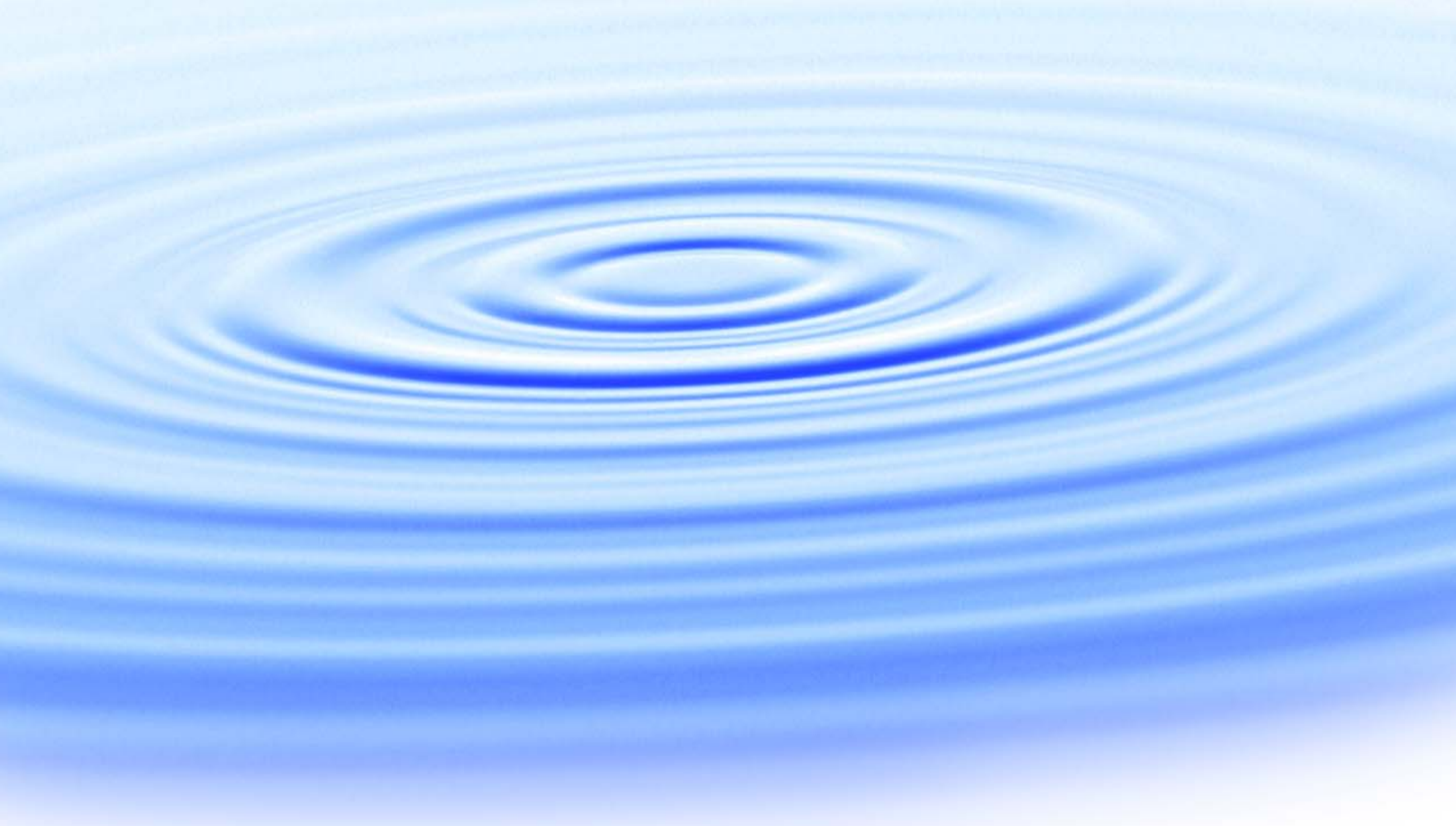
U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

STATE OF CALIFORNIA
ENERGY COMMISSION

WATEREUSE
RESEARCH

Evaluation and Optimization of Emerging and Existing Energy Recovery Devices for Desalination and Wastewater Membrane Treatment Plants



WateReuse Research Foundation

Evaluation and Optimization of Emerging and Existing Energy Recovery Devices for Desalination and Wastewater Membrane Treatment Plants

About the WateReuse Research Foundation

The mission of the WateReuse Research Foundation is to conduct and promote applied research on the reclamation, recycling, reuse, and desalination of water. The Foundation's research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high quality water through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

The Foundation's funding partners include the Bureau of Reclamation, the California State Water Resources Control Board, the California Energy Commission, and the California Department of Water Resources. Funding is also provided by the Foundation's Subscribers, water and wastewater agencies, and other interested organizations.

Evaluation and Optimization of Emerging and Existing Energy Recovery Devices for Desalination and Wastewater Membrane Treatment Plants

Robert Huehmer
CH2M HILL

Steve Alt
CH2M HILL

Jim Lozier
CH2M HILL

Amanda Kupp
CH2M HILL

Tyler Nading
CH2M HILL

Korkud Egrican
CH2M HILL

Brock Emerson
CH2M HILL

Cosponsors

Bureau of Reclamation
California Energy Commission

WateReuse Research Foundation
Alexandria, VA

Disclaimer

For more information, contact:

WateReuse Research Foundation
1199 North Fairfax Street, Suite 410
Alexandria, VA 22314
703-548-0880
703-548-5085 (fax)
www.WateReuse.org/Foundation

WateReuse Research Foundation Project Number: WRF-08-14
WateReuse Research Foundation Product Number: 08-14-1

ISBN: 978-1-934183-71-7

Contents

Figures

Tables

Acronyms

AACE	Association for the Advancement of Cost Engineering
APM	axial piston motor
APP	axial piston pump
AValue	membrane water permeability coefficient
AvgConc	average concentration of the ion
BCorrectionByIon	correction factor for the ion
BCS	brine conversion systems
BetaCoef	concentration polarization coefficient
BP	booster pump
BSU	Bonita Springs Utilities
BValue	membrane salt (ion) permeability coefficient
BW	brackish water
BWRO	brackish water reverse osmosis
CFU	colony forming units
CIP	clean in place
CP	concentration polarization
CRBS	Colorado River Basin States
DWEER	Dual Work Exchange Energy Recovery (Flowserve/Calder)
ERD	energy recovery device
ERI	Energy Recovery Inc.
FEDCO	Fluid Equipment Development Company
FS-ERD	Fluid Switcher Energy Recovery Device
gfd	gallons per square foot per day
gpd	gallons per day
gpm	gallon per minute
HALO	High Pressure Turbocharger (ERI)
HEMI	Hydraulic Energy Management Integration
HER	Hydraulic Energy Recovery
HP	high pressure
HPB	Hydraulic Pressure Booster (FEDCO)
HPP	high-pressure pump
HPP eff	high-pressure RO feed pump efficiency
HSD	homogenous solution diffusion
HTC	Hydraulic Turbocharger (ERI)
IDA	International Desalination Association
IPER	integrated pumping and energy recovery

kWh/kgal	kilowatt-hour per kilogallon
kWh/m^3	kilowatt-hour per cubic meter; a unit of energy consumption
LinX	Linear Exchanger
lmh	liter per square meter per hour
LP	low pressure
LPAWTP	Luggage Point Advanced Water Treatment Plant
LP-HEMI	low-pressure hydraulic energy management integration
LPWWTP	Luggage Point Wastewater Treatment Plant
LPT	Low Pressure Turbocharger (ERI)
L/s	liter per second
µmho/cm	micromhos per centimeter
MF	microfiltration
MG	million gallons
mgd	million gallons per day
mg/L	milligram per liter; a unit of concentration
MIX	volumetric mixing constant for the ERD
MLD	million liters per day
mri	membrane replacement interval
MWh/yr	megawatt-hour per year
NF	nanofiltration
ng/L	nanogram per liter
NPV	net present value
nte	net transfer efficiency (for an ERD)
NTU	nephelometric turbidity unit
OSHA	Occupational Safety and Health Administration
Pbr	brine pressure at ERD inlet
Pe	brine pressure at ERD exit
PEI	Pump Engineering, Inc. (ERI)
PermConc	permeate concentration of ion
PES	Pressure Exchange System
PFD	process flow diagram
PIT	Pelton impulse turbine
Pnet	net driving pressure
PSDP	Perth Seawater Desalination Plant
psig	pounds per square inch gauge; a unit of pressure
PWER kW	energy recovered by the Pelton wheel
PWMRi	present worth of the membrane replacements over the equipment life
PX	Pressure Exchanger (ERI)
REC	product recovery rate
RO	reverse osmosis
Rr	ratio of the RO brine (concentrate) flow to the RO feed flow

RR	reject ratio
RWE	Rotary Work Exchanger
SCADA	supervisory control and data acquisition
SDI	Silt Density Index
SEC	specific energy consumption
SW	seawater
SWRO	seawater reverse osmosis
TBSDF	Tampa Bay Seawater Desalination Facility
TDS	total dissolved solids
TFSP	Total Flux and Scaling Program
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
USEPA	U.S. Environmental Protection Agency
UV/AOP	ultraviolet disinfection/advanced oxidation
VFD	variable frequency drive
WRF	WateReuse Research Foundation

Foreword

The WateReuse Research Foundation, a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide high-quality water, protect public health, and improve the environment.

An Operating Plan guides the Foundation's research program. Under the plan, a research agenda of high-priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities, including water professionals, academics, and Foundation subscribers. The Foundation's research focuses on a broad range of water reuse research topics, including:

- Defining and addressing emerging contaminants
- Public perceptions of the benefits and risks of water reuse
- Management practices related to indirect potable reuse
- Groundwater recharge and aquifer storage and recovery
- Evaluation and methods for managing salinity and desalination
- Economics and marketing of water reuse

The Operating Plan outlines the role of the Foundation's Research Advisory Committee (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project and provide technical review and oversight. The Foundation's RAC and PACs consist of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the RAC and PACs and provide overall management of projects.

In WRF-08-14, a literature review and manufacturer assessment was conducted on energy recovery devices and their use in the desalination of brackish water, seawater, and wastewater. Based on typical municipal requirements, an integrated mass-balance, reverse-osmosis projection software, energy recovery, and cost estimating model was developed. The Excel-based tool permits utilities, engineers, and plant operating staff to provide greenfield, cost-based decisions on which, if any, commercially available energy recovery device to implement in their desalination facilities.

Richard Nagel
Chair
WateReuse Research Foundation

G. Wade Miller
Executive Director
WateReuse Research Foundation

Acknowledgments

This project was funded by the WateReuse Research Foundation in cooperation with the California Energy Commission and the Bureau of Reclamation.

The project team would like to thank each of the manufacturers and vendors that submitted data and information for use in this report, including Energy Recovery Inc. (ERI), Fluid Equipment Development Company (FEDCO), and Flowserve/Calder.

Principal Investigator
Robert Huehmer, *CH2M HILL*

Project Team
Steve Alt, *CH2M HILL*
Korkud Egrican, *CH2M HILL*
Amanda Kupp, *CH2M HILL*
Tyler Nading, *CH2M HILL*
Brock Emerson, *CH2M HILL*
Jim Lozier, *CH2M HILL*

Project Advisory Committee
Steve Dundorf, *U.S. Bureau of Reclamation*
Ernest Yeboah, *Inland Empire Utilities Agency*
Paul Roggensack, *California Energy Commission*
Srinivas (Vasu) Veerapaneni, *Black & Veatch*

Participating Organizations
American Water
Bonita Springs Utilities, FL
Calder AG
City of Chesapeake, VA
City of Fort Myers, FL
City of Scottsdale, AZ
Dow Filmtec
Eastern Municipal Water District, CA
El Paso Utilities District, TX
Energy Recovery, Inc.
Florida Keys Aqueduct Authority
Hydranautics
Irvine Ranch Water District, CA
Long Beach Water Department, CA
Sweetwater Authority, CA
Tampa Bay Water, FL
Toray Membranes USA
West Basin Municipal Water District, CA

Executive Summary

Water withdrawals from oceans, rivers, lakes, and ground in the United States exceeded 410 billion gallons per day in 2005 (Kenny et al., 2005). More than 201 billion gallons per day (gpd; approximately 48% of the total) are withdrawn to support power generation. Based on 2005 census data, the per capita withdrawal of water resources in the United States exceeded 1420 gpd (U.S. Census Bureau, 2005). In regions with low precipitation and seawater intrusion of coastal aquifers, coupled with population growth, it is anticipated that existing water resources will become increasingly stressed. The U.S. Bureau of Reclamation reported nearly 30 years ago that Lower Colorado River Basin water use exceeded the renewable water resources of the region (U.S. Geological Survey, 1984). As a result of these demands, water resource planners are turning to desalination of impaired waters such as saline groundwater, treated wastewater, estuarial surface water, and seawater to provide an alternative water supply for communities and industries. A recent study commissioned by the Colorado River Basin States (CRBS) identified 12 different augmentation options for water resources in the Lower Colorado River Basin. Of these, three options focused on the desalination of brackish water, seawater, and treated wastewater (CRBS, 2008).

Reverse osmosis (RO) is widely used to desalt brackish water and seawater for drinking and industrial water production and to reclaim wastewater effluent for indirect potable reuse and industrial use. There are many seawater reverse osmosis (SWRO) plants in the Middle East, where this is a predominant water source. Within the last five years, every major city in Australia has constructed a SWRO desalination plant to supplement the drinking water supply. As the total dissolved solids (TDS) of seawater are typically around 35,000 milligrams per liter (mg/L), this water will have a substantial osmotic pressure, and thus feed pressures of around 800 to 1000 psig are typically required. A major impediment to additional implementation of desalination technologies is the lack of an independent tool to evaluate energy consumption and minimization of energy use.

ES.1. Energy Consumption in Reverse Osmosis Systems

Early seawater desalination plants operated without energy recovery, with energy consumption greater than 10 kilowatt-hours per cubic meter (kWh/m^3) (Dundorf et al., 2007). The high energy consumption limited the application of RO for seawater desalination to locations where freshwater supplies were either absent or very limited. Over time, through steady improvements in the permeability (water mass transfer) of RO membranes, in combination with the development of improved energy recovery devices (ERDs), the energy consumption of SWRO systems has been reduced significantly. As shown in Figure ES-1, significant reductions in energy consumption have been achieved , with demonstration of energy consumption as low as 1.6 kWh/m^3 through the use of a conservative system design composed of high-permeability RO membranes, a positive displacement high-pressure pumps, and positive displacement work exchanger ERDs (Dundorf et al., 2007). For full-scale plants, energy consumption between 2.0 and 2.4 kWh/m^3 is typical, with full-plant energy consumption, including raw water pumping, pretreatment, chemical dosing, post-treatment, and residuals disposal, typically in the range of 3.0 to 3.5 kWh/m^3.

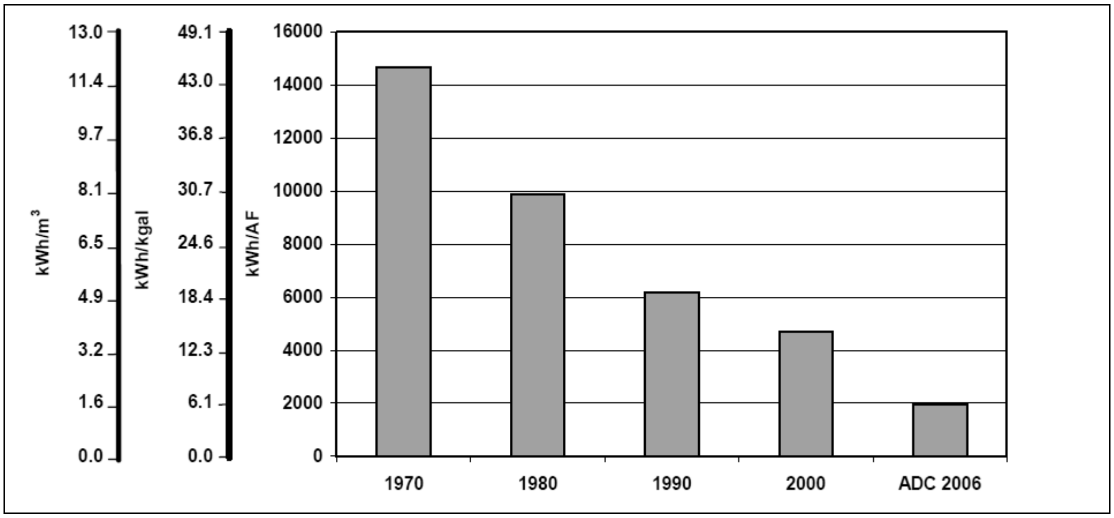


Figure ES.1. History of power consumption required for seawater desalination process equipment (Dundorf et al., 2007).

ES.2. Use of Energy Recovery Devices in Desalination

ERDs utilized in RO applications convert residual hydraulic energy into mechanical energy that is reapplied either to the RO feed (for seawater applications) or to an interstage feed (for brackish or wastewater applications) in order to reduce the energy input to the RO system. Two general classifications of ERDs are commercially available and are utilized in the desalination industry: centrifugal devices and isobaric devices. Table ES.1 outlines commercial ERDs that are available on the market.

Centrifugal devices can further be classified into direct-coupled devices and turbocharger devices. Direct-coupled devices, including the Pelton Wheel and Francis Turbine, are direct-coupled to a high-pressure pump (HPP) and motor shaft. Rotational energy imparted to the turbine from converted concentrate pressure is transferred directly to the motor shaft, reducing the motor power requirements. The HPPs for a direct-coupled device are sized for the full feed flow and pressure; however, the motor power can be reduced as a result of energy recovery.

In a turbocharger device, a turbine is direct-coupled to a pump impeller on a common shaft and located downstream from the HPP. Rotational energy imparted to the turbine from converted concentrate pressure is reconverted to pressure energy through the impeller and used to boost either the RO feed pressure (for seawater systems) or interstage pressure (for brackish or wastewater systems). The HPP is sized for the full feed flow, but the head requirement is decreased by the boost pressure provided through the turbocharger.

For isobaric devices, a side stream of the low-pressure feed and the concentrate stream are directed to a positive displacement device. Energy from the concentrate stream is imparted directly into the feed stream. A small booster pump is typically needed to raise the pressure of the side stream to the feed pressure. The HPP is sized for the permeate flow of the RO system and the full feed pressure. Isobaric devices typically have the highest efficiency of the ERDs, but require additional equipment and may allow leakage between the concentrate and feed/interstage streams.

Table ES.1. Commercially Available Energy Recovery Devices

Manufacturer	Device Type	Trade Name	Capacity Range (m^3/d) per Device*
Flowserve/Calder	Centrifugal	Pelton Wheel	360 to 24,000
PEI (division of ERI)	Centrifugal	Turbocharger	136 to 65,500
FEDCO	Centrifugal	Turbocharger	360 to 84,000
Danfoss	Isobaric	iSAVE	504 to 960
Energy Recovery Inc.	Isobaric	PX	109 to 1640
Flowserve/Calder	Isobaric	DWEER	2400 to 8,450
Aqualyng	Isobaric	Recuperator	Proprietary
Spectra Watermakers	Isobaric	Clark Pump	<10
Spectra Watermakers	Isobaric	Pearson Pump	24 to 40
KSB	Isobaric	SalTec	Up to 20,000

*Note that most ERDs are easily operated in parallel for larger capacities.

ES.3. Development of a Decision-Making Tool for Implementation of ERDs at Municipal Desalination Plants

As part of WRF-08-14, CH2M HILL developed a computer-based tool to evaluate current and emerging ERDs based on their performance, applicability, and life-cycle costs. The model covers all known and applicable commercially available ERDs and all associated systems that impact energy recovery.

The tool allows the user to develop an optimum RO system design (such as number of stages, recovery and flux, and flow and pressure of various streams) based on feed water quality and desired product water quality. The membrane type (low-pressure or high-rejection), number of passes, percentage of bypass, and ERD are examples of the options available to the user to customize the model run to a project. The tool is based upon common process configurations utilized in desalination plants.

The tool output will show the energy consumption when no ERD is used, display comparative performance (based on energy consumption, operating costs, and life-cycle costs) of these devices, and indicate the overall energy consumption, operating costs, and capital costs associated with the system. Figure ES.2 illustrates a screen capture of the tool's operator interface.

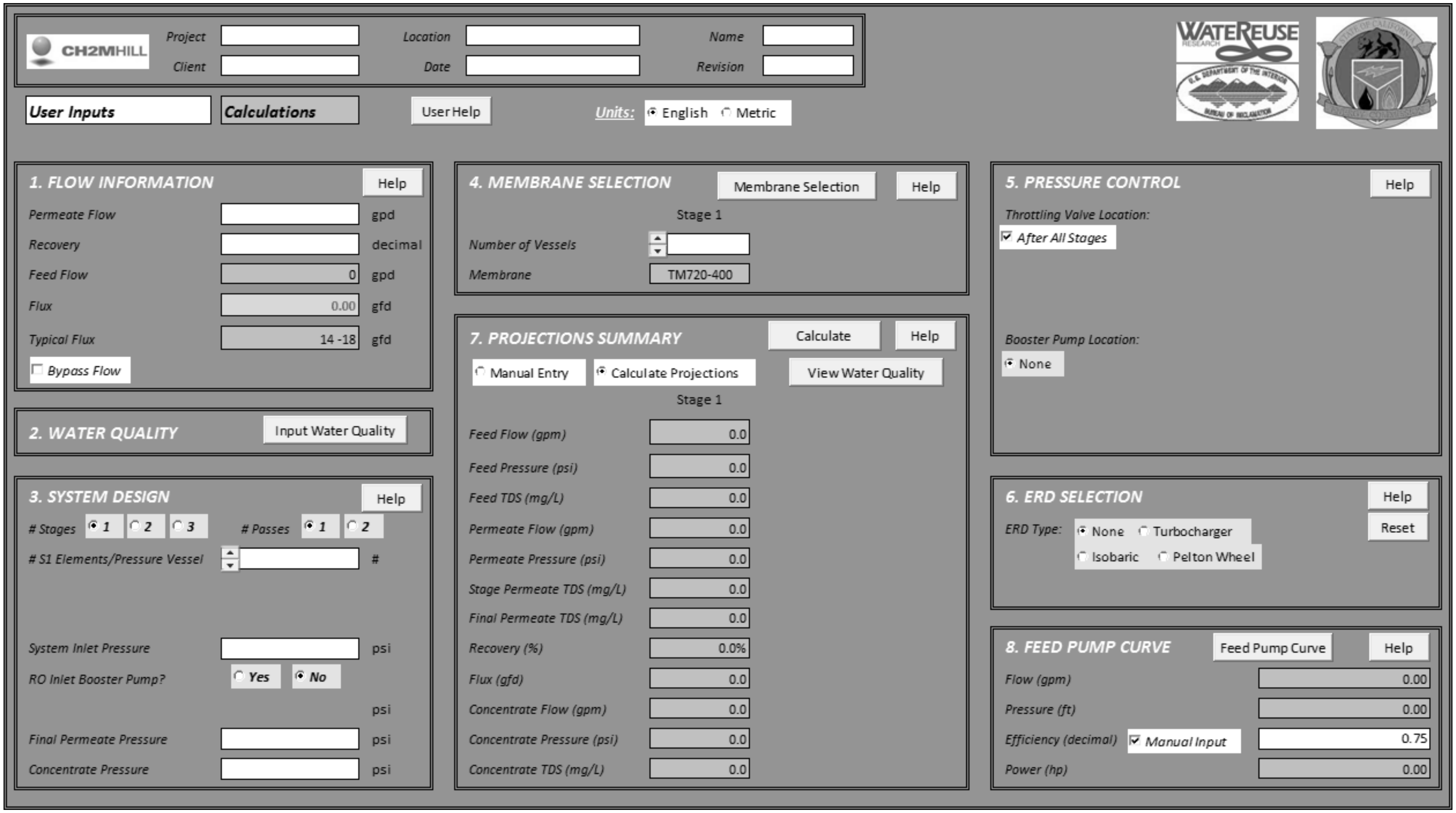


Figure ES.2. Screen shot of the operator interface for the ERD tool.

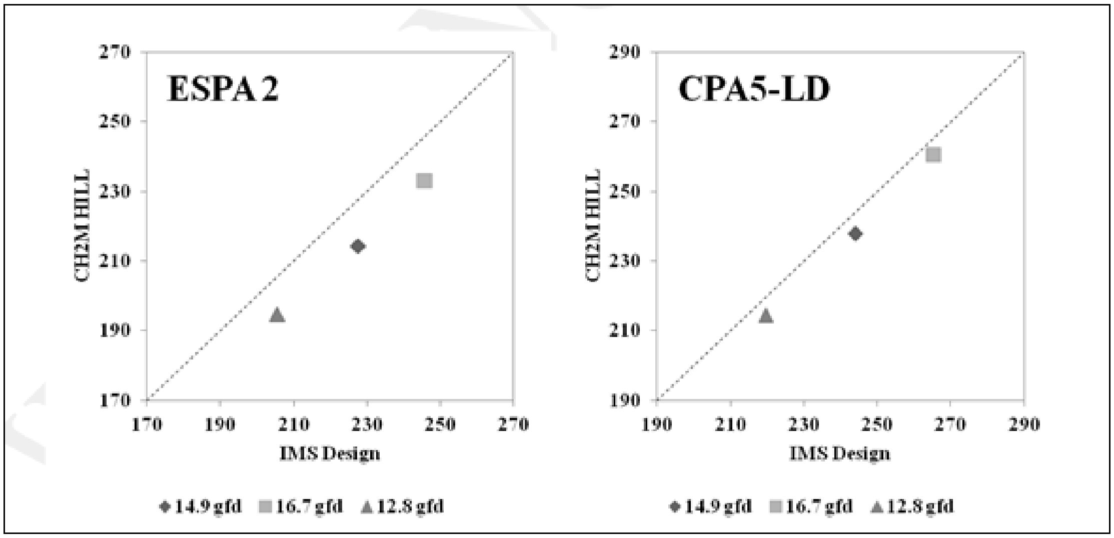


Figure ES.3. WRF-08-14, CH2M HILL developed tool vs. RO manufacturer's projection software, feed pressure (psi).

The tool utilizes a RO projection calculation algorithm similar to that developed by Thomas Wolfe of Perlorica under contract to the U.S. Environmental Protection Agency (USEPA), called the Total Flux and Scaling Program (TFSP). Figure ES.3 shows that the model provides a reasonable representation of the manufacturers' projection software.

Five different case studies were compared to the tool:

- Case Study #1: Eastern Municipal Water District, Perris I BWRO facility
    - This is a brackish groundwater desalter using a turbocharger ERD. The tool's prediction of feed and ERD boost pressure are within 5% of the actual April 2012 operational numbers.
- Case Study #2: Bonita Springs Utilities, BWRO facility
    - Bonita Springs is a brackish water desalter that has been in operation since 2004 and is experiencing increasing feed salinity. This plant was recently retrofitted with a turbocharger-type ERD. The tool confirms the engineer's estimate that the turbocharger is the best choice for the retrofit despite the fact that the isobaric ERDs have a substantially higher efficiency.
- Case Study #3: Luggage Point Advanced Water Treatment Plant, water reuse RO
    - Luggage Point incorporates a three-stage RO system operating on microfiltered effluent. The tool demonstrates the advantage of placing a turbocharger between Stages 2 and 3 versus Stages 1 and 2. The comparison between the actual operating data and the tool indicate that the predicted membrane feed pressure and turbocharger boost pressures are accurate within 5 and 7%, respectively.
- Case Study #4: Tampa Bay Water, desalination plant
    - Tampa Bay incorporates a two-pass RO system operating on ocean water. A Pelton wheel ERD is utilized. Energy consumption data for a single RO train was obtained from the operating staff and compared with the estimate provided by the tool. The tool was within 4% of the kilowatt (kW) value reported.

- Case Study #5: Perth Seawater Desalination Plant, Kwinana Beach, Australia
    - Perth is a two-pass RO system operating on ocean water. The system included ERI PX type isobaric ERDs and the tool confirms that the isobaric-type ERD is the best choice.

For available data, the tool provides a reasonable estimate of the capital and operating costs associated with the ERD selected.

ES.4. Conclusions

To fill a need in the desalination community, an Excel-based computer tool was developed with the following functionality:

- RO mass balance
- RO projections
- Incorporation of ERDs
- Calculation of power consumption
- Estimation of capital costs
- Estimation of electrical operating costs

The tool provides a valuable new resource for municipal planners, operators, and consulting engineers in evaluating energy recovery options in desalination of brackish water, treated wastewater, and seawater using RO technology.

Chapter 1

Introduction

Water quenches our thirst, cools our industries, and irrigates our fields. Upon it, approximately 95% of the international imports and exports of the United States are transported. Beneath it lies a substantial source of food. Without it, we cannot survive. As Jacques Cousteau once stated, “the cycle of life is intricately tied up with the cycle of water.”

Water withdrawals from oceans, rivers, lakes, and ground in the United States exceeded 410 billion gallons per day in 2005 (Kenny et al., 2005). More than 201 billion gpd (approximately 48% of the total) are withdrawn to support power generation. Based on 2005 census data, the total withdrawal of water resources per capita in the United States exceeded 1,420 gpd (U.S. Census Bureau, 2005). In regions with low precipitation and seawater intrusion of coastal aquifers, coupled with population growth, it is anticipated that existing water resources will become increasingly stressed. The U.S. Bureau of Reclamation reported nearly 30 years ago that Lower Colorado River Basin water use exceeded the renewable water resources of the region (U.S. Geological Survey, 1984).

Increasingly, water resource planners are turning to desalination of impaired waters such as saline groundwater, treated wastewater, estuarial surface water, and seawater to provide an alternative water supply for communities and industries. A recent study commissioned by the Colorado River Basin States (CRBS) identified 12 different augmentation options for water resources in the Lower Colorado River Basin. Of these, three options focused on the desalination of brackish water, seawater, and treated wastewater (Colorado River Basin States [CRBS], 2008).

Although desalinated seawater has been identified as a viable alternative water source, advocacy opposition groups have been organizing to limit the implementation of desalination, with a specific emphasis on the high energy consumption of seawater desalination. One group states that “More energy is required to produce water from desalination than from any other water-supply or demand-management option in California” (Cooley et al., 2006). Another advocacy agency indicates that “Unless existing technology becomes significantly more energy efficient, the total expense of desalination is not likely to decrease. In fact, with oil prices rising around the globe, it is possible that the technology will remain prohibitively expensive even if the equipment substantially improves” (Food and Water Watch, 2009). Although the analyses conducted by these opposition advocacy agencies are suspect, it is evident that the energy consumption of desalination continues to be a focus of those opposed to desalination. As a result, continued effort to minimize energy consumption by desalination plants and ensure that the industry is using accurate energy and cost reporting is important to ensure that desalination is recognized by the public as a viable water augmentation source.

1.1 Energy Losses in Reverse Osmosis Systems

Desalination in the United States and in many other parts of the world is typically performed using a process called reverse osmosis (RO). In the RO process, water is pumped tangentially along the surface of a semipermeable membrane in a cross-flow configuration. A portion of the water passes through the membrane to become high-quality permeate, whereas the remaining portion of the water, containing nearly all of the solutes, becomes the concentrate stream. A simplified process schematic for the RO process is shown in Figure 1.1.

A schematic of a spiral-wound membrane is shown in Figure 1.2. The element is formed from a number of membrane "leaves" connected to a central permeate tube. Each leaf consists of two sheets of membrane, with a permeate spacer between them. The membrane sheets are glued on three sides, with the final edge bonded to the permeate tube. A feed spacer is placed between each pair of leaves before all leaves are rolled around the tube. Once they are rolled, the anti-telescoping devices and a fiberglass wrap are added to complete the element.

In RO systems, elements are housed in pressure vessels, with each vessel containing as many as eight elements connected in series via product water interconnectors. Up to 15% of the feed water processed by an individual element is converted to permeate, or recovered. Thus, by arranging elements in series, up to 65% permeate recovery can be obtained within a single pressure vessel. To achieve the desired permeate capacity, pressure vessels are arranged in parallel to increase the capacity of the system; the parallel vessels are referred to as a stage or bank. To increase recovery further, banks of pressure vessels can be placed in series (staging), with up to three stages used to achieve recoveries as high as 90%. Typical recoveries for RO systems treating brackish water and secondary effluent are 70 to 90% using two and three stages. Recoveries for systems treating seawater range from 35 to 60% depending on seawater salinity and temperature. Seawater RO (SWRO) recoveries are lower because of high osmotic pressure coupled with a maximum operating pressure range for the RO elements (typically 1000 pounds per square inch gauge [psig]).

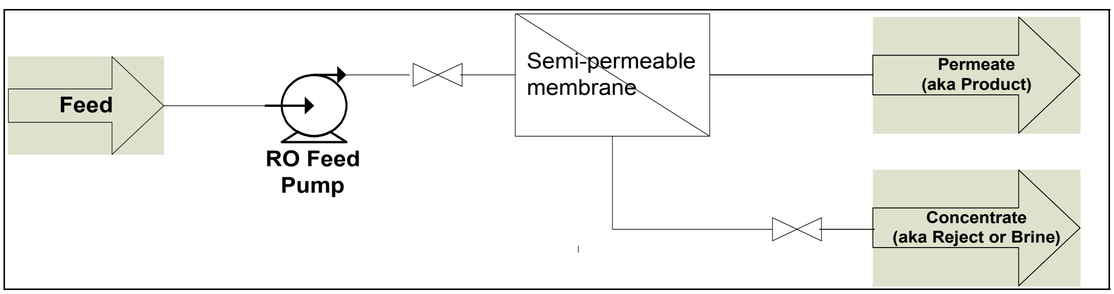


Figure 1.1. Simplified reverse osmosis flow diagram.

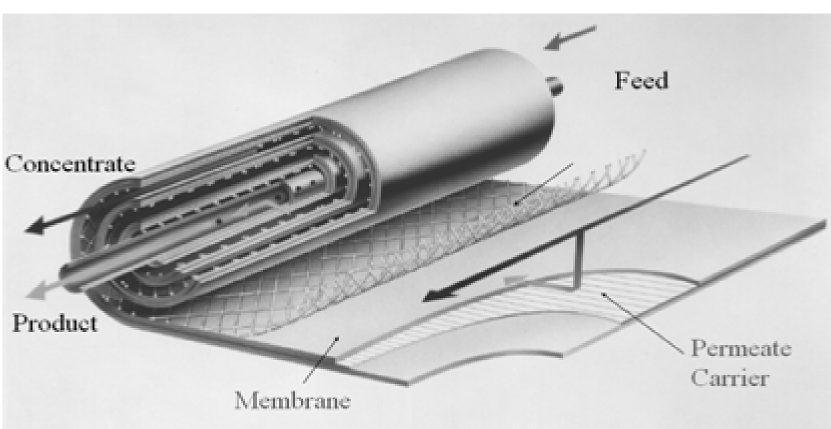


Figure 1.2. Schematic of a reverse osmosis membrane (Bartels et al., 2007).

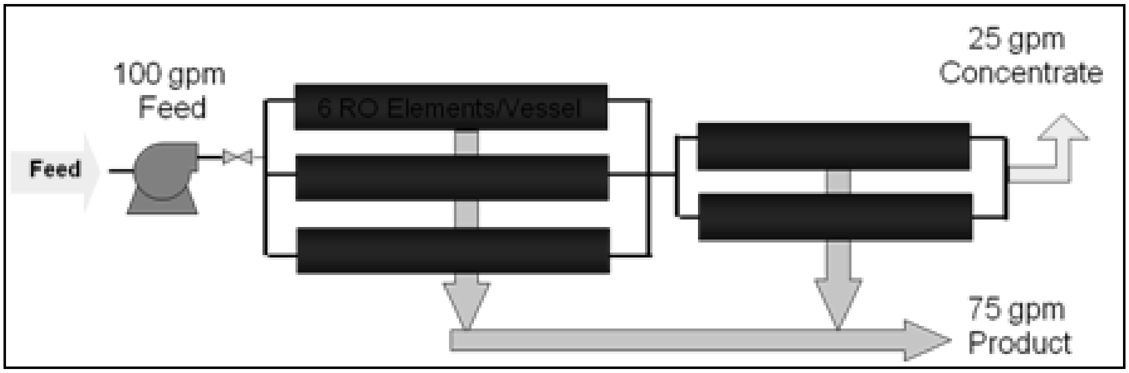


Figure 1.3. Sample two-stage RO system operating at 75% recovery.

Figure 1.3 displays a sample two-stage RO system operating at 75% recovery.

In general, the RO process can remove more than 99% of all dissolved minerals and more than 95% of organic compounds from water, as well as biological and colloidal suspended matter, including turbidity. Removal levels can be lower for specific solutes, depending on their characteristics (e.g., molecular size, charge, charge density). Given these removal levels, RO is a broad-spectrum removal technology and, as such, is widely utilized for treatment of a variety of impaired waters in both municipal and industrial applications and is the preferred desalination process.

RO is widely used to desalt brackish water and seawater for drinking and industrial water production and to reclaim wastewater effluent for indirect potable reuse and industrial use. There are many SWRO plants in coastal and island communities and the Middle East, where they are a predominant water source. Within the last five years, every major city in Australia has constructed a SWRO desalination plant to supplement its drinking water supply. As the TDS of seawater are typically around 35,000 milligrams per liter (mg/L), this water will have a substantial osmotic pressure, and thus feed pressures of around 800 to 1000 psig are typically required.

There are numerous applications where RO is used to reduce the total organic carbon (TOC) and total nitrogen of microfiltered municipal wastewater. Such applications produce water suitable for industrial processes, such as boiler feed water. Municipal wastewater RO applications usually involve rapid and irreversible fouling of the membrane surface over the first few weeks of operation. This fouling results in an increase in required feed pressure to maintain the system capacity. Thus, although the TDS of treated wastewater, and therefore its osmotic pressure, are low in comparison to seawater, reuse RO systems can still experience feed pressures of up to 300 psig.

Energy consumption in RO processes is influenced by a number of factors, including the osmotic pressure of the feed water, the water mass transfer characteristics of the membrane, system recovery, and the pressure drop across the element (from feed to concentrate).

Osmotic pressure is discussed in more detail in Chapter 3. The feed pressure to the RO membranes must overcome the osmotic pressure before a single drop of permeate will be produced. The osmotic pressure for a salt solution can be estimated as 1 pound per square inch (psi) per 100 mg/L TDS for fresh and brackish waters. As the feed water passes through the RO system, salinity on the feed side of the membrane increases as salts are concentrated in a decreasing volume of water. Thus, as recovery increases, solute concentrate in the feed-concentrate stream increases and osmotic pressure increases. The effect of the osmotic pressure as a function of element position in the example RO system is shown in Figure 1.4; assuming that the feed TDS is 1500 mg/L and all of the solutes are rejected by the RO membrane, the concentrate TDS will be 6000 mg/L, resulting in a concentrate osmotic pressure of 60 psi. (Brackish water RO membranes allow 0.5 to 1.0% of solutes to pass into the permeate, so concentrate TDS will be slightly less than 6000 mg/L.) To provide an equivalent "net driving pressure" over a two-stage system operating at 75% recovery compared to one operating at 50% recovery (to maintain equivalent permeate flow), a higher feed pressure is needed to counteract the increase in osmotic pressure.

There is a loss of pressure, typically 2 to 3 psi, as water passes through the feed spacer from the feed end of the element to the concentrate end, with actual loss a function of flow rate, spacer thickness, and geometry. As elements are placed in series, this feed-concentrate pressure loss or "drop" can become significant. Furthermore, as more membranes are placed in series in the RO system, the hydraulic resistance associated with differential pressure increases. This differential pressure exists both on the feed-concentrate spacers of the membrane and in the permeate spacer of the membrane. RO membrane differential pressure is a function of flow rate and membrane feed spacer thickness, but is estimated at approximately 3 psi per membrane for new membranes. With 12 membranes in series, per the previous example, this equates to about 35 psi. Therefore, we would require 95 psi to produce any water at the tail end of the system. Note that if the feed salinity to the system was 15,000 mg/L, the concentrate salinity would be approximately 60,000 mg/L and the concentrate would have an osmotic pressure of approximately 640 psi. This is why high-salinity water such as seawater requires such high feed pressures.

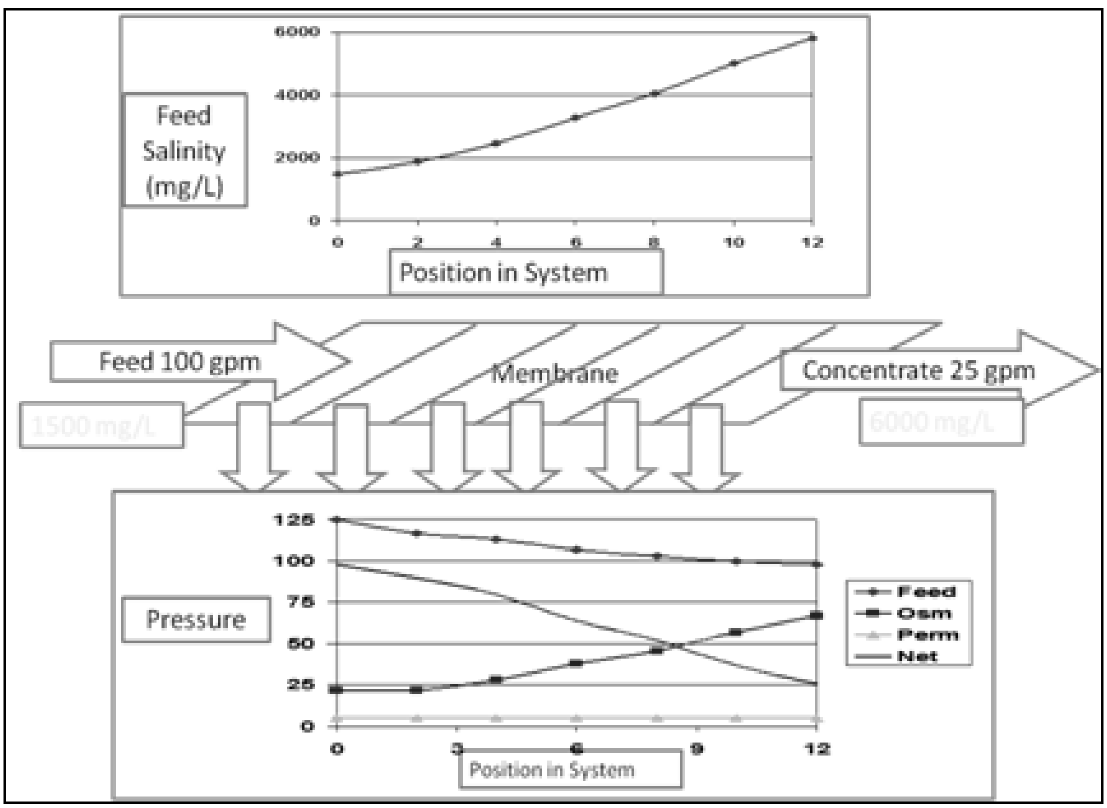


Figure 1.4. Effect of the osmotic pressure as a function of element position.

RO membrane technology has improved dramatically over the years. Currently, the mass transfer characteristics are so good that the membrane material resistance is minimal and the RO systems are operating near what is termed the "thermodynamic restriction," where the resistance that generates the required net driving pressure is essentially the osmotic pressure and hydraulic pressure differential only (Zhu et al., 2010).

1.2 Energy Consumption in Reverse Osmosis Systems

The desalination industry, through free market principles, has long recognized the impacts of energy consumption in desalination. Early seawater desalination plants operated without energy recovery, with energy consumption greater than 10 kilowatt-hours per cubic meter (kWh/m^3). This high energy consumption limited the application of RO for seawater desalination to locations where freshwater supplies were either absent or very limited. Over time, through steady improvements in the permeability (water mass transfer) of the RO membrane, in combination with the commercial development of energy recovery devices (ERDs), energy consumption of SWRO systems has been reduced significantly. As shown in Figure 1.5, testing performed by the Affordable Desalination Collaboration in 2007 demonstrated an energy consumption as low as 1.6 kWh/m^3 through the use of a conservative system design composed of high-permeability RO membranes, a positive displacement high-pressure pump (HPP), and a positive displacement work exchanger ERD (Dundorf et al., 2007). For full-scale plants, energy consumption between 2.0 and 2.4 kWh/m^3 is typical, with full-plant energy consumption, including raw water pumping, pretreatment, chemical dosing, post-treatment, and residuals disposal typically around 3.3 kWh/m^3.

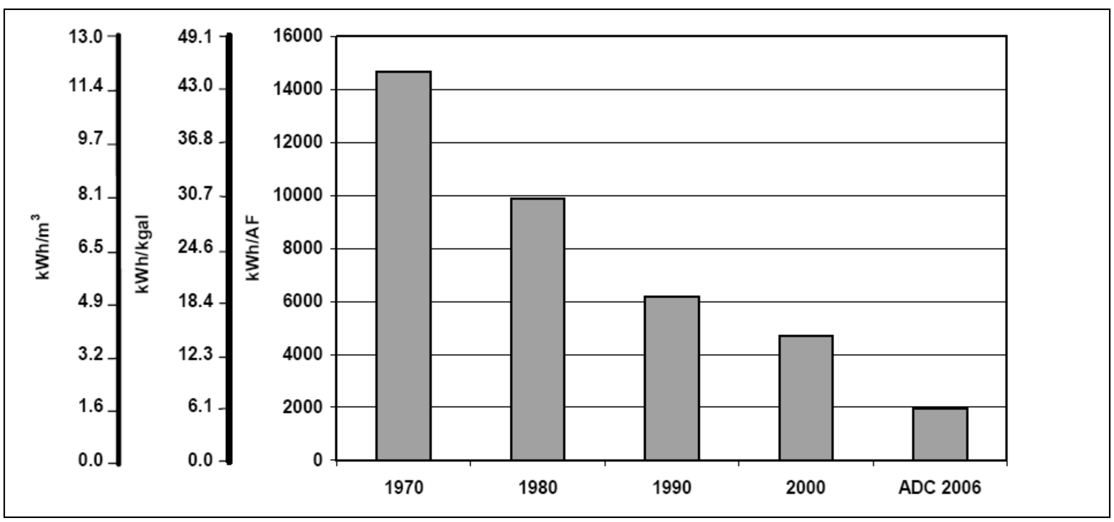


Figure 1.5. History of power consumption required for seawater desalination process equipment (Dundorf et al., 2007).

1.3 Use of Energy Recovery Devices in Desalination

ERDs utilized in RO applications convert residual hydraulic energy into mechanical energy that is reapplied either to the RO feed (for seawater applications) or to an interstage feed (for brackish or wastewater applications) in order to reduce the energy input to the RO system.

Two general classifications of ERDs are commercially available and utilized in the desalination industry: centrifugal devices and isobaric devices.

Centrifugal devices can further be classified into direct-coupled devices and turbocharger devices. Direct-coupled devices, including the Pelton Wheel and the Francis Turbine, are direct-coupled to the HPP and motor shaft. Rotational energy imparted to the turbine from converted concentrate pressure is directly transferred to the motor shaft, reducing the motor power requirements. The HPPs for a direct-coupled device are sized for the full feed flow and pressure; however, the motor power can be reduced as a result of the energy recovery.

In a turbocharger device, a turbine is direct-coupled to a pump impeller on a common shaft and located downstream of the HPP. Rotational energy imparted to the turbine from converted concentrate pressure is reconverted to pressure energy through the impeller and used to boost either the RO feed pressure (for seawater systems) or the interstage pressure (for brackish or wastewater systems). The HPP is sized for the full feed flow, but the head requirement is decreased by the boost pressure provided through the turbocharger.

For isobaric devices, a side stream of the low-pressure feed and the concentrate stream are directed to a positive displacement device. Energy from the concentrate stream is directly imparted into the feed stream. A small booster pump is typically required to raise the pressure of the side stream to the feed pressure. The HPP is typically sized for the permeate flow of the RO system and the full feed pressure. Isobaric devices typically have the highest efficiency of the ERDs, but require additional equipment, and may allow leakage between the concentrate and the feed/interstage streams.

Each of these devices is described in additional detail in Chapter 2.

Few independent evaluations of ERDs have been conducted to date. As a result, little comparative information is available to permit engineers and utilities to evaluate ERDs rapidly and easily for use in their facilities.

1.4 Report Organization

The objectives of this project are to create a thoroughly researched guidance manual that assesses currently available and emerging ERDs for desalination systems, and to create a computer tool including those commercially available ERDs for the treatment of brackish water, seawater, and wastewater effluent. This project was sponsored by the California Energy Commission and the WateReuse Foundation as part of the Foundation's Solicited Research Program. The U.S. Bureau of Reclamation is a funding partner for this project.

The report is organized into the following sections:

- Chapter 1, Introduction.
- Chapter 2, Literature Review—The literature review examines the history of energy recovery in desalination applications leading to the development of modern commercially available devices. Commercially available devices are reviewed and qualitatively compared. Several developing devices also are reviewed. Based on the results of the review, screening of the devices was conducted to determine the devices included in the model.

- Chapter 3, Model Development—Based on the screening study presented in Chapter 2, an Excel-based mass balance, RO projection, and cost model were developed. Chapter 3 reports on the model development, validation, and structure. A user manual is provided for the tool as well.
- Chapter 4, Case Studies—Case studies for five different utilities were conducted to evaluate the use of ERDs. Case studies were developed for two seawater, two brackish water, and one wastewater reuse facility. The individual case studies are presented in Chapter 4.
- Chapter 5, Conclusions and Recommendations

Chapter 2

Literature Review

With an expanding market for energy recovery, many of the commercially available ERDs utilize proprietary designs. Few ERDs have undergone third-party independent testing and analysis leading to the publication of a peer-reviewed paper. Much of the literature available is either vendor-produced, with obvious bias, or trade literature published by manufacturers or users. The authors have developed this literature review to provide an objective and unbiased technical review and assessment of the various ERDs available in the marketplace.

2.1 Methodology

This literature review incorporates published material from peer-reviewed journal articles, conference presentations and proceedings, patents, technical reports, user reviews, feasibility analyses, media reports, and information on vendor websites and brochures. To collect this literature, the key sources summarized in Table 2.1 were electronically searched for relevant information via publisher databases. Keywords used in the search included "reverse osmosis," "nanofiltration," and "energy recovery," which are related to all types of desalination.

Patent information related to ERDs was obtained by searching the U.S. Patent and Trademark Office database using the following keywords: "energy recovery," "reverse osmosis," "specific energy," and "desalination." This search yielded more than 50 relevant patent citations, from 1977 to October 22, 2010. Key patents were reviewed and are referenced in the sections that follow.

Table 2.1. Literature Review Sources

Peer-Reviewed Journals	Grey Literature	Conference Proceedings (previous 10 years)
Journal of Desalination Journal of Membrane Science International Water Association Water Science and Technology Water Science and Technology - Aqua Water Science and Technology: Water Supply Journal of Water Supply: Research and Technology - Aqua Water Research Desalination and Water Treatment Science and Engineering Journal American Water Works Association (AWWA) Journal of the American Institute of Chemical Engineering Journal of Chemical Engineering Research and Design International Desalination Association (IDA) Journal of Desalination and Water Reuse	Desalination and Reuse Quarterly Global Water Intelligence Water Desalination and Reuse Quarterly U.S. Patent and Trademark Database Vendor Literature Research Reports U.S. Bureau of Reclamation WaTER Studies Saline Water Conversion Corporation (SWCC) Studies Middle East Desalination Research Center (MEDRC) Studies American Water Works Research Foundation Research Reports WateReuse Foundation archives Texas Water Development Board Studies National Water Research Institute (NWRI) Studies	AWWA Annual Conference and Exhibition (AWWA ACE) AWWA Association Membrane Technology Conference (AWWA MTC) AWWA Water Quality Technology Conference (AWWA WQTC) American Membrane Technology Association Annual Conference and Exhibition (AMTA ACE) IDA Biennial Conference and Exhibition WateReuse Research Conference European Desalination Association Annual Conference

2.2 Energy Consumption in Reverse Osmosis

With increasing water scarcity, development of marginal or impaired water supplies for potable use has increased in both frequency and capacity. Marginal or impaired waters, such as wastewater effluent, brackish groundwater, and seawater, often contain multiple contaminants of concern, including TDS, organic compounds, and various emerging contaminants. Technologies used to treat these water supplies include desalination through nanofiltration (NF), electrodialysis, and most importantly, RO. RO is one of the predominant methods used to produce potable water from impaired waters.

Global growth in desalination of impaired waters has accelerated in the past decade, as illustrated in Figure 2.1 (International Desalination Association [IDA], 2010). The world-wide installed capacity, tracked by Global Water Intelligence (GWI), now exceeds 70 million cubic meters per day (m^3/d). Similar growth in application of desalination technologies has been tracked in the United States, as shown in Figure 2.2 (GWI, 2011).

Development of impaired waters in the United States has been focused on producing potable water from brackish water supplies. Brackish water desalination represents over 51% of U.S. desalination installations (GWI, 2011). In water-scarce regions, such as Arizona and California, large-scale wastewater reclamation projects using RO have been installed. One plant, the Ground Water Replenishment System, located in Orange County, California, has a capacity of more than 70 million gallons per day (mgd).

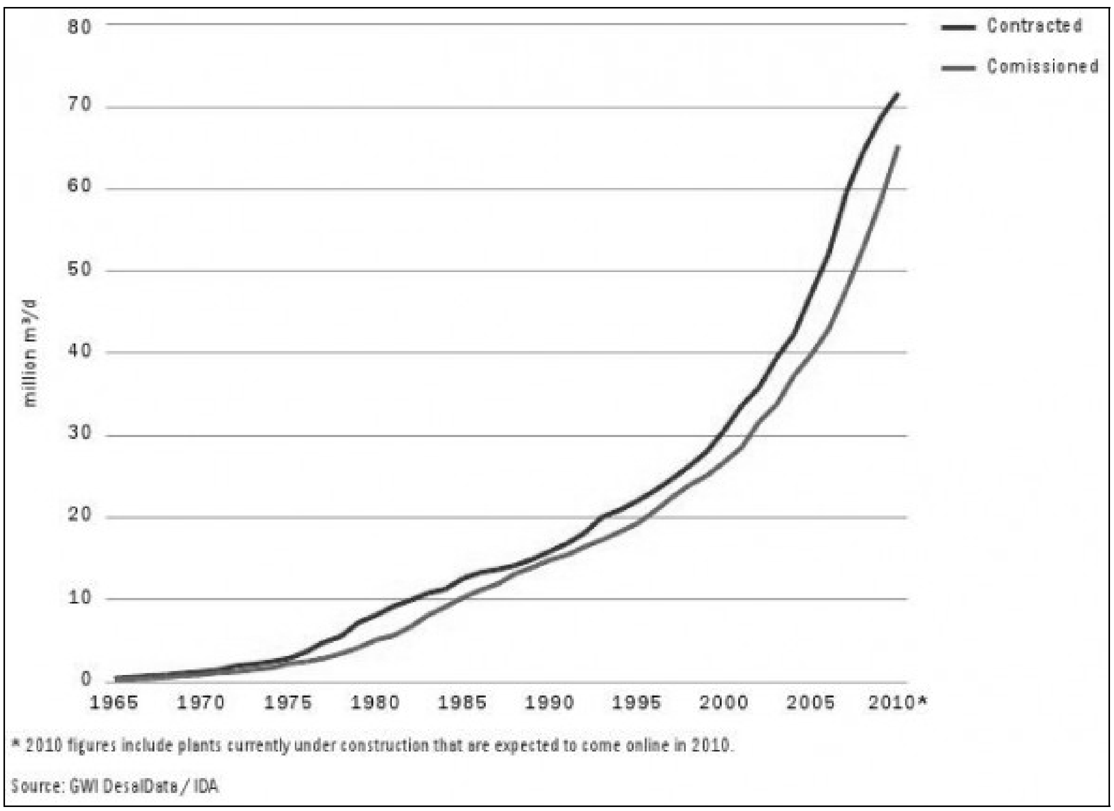


Figure 2.1. Global growth of desalination (seawater, brackish, etc.) between 1965 and 2010.

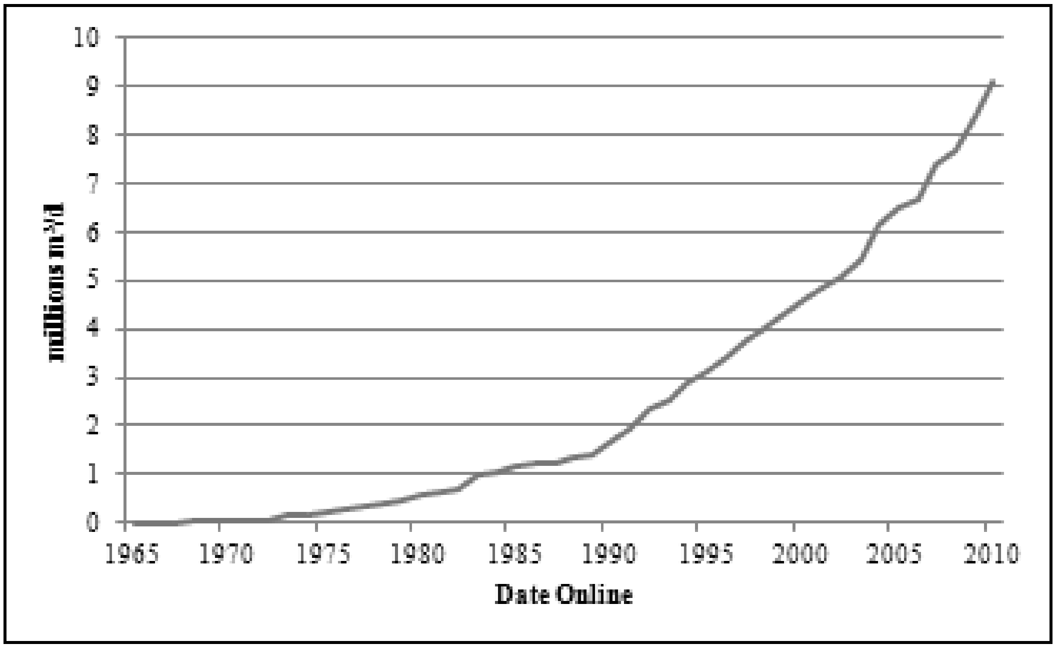


Figure 2.2. Cumulative online desalination (seawater, brackish, etc.) capacity in the United States, 1965–2010.

Seawater desalination is gaining interest as a method of further addressing projected water shortfalls in the United States, with one major SWRO facility currently in operation in southwest Florida (Tampa Bay). Significant opposition to seawater desalination plants has been mounted by various entities, particularly in California. One frequently cited reason for opposition is the high energy consumption of desalination plants, which, through increased greenhouse gas emissions, could impact climate change. The high energy consumption for RO-based seawater desalination, relative to desalination of brackish water and wastewater effluent as well as nondesalination technologies, is currently considered one of the primary obstacles to its expanded use in the United States.

