for RO (and other membranes) are not defined in 30 TAC 290.42, membranes are considered as other treatment processes under 290.42(g). The approval to use membranes (including RO) are reviewed as exceptions to TCEQ's rules.
Replaced permit with exception.

b. Page 2, last paragraph, first sentence: Please mention that TCEQ's rules are flexible to allow consideration of emergency situations. Nevertheless, TCEQ would like to have alternatives to pilot studies clearly defined.
Added sentence.

3.3.1 System design

The solubility models for industrial water treatment are very expensive and many facilities may not be able to afford them. Please address the issue in the Final report.
PHREEQC (USGS) and MINTEQ (EPA) are free solubility models.

3.3.2 Membrane composition

Please summarize ASTM 2010a methods in the Final report.
Added parenthetical summary.

3.4.2 Membrane materials and surface modifications

So many innovations would tend to raise the number of pilot testing of new equipment. Please address the issue in the Final report.
Added second paragraph in section 3.4.2.

3.4.4 Implications regarding permitting

a. Page 22, second paragraph, second sentence: The application of treatment to"typical" source water is an important point. Please define the term "typical". If TCEQ allows the use of a treatment process based on the fact that it has been demonstrated numerous times on "typical" source water, the term "typical" must be defined. Additionally, please explain if the source water is not within an allowable set of defined "typical" parameters, a more comprehensive evaluation may be needed.
Sentence was removed, and an explanation was added.

b. Page 22, second paragraph, last sentence: Please revise this discussion. As membranes become more popular, they are submitted by engineers that have not worked on membrane technology before and rely on the equipment manufacturers to do the design. TCEQ staff does not have much confidence in these submittals.
Added sentence.

4.1.1 Overview

Page 23, fourth paragraph, last sentence:

a. Please explain if the statement is referring to conductivity profiling as the direct method. Please describe conformance to LT2 requirements for resolution and sensitivity in this section.
Revised and added a sentence.

b. Please explore the subject more fully in the document.
Acknowledged.

4.2 Methods for predicting full-scale treatment system operation

a. Table 4-1: This table is confusing. Qualitative bulk is not defined. Sensitivity should be more detailed or quantified.
Headers were removed to clarify table. Examples were added in the table cells.

b. Page 24, second paragraph, last sentence: TCEQ is not able to approve black boxes. At the very least, TCEQ would need to know how computer model works. Please address the issue in the report.
Addressed.

c. Page 25, first paragraph, last sentence: When bench-scale, single-element or other data are allowed in lieu of a demonstration pilot, TCEQ's guidance document should specify the limiting conditions for the use of the data. In other words, bench-scale data cannot be used to support the hydraulics of an array or project recovery after a CIP. Please address the issue in the Final document.
Added sentence.

4.3.1 Filtration models

Please describe if tortuosity is easy to quantify. Additionally, please explain if tortuosity is a property of the material.
Added explanation.

4.4.1 Models

Page 30, third paragraph, first sentence: Please describe if the membrane manufacturers specify the allowable water quality parameters to be used as data input for the model.
Added sentence;

4.4.2 Bench-scale membrane testing

a. Page 31, third paragraph, third sentence: Please mention if the ICR manual is the industry accepted standard. Additionally, please describe in addition to the ICR manual, if there is an industry accepted standard that could also be applied to bench-scale tests.
The ICR manual is a manual developed by the EPA for guidance on ICR rule and testing requirements. Authors of the manual have conducted studies and presented findings in AWWA conferences. However, labeling the manual as an industry standard or not does not seem appropriate because the EPA does not label the manual as an industry standard,

and engineers may or may not consider it an industry standard. Other manuals were not found within this project literature research, but additional manuals may exist.

b. Page 31, last paragraph: Even with the relatively successful characterization as discussed on the following page, the use of bench-scale results should still be supported by other data to support a full-scale design. Please address the issue in the Final report.
   Added sentence.

c. Page 32, first paragraph, second sentence: Please define the term ‘membrane sterility test’.
   “Membrane *sterility* test was a typographical error; the text should have read, “membrane *screening* test” which is a short term RBSMT. In the specific research study cited, the test duration was four hours.