Energy consumption in RO-based desalination is a function of several variables, including but not limited to

- Feed water TDS
- Water temperature
- System recovery
- Membrane flux
- Membrane mass-transfer coefficients
- Pump
- Motor variable-speed drive efficiencies
- Flow control valve losses
- Minor losses in system pipe work
- Use of ERDs

Energy use and recovery in a RO system differ for seawater and brackish/effluent applications.

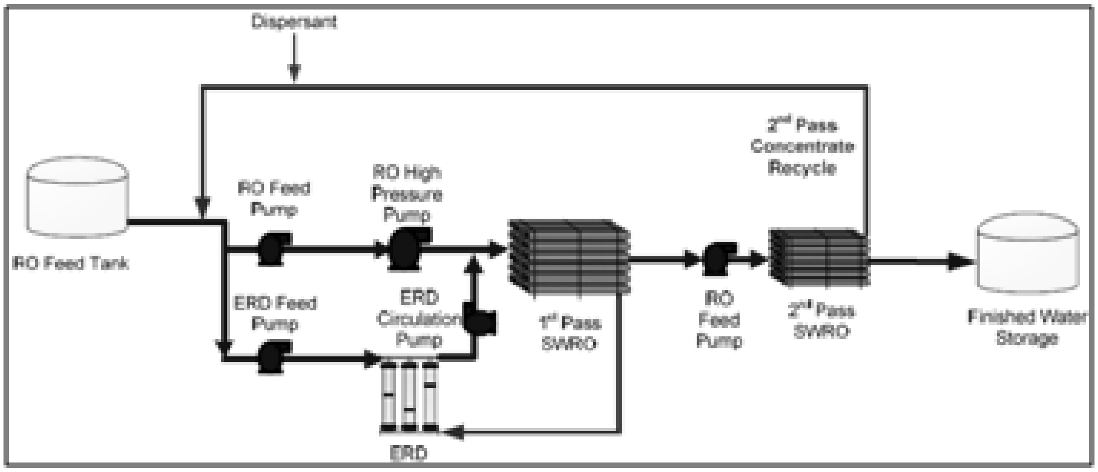


Figure 2.3. PFD of SWRO plant, Pilbara (CH2M HILL).

Figure 2.3 illustrates a typical SWRO desalination plant process flow diagram (PFD).

2.2.1 Methods for Measuring Energy Consumption and Recovery

Energy consumption values for water processes are typically reported in terms of specific energy consumption (SEC), which is calculated using the following equation:

$$SEC = \frac{\text{Total power consumed on an annual basis (kWh)}}{\text{Annual product water produced (m}^3\text{ or kgal)}} \qquad (2.1)$$

However, the industry lacks standards governing how energy consumption is calculated or reported. Published values may include only the energy required for the desalination process itself, or for the whole facility. External loads, such as raw water conveyance and finished water pumping, may be excluded. For theoretical calculations, minor expected losses may be ignored entirely. It is also important to recognize, particularly in the international marketplace, that transparency in reported SEC is not ensured. This variation in how SEC is reported makes comparison of processes and technologies difficult.

Despite this, three common methods of calculating energy consumption stand out in the literature: direct accounting, exergy analysis, and visual analysis, specifically Sankey diagrams. Direct accounting produces theoretical SEC values based on flow rates, pressures, efficiencies, and estimated losses. These calculations are most commonly used to determine the operating and connected loads of a desalination plant. The results are then used by electrical engineers to develop the single-line diagram and design for the electrical subsystems for a plant. For operating plants, direct measurements of the voltage and amperage draw of the plant components can be recorded and used to calculate SEC. Ideally, the power-consuming components associated with desalination can be monitored separately to determine the SEC for the desalination process alone.

In academia, the concept of “exergy” is frequently applied. Exergy analysis relies on thermodynamic theory to quantify the minimum work required to complete a process and the additional work consumed as a result of increases in entropy (Spiegler and El-Sayed, 2001). Exergy is calculated using measured or theoretical salinity, pressure, and temperature gradients at each unit process in a defined system boundary. This analysis is particularly valuable in evaluating the potential for energy reduction in each component of a desalination system and, thus, is useful to the desalination engineer. Exergy analysis has been applied to RO desalination by a number of researchers. For example, Cerci (2002) applied exergy analysis to a 7250 m^3/d (1.9 mgd) SWRO system in California. The total exergy required for desalination was 7.13 kW, with a total exergy input of 165.62 kW. Although much of the exergy consumed in the process is related to an expected pressure drop across the RO membrane interface, the exergy analysis showed that throttling of the brine stream pressure prior to discharge consumed considerable exergy. Introduction of an ERD was suggested as an energy-saving option to recover this available energy (Cerci, 2001).

Although exergy analysis is useful in the optimization of desalination processes and for calculating theoretical available energy for recovery, few engineers involved in desalination are familiar with exergy analysis. Therefore, exergy is of limited practical interest in most desalination applications.

Sankey diagrams also have been used to illustrate the transfer and flow of energy through a system. These diagrams use a separate line for each process flow and energy loss in the system. The width of each line denotes the relative energy utilized or lost in each process. Although a Sankey diagram does not indicate the potential for additional energy savings in each stream, it clearly communicates the energy used in each stream and the losses associated with each component. It is important to note that energy flows depicted in a Sankey diagram are not the same as exergy calculations. Figure 2.4 is a typical Sankey energy balance for a small SWRO system using a Clark Pump ERD to capture energy otherwise lost in the pressurized brine stream (Thomson et al., 2002).

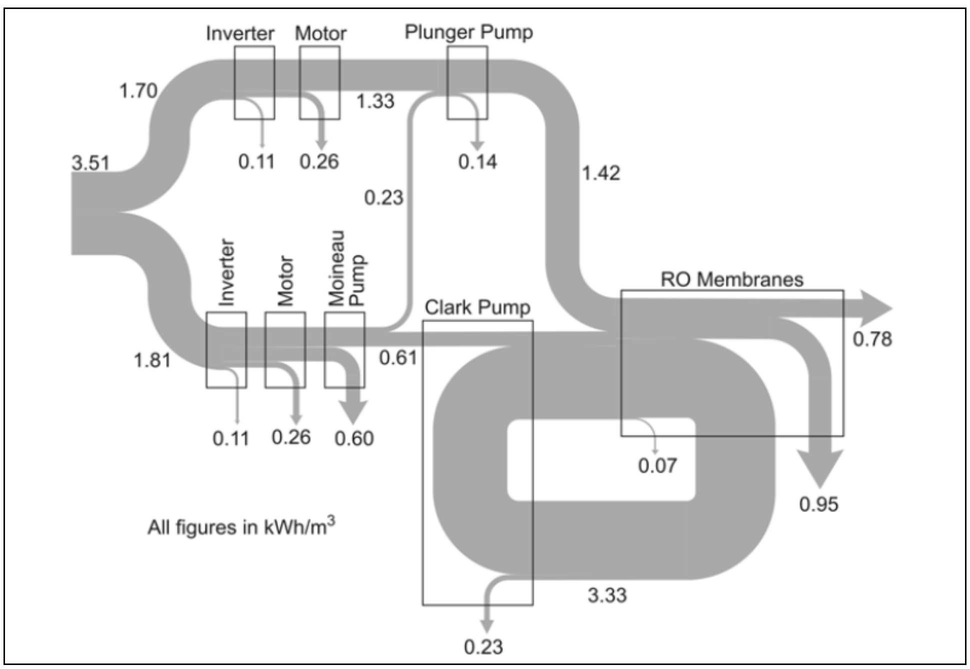


Figure 2.4. Example of Sankey diagram—SWRO system with Clark Pump (Thomson et al., 2002).

To meet the increasing demand for freshwater in the global energy crisis, the desalination industry is being pushed to improve the operational efficiency of the SWRO desalination system (Sun et al., 2008). Exergy analysis, Sankey diagrams, and other calculations in the literature show that the greatest opportunity to improve efficiency is implementing energy recovery from the brine stream. The need to develop efficient ERDs has therefore been the aim of many scientists and engineers since the 1970s.

2.2.2 Energy Consumption of Seawater Reverse Osmosis Plants

Desalination of seawater has historically been perceived as an expensive process because of its high energy demand. Early SWRO plants consumed between 12 and 15 kWh/m^3, depending on salinity, temperature, and other conditions (Plascencia, 2002; Veerapaneni, 2006). Because of high SEC values, almost half of the total cost of desalting water was the cost of energy, especially for small-scale SWRO desalination systems (Avlonitis et al., 2003).

Table 2.2 summarizes energy consumption for a number of seawater desalination systems.

2.3 History and Modern Development of Energy Recovery Devices

2.3.1 History of Energy Recovery

The history of recovering energy from high-pressure streams significantly predates membrane-based desalination. The first successful turbine was introduced in France by Benoit Fourneyron in 1829. This radial-flow turbine improved upon early turbines used in early industrial applications. Development of turbines, or reverse running pumps, continued throughout the nineteenth century, with new designs tested and introduced in the United States. The most notable design, because of its high efficiency, was introduced by James Francis in 1848. The Francis Turbine, also referred to as a reverse running pump, recovers energy from high-pressure streams by rotating a direct-coupled central shaft. Refined models of the Francis Turbine are still in use today (Constant, 1983; Darwish et al., 1989).

Independent of Francis Turbine development, the high energy needs of the California Gold Rush of the mid-1800s spawned the development of new water wheel devices to extract hydraulic energy. Lester Pelton experimented with paddle geometry and ultimately developed new water wheel paddles that captured more of the velocity head wasted by earlier turbine designs. Pelton received a patent in 1880 for the Pelton Wheel, illustrated in Figure 2.5 (Pelton, 1880; Constant, 1983).

Significant development of impulse turbines continued into the twentieth century. By the time Sidney Loeb patented the modern RO membrane in 1964 (Loeb and Sourirajan, 1964), both the Francis Turbine and the Pelton Wheel were highly refined and widely used in industry to recover hydraulic energy. Shortly after Loeb's discovery, work exchanger or isobaric device patents related to the recovery of hydraulic energy in the chemical processing industry were filed by Swaney (1961) and Ross (1963). The first piston work exchanger to be used with RO technology was invented by Cheng and Cheng (1970), with a later rotary design by Hashemi and Lott (1969).

Table 2.2. Examples of SWRO Plant Energy Consumption

Plant	Date of Estimate	ERD Technology	Total Plant Power Consumption [a]		Capacity	
			kWh/m^3	kWh/kgal	m^3/d	mgd
Tampa Bay Desalination Plant, U.S.A.	2008	PIT	3.71	14.0	94,625	25
Barcelona, Spain [b]	2009	PX	4.17	15.8	200,000	53
Perth I (actual), Australia	2008	PX	3.4	12.9	143,000	37.78
Perth I (design), Australia	2008	PX	3.7	14.0		
Larnaca, Cypress [c, d]	2001	PIT	4.35 (3.4 RO)		64,000	17
Ashkelon, Israel	2009	PX	3.9	14.8	333,080	88
Pt Lisas, Trinidad	2007	DWEER	3.80	14.4	136,260	36
Gold Coast, Australia [e]	2010	DWEER	3.58	13.5	131,952	35
Sydney, Australia	2008	DWEER	4.2	15.9	250,000	66.05
Ghalilah Unit 3, U.A.E. [f]	2005	PX	4	15.1	13,650	3.60
Tuas, Singapore [g]	2010	DWEER	4.1	15.5	110,000	29

[a] PIT = Pelton Impulse Turbine; PX = Pressure Exchanger; DWEER = Dual Work Exchange Energy Recovery

[b] RO system power consumption is included in Total Plant Power Consumption.

[c] Water-technology.net “Barcelona Sea Water Desalination Plant, Spain.”

[d] Larnaca Desalination Plant Operation—A Client and Contractor Perspective, Koutsakos et al., 2005. Water-technology.net “Larnaca SWRO.”

[e] Water-technology.net “Gold Coast Desalination Plant, Queensland Australia.”

[f] Stover et al., 2007 Includes 6 bar product water distribution pressure,

[g] Water-technology.net “Tuas Seawater Desalination Plant - Singapore.”

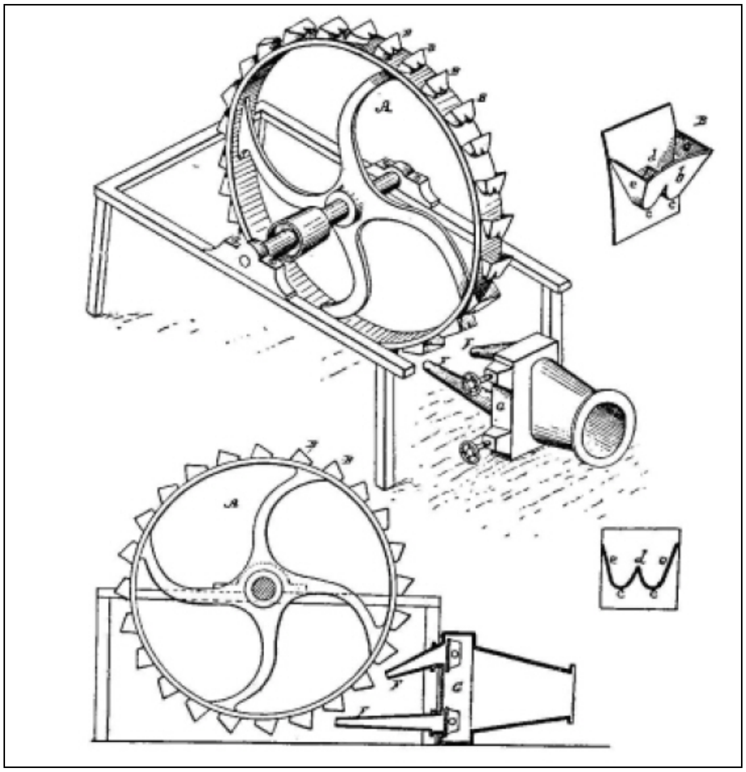


Figure 2.5. Pelton Wheel patent drawing (Pelton, 1880).

From these early devices, modern ERDs have evolved into two major categories:

- *Centrifugal Devices.* Centrifugal devices include various improvements and adaptations of the Pelton Wheel and Francis Turbine. Centrifugal devices may be coupled to a separate pump and motor shaft or directly coupled to a pump shaft to provide auxiliary pressure boost without the use of a pump. Centrifugal devices that are direct-coupled turbine–pump combinations are typically referred to as turbochargers.
- *Isobaric Devices.* Work exchangers are positive displacement devices, typically using two or more chambers or pistons, with or without a moveable plenum, to transfer energy from a concentrate to a feed. Work exchangers may be either stationary piston- or rotary-type devices. Stationary piston work exchangers, such as Flowserve/Calder's Dual Work Exchanger Energy Recovery (DWEER), utilize proprietary valving to sequence the flows through the device. Rotary work exchangers contain a number of different chambers within a cylinder. As the cylinders rotate, driven by water flow or an external motor, the cylinders change position relative to the inlet and outlet ports, thereby sequencing the flows through the device.

There have been several additional developments in energy recovery that are not adequately addressed by the two major categories. These devices differ by mechanism or output from the centrifugal and isobaric devices, and they are discussed in more detail in Section 2.3.3.

The modern development of each class of device is discussed separately. Devices chosen for further analysis and model development are further described in Section 2.3.3.

2.3.2 Modern Development of Centrifugal Devices

Modified Francis Turbines and Pelton Wheels increased efficiency and adoption in early SWRO facilities. The first large municipal SWRO incorporating Pelton Wheel technology was installed in Jeddah, Kingdom of Saudi Arabia, in 1978 and required 6.1 kWh/m^3 of energy. In the West, the first RO desalination plants to adopt ERD technology included facilities installed in the early 1980s in Key West, FL; Paradise Island, Bahamas; and the island of Malta (Moch and Harris, 2002). These facilities used a simplified Francis Turbine, an early version of a Pelton Wheel, and a more sophisticated Francis Turbine, respectively. Energy recoveries in these early adopting plants were about 25% of the RO input energy.

In 1978, a U.S. patent was granted to Everett Schwartzman for a direct-coupled Pelton Wheel device (Schwartzman, 1978). With a direct-coupled Pelton Wheel, the HPP, motor, and ERD are mounted on a common shaft. The ERD directly transfers recovered energy to the pump shaft, allowing a much smaller electric motor to be installed on the incoming stream. This device has been widely applied in seawater desalination, including modern plants such as the Tampa Bay Desalination Plant in Florida.

With attention focused on work exchanger devices, the next major development in centrifugal energy recovery was the turbocharger. Introduced in the 1980s by the brothers Robert and Eli Oklejas, the turbocharger is an integral turbine-driven centrifugal pump that transfers hydraulic energy from the concentrate to the feed stream. The system is entirely powered by the brine stream and has no electrical cooling or pneumatic requirements (Farooque et al., 2004). Field testing of an early prototype turbocharger in conjunction with a military SWRO system showed energy recovery efficiencies in the range of 17% to 29% (Lozier et al., 1989).

The first patent for a turbocharger was granted in 1990 to Robert and Eli Oklejas, who successfully commercialized the devices under Pump Engineering, Inc. (PEI) (Oklejas et al., 1990). In the early 1990s, PEI developed and patented three other designs that used power recovery pump turbine systems to recover energy from RO concentrate (Oklejas et al., 1991a, 1991b, 1992). Eli Oklejas went on to found the Fluid Equipment Development Company (FEDCO) in 1997, which also produces turbocharger devices. Under PEI, Robert Oklejas (2000) continued developing turbochargers and received a patent specifically designed for improving efficiency of a RO system. Several of FEDCO's and PEI's devices are discussed in further detail in Section 2.3.3.

Centrifugal devices offer maximum net transfer efficiencies of around 88% at the optimum design point. To optimize ERD performance and obtain the high efficiency necessary for cost-effective operation, SWRO plants were designed and operated at fixed water recovery rates—typically 45% for Mediterranean Sea and 35% for Arabian Sea waters (Stover et al., 2007). Modern commercial centrifugal devices are discussed in further detail in Section 2.4.

2.3.3 Modern Development of Isobaric Devices

This section describes early work exchangers, which were developed after centrifugal devices and made use of positive displacement via externally driven rotary displacement or stationary pistons, as well as several emerging isobaric devices that are patented but not yet commercial.

2.3.3.1 Rotary Work Exchangers

Following the early rotary work exchanger devices described previously (Swaney, 1961; Ross, 1963; Hashemi and Lott, 1969), significant advances have resulted in several commercialized devices that have similarities to the modern rotary work exchanger, including those by Hauge (1989, 1994, 1999). Hauge's early designs are known for metal components, which were later replaced with more durable ceramic.

Hauge (2003) developed and patented a system where a rotary work exchanger is used to transfer pressure energy from one flow to a second flow. The device consists of two end covers, a rotor, and a rotor liner that are mounted together via a center bolt in a pressurized housing. In this configuration, elastic deformation, essentially tensile stress, was reduced and the exchanger was protected from internal impact. These later designs are commercialized as Pressure Exchangers (PX) by Energy Recovery Inc. (ERI).

Several other rotary work exchanger devices have been patented but have not been placed in commercial production or application (Al-Hawaj, 2004; Brueckmann et al., 2005; Herrington and Hand, 2007; MacHarg, 2010). These advances are notable as they seek to address the shortcomings of commercially available devices.

Al-Hawaj (2004) patented a rotary work exchanger device with a freely moving spherical bearing in each internal chamber. This design reduced mixing in the rotating chambers, which slightly reduces the efficiency of traditional pressure exchangers.

Brueckmann et al. (2005) also patented a pressure exchanger system with at least two tubular chambers; in each chamber, several valves reverse the flow paths of high- and low-pressure fluid flows.

Herrington and Hand (2007) patented a combined ERD and pump device (assigned to MIOX Corporation). The device combines a dual-head reciprocating pump, an RO element, and a differential-pressure-activated valve, which offsets fluid pressure on the two pump heads and generates energy recovery (Herrington et al., 2007).

The most recently patented device is a combined axial-piston liquid pump and energy recovery pressure exchanger system developed by MacHarg (2010). This device comprises a pumping machine for pressurizing a primary liquid flow, a rotor-drum-type axial piston pump (APP), and an isobaric work exchanger that recovers energy from a secondary liquid flow. The system has benefits including fewer moving parts, small machine size, and lower capital and operating costs. This device is currently being commercialized as the Ocean X pressure exchanger.

2.3.3.2 Piston Work Exchangers

The first work exchanger device that employed stationary pistons was a design patented by Cheng and Cheng (1970). In 1971, another study was funded by the Office of Saline Water, now the U.S. Bureau of Reclamation, in which Cheng and Cheng examined piston- and bladder-style work exchangers. These early piston-type work exchangers experienced significant issues with valving, including erosion, wear, and pressure variations. Keefer (1984) developed and patented a volume exchange structure to minimize these impacts. Keefer's piston-type RO booster pump had several cylinders, each with a displacer rod carrying a displacer to divide the cylinder into pumping and expansion chambers to enable energy recovery.

Prior to the 1990s, most of the emphasis on and use of ERDs was associated with larger desalination systems. Gray (1996) and Permar (1997) patented portable water purification systems with hand-powered double-piston pumps. These devices are not commonly applicable to large-scale units because of fluctuations in flow and pressure. However, they are widely used on seagoing vessels as emergency devices for life rafts.

In 1998, Shumway patented the Linear Exchanger (LinX) valve while working for DesalCo Limited. This valve improved reliability, reduced maintenance requirements, and allowed for faster valve switching in piston work exchanger devices. LinX reduced the size and cost of ERDs such as the DWEER (discussed in Section 2.4).

Another innovation, the integrated pumping and energy recovery (IPER) system, also known as VARI-RO, was patented by Childs and Dabiri (2000). Child and Dabiri's system includes two cylinders with pump-driven pistons and was designed to overcome the limitations caused by fluctuations in flow and pressure experienced by other types of devices. In its operation, the hydraulic pump drives the common piston shaft to provide energy recovery and pumping.

El-Sayed et al. (2010) recently patented a new pressure exchange apparatus that increases the number of internal chambers typically present in a piston-type device.

Axial piston pumps, such as the device manufactured by Danfoss, are positive displacement pumps that have a variable stroke length, also known as swash plate pumps. These pumps have been operated successfully in reverse as ERDs. Danfoss has also introduced its iSave product, which combines an isobaric pressure exchanger with septum and an integrated vane pump to make up the losses in the high-pressure circuit of an RO system.

2.3.3.3 Emerging Isobaric Devices

There are a number of emerging ERDs, which are defined here as technologies that have very limited, if any, existing full-scale desalination applications. These emerging ERDs include the following products:

- VARI-RO
- RO Kinetic
- Hydraulic Energy Recovery (HER)
- Rotary Work Exchanger (RWE)
- Fluid Switcher Energy Recovery Device (FS-ERD)
- Rotary Isobaric Device APP

VARI-RO, the IPER system patented by Childs and Dabiri (2000), does not require external main and booster pumps, significantly simplifying installation. There are different versions of the VARI-RO IPER system, including VARI-RO EL (electric drive), VARI-RO ST (steam turbine drive), VARI-RO HR (heat recovery engine), VARI-RO NG (natural gas engine), and VARI-RO GEN (electric power generation). The last is an engine version that can provide the benefit of generating electric power (Childs and Dabiri, 1992, 1994, 1995).

Childs and Dabiri (1997, 1999) reported on the results of a VARI-RO unit tested using funding provided by the U.S. Bureau of Reclamation. During the two-year program, a prototype was designed, manufactured, and tested, demonstrating that the VARI-RO system was suitable for product water train capacities from 120 to 19,000 m^3/d (0.030 to 5 mgd). Childs and Dabiri reported that an energy savings of 20% to 50% can be projected, as compared to present commercially available methods for both SWRO and brackish water RO (BWRO) desalination. Purported benefits of the IPER system also include low cycle speeds, low noise, and reduced electric power surges on startup. The device is designed to operate at a single recovery, limiting the ability to vary recovery with changing feed water quality to manage energy consumption. Overall, no known sizable installations exist to date, and VARI-RO IPER systems have not yet been produced on a commercial scale. VARI-RO, Inc. had been contracted to provide a full-scale prototype for the Catalina Island desalination plant for Southern California Edison, but it has not been installed to date.

Several developing technologies could eliminate typical active mechanical devices in the recovery of energy. One of these developing technologies, the RO Kinetic pressure exchanger, is designed in a continuous closed loop or kinetic cycle. RO Kinetic, based in the Canary Islands, Spain, has a relatively small experience base and there are no known large-scale installations of the RO Kinetic ERD. However, there are several medium RO desalination plant installations. The two largest installations are the El Confital SWRO desalination plant and the El Fraile SWRO desalination plant, located on Tenerife in the Canary Islands. The El Confital SWRO plant has a nominal production capacity of 4000 m^3/d and has been reported to achieve a SEC of 2.13 kWh/m^3. The El Fraile SWRO desalination plant has a nominal production capacity of 1800 m^3/d, and the plant has been reported to achieve a SEC of 2.25 kWh/m^3 (Peñate et al., 2010).

Marketing literature claims a potential reduction in SEC to 2.10 kWh/m^3 using the RO Kinetic ERD, compared with conventional turbine-type ERDs in optimized facilities with SECs of 3.50 to 4.00 kWh/m^3. An efficiency of approximately 98% is reported. Because of minimal throttling and rotating equipment (typically fewer than five cycles per minute), the reported noise level produced by the RO Kinetic is negligible. This is advantageous because noise and/or vibrations often cause failure from fatigue in the materials of the system or in the rest of the plant (Plasencia, 2004) or require design changes in the facility to address health and safety concerns. There are no reports in the literature regarding the size and volume of the loops and the additional space requirements for the RO Kinetic ERD. Marketing literature does state that the system is a "very versatile installation with no need of great space requirements [and] can be installed in very diverse ways (vertically, horizontally, under the RO skid, in parallel to the skid or integrated into the skid structure)." As with all other ERDs, higher capacity is achieved by operating multiple units in parallel (Plasencia, 2002).

Several new ERDs have been developed in academia, including the HER, RWE, and FS-ERD. The HER device is very similar to the Clark Pump (Thomson et al., 2002) and the pressure exchanger–intensifier (Folley et al., 2008), except that the directional valves of the HER device are installed within the device and driven by the pistons. Because the switches of the directional valves belong to an instantaneous process, the pressure surges during the switches can be effectively weakened or even eliminated (Sun et al., 2008). The inventor claims a high-pressure transfer efficiency of approximately 94%. Simulated results show that the HER device can decrease the SEC of the SWRO system from 10 kWh/m^3 to 3.0 kWh/m^3.

The RWE is purported to be a compact variable-flow, positive-displacement pump and energy recovery system for SWRO and BWRO desalination. Similarly to ERI's PX, the pressure from the concentrate stream is used to rotate a cylinder containing multiple channels. Unlike the PX, the RWE provides a physical barrier between the feed water and concentrate. A single needle valve controls the rate of rotation of the device (Al-Hawaj, 2003). Although no working prototype has been described, the inventor purports that the RWE has simpler control requirements and lower mixing than other isobaric devices available on the market. As with most devices, an external booster pump is required to offset energy losses through the RO feed spacer and system piping.

In an attempt to improve upon existing two-cylinder isobaric ERDs, Tianjin University in China has developed the FS-ERD. The FS-ERD is composed of four portions: a rotary fluid switcher, two pressure cylinders, and a check valve nest. The core component is the rotary fluid switcher, which has four joint ports and two working phases, similarly to a two-position four-way valve. A piston installed in each cylinder isolates seawater from brine and ensures minimum mixing during operation. The position of the piston is detected to determine whether the pressurizing or depressurizing stroke has been accomplished and when the fluid switcher should be changed to the next working phase. Under this condition, the high-pressure brine stream is imported into Cylinder 1, and the prefilled low-pressure seawater feed is pressurized and pumped out; this is called the pressurizing stroke. Simultaneously, the high-pressure brine stream in cylinder 2 is depressurized and drained out by the incoming low-pressure seawater feed, called the depressurizing stroke. Thereafter, when the FS-ERD accomplishes its pressurizing stroke (and also its depressurizing stroke), the switcher rotates to working in the second phase at a low speed of 7.5 revolutions per minute (rpm), driven by a motor, which denotes that the stroke modes in cylinders are alternated (Wang et al., 2010). No known sizable installations exist to date, and the FS-ERD has not yet been produced on a commercial scale. However, a bench-scale demonstration of parallel FS-ERDs is in progress with a capacity of 2 × 500 m^3/d under typical SWRO operating pressure (Wang et al., 2010).

Based on typical product development timeframes, potential commercial application of these developing technologies is likely 5 to 10 years in the future.

The introduction of the more efficient isobaric devices, combined with improvements in pump/motor capacities with flat operating curves and membrane/element innovations, has lowered the energy consumption of a typical SWRO to 3.5 kWh/m^3 (Truby, 2006). In the opinion of a number of authors, isobaric devices became the most efficient ERDs on the market for SWRO plants (Hauge, 1995; Geisler et al., 1997; Andrews and Shumway, 1999; Kiang et al., 2005; Stover, 2007).

Most of the large SWRO plants being designed and built today utilize isobaric ERDs. With modern isobaric ERDs, efficiencies as high as 97% can be obtained over a range of membrane water recovery rates and/or feed water salinities. Consequently, energy consumption has been reported as low as 2.7 kW/m^3 (Sanz and Stover, 2007).

MacHarg (2011), through funding provided by the Texas Water Development Board, investigated the use of isobaric energy devices in BWRO applications. A pilot study was conducted at the Kay Bailey Hutchison Desalination Plant in western Texas. It was anticipated that the isobaric ERD could be applicable to the BWRO marketplace. Because of the difference in membrane configuration from single-stage SWRO systems, the isobaric ERDs would need to be configured differently as well. The pilot study demonstrated that the isobaric ERD could be successfully incorporated into the BWRO systems. The optimum operating point was at 80% energy recovery and the feed water had a TDS of ~3500 mg/L..

Full-scale model extrapolations to a 3-mgd RO train determined a 1.59 kilowatt-hours (kWh) per 1000 gallons SEC.

Brine-to-electricity is a generic term for systems that produce electricity from concentrate pressure, similarly to hydropower. This has been successfully used with low-pressure turbo devices and with Pelton Wheels. Generating asynchronous electricity allows the ERD system to rotate at peak efficiency speeds, unencumbered by the need to match a pump or motor speed. Additional electrical equipment is required to manage the electric load, match frequencies, and utilize this energy in the system.

2.3.4 Summary

Energy transfer efficiency as high as 90% can be achieved using work exchanger or positive-displacement-type devices. On the other hand, centrifugal devices are only able to achieve efficiencies of 50% to 75% (Andrews et al., 2001; Moch and Harris, 2002; MacHarg, 2002; Wang et al., 2010).

SWRO plants are currently being established around the world, with ever-increasing capacities (Wang et al., 2010). The power required to drive the HPP(s) is typically the largest component of the operating cost of these SWRO systems. To satisfy the increased needs of SWRO plant capacity, many enhancements have been put into practice, including increased ERD per unit size and parallel ERD facility operation (Kronenberg, 2002; Schneider, 2005). Parallel operation is considered to be the most promising, as this operation mode increases the ERD's capacity while having the potential to significantly reduce or even eliminate fluctuations of the ERD working streams (Sun et al., 2008). In a review of the desalination market, Henthorne (2004) indicated that the cost of desalting water has reached an all-time low of about $0.50/m^3, driven largely by increased installed capacity (economies of scale) and enhanced energy recovery.

Although energy consumption has been significantly reduced by the use of ERDs, improvements in membrane science have also contributed to this reduction. Gorenflo (2006) reports that membrane productivity has increased from 6000 to 9000 gpd. Productivity has increased past 9000 gpd and additional increases promise to further decrease the cost and energy consumption of desalination systems.

On the other hand, advances in ERD technology have not translated well to small-scale SWRO systems with less than 10 m^3/d of permeate production. Such small plants typically do not utilize ERDs to decrease the overall capital cost, but have SEC as high as 15 to 20 kWh/m^3 (Oklejas and Pergrande, 2000; Thomson et al., 2002). The payback period for installation of an ERD is much longer than with larger systems. To reduce relatively high operating costs, most existing small-scale SWRO systems are powered by renewable energy systems and grid-supplied energy. The absence of an ERD increases the amount of energy required to power desalination systems, and thus results in a very high water production cost (Tzen et al., 2003).

Table 2.3. Commercially Available Energy Recovery Devices

Manufacturer	Device Type	Trade Name	Capacity Range (m^3/d) per Device*
Flowserve/Calder	Centrifugal	Pelton Wheel	360 to 24,000
PEI (division of ERI)	Centrifugal	Turbocharger	136 to 65,500
FEDCO	Centrifugal	Turbocharger	360 to 84,000
Danfoss	Isobaric	iSAVE	504 to 960
Energy Recovery Inc.	Isobaric	PX	109 to 1,640
Flowserve/Calder	Isobaric	DWEER	2,400 to 8,450
Aqualyng	Isobaric	Recuperator	Proprietary
Spectra Watermakers	Isobaric	Clark Pump	<10
Spectra Watermakers	Isobaric	Pearson Pump	24 to 40
KSB	Isobaric	SalTec	Up to 20,000

*Note that the DWEER and ERI devices are easily operated in parallel for larger capacities.

2.4 Commercially Available Energy Recovery Devices

Currently, there are a limited number of ERDs responsible for over 90% of the total market share for SWRO systems. Isobaric devices, in particular ERI's PX and Flowserve/Calder's DWEER, are being installed in the majority of new facilities, particularly in energy-conscious environments. Where lower levels of energy efficiency are acceptable, turbo devices by PEI or FEDCO or the Flowserve/Calder Pelton Wheel are being installed. Other manufacturers, including Aqualyng and KSB, have minority stakes in the energy recovery market.

Table 2.3 summarizes the major commercially available ERDs. Each device type is discussed in additional detail in the remainder of this section.

For BWRO and reclaimed wastewater RO systems, nearly all ERD market share resides with turbocharger ERDs because of the better applicability of these devices to brackish water system configuration. However, there are a few exceptions; for example, the largest BWRO plant in the world, in Yuma, AZ, uses a Pelton Wheel.

2.4.1 Centrifugal Energy Recovery Devices

Although over 98% of ERDs installed in SWRO plants worldwide in 2000 were centrifugal devices, relatively few devices are commercially available. The lack of growth in this device type is due to greater advancement and higher efficiencies for isobaric devices. Still, the Francis Turbine, Pelton Wheel, and various turbocharger devices are still available for energy recovery applications.

The Francis Turbine, also known as a reverse running pump, is one of the oldest and most developed ERDs (Darwish et al., 1989). Because of its simplicity and ease of operation, the Francis Turbine quickly gained wide acceptance by SWRO industries. Francis Turbines are designed and sized to specific flow or pressure levels; thus, the pressure and flow range at which such a system runs with maximum efficiency is very narrow. Variations in pressure or flow and/or changes to operation mean that the Francis Turbine must be bypassed, resulting in efficiency losses (Goubeau and Guinard, 1985; Kundig and Lineiro1997; Stover, 2007). Also, the device generally does not generate power until 40% of the design condition is achieved (Moch, 2000). Overall, Francis Turbines have overall efficiency (maximum efficiency around 75%) lower than that of competing isobaric devices (91% to 96%).

Many existing medium- and large-scale SWRO plants use Francis Turbine technology. The 50,000 m^3/d Fukuoka SWRO Desalination Plant in Japan operates at a recovery of 60%. Several plants installed in Saudi Arabia before 2000 incorporate Francis Turbine ERDs, including facilities in Jubail, Yanbu, Duba, and Haql (Nada et al., 1995; Al-Kutbi and Baig, 1998). With further improvements in other ERD technologies, Francis Turbines are less likely to be installed in new plants (Moch, 2000; Manth et al., 2003).

A Pelton Wheel, commercially available through Flowserve/Calder, relies on the same impulse turbine principles described for the Francis Turbine. In its operation, the high-pressure concentrate is fed into the Pelton Wheel hydraulic impulse turbine, which then produces rotating power output to assist the main electric motor in driving the main HPP. The system consists of an adjustable input nozzle to convert water pressure into kinetic energy contained in a high-velocity jet (Darwish et al., 2007). Energy recovery starts at about 40% of system pressure. The inlet nozzle acts as a brine control valve, and no further pressure control is used on the RO system. The Pelton Wheel is illustrated in Figure 2.6, and design and operational characteristics are summarized in Appendix A.

Some authors report that the Pelton Wheel is a more economical ERD than the Francis Turbine (Inglesias, 1999), with some installations achieving an efficiency between 80% and 90% (Heckel and Stern, 2002). Some also report that the efficiency stays relatively high over the full operational range, including changes in flow and pressure (Scholl, 1997). However, other authors report that these units suffer from loss of efficiency, especially when operating in the off-duty range (Goubeau and Guinard, 1985; Kundig et al., 1997; Manth et al., 2003; Stover, 2007) or when not properly designed and installed in the RO plant (Oklejas and Manth, 2002). Stover (2004) reported that Pelton Wheel efficiencies typically range from 40% to 60%, but efficiencies as high as 81% can be achieved for 90% efficient devices coupled to 90% efficient pumps. Flowserve/Calder has recently reported that its Pelton Wheels can achieve efficiencies as high as 90%.

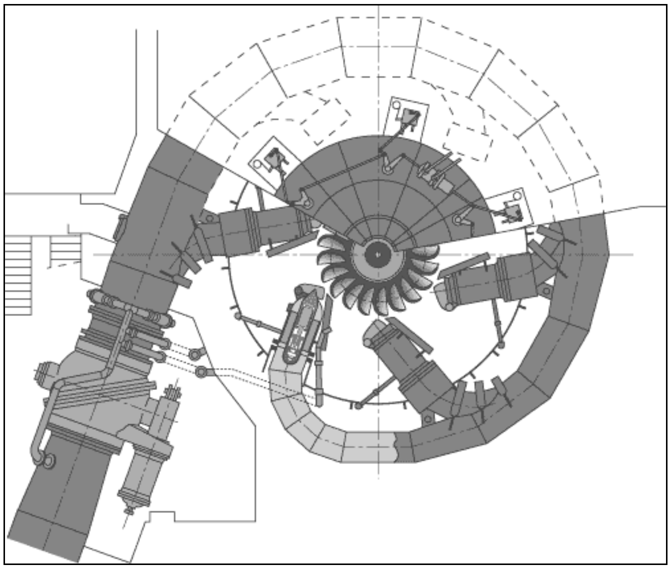


Figure 2.6. Schematic of Pelton Wheel.

Last, commercially available turbochargers are currently the most commonly applied centrifugal technology because of high-efficiency improvements. Turbochargers include a turbine portion (a single-stage radial inflow type similar to a reverse running pump) and a pump portion (a single-stage centrifugal pump with the impeller mounted on the turbine shaft). FEDCO and ERI offer turbochargers under the brand names Hydraulic Pressure Booster (HPB) and Turbo, respectively. A turbocharger device is illustrated in Figure 2.7.

FEDCO's Hydraulic Energy Management Integration (HEMI) is a turbocharger with the addition of motor and control logic to control system recovery and recover concentrate energy. The HEMI allows additional energy to be added to what has just been recovered from the concentrate, overcoming other losses in the system, such as membrane pressure drop, without the need for an additional, separate, booster pump.

Because performance is affected by variations in flow and pressure (Kundigand Lineiro, 1997; Stover, 2007), turbochargers typically have a bypass that enables the operator to control and balance flow. This bypass is needed when second-stage brine flow is above the level required for boost pressure, especially when the feed is subjected to large temperature variations, such as are typically seen in surface intake plants and/or for membrane aging (Farooque et al., 2004*)*. The device has a maximum possible efficiency of up to 85%, which is low compared to competing devices with top efficiencies of 91% to 96%.

The first commercial SWRO unit utilizing a turbocharger was sold in 1991 to Watersource, a Miami-based RO system builder, and installed in a U.S. Virgin Islands plant with a feed water flow of 150 gallons per minute (gpm) (9.5 liters per second [L/s]). Also, in 1991, two turbochargers were sold to be installed on Chiyoda's liquid natural gas project on Das Island, near Abu Dhabi. When commissioned, the plant produced 648 m^3/d (0.17 mgd) of permeate using DuPont's B-10 Twin Permeators per train operating at 65.5 bar (950 psi) and 34% recovery operating at an estimated SEC of 3.4 kWh/m^3 (12.9 kilowatt-hours per kilogallon [kWh/kgal]).

Figure 2.7. Hydraulic turbocharger.

Turbochargers are mainly used in conjunction with brine conversion systems (BCS) to increase water recovery up to 60%, with minimal increases in cost (Kihara et al., 2002). Vedavyasan (2002) reported that turbocharger installation in a SWRO plant can result in water cost reduction of 23% and a reduction in energy use of 18%. Overall, the hydraulic turbo charger–BCS system is reported to achieve an efficiency of about 70%, depending on capacity (Uchiyama et al., 1999).

The Magtaa SWRO, located on the Mediterranean coast of Algeria, produces 500,000 m^3/d using PEI HTCAT-7200 turbochargers (*Water and Desalination News*, October 2009). Medium BCS system plants are also being successfully operated in the Caribbean Islands (14,800 m^3/d) and at Mas Palomas, Gran Canaria, Spain (20,400 m^3/d) (von Gottberg et al., 2002). There are several small plants, built before 2000, with capacity ranging from 210 to 5,700 m^3/d that utilize a turbocharger–BCS system (Moch, 2000).

The design and operational characteristics of turbocharger devices are summarized in Appendix A.

2.4.2 Isobaric Energy Recovery Devices

The most efficient ERDs available on the market are those that employ the positive displacement principle. Many isobaric devices enable simple, variable adaption of discharge volume and hence recovery (Harris, 1999; MacHarg and Pique, 2002a) and possess a high device efficiency of approximately 98% (Geisler et al., 1997). Examples of positive displacement devices include ERI's PX (MacHarg 2001; Wang et al., 2005b; Stover, 2007), Flowserve/Calder's DWEER (Shumway, 1999; Andrews and Laker, 2001), Siemag's Pressure Exchange System (PES) (Geisler et al., 1999, 2001), and the Aqualyng system (Drablos, 2001). Because of higher efficiency, these devices are considered to be the most promising and competitive technologies on the market (Wang et al., 2005a).

There are currently seven different isobaric ERDs available, including

- Flowserve/Calder's DWEER
- Aqualyng's Recuperator
- KSB's SalTec
- Energy Recovery Inc.'s PX
- Spectra Watermakers's Clark Ppump and Pearson Pump
- Danfoss's iSave.

The differences between the seven devices lie predominantly in the design of equipment used to achieve pressure exchange and the control of the devices. Although all of the devices utilize positive displacement, all except for the PX use a multichamber piston-type arrangement to achieve energy exchange. The DWEER, SalTec, and Recuperator all operate with two or more chambers and valving mechanisms to change the sequencing (direction of travel) of the ERD. All of these systems can be used, assuming adequate capacity, over a range of recoveries. The nature of the isobaric ERD requires a booster pump to offset pressure losses that are due to piping, membranes, and the ERD before cycling water back into the system. The iSave has this pump built into the device.

In 2005, it was reported that the two largest SWRO desalination plants with DWEER devices were the Ashkelon plant in Israel and the Tuas plant in Singapore, with capacities of 100 million m^3/y (Kronenberg, 2004; Kiang et al,. 2005) and 30 mgd (Industry News, 2004), respectively. A number of early adopting plants, dating back to the 1980s, are located throughout the Caribbean and Europe. Andrews and Shumway (1999) detailed DWEER installations at different locations in the Caribbean Islands with capacities ranging from 3200 to 10,300 m^3/d and train sizes ranging from 1600 to 2500 m^3/d. Reductions in SEC were also reported at an ERD upgraded SWRO plant in Grand Cayman, Spain. The SWRO plant had an SEC of 3.00 kWh/m^3 prior to installation of a DWEER system, which reduced the SEC to 2.22 kWh/m^3 (Andrews et al., 2001).

Independent literature indicates that DWEER installations are reported to have extremely high efficiencies of about 95% (Oklejas, 2003; Kiang et al., 2005; Schneider, 2005; Wang et al., 2005a) Flowserve/Calder recently reported that the efficiencies can be as high as 98%. DWEER allows an almost constant efficiency over a wide range of changing conditions, especially considering the full range of operating pressure conditions typical in the RO industry (Schneider, 2005; Verbeek, 2005). Although DWEER is reported to have a design life in excess of 25 years, the valving has historically been subject to wear and failure. The development of the LiNX valve is credited with greatly improving the performance of the units. Also, because of the sequencing, it has been reported that pulsations and "water hammer" pressure surges have complicated or delayed the startup of new plants (*Membrane Technology News Bulletin,* July 2010).

The Aqualyng Process (Drablos, 2001) uses the saline reject in a sequential process to directly pressurize feed seawater. Although limited reports are available on the operation and performance of the Recuperator, Aqualyng has included it in several sizeable desalination plants. One recent example is a 50,000-m^3/d SWRO facility located in the Caofeidian Industrial Zone, 220 km east of Beijing, China (*Water and Desalination News,* March 2010).

Drablos (2002) also reported on the performance of Aqualyng Pressure Recuperation in SWRO plants in Gran Canaria, Spain.

In a pressure-exchanger device, high-pressure concentrate flows through the unit and transfers energy directly to a portion of the incoming lower-pressure seawater feed (Stover, 2004). The heart of the device is a single cylindrical ceramic rotor that facilitates pressure exchanges. Ceramic was selected as the ideal material for this application because it is tough, corrosion-proof, and dimensionally stable. The rotor contains axial ducts arranged in a circle around a center tension rod (*Membrane Technology News Bulletin,* 2004). The rotor spins within a ceramic sleeve and is enclosed on either end with dedicated feed and concentrate ceramic end covers. The bearing and sealing surfaces are the ceramic parts themselves, and bearing lubrication is provided by high-pressure feed water. The concentrate end cover contains a high-pressure concentrate port for incoming concentrate (HP IN) and a low-pressure concentrate port for outgoing concentrate (LP OUT). The feed water end cover likewise contains two feed water ports (LP IN and HP OUT). The pressure-exchanger system allows the feed and concentrate streams to come into direct contact, and minimal mixing of the streams occurs within the duct. Mixing increases the feed water TDS, requiring slightly higher feed pressures to maintain the desired flux and recovery (Stover, 2004).

ERI's marketing literature reports that the PX is the most energy-efficient commercially available ERD, with a flat performance curve and reported efficiencies of over 95% (Andrews et al., 2001; MacHarg and Pique, 2002a; Oklejas, 2003; Wang et al., 2005a, 2010; Stover, 2007;). However, the analysis typically excludes energy losses in the system caused by the backpressure required to minimize cavitation and the lower efficiencies of the booster pump. Noise from the device also often exceeds recommended Occupational Safety and Health Administration (OSHA) standards, requiring installation of noise enclosures or separate ERD rooms in the facility. The compact system can handle high flow capacity and unsteady conditions (Stover, 2007; Mambrettia et al., 2009). In addition, the control and instrumentation of the PX is more comprehensive than for most other ERDs, even though the device has only a single moving part with minimal required preventative maintenance.

MacHarg (2007) compared the performance of various ERDs at low to medium capacity; the results are summarized in Figure 2.8. At very low capacities, where highly efficient piston pumps can be applied, very low SEC can be achieved using pressure-exchanger technology (approaching 2.1 kWh/m^3). Otherwise, low- to medium-capacity systems typically possess higher SEC than higher-capacity systems, as a result of lower centrifugal pump efficiencies at low capacity. Several recent products have been targeted specifically toward these markets, including the iSave, Clark Pump, Pearson Pump, and APP ERD.

Specializing in small-capacity desalination systems, Spectra Watermakers has developed systems based on the Clark Pump and the Pearson Pump. The Clark Pump is single-vessel, two-chamber, isobaric ERD. Similar to larger isobaric, multichamber ERDs, an external pilot valve (reversing valve) controls the sequencing and flow of water through the device. The system is designed for fixed recovery, depending on the area displaced by the shaft on the concentrate side of the piston. Systems based on the Clark Pump are available in capacities ranging from 144 to 1,000 gpd.

The Pearson Pump is a positive-displacement, three-cylinder, reciprocating HPP with the same motors and crankcases used in conventional RO system feed pumps. The Pearson Pump head delivers water to the membranes in the same way as conventional feed pumps, but is capable of recovering the energy in the concentrate. This is done by returning the concentrate to the Pearson pump at high pressure, where it flows into the pump cylinders on the undersides of the pistons, transferring its energy to the feed water. The energy recovered from the concentrate reduces the load on the pump motor, thereby reducing energy consumption. Like other similar devices (such as Vari-RO), the Pearson Pump operates at a fixed recovery. The device is available in multiple designs ranging from 20% to 50% recovery with permeate production between 55 and 220 gal/h.

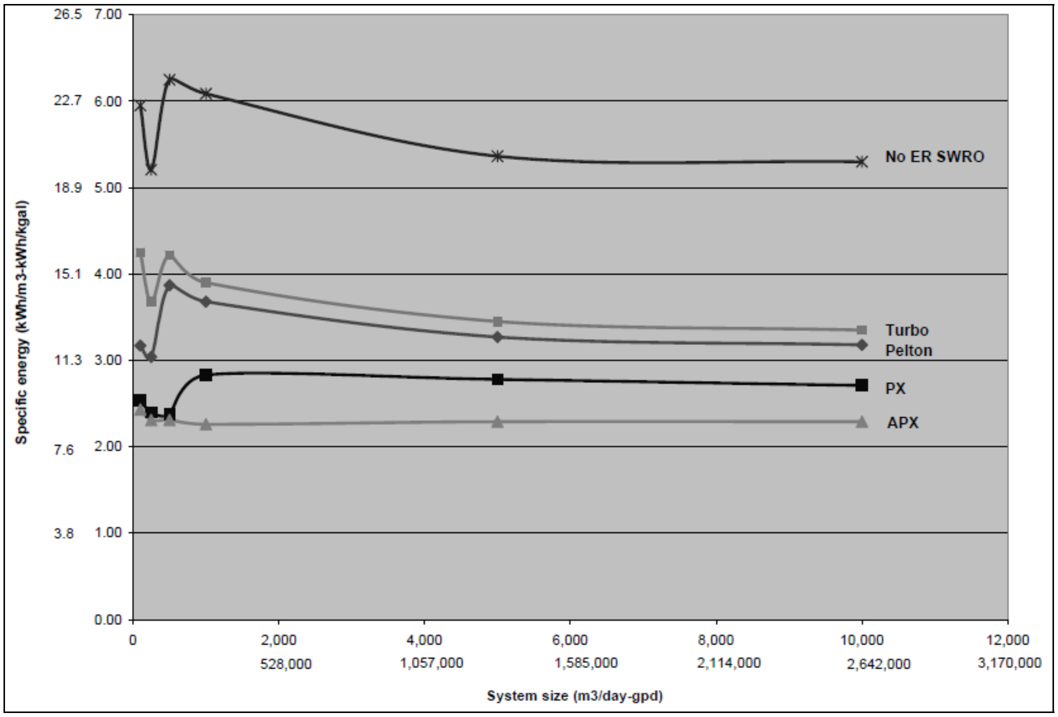


Figure 2.8. Typical SEC for energy recovery devices at low capacity (MacHarg, 2007).

Although Clark and Pearson pumps improve energy efficiency for very small applications, mid-size applications tend to possess lower efficiencies. Development of the APP–APM (axial piston motor) and iSave ERDs is anticipated to provide greater efficiencies in this flow range.

Danfoss, a company specializing in desalination and other HPP applications, has released the iSave, an isobaric ERD with integrated booster pump. The iSave consists of a pressure exchanger, a high-pressure positive displacement booster pump, and an electric motor, coupled into a single package, reducing footprint. The manufacturer claims that the technology used in the pressure exchanger is based on technology used in the Danfoss APPs, and the booster pump is based on the vane pump principle, enabling a very light and compact design. The iSave is a self-lubricating stainless steel device, duplex or super-duplex depending on the application. The vane pumps are fixed displacement pumps in which the flow is proportional to the number of revolutions of the driving shaft enabling flow control. The electric motor provides speed control of both the pressure exchanger and the high-pressure booster pump on the same shaft, preventing overspin and overflushing. A variable-frequency drive (VFD) controlling the speed of the iSave also provides fail-safe communication to the service staff. Current applications for the iSave device include marine and container-based installations. Few independent publications detailing performance of the iSave exist. Although the manufacturer claims up to 94% efficiency, the basis of this claim is unknown. If this figure includes the booster pump component, the iSave may be one of the most efficient ERDs available on the market. The iSave is targeted toward seawater desalination systems up to 4000 m^3/d capacity.

MacHarg (2007), with funding provided by the Office of Naval Research, reported on the development of a new class of axially driven, combination positive-displacement pump ERDs. In a patent awarded in 2010, MacHarg describes the invention as "a pumping machine, that can serve a system as the sole main pump for pressurizing a primary liquid flow, incorporates, in a single machine, a rotor-drum type APP and a pressure exchanger that recovers energy from a secondary liquid flow such as the brine discharge from an RO seawater desalination system, with benefits including fewer moving parts and small machine size along with lower capital and operating costs. A single rotor-drum containing the cylinders and pistons is located between two end blocks, one or both configured with manifold passageways, ports and sliding valves. A swash-plate at one end reciprocates the pistons axially when the rotor-drum is rotated. Two working chambers, primary and secondary, are formed at opposite ends of a single piston in each cylinder, thus enabling the single rotor-drum to function as a primary liquid-pressurizing axial pump with sliding valves at the primary end enabling primary liquid pumping, and as a secondary outflow-driven pressure exchanger PX recovering energy from pressure drop in the secondary liquid flow and thus contributing work to primary pumping, saving energy and reducing operating costs."

It is reported from field data that the APP-APM technology can successfully reduce the power consumption in mid-size SWRO systems to as low as 2.1 kWh/m^3 (MacHarg, 2007). Currently, full-scale production of this pump has not begun, but working prototypes have been developed.

2.5 Energy Recovery Devices and Process Configurations Selected for Model

2.5.1 Energy Recovery Devices

Many attempts have been made to compare and recommend the most appropriate devices for energy recovery (Mandil et al., 1998; Harris, 1999). The main objective of this evaluation is to use all the information collected from the literature review and present a comparative discussion of each of the ERD technologies relative to their applicability and effectiveness. Each of the ERDs discussed in Section 2.4 was evaluated on the basis of performance reported in the engineering literature, results of manufacturer or vendor studies, and the industry's experience with the ERD. Specifically, the ERD technologies were compared with respect to their reliability, flexibility, adaptability, potential for modifications, and other related relevant factors. These evaluation criteria are summarized in Table 2.4.

Based on the evaluation, the following ERDs were selected to be incorporated into the tool:

1. Turbochargers
   a. FEDCO HPB
   b. ERI Low Pressure Turbocharger (LPT), High Pressure Turbocharger (HALO), and Hydraulic Turbocharger (HTC)
2. Flowserve/Calder Pelton Wheels
3. Isobaric devices
   a. ERI PX

b. Flowserve/Calder DWEER

These ERDs were selected for incorporation into the tool based on their use in the vast majority of new RO installations because of their high efficiency, superior performance, and track record in the marketplace. The design and operational characteristics of the selected devices are summarized in Appendix A.

Table 2.4. Multicriterion Comparison of ERD Technologies

Type	Scale	Capacity (m³/d)	Recovery (%)	Mixing[a] (%)	Lubrication[b] (%)	Noise (dB)	Booster Pump	Efficiency (%)	Concentrate Backpressure (bar) min	max
PX	Commercial	109 to 1,640*	Variable	3.1% at 50% Recovery	1% of HPP Flow	>87 dB	Required	94 to 98%	1 bar	
DWEER	Commercial	2400 to 8,450*	Variable	< 2.5%	1% of HPP Flow	<80 dB	Required	Up to 98%	1 bar	
SalTec	Commercial		Variable			<80 dB	Required		1 bar	
Pelton Wheel	Commercial	360 to 24,000	Minimal variation	None	None	>87 dB	None	Up to 90%	0	Free discharge
Turbocharger–FEDCO	Commercial	360 to 84,000	Minimal variation	None	None	>87 dB	None	65 to 85%	1 bar	
Turbocharger–ERI	Commercial	136 to 65,500	Minimal variation	None	None	>87 dB	None	50 to 80%	1 bar	
HPB–Hemi	Commercial		Minimal variation	None	None	>87 dB	None			
iSave	Commercial	504 to 960	Variable			>87 dB	None	Up to 93%[c]	1 bar	
Clark Pump	Commercial		Fixed			<80 dB	None			
Pearson Pump	Commercial		Fixed			<80 dB	None			
APP–HP	Developing		Fixed*			<80 dB	None			
RWE	Developing					<80 dB	Required			
Aqualyng	Commercial		Variable			<80 dB	None			
FS–ERD	Developing					<80 dB	None			
HER	Developing		Fixed			<80 dB	None			
VariRO	Developing		Fixed			<80 dB	None			
RO Kinetic	Developing					<80 dB	Required			

*Note that the DWEER and ERI devices are easily operated in parallel for larger capacities.
[a]Mixing.
[b]Lubrication.
[c]Device + booster pump.

2.5.2 Process Configurations

Many RO + ERD process configurations are available. Parameters that influence the configuration are as follows:

1. *Source Water.* The type of source water has a tremendous influence on the design of the RO system, and thus how the ERD is implemented. For example, SWRO systems are typically single-stage, and the ERD is used to pressurize the feed. With brackish water systems, the ERD is typically used to boost the pressure of the second or third stage.
2. *Number of ERDs.* A system may incorporate one ERD per RO train or a common energy center (for seawater systems).

2.5.2.1 Seawater Desalination

ERDs are widely used on SWRO systems. Because of the high osmotic pressure inherent in seawater, the required feed pressures are high, typically 800 to 1000 psig, and recoveries are low (typically less than 50%). Therefore, most SWRO systems consist of a single stage. Recoveries beyond 50% are unusual because of the feed pressure limitations of the RO element (1000 psig) relative to the required feed pressure necessary to overcome the osmotic pressure at more than 50% recovery. Thus, the RO concentrate has a significant embodied energy content, as much as 60% of the energy input to the feed when recovery is low (around 35%). Thus, there is ample opportunity to recover the energy in the concentrate with an ERD. Turbochargers, Pelton Wheels, and isobaric devices have all been used successfully in SWRO systems.

The process configurations shown in Figures 2.9, 2.10, and 2.11 are typical for seawater.

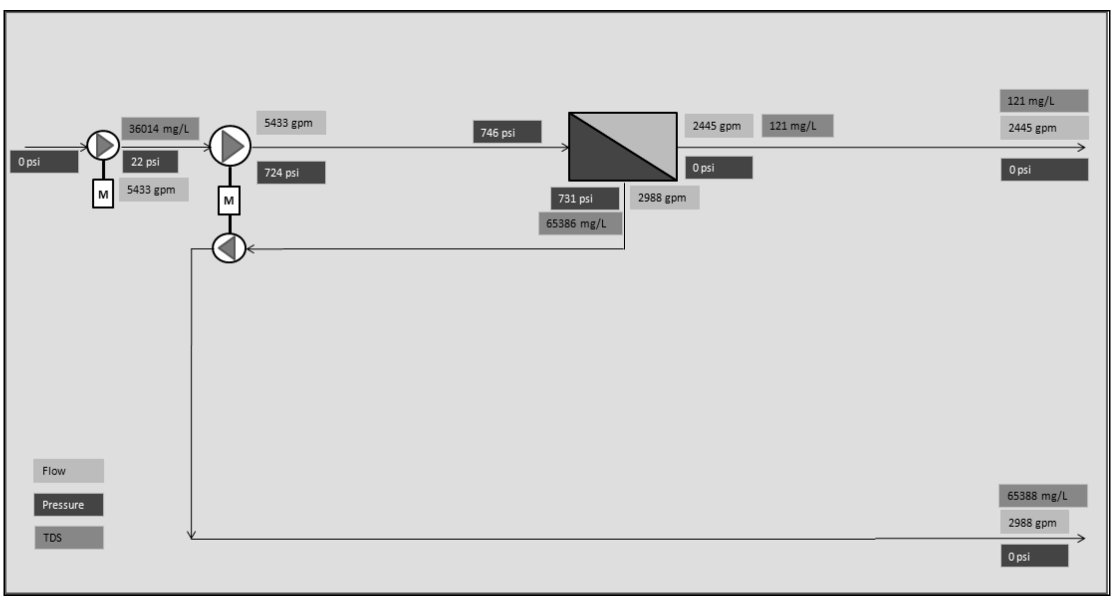


Figure 2.9. SWRO train with Pelton Wheel.

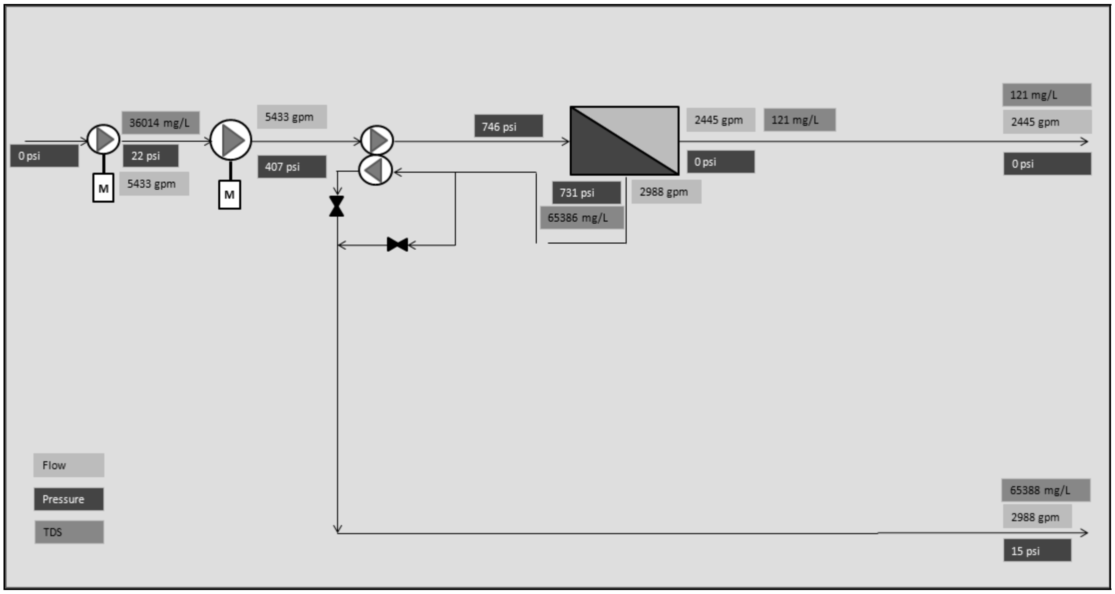


Figure 2.10. SWRO train with turbocharger.

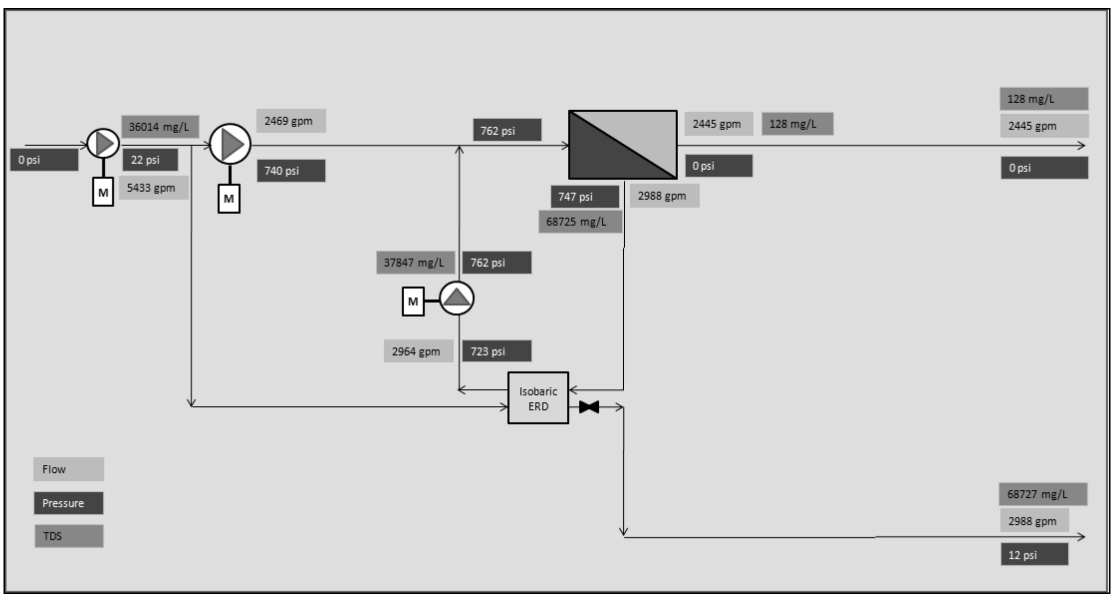


Figure 2.11. SWRO train with isobaric ERD.

2.5.2.2 Brackish Water and Wastewater RO

Because of lower salinity, and thus osmotic pressure, as well as the higher membrane/water transfer rate, brackish and wastewater RO systems are typically multistage and have recoveries in the 75 to 90% range. Pelton Wheels are usually not incorporated into these lower-pressure RO systems, although some early brackish plants did use Pelton Wheels (for example, the Yuma Desalting Plant in Arizona). For these multistage systems, the ERDs can be utilized to boost the feed, similarly to how they are used in single-stage systems; however, they are more commonly used to boost a subsequent stage to provide a better flux balance between stages.

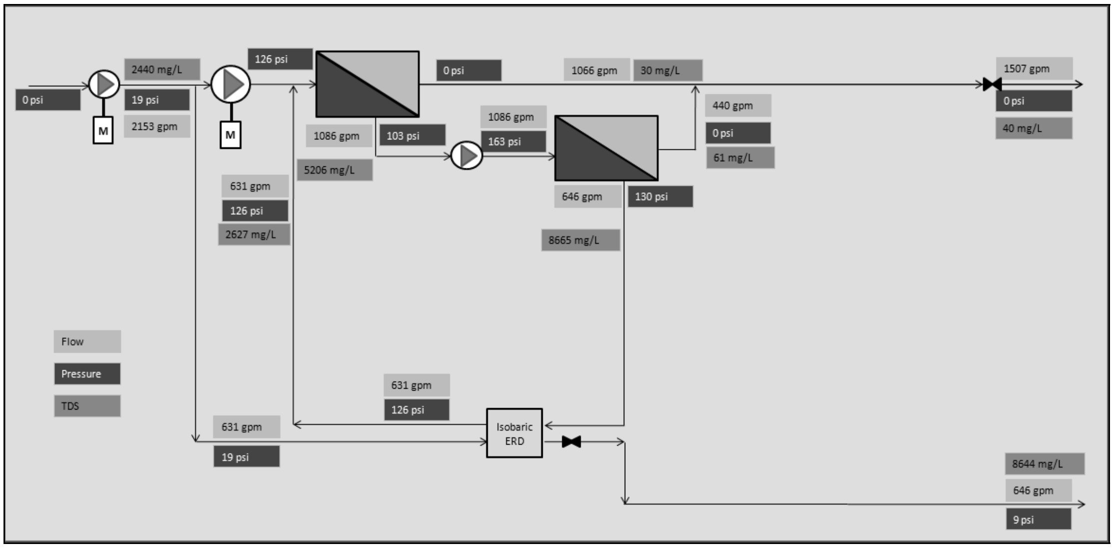


Figure 2.12. Two-stage BWRO with isobaric ERD boosting the feed.

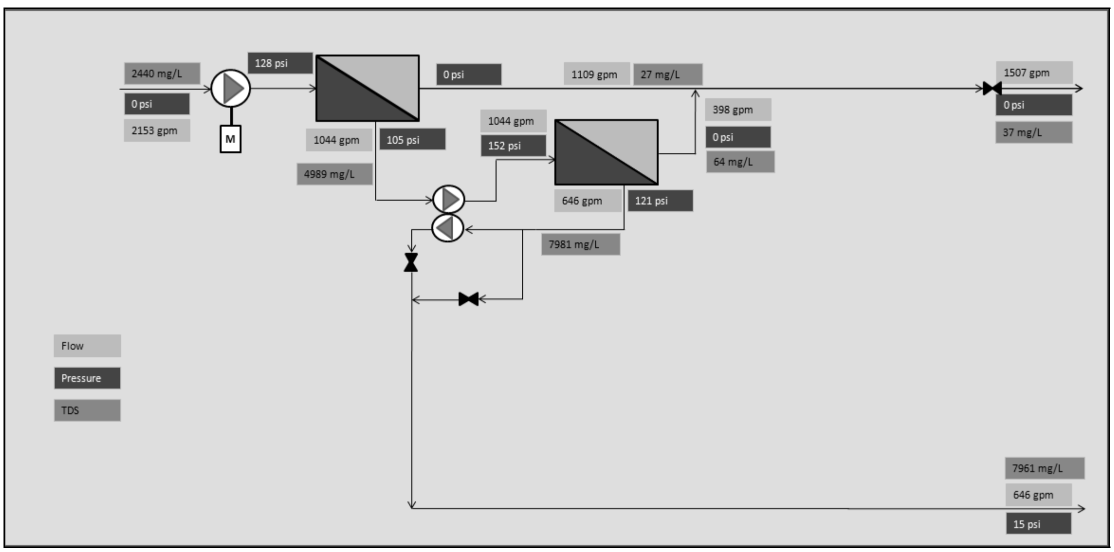


Figure 2.13. Two-stage BWRO with turbocharger.

Figure 2.12 presents an example of a multistage brackish RO with an isobaric ERD boosting the feed water.

Instead, the ERD can be used to boost a subsequent stage, as shown in Figures 2.13 and 2.14. Turbochargers incorporated into multistage RO systems are typically used to boost a subsequent stage, as the turbocharger efficiency is highly dependent on the ratio of the flow of concentrate water to the flow of the water boosted, termed the reject ratio. This is discussed in detail in Chapter 3.

For a three-stage RO system, the ERD can boost the feed, the second stage, or the third stage. With the turbocharger, the choice of whether to boost the second or third stage will be heavily influenced by the reject ratio.

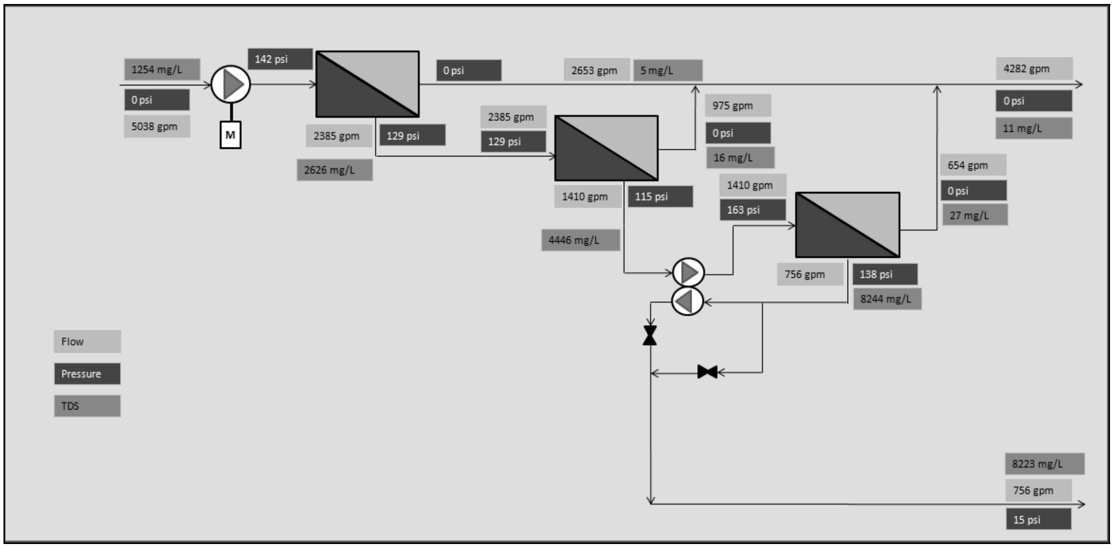


Figure 2.14. Three-stage BWRO with turbocharger boosting the third stage.

2.5.2.3 Standard Configuration Options (SWRO, BWRO, and Wastewater RO)

Feed Pressure Control. The feed pressure to the RO process varies based on a number of factors, including feed water temperature and salinity variations, as well as the water permeation rate of the RO elements that are due to aging, scaling, and fouling. To account for these factors, the pumping system is designed so that feed pressure can be varied in order to maintain a constant permeate flow rate. The configurations shown in Figures 2.9 through 2.14 incorporate a VFD on the high-pressure RO feed pump for pressure control. This is typical for medium and large BWRO and wastewater systems, as well as smaller SWRO systems, as this is the most energy-efficient method of feed pressure control, despite the fact that VFDs possess parasitic energy losses of approximately 1% to 2%. For medium- and large-capacity SWRO systems, VFDs have high capital costs, and design engineers will typically use a VFD on the smaller (motor) RO supply pump (upstream of the cartridge filter) to provide the necessary feed pressure range while reducing capital cost as well as increasing the efficiency of the HPP. Smaller RO systems may eliminate the VFD altogether and replace it with a throttling valve, either on the feed line between the high-pressure RO feed pump and the membranes or on the common permeate line leaving the RO train. Regardless of where the throttling valve is placed, this is not an energy-efficient method of pressure control, as the valve wastes energy that is not recovered by the ERD.

Stage Permeate Flow Control. In a multistage BWRO or wastewater RO system, the permeate flow in one or more stages is often controlled to prevent upstream stages from having substantially higher flux (permeate flow/membrane area) than downstream stages; this is termed “flux balancing.” A stage with a substantially higher permeate flux would be susceptible to rapid membrane fouling. Stage permeate flow can be influenced in a number of ways. Prior to the adoption of ERDs, flux balance was achieved by placing backpressure on the first stage and sometimes the second stage (in a three-stage system) using a throttling valve in the stage permeate line. This approach increases system energy consumption by requiring higher feed pressures to the train. The permeate backpressure approach using standard pressure vessels is limited. The standard permeate port design for 8-in. pressure vessels has a typical maximum design pressure of 125 psi. A second approach is to install a booster pump between stages to increase driving pressure to downstream stages. This is more energy-efficient because it matches driving force pressure to the feed salinity of each stage without wasting energy across a throttled valve. When energy recovery is incorporated into the RO design, flux balancing can be achieved in several ways. With a two-stage system, flux balancing is provided by the ERD’s pressure boost in Stage 2 using a turbocharger (see Figure 2.13).

As shown in the stage permeate flow examples in Figures 2.15 and 2.16, energy recovery can be combined with both permeate throttling and boost pumping. The three-stage RO system at the Luggage Point Advanced Water Treatment Plant in Brisbane, Australia uses the approach shown in Figure 2.15.

The options described here for feed-pressure control and stage permeate flow control are incorporated into the tool.

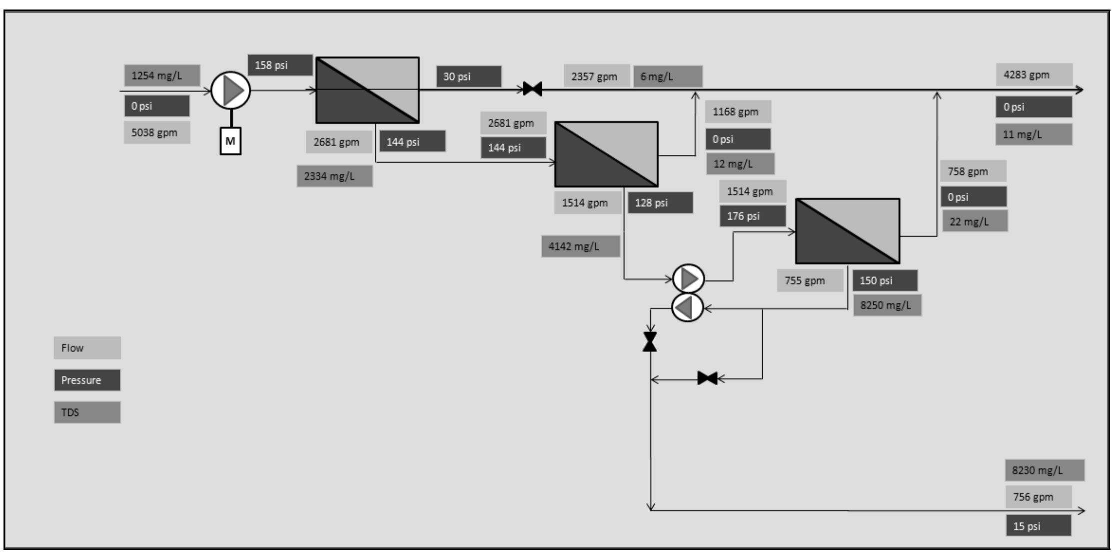


Figure 2.15. Three-stage BWRO with turbocharger boosting the third stage and a permeate backpressure valve on the first stage.

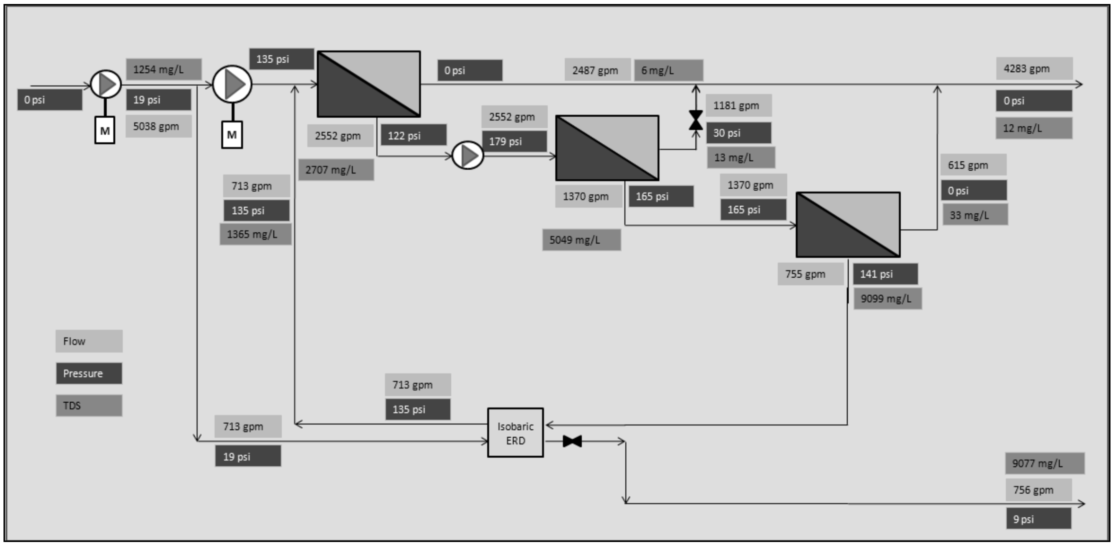


Figure 2.16. Three-stage BWRO with isobaric ERD boosting the feed and a permeate backpressure valve on the second stage.

2.5.2.4 The Pressure or Energy Center

The majority of RO installations that utilize energy recovery incorporate the ERD on a per RO train basis where the concentrate from a single RO train is processed through a dedicated ERD, where the pressure-boosted feed or interstage flow is within the same RO train. In contrast, some larger SWRO plants employ the "pressure center" (or energy center) concept, where the concentrate from multiple trains is combined and sent to a pressure center that contains multiple ERDs operating in parallel. The pressure-boosted feed stream exiting the ERDs is then conveyed to a common header that feeds water to multiple RO trains.

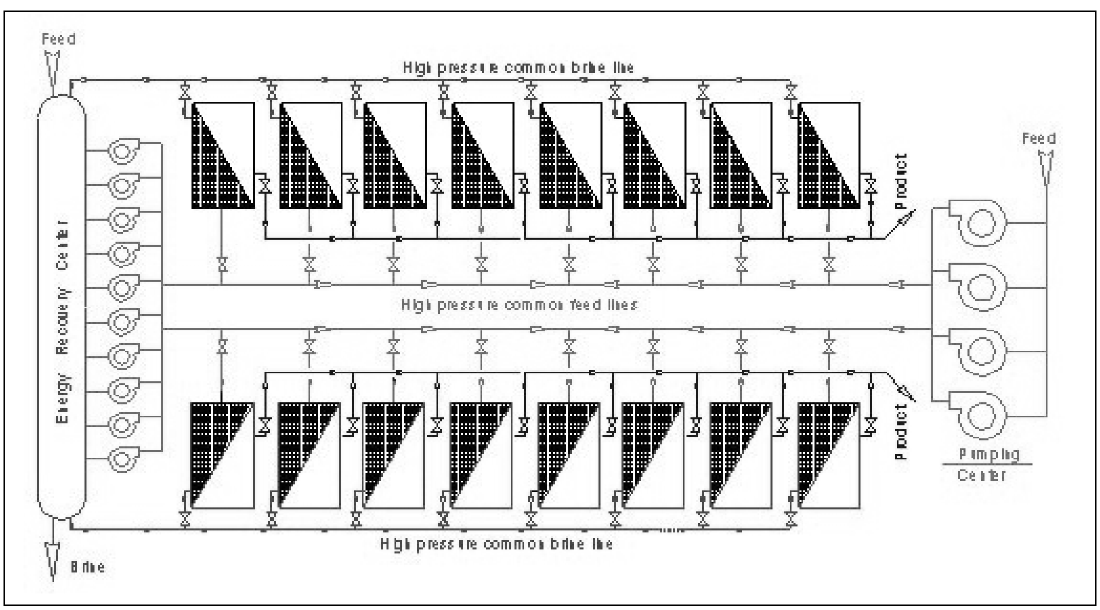


Figure 2.17. Pressure center schematic for Ashkelon Desalination Plant (IDE Technologies Website, www.IDE-tech.com).

Faigon and Liberman (2003) report on the use of centralized pumping systems to increase energy efficiency in a desalination plant. The authors discuss the use of centralized high-pressure pumping and centralized energy recovery. When fewer, larger HPPs are used, the pumps can operate at higher specific speeds with higher efficiencies. The Ashkelon Desalination Plant in Israel, which utilizes four 33% HPPs (in a 3 + 1 arrangement), reports HPP efficiency of approximately 90%. The pressure center schematic for the Ashkelon plant is provided in Figure 2.17.

However, the pressure center design introduces some process limitations. First, the systems are reported to take a comparatively longer time and more permeate flush water to start up and shut down. In addition, when such centralized systems are utilized, balancing the performance of different membrane trains is important to manage fouling. Two different design concepts are reported in the literature. The first utilizes feed-throttling valves on the inlet of each membrane train to control the membrane flux. In the second design, the flux of the individual trains is controlled using permeate backpressure. In either case, energy losses are incurred with the pressure center approach to balance intertrain fluxes. This energy loss can be on the order of ~3% of the total RO energy consumption.Chapter 3.

Chapter 3

Tool Development

3.1 Development of a Reverse Osmosis Model

A review by the authors of the current desalination literature and tools indicates that no existing model available on the market is capable of conducting RO projections, comparative energy calculations, and providing cost estimates. This tool provides these capabilities, providing new information to evaluate various ERDs for implementation into municipal brackish-water, treated wastewater, and seawater desalination applications.

This chapter describes the tool concept and key components.

3.1.1 Reverse Osmosis Theory[1]

In natural osmosis, a semipermeable membrane separates pure water (solvent) from a salt solution (solute). Pure water naturally passes through the membrane to dilute the salt solution; the driving force for the flow is the difference in chemical potential between the two liquids. Chemical potential is directly proportional to changes in temperature and pressure and inversely proportional to changes in solute concentration. Water flow continues until the pressure created by the hydraulic head equals the osmotic pressure of the salt solution. At this point, the two liquids are said to be in osmotic equilibrium. This process is illustrated in Figure 3.1a.

In RO, applying external pressure to the salt solution allows the net natural flow of water to be reversed, as illustrated in Figure 3.1b.

In any membrane process, flow characteristics are unique functions of the membrane polymer. For example, product flow or solute (salt) passage for a polyamide polymer is different from that for a cellulose acetate polymer, which is different from that for a polysulfone polymer. If the membrane area in a device is twice that of another device using the same polymer, the water flow will be double. Similarly, a thicker membrane will allow less water flow than a thinner membrane of the same polymer. Some factors, such as the membrane material, membrane area in a device, and membrane thickness, are set and controlled only by the membrane manufacturers and system suppliers. Other factors, including the pressure applied in the system and the concentration differential across the membrane, can be adjusted by the end user.The high feed pressure requirements associated with RO make it an ideal environment for the use of ERDs and systems.

---

[1] Taken from American Water Works Association (1998).

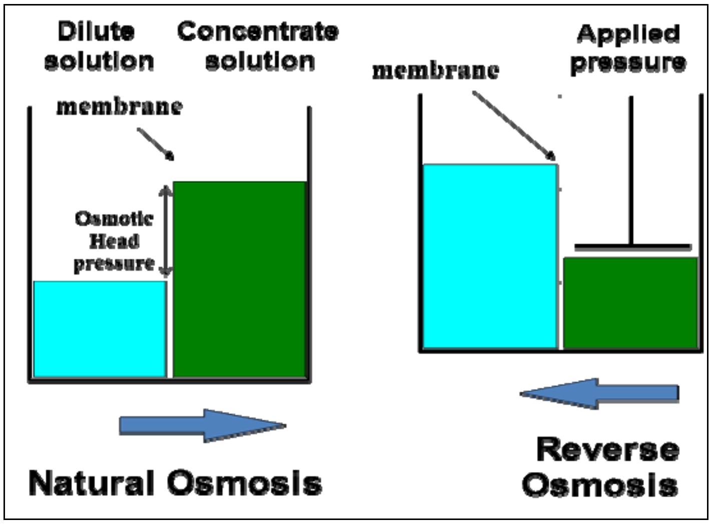


Figure 3.1. Natural osmotic flow and reverse osmosis.

3.1.2 Design Equations

This section describes the fundamentals associated with diffusion-controlled membrane processes, such as RO. In these processes, water is forced through a membrane by a pressure differential (a type of motion called convection), and dissolved salts pass through the membrane because of a concentration differential (a type of motion called diffusion). Because the membrane is semipermeable, both dissolved salts and water are transported to differing degrees through the molecular structure of the active surface layer of the membrane.

The standard model for describing the RO process is the homogenous solution diffusion (HSD) model, which illustrates the effects of feed concentration, membrane characteristics, recovery, and pressure on permeate concentration. The HSD model incorporates operational parameters such as water quality, water recovery, and membrane-specific coefficients to determine system performance. The HSD model does not consider the effects of certain chemical and physical constraints, and it makes certain simplifying assumptions.

Figure 3.2 shows a single membrane element, as well as the terminology typically used to describe flow and concentration. The following equations are commonly used for RO and NF membrane processes to determine system efficiency.

Mass balance for water flow:

$$Q_f = Q_p + Q_c, \tag{3.1}$$

where Q_f = feed water flow rate, Q_p = permeate flow rate, and Q_c = concentrate flow rate.

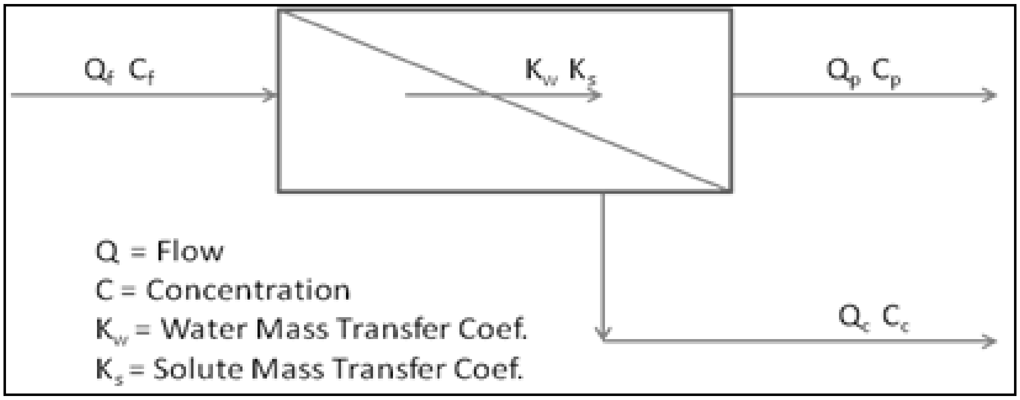


Figure 3.2. Schematic diagram of a reverse osmosis membrane element.

Mass balance for solute flux:

$$Q_f C_f = Q_p C_p + Q_c C_c, \tag{3.2}$$

where C_f = feed water solute concentration, C_p = permeate solute concentration, and C_c = concentrate solute concentration.

Product recovery rate:

$$\text{REC} = \frac{Q_p}{Q_f} \tag{3.3}$$

where REC = decimal fraction of product water recovered from feed water.

Further equations for calculating the water and salt flux through the membrane, osmotic pressure, mass transfer coefficients, and permeate concentration are included in AWWA (1998).

3.1.3. Calculation Methodology

This section describes the calculation methodology for the RO projection portion of the tool. The calculations are used to determine the physical parameters of the RO projection, including pressures, fluxes, and water quality.

3.1.3.1 General Comments

The tool flow is designed as shown in Figure 3.3.

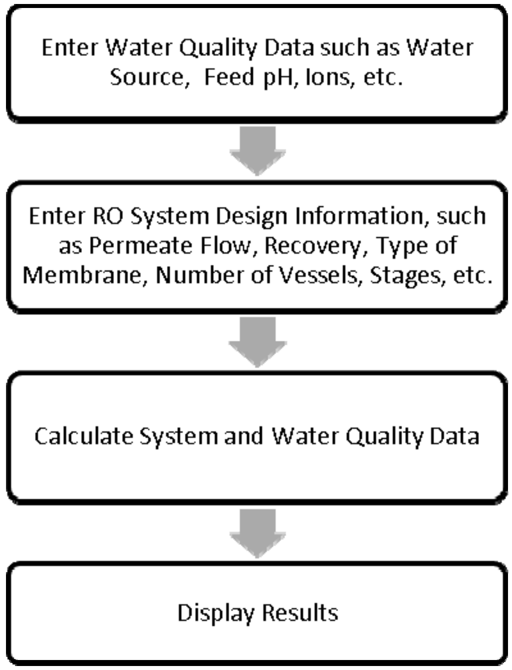


Figure 3.3. General program (tool) flow.

The data and calculations are organized by type and function onto different "sheets" or tabs on the spreadsheet. Buttons on the sheets provide an alternate means of navigation between sections.

3.1.3.2 Reverse Osmosis System Calculation Methods[2]

The general approach used in the tool is the same as that used by most commercial membrane design programs, including IMSDesign by Hydranautics and ROSA by Dow Water and Process Solutions. Essentially, the user enters a system design and feed water quality, and the program executes detailed calculations.

With a reasonable design, convergence is usually quite rapid. The tool makes one simplification over most commercial programs that greatly increases the calculation rates: each vessel is converted to the form of one element, which directly returns the performance for each stage in the system. With this simplification, the output file does not calculate information (e.g., flux, recovery) by element. Rather, the tool calculates salt flux on an ion-by-ion basis during each pass through the system and balances carbonates in the concentrate and permeate analyses while accounting for the free passage of carbon dioxide (CO_2) through the membranes.

---

[2] The calculation methodology in the tool is similar to that used in the Total Flux and Scalant Program (TFSP) by Tom Wolfe of Perlorica Inc., February 2000.

Water flux, or more properly the flow rate, is calculated according to

$$Q = AValue * A * \left[P_f - \frac{dP}{2} - (\pi_m - \pi_p) \right], \tag{3.4}$$

where Avalue = membrane water permeability coefficient, A = membrane area, P_f = membrane feed pressure, dP = membrane differential pressure (Feed – Brine), π_m = osmotic pressure, membrane, and π_p = osmotic pressure, permeate.

The concentration of each ion in the permeate is calculated as follows. A variable, MembDiffCalc, is first defined for each ion. MembDiffCalc is the effective difference in concentration of the ion from the membrane surface to the permeate,

$$MembDiffCalc = C_{avg} * CP - C_p, \tag{3.5}$$

where C_{avg} = average concentration of the ion, CP = concentration polarization, and C_p = permeate concentration of ion,

$$C_p = MembDiffCalc * \left[\frac{BValue * BCorrectionByIon}{Pnet * AValue + BValue} \right], \tag{3.6}$$

where Bvalue = membrane salt (ion) permeability coefficient, BcorrectionByIon = correction factor for the ion, and Pnet = net driving pressure.

Pnet is the feed pressure less one-half the differential pressure less the osmotic pressure difference between the average feed stream and the permeate. "BcorrectionByIon" is an ion-specific constant stored in the spreadsheet. This is the ratio of salt flux for the ion in question to either chloride or sodium.

Because the permeate concentration has some effect on the water flux and required pressure, an iterative approach is necessary to solve the system. The general steps are as follows:

1. Acquire a valid feed water analysis and target feed pH from the user-supplied data. Enter these values into the internal variables.
2. Acquire flow and recovery information from the graphic screen.
3. Acquire from the user the suggested array, stage, and vessel layout and save in the internal variables. Typically, a system with higher recovery needs more stages. For example, a 75% recovery system might specify six elements per vessel, two stages total in the array, and an array layout of 16:8—that is, 16 first-stage vessels feeding 8 vessels in Stage 2.
4. Acquire from the user the selected membrane element information. When the user selects the type of element, the program loads the specific data about the element, such as A value, B value, B value relative to sodium (Na) or chloride (Cl) for each ion (dependent on membrane type), area in square meters (m^2), and differential pressure coefficients.

5. Set up the selected membrane element in the vessel and calculate delta pressure and concentration polarization coefficients (called the "BetaCoef" in the code) for the selected elements:

$$CP = EXP\ (BetaCoef * REC), \tag{3.7}$$

where BetaCoef = concentration polarization coefficient and REC = recovery.

6. At this point, calculations are ready to begin. The first step is to guess the applied pressure needed to produce the water flow rate required. To do this, the total membrane area in the system and the feed osmotic pressure are calculated. Based on nominal recovery and nominal rejection for the element, a concentrate concentration is estimated by mass balance. The concentrate osmotic pressure is then calculated. Next, a differential pressure is calculated for the first and last elements in the system and the average is used to guess a differential pressure for the system. The "guess" pressure needed is then calculated:

$$Guess = \frac{Q}{AValue * A} + Total\ dP + \frac{\pi_f + \pi_p}{2}, \tag{3.8}$$

where A = total membrane area in the system, TotaldP = total differential pressure, π_f = feed osmotic pressure, and π_p = permeate osmotic pressure.

7. Guess the net pressure, which includes osmotic pressure and differential pressure losses, so that the applied pressure is increased by the average of the feed and concentrate osmotic pressures and the differential pressure. Osmotic pressure is calculated and summed for each ion in the analysis. TOC contributions (if any) are ignored in the osmotic pressure estimation because the contribution is highly dependent on the type of organic carbon present:

$$\pi = RT * \sum_{all\ ions} \alpha_i [c]_i, \tag{3.9}$$

where R = universal gas constant, T = temperature, α_i = activity coefficient, and c_i = concentration ($[c_i]$ = molar concentration).

8. The calculations are arranged in a do-while loop that starts with an assumed applied pressure. From this pressure, flow rates and concentrations are calculated on a vessel-by-vessel basis through the system. The total calculated flow is then compared to the user-provided target permeate flow. If the result is low, then the pressure is raised proportionally; if high, then the pressure is lowered proportionally. Once the calculated flow is within 0.05% of the target flow, the calculation program terminates and data are returned to the spreadsheet for display to the user.
9. If convergence cannot be obtained, the user is alerted. Failure to converge usually occurs when too few or too many vessels are specified for the flow rates that are required. The applied pressure required to produce the needed flow cannot be reconciled with the differential pressures necessary to pass the flow through the system in such a case.

3.1.3.3 Differential Pressure

The TFSP equation for differential pressure was based on feed brine flow but does not account for membrane feed spacer thickness differences. The TFSP equation is

$$dP = dPCoef * \left[\frac{(Q_f + Q_c)}{2} \right]^{1.5} . \tag{3.10}$$

For higher accuracy, the tool uses Equation 3.10, but varies the differential pressure coefficient depending on the feed spacer thickness.

3.1.3.4 Carbonate Equilibrium and pH

The calculation of the appropriate carbonate and pH distribution is an important part of this program. Note that membrane systems readily pass CO_2, whereas bicarbonate (HCO_3^-) and carbonate (CO_3^{-2}) ions are quite well rejected. Thus, the permeate side of the membrane is enriched with CO_2, whereas the feed/concentrate side of the membrane is enriched with CO_3^{-2} and HCO_3^-. The net effect of this separation is to lower the pH of the permeate while raising the concentrate pH. The tool effectively models this behavior.

The steps necessary to calculate the CO_3 equilibrium are as follows:

1. The solution ionic strength is calculated, defined as:

$$IS = 0.5 * \sum_{all\ ions} [c_i] * z_i , \tag{3.11}$$

   where z_i = ionic charge, and pK1 and pK2 are corrected for the solution temperature.

2. Ionic strength corrections are then applied to pK1 and pK2. The methods are described in Stumm and Morgan (1996).

3. pK1 and pK2 are converted back to K1 and K2 values.

4. The hydronium ion [H+] concentration is calculated from solution pH.

5. The mole fraction (fraction of the total inorganic carbon) for HCO_3^- is calculated from K1, K2, and the pH. If the HCO_3- concentration was specified, then the total carbon is calculated from the mole fraction of HCO_3^-. If total carbon was specified, then the HCO_3^- concentration is calculated using the mole fraction of HCO_3:$^-$

$$MHCO_3 = \left(\frac{(H^+)}{K1} + 1 + \frac{K2}{H^+} \right)^{-1} , \tag{3.12}$$

$$TC = \frac{[HCO_3]}{MHCO_3} , \tag{3.13}$$

where $MHCO_3^{--}$= mole fraction of HCO_3^- and TC = total carbon.

6. Knowing the total carbon, the CO_2 and CO_3^{-2} values are then calculated from the pH and from K1 and K2, as shown in Equations 3.14 and 3.15. The values are in moles per liter:

$$[CO_3] = TC * \left(\frac{(H^+)^2}{K1 * K2} + 1 + \frac{H^+}{K2} \right)^{-1} \tag{3.14}$$

$$[CO_2] = TC * \left(\frac{(K1)^2}{H^+} + 1 + \frac{K1 * K2}{(H^+)^2} \right)^{-1} \tag{3.15}$$

7. Once the carbonate equilibrium is determined, the pH for the permeate and concentrate streams is then calculated using

$$pH = \log\left[0.82 * \frac{HCO_3}{CO_2} \right] + 6.3 \tag{3.16}$$

3.1.4 ERD Calculation Sequences

If the application includes an ERD, additional calculations are necessary, depending on the device selected.

3.1.4.1 Turbocharger

A turbocharger is an integral turbine-driven centrifugal pump that transfers hydraulic energy from the RO concentrate to the RO feed stream. The energy transfer results in a feed pressure increase. Figure 3.4 presents a PFD of a single-stage RO unit with a turbocharger boosting the feed. Note that the high-pressure RO feed pump effluent passes through the turbocharger, resulting in a pressure boost. The turbocharger has no effect on the amount of flow that passes through the high-pressure feed pump; however, the pressure required from the high-pressure RO feed pump is lowered by the boost pressure of the turbocharger.

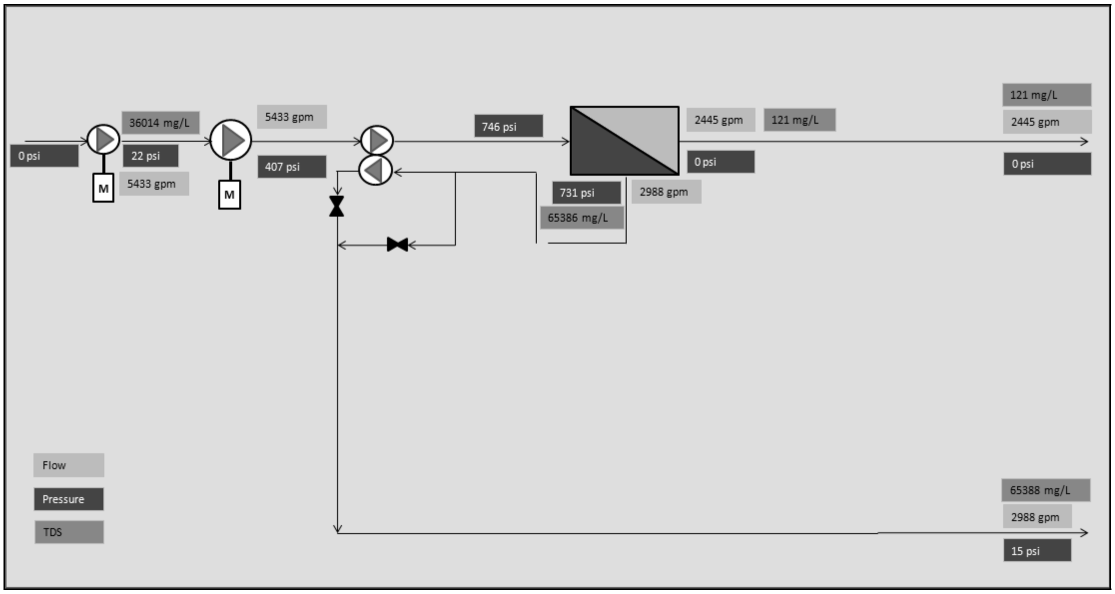


Figure 3.4. Single-stage RO system with hydraulic turbocharger.

The turbocharger boost pressure can be calculated using the equation

$$\text{Boost Pressure} = \text{nte} \cdot \text{Rr} \cdot (\text{Pbr} - \text{Pe}), \tag{3.17}$$

where nte = net transfer efficiency of the turbocharger, Rr = ratio of the RO concentrate flow to the RO feed flow, Pbr = brine pressure at the turbocharger inlet, and Pe = brine pressure at the turbocharger exit.

Through the transfer of energy from the concentrate to the feed, the pressure that must be developed by the HPP is decreased and the pump power requirement is likewise decreased. The amount of power or energy saved through energy recovery by the turbocharger can be calculated as follows:

$$\text{Energy Savings} = \text{Boost Pressure} \cdot \text{Boostflow} \cdot c, \tag{3.18}$$

where c = conversion factor, equal to 0.000436 if the units of flow and pressure are gpm, and Boostflow = flow rate boosted by the turbocharger.

In addition to boosting the feed pressure to an RO system, as shown in Figure 3.4, a turbocharger can also be used to provide an interstage boost in a multistage BWRO system array, as shown in Figure 3.5.

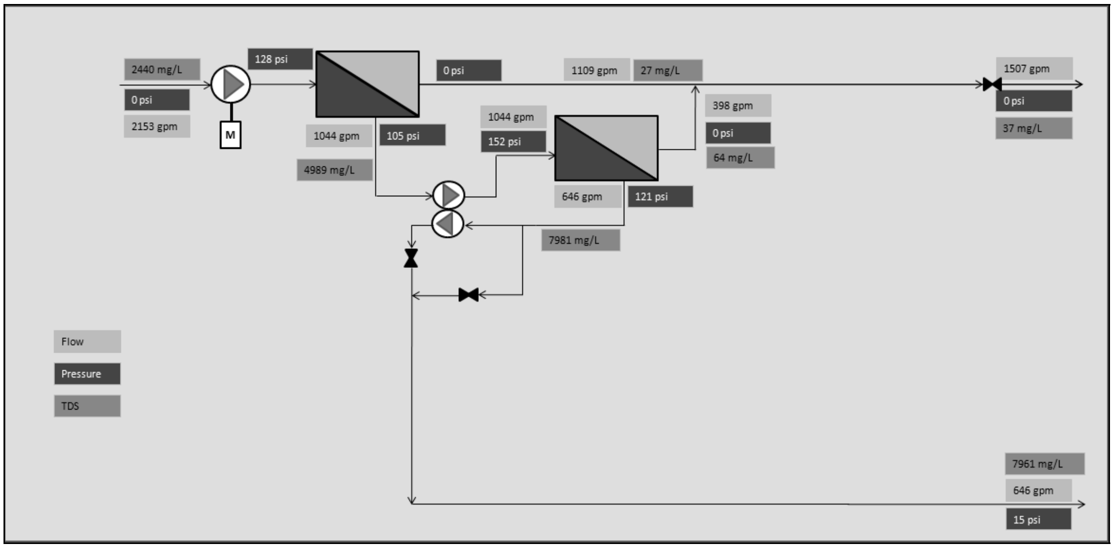


Figure 3.5. Two-stage RO system with turbocharger boosting pressure to second stage.

The transfer efficiency of the turbocharger is a function of the device itself, the feed flow rate boosted, and what is termed the reject ratio. The flow dependence is rather small as long as it is within the design criteria of the device, and it is specific to the turbocharger design. Per Figure 3.6, however, the impact that the reject ratio has on the efficiency is substantial. The efficiencies are highest when the reject ratio is between 60% and 75% and fall off sharply at values below 50%. The reject ratio is the high-pressure concentrate flow into the turbocharger divided by the low-pressure flow that is boosted by the device.

Analysis of the two-stage turbocharger system depicted in Figure 3.5 demonstrates why multistage RO systems typically boost the interstage feed and not the feed to the entire system. In the example shown in Figure 3.5, the reject ratio for the interstage boost is equal to 260 gpm divided by 521 gpm, or 50%. If the feed to the RO was boosted, the reject ratio would be 260 gpm divided by 1,302 gpm, or 20%, resulting in a drastically lower turbocharger transfer efficiency.

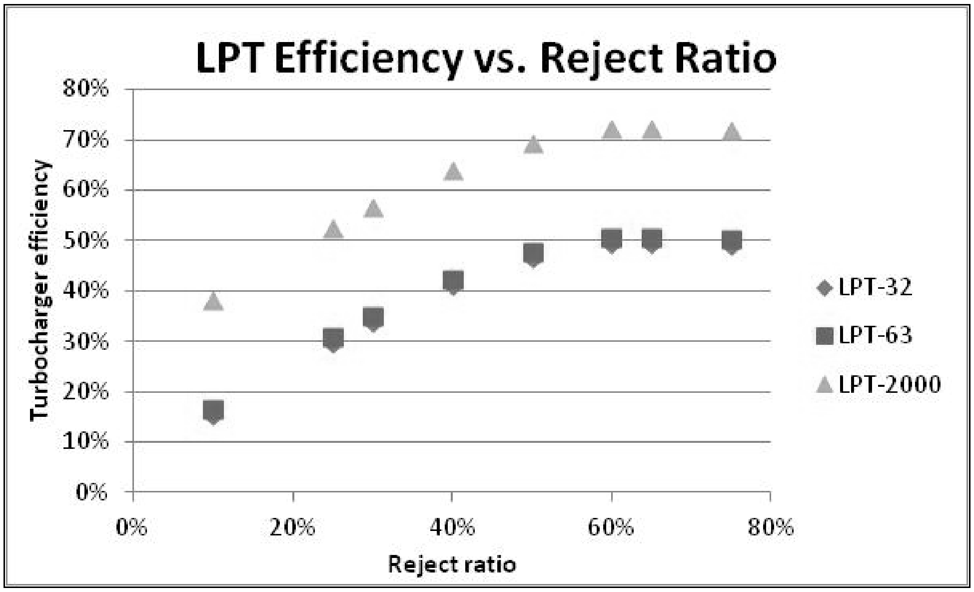


Figure 3.6. Turbocharger dependence on reject ratio.

The efficiency dependence on reject ratio is defined as follows:

if 60% < RR < 70%, if RR < 60%, $nte(RR) = nte(Device) - abs(RR - 0.6)^{1.55}$;

if RR >70%, $nte(RR) = nte(Device) - abs\ (RR - 0.7)^2$,

where RR = reject ratio = concentrate flow divided by boosted flow, and nte = device-rated net transfer efficiency.

3.1.4.2 Isobaric ERD

Isobaric ERDs can be grouped into pressure exchangers and work exchangers, but the principles are similar. The high-pressure RO brine is passed to the ERD, where the pressure energy is transferred to a portion of the feed. This feed stream is then directed to a small booster pump that is sized to boost the pressure back to that required for the membrane feed. As a result, the flow requirement on the high-pressure RO feed pump is dramatically reduced. With the isobaric ERDs, the high-pressure RO feed pump capacity is similar to that of the RO permeate flow, not the full feed flow, as in all other applications.

A single-stage RO system equipped with an isobaric ERD is illustrated in Figure 3.7.

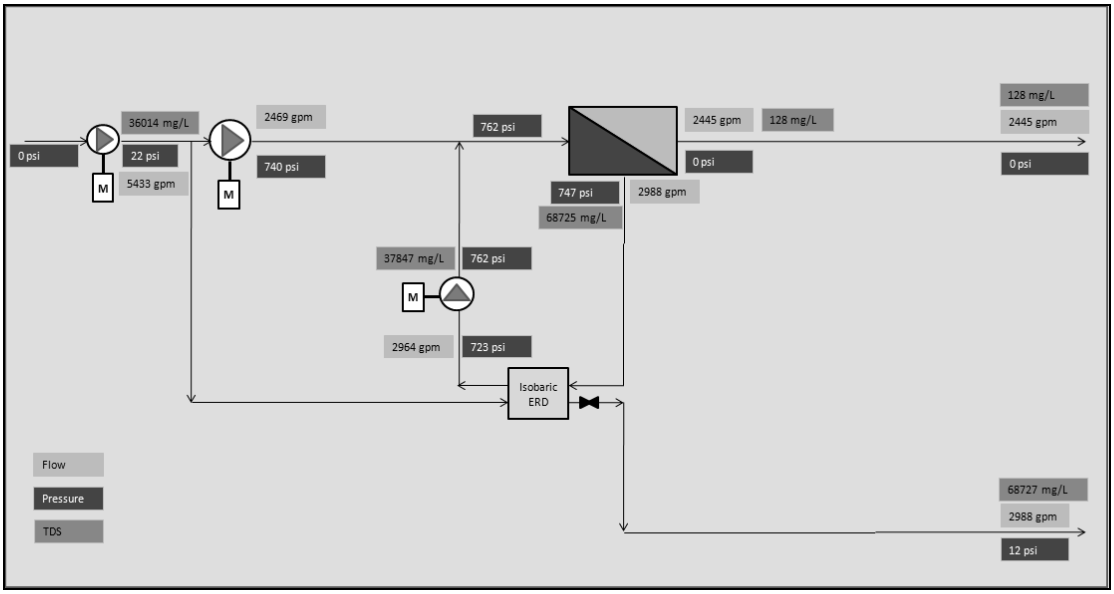


Figure 3.7. Single-stage RO system with isobaric ERD.

Because of the nature of the operation of the isobaric ERDs, a small amount of flow is transferred from the RO brine side of the device to the seawater stream. This flow is called lubrication flow or leakage and results in a small loss of efficiency. The amount of lubrication flow is a function of numerous variables, including pressure, temperature, and system flow, and can be estimated by the equation

$$\text{Lubrication Flow} = \%\text{Leakage} \cdot (\text{HPP Flow}), \tag{3.19}$$

where HPP Flow = flow rate of the high-pressure RO feed pump and %Leakage = 1%.

Isobaric ERD operation adds to the salinity of the membrane feed water though the previously defined leakage. This salinity increase or "mixing" varies with the membrane recovery rate as follows:

$$\text{Salinity Increase} = \text{REC} \cdot \text{MIX} \cdot 1.04, \tag{3.20}$$

where REC = RO recovery, equivalent to the RO permeate flow divided by the RO feed flow, and MIX = volumetric mixing constant for the ERD.

The net result of the lubrication flow and the salinity increase is a decrease in the amount of energy that the isobaric device can recover. Lubrication represents a decrease in the amount of flow that the ERD passes to the membrane feed, and the salinity increase associated with the isobaric ERD results in an increase in the required net driving pressure of the membrane operation.

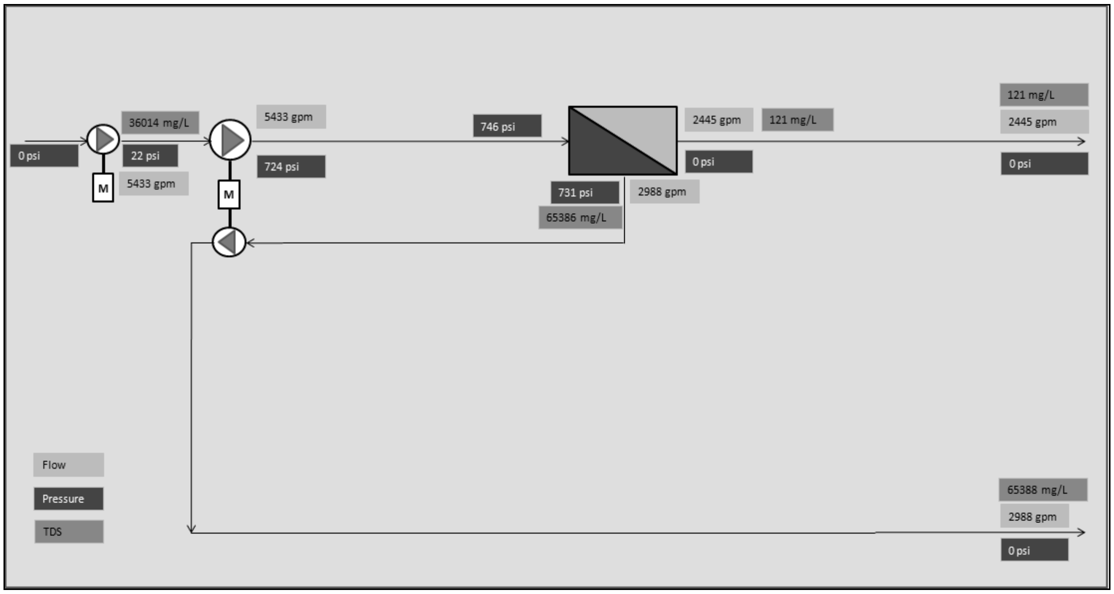


Figure 3.8. RO system with Pelton Wheel.

Per Figure 3.7, an RO system with an isobaric ERD will require a booster pump. Therefore, the energy use of such a system will involve the energy requirements of the high-pressure RO feed pump and the booster pump. Each can be calculated as shown in the following equations. Note that the power equations in this section are normalized to the permeate flow of the system and are expressed in kWh/1,000 gal permeate. To calculate straight kW, the total is multiplied by 1,000/24:

$$\text{HPP kWh/1,000 gal permeate} = c \cdot [(1 + \%\text{Leakage}) \cdot \text{HPP P}) / \text{HPP eff} / \text{HPP motor eff}], \quad (3.21)$$

where *c* =conversion factor, equal to 0.007248 if pressure units are in psi; HPP P = pressure increase of the high-pressure RO feed pump; HPP eff = high-pressure RO feed pump efficiency; and HPP motor eff = high-pressure RO feed pump efficiency.

$$\text{Booster kWh/1,000 gal permeate} = c \cdot [(1 - \%\text{Leakage}) \cdot (1 - \text{REC}) / \text{REC} \cdot (\text{HPP dP} + \text{Mem d}P + \text{Pipe dP}) / \text{Booster Pumpeff} / \text{Booster motor eff}] \quad (3.22)$$

where *c* = conversion factor, equal to 0.007248 if pressure units are in psi; REC = RO recovery, equivalent to the RO permeate flow divided by the RO feed flow; HPP dP = pressure increase of the high-pressure RO feed pump; Mem dP = membrane pressure drop (feed – brine); Pipe dP = ERD piping pressure drop; HPP eff = high-pressure RO feed pump efficiency; and HPP motor eff = high-pressure RO feed pump efficiency.

3.1.4.3 Pelton Wheel or Impulse Turbine

The Pelton Wheel converts pressure energy in the RO concentrate into kinetic energy of a rotating wheel. This rotating power output is used to assist the main rotor in driving the RO HPP. Pelton Wheels are usually directly coupled to the pump/motor arrangement, as shown in Figure 3.8.

Energy consumption for the high-pressure RO feed pump/Pelton Wheel combination is calculated using the following equations:

$$\text{HPP kWh/1,000 gal permeate} = c \cdot \text{HPP dP/REC/HPP eff/HPP motor eff,} \qquad \text{(Eq. 3.23).}$$

where c = conversion factor, equal to 0.007248 if pressure units are in psi; HPP dP = pressure increase of the high-pressure RO feed pump REC = RO recovery, equivalent to the RO permeate flow divided by the RO feed flow; HPP eff = high-pressure RO feed pump efficiency; and HPP motor eff = high-pressure RO feed pump efficiency.

$$\text{PWER kWh/1,000 gal permeate} = c \cdot (\text{Pbr} - \text{Pe}) \cdot (1\text{-REC}) / \text{REC} \cdot \text{nte,} \qquad \text{(Eq. 3.24).}$$

where PWER kW = energy recovered by the Pelton Wheel; c = conversion factor; Pbr = brine pressure at Pelton Wheel; inletPe = brine pressure at Pelton Wheel; exitREC = RO recovery, equivalent to the RO permeate flow divided by the RO feed flow; and nte = net transfer efficiency of the Pelton Wheel.

3.1.5 Projection Model Validation

The tool developed by CH2M HILL is essentially an RO projection software program incorporating ERDs. The tool allows the user to select RO membranes from different RO manufacturers and ERDs from various ERD manufacturers and provides both an energy analysis and a rough capital cost estimate of the RO system. To CH2M HILL's knowledge, no other tool offers this information.

Validation of the model consists of

1. Executing a set of RO projections on software provided by RO manufacturers to determine that the RO membrane performance is accurately portrayed by the tool.
2. Running a set of analyses from the ERD manufacturer software to establish the accuracy of the ERD effect on energy cost.
3. Refining the capital cost estimates. The cost results were discussed with the individual ERD vendors to confirm accuracy.