4.4.4 Demonstration-scale pilot testing

Page 34, third paragraph, second sentence: Please mention clearly if the membranes rejected only salt or they rejected some other contaminants too.
Added sentence to clarify the groundwater composition for this pilot test. Yes, the membrane rejected other contaminants, as well.

5.2.2 TCEQ permitting process

a. There are no permits in drinking water. TCEQ performs exception approvals, plan approvals and operational monitoring once a plant is built. Please address the issue in the Final report.
   Replaced permitting with approval process.
b. Page 36, third paragraph, second sentence: The Utilities Technical Review Team has 60 days to complete review of plans and specifications. Typically, their review time is less than 60 days. Please revise the statement to match the requirements.
   Revised sentence.
c. Page 36, fifth paragraph: The discussion in this paragraph does not completely summarize regulations for groundwater and surface water sources. Therefore, please consider either deleting the entire paragraph, or summarizing regulations in this paragraph that cover regulations for groundwater and surface water sources entirely.
   Deleted paragraph.

5.2.3 Demonstration piloting requirements for membrane performance verification

a. Page 37, second paragraph, third sentence: If an engineer requests to conduct a membrane pilot study, TCEQ always ask for a protocol. Please address the issue in the Final report.
   Revised sentence.

b. Page 37, third paragraph, last sentence: Modifications to the pilot process made during Stage 2 or 3 of the TCEQ approved process may require repeating the study. Stage 1 of the TCEQ process allows for modifications and optimization of the process prior to the other stages. Please clarify the issue in the Final report.
   Revised sentence.

c. Page 37, fourth paragraph, first sentence: The pilot study is 90 days overall (minimum). Stage 2 must be at least 30 days. Stage 3 must be at least 10 days. Please clarify the requirements in the Final report.
   Revised sentence.

d. Page 37, fourth paragraph, fifth sentence: Direct integrity test must also be conducted at least once every 7 days or daily for systems in Bin 2, 3, or 4. Please clarify the requirement in the Final report.
   Added sentence.

e. Page 37, fourth paragraph: The second stage is for demonstrating continuous consistent performance. The third stage is to demonstrate specific flux recovery following a CIP procedure (effectiveness of the cleaning procedure). Please clarify the issue in the Final report.
   Added clarifications.

f. Page 38, first paragraph: Please replace the word, 'tiled' with the word 'titled'.
Corrected spelling.

g. Page 38, third paragraph, first sentence: "well predicted" needs substantiation in this context of supplanting the acquisition of empirical data from a pilot study with predicted data. Please address the issue in the Final report.
Revised sentence.

5.3.1 Arizona

a. Page 42, fourth paragraph: Please describe the pilot testing requirements for the source waters from reservoirs in the Final report.
Piloting requirements are the same as for surface water because surface water sources are rivers, lakes, and reservoirs.
b. Page 43, third paragraph, last sentence: MF and UF manufacturers configure their equipment very differently. There should be a resubmittal of Arizona's first stage requirements. The direct integrity test calculations are unique and must be verified for compliance with LT2. The state will also need the challenge data for the new modules for review. Please address the issues in the Final report.
The LT2 Rule applies only to membrane filtration systems used to remove *Cryptosporidium* in Bins 2 – 4. At a State's discretion, the LT2 framework may be applied to the use of membranes for compliance with other rules (SWTR, IESWTR, etc.). Arizona does appear to have adopted the LT2 framework as a standard procedure for all membrane applications.