3.2 Cost Modeling

The decision to use an ERD for a particular RO application is typically based on economics: Will the initial capital cost associated with the installation of the ERD equipment be captured by the savings in operational energy in a reasonable period of time? If the answer is yes, then the question becomes: Which ERD will achieve the lowest cost of water produced for the application?

The tool is designed to answer these questions. An Association for the Advancement of Cost Engineering (AACE) Class IV Capital Cost estimate is generated for the RO mechanical equipment and additional ERD equipment required. The tool also calculates a net present value (NPV) estimate of the operational ERD savings over the life of the RO mechanical equipment. The average annual operational savings, the total net present cost of the ERD, and the payback period are then presented to the user.

3.2.1 Cost Model Structure

The costs are based on the AACE standards. Class IV (+50%/-30%) estimates are generally prepared based on limited information. They have a fairly wide accuracy range and are used for project screening, determination of feasibility, concept evaluation, and preliminary budget approval. They represent pricing for designs that are between 1% and 15% complete. At the time of the estimate, designs typically comprise a minimum of the following: plant capacity, block schematics, indicated layout, PFDs for main process systems, and preliminary engineered process and utility equipment lists.

The cost estimates in the model are in 2011 dollars. To keep the tool valid for the future, the user can select the construction start date and an inflation rate. This is used to escalate the construction and O&M costs to the appropriate year.

3.2.2 Reverse Osmosis Configurations

The tool executes a model of the following four major RO configurations:

1. RO equipped with a turbocharger-type ERD
2. RO equipped with an isobaric-type ERD
3. RO equipped with a Pelton Wheel-type ERD
4. RO with no ERD

There are many subconfigurations: the use of a VFD on the feed pump, the use of an interstage booster pump, the possibility of having permeate backpressure on one or more stages of the RO system, etc. Each of these can be used with one of the four major RO configurations. All four configurations are possible for high-salinity SWRO applications within the tool. Configurations 1, 2, and 4 are options for lower-pressure brackish systems. It is not economically feasible to add a Pelton Wheel to a low-pressure RO system.

3.2.3 Capital Cost Model

3.2.3.1 Direct Costs

Direct cost inputs to the cost portion of the model include the RO mechanical equipment and the ERD-related equipment. Direct costs thus include the RO high-pressure feed pump and VFD or discharge throttling valve, RO pressure vessels and support rack assembly, RO membranes, interconnecting piping, valves, and instrumentation. The ERD-related equipment includes not only the ERD itself, but any interconnecting piping, valves, and instrumentation required for its operation and control.

Ancillary equipment required for the RO system that is not related to the ERD is not included in this cost model. The goal of the tool is not to calculate the overall cost of making water, but rather to determine if an ERD makes economic sense and, if so, which ERD makes the most economic sense. This is performed by determining the capital cost and energy cost differences between systems with and without an ERD.

The membrane element costs and ERD-related costs were generated using a combination of ERD vendor quotations and previous quotations that CH2M HILL has accumulated for ERD-related equipment. These costs conform to AACE Class II (+20%/-15%) standards, whereas all other costs represent Class IV estimates. The RO mechanical equipment cost consists of the piping, valves, and pumps included in the specified system. The piping and valve costs are estimated by generating a typical layout for the user-selected scenario and measuring the amount of piping needed. The pump costs are estimated using a dollars per horsepower ($/hp) equation developed by CH2M HILL. Installation costs were included for all direct costs in this model.

The four major RO configurations have differences in equipment and system operation. Those differences in relation to the capital cost model are as follows:

- *Turbocharger.* An RO system using a turbocharger will include the cost of the turbocharger itself, piping to and from the turbocharger, and some valves and instrumentation. In addition, a turbocharger is essentially a pressure-boosting device. Because the turbocharger increases the net driving pressure of the RO system by boosting the pressure of the feed or interstage flow, it reduces the pressure that must be developed by the HPP and thereby reduces its power input. Thus, introduction of a turbocharger into a new system results in a capital cost decrease associated with the lower horsepower (size) of the HPP. The tool includes this cost savings in its analysis of the capital costs related to the turbocharger ERD.
- *Isobaric ERD.* As with the turbocharger, inclusion of an isobaric ERD in the RO system will result in additional costs for the ERD, piping valves, instrumentation, etc. However, with an isobaric ERD, the net effect on the HPP is a substantial decrease in flow, not pressure. Regardless, the size of the high-pressure feed pump and motor are reduced, and again, there is an associated cost savings or offset for a new system. Isobaric ERDs require an additional booster pump in the system to add a small amount of pressure to the ERD effluent stream in order to reintroduce this water to the membrane feed.
- *Pelton Wheel.* The Pelton Wheel is directly connected to the pump motor. Interconnecting piping and a very small amount of additional equipment is required. The Pelton Wheel, like the turbocharger and the isobaric ERDs, provides a reduction in the high-pressure feed pump costs. With the Pelton Wheel ERD, this cost savings is offset by the requirement for a smaller HPP motor.

3.2.3.2 Indirect Costs

The user has the ability to add indirect costs to the cost model. The "Cost Summary" page has user-input boxes for a mechanical allowance, electrical allowance, profit, engineering, and contingencies. These indirect costs are applied to the final process mechanical installed cost to generate a total capital cost.

3.2.4 Operating Cost Models

Operating cost inputs in the model include power consumption of the RO system and membrane replacement cost. Each of these is an ongoing cost over the expected life of the equipment. In order for the tool to compare these ongoing costs to the initial capital cost of the ERD-related equipment and generate a payback period, the operating costs are calculated by a present-worth factor. The present worth normalizes annual operating costs over a fixed time period to a present worth amount.

3.2.4.1 Energy Consumption

The tool uses complex algorithms to determine the net driving pressure required for the RO system based on feed water salinity, water temperature, recovery, membrane, etc. The net driving pressure will depend on the configuration of the system and may include inputs from the high-pressure RO feed pump, interstage booster pump (if applicable), ERD booster pump, etc. The user can use the tool to determine the differences in energy consumption and capital investment between a RO system designed with and without an ERD.

A NPV calculation is used to find the total investment needed in today's dollars to pay the future power costs for the duration of the plant. This calculation utilizes user inputs for inflation rate, discount rate, and plant duration, as well as the calculated annual power cost. A sample NPV calculation is as follows:

$$NPV\ (\$)\ \sum_{\mathrm{n=1}}^{\mathrm{Duration}} \frac{\text{Annual Power Cost}*(1+\text{Inflation Rate})^{\mathrm{n}}}{(1+\text{Discount Rate})^{\mathrm{n}}} \qquad \text{(Eq. 3.25).}$$

The NPV power cost is then compared with the NPV power cost that would be required if there were no ERD. This provides the total life-cycle cost savings associated with implementing the ERD. Let us hypothetically state that the addition of an isobaric ERD on a 5-mgd (permeate) SWRO train will provide a life-cycle cost savings of \$5,000,000 and will require an initial capital investment of \$915,000. The tool would determine the payback period as follows:

$$Payback\ period\ (years) = \frac{ERD\ Capital\ Cost\ (\$)}{(\text{NPV(ERD)}-\text{NPV(No ERD)})/\text{Duration}} \qquad \text{(Eq. 3.26).}$$

If the life-cycle cost savings is assumed to be consistent throughout the duration of the plant, the annual savings can be calculated by dividing \$1,500,000 by the estimated duration of the plant. If the duration is 20 years, this will provide an average annual savings of \$250,000. The payback period will be \$915,000 divided by \$250,000, or 3.66 years.

3.2.4.2 Membrane Replacement

RO membranes are periodically replaced in an RO system. The replacement rate is usually determined by an increase in required net driving pressure (membrane fouling), a degradation in water quality, or a combination of these. Typical membrane replacement intervals vary from 3 to 10 years.

Because RO membrane replacement is done periodically, unlike power use, this is not a relatively continuous cost. Thus, the calculation for the NPV cost of the membrane replacement over the life of the RO equipment differs from that of the power cost. The calculation first determines the number of membrane replacements over the life of the RO equipment, and then calculates the NPV cost of each membrane replacement individually. These individual costs are then summed to determine the NPV cost of the membrane replacement over the life of the equipment:

$$PWMRi = \frac{C_{mem} * (1+I)^{mri}}{(1+D)^{mri}} + \frac{C_{mem} * (1+I)^{mri \times 2}}{(1+D)^{mri \times 2}} + \cdots + \frac{C_{mem} * (1+I)^{mri \times n}}{(1+I)^{mri \times n}} \quad \text{(Eq. 3.27)}$$

where PWMRi = present worth of the membrane replacements over the equipment life, C_{mem} = actual membrane replacement cost expended, I = inflation rate, D = discount rate, mri = membrane replacement interval, n = total number of membrane replacements over the equipment life, and Y = number of years remaining in the last membrane replacement when equipment life is reached.

Note that the membrane cost, and thus membrane replacement cost, does not affect the addition of an ERD to the system. The costs of membrane replacements are calculated and presented in the tool, but they do not change the ERD payback period.

3.2.4.3 Operating Cost Accuracy

The two components of the operating cost are the power cost and the membrane replacement cost, with power cost being the overwhelming contributor. With the tool, power cost is calculated from the RO system's net driving pressure, ERD efficiency, and user inputs for pump efficiency and unit energy cost. Membrane replacement cost is calculated using user inputs for membrane replacement frequency and the future membrane replacement cost.

Appendix A presents two validation examples where membrane feed pressure as calculated using the tool is compared with those calculated using membrane projection software programs from DOW, Toray, and Hydranautics. Membrane feed pressure, which is directly related to net driving pressure, is the primary determinant of the power cost of an RO system. The comparison shows that, on the average, the tool calculates the membrane feed pressure within 7.5% of pressures calculated by the manufacturers' programs.

The tool calculates the energy efficiency of each ERD using algorithms supplied directly from the ERD manufacturers, as shown in Section 3.1. Based on information supplied by these manufacturers, it is assumed that these calculations are within 5% of the actual ERD efficiency.

If the user has accurate power cost information and pump efficiency information, the accuracy of the power cost relies on the feed pressure calculation and the ERD efficiency calculation. This introduces a maximum error of 12.875% into the power cost calculation. However, the tool has the flexibility to bypass the feed pressure calculation and instead let the user input pressure information directly from a projection software program. This reduces the operating cost error from 12.875% to 5%, as the uncertainty associated with the feed pressure calculation is eliminated.

The membrane replacement cost accuracy is based on user inputs and is assumed to be within 5% accuracy, based on the user having access to membrane replacement cost information from one or more manufacturers. Because the membrane replacement cost contributes little to the total operating cost, a lower cost accuracy for this input will have only a minor impact on the total accuracy of the operating cost.

For each scenario evaluated in the tool, the operating cost accuracy is calculated. The tool then combines this with the capital cost accuracy to generate a total present worth cost accuracy.

3.3 Model Tutorial

The tool was created to accommodate a wide variety of SWRO and BWRO system designs. To be able to take advantage of all the tool capabilities, it is important that the user understands how to navigate the graphical user interface. This section provides the user with a walk-through of all the functionalities of the tool.

The tool is protected and will prompt the user to enter a password upon opening. The password is “WRF” (case-sensitive). Each of the sheets within the tool is also protected with the same password.

3.3.1 Graphical User Interface Overview

When the model is opened, a disclaimer window appears that provides the user with general information about the tool. An “About” page is always active in the worksheet that contains more information on the tool, including whom to contact with questions and version information. Navigation through the tool occurs through the “Summary” worksheet, as there is always an option to return to the “Summary” worksheet. Because all other worksheets are hidden, buttons are required to switch from sheet to sheet. Section 3.3.2 summarizes each of the additional worksheets in the model.

The “Summary” worksheet consists of a combination of input cells, output cells, buttons, radio boxes, and check boxes. Any cell with a white background is a user input and must be populated. Any cell with a grey background is a calculated value and cannot be changed.

Buttons are provided on the “Summary” worksheet not only to navigate through the model, but also to provide basic help information. The “User Help” button at the top of the worksheet provides an overview of how to use the tool, whereas the many “Help” buttons on the worksheet describe in more detail how to properly enter the design information. The “English” and “Metric” radio buttons at the top of the “Summary” worksheet enable the user to toggle between these units.

Figure 3.9 provides a screen shot of the tool’s “Summary” worksheet.

3.3.2 Model Inputs

This section details how to input the information needed for a complete RO system design. The “Summary” worksheet is split into eight different input boxes. Once the user populates each box with the required information, system projections can be calculated and the PFD can be viewed.

3.3.2.1 Flow Information

Box 1 on the “Summary” worksheet requires user input of permeate flow and recovery. When this information has been entered, the feed flow and flux are calculated. The flux is calculated using the equation

$$Flux\ (gfd) = \frac{Permeate\ Flow\ (gpd)}{Total\ Membrane\ Area\ (sf)} \tag{Eq. 3.28}$$

Because flux is a function of permeate flow and total membrane area, the flux will change as the “System Design” and “Membrane Selection” boxes are populated. The typical flux for the water quality selected in the “Water Quality” box is also shown in the “Flow Information” box. Box 1 also allows the user to include bypass flow blended with the permeate flow. Selecting this box requires the user to input the desired permeate TDS, and the program calculates the amount of bypass flow that does not go through the HPP and membrane. Including bypass flow will change the flux of the system because of the decreased feed flow, so an iterative approach may be needed to find the best system design that includes bypass flow.

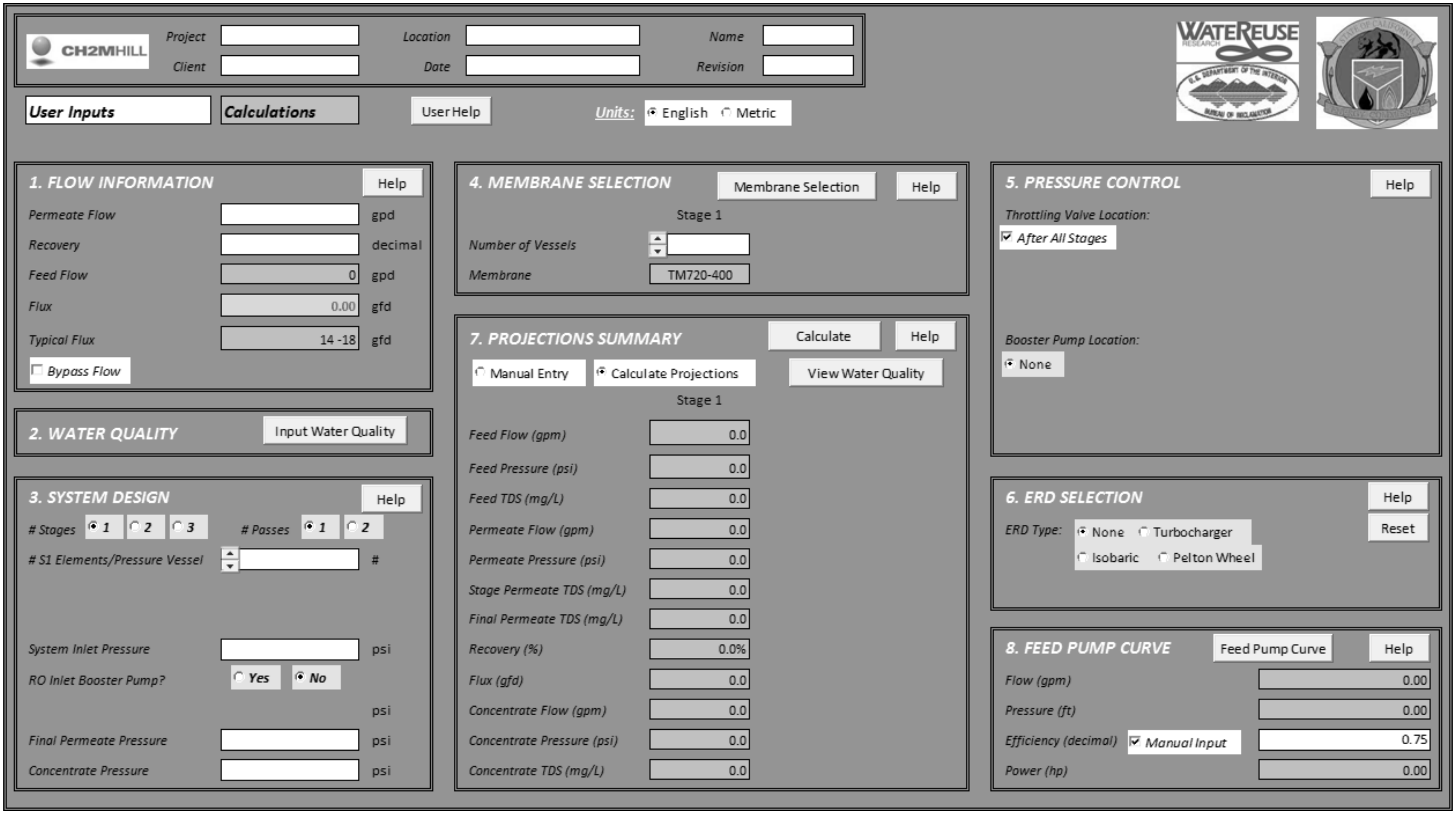


Figure 3.9. "Summary" worksheet.

Table 3.1. Valid Flux Ranges

Water Type	Valid Flux Range (gfd)
RO permeate	18–24
Brackish water from well	14–18
MF/UF pretreated brackish well water	14–18
Conventional pretreated brackish well water	10–14
Seawater from well	8–12
UF/MF pretreated seawater	8–12
Conventionally pretreated seawater	7–10
UF/MF pretreated tertiary waste water	9–14
Conventionally pretreated tertiary wastewater	7–10

3.3.2.2 Water Quality

The user is directed to the Water Quality Worksheet by clicking on the “Input Water Quality” button in the “Water Quality” box. At the top of this worksheet, the user is required to select the source or type of feed water and then enter the feed water temperature and pH. The water type is used to suggest the valid flux range, shown in the “Flow Information” box on the “Summary” worksheet. Valid flux ranges are shown in Table 3.1.

Via radio buttons, the user can then choose to enter only the feed water TDS and have the program use sodium and chloride ions only, or to specify individual ions and enter the concentrations of specific ions. The osmotic pressure, ionic strength, TDS, and ion balance of the feed water are shown at the bottom of the page.

Once a projection has been run, columns E through N will be populated with the appropriate ion concentrations. The “Adjusted RO Feed” column will be different than the “RO Feed” column only for systems that include an isobaric ERD. The difference reflects leakage of high-pressure concentrate into the low-pressure feed through the lubrication function of the ERD. The device salinity leakage is shown on the “Isobaric ERD Selection” page. The “RO Permeate” and “RO Concentrate” columns show the ion concentrations for the overall permeate and concentrate flow streams, respectively, whereas the “Blended RO Permeate” column shows the overall permeate concentrations including any bypass flow. The remaining columns give the permeate and concentrate ion concentrations for each stage in the system. The pH, ion balance, TDS, osmotic pressure, and activity coefficient for each flow stream are shown at the bottom of the page for each of the flow streams.

3.3.2.3 System Design

Box 3 on the “Summary” worksheet contains the “System Design” information. This box has inputs for the user to choose the number of stages and passes in the design and the number of elements per vessel for each of the stages. The tool can accommodate three stages for BWRO systems but only two stages for SWRO systems. The user can choose between one and eight elements per vessel for each stage in the design.

If the user chooses a two-pass system, the program asks the user to enter the desired permeate concentrations for chloride, bromide, and boron. From CH2M HILL's experience, two-pass RO is needed primarily to reduce the concentrations of one or more of these three ions. The tool then estimates the second pass power that would be required for the system based on the feed and desired ion concentrations. CH2M HILL used available membrane projections software to generate a relationship between the desired percent removal of the ions and the second-pass energy consumption. As this additional second-pass RO power requirement does not affect the viability of ERDs, it is not included in the system's overall power consumption.

The "System Design" box also allows the user to enter the system feed, permeate, and concentrate pressures. The "System Inlet Pressure" cell refers to the pressure of the flow stream coming into the RO system. If this pressure needs to be increased prior to the HPP, either for pump suction pressure requirements or to meet the incoming pressure demand of an isobaric ERD, the user can choose to include an RO inlet booster pump and specify the boost pressure. The power required by this pump will then be included in the system power summary.

The "Final Permeate Pressure" cell allows the user to enter the required permeate pressure, excluding permeate backpressure. If the system requires residual permeate pressure, the user should also consider adding a throttling valve "After All Stages" in the "Pressure Control" box. The "Concentrate Pressure" input cell is the pressure of the concentrate flow stream after passing through the ERD or throttling valve. This input is restricted based on the type of ERD that is selected. For example, the Pelton Wheel ERD requires a concentrate pressure of 0 psi, whereas the turbocharger and isobaric devices both require a device-specific minimum concentrate pressure.

The isobaric ERD requires the feed pressure to be at least 10 psi higher than the required minimum concentrate pressure. Thus, if an isobaric ERD is selected, the minimum concentrate pressure will be calculated, and an RO inlet booster pump will be added if needed to increase the feed pressure as required by the device.

3.3.2.4 Membrane Selection

The "Membrane Selection" box allows the user to select the number of vessels per stage. Only the stages specified in the "System Design" box will be visible to enter the number of vessels. The user is advised to follow a vessel ratio of 2:1 for two-stage systems or 4:2:1 for three-stage systems. Unbalanced vessel ratios can result in the system failing to perform accurate projection calculations.

Clicking on the "Membrane Selection" button directs the user to the "Membrane Database" page of the tool, where the user can select the manufacturer and the membrane model. Although it is advised to select the same membrane for all stages in a multistage system, different membranes can be selected for each stage. Clicking on the "View Membrane Database" button shows the user all membranes available for selection.

There are input cells for the membrane age and the percentage annual flux decline. These cells are used to account for membrane fouling. A typical annual flux decline is 5% to 10%. If a new membrane is being evaluated, the user should choose a membrane age of 0 years. Each year of membrane age increases the feed pressure required to meet the permeate flow requirements.

Once a membrane is selected, the tool provides an approximate cost. The user can enter a value in the “User-Override Cost” box if the specific membrane cost is known. The “Application” box will show whether the selected membrane should be applied to a BWRO or SWRO system. The model limits BWRO membranes to feed water with less than 10,000 mg/L TDS and SWRO membranes to feed water with greater than 3,000 mg/L TDS. The model will not calculate projection data if the wrong application is selected.

Clicking the “Add My Own Membrane” box allows the user to add a membrane to the membrane database. If this option is chosen, all fields must be filled in before the user can return to the “Summary” worksheet.

After returning to the “Summary” worksheet, the user should verify that the flux shown in the “Flow Information” box is the desired flux. Once the “Membrane Selection” box has been completed, the flux will not change.

3.3.2.5 Pressure Control

The “Pressure Control” box allows the user to specify if there are throttling valves or booster pumps included in the system design. A throttling valve can be located on either the Stage 1 or Stage 2 permeate piping, or on the common permeate piping for all the stages. If Stage 1 or Stage 2 permeate throttling is selected, the user can enter the throttled pressure in the “Pressure Control” box. If a throttling valve after all stages is selected, the user should enter the final permeate pressure in the “System Design” box.

The user can choose to have an interstage booster pump after Stage 1 and/or after Stage 2. If an interstage booster pump is selected, the user can then specify the amount of pressure boost that each pump will provide to the system. The “Power Summary” page gives the user the option to include VFDs on any of the pumps included in the system, including the high-pressure feed pump. For a multistage isobaric system, the tool will automatically include an interstage boost pump before the second stage and will calculate the amount of pressure required so that an isobaric circulation pump is not needed.

3.3.2.6 ERD Selection

The “ERD Selection” box has radio buttons for the user to select both the manufacturer and the type of ERD included in the system. If “Turbocharger” is selected, the user also needs to specify where the turbocharger will be applied. Selection of the type of ERD is the only input required in this box. After projections have been calculated in the “Projections Summary” box, the “ERD Details” button will be visible in the “ERD Selection” box. Clicking this button will direct the user to an ERD-specific worksheet.

On the “Isobaric ERD Selection” page, the device is sized based on the system flow information and the user-entered manufacturer. Relevant system data is shown on the page, including the total boost pressure provided by the ERD. The “User-Override Cost” box can be used if the user has specific cost information. If the manufacturer is changed, projection data needs to be recalculated in order to view accurate data. For a single-stage system, an isobaric circulation pump is automatically included so that the pressurized feed stream can achieve the Stage 1 required feed pressure. For multistage systems, the tool includes an interstage booster pump instead of a circulation pump.

The only Pelton wheel device available on the "Pelton wheel ERD Selection" page of the tool is from Flowserve/Calder. If a Pelton wheel ERD is selected, then a specific Flowserve model will automatically be chosen and an approximate cost for the device will be shown. The "User-Override Cost" box can be used if the user has specific cost information.

The "Turbocharger ERD Selection" page also shows the specific device that was selected, along with the relevant system data. The "User-Override Cost" box can be used if the user has specific cost information. If the manufacturer is changed, projection data needs to be recalculated in order to view accurate data. The pressure boost provided by the ERD is shown in the box on the lower left of the page.

3.3.2.7 Projections Summary

The tool has the capability to calculate the key outputs (e.g., required feed pressure, feed, permeate and concentrate TDS, and individual ion concentrations) from the RO software portion of the model as a typical projection using the calculations shown in Section 3.1. However, the user can also input projection information from a different software program or from an existing system by checking the "Manual Entry" box in the "Projections Summary" box. In this case, the boxes in the "Projections Summary" box and the ion concentrations on the "Water Quality" page are converted from outputs to inputs, and the user can enter the necessary information. The "Power Summary" and "Cost Summary" pages will then use the input information to complete the respective evaluations.

If the user wants to evaluate multistage systems with manually entered information, the correct interstage boost (either from the interstage turbocharger or from the interstage booster pump in an isobaric application) needs to be entered. Otherwise, the user should use the program's internal calculations to estimate the projection information.

3.3.2.8 Feed Pump Information

The final step for input information is the "Feed Pump Information" box. Once the projection data have been calculated, the high-pressure feed pump flow, pressure, and power are calculated. The user can enter a fixed pump efficiency by checking the "Manual Input" box and entering the efficiency. Pump horsepower is calculated in the tool as

$$Power\ (hp) = \frac{Flow\ (gpm) * Pressure\ (ft)}{Efficiency * 3960} \quad \text{(Eq. 3.29)}$$

If the user wants to enter data from a specific pump curve to find the pump efficiency and operating speed, he or she should leave the "Manual Input" box unchecked and should click the "Feed Pump Curve" button. This will direct the user to the "Feed Pump Curve" page, where he or she can input flow, pressure, and efficiency data points. The accuracy of the efficiency estimate will increase as more data points are provided. The pump flow and pressure are shown in the "Current Design Points" box. After the pump curve has been entered, the user can click the "Calculate" button to find the estimated speed, efficiency, and power at the design points shown.

This functionality is included in the tool so that users can evaluate the effect that changes in the feed pump design points have on the feed pump efficiency. Because of the high-pressure requirement of RO systems, a small change in feed pump efficiency can result in significant changes in power consumption. This functionality allows the reduced speed pump efficiency to be included in the power summary, an aspect that is often overlooked in ERD power consumption evaluations. The reduced speed efficiency is calculated using the centrifugal pump affinity laws shown in the equation

$$\frac{N_1}{N_2} = \frac{Q_1}{Q_2} = \sqrt{\frac{H_1}{H_2}} = \sqrt[3]{\frac{P_1}{P_2}} \qquad \text{(Eq. 3.30)}$$

where N = pump speed, Q = pump flow, H = pump pressure, and P = pump power.

3.3.3 Model Outputs

This program performs the system calculations as shown in Section 3.1. The user should be aware that the tool will predict different membrane permeate water quality and net driving pressure requirements than the software programs developed by the membrane manufacturers. The user should refer to the separate software projection programs of the manufacturers to get this information.

The model outputs of this tool include projection information, an overall PFD of the system, a power summary, and a cost summary.

3.3.3.1 Reverse Osmosis Projections Data

If the user clicks the “Calculate” button in the “Projections Summary” box, the tool will calculate projections data using the calculations described in Section 3.1. In some cases, the system will be unable to converge and provide an output. When this happens, a message box will alert the user that the system design must be altered in order to calculate the projections data. If projections are successful, the “Projections Summary” box and the “Water Quality” page will be populated with the projections data. The water quality information can be seen by clicking the “View Water Quality” button.

If the user chooses to manually enter in the projection information, the “Calculate” button must still be clicked before proceeding with model outputs. Clicking the “Calculate” button—either in manual entry or not—will give the user the option to view the system PFD or to view the power and cost summary.

3.3.3.2 System PFDs

Once the user has clicked “Calculate,” either the “SWRO PFD” or the “BWRO PFD” button will appear at the top of the page, depending on the type of membrane selected. Clicking on this button will show a PFD of the system, including the ERD. The button will be hidden if system information is changed in order to prevent the PFD from showing erroneous data.

Two separate PFD configurations (SWRO and BWRO) are provided because each system has unique features. As described in Section 3.3.2.3, the SWRO system can accommodate only one- or two-stage designs, whereas the BWRO system can accommodate only two- or three-stage designs. Two ERD selections, the Pelton Wheel and the turbocharger, located before Stage 1, are used predominantly in SWRO systems. A BRWO PFD cannot be created with either of those two ERD selections.

3.3.3.3 Scenario Evaluation

The purpose of this tool is to allow the user to enter different system designs and evaluate the effectiveness of different ERDs. Similarly to the "PFD" button, once the user has clicked the "Calculate" button, the "Save Scenario" button will also appear at the top of the page. Clicking this button allows the user to give a unique name to the scenario (e.g., ERI Isobaric) and then directs the user to the "Power Summary" page to see the total power consumption of the current system design. From this page, the user can also navigate to the "Cost Summary" page. These two pages are set up to let the user compare up to ten different ERD configurations. In trying to find the best ERD for a project, the user is advised to enter in the system information, calculate the projections, save the scenario, and then repeat the steps for the alternate ERD configurations.

3.3.3.4 Power Summary

The "Power Summary" page has two tables: "Power Summary" and "Pump Summary." The "Power Summary" table shows the recently saved scenario and compares it with any previously saved scenarios. Criteria evaluated in this tool are the power requirement of each pump in the system, the total number of pumps included in the design, and the total power consumption (in horsepower and in megawatt-hours per year). If a two-pass system is chosen, the estimated additional power requirement of the second pass will be shown in the "Comments" column of this table. An acronym key is shown on the left side of the page to explain what each of the columns in the "Power Summary" table represents.

The "Pump Summary" table lists all the pumps required in the design. This tool can accommodate up to five different pumps: a high-pressure feed pump, an RO booster pump, two interstage booster pumps, and an isobaric circulation pump. For each pump included in the design, the user can enter the number of duty and standby pumps and can choose to include a VFD. Motor and VFD efficiencies can always be entered in this table, whereas pump efficiencies can only be entered for the pumps for which efficiencies have yet to be specified. If information in the "Pump Summary" table is changed, the user must click "Save Current Scenario" to update the table with the change. The "Pump Summary" table is only for the current design; it does not show information for the saved scenarios shown in the "Power Summary" table.

3.3.3.5 Cost Summary

The "Cost Summary" page has a "Cost Summary" table and several inputs required to complete the cost evaluation. Similarly to the "Power Summary" table, saved scenarios are shown and compared on the "Cost Summary" table so the most recently saved scenario can be compared against previously saved scenarios. Criteria evaluated in this table include annual power cost, ERD capital cost, ERD cost level of accuracy, ERD payback period, total RO process-mechanical cost, total annual RO process-mechanical operating cost, present worth cost (in dollars per thousand gallons of permeate), and present worth accuracy. The user can view a detailed breakdown of the ERD cost estimate by clicking the "Cost Breakdown" button.

The accuracy of the cost estimate is shown in the cost summary table. This calculation is based on the assumption that the ERD cost estimates conform to Association for the AACE Class 2 estimates (+20%/-15%), whereas the cost estimates for the rest of the system (pumps, piping, valves, membranes) are conceptual estimates and conform to Class 4 estimates

(+50%/-30%). The accuracy calculation takes into account the percentage of the ERD cost that comes from a Class 2 estimate and presents the overall accuracy. Similarly, the overall accuracy of the present worth cost takes into account the accuracy of the capital cost and operating cost. Section 3.2.3.1 discusses how the cost estimates were generated, whereas Section 3.2.4.3 discusses how the operating cost accuracy is calculated.

Inputs at the bottom of the "Cost Summary" page are needed to complete the full analysis. These inputs include standard project allowances as well as the construction start date, inflation factor, power cost, discount rate, and life cycle duration. The costs provided in this tool are in 2011 U.S. dollars (US$). Choosing the appropriate construction start date will inflate the calculated costs based on the inputted inflation rate. These inputs provide the basis for the payback period and NPV calculations.

Radio buttons are provided on the "Cost Summary" page to allow the user to select whether the ERD will be a new build or a retrofit. If the ERD is a new build, the tool will calculate the approximate cost savings associated with purchasing a smaller HPP. This is only applicable for isobaric and turbocharger applications. For Pelton Wheel ERDs, a cost is calculated for the savings associated with purchasing a smaller motor. These cost reductions are included in the payback period calculation. If the ERD is a retrofit, the user is asked if a new HPP must be purchased. This is often the case for installing an isobaric ERD, as the HPP flow is decreased by anywhere between 25% and 50%.

Similar to the "Power Summary" page, if any of the inputs are changed, the user must click "Save Current Scenario" to navigate back to the "Power Summary" or "Summary" pages. This prevents inaccurate information from being shown.

Refer to Sections 3.2.3 and 3.2.4 for details on what is included in the capital cost estimates, how the present worth calculations are executed for energy and membrane costs, and a sample of a payback period calculation.

The "Power Summary" and "Cost Summary" buttons also include an "Add No ERD Scenario" button that adds a case to the "Power Summary" and "Cost Summary" pages with no ERD. This allows the user to evaluate different ERD scenarios against a system with no ERD. Clicking on the "Clear Row" button will delete the most recently saved scenario. At all times, the scenarios shown on the "Power Summary" page are also shown on the "Cost Summary" page.

3.3.3.6 Cost Breakdown

The user can click the "Cost Breakdown" button on the "Cost Summary" page to see the different components included in the ERD cost. This typically includes the ERD device, any pumps required for ERD operation, and valves, flowmeters, and piping that are associated with the ERD. Note that only pumps specific to the ERD are included in the ERD cost, such as the isobaric circulation pump.

This page also allows the user to override any of the costs included in the ERD cost. The unit costs used in the model are shown, and an override input for each cost allows the user to enter in a more accurate cost if it is available. Costs entered include installation and inflation to the construction start year, so any override costs should be up-to-date installed costs.

A schematic of the overall cost structure is displayed on the “Cost Breakdown” page. This schematic shows the percentage of the total RO cost that is the ERD cost as well as the percentage of the ERD cost that is the device cost. Capital cost estimate accuracy ranges are also shown on the schematic.

3.3.3.7 Print Scenario

Once the user has clicked “Save Scenario” and returned to the “Summary” worksheet, the “Print” button will be visible at the top of the page. This button is only visible for recently saved scenarios and will be hidden if any of the system inputs are changed. Clicking the “Print” button will generate a print preview of the “Summary” worksheet and “Water Quality,” “Power Summary,” “Cost Summary,” and “PFD” pages for the user’s convenience.

Chapter 4

Case Studies

4.1 Introduction

Case studies of actual treatment plants were used to gather operational and design data for the energy recovery model and to evaluate the process for selecting the ERD at each facility.

The facilities presented here were selected to provide a variety of source waters and ERDs, and include two BWRO plants, one tertiary reuse facility, and two SWRO plants. The plants selected and ERDs installed are listed in Table 4.1.

Each case study had the following objectives:

- Gather all relevant cost and performance data.
- Demonstrate the benefits of the ERD in reducing energy consumption and cost.
- Evaluate and compare the operating data, cost, and energy savings.
- Highlight other noncost issues that may have been factored into the decision-making process.

The information gathered through the case studies was used to run the cost model. Cost model verification is presented in Appendix B.

Table 4.1. Facilities Selected for Case Studies

Facility/Utility	Type	ERD Installed	TDS (mg/L)	Capacity (mgd)
Eastern Municipal Water District, Perris I, CA	BWRO	ERI HTC	1500–3500	4.5
Bonita Springs Utilities, FL	BWRO	To be retrofitted with ERI HTC	3850–8000	6
Luggage Point Advanced Water Treatment Plant, Brisbane, Australia	Reuse RO	ERI HTC	1250–1500	18.5
Tampa Bay Seawater Desalination Facility, FL	SWRO	Pelton Wheel	18,500–31,000	25
Perth Seawater Desalination Plant, Kwinana, Australia	SWRO	ERI PX	36,000–37,100	38

4.2 Case Study #1: Eastern Municipal Water District, Perris I BWRO Facility

4.2.1 Basis of Selection

The Eastern Municipal Water District (EMWD) Perris I facility treats brackish well water with a TDS of 1500 to 3500 mg/L. It is a recently constructed facility that has been built incorporating modern ERDs.

4.2.1.1 Plant Description

The EMWD is located in Riverside County, east of Los Angeles in southern California. The EMWD has commissioned and constructed two desalination facilities to reduce the salt buildup in its basin and to utilize its local groundwater as a source for industrial and potable water supply. Perris I was commissioned in 2006 with a total capacity of 17,000 m^3/d (4.49 mgd).

Potable water is obtained by blending desalted water with untreated well water prior to chlorination. The desalination facility is currently fed by a system of 11 groundwater wells located within the San Jacinto basin. The quality of the brackish well water varies considerably throughout the basin, with TDS levels between 990 and 4000 mg/L.

This desalination facility includes pretreatment, a membrane RO package, chemical storage and feed systems, a decarbonator to remove CO_2 in the RO permeate, and chlorine contact equipment.

The pretreatment of the well water consists of 5-micrometer (µm) cartridge filters and chemical injection systems located upstream of the RO trains. A threshold inhibitor and sulfuric acid are used for scaling control.

Two HPPs feed two two-stage RO trains. Each train is composed of 60 pressure vessels (42 first-stage and 18 second-stage), each containing six membranes, for a total surface of approximately 14,400 m^2 (155,000 ft^2) for each train and a design-specific flux of 24.6 liters per square meter per hour (lmh) (14.4 gfd).

A decarbonator tower is installed downstream of the RO process to remove excess CO_2 in the RO permeate. Sodium hydroxide (NaOH) is added to increase the final pH for water corrosivity control.

A clear well equipped with vertical turbine pumps in a wet well provides chlorine contact capability to inactivate viruses in order to ensure that the treated water is suitable for drinking. Aqueous ammonia is injected downstream of the clear well to develop a combined chlorine residual in the finished water.

4.2.1.2 Desalination Plant Features

Table 4.2 summarizes the Perris I plant features.

Table 4.2. EMWD Perris I BWRO Plant Features

Parameter	Feature
Production capacity	18,930 m^3/d (5 mgd—4.5 mgd RO permeate + 0.5 mgd blend water)
Number of trains	2 @ 8500 m^3/d (2.17 mgd) each
Date commissioned	2006
Feed water source	Groundwater (11 wells)
Feed water TDS	1500–3500 mg/L
Product water TDS	<100 mg/L RO permeate <450 mg/L potable water
Feed water temperature	18–22 °C (64.4–71.6 °F)
Number of stages	2
Energy consumption per water produced (entire plant)	1.1 kWh/m^3 (4.16 kWh/kgal)
Operating pressure, Stage 1	9–12 barg (130.5–174.1 psig)
Operating pressure, Stage 2	11–13 barg (159.5–188.5 psig)
System recovery	70–75%
Recovery, Stage 1	50–55%
Recovery, Stage 2	35–45%
Membrane supplier	Filmtec (BW30LE-440)
Project delivery method	Design–bid–build
Capital cost	$20,000,000 (2003–2006)
Operating cost	$753,500 per year
Estimated total water cost	$0.6/$m^3$ ($2.27/kgal)
Energy recovery device	ERI HTC

4.2.1.3 Water Quality

The source water for the Perris I plant is a mix of 11 well water sources. RO permeate produced in the process can be used as either industrial water or potable water. Production of drinking water is achieved by blending the RO permeate with raw water (the ratio of raw water to permeate is 1:9) to add beneficial salts and reduce the cost of finished water production. Table 4.3 provides a summary of the plant’s source water quality.

4.2.1.4 Chemical Use

Chemicals in a membrane process are typically used to manage the potential for fouling, biofouling, and scaling. At the centralized Perris I plant, the well water presents very low suspended solids, and thus cartridge filtration is sufficient to remove the turbidity.

Sulfuric acid is used to decrease the pH to 5.5–6, and a threshold inhibitor is added upstream of the cartridge filters to limit scaling. If needed to convert alkalinity to CO_2 for alkalinity reduction, sulfuric acid (H_2SO_4) can be added to the RO permeate upstream of the decarbonator tower. Excess CO_2 is then removed in the decarbonator tower. Sodium hypochlorite (NaOCl) is added upstream of the chlorine contact tank for the final disinfection, providing a minimum of 4-log virus inactivation. Sodium hydroxide (NaOH) is added to the finished water for pH correction and corrosion control. Prior to distribution, aqueous ammonia is added to convert free chlorine to combine chlorine (chloramines.)

Table 4.3. Typical EMWD Perris I BWRO Water Quality

Constituent	Units	Feed Water	RO Concentrate	RO Permeate	Finished Water
pH	pH	6.9	—	~5	7–9
Temperature	°C	—	—	18–22	18–22
Total dissolved solids	mg/L	2375	7800	<100	<450
Total alkalinity	mg/L as $CaCO_3$	305	—	—	—
Total hardness	mg/L as $CaCO_3$	1075	—	—	—
Silica	mg/L as SiO_2	59	—	—	—
Aluminum	mg/L	0.2	—	—	—
Barium	mg/L	0.4	—	—	—
Calcium	mg/L	320	—	—	—
Iron	mg/L	0.35	—	—	—
Magnesium	mg/L	66	—	—	—
Manganese	mg/L	0.25	—	—	—
Potassium	mg/L	9.4	—	—	—
Sodium	mg/L	283	—	—	—
Strontium	mg/L	1.85	—	—	—
Bicarbonate	mg/L	301	—	20	50
Chloride	mg/L	987	—	< 60	<250
Sulfate	mg/L	338	—	< 100	<250

4.2.2 ERD Evaluation and Selection

The Perris I desalination plant was commissioned in 2006. An ERI HTC ERD was selected during design and included in the final design of the facility.

Figure 4.1 displays the PFD of the facility. The PFD is from the plant supervisory control and data acquisition (SCADA) system and shows the data on one of the RO trains in operation in April 2012.

The HTC ERD was sized based on the following plant parameters:

- RO permeate capacity flow = 4.5 mgd
- Total RO permeate flow = 4.34 mgd and raw water bypass = 0.16 mgd
- RO system recovery = 70%
- Total RO concentrate flow = 1.9 mgd= 1320 gpm
- Stage 2 concentrate pressure = 240 psig
- System line and valve losses

On the basis of these parameters, the ERD system's preliminary sizing was

- 1 unit per RO train
- 37 kW peak output, per unit
- 75% to 78% efficiency, ERD unit only

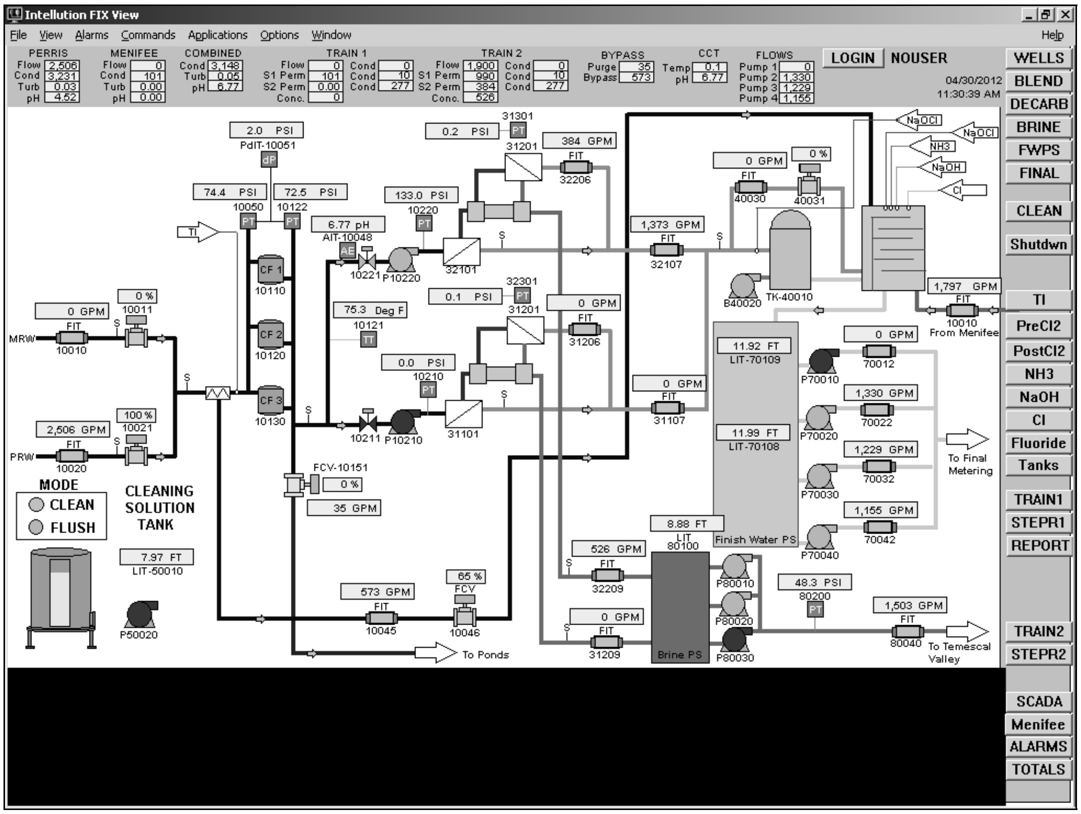


Figure 4.1. EMWD Perris I SCADA system process flow.

The engineer's estimate of ERD equipment costs for two turbines, and several other improvements including bypass valves and ERD auxiliary equipment, was $35,000 per ERD with an installation cost of $15,000 per ERD. The costs were balanced by the following energy generation assumption:

- Average operation generator output = 22 kW, 90% annual operation (330 days)
- Energy cost = $0.15 per kilowatt-hour
- Return on investment = approximately $100,000/$52,000, or 1.92 years for two ERDs, excluding design costs and maintenance costs

Each ERD discharges RO concentrate flow into a common discharge header that conveys the flow by gravity to the brine pump station.

4.2.3 Modeling Simulation of Case Study

4.2.3.1 Results of Modeling Simulation

The PFD shown in Figure 4.2, produced by the model, is representative of one of the Perris RO trains.

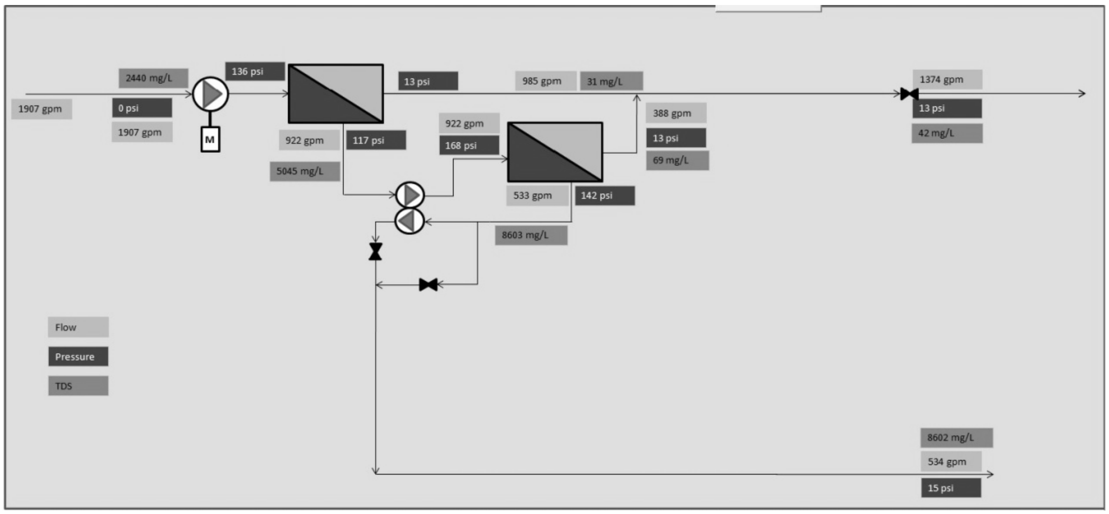


Figure 4.2. EMWD Perris I BWRO PFD.

4.2.3.2 Comparison on Model Simulation to Recorded Data

As shown in Table 4.4, the model is accurate in predicting the operating performance of the Perris I BWRO plant.

4.2.4 Conclusion

The model demonstrates that the cost of HTC[T] ERD equipment is approximately $86,000 per RO train. This number reflects a turbocharger cost of $32,000, an additional piping installed cost of $21,000, and $38,000 in valves and instruments. The cost for the turbocharger itself is similar to the engineer's estimate presented in Section 4.2.2. However, the engineer's estimate of $50,000 per train does not appear to include all of the necessary interconnect piping valves and instrumentation.

With this level of cost estimate, it is typical to escalate the equipment cost to account for additional costs associated with installation (20%), engineering (10%), profit margin (10%), electrical costs (1%), and contingencies (10%). Therefore, the total installed ERD equipment estimate for the plant is $140,000.

The estimated power usages are 164 kW per RO train without a turbocharger, and 143 kW per RO train with the turbocharger. At $0.15 per kWh, the difference in energy savings is $28,000 per year.

Table 4.4. Model Comparison to Plant Data

	RO Feed Pressure (psi)	Permeate Backpressure (psi)	Turbocharger Boost Pressure (psi)	Reverse Osmosis (kWh/1,000 gal)
Model prediction	136	13	51	1.83
Actual operation April 2012	133	13	47	1.79

Table 4.5. EMWD Perris I BWRO Present Worth Cost and Payback Period

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal)	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Turbocharger	ERD Payback Period (years)
6%	0.31	0.29	9
3%	0.37	0.35	7
0%	0.48	0.45	5

The payback period and present worth cost of the RO equipment and energy are strongly dependent on the discount rate assumed for the present worth duration. The present worth duration is typically linked with the expected life of the RO equipment, and an industry standard is 25 years. Assuming an energy cost of $0.15 per kWh[3] and a present worth duration of 25 years, the tool estimates the costs and payback periods presented in Table 4.5.

An ERD payback period of less than 25 years indicates that a turbocharger is economically beneficial for the Perris I BWRO plant. The energy savings of 1.83 kWh/1,000 gal with the turbocharger versus 2.10 kWh/1,000 gal without the turbocharger overcomes the initial turbocharger capital investment.

4.2.5 Lessons Learned

At the time of the facility design, limited groundwater quality information was available. From these data, the well water quality was estimated to have a TDS range of 3000 to 7000 mg/L, with silica levels sufficiently high to limit product water recovery to 70%. After piloting and additional water quality monitoring, TDS was found to be significantly lower, varying between 1700 and 2200 mg/L. The lower TDS has resulted in lower-than-design RO train feed pressures based on the lower osmotic pressure of the well water. Consequently, pressures in the RO concentrate stream feeding the interstage HTC were lower than design, causing the turbocharger to operate outside of its design pressure range.

Because the turbocharger was sized to take a greater pressure drop across the turbine than was actually applied, the amount of interstage pressure boost was less than design, and the amount of Stage 2 concentrate capable of passing through the turbine was less than required to achieve the design product water recovery.

[3] Energy costs are based on local electrical costs and vary by case study.

To compensate for these operational deficiencies, the RO train was operated using first-stage permeate backpressure in conjunction with concentrate bypass around the turbocharger. This mode of operation is not optimal, as more feed pressure is being consumed through product water backpressure than is necessary to achieve the desired permeate flow. To minimize energy consumption while meeting RO permeate demands, the following options were evaluated and discussed with the turbocharger supplier, ERI:

- Modify existing turbochargers through replacement of nozzles and/or bypasses
- Replace turbochargers

ERI indicated that replacement of the existing turbochargers or upgrading the existing turbochargers may not offer any cost benefit compared to continued operation of the existing turbochargers as currently configured. Applying permeate backpressure to balance the flux, as practiced currently, was determined to be the best way to balance flux under lower feed TDS concentration. The results of recovery optimization testing indicated that recovery could be increased as high as 75%. This information will be shared with ERI to further assess turbocharger performance and determine the need for any modification of the existing turbochargers.

A second desalination plant, Perris II, has recently been designed for the municipality. For the Perris II system, PX, HTC, and interstage booster pump systems were evaluated based on system cost, including construction, power, and life-cycle costs. The new design incorporates higher system efficiency and better process control, as well as improved operation based on a better understanding of the feed water quality, the outcome of the Perris I optimization project, and an improved well operation strategy. Based on this comprehensive evaluation, a turbocharger was selected for use in the RO train at the Perris II plant.

4.3 Case Study #2: Bonita Springs Utilities, BWRO Facility

4.3.1 Basis of Selection

The Bonita Springs Utilities (BSU) BWRO facility, commissioned in 2004, treats brackish Floridan aquifer water using four RO trains that each produce 1.5 mgd of permeate. The RO facility has a total capacity of 6.0 mgd. The RO process removes salts from the brackish feed water.

Over the years, BSU has experienced changes in performance of the BWRO. To address these changes, BSU decided to modify the plant's RO trains. As part of the modifications, the facility will be retrofitted with ERDs.

4.3.1.1 Plant Description

The existing RO trains are designed to produce 1.5 mgd operating on a wide range of feed water qualities at an average flux rate of 14.9 gfd. The RO trains have two stages, with 24 pressure vessels in Stage 1 and 12 pressure vessels in Stage 2. Each train has a dedicated membrane feed pump with VFD and automatic concentrate control valve. The concentrate control valve and the feed pump VFD control the permeate flow and the recovery. Flux balancing between the first and second stages is accomplished by backpressuring the first-stage permeate valve. A PFD of the plant is provided in Figure 4.3.

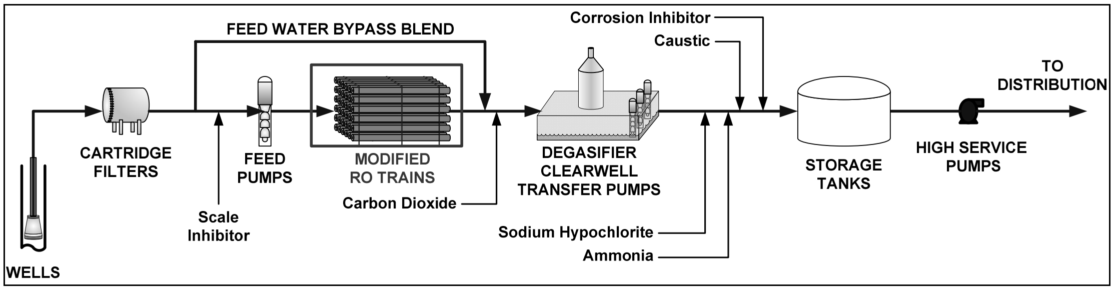


Figure 4.3. Bonita Springs Utilities BWRO plant PFD

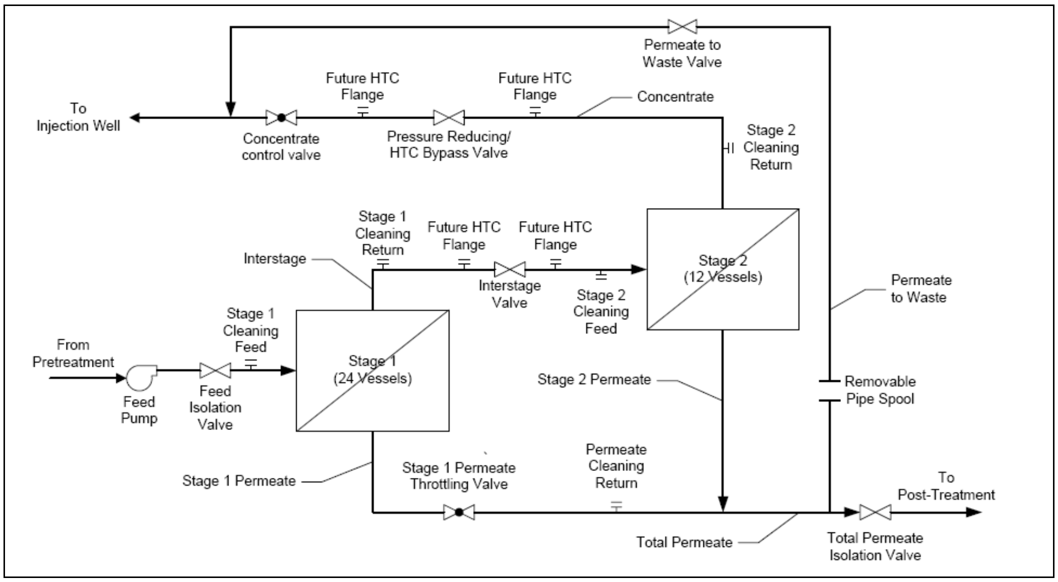


Figure 4.4. Bonita Springs Utilities RO train PFD with future HTC flanges

The original facility design included provisions to add an interstage hydraulic turbocharger ERD on each train as feed TDS increased and the economics became more favorable. Figure 4.4 shows a typical PFD for the existing RO trains.

4.3.1.2 Desalination Plant Features

Table 4.6 summarizes the BSU plant features.

4.3.1.3 Chemical Use

BSU uses the following chemicals in the BWRO treatment process:

- Scale inhibitor dosed prior to the RO membranes
- Carbon dioxide dosed post RO membranes
- Sodium hypochlorite
- Ammonia
- Caustic
- Corrosion Inhibitor dosed post the clearwell transfer pump

4.3.1.4 Water Quality

The average salinity of the existing Floridan brackish wells has been increasing since plant startup in 2004. There has been an upward trend in both chloride concentration and conductivity since early 2007. Before 2007, the well conductivity and chloride levels were relatively constant.

Table 4.6. Bonita Springs Utilities BWRO Plant Features

Parameter	Feature
Permeate capacity	6 mgd (4 RO trains @ 1.5 mgd each)
Design permeate recovery	65% to 85%
Current TDS	4684 mg/L
Max design feed TDS	8100 mg/L
Design feed pressure	200 to 460 psi
Maximum differential pressure (single stage)	50 psig
Average permeate flux	14.9 gfd
Number of pressure vessels	36
Array (Stage1:Stage 2)	24:12
Elements per pressure vessel	7
Total number of elements per train	252
Membrane element area, each	400 ft^2
Element type	High Rejection BWRO (GEWT AG8040F)
Feed pump suction pressure design range	20 – 60 psi
Feed pump primary design point	1390 gpm @ 940 ft (407 psi) TDH
Feed pump secondary design points	1225 gpm @ 982 ft (425 psi) TDH 1602 gpm @ 882 ft (382 psi) TDH
Feed pump motor horsepower	500
ERD	None initially, will be added via retrofit

The average conductivity of all of the wells has been increasing approximately 2.5% each year from 2007 to 2011. Projecting this same trend over the anticipated 10-year life of the membrane elements, the average combined well water conductivity would increase from the original 6400 micromhos per centimeter (µmho/cm) to approximately 8400 µmho/cm. This corresponds to an increase in feed TDS from the original 3,850 mg/L to approximately 5000 mg/L. The value of 5000 mg/L TDS, called the “10-year design” water quality, was used in a sensitivity analysis of membrane projections.

Table 4.7 presents the raw water quality collected in 2007. The “design” 3850 mg/L TDS water quality is also shown, along with the BSU finished water quality goals identified in the 2007 expansion design. The water quality design was used for the membrane element assessment, energy calculations, train sizing, and feed pump analysis. The 10-year design water quality was used to verify the ability of the proposed ERD and membrane selection to meet the anticipated water quality in the near future. The maximum future design water quality was also considered in the ERD design.

4.3.2 ERD Evaluation and Selection

Membrane projections were performed using projection software from multiple manufacturers to simulate the BSU RO system using both low-pressure and high-rejection brackish water membrane elements. The analysis used the design permeate flow of 1.5 mgd per train and 80% permeate recovery with 24 first-stage vessels and 12 second-stage vessels. RO projection results are summarized in Table 4.8.

Table 4.7. Water Quality

Constituent	Units	2007 Composite Wells	Design	10-Year Design	Maximum Future Design	Finished Water Goal
pH	—	7.6	7.5	7.5	7.70	<8.5
TDS	mg/L	3,360	3850	5000	8129	<400
Calcium	mg/L	115	121	150	188	—
Magnesium	mg/L	131	124	160	300	—
Sodium	mg/L	900	1035	1300	2267	<128
Chloride	mg/L	1650	1595	2000	3950	<200
Sulfate	mg/L	652	681	850	990	<200
Total hardness	mg/L as CaCO3	830	815	1035	1700	<100
Total alkalinity	mg/L as CaCO3	164	175	175	175	>30
Temperature*	°C			15		

* Temperature use in model evaluation is noted.

Table 4.8. Membrane Element RO Train Projection Summary

Flow Stream	Flow (gpm)	Pressure (psi)
Influent	1302	0
Stage 1 feed	1302	131–208
Stage1 permeate	696–888	13–40
Stage 1 concentrate	415–606	116–198
Stage 2 feed	415–606	186–281
Stage 2 permeate	154–326	13
Stage 2 concentrate	261	176–251

The projections included a variable 47- to 120-psi interstage pressure boost between the first-stage concentrate and the second-stage feed. It was assumed that 20 psi residual concentrate pressure was needed for disposal in the injection well.

Three ERDs were considered for the BSU facility:

- ERI's HTC, Model LPT-500
- ERI's PX ERD
- FEDCO's low-pressure hydraulic energy management integration (LP-HEMI).

A new ERD will be installed on each of the four existing RO membrane trains. Figure 4.5 shows a typical turbocharger installation within each train.

Each ERD or additional booster pump[4] will be installed on a concrete pad located next to the RO train. New piping will be connected to the existing blind flanges using concentric reducers. All new piping will be Schedule 10S 316L and will be electropolished to match the existing piping. The proposed new ERD will be installed using the existing train connections and will use the existing electrical connections and instrumentation.

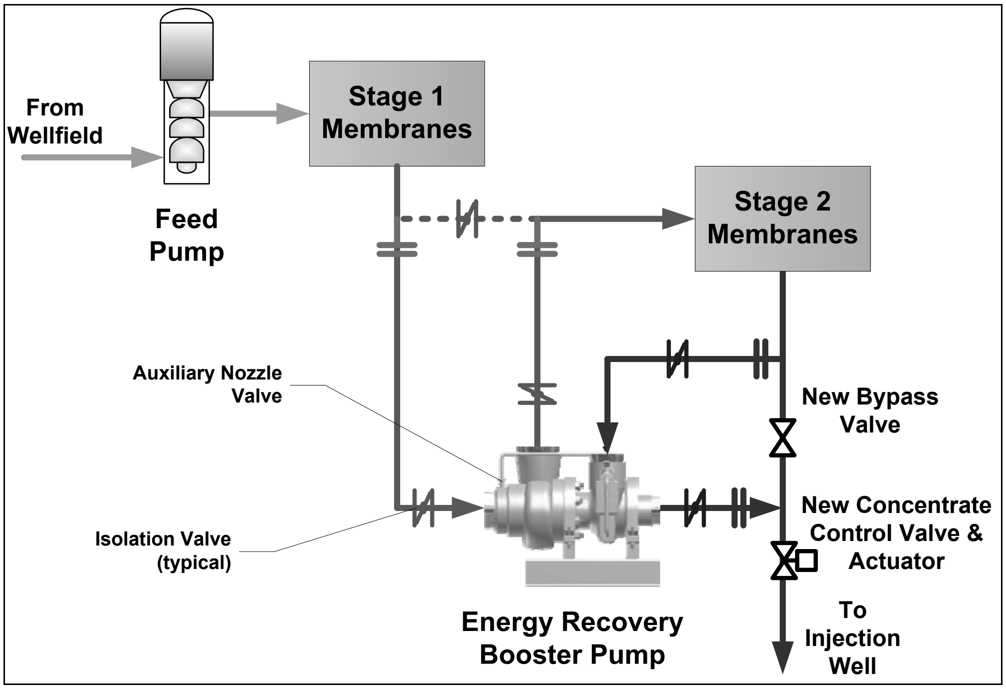


Figure 4.5. Bonita Springs Utilities turbocharger schematic.

A cost analysis was performed using the projected performance of several membrane types and the projected performance of ERI's LPT-500, LP-HEMI, and PX ERDs. The analysis included actual feed pump and well pump efficiencies, as well as estimated ERD efficiency and powered interstage feed pump efficiency for the PX and LP-HEMI options. Analysis results are presented in Table 4.9.

Table 4.9. ERD Analysis Criteria and Assumption Summary for BSU (Design)

Criteria	Design	LPT-500	LP-HEMI	PX
Well pump efficiency (%)	67%	67%	67%	67%
Well pump flow (gpm)[a]	3906	3906	3906	3906
Well pump TDH (psi)[b]	50	50	50	50
Feed pump efficiency (%)	74%	74%	74%	67%
Feed pump flow per RO train (gpm)	1302	1302	1302	1042
Feed pump suction pressure (psi)	30	30	30	30
Feed pump discharge pressure (psi)	260–300	157–208	131–196	157–208
Interstage boost pump efficiency (%)	—	—	67–72%	71%
Design interstage flow (gpm)[c]	—	510	600	510
Design concentrate flow (gpm)[c]	261	261	261	261
Interstage flow per train (gpm)	~520	415–587	503–606	453–574

[4] For FEDCO and ERI PX™ options.

Criteria	Design	LPT-500	LP-HEMI	PX
Interstage boost pressure (psi)	—	46–85	50–120	50–60
ERD efficiency (%)	—	52–60%	75–80%	88%
Net energy recovery efficiency (%)[d]	—	52–60%	54–56%	—
Unit power cost	$0.08/kWh	$0.08/kWh	$0.08/kWh	$0.08/kWh
Annual average production (mgd)	4.5	4.5	4.5	4.5

[a] Assumed average total dynamic head (TDH) of all well pumps.

[b] Assumed combined well pump flow rate for an average of three RO trains in operation at 80% recovery.

[c] Design point for peak efficiency.

[d] Accounts for both turbine-side and boost-pump-side efficiency of LP-HEMI and LPT-500.

Table 4.10. BSU ERD Power and Construction Costs

Criteria	Current	LPT-500	LP-HEMI	PX
SEC (kWh/1000 gal)	~3.80	2.28–3.06	2.14–2.94	2.26–3.13
Annual power cost ($1000)	~$500	$300–$400	$280–$386	$300–$410
Construction cost	—	$635,000	$785,000	$800,000

Table 4.10 presents SEC, estimated annual power costs, and the -30% to +50% construction costs for the proposed LPT-500, LP-HEMI, and PX ERDs. The power consumption and annual power costs were based on criteria and assumptions presented in Table 4.6. The costs reflect a 75% average plant operating factor and 80% RO system recovery. Power usage assumes operation of well pumps, RO train feed pumps, and interstage boost pumps for the PX and LP-HEMI options only.

The net power costs shown were developed for operations near the current design conditions and do not reflect the reduced efficiency if the trains are expanded in the future or if recovery is decreased.

Budgetary estimates for the PX, LPT–500, and LP–HEMI devices were provided from ERI and FEDCO. The PX estimate includes eight BPX180 devices, two units per train. The HTC estimate includes four LPT–500 devices, one unit per train. The LP–HEMI estimate includes four LPH–160/125T devices, one per train. The LPT–500 device does not have an electrical requirement; however, the LP–HEMI and PX options include a powered 30- to 40-hp interstage booster pump and required appurtenances. Ancillary equipment (piping, valves, flow meters, pressure transmitters, etc.) is also included in the estimate for each option.

All of the evaluated ERDs will reduce the annual power cost for the BSU plant. Although the PX option can save up to approximately $7000 per year depending on membrane selection, almost all membrane element options result in increased cost for the PX system. Given that the PX system is more complex to operate and has a higher up-front construction cost, the PX system was eliminated from further consideration by BSU.

Implementing the LPT-500 has a lower construction cost and will result in a lower operating cost under most operating conditions near its design flow. However, if the RO trains are expanded in the future or if the train recovery changes, the LPT-500 efficiency will decrease significantly. Alternatively, the impellers can be replaced to accommodate the new design operating conditions. The cost of new impellers for the system was approximated at $100,000.

The LP-HEMI offers significant operating flexibility and efficient operation over most potential future operating conditions without the need for modification. However, this flexibility requires additional construction cost.

The hydraulic pressure booster (HPB) from FEDCO combines the principles of the centrifugal ERD with a powered pump to add flexibility to the system. The efficiency of an HPB is similar to the efficiency of the HTC and is typically between 55% and 65%. Unlike the HTC, the HPB has a motor that can provide a pressure boost greater than what can be recovered from the brine. This capability allows better system control by providing flexibility to balance the flux between different stages without using significant backpressure. The HPB was included in the suggested selection criteria to BSU.

Table 4.11. BSU Qualitative Analysis

ERD Technology	Advantages	Disadvantages
LPT-500	Minimal maintenance requirements Previous experience at nearby RO facilities Power not required for operation	Set performance; limited flexibility in operation with varying conditions Limited efficiency over wide water quality range Less efficient than PX Bypass valve may result in high noise level
LP-HEMI	Adapts to varying system flows with minimal efficiency loss Provides better flux balancing without the need for Stage 1 permeate throttling Improves control which eliminates concentrate throttling or ERD bypass Higher efficiencies and reduced noise	Requires an electrical connection More costly than LPT-500 Less efficient than PX
PX	Reduces feed pump flow More efficient than centrifugal ERDs Low maintenance requirements	Limited application in BWRO systems Requires a powered interstage booster pump and control valve Complex control and maintenance Two units per train required Relatively large footprint Very high system noise Small increases in recovery or interstage flow will require additional units
HPB	Adaptable to new design points and increased pressure boosts Provides added flexibility to the system in flux balancing Eliminates the need for backpressure	Requires an electrical connection More costly than ERDs Has a power cost associated with pumping Less efficient than PX

A qualitative analysis was conducted on all four technologies and is presented in Table 4.11.

The LPT-500, HPB, and LP-HEMI ERDs all accomplish the same function of boosting interstage pressure using energy recovered from the waste concentrate stream. All of the options would be installed in the same location using existing blind flanges on each RO skid.

Only the LP-HEMI differs in that electrical power is needed to further boost the interstage pressure to improve efficiency. BSU will competitively bid all three ERD options and will install the option with the lowest life-cycle cost that meets the overall construction budget. Table 4.12 summarizes the BSU selection criteria.

Table 4.12. BSU Selection Criteria

Parameter	Criteria
ERD	HTC (ERI LPT-500), FEDCO HPB-500, or FEDCO LPT-12
Design interstage flow	415–700 gpm
Design concentrate flow	184–446 gpm (70% to 85% recovery at 1.5 mgd permeate)
Interstage pipe connection size	6-in.
Concentrate pipe connection size	4-in.h
Energy recovery efficiency	50% to 70%*
Projected interstage boost pressure	40–125 psi
Residual concentrate pressure	5–20 psi (based on injection well requirements)
Concentrate control valve type	Characterized seat ball valve with 480V actuator
Concentrate valve size	3-in.
Valve control	Automatic to adjust concentrate flow
Isolation valves	Manual butterfly

*Acceptable efficiency of the ERD device itself

4.3.3 Modeling Simulation of Case Study

4.3.3.1 Results of Modeling Simulation

The model produced the PFDs shown in Figures 4.6 and 4.7 for a BSU RO train operating at 75% recovery with an ERI LPT-500 turbocharger ERD and a PX ERD, respectively. The FEDCO LP-HEMI was not included in the tool, as no cost information was provided for these devices. Note that the tool does not account for the energy consumption of the well or intake pumps upstream of the high-pressure RO feed pump. Thus, to compare the RO train SEC value between the tool and the design, the incoming pressure to the high-pressure RO pump in the tool is assumed to be zero.

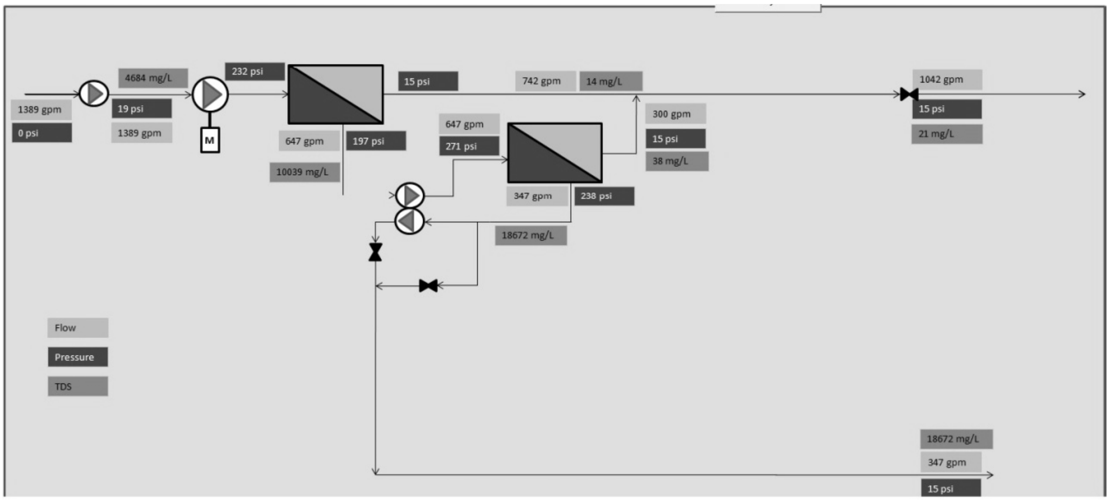


Figure 4.6. Bonita Springs Utilities RO train with LPT-500 turbocharger.

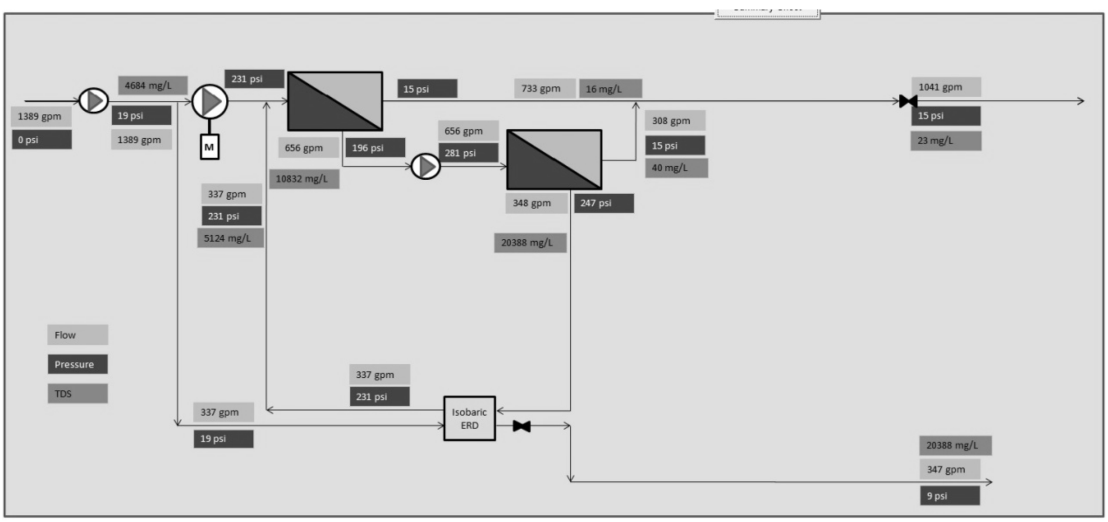


Figure 4.7. Bonita Springs Utilities RO train with ERI PX.

4.3.3.2 Comparison on Model Simulation to Actual Operation

The BWRO plant is not yet operational with an ERD; thus, no existing operational data are available for comparison. The value of this case study is in the comparison of the engineering estimates generated in order to select the appropriate ERD and similar estimates by the tool.

4.3.4 Conclusion

The tool predicts the construction costs shown in Table 4.13 for a single RO train relative to the ERD installation. The supporting equipment consists of interconnecting piping, valves, and instrumentation. The installed cost includes 53% extra for engineering profit and contingencies. The engineer's estimate for the total installed cost of all ERDs on all trains was $635,000 for the LPT-500 and $800,000 for the PX system, respectively. The estimated cost of the PX implementation is within 5% of the tool's estimate.

The tool predicts the energy costs and payback periods shown in Table 4.14 for the two ERDs. Feed pump efficiencies used in the calculations are taken from Table 4.9. The SEC values calculated by the tool are within the range of the engineer's estimate. The values calculated by the engineer include detailed analysis run by each of the ERD vendors for this particular project.

Table 4.13. BSU Construction Costs for LPT-500 and ERI-PX Model BPX-180

	Number of Devices, per RO Train	Estimated Cost of ERD and Supporting Equipment, per RO Train	Estimated Installed Cost, per RO Train	Total Estimated Installed Cost, All Trains	Engineer's Estimate
LPT-500	1	$72,000	$119,800	$480,000	$635,000
PX Model BPX-180	2	$124,300	$204,500	$818,000	$800,000

Table 4.14. BSU Energy Use with LPT-500 and ERI-PX Model BPX-180

	ERD Efficiency	ERD Efficiency (Engineer's Estimate)	Energy Use (kWh/1000 gallons)
LPT-500	64%	52–60%	3.24
PX Model BPX-180	96%	88%	3.31

The tool predicts that the estimated power usage for the BSU plant without an ERD is 232 kW per RO train. This estimate is with 15 psi permeate backpressure and does not include an interstage boost pump (which would lower this value to about 227 kW). The estimated power usages are 202 kW per RO train with the LPT-500 turbocharger and 207 kW with the PX. Based on the lower capital cost and energy cost, the tool confirms that the turbocharger is the better choice for the BSU retrofit.

The payback period and present worth cost of the RO equipment and energy use are strongly dependent on the discount rate assumed for the present worth duration. The present worth duration is typically linked with the expected life of the RO equipment, and the industry standard is 25 years. Assuming an energy cost of $0.08 per kWh, and a present worth duration of 25 years, the tool estimates the following costs and payback period shown in Table 4.15 for the LPT-500 turbocharger.

4.3.5 Lessons Learned

Despite the fact that the isobaric ERD, in this case the ERI PX, has a much higher efficiency than the turbocharger, the turbocharger was clearly the best selection for the BSU retrofit.

The isobaric ERDs operate in parallel to the RO high-pressure feed pump, reducing the feed pump duty flow. For retrofit of a system with an existing RO feed pump, this moves the pump off its best efficiency point. The PX retrofit would reduce the operating efficiency of the high-pressure RO feed pump to 67%.

The turbocharger, on the other hand, is a pressure booster and would not change the duty flow of the existing HPP. The pressure required by the pump would decrease, but this resulted in pump efficiency of 71%. Thus, the retrofit with the turbocharger would result in a better HPP operating efficiency.

In addition, isobaric ERD systems require not only the ERD but a separate circulating pump as well (see Figure 4.7). For smaller RO systems such as the BSU plant, the installed ERD cost for isobaric systems is comparably higher than that of a turbocharger, which does not require a separate pump. For larger RO trains, the cost of the circulating pump represents a smaller portion of the overall cost of the ERD equipment.

The LP-HEMI may indeed be the best turbocharger choice for BSU; unfortunately, cost data for these devices were not supplied by the vendor to be used in the tool.

Table 4.15. BSU Present Worth Cost and Payback Period

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal) No ERD	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Turbocharger	ERD Payback period (years)
6%	0.29	0.28	10
3%	0.36	0.34	8
0%	0.46	0.43	5

4.4 Case Study #3: Luggage Point Advanced Water Treatment Plant, Water Reuse RO

4.4.1 Basis of Selection

The Luggage Point Advanced Water Treatment Plant (LPAWTP) was constructed in response to a period of unprecedented population growth in Brisbane and South East Queensland, Australia, combined with a prolonged drought from 2002 to 2008, which created an acute shortage of water in the region.

The LPAWTP treats secondary effluent from the adjacent Luggage Point Wastewater Treatment Plant (LPWWTP) to a level that meets drinking water quality standards to augment the city of Brisbane's largest potable water source, Lake Wivenhoe, and to provide high-quality water to two power plants.

4.4.1.1 Plant Description

The LPAWTP uses a multibarrier treatment approach that includes chemically assisted clarification, microfiltration (MF), RO, and ultraviolet disinfection/advanced oxidation (UV/AOP) to treat secondary wastewater effluent from the LPWWTP. Raw water from the wastewater plant is first pumped to raw water storage tanks at the LPAWTP site. The raw water then goes through flocculation and clarification, with ferric chloride used as a coagulant. The clarified water is pumped to the MF system,further treated by RO and UV/AOP, and then chemically stabilized. Preformed chlorimines are dosed either ahead of flocculation or prior to the MF system.

Sludge generated in the clarifiers and the MF prescreens is directed to a gravity thickener that is dewatered by centrifuges. MF backwash water is chemically clarified using a dedicated system, and the supernatant returned to the raw water storage tanks.

Figure 4.8 presents a schematic of the overall plant treatment processes.

The RO system at the LPAWTP has an annual average capacity of 17.4 mgd (66 million liters per day [MLD]) and a maximum daily output of 18.5 mgd (70 MLD).

The RO system consists of four trains (three duty and one standby). The design recovery of the overall RO plant is 85%. To achieve 85% recovery, a three-stage system is used. The RO process flow is shown in the PFD in Figure 4.8.

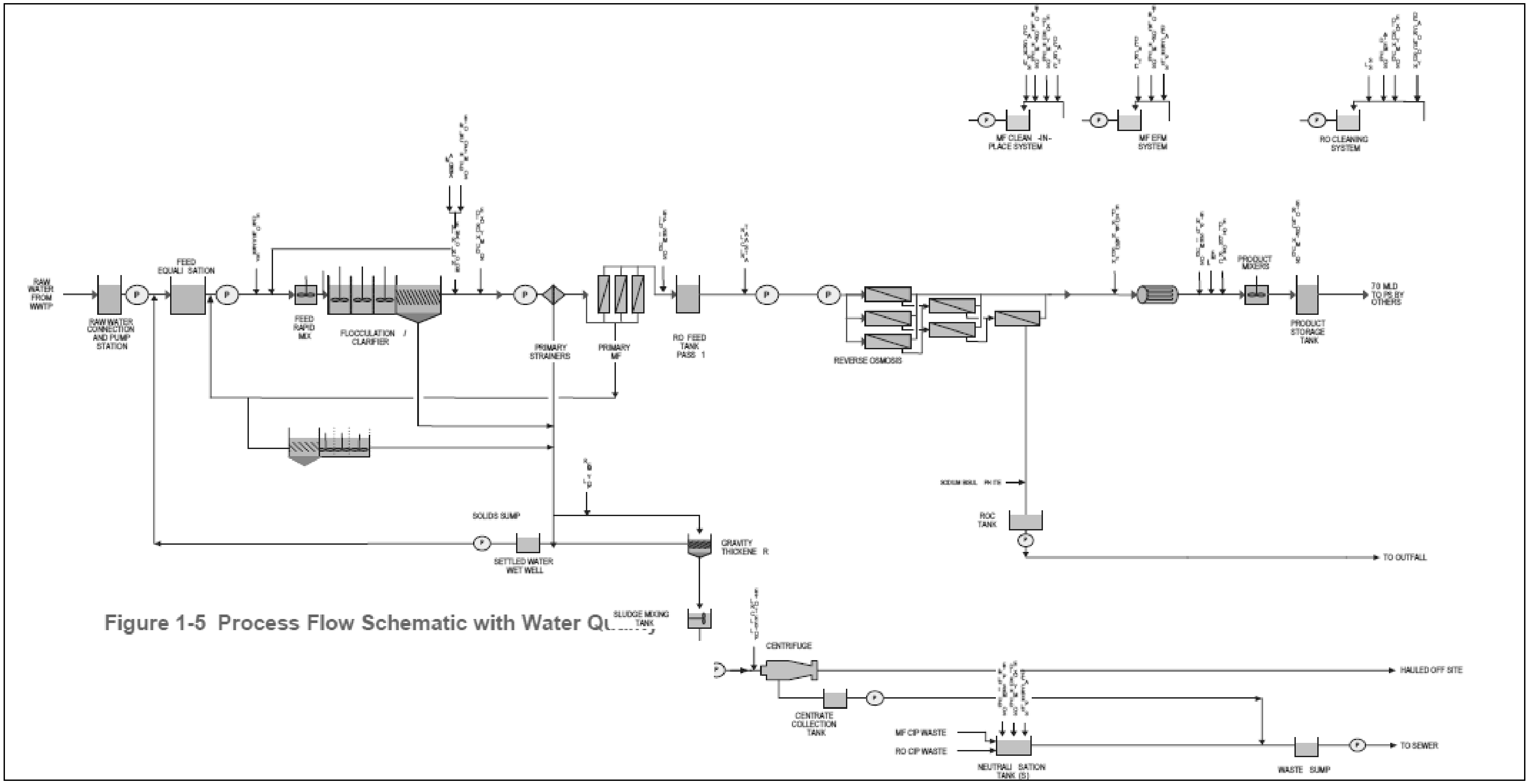


Figure 4.8. Luggage Point AWTP PFD.

Table 4.16. Reverse Osmosis Design Criteria

Parameter	Feature
Maximum permeate capacity	18.5 mgd (70 MLD)
Trains	4 (3 online/1 standby)
Overall design permeate recovery	85%
Maximum design feed TDS	1500 mg/L
Design feed pressure	319 psi (2200 kilopascals [kPa])
Average permeate flux	10.5 gfd (17.8 lmh)
Stage 1 permeate backpressure and design backpressure valve	60 psi (414 kPa)
Design temperature (minimum)	19 °C
Number of pressure vessels installed per train	210
Array (Stage1:Stage 2:Stage 3)	120 × 60 × 30
Elements per pressure vessel	7
Total number of elements per train	1470
Element manufacturer and model	Toray, TML20-400 BWRO
Membrane element area	400 ft^2
Number of RO booster pumps	3 duty/1 standby
RO booster pump design point (each)	Maximum—5040 gpm (318 L/s) @ 30 psi (210 kPa) TDH Minimum—3994 gpm (252 L/s)
RO booster pump horsepower	450 hp (335 kW)
Number of RO Feed pumps	3 duty/1 standby
RO feed pump design point (each)	5040 gpm (318 L/s) @ 320 psi (2200 kPa) TDH
RO feed pump suction pressure	43.5—101.5 psi (300—700 kPa)
RO feed pump motor horsepower	845 hp (630 kW)

Each RO process train consists of one RO booster pump, one cartridge filter, one feed pump, and one membrane skid. Antiscalant is dosed prior to cartridge filtration to limit scaling.

4.4.1.2 Reverse Osmosis Plant Features

Table 4.16 presents the RO design criteria for the LPAWTP.

4.4.1.3 Water Quality

The RO system receives secondary treated (clarified and microfiltered) effluent. The purpose of the RO system is to reduce the concentration of dissolved inorganics and organics in the feed water, as well as provide one of three barriers to pathogens. The RO feed water pH is in the range from 6.5 to 7.3 because of ferric dosing in the flocculation/coagulation process. The phosphate is reduced in the clarification process, and solids are removed in the MF process. Organics reduction is approximately 30% to 50% through clarification and MF.

Table 4.17 summarizes the RO feed water quality.

Water produced at the LPAWTP is designed to meet the water quality standards listed in Table 4.18.

Table 4.17. Reverse Osmosis Feed Water Quality

Constituent	Units	90th Percentile Concentration	50th Percentile Concentration
Calcium	mg/L	46	42
Magnesium	mg/L	48	39
Sodium	mg/L	422	333
Potassium	mg/L	32	27
Barium	mg/L	0.022	0.017
Ammonia	mg/L	0.66	0.13
Aluminum	mg/L	0.06	0.03
Iron, total	mg/L	0.17	0.13
Manganese, total	mg/L	0.14	0.11
Copper	mg/L	640	530
Sulfate	mg/L	120	100
Nitrate	mg/L	22	11
Bicarbonate	mg/L	224	198
Carbonate	mg/L	0.10	0.04
Phosphate	mg/L	6	3
Fluoride	mg/L	1.4	0.9
Silt density index (SDI) (15 min)	mg/L	<3.0	
Conductivity	µS/cm	2600	2040
TDS (sum)	mg/L	1500	1250
Temperature	°C	30	25
pH	–	7.0	6.6
Silica	mg/L	11	10
Total suspended solids	mg/L	<1.0	<1.0
Turbidity	NTU	<0.3	<0.1
Biochemical oxygen demand	mg/L	5	2.5
Total Kjeldahl nitrogen	mg/L	3.3	2.0
Organic nitrogen	mg/L	7.0	5.0
Nitrate as N	mg/L	4.7	2.8
Total phosphorus	mg/L	2.0	1.0

Table 4.18. Water Quality Goals

Constituent	Units	Water Quality Standard	Statistical Basis
Total nitrogen	mg/L	0.8-1.2	Annual 50th Percentile
Total phosphorous	mg/L	0.13	21 day, 50th Percentile
Clostridium perfringens—median	cfu/100 mL	1	Annual
Clostridium perfringens—95th percentile	cfu/100 mL	10	Annual
Hardness as $CaCO_s$	mg/L	>50	21 day average
Alkalinity	mg/L	>40	21 day average
Calcium carbonate precipitation potential	—	0 to -5	Maxima/minima
Total organic carbon	mg/L	1	Maximum
Nitrododimethylamine	ng/L	10	Values to be less than or equal to the value listed in 90% of samples
Estrone	ng/L	3	Values to be less than or equal to the value listed in 90% of samples
17-beta estradiol	ng/L	1	Values to be less than or equal to the value listed in 90% of samples
Ethinylestradiol	ng/L	0.1	Values to be less than or equal to the value listed in 90% of samples
Total predicted no-effect concentration	ng/L	1	Values to be less than or equal to the value listed in 90% of samples
Nonylphenol	ng/L	7	Values to be less than or equal to the value listed in 90% of samples

4.4.1.4 Chemical Use

Fourteen chemicals are used at the LPAWTP site for all the processes. The chemicals and the associated feed points are as follows:

- Ferric chloride, clarification
- Sodium hydroxide, MF cleaning, RO clean in place (CIP), neutralization
- Aqueous ammonia, clarification/MF feed, chloramination
- Sodium hypochlorite, clarification/MF feed (chloramination), finished water, MF cleaning
- Sodium bisulfite, finished water, MF/CIP neutralization, MF filtrate
- Hydrogen peroxide, UV influent
- Carbon dioxide, finished water
- Antiscalant, RO first pass
- Sodium lauryl sulfate, RO CIP
- Hydrochloric acid, RO CIP
- Citric acid, MF CIP, RO cleaning

- Sulfuric acid, MF CIP, neutralization, MF cleaning
- Polymer, clarification, centrifuge dewatering, thickening MF backwash system
- Lime, finished water

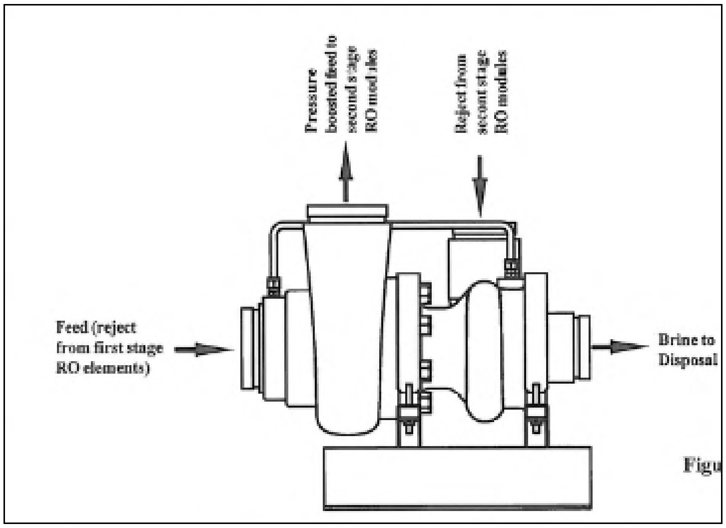


Figure 4.9. Flow streams for a turbocharger.

4.4.2 ERD Evaluation and Selection

Four ERI HTCs, one per RO train, are installed at the LPAWTP. The HTC provides a pressure boost between second-stage concentrate and third-stage feed. The third-stage reject is used for pressure boost. Figure 4.9 illustrates typical streams for a turbocharger.

Information on the ERDs at the LPAWTP is summarized as follows:

- ERD type: HTC
- Number of ERDs: four (one on each train)
- Manufacturer: ERI
- Model: LPT-2000
- Maximum operating pressure: 600 psi

The HTCs enable a reduction in the size of the RO feed pump motors to 845 hp (630 kW), thereby providing lower operating costs and the ability to balance flux rates in each stage to reduce the fouling potential.

A detailed quantitative analysis of energy recovery was not conducted during the design phase of the LPAWTP. Turbocharger ERDs were selected because of the number of installations and reliability, and the devices have proven to be effective. An ERD installation at the plant is shown in Figure 4.10.

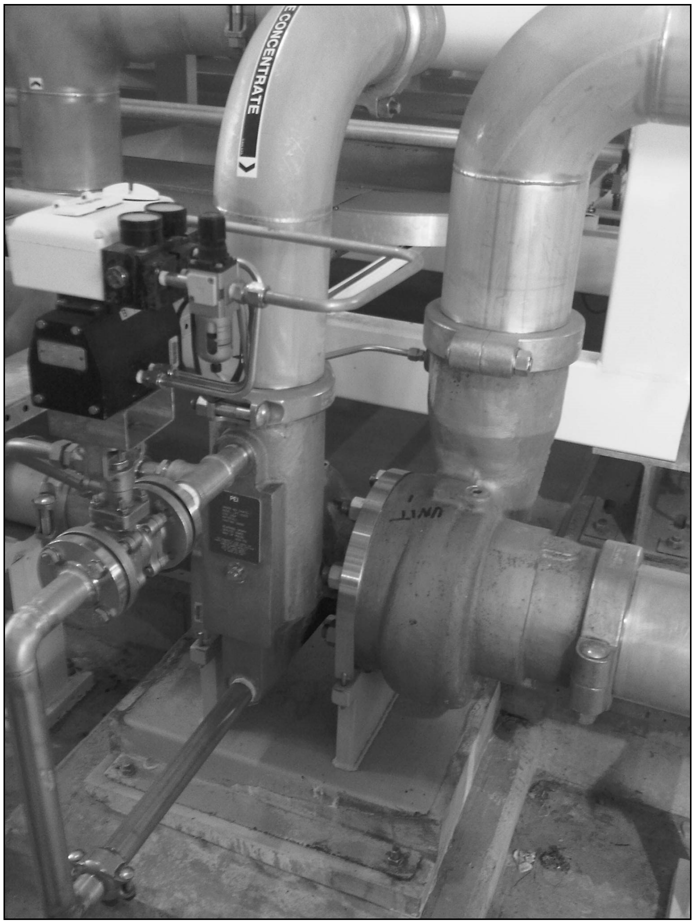


Figure 4.10. Turbocharger installation at LPAWTP.

4.4.3 Modeling Simulation of Case Study

4.4.3.1 Results of Modeling Simulation

LPAWTP has a three-stage RO system. For multistage RO systems, the turbochargers are typically installed between stages to provide a multistage boost and therefore a higher net driving pressure for downstream stages. This has the benefit of providing additional balance to the individual stage flux rates in the RO train. Hypothetically, a turbocharger could be installed to boost the feed to the entire system, but this is rarely done. Turbocharger efficiencies, as explained in Chapter 3, are heavily influenced by the reject ratio, which is the ratio of the concentrate flow over the boosted flow (the feed flow in this case). If this ratio is substantially lower than 50%, the efficiency of the turbocharger suffers. If the recovery of the RO system is 60% or higher, the reject ratio for boosting the RO feed will be 40% or lower.

Therefore, in a three-stage system, the turbocharger can be inserted before either the second or third stage. The tool provided the PFDs shown in Figures 4.11, 4.12, and 4.13 for single RO trains for the LPAWTP with no turbocharger, turbocharger insertion upstream of the second stage, and turbocharger insertion upstream of the third stage, respectively.

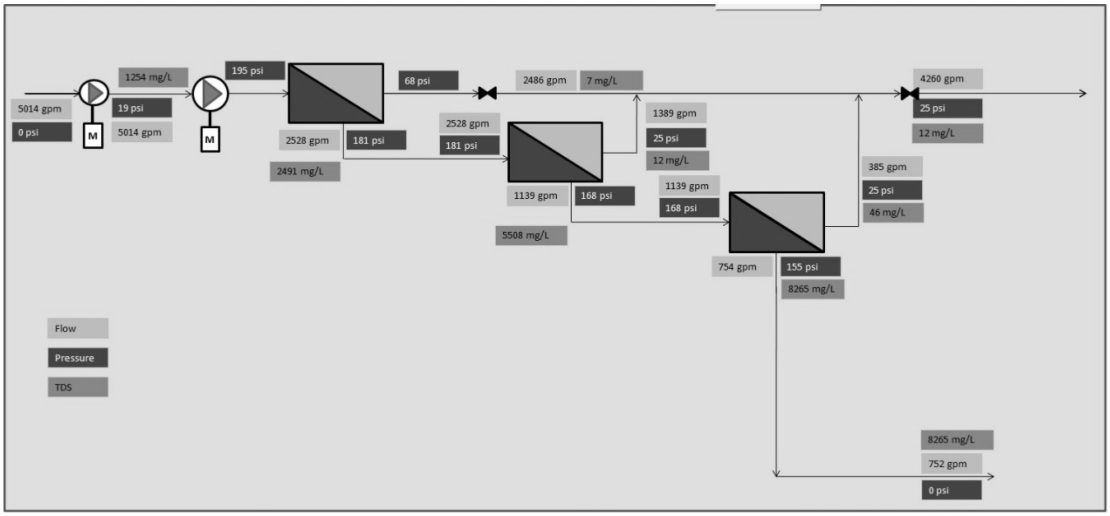


Figure 4.11. Tool PFD of LPAWTP RO train.

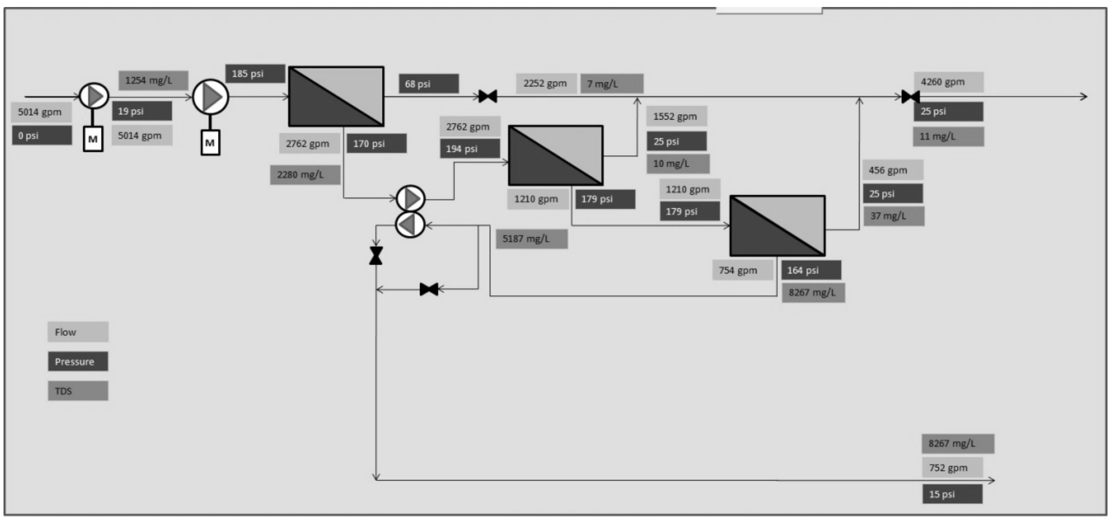


Figure 4.12. Tool PFD of LPAWTP RO train with turbocharger upstream of Stage 2.

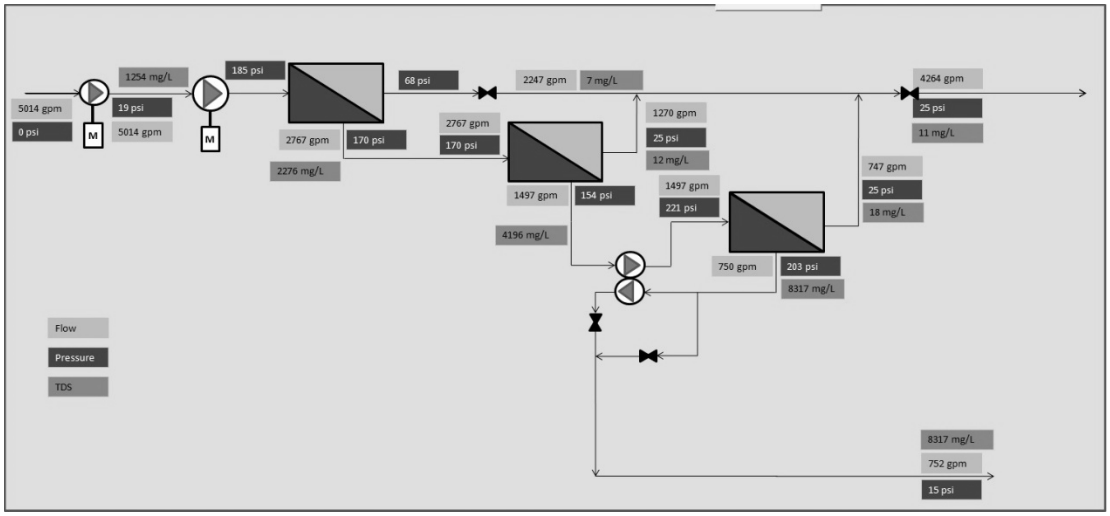


Figure 4.13. Tool PFD of LPAWTP RO train with turbocharger upstream of Stage 3.

4.4.3.2 Comparison of Tool Simulation to Actual Operation

The turbocharger was installed as a boost to the third stage. A snapshot of the actual data from the site taken June 8, 2011 is shown in Figure 4.10 and compared with the operation predicted by the tool. The operational permeate backpressure is 25 psi, and an additional 43 psi is applied to the first stage for flux balancing. Actual permeate flow, feed temperature, and recovery were 4262 gpm, 21 °C, and 80%, respectively.

4.4.4 Conclusion

The tool estimates that the power usages at the LPAQTP are as follows:

- 544 kW per RO train without a turbocharger
- 514 kW per RO train with the turbocharger placed before either the second or third stage

At $0.08 per kWh, the difference in energy savings is approximately $21,000 per year.

With this amount of energy savings, the question is whether it is really worthwhile to add a turbocharger to the system, and, if so, where to place it. These questions can be answered by comparing the present worth of RO equipment and energy, as well as the ERD payback period. The payback period and present worth cost of the RO equipment and energy use are strongly dependent on the discount rate assumed for the present worth duration. The present worth duration is typically linked with the expected life of the RO equipment, and the industry standard is 25 years. Assuming an energy cost of $0.08 per kWh, and a present worth duration of 25 years, the tool estimates the costs and payback period presented in Table 4.20.

Table 4.19. Luggage Point Snapshot vs. Tool Prediction

Constituent	Units	Actual Operation	Tool Prediction
First-stage feed pressure	psi	176	185
First-stage concentrate flow/pressure	gpm/psi	2551/159	2767/170
Second-stage concentrate flow/pressure	gpm/psi	1411/146	1497/154
Third-stage feed/ turbocharger boost pressure	psi/psi	218/72	221/67

Table 4.20. Present Worth Cost and Payback Period

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1000 gal)	Present Worth Cost of RO Equipment and Power ($/1000 gal) with Turbocharger Before Second or Third Stage	ERD Payback Period (years) with Turbocharger Before Second/Third Stage
6%	0.23	0.22	23/12
3%	0.27	0.26	17/9
0%	0.34	0.33	12/6

Based on the present worth costs, it is not apparent that the addition of a turbocharger to the LPAWTP is economically beneficial. However, close examination of the ERD payback period shows that turbocharger implementation is economically beneficial, as the payoff occurs before the life of the equipment ends, regardless of the discount rate assumed during the present worth duration. The reason for the difference in payback period between stages is that the turbocharger size and cost are related to the quantity of the flow that is boosted. This flow is lowest in front of the third stage. For the LPAWTP, the difference in installed capital cost between placing the turbocharger in front of the second stage or the third stage amounted to about $110,000, with $70,000 of this attributed to the smaller turbocharger cost. This savings tipped the balance in favor of placing the turbocharger in front of the third stage of the system.

The comparison between the actual operating data and the tool (Table 4.19) indicate that the predicted membrane feed pressure and turbocharger boost pressures are accurate within 5% and 7%, respectively.

4.4.5 Lessons Learned

The efficiency of a turbocharger is strongly influenced by the reject ratio and the boosted flow. For these reasons, it is typical to place the turbocharger between stages in a multistage RO train and, in most cases, before the last stage of the RO train.

4.5 Case Study #4: Tampa Bay Water, Desalination Plant

4.5.1 Basis of Selection

Tampa Bay Water is Florida's largest wholesale water provider. The Tampa Bay Seawater Desalination Facility (TBSDF) is one of the treatment facilities it operates.

4.5.1.1 Plant Description

The TBSDF is located near Apollo Beach in southern Hillsborough County. It is currently the largest operating SWRO facility in North America, with an average capacity of 25 mgd. The plant consists of the following treatment process trains:

- Raw water screening
- Coagulation and flocculation systems
- Single-stage sand filtration system followed by diatomaceous earth precoat filtration system
- Chemical storage and feed systems
- Residuals treatment system
- SWRO system

The basis of design for the pretreatment unit processes has been to meet the following water quality goals for the RO feed water:

- Turbidity < 1.0 NTU
- SDI < 4.0
- pH 6.5

Additional pretreatment goals include:

- SDI_{15} < 2 with a standard deviation of 1
- Particle counts 2-3 µm (per mL) < 50
- Total iron (µg/L) < 20

The TBSDF has been designed with a minimum permeate production capacity of 8 mgd, an average flow of 25 mgd, and a maximum flow of 28.75 mgd.

TBSDF consists of a two-pass RO system. The first pass has seven trains, with six of the trains used to meet the average 25-mgd production. The seventh first-pass train is used when the maximum flow of 28.75 mgd is required.

Each first-pass RO train includes the following components:

- 5-µm cartridge filter
- High-pressure feed pump
- RO membrane skid
- Pelton-Wheel-type energy recovery turbine

The second pass has six trains. The number of online trains depends on the chloride level in the first-pass permeate, which in turn is a function of feed water salinity, temperature, and membrane flux.

The profile of ions in the feed water remains relatively constant over the range of salinity. The variation in feed water salinity is attributable to the dilution effects of brackish rivers, creeks, and rainfall.

A schematic for the plant's pretreatment process is presented in Figure 4.14. The RO system schematic is included in Figure 4.15.

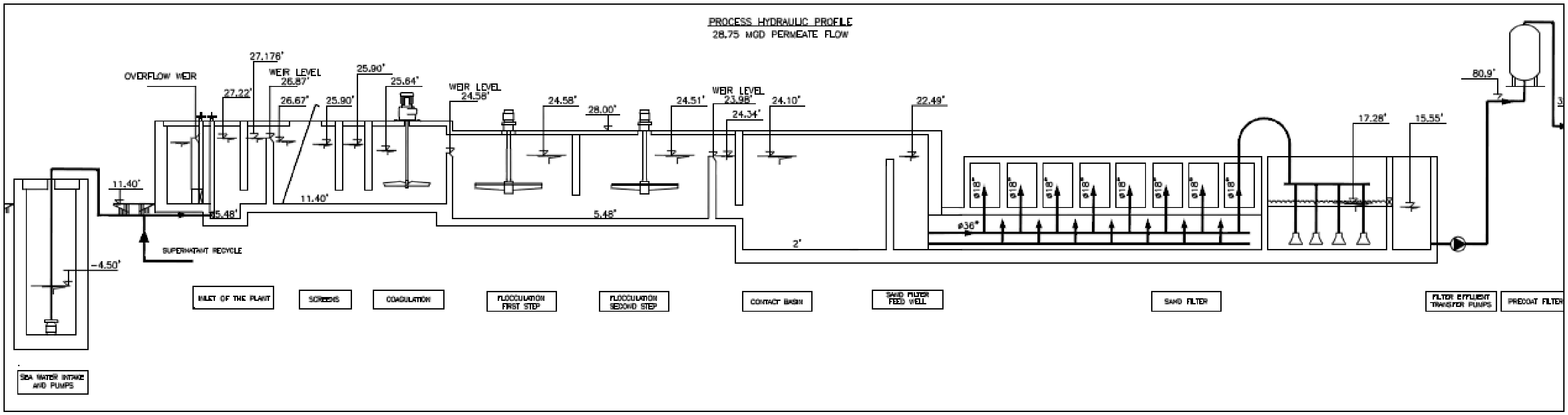


Figure 4.14. TBSDF pretreatment PFD.

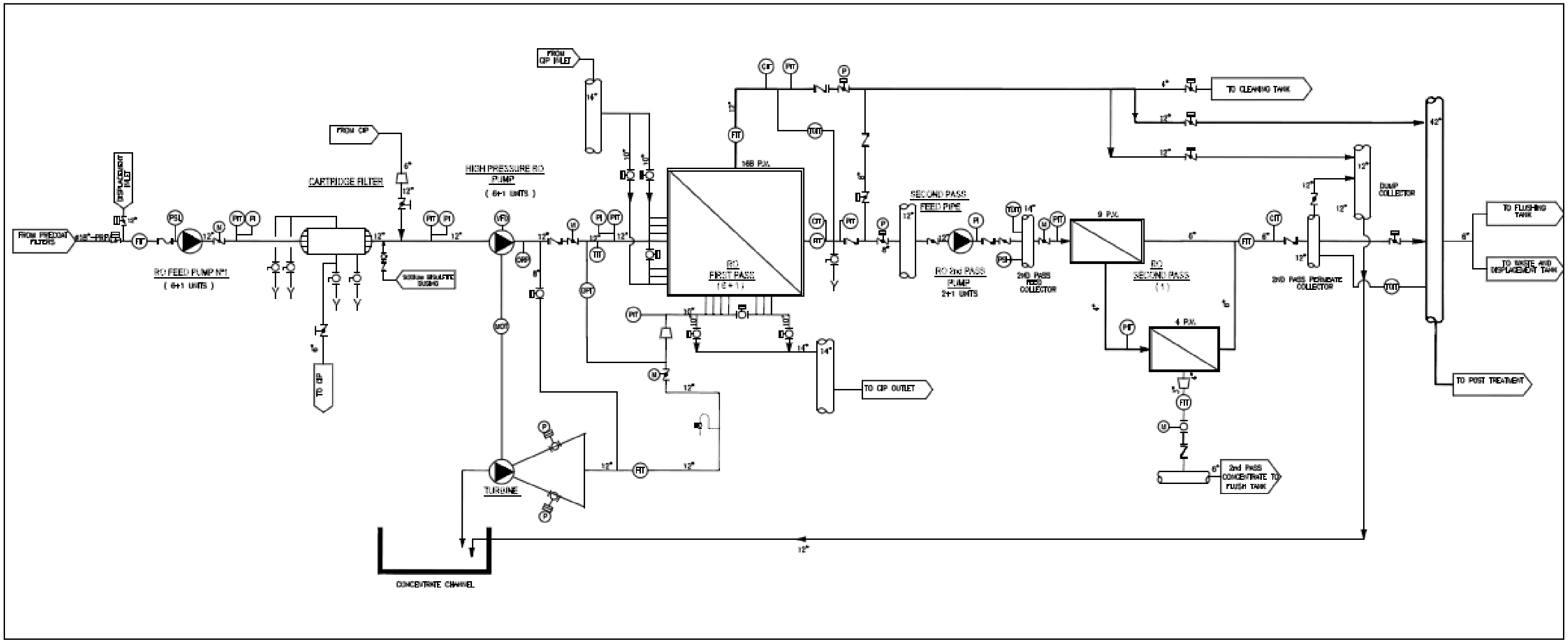


Figure 4.15. TBSDF RO system PFD.

Table 4.21. TBSDF Reverse Osmosis Plant Features

Parameter	Units	First Pass	Second Pass
Permeate capacity	mgd (m^3/d)	25 (95,000)	
Number of trains	trains	7	6
Design permeate recovery	%	60	90
Design feed TDS	mg/L	18,500–31,000	700–2200
Design feed pressure	psi (kPa)	564–985 (3889–6791)	126–250 (869–1725)
Average permeate flux	gfd (lmh)	8.5 (14.5)	11–23 (18.7–39.1)
Number of pressure vessels per train	vessels	168	13
Array	array	168	9 × 4
Elements per pressure vessel	elements	8	8
Total number of elements per train	elements/train	1344	104
Membrane element area, each	ft^2	380	380
Element type		SW30HR-380	SW30HR-380
Number of RO feed pumps	pumps	7	3
Feed pump motor horsepower	HP	2000	450
Feed pump capacity	gpm	4907	2130
Energy recovery device	—	Pelton Wheel	N/A

4.5.1.2 Desalination Plant Features

Table 4.21 summarizes the features of the TBSDF.

4.5.1.3 Water Quality

Table 4.22 presents the feed water quality assumed for the TBSDF design.

Water quality standards have been assigned by Tampa Bay Water to define the specific treatment requirements and the basis of design for the TBSDF. The contractual standards are more stringent than local and federal drinking water standards. Table 4.23 lists the product water quality parameters.

Table 4.22. TBSDF SWRO Feed Water Design Values

Parameter	Units	Source Water Quality
pH	—	8.5
Total dissolved solids	mg/L	31,000
Turbidity	NTU	15
Temperature	°C	15
Chloride	mg/L	18,000
Calcium hardness	mg/L as $CaCO_3$	900
Bromide	mg/L	1.2

Table 4.23. TBSDF Product Water Quality Contract Standards

Parameter	Units	Contractual Standard
Antimony	mg/L	0.006 (max)
Arsenic	mg/L	0.01 (max)
Asbestos	mg/L	7 (max)
Barium	mg/L	2 (max)
Beryllium	mg/L	0.004
Cadmium	mg/L	0.005
Chromium	mg/L	0.1
Cyanide	mg/L	0.2
Fluoride	mg/L	0.8
Lead	mg/L	0.015
Mercury	mg/L	0.002
Nickel	mg/L	0.1
Selenium	mg/L	0.05
Sodium	mg/L	80
Thallium	mg/L	0.002
Microbiological—total coliform	CFU/100 mL	<1
Radiochemical—gross alpha	pCi/L	5
Turbidity	NTU	0.3
Aluminum	mg/L	0.2
Chloride	mg/L	100
Copper	mg/L	1.0
Iron	mg/L	0.15
Manganese	mg/L	0.05
Silver	mg/L	0.1
Sulfate	mg/L	100
Zinc	mg/L	5
Color	PCU	15
Odor	TON	2 (max-avg)/3 (max)
pH		7.4 (min-week-avg)
Total dissolved solids	mg/L	500
Foaming agents	mg/L	0.5
Conductivity	µmho/cm	850
Temperature	°C	35
Total alkalinity	mg/L as CaCO3	40 (min-avg)
Total sulfide	mg/L	0.1 (avg)
Total hardness	mg/L as CaCO3	300
Calcium hardness	mg/L as CaCO3	50 (min-avg)/250 (max-avg)
TOC	mg/L	3.6 (max-avg)/6.6 (max)
Total phosphorus	mg/L	1
Ortho phosphorus	mg/L as P	1
Ammonia	mg/L as N	1
Assimilable organic carbon	µg/L	100
Heterotrophic plate count	CFU/ 1 mL	5
Bromide	mg/L	0.45
Chlorine residual	mg/L	4.0

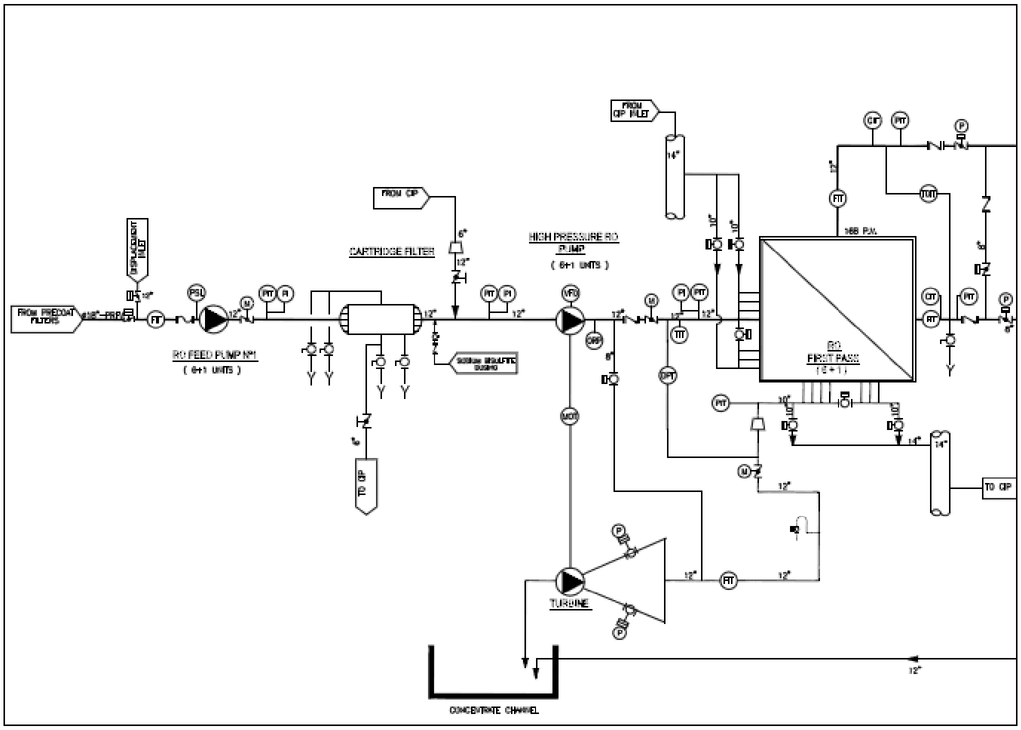


Figure 4.16. TBSDF ERD schematic.