5.3.2 California

a. Page 44, third paragraph: Please mention in the discussion if pilot testing of groundwater sources is required for primary constituents like arsenic or radium.
Added sentence; arsenic and radium have BAT specified in the regulations.
b. Page 44, fourth paragraph, first sentence: Even with a BAT, evaluating removal efficiency with a pilot may be appropriate. Please address the issue in the Final report.
Acknowledged. Califoronia's method of handling BAT and non-BAT is summarized. No pilot testing is required if BAT is specified and capable of meeting respective maximum contaminant levels. Non-BATs are required to pilot test to demonstrate technology performance, which includes removal efficiency.

c. Page 44, fourth paragraph, last sentence: Texas does this too. The engineers in Texas are asked to find the alternate site pilot data and receive permission from the folks who paid for the pilot.
   Acknowledged.

5.3.3 Florida

a. Page 45, third paragraph: For compliance with LT2, there should be language that says under no circumstances can the granted removal be greater than demonstrated by the challenge study or the approved direct integrity test. This is the most removal credit that Florida will give assuming that challenge data and the direct integrity test parameters support higher removals. Please clarify the issue in the Final report.
   Language is not included in FL regulations. According to FAC, the pilot testing results are used to set the turbidity performance requirements. As mentioned above, the LT2 framework only applies to membranes used for *Cryptosporidium* removal for water systems in Bins 2 – 4, and may be applied to other uses of membranes at the State's discretion.

b. Page 45, Fourth paragraph, second sentence and third sentence: Please mention if Florida has different requirements for groundwater RO treating primary contaminants, arsenic, radium, and nitrate.
   No regulations for removing primary contaminants from groundwater with RO were found in the FAC.

c. Page 45, last paragraph, last sentence: Monthly operating reports in Texas will also be tracking membrane plant performance. Please address the issue in the Final report.
   Added sentence.

5.3.4 Illinois

a. Page 46, second paragraph, second to the last sentence: Please replace the words 'National Science Foundation' with the words 'National Science Foundation Standard 61'.
   "National Science Foundation" was a typographical error. Text was replaced with "NSF International".
b. Page 46, third paragraph: Please mention if Illinois requires groundwater pilot testing in all cases. Additionally, please mention if there are any alternatives.
   Revised sentence. Pilot testing is required for groundwater sources. At a minimum they would like to see single-element testing and they consider the timeframe for the pilot that is recommended by the responsible engineer. .

5.3.5 New Mexico

Page 47, third paragraph: Although not a requirement, federal guidance documents for RO treatment of radionuclides and arsenic discuss the pilot testing. Any water source with primary contaminants is viewed differently by the federal government. Most guidance includes discussion on pilot testing. Please address the issue in the Final report. Typically, these rules list pilot studies as an option to demonstrate the contaminant removal abilities of non-BAT technologies. The associated guidance documents may provide information on pilot testing, when it is warranted.

5.3.7 Virginia

Page 49, second paragraph: Please mention clearly if "bad" water quality is a judgment call by the state regulator.
Revised sentence.

5.3.8 Wisconsin

Page 50, second paragraph: Please discuss if poor water quality is defined in Wisconsin rules.
Revised sentence.

6. Conclusions

a. Page 51, first paragraph: The cumulative cost of extrapolation errors from these four prediction methods may be too high, negating any or all benefits of their use to replace the pilot study. Please address the issue in the Final report.
Added sentence.
b. Page 51, second paragraph: Please mention that the use of NF or RO for virus reduction credit under the GWR is discussed in Appendix E of the USEPA Membrane Filtration Guidance Manual. In particular, please refer to discussion on the challenges for detecting virus size breaches.
Added sentence.
c. Page 51, last paragraph: In the discussion, please add that TCEQ's requirements can provide some assurance to the water system that the purchased treatment process will be effective and that the potential challenges to a treatment process have been investigated.
Added sentence.
d. Page 52, first paragraph: "proper engineering consideration" still needs testing to prove its worthiness, and the pilot study accomplishes this. Please address the issue in the Final report. Added sentence.