4.5.1.4 Chemical Use

The following chemicals are used in the TBSDF treatment process:

- Chlorine dioxide, intake and RO permeate
- Ferric sulfate, before filters
- Polymer (if required), sand filter influent
- Sulfuric acid, RO feed
- Sodium bisulfite, RO feed
- Lime, RO permeate

4.5.2 ERD Evaluation and Selection

A Pelton-Wheel-type ERD is used at the TBDSF. The ERD is fed by the first-pass concentrate. A schematic of the ERD is shown in Figure 4.16.

The selection of the Pelton Wheel ERD was largely driven by lack of an established experience base for isobaric devices of sufficient capacity at the time the plant was initially designed. During the initial design, conducted by Stone & Webster in 1999, an evaluation of ERD technology was conducted. Based on the evaluation, no isobaric devices of sufficient capacity were available that had sufficient experience to manage the risk. The first installation of PX units was in 1997, with no sizable installations prior to Tampa Bay.

Each high-pressure feed pump at the TBSDF utilizes a Pelton-Wheel-type ERD manufactured by Calder AG, Model RO-350-100-2. The ERD produces energy by recovering the excess high-pressure energy in the first-pass concentrate stream before it is discharged. Each ERD is driven by concentrate flow at a variable pressure range of 572 to 970 psi.

The ERD installed allowed a 27% reduction in the high-pressure feed pump motor sizing. During the design phase, it was estimated that a 28% to 32% energy cost reduction would be achieved in the operation of the first-pass RO system. This equated to an energy cost savings of 24% to 28% in the entire plant operation. The ERDs at the TBSDF are believed to be 86% to 88% efficient.

4.5.3 Modeling Simulation of Case Study

4.5.3.1 Results of Modeling Simulation

The TBSDF operating staff reports that the energy use of a single RO train is approximately 1325 kW in May 2012 under the following conditions:

- 2750 gpm permeate flow
- 58.5% recovery
- Membrane feed pressure 950 psig
- HP RO feed pump suction pressure 200 psig

Under these conditions, the tool produces the PFD shown in Figure 4.17 of a sample TBSDF first-pass RO train with a Pelton Wheel ERD.

4.5.3.2 Comparison of Model Simulation to Recorded Data

The tool predicts that the energy use of the RO feed pump/Pelton Wheel combination will be 1355 kW operating under the conditions listed in Section 4.5.3.1. This is within 4% of the value reported by the operating staff of the plant.

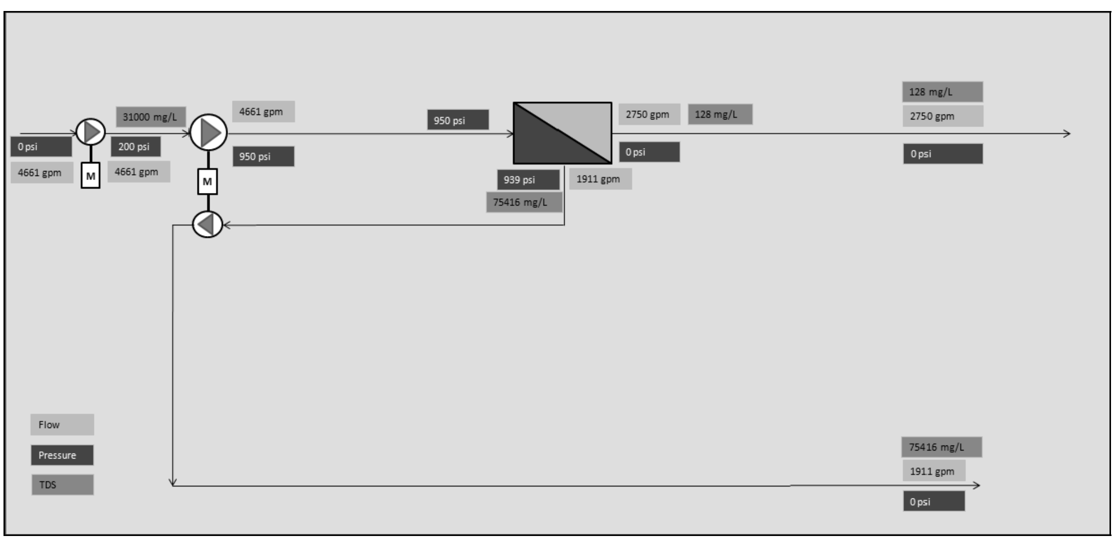


Figure 4.17. Model PFD of Tampa Bay first-pass RO train with Pelton Wheel.

Table 4.24. TBSDF First-Pass Reverse Osmosis Model Prediction

	ERD Efficiency	Energy Use (kWh/1,000 gal)	Percent Reduction in Energy Use
No ERD	N/A	15.1	N/A
Pelton Wheel Calder RO-350-100-2	88%	10.9	28%
Isobaric ERD	98%	9.8	35%

4.5.4 Conclusion

The tool predicts energy use of the individual TBSDF RO trains as shown in Table 4.24.

According to the tool, the Pelton Wheel lowers the energy use of the RO by 28%, which is within the estimated range of 28% to 32% and is in agreement with the engineer's estimate. It is unfortunate that the isobaric ERD was not included in the first-pass design in lieu of the Pelton Wheel as the energy savings would have been substantially higher.

Although the energy savings with the ERDs is substantial, it is important to analyze the present worth costs to understand the payback period. Table 4.25 summarizes the present worth cost of energy and RO train equipment assuming an energy cost of $0.08 per kWh and a present worth duration of 25 years.

4.5.5 Lessons Learned

The Pelton Wheel was an appropriate ERD for use at the TBSDF at the time it was designed as it provides a lower cost of water produced than having no ERD. However, today's choice would clearly one of the isobaric ERDs, which deliver the lowest present worth cost.

Table 4.25. Present Worth Cost of First-Pass TBSDF

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal) No ERD	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Pelton Wheel	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Isobaric ERD	Pelton Wheel Payback Period (years)
6%	0.91	0.74	0.69	0.7
3%	1.1	0.92	0.85	0.5
0%	1.5	1.2	1.1	0.4

4.6 Case Study #5: Perth Seawater Desalination Plant, Kwinana Beach, Australia

4.6.1 Basis of Selection

The Perth Seawater Desalination Plant (PSDP) in Kwinana Beach in Perth, Western Australia, was started up in November 2006. The SWRO plant has a total capacity of 38 mgd (144,000 m^3/d). At the time of commissioning, the PSDP was the biggest SWRO plant in the southern hemisphere and the largest water supplier for the city of Perth, supplying 17% of the city's demand. The main treatment objectives at the PSDP are to have TDS below 200 mg/L, maximum bromide concentration of 100 µg/L, and alkalinity as $CaCO_3$ higher than 50 mg/L.

During the design phase of the PSDP, the public demanded that the energy use be offset with renewable energy generation. Because the SWRO process is energy-intensive, the plant was an ideal candidate for several options. The joint venture responsible for the design and construction was instrumental in the development of a wind farm in Western Australia. The wind farm has a capacity of 80 megawatts (MW)—three times the maximum demand of the PSDP. In addition to this renewable energy plant, ERI's PX technology was implemented in the design to further reduce energy use at the plant.

4.6.1.1 Plant Description

The PSDP draws feed seawater from an intake in nearby Cockburn Sound, approximately 660 ft (200 m) offshore. Six pumps convey water through traveling screens. A total of 24 dual-media filter vessels and 14 5-µm cartridge filters are used as a pretreatment step before further treatment with a two-pass RO process. The plant is built in two identical halves, and one half can be operated while the other is off line for maintenance. Redundancy is built into the overall capacity for expected maintenance downtime.

The first pass consists of 12 SWRO trains and is fed with six split-case high-pressure centrifugal pumps. Each pump has a capacity of 5040 gpm (1144 m^3/hr) and is driven by 3490-hp (2600-kW) motors. The maximum efficiency of the pumps is 86%. Each first-pass train has 162 Protec 7M side-port pressure vessels with seven Filmtec SW30HR-LE400 membrane elements per vessel. The permeate from the first pass goes through further treatment in the second pass.

The second pass consists of six low-pressure BWRO trains with 104 vessels each. Each vessel houses seven BW30-LE440 membrane modules. Each pass has over 10% free space for expansion.

Treated water is stored in a 330,000-gal (12,500-m^3) onsite tank and transferred to Thompson Reservoir located 7.5 mi (12 km) east of the plant. The PSDP is installed with a sludge treatment facility.

The general PFD for the plant is presented in Figure 4.18.

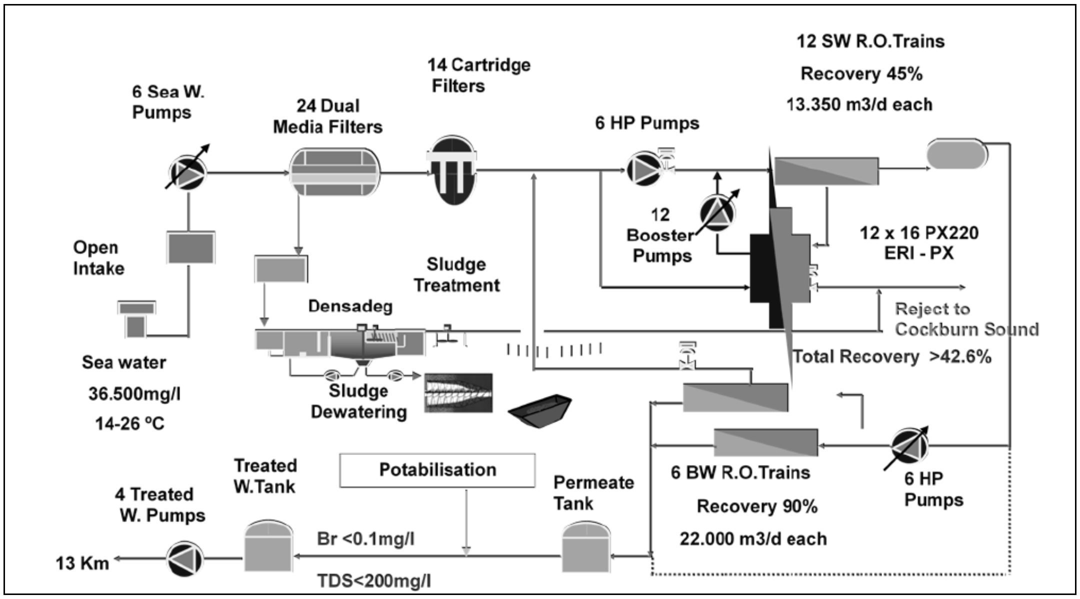


Figure 4.18. PSDP flow diagram.

The RO system schematic is presented in Figure 4.19.

Energy recovery is provided by 12 trains of 16 ERI Model PX-220 ERDs. Each train has a capacity of 3520 gpm (800 m^3/h). Figure 4.20 shows a flow diagram for the energy recovery setup at the PSDP.

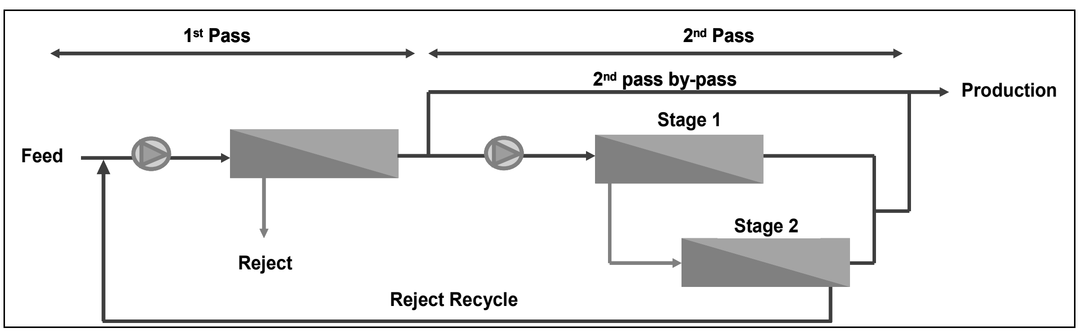


Figure 4.19. PSDP RO system schematic arrangement.

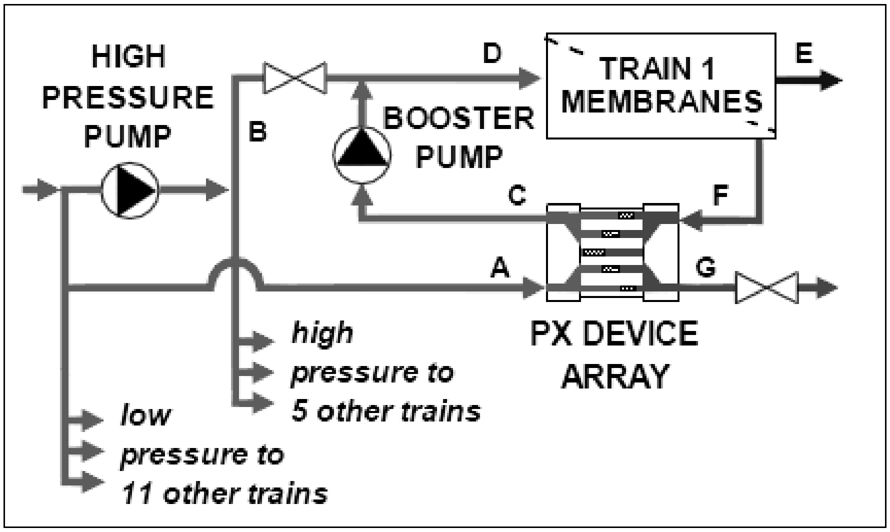


Figure 4.20. PSDP first-pass SWRO process and energy recovery schematic.

4.6.1.2 Desalination Plant Features

Table 4.26 summarizes the PSDP features.

Table 4.26. Desalination Plant Features

Parameter	Feature
Permeate capacity	38 mgd (144,000 m^3/d)
Design permeate recovery	45%—first pass 90%—second pass
Design feed TDS	36,000 – 37,100 mg/L
Design feed pressure	908 psi (6260 kPa)
Maximum differential pressure (first pass - second pass)	760 psi (5240 kPa)
Average permeate flux	7.76 gfd (13.2 lmh)—first pass 19.9 gfd (33.9 lmh)—second pass
Number of pressure vessels per train	162—first pass 104—second pass
Elements per pressure vessel	7
Total number of elements per train	1,134—first pass 728—second pass
Membrane element area, each	400 ft^2—first pass 440 ft^2—second pass
Element type	High-pressure SWRO (Filmtec SW30HR-LE400)—first pass Low-pressure BWRO (Filmtec BW30LE440)—second pass
Feed pump design point	5037 gpm (1,144 m^3/h) @ 908 psi (6260 kPa) TDH—first pass 4033 gpm (916 m^3/h) @ 145 psi (1000 kPa) TDH—second pass primary 4482 gpm (1018 m^3/h) @ 232 (1600 kPa) TDH—second pass secondary
Feed pump motor horsepower	2340 kW—first pass
Energy recovery device	Pressure exchanger—ERI PX 220

Table 4.27. Seawater Results Obtained by the Joint Venture during the Water Study and Pilot Plant Program

		Water Study		Pilot Plant
Analysis	**Units**	**1/07/2004**	**7/07/2004**	**7/12/2004**
Temperature	°C	18	17.6	23.5
pH	—	8.24	8.24	8.17
Conductivity	mS/cm	53.2	53.5	53.5
Sodium	mg/L	11,250	11,400	11,350
Potassium	mg/L	390	390	420
Calcium	mg/L	410	405	435
Magnesium	mg/L	1300	1355	1380
Boron	mg/L	4.9	4.9	4.7
Strontium	mg/L	8	7.7	8.4
Bromide	mg/L	67	68	62.5
Fluoride	mg/L	1.5	1.5	0.6
Chloride	mg/L	19,700	19,700	20,500
Sulfate	mg/L	2730	2760	2770
Bicarbonate	mg/L	152	154	160
TDS by summation	mg/L	36,013	36,246	37,091
Sum of major cations	meq/L	629.0	639.9	642.0
Sum of major anions	meq/L	615.2	615.9	638.6

4.6.1.3 Water Quality

A seawater testing program undertaken between June and August 2002 reported a variation in the TDS between 35,500 and 36,730 mg/L. The ionic composition was not reported.

Results of the seawater analyses carried out as part of the joint-venture pilot plant program conducted in 2004 are shown in Table 4.27.

The ionic breakdown used in the plant design is presented in Table 4.28.

Table 4.28. Feed Water Ionic Breakdown

Constituent	Units	Lower Salinity	Average Salinity	Higher Salinity	Finished Water Goal
pH	–	8.25	8.25	8.25	7.50–8.0
TDS	mg/L	36,000	36,500	37,100	<200
Calcium	mg/L	405	420	435	
Bromide	mg/L		67		<0.1
Boron	mg/L		4.7		<2.0
Magnesium	mg/L	1300	1340	1380	<0.02
Sodium	mg/L	11,090	11,190	11,335	
Chloride	mg/L	19,858	20,152	20,511	0.5–1
Sulfate	mg/L	2730	2750	2770	
Total hardness	mg/L as $CaCO_3$	6500	6600	6700	<10
Total alkalinity	mg/L as $CaCO_3$		152–160		<50

4.6.1.4 Chemical Use

The following chemicals are used in the PSDP treatment process:

- Sulfuric acid for pH correction of the pressure filter influent
- Ferric chloride, primary coagulant to pressure filter influent
- Coagulant aid for enhanced coagulation prior to the pressure filters
- Anti-scalant, Nalco PC1020, as scale inhibitor dosed to the RO feed
- Sodium hypochlorite for shock dosing of the intake pipeline
- Sodium metabisulfite to neutralize any residual chlorine in the seawater following shock dosing with sodium hypochlorite
- Lime and carbon dioxide to increase permeate calcium alkalinity and pH to stabilize the finished water
- Chlorine for primary and secondary disinfection of the RO permeate
- Fluorosilicic acid to provide for fluoridation of the finished water

4.6.2 ERD Evaluation and Selection

During plant design, the Pelton Wheel, DWEER, and PX ERDs were considered. No other ERDs were considered commercially and technically viable.

The PX ERD was chosen during design after a life-cycle cost analysis of the three ERD alternatives. It was believed that the initial capital cost would be offset by operating cost savings over a 20- to 25-year period because of the size of the plant. It was determined that the PX pressure exchangers would reduce the overall energy consumption by 60%, compared to 20% for a Pelton Wheel-type ERD.

There were several advantages and disadvantages associated with all of the systems. A Pelton Wheel must discharge at atmospheric pressure, which would require an open outlet channel on the plant floor. Because of the location of the plant, further pumping would be required to discharge the brine.

The DWEER and PX devices transfer energy directly to the feed seawater by the use of a smaller booster pump. This would equate to a significant reduction in required power; however, both systems increase the salinity of the feed water because of cross contamination, resulting in a slight increase in energy use. On the other hand, neither device would require extra pumping of the discharge waste because of slight pressure in the line. Both devices also had 0.5 kWh/m^3 less power requirement than a Pelton Wheel.

In evaluating reliability for maintenance requirements, the DWEER technology was considered the least favorable because of all the moving parts and valves associated with the system.

The PX device was selected for use at the PSDP. A dedicated pressure exchanger train with 16 PX-220 devices was installed on each first-pass RO train. A dedicated booster pump also was installed after each pressure exchanger train to boost the RO feed pressure. The process schematic is presented in Figure 4.21.

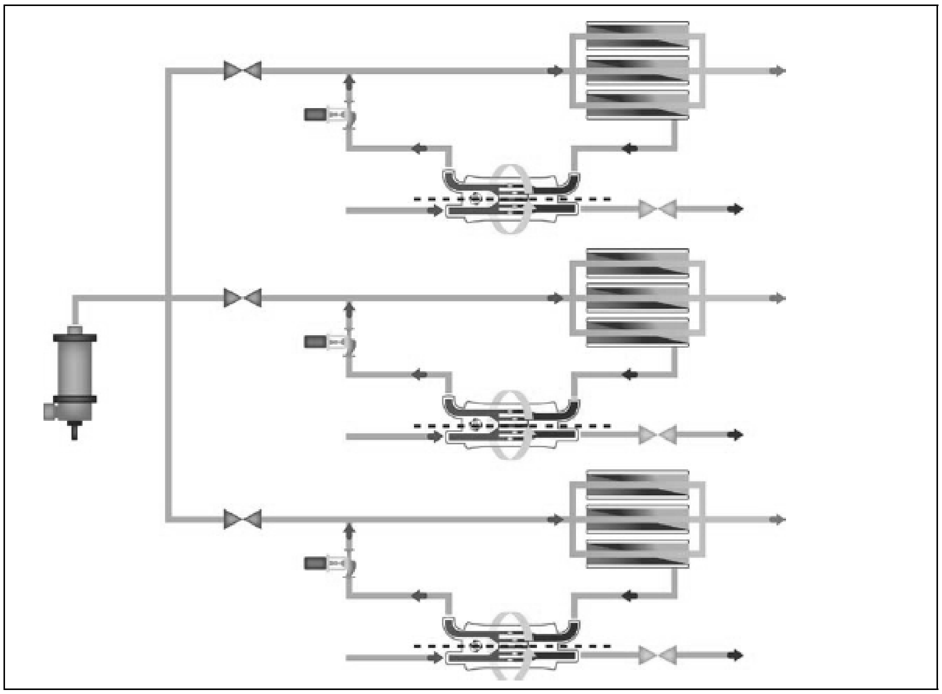


Figure 4.21. PSDP PX schematic.

The PSDP operational data indicate that the ERDs were 96% efficient. Feedback from the PX system's operation is positive.

The plant energy consumption ranges from 3.2 to 3.8 kWh/m^3, including intake and transfer into the distribution system. On the average, the SEC for the HPP is 2.40 kWh/m^3, and the energy consumption for the booster pump after the ERD is 0.07 kWh/m^3, bringing the total average SEC for the plant to 2.5 kWh/m^3.

A PX-220 train (16 PX-220 array) used at the PSDP has a maximum flow of 3520 gpm (800 m^3/h), but operates on an average flow of 2976 gpm (675 m^3/h). A photograph of one of the plant's 12 PX-220 trains, containing 16 PX-220 units operating in parallel, is presented in Figure 4.22.

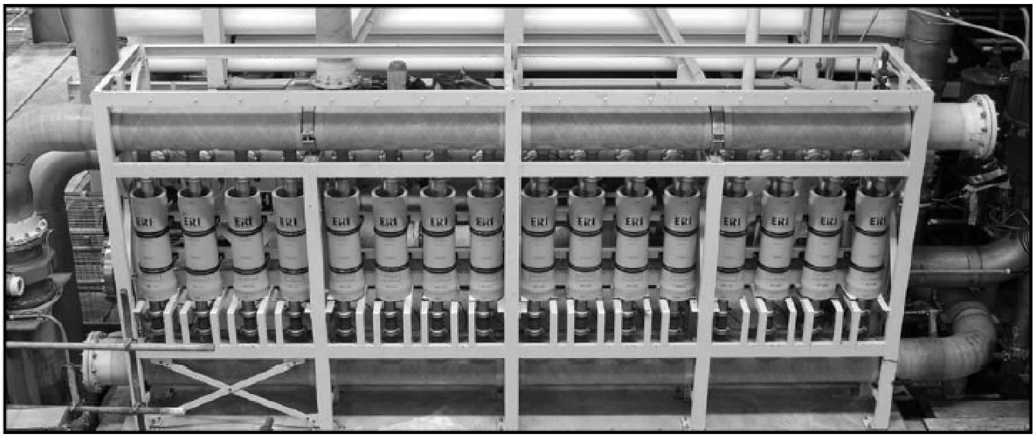


Figure 4.22. PSDP typical PX-220 train.

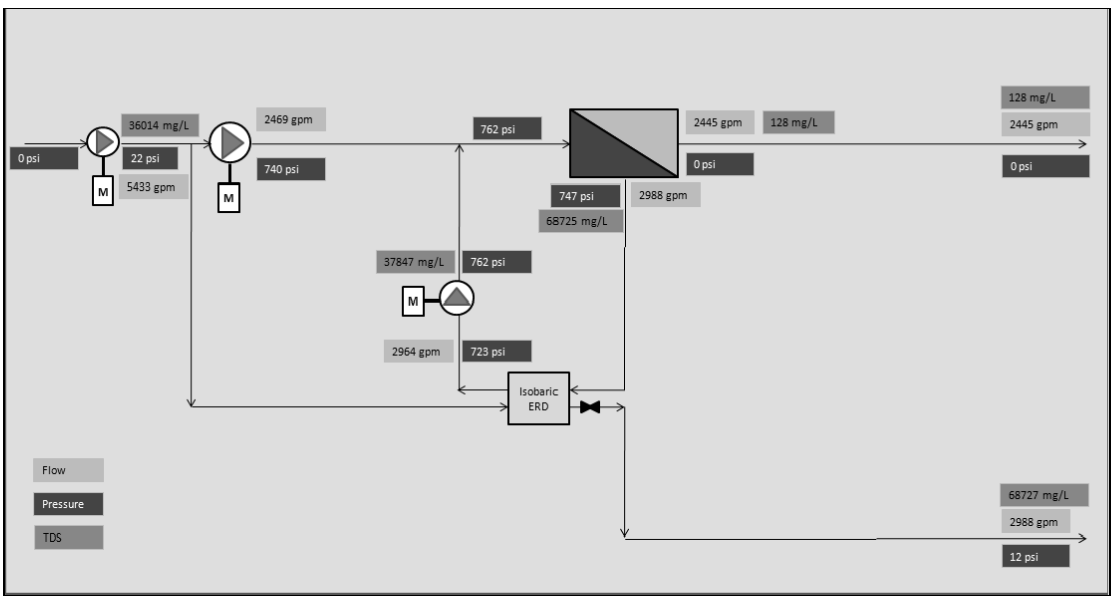


Figure 4.23. Model PFD of PSDP train.

Booster pumps for each RO train have a capacity of 2910 gpm (661 m^3/h) at 39 m of differential head, and are driven by 112-kW VFD controlled motors.

4.6.3 Modeling Simulation of Case Study

4.6.3.1 Results of Modeling Simulation

The tool provided the PFD shown in Figure 4.23 for a PSDP RO train incorporating the PX isobaric ERD.

4.6.3.2 Comparison on Model Simulation to Recorded Data

Based on the tool's calculations, the PSDP RO energy consumption with the PX ERD will be 7.7 kWh/1000 gal, or 2.0 kWh/m^3. This assumes that the RO high-pressure feed pump is operating at its maximum efficiency of 86%. Although 2.0 kWh/m^3 is substantially less than the 2.5 kWh/m^3 reported from Kwinana, the feed pumps at Kwinana are not dedicated per train. The plant uses a common feed pumping scheme, and individual RO train feed throttling valves control the feed pressure and permeate flow of each train. These valves will waste some energy, which possibly explains the difference.

4.6.4 Conclusion

The PX, DWEER, and Pelton Wheel ERDs were considered for the PSDP. Table 4.29 summarizes the predicted energy use of the RO system with each of these ERDs, as well as the system with no ERD. As with most SWRO systems, the introduction of an ERD will provide substantial energy savings. The tool predicts that the isobaric ERDs, namely the PX and the DWEER, will reduce the energy consumption by slightly over 50%. Although this is not quite the 60% assumed during the design phase, it is substantial nonetheless.

Table 4.29. PSDP Model Predictions

ERD	Predicted RO Energy Use (kWh/1,000 gal)	Predicted RO Energy Use (kWh/m^3)	Percent Energy Savings
None	15.0	4.0	N/A
DWEER	7.5	2.0	50
PX	7.7	2.0	49
Pelton Wheel	9.2	2.4	39

Table 4.30. PSDP Present Worth Comparisons for PX, DWEER, and Pelton Wheel

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal) No ERD	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with ERI PX	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with DWEER	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Pelton Wheel
6%	0.95	0.63	0.62	0.70
3%	1.2	0.77	0.75	0.85
0%	1.6	1.0	0.96	1.1

Table 4.31. Present Worth and Payback Period

Discount Rate	ERI PX Payback Period (years)
6%	1.2
3%	0.77
0%	0.60

A reduction in SEC is the major benefit of incorporating an ERD into the RO system design, but the capital costs of adding the equipment need to be included in the analysis to determine the best ERD selection. This is achieved by analyzing the present worth costs of both RO equipment, including the necessary ERD equipment, and the energy use over the equipment life. Payback period and present worth cost of the RO equipment and energy use are strongly dependent on the discount rate assumed for the present worth duration. The present worth duration is typically linked with the expected life of the RO equipment, and the industry standard is 25 years. Assuming an energy cost of $0.08 per kWh and a present worth duration of 25 years, the tool estimates the present worth costs shown in Table 4.30.

Based on the tool's present worth calculations, either the DWEER or the PX is the most economical choice of ERD to implement. The present worth cost of the Pelton Wheel is substantially higher.

The energy savings associated with implementing the PX at the PSDP are estimated to be $815,000 per year per RO train. This results in a very rapid payback period for the ERD equipment, as shown in Table.31.

4.6.5 Lessons Learned

For SWRO, the payback period for the implementation of an ERD is quite short, as the energy savings are substantial compared to the capital cost investment of the ERD equipment. Furthermore, the isobaric ERDs, such as DWEER and PX, have efficiencies in excess of 95%, substantially higher than the Pelton Wheel, which has a maximum efficiency of about 90%. For this reason, the isobaric ERDs are being implemented on the majority of the larger SWRO systems today.

Chapter 5

Conclusion and Recommendations

5.1 Conclusions

5.1.1 Model Use

The goal of this project is to provide a useful planning tool to help utilities, regulators, engineers, and other stakeholders determine whether an ERD is appropriate (i.e., cost-effective) for a RO application and, if so, to select the most appropriate ERD for the specific application.

The tool is structured so that the common user can input basic system parameters through a single interface page and then select one or more ERDs for consideration. The tool then works through a series of calculations and outputs the results for each ERD selected. The advanced user can use the tool to compare various system parameters and their impact on ERD selection and costs. Although this tool will produce membrane projections, it is not intended to replace currently available projection software for RO manufacturers. Instead, the projections are estimates to support the ERD selection analysis.

The tool produces energy consumption comparison and costing information for various ERDs. These outputs are estimates to be used for preliminary planning purposes. Stakeholders should continue to work with engineers and vendors to obtain specific system quotes for ERD equipment.

5.1.2 ERD Selection for Inclusion in the Model

In developing the model, ERD products were included based on a number of criteria. First, only products that were commercially available at the time of model development were included. Second, the selected device had to have been installed in more than five applications.

Most municipal desalination plants are 0.2 mgd or greater capacity. Therefore, technologies currently available only in installations less than 100,000 gpd were eliminated from consideration. Certain ERDs, like the DWEER, have a minimum capacity unsuitable for small RO systems.

Last, devices where adequate cost or performance data were not provided by the manufacturer or were not readily available from the literature were not included in the model.

Tables 5.1 and 5.2 list decision matrices for the selected centrifugal and isobaric ERDs, respectively.

Table 5.1. Centrifugal ERD Selection Information

	High-Pressure Pump/Motor Type			Turbocharger Type	
Parameter	**Flowserve/ Calder Pelton Wheel**	**Deutching Pumpen Pelton Wheel**	**Francis Turbine***	**PEI**	**FEDCO**
Commercially available?	Yes	Yes	Yes	Yes	Yes
Adequate number of installations (>5)?	Yes	Yes	Yes	Yes	Yes
Capacity appropriate to municipal clients?	Yes	Yes	Yes	Yes	Yes
Adequate cost/ performance information provided or available?	Yes	No	No	Yes	Yes
Included in model?	Yes	No	No*	Yes	Yes

*The Francis turbine is no longer a popular option, as other ERDs have higher efficiency.

Table 5.2. Isobaric ERD Selection Information

Parameter	PX	DWEER	SALTEC	RECUPER-ATOR	iSAVE
Commercially available?	Yes	Yes	Yes	Yes	Yes
Adequate number of installations (>5)?	Yes	Yes	Yes	Yes	Yes
Capacity appropriate to municipal clients?	Yes	Yes	Yes	Yes	Yes
Adequate cost/performance information provided or available?	Yes	Yes	No	No	No
Included in model?	Yes	Yes	No	No	No

To summarize, the following ERDs were selected for incorporation into the tool:

1. Turbochargers:
    a. FEDCO HPB.
    b. ERI LPT, HALO, and HTC. The LPT is for applications lower than 570 psig; HALO and HTC are smaller- and larger-volume turbochargers, respectively, for higher-pressure applications.
2. Flowserve/Calder Pelton Wheel.

3. Isobaric devices.
    a. ERI PX
    b. Flowserve/Calder DWEER

As more information is made available on the devices listed in Tables 5.1 and 5.2 that were not included in the model, as well as on other devices that become commercially available, the tool should be expanded to include these devices.

Table 5.3. Expanded Present Worth Cost of First-Pass TBSDF

Discount Rate	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Pelton Wheel	Present Worth Cost of RO Equipment and Power ($/1,000 gal) with Isobaric	Pelton Wheel Payback Period (years)	Isobaric Payback Period (years)
6%	0.68	0.62	1.2	**1.7**
3%	0.86	0.78	0.9	**1.3**
0%	1.2	1.0	0.6	**0.9**

5.1.3 Considerations for ERD Selection

5.1.3.1 Present Worth, Payback Period, ERD Efficiency

The decision on whether including an ERD in an RO system is economically worthwhile is based on the payback period. If the payback period is less than the projected equipment life, then ERD inclusion will save money over the duration of the equipment life.

However, ERD selection should be based on the present worth of equipment cost and energy, not on payback period or ERD efficiency. The tool returns both present worth project costs and payback period estimates. The ERD with the lowest present worth of the RO equipment and energy will have the lowest cost to the end user, regardless of the ERD efficiency or payback period. For example, in the Tampa Bay case study presented in Chapter 4, the isobaric ERD would have been a better choice than the Pelton Wheel, based on the present worth costs. The case study did not include the payback period for the isobaric system, which is presented in Table 5.3. The isobaric ERD would still have been a better option for Tampa Bay despite the fact that the payback period for the Pelton Wheel was shorter. The Pelton Wheel provides the lowest invested cost over the life of the project, whereas the payback period only determines how quickly the cost of the ERD will be recuperated.

The isobaric ERDs provide the highest efficiencies but are not always the best selection, particularly for brackish water or wastewater applications where multistage RO systems are used. The Bonita Springs case study showed that a turbocharger was the better choice, producing the lowest present worth cost despite the fact that the ERI PX had a much higher efficiency. On smaller BWRO systems such as the one used at Bonita Springs, the extra capital cost of the circulation pump and other auxiliary ERD equipment associated with the PX is not always outweighed by the better energy savings associated with the higher efficiency of the PX. The tradeoff between efficiency and initial capital cost needs to be reviewed on a case-by-case basis. In the case of Bonita Springs, the lower present worth for the HTC was influenced by ERD inclusion as a retrofit, where its use reduced the efficiency of the HPP. In a new application, the HPP would have been selected based on ERD use and its efficiency would have been maximized, thereby making the PX more attractive.

5.1.3.2 The Discount and Inflation Rates

The NPV power cost is used to compare future power costs against the initial capital cost in order to determine the payback period of the ERD. The NPV calculations are highly dependent on the discount and inflation rates inputted into the tool. Default values of 6% and 3%, respectively, are loaded into the tool, but the user is advised to find the rates that the client or utility has experienced in the past.

These rates have a significant impact on the NPV power cost calculated in the tool. At higher discount rates, the benefit of the energy cost savings is reduced in comparison to capital expenditures as future power costs become less costly in today's dollars. Thus, higher discount rates diminish the power savings of the ERD and increase the payback period. Higher inflation rates make future power costs higher, making the ERD more viable by decreasing the payback period.

5.1.3.3 Concentrate Backpressure

Backpressure applied to the concentrate discharge stream of the ERD will have an adverse impact on the energy recovered by a turbocharger or a Pelton Wheel. In southern California, for example, the RO desalting systems in the Inland Empire area discharge concentrate into a "Brine Line" formerly called the Santa Ana Regional Interceptor. This 93-mi gravity pipeline transmits nonreclaimable wastewater from the upper Santa Ana River basin to the ocean for disposal after treatment. The Inland Empire Brine Line is long, and the pressure in the line can be substantial.

In the case of the turbocharger, the pressure that is available to recover is equal to the concentrate pressure from the RO system minus the concentrate backpressure required to convey the concentrate to its discharge location. Thus, the higher the concentrate backpressure, the less energy can be recovered with a turbocharger. On the other hand, the PX isobaric system can handle substantial amounts of concentrate backpressure with little effect on energy recovery by the PX. For the PX, the low-pressure feed to the device needs to be approximately 10 psi higher than the concentrate effluent pressure; this additional feed pressure is typically available.

For example, if an Inland Empire desalination plant has an RO concentrate of 100 psig, and the Brine Line at that location has a backpressure of 25 psi, the net transfer efficiency (nte) of the turbocharger ERD—that is, the energy recovered by the device—would approximate nte × (100–25 psi), whereas the PX could recover approximately nte × 100 psi. This effect can be analyzed in the tool by increasing the concentrate pressure on the "Summary" page.

One of the disadvantages of a Pelton Wheel is that the concentrate exit flows freely from the device under atmospheric pressure (Wilf, 2004). If the water subsequently needs to be repressurized for disposal, this energy must come from a pump. The energy required for this pump must be subtracted from the energy recovered by the Pelton Wheel. The use of a secondary concentrate discharge pump for concentrate "repumping" is not included in the ERD.

5.1.3.4 SWRO and BWRO/Reclaimed Wastewater

As discussed in Chapter 2, most SWRO trains are single-stage, operate at recoveries in the range of 40% to 50%, and can have concentrate pressures as high as 960 psig. These characteristics are ideally suited to isobaric ERDs. At these high concentrate flows and pressures, the energy recovered through the ERD results in a rapid payback period. Any additional capital costs involved with incorporation of the ERD are minor compared with the significant energy savings available at these high pressures. The Kwinana, Australia case study demonstrated a payback period of less than 3 years for the ERI PX. In general, there is a significant amount of energy available in the concentrate stream of a SWRO system, and ERDs, particularly the isobaric type, are ideally suited to capture and reuse this energy within the RO system, greatly reducing the system's energy consumption compared to that of one not using an ERD.

In contrast, the Luggage Point and Perris case studies for wastewater and BWRO systems, respectively, showed a payback period greater than 5 years for ERDs. This is an indication that the capital cost of the ERD equipment is significant in comparison to the energy that can be saved through ERD use. Furthermore, because these RO systems are designed with multistage trains, turbocharger use is favored (for interstage boost) despite reduced energy recovery efficiency compared with that achieved by an isobaric device.

5.1.4 Location of Turbocharger in a Multistage RO Train

Turbocharger capital cost is proportional to the boosted flow rate of the ERD. For this reason, the Luggage Point case study demonstrated that it was slightly more economical to place the turbocharger in front of the third stage rather than in front of the second stage of the RO train.

Furthermore, the location of the turbocharger can greatly affect the efficiency of the device. As discussed in Section 3.1.3.1, if the reject ratio of a system drops below 60%, the efficiency of the turbocharger is reduced. As a result, in a multistage RO train, it is better to place the turbocharger in a position to provide an interstage boost than to boost the feed pressure to the entire RO train.

5.1.5 ERD Retrofits for Existing Reverse Osmosis Plants

Evaluation of the existing RO operations is required when a plant is considered for an ERD retrofit. At a minimum, the high-pressure feed pump operation would need to be evaluated because a change in the pump's operating point (or range) may reduce the pump's hydraulic efficiency and counteract the energy savings benefit provided by ERD use. Depending on the mode of operation, the selected ERD will determine whether additional improvements are required at feed pumping.

5.1.5.1 Isobaric Energy Recovery Devices—Reduced High-Pressure Pump Capacity

The isobaric ERDs function by transferring energy from the RO concentrate to the portion of the feed stream that bypasses the HPP. If the RO train capacity is unchanged, the required capacity of the high-pressure RO feed pump will be decreased by the introduction of an isobaric ERD. A number of factors, including the recovery of the system, will affect the severity of this issue. For the Bonita Springs example, where the RO trains operate at 65% to 85% recovery, this resulted in the pump operating at a point where its efficiency was less than optimal. For a higher-pressure SWRO train, the capacity turndown would be on the order of

50%, and the pump may require replacement or a substantial amount of retrofitting. One way of working around this issue is to simultaneously increase the capacity of the RO train while installing the isobaric ERD.

5.1.5.2 Turbochargers—Reduced High-Pressure Pump Pressure

The turbocharger is a pressure-boosting device. If the RO train is single-stage, the turbocharger is placed in series with the high-pressure feed pump, reducing the required discharge pressure of the pump. The ratio of the turbocharger boost to the original pump discharge pressure will determine the amount the discharge pressure is reduced. If the turbocharger is placed between stages in a multistage RO train, the high-pressure RO feed pump discharge pressure will be decreased by a smaller margin, but still needs to be investigated.

5.1.5.3 Pelton Wheel—Motor Replacement

Pelton Wheels are directly coupled to the HPP and motor shaft. A retrofit of an existing pump motor combination would require a motor replacement, at a minimum.

5.1.6 Energy Recovery Device Footprint

Turbochargers are offered in various different sizes geared toward matching the RO system concentrate flow with a single device. The footprint of the unit itself can vary from 1 to 9 ft^2, with piping requirements adding to this area. Figure 2.10 displays a turbocharger unit. Pelton wheels are sized to match the HPP. The isobaric ERDs, including the PX and DWEER, typically are configured with numerous units operating in parallel on a single RO train. The ERI units are stacked as in Figure 4.22 with the footprint getting larger as additional units are added. The DWEERs are typically stacked vertically and have the same footprint regardless of the number of units included. DWEERs are currently offered in two sizes with footprints of 5 ft $\times$ 30 ft and 5 ft $\times$ 25 ft, not including piping. In general, the isobaric ERD footprint is substantially larger than that required by a turbocharger. Each of these ERDs can be placed adjacent to the pressure vessels on the RO train.

In summary, the differences of the ERDs need to be considered. The user is encouraged to contact the ERD vendors to get details particular to their application.

5.2 Recommendations for Future Work

An annual review and update of the model is recommended. As evident in the literature review, the ERD market is expanding and evolving. As new technologies are brought to market and proved to be effective, the model should be updated to incorporate these technologies in order to remain relevant and of value to the WateReuse Research Foundation.

References

A1-Hawaj, O. M. The Work Exchanger for Reverse Osmosis Plants. *Desalination* **2003,** *157*, 23–27.

Al-Kutbi, A. A.; Baig, M. B. Design Features of 20 MGD Sea Water Reverse Osmosis (SWRO) Desalination Plant, Al-Jubail Saudi Arabia. *Desalination* **1998,** *118*, 325–333.

American Water Works Association [AWWA]. *Reverse Osmosis and Nanofiltration,* 1st ed.; AWWA: Denver, CO, 1998.

Andrews, W. T.; Laker, D. S. A Twelve-Year History of Large Scale Application of Work-Exchanger Energy Recovery Technology. *Desalination* **2001,** *138*, 201–206.

Andrews, W. T.; Pergande, W. F.; McTaggart, G. S. Energy Performance Enhancements of a 950 m^3/d Seawater Reverse Osmosis Unit in Grand Cayman. *Desalination* **2001,** *135*, 195–204.

Andrews, W. T.; Shumway, S. A. Design Study of a 20,000 m^3/Day Seawater Reverse Osmosis Work-Exchanger Energy Recovery System. In *Proceedings of IDA World Congress,* San Diego, CA, 1999; International Desalination Association: Topsfield, MA, 1999.

Avlonitis, S. A.; Kouroumbas, K.; Vlachakis, N. Energy Consumption and Membrane Replacement Cost for Seawater RO Desalination Plants. *Desalination* **2003,** *157*, 151–158.

Bartels, Craig; Hirose, Masahiko; Fujioka, Hiroki. Performance Advancement in the Spiral Wound RO/NF Element Design. In *Proceedings of EDS Conference,* Halkidiki, Greece, April 2007: European Desalination Society: Rome, Italy 2007.

Cerci, Y. Exergy Analysis of a Reverse Osmosis Desalination Plant in California. *Desalination* **2002,** *142,* 257–266.

Childs, W. D.; Dabiri, A. E. Desalination Cost Savings of VARI-RO™ Pumping Technology. *Desalination* **1992,** *87,* 109–135.

Childs, W. D.; Dabiri, A. E. Increased Water Production Using a Heat Recovery Engine for “Direct Drive” VARI-RO™ Pumping. *Desalination* **1994,** *96*, 81–88.

Childs, W. D.; Dabiri, A. E. VARI-RO™ “Low Energy” Desalting for the San Diego Region. *Desalination* **1995,** *103*, 49–58.

Childs, W. D.; Dabiri, A. E. Vari-RO Low Energy Desalting, Test Results. In *Proceedings of IDA World Congress,* Madrid, Spain, 1997; International Desalination Association: Topsfield, MA, 1997.

Childs, W. D.; Dabiri, A. E. VARI-RO Direct Drive Engine, Dramatically Lower Energy Costs. In *Proceedings of IDA World Congress,* San Diego, CA, 1999; International Desalination Association: Topsfield, MA, 1999.

Colorado River Basin States [CRBS]. *Study of Long Term Augmentation Options for the Water Supply of the Colorado River System*. March 2008.

Constant, E. W. Scientific Theory and Technological Testability: Science, Dynamometers, and Water Turbines in the 19th Century. *Technology and Culture* **1983,** *24(2)*, 183–198.

Cooley, H.; Gleick, P. H.; Wolff, G. *Desalination, with a Grain of Salt. A California Perspective;* Pacific Institute: Oakland, CA, 2006.

Darwish, M. A.; Abdel-Jawad, M.; Hauge, L. J. A New Dual-Function Device for Optimal Energy Recovery and Pumping for All Capacities of RO Systems. *Desalination* **1989,** *75*, 25–39.

Darwish, M. A.; Yousef, F. A.; Al-Najem, N. M. Energy Consumption and Costs with a Multi-stage Flashing (MSF) Desalting System. *Desalination* **2007,** *109(3),* 285–302

Dpto. Técnico Tecnovalia, *Sistema de ahorro de energía (June 2006)*. R.O. Kinetic, Infoenviro.

Drablos, L. Aqualyng™—A New System for SWRO with Pressure Recuperation. *Desalination* **2001,** *139*, 149–153.

Drablos, L. Experience on Operation of Aqualyng Pressure Recuperation SWRO Plants in Gran Canaria since September 1999. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Dundorf, S.; MacHarg, J.; Seacord, T. F. Optimizing Lower Energy Seawater Desalination, The Affordable Desalination Collaboration. In *Proceedings of IDA World Congress,* Maspalomas, Spain, 2007; International Desalination Association: Topsfield, MA, 2007.

Faigon, M.; Liberman, B. Pressure Center and Boron Removal in Ashkelon Desalination Plant. In *Proceedings of IDA World Congress,* Bahamas, 2003; International Desalination Association: Topsfield, MA, 2003.

Farooque, A. M.; Jamaluddin, A. T. M.; Al-Reweli, A. R. *Comparative Study of Various Energy Recovery Devices Used in SWRO Process;* Technical Report No. 3807/EVP 02005; Saline Water Desalination Research Institute: Al-Jubail, Saudi Arabia, 2004.

Folley, M.; Suarez, B. P.; Whittaker, T. An Autonomous Wave-Powered Desalination System. *Desalination* **2008,** *220*, 412–421.

Food and Water Watch. *Desalination. An Ocean of Problems;* Food and Water Watch: Washington, DC, 2009.

Geisler, P.; Hahnenstein, F. U.; Krumm, W.; Peters, T. Pressure Exchange System for Energy Recovery in Reverse Osmosis Plants. *Desalination* **1999,** *122*, 151–156.

Geisler, P.; Krumm, W.; Peters, T. A. Reduction of the Energy Demand for Seawater RO with the Pressure Exchange System PES. *Desalination* **2001,** *135*, 205.

Geisler, P.; Peters, T. H.; Krumm, W.; Hahnenstein, F. U. Pressure Exchange System for Energy Recovery at Reverse Osmosis Plants. In *Proceedings of IDA World Congress,* Madrid, Spain, 1997; International Desalination Association: Topsfield, MA, 1997.

Global Water Intelligence [GWI]. 2011 DesalData.com. http://www.desaldata.com (2011).

Gorenflo, A. A Novel Design Approach for Seawater Plants. In *Proceedings of IDA Water Forum,* Dubai, U.A.E., 2006; International Desalination Association: Topsfield, MA, 2006.

Goubeau, P.; Guinard, P. Energy Recovery Pump in Reverse Osmosis Desalination Plants. *Desalination* **1985,** *54*, 117–126.

Harris, C. Energy Recovery for Desalination. *Desalination* **1999,** *125*, 173–180.

Hauge, L. J. The Pressure Exchanger—A Key to Substantial Lower Desalination Cost. *Desalination* **1995,** *102*, 219–223.

Heckel, T. A.; Stern, J. RO Energy Recovery: Improving the Past Defining the Future Electronic Reintegration System. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Henthorne, L. Introduction to Desalination Global Market and Pretreatment Use. In *Proceedings of IDA RO Workshop,* Tampa, FL, 2004; International Desalination Association: Topsfield, MA, 2004.

Industry News. *International Desalination and Water Reuse Quarterly* **2004,** 53.

Inglesias, M. F. Pelton Turbines Compared to Counter-pressure Turbines in the Recuperation of Energy in Desalination Plants. In *Proceedings of IDA World Congress,* San Diego, CA, 1999; International Desalination Association: Topsfield, MA, 1999.

International Desalination Association [IDA]. *IDA Yearbook*; International Desalination Association: Topsfield, MA, 2010.

Kenny, J. F.; Barber, N. L.; Hutson, S. S.; Linsey, K. S.; Lovelace, J. K.; Maupin, M. A. *Estimated Use of Water in the United States in 2005*. U.S. Geological Survey Circular 1344, pp. 1–52; U.S. Geological Survey: 2005.

Kiang, F. H.; Arasu, S.; Yong, W. W. L.; Ratnayaka, D. D. Supply of Desalinated Water by the Private Sector Singapore's First Public–Private-Partnership Initiative. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Kihara, D. M.; Yamamura, H.; Jinno, S.; Kurihara, M. Operation and Reliability of Very High Recovery Seawater Desalination Technologies by Brine Conversion Two Stage RO. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Kronenberg, G. The Ashkelon 100 MCM/Year BOT Project. *Desalination* **2002,** *152*, 103–112.

Kronenberg, G. The Largest SWRO Plant in the World—Ashkelon 100 Million m^3/y BOT Project. *Desalination* **2004,** *166*, 457–463.

Kundig, E.; Calder-Potts, I.; Weatherholt, B. The Cost of Desalting Water. A Quantitative Comparison of 7 R.O. Plants in Operation All Fitted with Energy Recovery Devices. In *Proceedings of IDA World Congress,* Madrid, Spain, 1997; International Desalination Association: Topsfield, MA, 1997.

Kundig, E.; Lineiro, J. M. Advancements and Improvements on Power Recovery Turbines. In *Proceedings of IDA World Congress,* Madrid, Spain, 1997. International Desalination Association: Topsfield, MA, 1997.

Lozier, J.; Oklejas, E.; Silbernagel, M. The Hydraulic Turbocharger: A New Type of Device for the Reduction of Feed Pump Energy Consumption in Reverse Osmosis Systems. *Desalination* **1989,** 75, 71–83.

MacHarg, J. P. Exchanger Tests Verify 2.0 kWh/m^3 SWRO Energy Use. *Desalination & Water Reuse* **2001,** *11/1*, 42–45.

MacHarg, J. P. The Evolution of SWRO Energy-Recovery Systems. *Desalination & Water Reuse* **2002,** *11/3*, 48.

MacHarg, J. P. Axial Piston-Pressure Exchanger Development Program. In *Proceedings of American Membrane Technology Association Annual Conference,* Las Vegas, NV, February 2, 2007.

MacHarg, J. P. *Energy Optimization of Brackish Groundwater Reverse Osmosis Desalination*; Contract 0804830845; Affordable Desalination Collaboration/Texas Water Development Board: Austin, TX, 2011.

MacHarg, J. P.; Pique, G. G. How to Design and Operate SWRO Systems Built around a New Pressure Exchanger Device. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Mambrettia, S.; Orsia, E.; Gagliardib, S.; Stover, R. Behaviour of Energy Recovery Devices in Unsteady Flow Conditions and Application in the Modelling of the Hamma Desalination Plant. *Desalination* **2009,** *238*, 233–245.

Mandil, M. A.; Farag, H. A.; Naim, M. N.; Attia, M. K. Feed Salinity and Cost Effectiveness of Energy Recovery in Reverse Osmosis Desalination. *Desalination* **1998,** *120*, 89.

Manth, T.; Gabor, M.; Oklejas, E., Jr. Minimizing RO Energy Consumption under Variable Conditions of Operation. *Desalination* **2003,** *157*, 9–21.

Membrane Technology News Bulletin (2004, April 2008, May 2009, November 2009, and July 2010).

Moch, C. H., Jr. What Seawater Energy Recovery System Should I Use? A Modern Comparative Study. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Moch, I., Jr. The Case for and Feasibility of Very High Recovery Sea Water Reverse Osmosis Plants. *Desalination & Water Reuse* **2000,** 44.

Nada, N.; Yanaga, Y.; Tanaka, K. Design Features of the Largest SWRO Plant in the World—33.8 MGD in Madina and Yanbu. In *Proceedings of IDA World Congress,* Abu Dhabi, U.A.E., 1995; International Desalination Association: Topsfield, MA, 1995.

Oklejas, E. Minimizing Specific RO Energy Consumption Using the “Prop” Concept. In *Proceedings of IDA World Congress,* Bahamas, 2003; International Desalination Association: Topsfield, MA, 2003.

Oklejas, E.; Manth, T. Energy Efficiency Considerations for RO Plants: A Comparative Study. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Oklejas, E.; Pergande, W. Integration of Advanced High-Pressure Pumps and Energy Recovery Equipment Yields Reduced Capital and Operating Costs of Seawater RO Systems. *Desalination* **2000,** *127*, 181–188.

Peñate, B.; de la Fuente, J. A.; Barreto, M. Operation of the RO Kinetic® Energy Recovery System: Description and Real Experiences. *Desalination* **2010,** *252*, 179–185.

Plasencia, J. P. Energy-Saving RO System Taps Kinetic Forces. *Water and Waste Water International*. **2004.**

Plasencia, J. R. O. KINETIC: El sistema de ahorro de energía. Presented at the AEDyR Conference: Málaga, Spain, 2002.

Sanz, Miguel Angel; Stover, Richard L. Low Energy Consumption in the Perth Seawater Desalination Plant. In *Proceedings of IDA World Congress,* Maspalomas, Spain, 2007; International Desalination Association: Topsfield, MA, 2007.

Schneider, B. Selection, Operation and Control of a Work Exchanger Energy Recovery System Based on the Singapore Project. *Desalination* **2005,** *184 (1–3),* 197–210.

Scholl, H. G. New Concept to Increase Overall Efficiency in RO plants. In *Proceedings of IDA World Congress,* Madrid, Spain, 1997; International Desalination Association: Topsfield, MA, 1997.

Shumway, S. A. The Work Exchanger for SWRO Energy Recovery. *Desalination & Water Reuse* **1999,** *8/4,* 27.

Spiegler, K. S.; El-Sayed, Y. M. The Energetics of Desalination Processes. *Desalination* **2001,** *134*, 109–128.

Stover, R. L. Development of a Fourth Generation Energy Recovery Device—A CTO's Notebook. *Desalination* **2004,** *165*, 313–321.

Stover, R. L. Seawater Reverse Osmosis with Isobaric Energy Recovery Devices. *Desalination* **2007,** *203,* 168–175.

Stover, R. L.; Martin, J.; Nelson, M. The 200,000 m^3/Day Hamma Seawater Desalination Plant—Largest Single-Train SWRO Capacity in the World and Alternative to Pressure Center Design. In *Proceedings of IDA World Congress,* Maspolomas, Spain, 2007; International Desalination Association: Topsfield, MA, 2007.

Stumm, W.; Morgan, J. J. *Aquatic Chemistry, Chemical Equilibria and Rates in Natural Waters,* 3rd ed.; Wiley: New York, 1996.

Sun, J.; Wang, Y.; Xu, S.; Wang, S. Energy Recovery Device with a Fluid Switcher for Seawater Reverse Osmosis System. *Chinese Journal of Chemical Engineering* **2008,** *16(2)*, 329–332.

Thomson, M.; Miranda, M. S.; Infield, D. A Small-Scale Seawater Reverse-Osmosis with Excellent Energy Efficiency over a Wide Operating Range. *Desalination* **2002,** *153*, 229–236.

Truby, R. L. Seawater Reverse Osmosis (SWRO) Energy Efficiency and The Affordable Desalination Collaboration. In *Proceedings of IDA Forum and Exhibition,* Tianjin, China, 2006; International Desalination Association: Topsfield, MA, 2006.

Tzen, E.; Theofilloyianakos, D.; Sigalas, M.; Karamanis, K. Design and Development of a Hybrid Autonomous System for Seawater Desalination. *Desalination* **2004,** *166, 267-274.*

U.S. Census Bureau. *2005 American Community Survey.* http://www.census.gov/acs (2005).

U.S. Geological Survey. *National Water Summary 1983—Hydrologic Events and Issues*. Water-Supply Paper 2250, pp. 1–243; U.S. Geological Survey: 1984.

Uchiyama, T.; Oklejas, M.; Moch, I., Jr. Using a Hydraulic Turbo Charger and Pelton Wheel for Energy Recovery in the Same Seawater RO Plant. In *Proceedings of IDA World Congress,* San Diego, CA, 1999; International Desalination Association: Topsfield, MA, 1999.

Vedavyasan, C. V. Cost Reductions of Desalinated Water by Creative Design. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Veerapaneni, S. Energy Consumption Optimization and Recovery in Seawater RO Process. In *Proceedings of IDA Water Forum,* Dubai, U.A.E., 2006; International Desalination Association: Topsfield, MA, 2006.

Verbeek, V. From Concept Design to Installation and Commissioning, Energy Recovery for SWRO in Singapore Victor. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

von Gottberg, A. J. M.; Talavera, J. L. P.; Pang, A. Optimizing Water Recovery and Energy Consumption for Seawater RO Systems. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Wang, X.; Wang, Y.; Wang, J.; Xu, S.; Wang, Y.; Wang, S. Comparative Study on Stand-Alone and Parallel Operating Schemes of Energy Recovery Device for SWRO System. *Desalination* **2010,** *254(1–3),* 170–174.

Wang, Y.; Wang, S.; Xu, S. Investigations on Characteristics and Efficiency of a Positive Displacement Energy Recovery Unit. *Desalination* **2005a,** *177*, 179–185.

Wang, Y.; Wang, S.; Xu, S. Solutions for Mixing Behavior in a Cylinder of Positive Displacement ERD. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005b.

Water-technology.net. *Gold Coast Desalination Plant, Queensland Australia*. http://www.water-technology.net/projects/gold-coast-plant (accessed October 2011, 2007).

Wilf, M. Fundamentals of RO-NF Technology. In *International Conference on Desalination Costing,* Middle East Desalination Research Center, Limassol, Cyprus, December 2004; European Desalination Society: Rome, Italy 2004.

Zhu, A.; Rahardianto, A.; Christofides, P. D.; Cohen, Y. Reverse Osmosis Desalination with High Permeability Membranes—Cost Optimization and Research Needs. *Desalination and Water Treatment* **2010,** *15(1–3)*, 256–266.

Additional References (Reviewed but Not Directly Cited).

Ali, N.; Mohammad, A. W.; Ahmad, A. L. Use of Nanofiltration Predictive Model for Membrane Selection and System Cost Assessment. *Separation and Purification Technology.* **2005,** *41(1),* 29–37.

Andrews, W. T.; Bergman, R. A. The Malta Seawater RO Facility. *Desalination* **1986,** *60(2),* 135–144.

Andrews, W. T.; Bullock, D. C. *Deep Sea Reverse Osmosis: The Final Quantum Jump.* CWWA: 1991.

Andrews, W. T.; Crowley, K.; McTaggart, R.; Shumway, S.; Woolley, D. Installation of a New Seawater Desalination Plant at Lower Valley, Grand Cayman. In *K.A.E. Curaçao: Next Breakthrough in Seawater Desalination,* Vol. 1, pp. 1–8; June 2008.

Andrews, W. T.; Verbeek, V. Energy Efficiency Considerations of Typical Seawater Reverse Osmosis Membrane Arrays. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Bahamas, W. T.; Andrews, S. A.; Shumway, B. R. Design of a 10,000 cu-m/d Seawater Reverse Osmosis Plant on New Providence Island. In *Proceedings of IDA World Congress,* Madrid, Spain, 1997; International Desalination Association: Topsfield, MA, 1997.

Beat, S. Selection, Operation and Control of a Work Exchanger Energy Recovery System Based on the Singapore Project. *Desalination* **2005,** *184*, 197–210.

Bednarski, J.; Minamide, M.; Morin, O. J. In *Proceedings of IDA World Congress,* Madrid, Spain, 1997; International Desalination Association: Topsfield, MA, 1997.

Behrends, H.; Baumgarten, S.; Matz, B.; Schill, J.; Stoffel, B. Technical Features of High-Pressure Pumps for RO Facilities. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Bergman, R. A. Membrane Softening versus Lime Softening in Florida: A Cost Comparison Update. *Desalination* **1995,** *102,* 11–24.

Bross, S.; Kochanowski, W.; El Maraghy, N. Field Test Results of an Advanced SWRO Core Hydraulic System. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Bross, S.; Kochanowski, W.; Ellegaard, M.; Schwarz, G. SWRO-Core-Hydraulic-Module. The Right Concept Decides in Terms of Energy Consumption and Reliability. In *Proceedings of IDA World Congress,* Bahamas, 2003; International Desalination Association: Topsfield, MA, 2003.

Brown, D. L. *Desalination and Water Reuse Quarterly* **1996,** *6*, 20.

Buros, O. K. *The ABCs of Desalting,* 2nd ed.; International Desalination Association: Topsfield, MA, 2000.

Busch, M.; Mickols, W. E.; Prabhakaran, S.; Lomax, I.; Tonner, J. Boron Removal at the Lowest Cost. In *Proceedings of IDA World Congress*, Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Cameron, I. B.; Clemente, R. B. SWRO with ERI's (PX)™ Pressure Exchanger Device—A Global Survey. *Desalination* **2008,** *221*, 136–142.

Childs, W.; Butler, B.; Vinciczky, A.; Fujii, S. Adaptive Pressure Method for Lower Seawater Desalination Costs. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Cortes, F. I. A.; Dominguez, A. M. Desalinización del agua. *Ingenieria Hidraulica en Mexico* **2000,** *15*, 27–49.

Costa, A. R.; de Pinho, M. N. Performance and Cost Estimation of Nanofiltration for Surface Water Treatment in Drinking Water Production. *Desalination* **2006,** *196(1–3)*, 55–65.

Drioli, J. E.; Lagana, F.; Criscuoli, A.; Barbieri, G. Integrated Membrane Operations in Desalination Processes. *Desalination* **1999,** *122*, 141.

ERI. *Isobaric Device Flow Performance in Arrays: How Does the SWRO Plant Designer and Operator Control Flow?* Energy Recovery Technical Bulletin; May 28, 2004.

Eriksson, P. K. Evaluation of Nanofiltration as Pretreatment to Reverse Osmosis in Seawater Desalination. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Frioui, S. Oumeddour, R. Investment and Production Costs of Desalination Plants by Semi-empirical Method. *Desalination* **2008,** *223(1–3)*, 457–463.

Glueckstern, T. P.; Priel, M. Advanced Concept of Large Seawater Desalination Systems for Israel. *Desalination* **1998,** *119*, 33.

Halim, I.; Meichao, Z.; Jang, S. Process Simulation and Economic Optimization for a Brackish-Seawater Mixed Feed Reverse Osmosis. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Hauge, L. J.; Ludvigsen, F. Field Installation of Pressure Exchanger in a 80 m^3/D SWRO Plant. In *Proceedings of IDA World Congress,* San Diego, CA, 1999; International Desalination Association: Topsfield, MA, 1999.

Kallenberg, K.; Perez-Vera, J. L.; Yamamura, H.; Kurihara, M. Brine Conversion (BCS) Enhances SWRO Desalination Case Histories, Operating Data, Novel Design Features. In *Proceedings of IDA World Congress,* San Diego, CA, 1999; International Desalination Association: Topsfield, MA, 1999.

Kamal, I. A Uniform Basis for Desalination Energy Cost Comparison in Dual-Purpose Power/Desalination Plants. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Kim, Y. M.; Lee, Y. S.; Lee, Y. G.; Kim, S. J.; Yang, D. R.; Kim, I. S.; Kim, J. H. Development of a Package Model for Process Simulation and Cost Estimation of Seawater Reverse Osmosis Desalination Plant. *Desalination* **2009,** *247 (1–3),* 326–335.

Kronenberg, G. The LT-MED Process for Combined Power Generation and Sea Water Desalination. In *Proceedings of IDA World Congress,* Abu Dhabi, U.A.E., 1995; International Desalination Association: Topsfield, MA, 1995.

Kronenberg, G. Ashkelon 100 MCM/year BOT Project. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

MacHarg, J. P.; Coker, S. D.; Seacord, T. F. The Affordable Desalination Collaboration. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Maeda, Y. A Novel Design Approach for Seawater Plants. In *Proceedings of Desalination and Water Reuse International Forum & Exhibition,* Tianjin, China, 2006; International Desalination Association: Topsfield, MA, 2006.

Malek, S. A.; Hawlader, M. N. A.; Ho, J. C. Design and Economics of RO Seawater Desalination. *Desalination* **1996,** *105*, 245–261.

Methnani, M. DEEP: A Tool for Evaluation Co-generated Power and Desalination Strategies. *Desalination* **2004,** *166*, 11–15.

Methnani, M. Recent Model Developments for the Desalination Economic Evaluation Program. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Mickols, W. E.; Busch, M.; Maeda, Y.; Tonner, J. A Novel Design Approach for Seawater Plants. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Moch, I., Jr.; Oklejas, M.; Terrasi, K.; Oklejas, R. A. Advanced High Efficiency Energy Recovery. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Mohameda, E. S.; Papadakis, G.; Mathioulakis, E.; Belessiotis, V. An Experimental Comparative Study of the Technical and Economic Performance of a Small Reverse Osmosis Desalination System Equipped with an Hydraulic Energy Recovery Unit. *Desalination* **2006,** *194*, 239–250.

Mubeen, F. M. Comparison of Theoretical and Actual Energy Requirements for SWRO Plants. In *Proceedings of IDA World Congress,* Madrid, Spain, 1997; International Desalination Association: Topsfield, MA, 1997.

Mubeen, F. M. Past and Present SWRO Desalination Plants—A Material Perspective. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Pittner, G. A. The Economics of Desalination Processes. In Reverse Osmosis: Membrane Technology, Water Chemistry and Industrial Applications; Amjad, Z., Ed.; Chapman Hall, Van Nostrand: New York, 1993; pp. 103–112.

Reddy, K. V.; Ghaffour, N. Overview of the Cost of Desalinated Water and Costing Methodologies. *Desalination* **2007,** *205(1–3),* 340–353.

Redondo, J. A. Brackish-, Sea- and Wastewater Desalination. *Desalination* **2001,** *138*, 29–40.

Rubio, M.; Zarzo, D.; Hernandez, J. Practical Application of Energy Recovery Turbines in Brackish Water Desalination Systems. In *Proceedings of IDA World Congress,* Madrid, Spain, 1997; International Desalination Association: Topsfield, MA, 1997.

Rueda, J. A.; Cortacans, J. A. Improvement in the Efficiency & Decrease in the Energetic Cost in the Extension of a Reverse Osmosis Plant. In *Proceedings of IDA World Congress,* San Diego, CA,1999; International Desalination Association: Topsfield, MA, 1999.

Rybar, S.; Talo, S.; Vodnar, M.; Vartolomei, F. L.; Experience with Renewable Energy Source and SWRO Desalination in Gran Canaria. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Semiat, R. Desalination: Present and Future. *Water International* **2000,** *25*, 54–65.

Silbernagel, M.; Kuepper, T. Evaluation of a Pressure Boosting Pump/Turbine Device for Reverse Osmosis Energy Recovery: Extended Testing on a Seawater Desalination System. *Desalination* **1992,** *88*, 311–319.

Spiegler, F. K. S.; El-Sayed, Y. M.*A Desalination Primer;* Balaban Desalination Publications: Santa Maria Imbaro, Italy, 1994.

Stover, R. L. The (PX)™ Pressure Exchanger Energy Recovery Device For large SWRO Plants. In *Proceedings of Desalination and Water Reuse International Forum & Exhibition,* Tianjin, China, 2006; International Desalination Association: Topsfield, MA, 2006.

Stover, R. L. SWARO Simulator. *Desalination* **2008,** *221*, 126–135.

Stover, R. L.; Ameglio, A.; Khan, P. A. K. The Ghalilah SWRO Plant: An Overview of the Solutions Adopted to Minimize Energy Consumption. *Desalination* **2005,** *184*, 217–221.

Sun, J.; Wang, Y.; Xu, S.; Wang,S.; Wang, Y. Performance Prediction of Hydraulic Energy Recovery (HER) Device with Novel Mechanics for Small-Scale SWRO Desalination System. *Desalination* **2009,** *249*, 667–671.

Taylor, J. S.; Jacobs, E. P. Reverse Osmosis and Nanofiltration. In *Water Treatment Membrane Processes;* American Water Works Association, Ed.; McGraw-Hill: New York, 1996.

U.S. Bureau of Reclamation. Document WaTER. http://www.usbr.gov/pmts/water/media/spreadsheets/WaTER.xls (accessed May 3, 2009).

Veerapaneni, S.; Jordan, B.; Leitner, G.; Freeman, S. Optimization of RO Desalination Process Energy Consumption. In *Proceedings of IDA World Congress,* Singapore, 2005; International Desalination Association: Topsfield, MA, 2005.

Villa Sallangos, O. L. Operating Experience of the Dhekelia Seawater Desalination Plant Using an Innovative Energy Recovery System. *Desalination* **2005,** *173*, 91–102.

Von Gottberg, A. J. M.; Talavera, J. L. P.; Pang, A. Optimizing Water Recovery and Energy Consumption for Seawater RO System. In *Proceedings of IDA World Congress,* Bahrain, 2002; International Desalination Association: Topsfield, MA, 2002.

Wahlgren, R. V. Atmospheric Water Vapour Processor Designs for Potable Water Production: A Review. *Water Research* **2001,** *35(1),* 1–22.

Weber, W. A. *Physicochemical Processes for Water Quality Control;* Wiley: New York, 1972.

Wilf, U. M.; Klinko, K. Optimization of Seawater RO Systems Design. *Desalination* **2001,** *138*, 299–306.

Wittholz, M. K.; O'Neill, B. K.; Colby, C. B., Lewis, D. Estimating the Cost of Desalination Plants Using a Cost Database. *Desalination* **2008,** *229(1–3),* 10–20.

Younos, T.M. *The Feasibility of Using Desalination to Supplement Drinking Water Supplies in Eastern Virginia;* SR25-2004; Virginia Water Resources Research Center: Richmond, VA, 2004.

Zimerman, Z. Development of Large Capacity High Efficiency Mechanical Vapor Compression (MVC) Units. *Desalination* **1994,** *96*, 51.

Patents

Al-Hawaj, O. M. Rotary Work Exchanger and Method. U.S. Patent 6,773,226, August 10, 2004.

Brueckmann, F.; Knoebl, W.; Bruhns, U.; Kochanowski, W. Pressure Exchanger System. U.S. Patent 2005/0166978, August 4, 2005.

Cheng, C.; Cheng, S. Method and Apparatus for Pressurizing and Depressurizing of Fluids. U.S. Patent 3,489,159, January 13, 1970.

Childs, W. D.; Dabiri, A. Integrated Pumping and/or Energy Recovery System. U.S. Patent 6,017,200, January 25, 2000.

El-Sayed, E. E. F.; Abdel-Jawad, M.; Al-Odwani, A. Pressure Exchange Apparatus. U.S. Patent 7,661,932, February 16, 2010.

Gray, B. D. Portable Water Purification System with Double Piston Pump. U.S. Patent 5,496,466, March 5, 1996.

Hashemi, H. T.; Lott, J. L. Engine for Exchanging Energy Between High and Low Pressure Streams. U.S. Patent 3,431,747, March 11, 1969.

Hauge, L. J. Pressure Exchanger for Liquids. U.S. Patent 4,887,942, December 19, 1989.

Hauge, L. J. Pressure Exchanger Having Axially Inclined Rotor Ducts. U.S. Patent 5,338,158, August 16, 1994.

Hauge, L. J. Pressure Exchanger Having a Rotor with Automatic Axial Alignment. U.S. Patent 5,988,993, November 23, 1999.

Hauge, L. J. Pressure Exchanger. U.S. Patent 6,659,731, December 9, 2003.

Herrington, R. E.; Hand, F. R. Dual Head Pump Driven Filtration System. U.S. Patent 7,297,268, November 20, 2007.

Keefer, B. G. Reverse Osmosis Method and Apparatus. U.S. Patent 4,187,173, February 5, 1980.

Keefer, B. G. Multi-cylinder Reverse Osmosis Apparatus and Method. U.S. Patent 4,434,056, February 28, 1984.

Loeb, S.; Sourirajan, S. High Flow Porous Membranes for Seperating Water from Saline Solutions. U.S. Patent 3,133,132, May 12, 1964.

MacHarg, J. Combined Axial Piston Liquid Pump and Energy Recovery Pressure Exchanger. U.S. Patent 7,799,221, September 21, 2010.

Oklejas, R. Apparatus for Improving Efficiency of a Reverse Osmosis System. U.S. Patent 6,139,740, October 31, 2000.

Oklejas, R.; Oklejas, E. Power Recovery Pump Turbine. U.S. Patent 4,966,708, October 30, 1990.

Oklejas, R.; Oklejas, E. Power Recovery Pump Turbine. U.S. Patent 4,983,305, January 8, 1991a.

Oklejas, R.; Oklejas, E. Power Recovery Turbine Pump. U.S. Patent 5,049,045, September 17, 1991b.

Oklejas, R.; Oklejas, E. Centrifugal Pump. U.S. Patent 5,082,428, January 21, 1992.

Pelton, L. A. Water-Wheel. U.S. Patent 233,692, October 26, 1880.

Permar, C. Liquid Treatment Apparatus for Providing a Flow of Pressurized Liquid. U.S. Patent 5,462,414, October 31, 1995.

Permar, C. Liquid Treatment Apparatus for Filtering Liquid Under Pressure. U.S. Patent 5,628,198, May 13, 1997.

Rojanskiy, H.; Ophir, A. Three-way Poppet Valve for Work Exchanger. U.S.Patent 7,540,230, June 2, 2009.

Ross, C. J. Continuous Flow Displacement Pump. U.S. Patent 3,090,325, May 21, 1963.

Schwartzman, E. H. Turbine Booster Pump System. U.S. Patent 4,067,665, January 10, 1978.

Shumway, S. Linear Spool Valve Device for Work Exchanger System. U.S. Patent 5,797,429, Aug 25, 1998.

Stover, R. L. Rotary Pressure Exchanger. U.S. Patent 7,201,557, April 10, 2007.

Swaney, Pneumatic System for Pumping Liquids. Patent 3,005,417, October 24, 1961.

Additional Tangentially Related Patents (Reviewed but Not Directly Cited)

Bachle, W. H.; Peck, J. V.; Stantial, T. D.; Williams, R. H. Piston Pump. U.S. Patent 3,966,364, June 29, 1976.

Elliott-Moore, P. Pressure Energy Recovery Device. U.S. Patent 6,447,259, September 10, 2002.

Haudenschild, C. Highly Efficient Durable Fluid Pump and Method. U.S. Patent 2007/0128056 A1, April 19, 2011.

Hellat, J.; Keller, J. Pressure Wave Machine Operating as Pressure Exchanger, in Particular for use as the High Pressure Compressor for Gas Turbines. U.S. Patent 4 679 393, July 14, 1987.

Hembree, R. D.; Carmein, D. E. Energy Recovery Apparatus. U.S. Patent 4,793,153, December 27, 1988.

Jenkyn-Thomas, W. D. Pump for a Desalination Plant. U.S. Patent 3,558,242, January 26, 1971.

Lopez, F. Apparatus for Purifying Water, Especially Salt Water, by Reverse Osmosis. U.S. Patent 4,740,301, April 26, 1988.

Manjikian, S. Reverse Osmosis Sysetem Adaptablefor Manual Operation. U.S. Patent 3,830,372, August 2, 1974.

Miers, G. Manually Operated Reverse Osmosis Desalinization System. U.S. Patent 5,531,887, July 2, 1996.

Patapoff, W.; Wong, J. L. Miniaturized Handheld Desalination Field Unit. U.S. Patent 5,685,980, November 11, 1997.

Polizos, T.; Babcock, T.; Hauge, L. J.; Hermanstad, R. A. Pressure Exchanger with an Anti-cavitation Pressure Relief System in the End Covers. U.S. Patent 6,540,487, April 1, 2003.

Prueitt, M. L. Solar Energy Desalination System. U.S. Patent 6,804,962, October 19, 2004.

Schoenmeyr, I. Hydroboost Piston Pump for Reverse Osmosis System. U.S. Patent 5,503,736, April 2, 1996.

Shumway, S. Pressure Exchange Apparatus. U.S. Patent 6,537,035, March 25, 2003.

Tonner, J. B. Method of Recovering Energy from Reverse Osmosis Waste Streams. U.S. Patent 5,306,428, April 26, 1994.

Verde, R. Equipment for Desalination of Water by Reverse Osmosis with Energy Recovery. U.S. Patent 6,491,813, December 10, 2002.

Walker, F. M. Means for Transferring Fluids in an Absorption Refrigeration System. U.S. Patent 3,293,881, December 27, 1966.

Wanner, W. F. Fluid Pump. U.S. Patent 3,791,768, Feb 1, 1974.

Appendix A

Energy Recovery Device Summaries

A.1 Centrifugal Energy Recovery Device

Pelton Wheel/ERT		www.flowserve.com	
Name	Flowserve/Calder	Stock Symbol	FLS
Location	USA/Switzerland	Year Listed	1997
Founded	1790/1981	Annual Gross Revenue	$1.409 billion
Primary Market	Energy recovery in RO desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	Flowserve
Notes	Energy recovery turbine (ERT)		
Key Trademarks	None		

Products

Pelton Wheel

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
RO-350-70	66–660	15–150	≤86%
RO-350-100	250–1100	57–250	≤87%
RO-350-100-2	525–2200	119–500	≤88%
RO-350-100-4	1100–4400	250–1000	≤90%

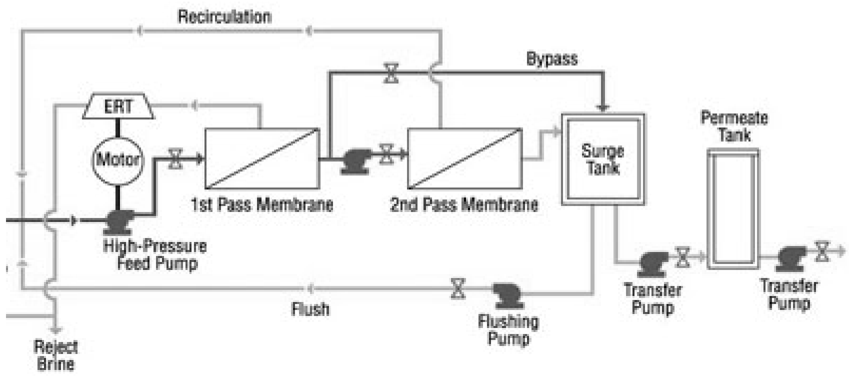
Process Description

The Pelton Wwheel is direct-coupled to the high-pressure pump (HPP) and motor shaft. Rotational energy from the concentrate is directly transferred to the motor shaft, reducing the power requirements. The HPPs for a direct-coupled device are sized for the full flow and pressure; however the motor power can be reduced as a result of the energy recovery.

In its operation, the high-pressure concentrate is fed into the Pelton wheel hydraulic impulse turbine, which then produces rotating power output to assist the main electric motor in driving the main HPP. The system consists of an adjustable input nozzle to convert water pressure into kinetic energy contained in a high velocity jet (Darwish et al., 2007). Energy recovery starts at about 40% of system pressure and the inlet nozzle acts as a brine control valve and no further pressure control is used on the RO system.

Pelton Wheel/ERT	www.flowserve.com

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Las Palmas	Spain	45,000	11.9	Seawater
Trinidad	Trinidad	100,000	26.4	Seawater
Carboneras	Spain	140,000	37.0	Seawater
Tampa	USA	45,000	11.9	Seawater
Fujairah	UAE	180,000	47.6	Seawater

Turbochargers		www.energy-recovery.inc	
Name	Energy Recovery Inc.	Stock Symbol	n/a
Location	USA	Year Listed	n/a
Founded	1986 (PEI bought by ERI in 2009)	Annual Gross Revenue	n/a
Primary Market	Pumps and energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	ERI
Notes			
Key Trademarks	None		
Products	Turbochargers		

Turbochargers

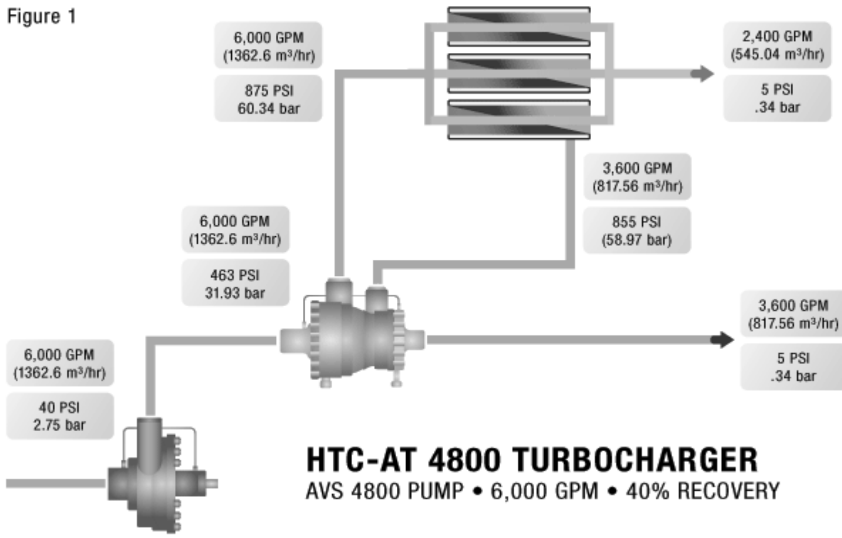
Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
LPT-32	25–55	6–12	49%
LPT-63	45–95	10–22	50%
LPT-125	70–185	16–42	52%
LPT-250	150–375	34–85	56%
LPT-500	300–750	68–170	62%
LPT-1000	600–1500	136–341	69%
LPT-2000	1000–2500	227–568	72%
LPT-4000	2300–4500	522–1022	72%
HALO-50	35–60	8–14	57%
HALO-75	60–85	14–19	57%
HALO-100	85–130	19–30	58%
HALO-150	130–180	30–41	60%
HALO-225	180–270	41–61	61%
HALO-300	270–350	61–80	63%
HALO-450	350–525	80–119	65%
HALO-600	600–900	136–204	68%
HALO-900	900–1300	204–295	69%
HALO-1200	1300–1500	295–341	70%
HTC-AT 1800	1500–2100	341–477	72%
HTC-AT 2400	2100–3000	477–681	73%
HTC-AT 3600	3000–4200	681–954	75%
HTC-AT 4800	4200–6000	954–1363	76%
HTC-AT 7200	6000–8400	1363–1908	78%
HTC-AT 9600	8400–12,000	1908–2726	80%

Process Description

In a turbocharger device, a Francis turbine is direct-coupled to pump impeller on a common shaft and located downstream of the HPP. The HPP is sized for the full-feed flow, but the head requirement is decreased by the boost provided in the turbocharger.

Process Schematic

Figure 1



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
—	Algeria	500,000	132.1	AT-7200
—	UAE	113,000	29.9	AT-4800
—	UAE	45,000	11.9	AT-3600
—	India	45,000	11.9	AT-3600
—	Singapore	113,000	29.9	AT-2400
—	Thailand	15,000	4.0	AT-2400

HPB/HPB-HEMI		http://www.fedco-usa.com/	
Name	FEDCO	Stock Symbol	n/a
Location	USA	Year Listed	n/a
Founded	1997	Annual Gross Revenue	n/a
Primary Market	Pumps and energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	None
Notes	Low-pressure energy recovery for BWRO applications is supplied via separate pump and turbine modules. FEDCO custom designs and manufactures the turbine portion for specified brine flow and pressure ranges.		
Key Trademarks	HPB, HEMI		
Products	Turbochargers—High-Pressure		

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
HPB 20	66–120	15–27	64%
HPB 30	100–167	23–38	66%
HPB 40	132–220	30–50	67%
HPB 60	200–330	45–75	71%
HPB 80	265–440	60–100	72%
HPB 120	400–660	91–150	73%
HPB 160	528–880	120–200	74%
HPB 250	825–1380	187–313	76%
HPB 350	1150–1930	261–438	77%
HPB 500	1650–2750	375–625	78%
HPB 700	2310–3850	525–874	79%
HPB 1000	3300–5500	750–1249	80%
HPB 1400	4620–7700	1049–1749	81%
HPB 2000	6600–11,000	1499–2498	82%
HPB 2800	9240–15,400	2099–3498	85%

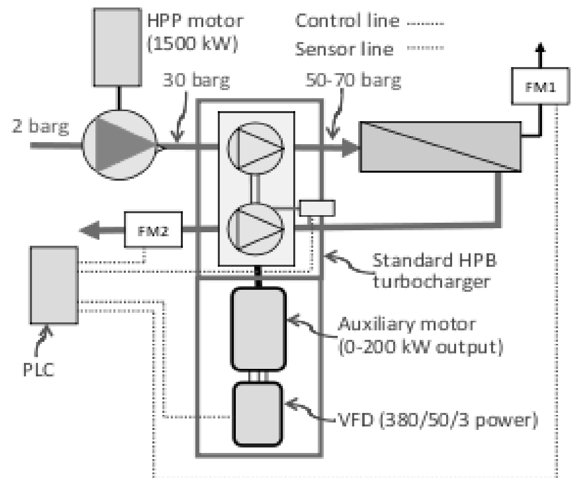
Turbochargers—Low-Pressure

LP HEMI	Custom-made for applications

Process Description	In a turbocharger device, a Francis turbine is direct-coupled to pump impeller on a common shaft and located downstream of the HPP. The HPP is sized for the full-feed flow, but the head requirement is decreased by the boost provided in the turbocharger.

HPB/HPB-HEMI	http://www.fedco-usa.com/

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
King Abdul Aziz International Airport Jeddah	Saudi Arabia	36,600	9.7	Seawater
Jeddah 3 (In Construction)	Saudi Arabia	260,000	68.7	Seawater
Turks & Caicos Water Authority	British West Indies	7,000	1.8	Seawater
NEWater—Changi plant	Singapore	240,000	63.4	Brackish
N. Lee County, FL	USA	47,000	12.4	Brackish
Adani, IOCL Paradeep	India	20,000	5.3	Seawater

A.2 Isobaric Energy Recovery Device

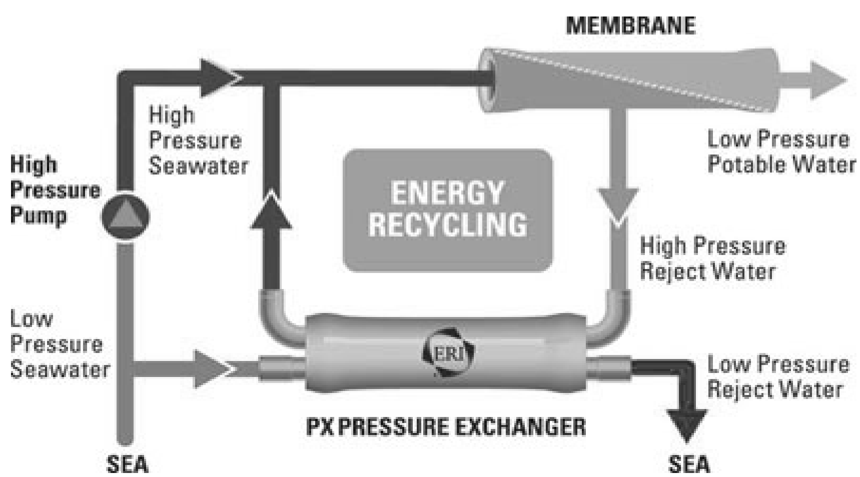
ENERGY RECOVERY INC.		http://www.energyrecovery.inc/	
Name	Energy Recovery Inc. (ERI)	Stock Symbol	ERII
Location	California, USA	Year Listed	2008
Founded	1997	Annual Gross Revenue	$50M
Primary Market	Energy recovery in desalination applications	Secondary Market	None
Subsidiaries	Pump Engineering Inc.	Parent Company	Not applicable
Notes	ERI's proprietary rotary energy recovery device is called a PX pressure exchanger. ERI's marketing literature claims over 400 installations utilizing this technology, representing 70% of the current market share. Marketing literature also claims over 94% efficiency.		
Key Trademarks	PX (pressure exchanger)		
Products			

Isobaric Energy Recovery Devices

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
PX-300	200–300	45–68	96.8
PX-260	180–260	41–59	96.8
PX-220	140–220	32–50	96.8
PX-180	100–180	23–41	96.8
PX-140S	90–140	20–32	95.0
PX-90S	60–90	14–20	95.0
PX-70S	40–70	9–16	94.2
PX-45S	30–45	7–10	94.2
PX-30S	20–30	4.5–6.8	94.2

Circulation Pumps

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency
VP-6891	1100–2200	250–500	75%
VP-4671	400–1100	91–250	80%
VP-3471	175–530	40–120	75%
HP-2402	130–230	30–52	59%
HP-2403	230–300	52–68	61%
HP-1253	100–160	23–36	68%
HP-1254	160–200	36–45	65%
HP-8503	50–70	11–16	70%
HP-8504	70–100	16–23	68%

ENERGY RECOVERY INC.	http://www.energyrecovery.inc/
Process Description	In a PX device, high-pressure concentrate flows through the unit and transfers energy directly to a portion of the incoming lower pressure seawater feed (Stover, 2004). The heart of the device is a single cylindrical ceramic rotor that facilitates pressure exchanges. Ceramic was selected as the ideal material for this application because it is very tough, corrosion proof, and dimensionally stable. The rotor contains axial ducts arranged in a circle around a center tension rod (*Membrane Technology News Bulletin,* 2004). The rotor spins within a ceramic sleeve, and is enclosed on either end with dedicated feed and concentrate ceramic end covers. Bearing and sealing surfaces are the ceramic parts themselves, and bearing lubrication is provided by high-pressure feed water. The concentrate end cover contains a high-pressure (HP) concentrate port for incoming HP concentrate (HP IN), and a low-pressure (LP) concentrate port for outgoing concentrate (LP OUT). The feed water end cover likewise contains two feed water ports (LP IN and HP OUT). The PX device uses the high-pressure concentrate to directly pressurize feed water. The flow rate of concentrate is slightly greater than that of the feed water because a small amount of high-pressure feed water is used to lubricate the rotor. Therefore, the PX device provides the membranes the concentrate portion of the feed flow and the HPP provides the permeate portion of the feed flow and the small lubrication flow. In operation, a rotor duct is exposed to both the LP IN and LP OUT end cover ports. The LP feed water fills the rotor duct. The rotor duct then enters a Seal Zone where flow stops and the duct is sealed from the HP- and LP-flow circuits. Then the duct continues to rotate and is exposed to the incoming HP concentrate, which pressurizes the feed water and displaces it toward the membranes. The rotor then advances until the duct seals and the cycle begins again. The PX system is designed in way that the feed water and concentrate come into direct contact in the rotor, with minimal mixing of the streams within the duct. Mixing increases the feed water TDS, requiring slightly higher feed pressures to maintain the desired flux and recovery.
Process Schematic	

ENERGY RECOVERY INC.	http://www.energyrecovery.inc/

	Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Key Installations					
	Hadera Desalination plant	Israel	388,000–462,000	102.5–122	Seawater
	Torrevieja	Spain	240,000	63.4	Seawater
	Tenes Desalination Algeria	Algeria	200,000	52.8	Seawater
	Barcelona	Spain	200,000	52.8	Seawater
	Hamma	Algeria	200,000	52.8	Seawater
	Kwinana Seawater Desalination Plant	Australia	160,000	42.3	Seawater
	Southern Seawater Desalination Plant	Australia	100,000	26.4	Seawater
	Port Stanvac	Australia	135,000	35.7	Seawater
Comments	PX devices are also available with lower pressure ratings for brackish water applications.				

DWEER		www.flowserve.com	
Name	Flowserve/Calder	Stock Symbol	FLS
Location	USA/Switzerland	Year Listed	1997
Founded	1790/1981 Flowserve purchased Calder in 2009	Annual Gross Revenue	$1.409 billion
Primary Market	Energy recovery in RO desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	Flowserve
Notes			
Key Trademarks Products	DWEER		

Isobaric Energy Recovery Devices

Name	Capacity (m^3/d)	Capacity (mgd)	Efficiency	Mixing
"A"; D-1550	790–1550	179–352	98%	<2.5%
"B"; D-1050	440–1100	100–250	98%	<2.5%

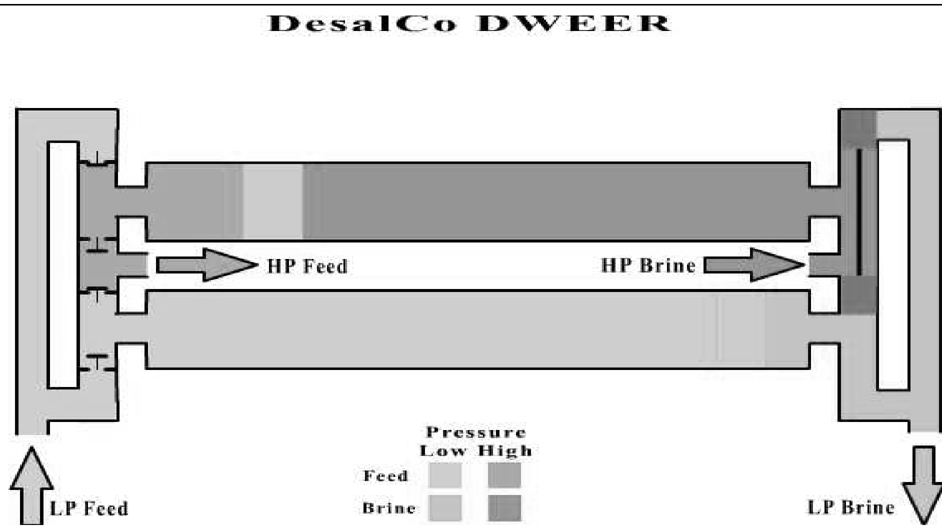
DWEER **www.flowserve.com**

Process Description

The DWEER uses positive displacement pistons, which are normally housed within pressure vessels to sequence energy recovery (Andrews et al., 2001). The DWEER work exchanger is designed with a minimum of two pressure vessels in parallel. In its operation, DWEER transfers the fluid pressure in the brine stream to fluid pressure in the feed across a piston, where it reduces mixing of the brine and feed. One vessel is in the working stroke while the other is filled with fresh seawater. As soon as the piston of the working pressure vessel finishes its working stroke and the filling vessel is fully filled with fresh feed water, the brine and feed line are switched (Schneider, 2005). If the piston is designed for minimum drag, the transfer of energy in this scheme is essentially 100%. For this reason, the fundamental exchange of energy between the brine and seawater feed is more efficient than centrifugal devices relying on shaft conversion of power (Farooque et al., 2004).

It is important to note that in an actual RO system, there is a pressure drop between the feed entering the RO module and the brine exiting from it and entering the DWEER. Because of this loss, it is not possible for the effluent from the DWEER to flow back into the feed. The pressure vessel has a limited volume, so a valve causes the two vessels to exchange functions before the piston in that volume completes its stroke. By installing a booster pump, flow and pressure equilibrium conditions are established. Typically such a pump is designed for a differential head of about 30 to 40 m (Schneider et al., 2005). The flow exiting the DWEER is now able to match the discharge pressure of the HPP (which has a capacity equivalent to the permeate flow), and hence allowing the system to operate in a loop (Farooque et al., 2004).

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Grand Cayman	Cayman Islands	4,900	1.3	Seawater
Ashkelon	Israel	330,000	87.2	Seawater
Tuas	Singapore	110,000	29.1	Seawater

Recuperator		www.aqualyng.com	
Name	Aqualyng	Stock Symbol	n/a
Location	Norway	Year Listed	n/a
Founded	1992	Annual Gross Revenue	Not Reported
Primary Market	Reverse osmosis systems	Secondary Market	None
Subsidiaries	None	Parent Company	Aqualyng AS

Notes: The Aqualyng Recuperator is not offered for sale as a standalone product, but is instead supplied as a proprietary energy recovery device in an Aqualyng desalination system.

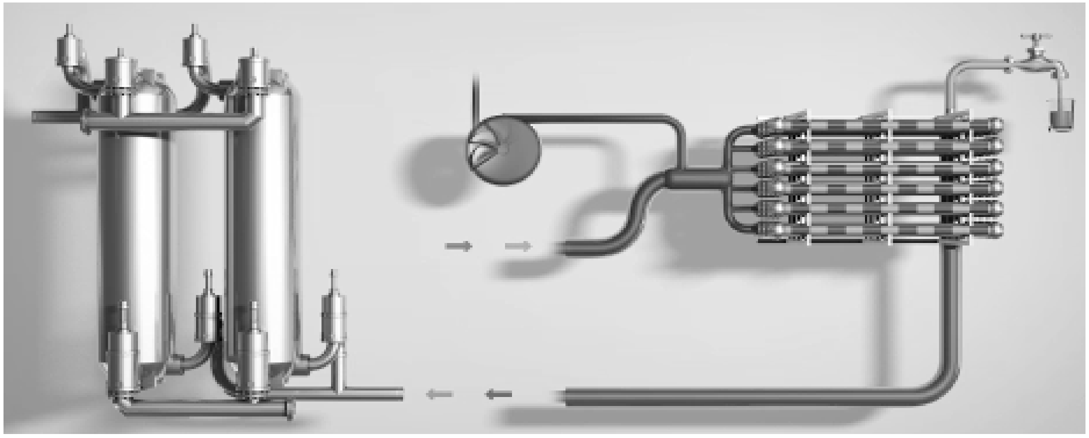
Key Trademarks: Recuperator

Products

(TYPE)

Name	Capacity (m^3/d)	Capacity (mgd)
RO-500STD	92	21
RO-1000STD	183	42
RO-2000STD	367	83
RO-5000STD	917	208
RO-10000STD	1835	417

Process Description: In its operation, the Recuperator uses the saline reject in a sequential process to directly pressurize seawater in two upright pressure exchange vessels (Drablos et al. 2002). The process is designed to achieve the same flow and pressure as the saline reject without mixing of respective fluids. To compensate for the pressure drop across the membranes (0.5–1.5 bar) and in the recuperator system (0.2–0.6 bar), the system is fitted with a booster pump. The system is highly automated without interruptions in flow of high-pressure seawater to the membranes.

	Recuperator	www.aqualyng.com
Process Schematic		

Key Installations	Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
	Caofeidian	China	50,000	13.2	Seawater

Clark Pump		http://www.spectrawatermakers.com/	
Name	Spectra Watermakers Inc.	Stock Symbol	n/a
Location	California	Year Listed	n/a
Founded	1997	Annual Gross Revenue	n/a
Primary Market	Small capacity RO energy recovery devices	Secondary Market	None
Subsidiaries	n/a	Parent Company	n/a

Notes

Spectra Watermakers is privately held U.S.-based company specializing in the supply of compact desalination devices for the marine industry. The Clark Pump is a highly efficient, low-flow device utilized in small package systems. The prime market for systems of this size include yachting desalination systems and autonomous renewable energy powered systems.

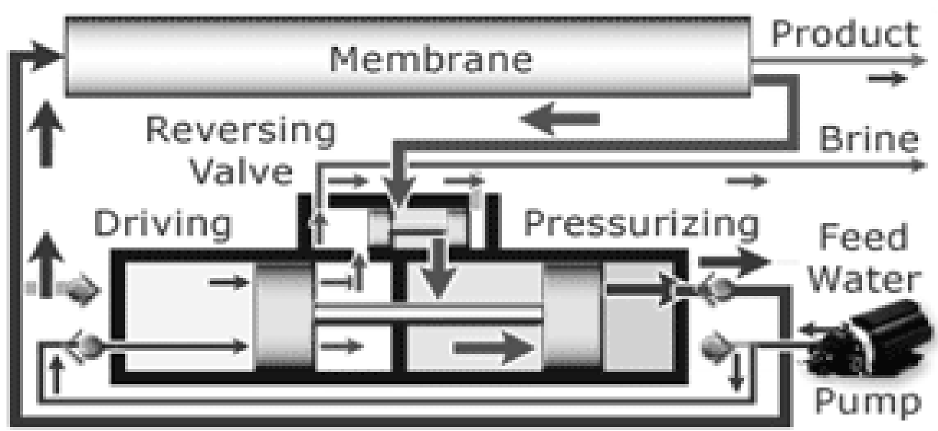
Key Trademarks Products

None

Process Description

The Clark Pump is a single-vessel, two-chamber, isobaric energy recovery device. Similar to larger isobaric, multichamber ERDs, an external pilot valve (reversing valve) controls the sequencing and flow of water through the device. The system is designed for a fixed recovery depending on the area displaced by the shaft on the concentrate side of the piston.

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Numerous small installations	Global			

Comments

Although the Clark Pump is applicable to low-capacity applications, it is not applicable at this time for larger installations.

Pearson Pump		http://www.spectrawatermakers.com/	
Name	Spectrawater Makers	Stock Symbol	n/a
Location	California	Year Listed	n/a
Founded	Not reported	Annual Gross Revenue	n/a
Primary Market	Small capacity RO energy recovery devices	Secondary Market	None
Subsidiaries	n/a	Parent Company	n/a

Notes

Spectra Watermakers is privately held US based company specializing in the supply of compact desalination devices for the marine industry. The Pearson Pump is a highly efficiency, low-flow device utilized in small package systems. The prime market for systems of this size includes yachting desalination systems and autonomous renewable energy powered systems.

Key Trademarks

None

Products

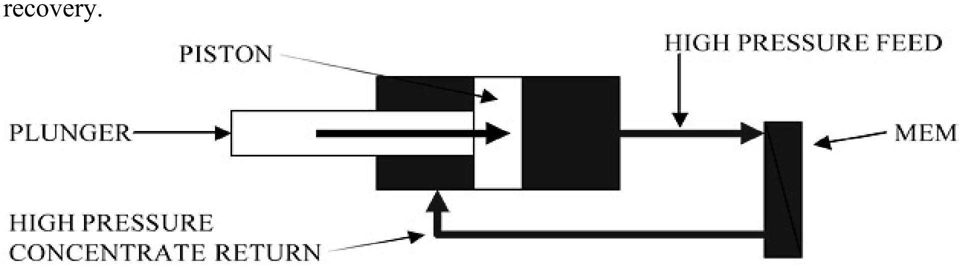
(TYPE)

Name	Capacity (m^3/d)	Capacity (mgd)	Recovery	Efficiency
Pearson Pump	3.5–6.5	0.8–1.5	20% 30% 50%	≤80%

Process Description

The Pearson Pump is a positive displacement three cylinder reciprocating HPP with the same motors and crankcases used in conventional RO system feed pumps. The Pearson Pump head delivers water to the membranes in the same way as conventional feed pumps but is capable of recovering the energy in the concentrate. This is done by returning the concentrate to the Pearson Pump at high pressure, where it flows into the pump cylinders on the undersides of the pistons, transferring its energy to the feed water being discharged to the membranes. The energy recovered from the concentrate reduces the load on the pump motor, reducing the electrical consumption dramatically. Like other similar devices (such as Vari-RO), the Pearson pump operates at a fixed recovery. The device is available in multiple designs ranging in recovery from 20% to 50% recovery.

Process Schematic



Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Numerous small installations	Global			

iSAVE		http://www.isave.danfoss.com	
Name	Danfoss	Stock Symbol	n/a
Location	Denmark	Year Listed	n/a
Founded	1933	Annual Gross Revenue	31,550m DKK
Primary Market	Energy Recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	n/a

Notes

The iSave energy recovery device couples an isobaric ERD and booster pump into a single system, eliminating a unit process in the implementation of seawater desalination. They are targeted at individual trains of less than 4,000 m^3/d. Although sales figures for the iSave are not available, over 15,000 pumps were reported sold in 2009.

Key Trademarks

iSAVE

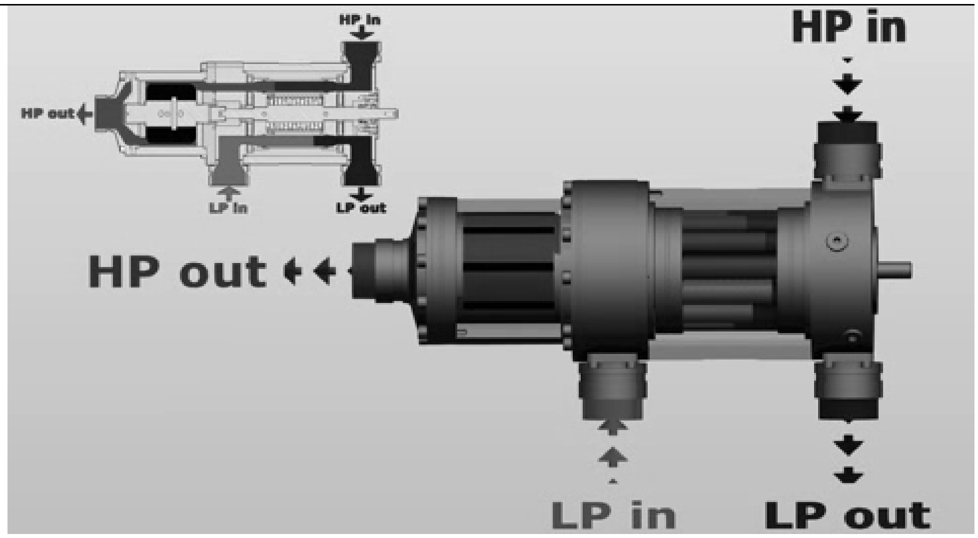
Products

iSave Integrated Pump and Energy Recovery System

Name	Capacity (m^3/d)	Capacity (mgd)	Efficiency
iSave 21	62–92	14–21	Up to 93%
iSave 40	97–176	22–40	Up to 93%
iSave 60	172–264	39–60	Up to 94%
iSave 77	260–339	59–77	Up to 95%

Process Description

The iSave consists of an isobaric pressure exchanger (PE), a high-pressure positive displacement booster pump (BP), and an electric motor coupled into a single package. The technology utilized in the isobaric exchangers is based upon technology used in the Danfoss APP pumps, and the high-pressure booster pumps are based on the vane pump principle enabling a very light and compact design. The iSave is a self-lubricating device and is constructed of stainless steel, duplex or super-duplex depending upon the application. The vane pumps are fixed displacement pumps in which the flow is proportional to the number of revolutions of the driving shaft enabling flow control. The electric motor provides speed control of both the pressure exchanger and the high-pressure booster pump on the same shaft—preventing over spin / over flushing. A VFD controlling the speed of the iSave also provides fail-safe communication to the service staff. Current applications for the iSave device include marine and container based installations.

	iSAVE	http://www.isave.danfoss.com
Process Schematic		

Key Installations	Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
	Numerous small installations	Global			

Comments	Like many other ERDs, the salinity of the feed is increased as a result of leakage within the device. Typical leakage increases the salinity on the order of 2%–5% of the feed water salinity, depending on RO recovery and unit flow rates.

SALTEC		www.ksb.com	
Name	KSB	Stock Symbol	KSBG
Location	Germany	Year Listed	1895
Founded	1871	Annual Gross Revenue	>€1,900M
Primary Market	Pumps and Energy Recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	None
Notes	SalTec ERD developed in 2004		
Key Trademarks	SalTec		

Products

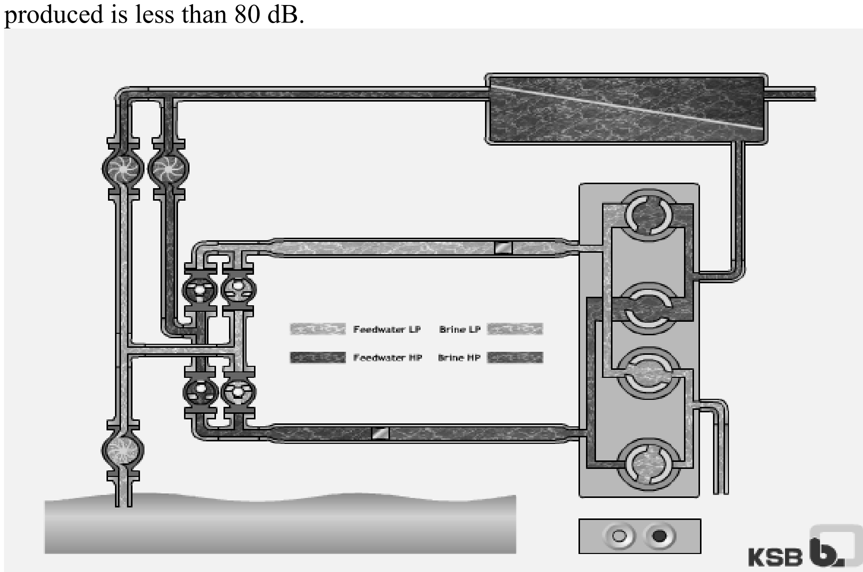
Isobaric Energy Recovery Devices

Name	Capacity (gpm)	Capacity (m^3/h)	Efficiency	Mixing
DT160	704	160	Not Reported	<1%
DT250	1101	250	Not Reported	<1%

Process Description

SalTec N System includes a HPP, pressure exchanger, and booster pump. Noise produced is less than 80 dB.

Process Schematic

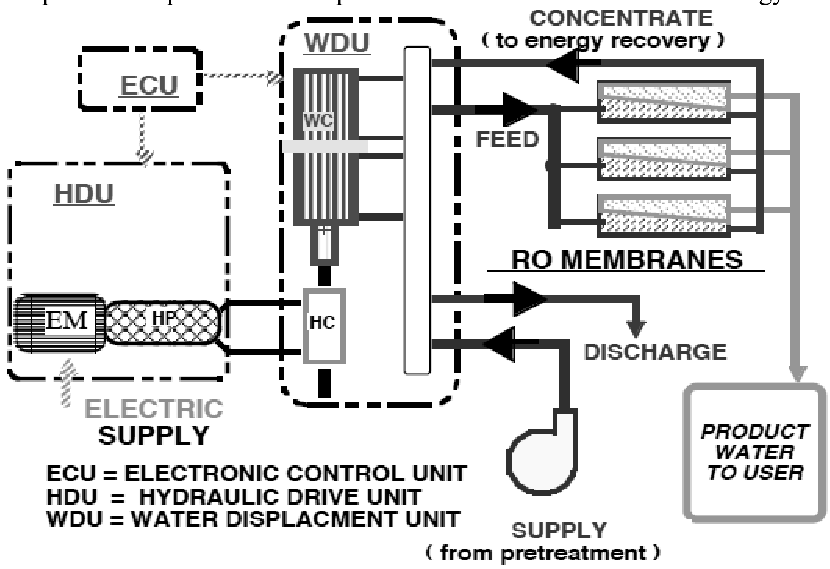


Key Installations

Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Pembrook (2008)	Malta	40,000	10.6	Seawater
Sharm El Shiekh (2004)	Egypt	1,920	0.51	Seawater

IPER			n/a
Name	Vari-RO Inc.	Stock Symbol	n/a
Location	California	Year Listed	n/a
Founded	2003 (Bought by GE in 2011)	Annual Gross Revenue	n/a
Primary Market	Pumps and Energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	GE
Notes	Currently, Vari-RO has no full-scale operating installations.		
Key Trademarks	Vari-RO, IPER		
Products	Not commercially available		
Process Description	This positive displacement ERD system is suitable for large capacity RO desalting facilities. It has three double acting pistons that operate in complementary fashion to provide smooth, low pulsation discharge flow. The variable flow feature of the VARI-RO technology allows the system to be started unloaded and gradually brought up to design flow conditions. Also, the flow and pressure can be adjusted during operation to optimize system performance; or to compensate for performance improvements of new membrane technology.		

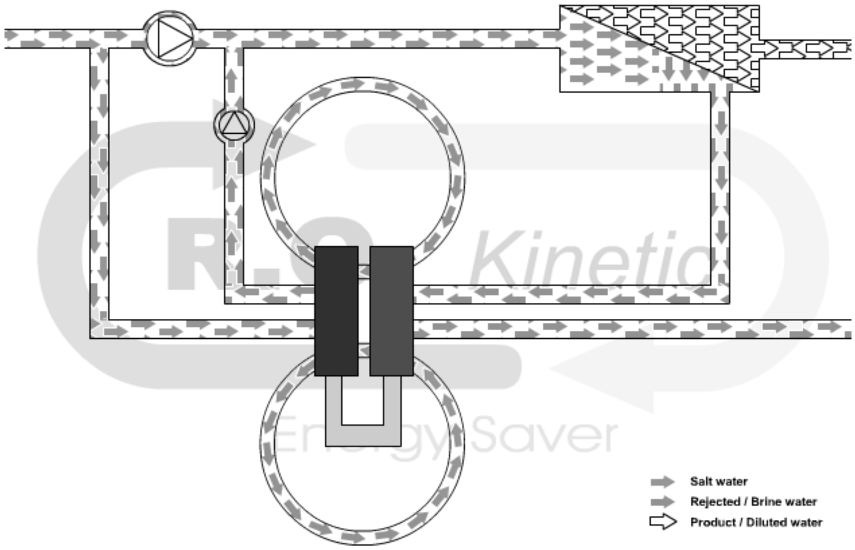
Process Schematic



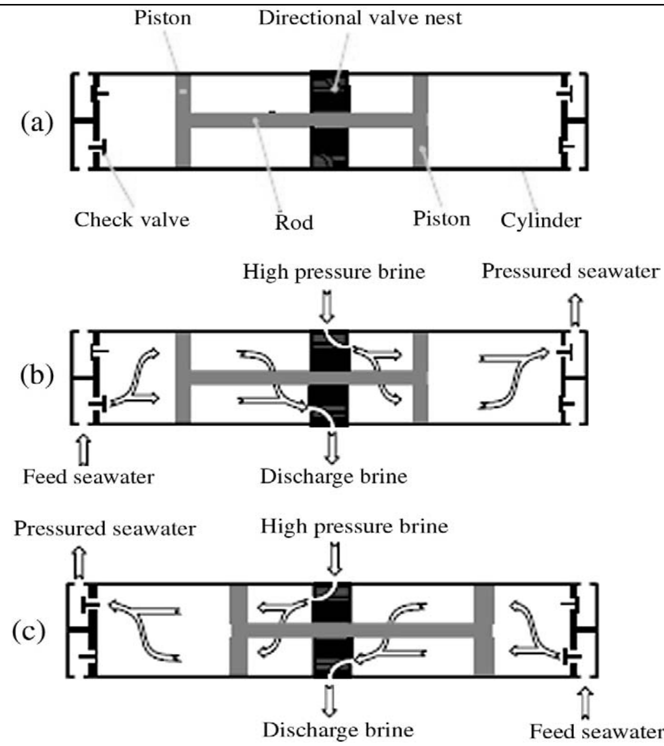
Key Installations

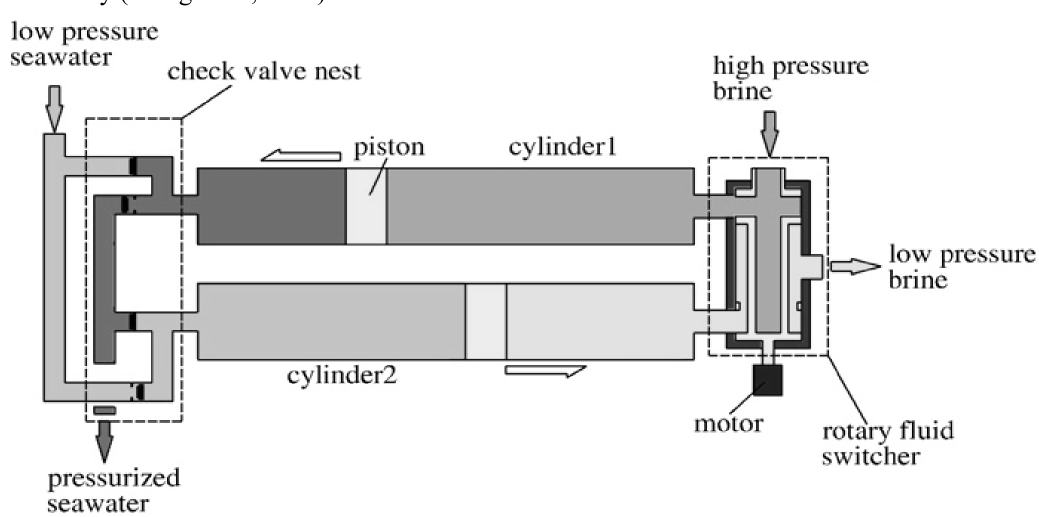
Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
Catalina Island SWRO	California			SWRO (in construction)

RO-KINETIC		n/a	
Name	RO Kinetic	Stock Symbol	n/a
Location	Canary Islands	Year Listed	n/a
Founded	n/a	Annual Gross Revenue	Not Reported.
Primary Market	Pumps and Energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	None
Notes	Developing ERD device		
Key Trademarks	RO Kinetic		
Products	Proprietary desalination system/ERD		
Process Description	RO Kinetic pressure exchangers are designed in the form of a ring or closed loop. The water entering or leaving must be pressurized or depressurized, and is always in continual motion to avoid unnecessary consumption of kinetic energy from stops in the operation. Furthermore, the device is designed so that the ratio between length and diameter reduces the chances of excessive pressure drops or mixing (Peñate et al., 2010). The system housing consists of two bodies of servo-controlled valves, separated by two inertia valves. The banks of valves distribute input of seawater and output of brine from the pressure exchangers sequentially. The design of these valves prevent cavitations, turbulence or excessive pressure drops. The inertia valves are an extension to the pressure exchangers. To avoid the water shocks that may occur during the small stop that takes place during the valve operation while the chambers are filling up, the RO Kinetic® installation is also equipped with an expansion bladder in order to act as a water hammer damper (Peñate et al., 2010). In its operation, the passage of the water from one chamber to another is done with practically no interruption, because of the speed with which valves are activated. The feed water accumulated in one of the pressure exchangers is pressurized with a HPP. This step is accomplished by making a closed circuit between the membrane output and the reverse osmosis (RO) module input, where a water tank (pressure exchanger) and a booster pump are fitted into the line. The brine output from the RO rack and the seawater input to the membranes are at the same static pressure, supplied by the HPP. The brine is then fed into the pressure exchanger and displaces the feed water contained in the chamber, forcing it into the module input. To achieve this, the pressure differential (ΔP) caused by pressure drops (1 to 2 bars) that take place in the membranes and in the pressure exchangers must be overcome. Hence, the booster pump is designed to overcome this pressure drop of about 3 bars. It is reported that the system can achieve a maximum energy efficiency of approximately 98%. It is reported that this system is the only system in the world that takes maximum advantage of the kinetic energy, working in a continuous kinetic cycle (Dpto. Técnico Tecnovalia, 2006). This process can reach SEC levels of 2.10 kWh/m^3 (for a SWRO plant with a nominal production capacity of 2000 m^3/day), compared with 3.50 to 4.00 kWh/m^3 in optimized facilities turbine-type energy recovery devices. The reduction of the SEC is between 25 and 50% compared to plants with conventional ERDs. This reduction, of practically 50% of the variable costs in the desalination plant, represents a reduction of 25% of the total cost (Peñate et al., 2010).		

	RO-KINETIC			**n/a**	
Process Schematic					
Key Installations	Name	Location	Capacity (m^3/d)	Capacity (mgd)	Type
	El Fraile	Canary Islands	1800	0.48	Seawater
	El Confital	Canary Islands	4000	1.06	Seawater
	Arona Hotel	Canary Islands	200	0.05	Seawater
	Aguas de Ponta Preta	Cape Verde	1000	0.26	Seawater
	Aguas de Ponta Preta	Cape Verde	1000	0.26	Seawater
	Aguas de Porto Novo	Cape Verde	500	0.13	Seawater
Comments	Model #s: K-200, K-1000				

Hydraulic Energy Recovery (HER)		www.tju.edu.cn/	
Name	HER	Stock Symbol	n/a
Location	China	Year Listed	n/a
Founded	Not reported	Annual Gross Revenue	n/a
Primary Market	Small-capacity RO energy recovery devices	Secondary Market	None
Subsidiaries	n/a	Parent Company	n/a
Notes	HER has not yet been produced on a commercial scale. However, the simulation work indicates that the HER device has a promising application in small-scale SWRO system.		
Key Trademarks	HER		
Products	Not commercially available		
Process Description	The HER device recovers the hydraulic energy from the high-pressure brine steam and returns it directly to the feed seawater. The two pistons are connected by a central rod and are assembled in two cylinders, respectively. The middle locator of the two cylinders is the directional valve nest, which achieves the switch of flow direction of high-pressure brine and discharge brine. The four check valves are installed at the end of the cylinders. The feed and the high-pressure brine both act to push the pistons to move, thus driving the pressured seawater. When one piston reaches the front of the directional valve nest, it pushes the directional valves to the next station, after that the moving direction of the pistons are reversed, as shown in Fig. c, and the piston travels back to the left, until it again reverses. Directional valves timing is critical to minimize pressure surges and avoid the water hammer caused by the change of flows in the cylinders. For this reason, four check valves are used and accumulators should be installed in SWRO system. Unlike the Clark pump (Thomas et al., 2002) and the Pressure exchanger–intensifier (Folley et al., 2008), directional valves of the HER device are installed inside and are driven by the pistons. Because the switches of the directional valves belong to an instantaneous process, the pressure surges during the switches can be effectively weakened or even eliminated (Sun et al., 2008). The device has a high-pressure transfer efficiency of approximately 94%. The simulated results show that the HER device can decrease the SEC of the SWRO system from 10 kWh/m^3 to 3.0 kWh/m^3. The pressure transfer efficiency of the HER device is approximately 94%.		

Hydraulic Energy Recovery (HER)	www.tju.edu.cn/
Process Schematic	
Key Installations	None

FS-ERD			n/a
Name	FS-ERD	Stock Symbol	n/a
Location	China	Year Listed	n/a
Founded	n/a	Annual Gross Revenue	n/a
Primary Market	Energy recovery in desalination applications	Secondary Market	None
Subsidiaries	None	Parent Company	n/a
Notes	Chinese research institution		
Key Trademarks	FS-ERD		
Products	Not commercially available		
Process Description	The FS-ERD is mainly composed of three parts: a rotary fluid switcher, two pressure cylinders, and a check valve nest. The core component of the FS-ERD is the rotary fluid switcher, which has four joint ports and two working phases similar to a two position four-way valve. A piston is installed in each cylinder to isolate seawater from brine and ensure minimum mixing between them during the operation. The position of the piston is detected to judge whether the pressurizing or depressurizing stroke has been accomplished, and when the fluid switcher should be changed to the next working phase. In the first phase, the HP brine stream is imported into cylinder 1 and therein the pre-filled low-pressure (LP) seawater feed is pressurized and pumped out, which is called the pressurizing stroke. Simultaneously, the HP brine stream in cylinder 2 would be depressurized and drained out by the incoming LP seawater feed, which is called the depressurizing stroke. Thereafter, when the FS-ERD accomplishes its pressurizing stroke (and also the depressurizing stroke), the switcher would rotate to working in the second phase at a low speed of 7.5 rpm driven by motor, which denotes that the stroke modes in cylinders are alternated to each other (Wang et al., 2010). No known sizable installations exist to date, FS-ERD and has not yet been produced on a commercial scale. However, the demonstration of parallel FS-ERDs under a real SWRO operating pressure is in progress at the FS-ERD test stand with a capacity of 2×500 m^3/d in our laboratory (Wang et al., 2010).		
Process Schematic			
Key Installations	None		

Appendix B

Validation of CH2M HILL Tool

B.1 Projection Validation. Bonita Springs

B.1.1 Bonita—Hydranautics IMS Design

Table B.1. Bonita Hydranautics Comparison

			IMS Design			CH2M HILL			
Case	Element	Flux (gfd)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	% Change in Feed Pres.
1	ESPA2	14.9	227.6	55.2	61.6	214.4	30.7	57.8	-6%
2	ESPA2	16.7	245.8	48.5	73.1	233.3	28.3	68.8	-5%
3	ESPA2	12.8	205.5	50.9	11.4	194.8	40.0	44.9	-5%
4	CPA5-LD	14.9	244.1	43.0	31.5	238.1	19.7	38.5	-2%
5	CPA5-LD	16.7	265.1	37.9	37.1	260.6	17.7	46.0	-2%
6	CPA5-LD	12.8	219.7	50.9	25.6	214.6	24.1	30.1	-2%

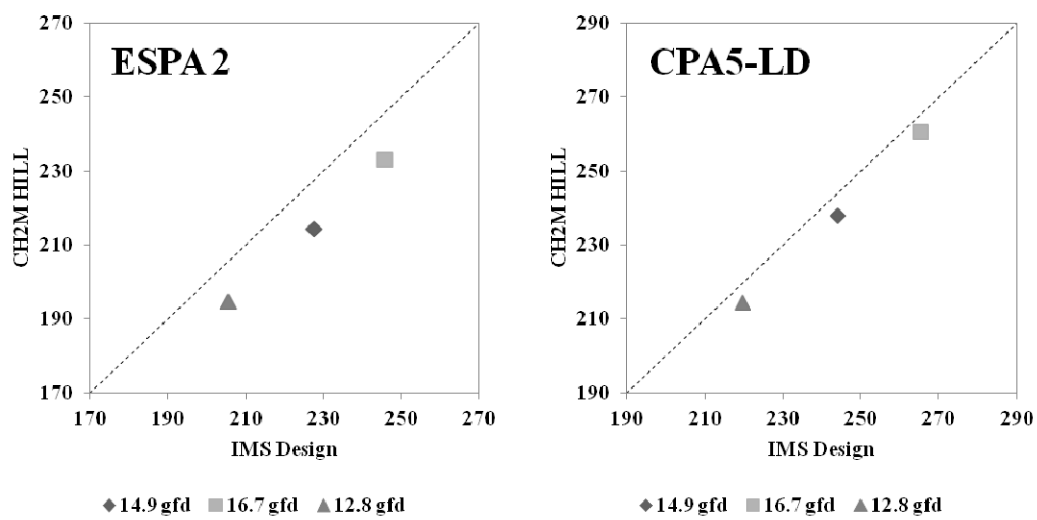


Figure B.1. Bonita Hydranautics Feed Pressure (psi)

B.1.2 Bonita—DOW ROSA

Table B.2. Bonita DOW Comparison

			ROSA			CH2M HILL			%
Case	**Element**	**Flux (gfd)**	**Feed Pressure (psig)**	**Permeate TDS (mg/L)**	**dP (psid)**	**Feed Pressure (psig)**	**Permeate TDS (mg/L)**	**dP (psid)**	**Change in Feed Pres.**
1	LE-400	14.9	221.14	52.4	72.3	191.54	97.8	49.2	-13%
2	LE-400	16.7	239.18	46.5	85.15	207.50	95.5	58.4	-13%
3	LE-400	12.8	199.48	61.3	58.8	176.86	147.1	37.8	-11%
4	BW30-440i	13.5	267.69	33.5	71.76	240.69	37.4	55.5	-10%
5	BW30-440i	15.2	293.34	29.9	84.12	263.20	33.8	66.2	-10%
6	BW30-440i	11.6	237.76	39.1	58.66	216.37	46.1	43.4	-9%

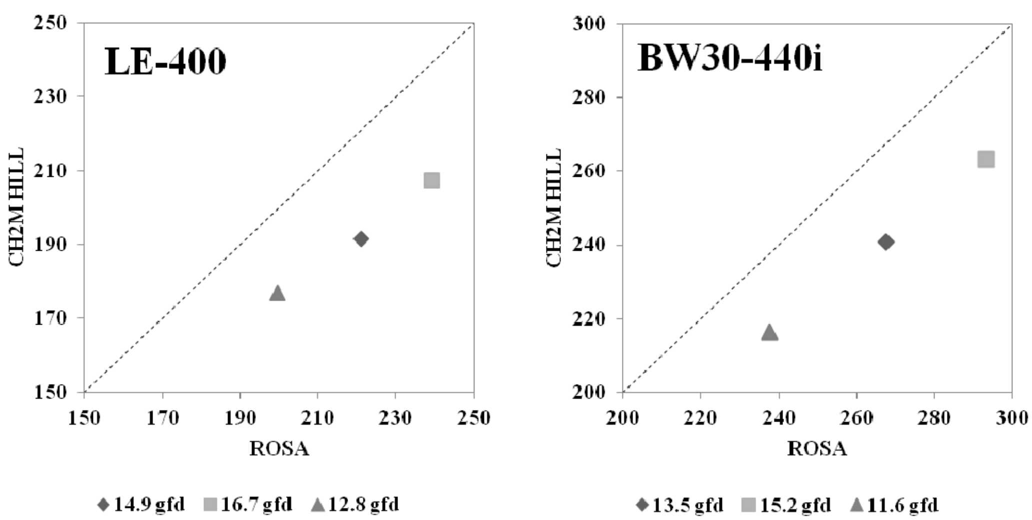


Figure B.2. Bonita DOW Feed Pressure (psi)

B.1.3 Bonita—TorayDS

Table B.3. Bonita Toray Comparison

			Toray			CH2M HILL			%
Case	Element	Flux (gfd)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Change in Feed Pres.
1	TML20-400	14.9	266.92	23.1	32.93	249.09	17.7	38.9	-7%
2	TML20-400	16.7	290.84	21.0	38.69	273.01	15.9	46.5	-6%
3	TML20-400	12.8	239.37	26.3	26.7	223.79	21.5	30.5	-7%
4	TM720L-430	13.8	218.77	42.9	36.65	209.34	38.5	52.4	-4%
5	TM720L-430	15.6	235.25	38.3	43.38	227.70	35.5	62.3	-3%
6	TM720L-430	11.9	199.49	50.0	29.43	190.63	50.4	40.7	-4%

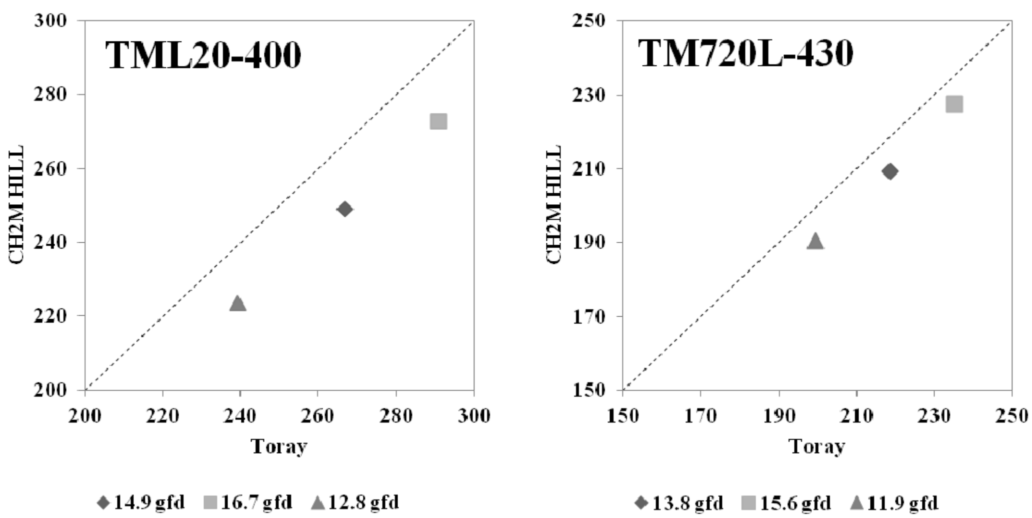


Figure B.3. Bonita Toray Feed Pressure (psi)

B.2 Projection Validation. Kwinana

B.2.1 IMS Design

Table B.4. Kwinana Hydranautics Comparison

			IMS Design			CH2M HILL			
Case	Element	Flux (gfd)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	Feed Pressure (psig)	Permeate TDS (mg/L)	dP (psid)	% Change in Feed Pres.
1	SWC4B	7.8	820.7	129.0	15.9	766.8	112.9	12.6	-7%
2	SWC4B	9.0	859.9	110.7	20.3	806.4	97.6	15.7	-6%
3	SWC4B	6.6	787.4	152.7	13.1	729.7	132.3	10.0	-7%
4	SWC6	7.8	730.8	275.2	16.0	657.4	207.8	16.7	-10%
5	SWC6	9.0	748.2	235.4	18.9	680.2	179.7	20.8	-9%
6	SWC6	6.6	716.3	327.0	11.6		Did Not Converge		-

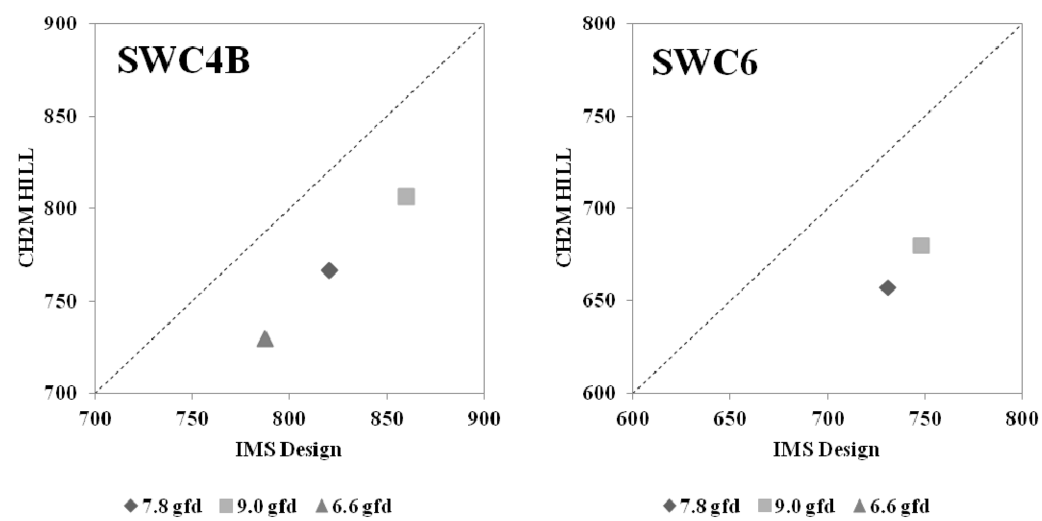


Figure B.4. Kwinana Hydranautics Feed Pressure (psi)

B.2.2 Kwinana—ROSA

Table B.5. Kwinana DOW Comparison

			ROSA			CH2M HILL			
Case	**Element**	**Flux (gfd)**	**Feed Pressure (psig)**	**Permeate TDS (mg/L)**	**dP (psid)**	**Feed Pressure (psig)**	**Permeate TDS (mg/L)**	**dP (psid)**	**% Change in Feed Pres.**
1	SW XHR-400i	7.8	833.9	110.8	22.0	788.3	94.9	15.1	-5%
2	SW XHR-400i	9.0	876.2	95.4	26.2	831.3	82.0	18.8	-5%
3	SW XHR-400i	6.6	796.2	129.2	18.4	748.0	111.3	11.9	-6%
4	SW30ULE-440i	7.1	721.1	360.2	19.4	655.4	314.7	15.1	-9%
5	SW30ULE-440i	8.2	740.1	312.0	23.1	678.2	272.3	18.8	-8%
6	SW30ULE-440i	6.0	703.1	421.4	16.4	Did Not Converge			-

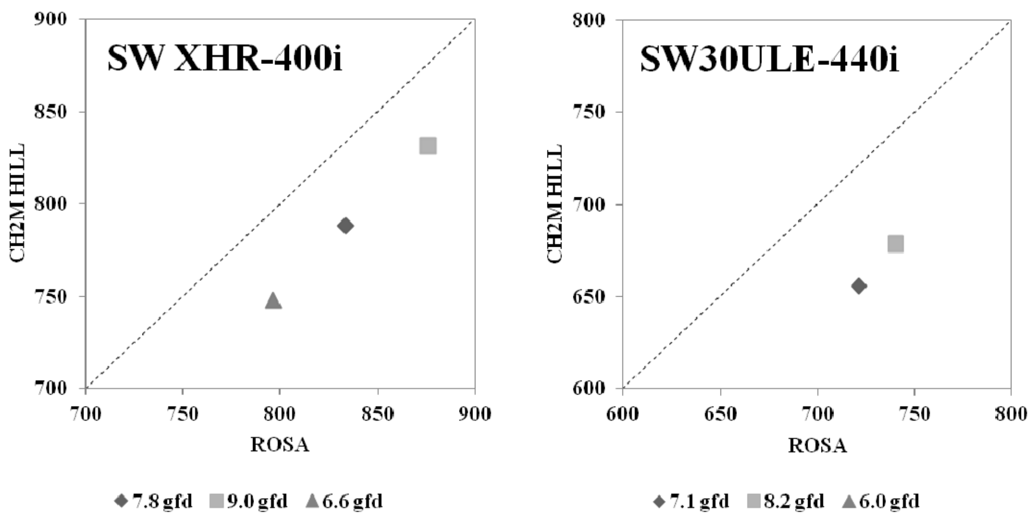


Figure B.5. Kwinana DOW Feed Pressure (psi)

B.2.3 Kwinana—Toray

Table B.6. Kwinana Toray Comparison

Case	Element	Flux (gfd)	Toray Feed Pressure (psig)	Toray Permeate TDS (mg/L)	Toray dP (psid)	CH2M HILL Feed Pressure (psig)	CH2M HILL Permeate TDS (mg/L)	CH2M HILL dP (psid)	% Change in Feed Pres.
1	TM820-400	7.8	855.7	129.6	11.8	766.5	142.7	12.6	-10%
2	TM820-400	9.0	904.2	114.1	14.3	806.1	123.4	15.7	-11%
3	TM820-400	6.6	813.0	149.8	9.5	729.4	167.2	10.0	-10%
4	TM820F-400	7.8	781.0	214.4	11.5	699.8	236.5	15.1	-10%
5	TM820F-400	9.0	811.6	187.0	14.0	729.3	204.6	18.8	-10%
6	TM820F-400	6.6	753.5	249.6	9.3	672.1	277.1	11.9	-11%

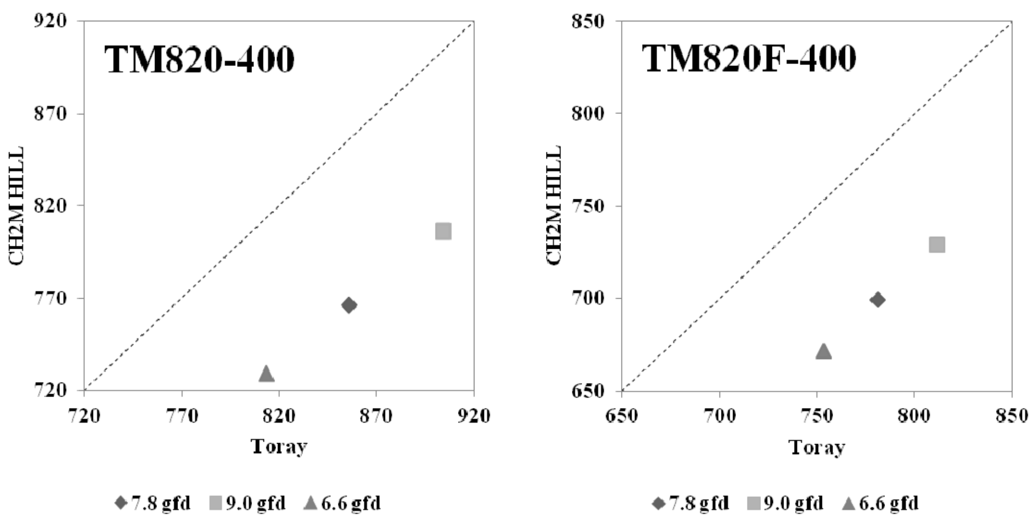


Figure B.6. Kwinana Toray Feed Pressure (psi)

B.3 Capital Cost Validation

Table B.7. Comparison of Tool vs. ADC (MacHarg, 2011)

	ADC	Tool
	(kWh/1000 gal)	
SEC (with ERI PX)	1.59/1.7*	1.65

*1.59 for new membranes, 1.7 with 5 year membrane life

Table B.8. Capital Cost of ERD Equipment/RO Train

	Capital Cost	
ERD Equipment/RO Train	**ADC**	**Tool**
BPX-300 (2)	$64,000	$62,000
Interstage/Boost Pump w/ VFD	$62,500	$66,900
Instrumentation	$15,000	$16,000
Piping and Fittings	$23,500	$14,600
Valving	$15,000	$9,000
Programming	$7,000	
Engineering	$25,000	$38,000
Construction Installation	$60,000	$58,200**
Startup/Commissioning	$3,000	
Contingency	$27,500	$46,200***
TOTAL	$302,500	$311,200

** Tool Installation factor is 35%

***Tool Contingencies include 10%, plus 10% engineering, plus 10% profit, plus 1% electrical, plus 2% mechanical

Appendix C

Visual Basic for Applications Code

The main procedures used to estimate the net driving pressure are shown in the following. The entire Visual Basic code can be viewed in Excel by opening the Visual Basic Editor (Alt+F11 on PCs once Excel is open).

Module 2

```
Sub CalcProjections()
'main routine to estimate required feed pressure
'Get information from tool inputs
Temperature = Worksheets("Water Quality").Range("Temp_C")
FeedpH = Worksheets("Water Quality").Range("pH_input")
RealRecovery = Worksheets("Summary").Range("Recovery")
S1BackPress = 0
S2BackPress = 0
If Worksheets("Summary").OptionButton20 = False Then 'inputs come in as english units
SheetFeedFlow = Range("FeedFlow") 'gpd
SheetPermFlow = Range("PermFlow") 'gpd
BPPress(1) = Range("BP1Press") 'psi
BPPress(2) = Range("BP2Press") 'psi
S1BackPress = Range("PermBackPress") 'psi
S2BackPress = Range("Perm2BackPress") 'psi
Else 'inputs come in as metric units
SheetFeedFlow = Range("FeedFlow") / 0.003785 'm3/d to gpd
SheetPermFlow = Range("PermFlow") / 0.003785 'm3/d to gpd
BPPress(1) = Range("BP1Press") / 6.895 'kPa to psi
BPPress(2) = Range("BP2Press") / 6.895 'kPa to psi
S1BackPress = Range("PermBackPress") / 6.895 'kPa to psi
S2BackPress = Range("Perm2BackPress") / 6.895 'kPa to psi
End If

'Bring in number of vessels for each stage
NumVessels(1) = Range("NVesselsS1")
NumStages = Worksheets("BWRO Flow Balance").Range("NumStages")
If NumStages > 1 Then
NumVessels(2) = Range("NVesselsS2")
Else
NumVessels(2) = 0
End If
If NumStages > 2 Then
NumVessels(3) = Range("NVesselsS3")
Else
NumVessels(3) = 0
End If
```

```
TotVessels = (NumVessels(1) + NumVessels(2) + NumVessels(3))

'Get information for bypass flow and make first guess
DesiredTDS = Worksheets("Water Quality").Range("BypassTDS")
FeedTDS = Worksheets("Water Quality").Range("FeedTDS")
CombinedPermTDS = 100000
If Worksheets("Summary").CheckBox2 = True Then
GuessBypassFlow = SheetPermFlow * (DesiredTDS - FeedTDS * 0.01) / (FeedTDS * 0.99)
If GuessBypassFlow < 0 Then GuessBypassFlow = TotPermFlow * 0.01
Else
GuessBypassFlow = 0
End If
l = 0

'Begin first loop for bypass flows.
'Guess bypass flow required to meet TDS needs based on 99% removal. May not be correct.
'Return to this step until within 10% of required TDS.
Do While Abs(DesiredTDS - CombinedPermTDS) / DesiredTDS > 0.1
l = l + 1
If l = 25 Then 'Only allow 25 iterations to find correct bypass flow.
MsgBox ("Error: Could not find accurate bypass flow.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
Worksheets("Summary").Protect ("WRF")
End
End If

'Redefine main flow streams without bypass flow
TotPermFlow = SheetPermFlow - GuessBypassFlow
TotFeedFlow = TotPermFlow / RealRecovery
TotConcFlow = TotFeedFlow – TotPermFlow

'Assume equal feed flow to each S1 vessel
FeedFlow = TotFeedFlow / NumVessels(1)
If FeedFlow > 115200 Then 'gpd
MsgBox ("Error: Greater than 80 gpm feed flow to a stage 1 vessel. Reconfigure system to
view projections.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
Worksheets("Summary").Protect ("WRF")
End
End If

'First guess at perm flow on a vessel by vessel basis
'Assumes same perm flow for each vessel
PermFlow = TotPermFlow / TotVessels
ConcFlow = FeedFlow - PermFlow
Recovery = PermFlow / FeedFlow

InitializeIons 'Initialize ions procedure: initialize charge, weight, name
OsmoticPressure(1) = OsmoticPressureCalc(FeedIons(), Temperature) 'Calc osmotic
pressure procedure
Istr(1) = IonicStrength(FeedIons()) 'Calc Ionic Strength procedure
```

dp(1) = **DeltaPressure**(FeedFlow, ConcFlow, SpacerThickness(1), NumElements(1))
'procedure to get dp for S1
GetElementData *'procedure to get BetaCoef, AValue, BValue based on selected membrane*

'Calculate the total area of all vessels
VesselArea(1) = Area(1) * NumElements(1)
VesselArea(2) = Area(2) * NumElements(2)
VesselArea(3) = Area(3) * NumElements(3)
StageArea(1) = VesselArea(1) * NumVessels(1)
StageArea(2) = VesselArea(2) * NumVessels(2)
StageArea(3) = VesselArea(3) * NumVessels(3)
AreaTot = StageArea(1) + StageArea(2) + StageArea(3)

s = 1 *'First stage*
'First guess at the feed pressure
FirstPressure = (PermFlow / 24 / 60 / 15850 / (VesselArea(1) / 10.76) / Avalue(1) * 14.7) * (1 - FluxDecline(s)) ^ MembraneAge(s) + dp(s) / 2 + OsmoticPressure(s) * 1.5
'15850 converts from gpm to m3/sec; 14.7 converts from atm to psi
dp(s) = **DeltaPressure**(FeedFlow, ConcFlow, SpacerThickness(s), NumElements(s))
NewPressure = FirstPressure

'First guess at net driving pressure based on first pressure
PNet = (NewPressure - OsmoticPressure(s) * 1.5 - dp(s) / 2 - S1BackPress) * (1 - FluxDecline(s)) ^ MembraneAge(s)
FirstSaltPass = Bvalue(s) / (NewPressure / 14.7 * Avalue(s) + Bvalue(s)) 'no units
nIters = 0
CalcTotPermFlow = 0

'Begin loop to estimate the feed pressure. This is the main loop for the program and is based on code from TFSP.
Do While Abs(TotPermFlow - CalcTotPermFlow) / TotPermFlow > 0.0005 Or nIters < 5
nIters = nIters + 1
If nIters > 150 Then *'Stop the program after 150 attempts to converge*
MsgBox ("The program failed to converge. Please verify that all inputs are accurate.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
Worksheets("Summary").Protect ("WRF")
End
End If
s = 1
FeedFlow = TotFeedFlow / NumVessels(1)
For i = 1 To LastIon
ProjFeedIons(i) = FeedIons(i)
If nIters = 1 Then
'Set a first guess for beta since it cannot be calculated yet and use it to guess permeate and concentrate concentrations
Beta = 1.05
PermConc(i, s) = FirstSaltPass * IONS(i).Pass * FeedIons(i) 'Calculate first guess at ions
ConcConc(i, s) = (FeedIons(i) * FeedFlow - PermConc(i, s) * PermFlow) / ConcFlow
End If
TotConcConc(i) = TotFeedFlow * FeedIons(i) / TotConcFlow 'estimation
If NumStages = 1 Then ConcConc(i, s) = TotConcConc(i)

```
If ConcConc(i, s) = 0 Then
MembDiffCalc(i) = (ProjFeedIons(i) + ConcConc(i, s)) / 2 - PermConc(i, s)
Else
If ConcConc(i, s) = ProjFeedIons(i) Then
MsgBox ("The program failed to converge. Please verify that all inputs are accurate.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
Worksheets("Summary").Protect ("WRF")
End
End If
MembDiffCalc(i) = Beta * (ProjFeedIons(i) - ConcConc(i, s)) / Log(ProjFeedIons(i) /
ConcConc(i, s)) - PermConc(i, s)
End If
Next i
'Pass through CO2
PermConc(SP_CO2, s) = ProjFeedIons(SP_CO2)
ConcConc(SP_CO2, s) = ProjFeedIons(SP_CO2)

'For future iterations, bring in the pressure from the end of the previous iteration
Pressure(s) = NewPressure
'Use the initial concentrations to guess the osmotic pressure at the membrane
BreakOsPress = OsmoticPressureCalc(MembDiffCalc(), Temperature)

'Recalculate PNet with the updated pressure and osmotic pressure
PNet = (Pressure(s) - BreakOsPress - dp(s) / 2 - S1BackPress) * (1 - FluxDecline(s)) ^
MembraneAge(s)

'CalcPermFlow per vessel
CalcPermFlow(s) = Avalue(s) * VesselArea(s) / 10.76 * PNet / 14.7 * 15850 * 24 * 60 'gpd
CalcPermFlow(2) = 0
CalcPermFlow(3) = 0

    'Now calculate the beta coefficient and use it to recalculate permeate and concentrate
    concentrations
If CalcPermFlow(s) <= 0 Then
CalcPermFlow(s) = 0
CalcRecovery = 0
Beta = 1
Else
CalcRecovery = CalcPermFlow(s) / FeedFlow
Beta = Exp(BetaCoef(s) * CalcRecovery) 'Beta Coefficient
End If
CalcConcFlow(s) = FeedFlow - CalcPermFlow(s)
If CalcConcFlow(s) < 0 Then CalcConcFlow(s) = 0.1 * FeedFlow
dp(s) = DeltaPressure(FeedFlow, CalcConcFlow(s), SpacerThickness(s), NumElements(s))

'Calc salt pass and use it to recalculate concentrations with new PNet
SaltPass = Beta * Bvalue(s) / (PNet / 14.7 * Avalue(s) + Bvalue(s))
For i = 1 To LastIon
PermConc(i, s) = SaltPass * IONS(i).Pass * ProjFeedIons(i)
ConcConc(i, s) = (ProjFeedIons(i) * FeedFlow - PermConc(i, s) * CalcPermFlow(s)) /
CalcConcFlow(s)
```

```
Next i

'send information for next stages
ConcPress(s) = Pressure(s) - dp(s)
Do While s < NumStages ' same routine for 2 and 3 stage systems
s = s + 1
FeedFlow = CalcConcFlow(s - 1) * NumVessels(s - 1) / NumVessels(s)

'Add in boost from interstage ERD or booster pumps
If nIters = 1 Then
TurboBoost = 0
IsoBoost = 0
Else
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Interstage Turbocharger"
And NumStages > 1 Then
If Worksheets("Summary").OptionButton18 = True And s = 2 Then
TurboBoost = CalcTurboBoost(ConcPress(NumStages), TotConcFlow, FeedFlow *
NumVessels(s), s)
Else
If Worksheets("Summary").OptionButton19 = True And s = 3 Then
TurboBoost = CalcTurboBoost(ConcPress(NumStages), TotConcFlow, FeedFlow *
NumVessels(s), s)
Else
TurboBoost = 0
End If
End If
End If
If Worksheets("Summary").OptionButton13 = True And NumStages > 1 And s = 2 Then
IsoBoost = CalcIsoBoost(ConcPress(NumStages), Pressure(1))
End If
End If
If Worksheets("Summary").OptionButton13 = True And NumStages > 1 And s = 2 Then
BPPress(1) = BPPress(1) + IsoBoost
Pressure(s) = ConcPress(s - 1) + BPPress(s - 1) + TurboBoost

        'Estimate the Salt pass with the new pressure including any boost and then calc ion
      concentrations
FirstSaltPass = Bvalue(s) / (Pressure(s) / 14.7 * Avalue(s) + Bvalue(s)) 'no units
For i = 1 To LastIon
ProjFeedIons(i) = ConcConc(i, s - 1)
PermConc(i, s) = FirstSaltPass * IONS(i).Pass * ProjFeedIons(i) 'Calculate first guess at ions
of next stage
ConcConc(i, s) = (ProjFeedIons(i) * FeedFlow - PermConc(i, s) * PermFlow) / ConcFlow
If ConcConc(i, s) = 0 Then
MembDiffCalc(i) = (ProjFeedIons(i) + ConcConc(i, s)) / 2 - PermConc(i, s)
Else
MembDiffCalc(i) = Beta * (ProjFeedIons(i) - ConcConc(i, s)) / Log(ProjFeedIons(i) /
ConcConc(i, s)) - PermConc(i, s)
End If
Next i
```

```
‘Calculate the osmotic pressure at the membrane and use to calc NDP (PNet)
BreakOsPress = OsmoticPressureCalc(MembDiffCalc(), Temperature)
PNet = (Pressure(s) - BreakOsPress - dp(s - 1) / 2) * (1 - FluxDecline(s)) ^ MembraneAge(s)
If s = 2 Then PNet = (Pressure(s) - BreakOsPress - dp(s - 1) / 2 - S2BackPress) * (1 -
FluxDecline(s)) ^ MembraneAge(s)
If PNet < 0 Then PNet = 0
CalcPermFlow(s) = Avalue(s) * VesselArea(s) / 10.76 * PNet / 14.7 * 15850 * 24 * 60 'gpd
CalcConcFlow(s) = FeedFlow - CalcPermFlow(s)
CalcRecovery = CalcPermFlow(s) / FeedFlow

‘Now calc beta coefficient and ion concentrations
Beta = Exp(BetaCoef(s) * CalcRecovery)
SaltPass = Beta * Bvalue(s) / (PNet / 14.7 * Avalue(s) + Bvalue(s))
For i = 1 To LastIon
PermConc(i, s) = SaltPass * IONS(i).Pass * ProjFeedIons(i)
ConcConc(i, s) = (ProjFeedIons(i) * FeedFlow - PermConc(i, s) * CalcPermFlow(s)) /
CalcConcFlow(s)
Next i
dp(s) = DeltaPressure(FeedFlow, CalcConcFlow(s), SpacerThickness(s), NumElements(s))
If CalcPermFlow(s) > 0 Then
ConcPress(s) = Pressure(s) - dp(s)
Else
ConcPress(s) = Pressure(s)
End If
OsmoticPressure(s) = OsmoticPressureCalc(ProjFeedIons(), Temperature)
'OP(1)=adjfeed; OP(2)=S2 feed; OP(3)=S3 feed; OP(4)=S3conc
Istr(s) = IonicStrength(ProjFeedIons())
Loop ‘loop back for 3 stage system
For i = 1 To LastIon
ProjFeedIons(i) = ConcConc(i, s)
Next i
OsmoticPressure(s + 1) = OsmoticPressureCalc(ProjFeedIons(), Temperature)
Istr(s) = IonicStrength(ProjFeedIons())
CalcTotPermFlow = CalcPermFlow(1) * NumVessels(1) + CalcPermFlow(2) *
NumVessels(2) + CalcPermFlow(3) * NumVessels(3)

'compare CalcPermFlow with TargetPermFlow and iterate Pressure
DeltaFlow = TotPermFlow - CalcTotPermFlow
DeltaPercent = Abs(TotPermFlow - CalcTotPermFlow) / TotPermFlow
'use a brute force convergence
OldPressure = NewPressure
Select Case DeltaFlow
Case Is > 0 ' the pressure needs to go up
If DeltaPercent > 1 Then
NewPressure = OldPressure + OldPressure * DeltaPercent
ElseIf DeltaPercent > 0.01 Then
NewPressure = OldPressure + OldPressure * DeltaPercent / 5
ElseIf DeltaPercent > 0.001 Then
NewPressure = OldPressure + OldPressure * DeltaPercent / 8
ElseIf DeltaPercent > 0.0008 Then
NewPressure = OldPressure + OldPressure * DeltaPercent / 10
```

```
ElseIf DeltaPercent > 0.0005 Then
NewPressure = OldPressure + OldPressure * DeltaPercent / 20
Else
NewPressure = OldPressure
End If
Case Is < 0 ' the pressure needs to go down
If DeltaPercent > 1 Then
NewPressure = OldPressure - OldPressure * DeltaPercent
ElseIf DeltaPercent > 0.01 Then
NewPressure = OldPressure - OldPressure * DeltaPercent / 5
ElseIf DeltaPercent > 0.001 Then
NewPressure = OldPressure - OldPressure * DeltaPercent / 8
ElseIf DeltaPercent > 0.0008 Then
NewPressure = OldPressure - OldPressure * DeltaPercent / 10
ElseIf DeltaPercent > 0.0005 Then
NewPressure = OldPressure - OldPressure * DeltaPercent / 20
Else
NewPressure = OldPressure
End If
End Select
Loop ‘loop back to amin projections routine

S1PermFlow = CalcPermFlow(1) * NumVessels(1)
S1ConcFlow = TotFeedFlow - S1PermFlow
S2PermFlow = CalcPermFlow(2) * NumVessels(2)
S2ConcFlow = S1ConcFlow - S2PermFlow
S3PermFlow = CalcPermFlow(3) * NumVessels(3)
S3ConcFlow = S2ConcFlow - S3PermFlow
PermTDS = 0
For i = 1 To LastIon
TotPermConc(i) = (PermConc(i, 1) * S1PermFlow + PermConc(i, 2) * S2PermFlow +
PermConc(i, 3) * S3PermFlow) / CalcTotPermFlow
Perm1Conc(i) = PermConc(i, 1)
Perm2Conc(i) = PermConc(i, 2)
Perm3Conc(i) = PermConc(i, 3)
BlendedPermConc(i) = (FeedIons(i) * GuessBypassFlow + TotPermConc(i) * TotPermFlow)
/ (TotPermFlow + GuessBypassFlow)
PermTDS = PermTDS + TotPermConc(i)
Next i

If Worksheets("Summary").CheckBox2 = True Then
CombinedPermTDS = (FeedTDS * GuessBypassFlow + PermTDS * TotPermFlow) /
(TotPermFlow + GuessBypassFlow)
If (DesiredTDS - CombinedPermTDS) / DesiredTDS > 0.1 Then
GuessBypassFlow = GuessBypassFlow * 1.1
End If
If (DesiredTDS - CombinedPermTDS) / DesiredTDS < -0.1 Then
GuessBypassFlow = GuessBypassFlow * 0.9
End If
Else
CombinedPermTDS = DesiredTDS
```

```
End If
Loop ‘loop back to bypass flow calc

‘check to make sure no rules of thumb are broken
If Pressure(1) > 1200 Then
MsgBox ("Error: Feed pressure is greater than 1200 psi. Please revise system design.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
End
End If
If Worksheets("Membrane Database").Range("S1Application") = "BWRO" Then
If Pressure(1) > 600 Then
MsgBox ("Error: Feed pressure is greater than 600 psi. Please select a SWRO membrane.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
End
End If
End If
If NumStages > 1 Then
If CalcConcFlow(1) * NumVessels(1) / NumVessels(2) > 115200 Then 'gpd
MsgBox ("Error: Greater than 80 gpm feed flow to a stage 2 vessel. Reconfigure system to
view projections.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
End
End If
End If
If NumStages > 2 Then
If CalcConcFlow(2) * NumVessels(2) / NumVessels(3) > 115200 Then 'gpd
MsgBox ("Error: Greater than 80 gpm feed flow to a stage 3 vessel. Reconfigure system to
view projections.")
Worksheets("BWRO Flow Balance").Range("Proj") = ""
End
End If
End If

‘prepare information to be written out to tool
OsmoticPressure(5) = OsmoticPressureCalc(Perm1Conc(), Temperature)
OsmoticPressure(6) = OsmoticPressureCalc(Perm2Conc(), Temperature)
OsmoticPressure(7) = OsmoticPressureCalc(Perm3Conc(), Temperature)
OsmoticPressure(8) = OsmoticPressureCalc(TotPermConc(), Temperature)
OsmoticPressure(9) = OsmoticPressureCalc(BlendedPermConc(), Temperature)
'OP(5)=S1 perm; OP(6)=S2 perm; OP(7)=S3 perm; OP(8)=tot perm; OP(9)=blended perm
Istr(5) = IonicStrength(Perm1Conc())
Istr(6) = IonicStrength(Perm2Conc())
Istr(7) = IonicStrength(Perm3Conc())
Istr(8) = IonicStrength(TotPermConc())
Istr(9) = IonicStrength(BlendedPermConc())
Worksheets("Cost Summary").Range("NoERDkW") = "N/A"
Worksheets("Cost Summary").Range("NoERDCost") = "N/A"
PutDataOnSheets ‘procedure that writes out to the tool
End Sub

Public Sub InitializeIons()
```

```
'Store ion information

'Charge
IONS(SP_Ca).Charge = 2
IONS(SP_Mg).Charge = 2
IONS(SP_Na).Charge = 1
IONS(SP_K).Charge = 1
IONS(SP_NH4).Charge = 1
IONS(SP_Sr).Charge = 2
IONS(SP_Ba).Charge = 2
IONS(SP_Fe3).Charge = 3
IONS(SP_Al).Charge = 3
IONS(SP_B).Charge = 3
IONS(SP_CO3).Charge = -2
IONS(SP_HCO3).Charge = -1
IONS(SP_CO2).Charge = -2
IONS(SP_SO4).Charge = -2
IONS(SP_Cl).Charge = -1
IONS(SP_Br).Charge = -1
IONS(SP_NO3).Charge = -1
IONS(SP_F).Charge = -1
IONS(SP_PO4).Charge = -3
IONS(SP_SiO2).Charge = 2

'Molecular Weight
IONS(SP_Ca).MolWt = 40.08
IONS(SP_Mg).MolWt = 24.305
IONS(SP_Na).MolWt = 22.99
IONS(SP_K).MolWt = 39.098
IONS(SP_NH4).MolWt = 18.04
IONS(SP_Sr).MolWt = 87.62
IONS(SP_Ba).MolWt = 137.34
IONS(SP_Fe3).MolWt = 55.847
IONS(SP_Al).MolWt = 26.98154
IONS(SP_B).MolWt = 10.811
IONS(SP_CO3).MolWt = 60.01
IONS(SP_HCO3).MolWt = 61.01
IONS(SP_CO2).MolWt = 44.04
IONS(SP_SO4).MolWt = 96.06
IONS(SP_Br).MolWt = 79.904
IONS(SP_Cl).MolWt = 35.45
IONS(SP_NO3).MolWt = 62.005
IONS(SP_F).MolWt = 19
IONS(SP_PO4).MolWt = 94.9738
IONS(SP_SiO2).MolWt = 60.08

'Name
IONS(SP_Na).Name = "Na = 1"
IONS(SP_K).Name = "K = 2"
IONS(SP_Ca).Name = "Ca = 3"
IONS(SP_Mg).Name = "Mg = 4"
```

```
IONS(SP_Sr).Name = "Sr = 5"
IONS(SP_Ba).Name = "Ba = 6"
IONS(SP_Al).Name = "Al = 7"
IONS(SP_Fe3).Name = "Fe3 = 8"
IONS(SP_NH4).Name = "NH4 = 9"
IONS(SP_HCO3).Name = "HCO3 = 10"
IONS(SP_CO2).Name = "CO2 = 11"
IONS(SP_CO3).Name = "CO3 = 12"
IONS(SP_Br).Name = "Br = 13"
IONS(SP_Cl).Name = "Cl = 14"
IONS(SP_F).Name = "F = 15"
IONS(SP_SO4).Name = "SO4 = 16"
IONS(SP_NO3).Name = "NO3 = 17"
IONS(SP_PO4).Name = "PO4 = 18"
IONS(SP_SiO2).Name = "SiO2 = 19"

'Input values
FeedIons(SP_Na) = Range("User_Na").Value
FeedIons(SP_K) = Range("User_K").Value
FeedIons(SP_Ca) = Range("User_CA").Value
FeedIons(SP_Mg) = Range("User_MG").Value
FeedIons(SP_Sr) = Range("User_SR").Value
FeedIons(SP_Ba) = Range("User_BA").Value
FeedIons(SP_Al) = Range("User_AL").Value
FeedIons(SP_Fe3) = Range("User_FE3").Value
FeedIons(SP_B) = Range("User_B").Value
FeedIons(SP_NH4) = Range("User_NH4").Value
FeedIons(SP_HCO3) = Range("User_HCO3").Value
FeedIons(SP_CO2) = Range("User_CO2").Value
FeedIons(SP_CO3) = Range("User_CO3").Value
FeedIons(SP_Br) = Range("User_BR").Value
FeedIons(SP_Cl) = Range("User_CL").Value
FeedIons(SP_F) = Range("User_F").Value
FeedIons(SP_SO4) = Range("User_SO4").Value
FeedIons(SP_NO3) = Range("User_NO3").Value
FeedIons(SP_PO4) = Range("User_PO4").Value
FeedIons(SP_SiO2) = Range("User_SIO2").Value

'Account for leakage flow across Isobaric ERD
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Isobaric" Then
For i = 1 To LastIon
Leakage = Range("IsoLeak")
FeedIons(i) = FeedIons(i) + Leakage * FeedIons(i) / (1 - Recovery)
Next i
End If

'passage coefficients - all relative to Na and Cl
IONS(SP_Ca).Pass = 0.25
IONS(SP_Mg).Pass = 0.25
IONS(SP_Na).Pass = 1
IONS(SP_K).Pass = 1.3
```

```
IONS(SP_NH4).Pass = 2
IONS(SP_Sr).Pass = 0.25
IONS(SP_Ba).Pass = 0.25
IONS(SP_Fe3).Pass = 0.25
IONS(SP_Al).Pass = 0.25
IONS(SP_B).Pass = 40
IONS(SP_CO3).Pass = 0.25
IONS(SP_HCO3).Pass = 1
IONS(SP_CO2).Pass = 0.25
IONS(SP_SO4).Pass = 0.25
IONS(SP_Cl).Pass = 1
IONS(SP_Br).Pass = 1.3
IONS(SP_NO3).Pass = 1.5
IONS(SP_F).Pass = 0.7
IONS(SP_PO4).Pass = 0.2
IONS(SP_SiO2).Pass = 0.75
End Sub

Sub GetElementData()
'Read information from Membrane selection worksheet and calculate beta coefficient and
membrane specific passage coefficients

S1ElemFlow = Range("S1ElemFlow") 'gpd
S1ElemPress = Range("S1ElemPress") 'psi
S1ElemTDS = Range("S1ElemTDS") 'mg/L
S1ElemRej = Range("S1ElemRej") / 100 '%
Area(1) = Range("S1Area") 'sf
S1ElemLength = Range("S1ElemLength") 'in
S1ElemRecovery = Range("S1ElemRec") / 100 'in
SpacerThickness(1) = Range("S1SpaceThick")
NumElements(1) = Range("NumS1Elements")
S1AdjustedLength = S1ElemLength * NumElements(1)
MembraneAge(1) = Range("S1MemAge")
FluxDecline(1) = Range("S1FluxDec")

ATempCorr = Exp((1 / (273 + Temperature) - 1 / 298) * 3020)
S1CalcConcentration = ((S1ElemFlow / S1ElemRecovery) * S1ElemTDS - S1ElemFlow *
S1ElemTDS * (1 - S1ElemRej)) / (S1ElemFlow / S1ElemRecovery * (1 - S1ElemRecovery))
'mg/L
S1ConcentrationDiff = (S1ElemTDS + S1CalcConcentration) / 2 - S1ElemTDS * (1 -
S1ElemRej) 'mg/L
Bvalue(1) = S1ElemFlow * S1ElemTDS * (1 - S1ElemRej) / (Area(1) *
S1ConcentrationDiff) / 2120315 / ATempCorr
''(mg/L)*(gal/day)*(1 day/86400 s)*(1ft3/7.48 gal)*(0.3048m/ft)/(ft2*mg/L)=m/s
Avalue(1) = S1ElemFlow / (Area(1) * (S1ElemPress - OsmoticPressure(1))) / 144239 /
ATempCorr
'(gal/day)*(1day/86400s)*(1ft3/7.48gal)*(.3048m/ft)*(14.7psi/atm)/(ft2*psi) - convert to
m/s/atm
BetaCoef(1) = -0.3492 * Log(S1AdjustedLength) + 2.0152

S2ElemFlow = Range("S2ElemFlow") 'gpd
```

```
S2ElemPress = Range("S2ElemPress") 'psi
S2ElemTDS = Range("S2ElemTDS") 'mg/L
S2ElemRej = Range("S2ElemRej") / 100 '%
Area(2) = Range("S2Area") 'sf
S2ElemLength = Range("S2ElemLength") 'in
S2ElemRecovery = Range("S2ElemRec") / 100 'in
SpacerThickness(2) = Range("S2SpaceThick")
NumElements(2) = Range("NumS2Elements")
S2AdjustedLength = S2ElemLength * NumElements(2)
MembraneAge(2) = Range("S2MemAge")
FluxDecline(2) = Range("S2FluxDec")

S2CalcConcentration = ((S2ElemFlow / S2ElemRecovery) * S2ElemTDS - S2ElemFlow *
S2ElemTDS * (1 - S2ElemRej)) / (S2ElemFlow / S2ElemRecovery * (1 - S2ElemRecovery))
'mg/L
S2ConcentrationDiff = (S2ElemTDS + S2CalcConcentration) / 2 - S2ElemTDS * (1 -
S2ElemRej) 'mg/L
Bvalue(2) = S2ElemFlow * S2ElemTDS * (1 - S2ElemRej) / (Area(2) *
S2ConcentrationDiff) / 2120315 / ATempCorr
''(mg/L)*(gal/day)*(1 day/86400 s)*(1ft3/7.48 gal)*(0.3048m/ft)/(ft2*mg/L)=m/s
Avalue(2) = S2ElemFlow / (Area(2) * (S2ElemPress - OsmoticPressure(1))) / 144239 /
ATempCorr
'(gal/day)*(1day/86400s)*(1ft3/7.48gal)*(.3048m/ft)*(14.7psi/atm)/(ft2*psi) - convert to
m/s/atm
BetaCoef(2) = 0
If NumStages > 1 Then
BetaCoef(2) = -0.3492 * Log(S2AdjustedLength) + 2.0152
End If

S3ElemFlow = Range("S3ElemFlow") 'gpd
S3ElemPress = Range("S3ElemPress") 'psi
S3ElemTDS = Range("S3ElemTDS") 'mg/L
S3ElemRej = Range("S3ElemRej") / 100 '%
Area(3) = Range("S3Area") 'sf
S3ElemLength = Range("S3ElemLength") 'in
S3ElemRecovery = Range("S3ElemRec") / 100 'in
SpacerThickness(3) = Range("S3SpaceThick")
NumElements(3) = Range("NumS3Elements")
S3AdjustedLength = S3ElemLength * NumElements(3)
MembraneAge(3) = Range("S3MemAge")
FluxDecline(3) = Range("S3FluxDec")

S3CalcConcentration = ((S3ElemFlow / S3ElemRecovery) * S3ElemTDS - S3ElemFlow *
S3ElemTDS * (1 - S3ElemRej)) / (S3ElemFlow / S3ElemRecovery * (1 - S3ElemRecovery))
'mg/L
S3ConcentrationDiff = (S3ElemTDS + S3CalcConcentration) / 2 - S3ElemTDS * (1 -
S3ElemRej) 'mg/L
Bvalue(3) = S3ElemFlow * S3ElemTDS * (1 - S3ElemRej) / (Area(3) *
S3ConcentrationDiff) / 2120315 / ATempCorr
''(mg/L)*(gal/day)*(1 day/86400 s)*(1ft3/7.48 gal)*(0.3048m/ft)/(ft2*mg/L)=m/s
```

Avalue(3) = S3ElemFlow / (Area(3) * (S3ElemPress - OsmoticPressure(1))) / 144239 / ATempCorr
'(gal/day)*(1day/86400s)*(1ft3/7.48gal)*(.3048m/ft)*(14.7psi/atm)/(ft2*psi) - convert to m/s/atm
BetaCoef(3) = 0
If NumStages > 2 Then
BetaCoef(3) = -0.3492 * Log(S3AdjustedLength) + 2.0152
End If
End Sub

Public Function CalcTurboBoost(TConcPress As Double, TConcFlow As Double,
'Calculate the interstage turbo boost

If Worksheets("Summary").OptionButton20 = False Then
TPermPress = Worksheets("Summary").Range("PermPress")
Else
TPermPress = Worksheets("Summary").Range("PermPress") / 6.895 'kPa to psi
End If
RowStart = Worksheets("Turbocharger ERD Selection").Range("TurboTableStart").row
ColumnStart = Worksheets("Turbocharger ERD Selection").Range("TurboTableStart").Column
TurboModelStart = Worksheets("Turbocharger ERD Selection").Range("TurboModelStart").Column
If Worksheets("Turbocharger ERD Selection").OptionButton1 = True Then
i = 1 'ERI
If Worksheets("Membrane Database").Range("S1Application") = "SWRO" Then i = 9
Else
i = 25 'Fedco
End If
TableFlow = 0
Do While TFeedFlow / 1440 > TableFlow
TableFlow = Worksheets("Turbocharger ERD Selection").Cells(RowStart + i, ColumnStart).Value
i = i + 1
Loop
If i = 1 Then i = 2
Worksheets("Turbocharger ERD Selection").Range("TurboModel") = Worksheets("Turbocharger ERD Selection").Cells(RowStart + i - 1, TurboModelStart)
SystemConcPress = Worksheets("Turbocharger ERD Selection").Cells(RowStart + i - 1, TurboModelStart + 8)
'Find the smallest model that will work for the system and calc efficiency based on manufacturer's equations
ModelNum = Worksheets("Turbocharger ERD Selection").Cells(RowStart + i - 1, TurboModelStart - 1)
If ModelNum < 9 Then
TurboEff = (2.27331E-11 * (TFeedFlow / 1440) ^ 3) - (0.000000157469 * (TFeedFlow / 1440) ^ 2) + (0.000357 * (TFeedFlow / 1440)) + 0.479619722
ElseIf ModelNum < 19 Then
TurboEff = (0.000000000064769 * (TFeedFlow / 1440) ^ 3) - (0.000000235344 * (TFeedFlow / 1440) ^ 2) + (0.000307834 * (TFeedFlow / 1440)) + 0.553423744
ElseIf ModelNum < 25 Then

```
TurboEff = (-3.098E-14 * (TFeedFlow / 1440) ^ 3) - (1.88805E-12 * (TFeedFlow / 1440) ^
2) + (0.0000133228 * (TFeedFlow / 1440)) + 0.70108
Else
TurboEff = 0.038728 * WorksheetFunction.Ln(TFeedFlow / 1440) + 0.471545
End If
If TFeedFlow = 0 Then
Boost = 0
Else
RejectRatio = TConcFlow / TFeedFlow
If Worksheets("Turbocharger ERD Selection").OptionButton1 = True Then
If RejectRatio < 0.6 Then
TurboEff = TurboEff - (Abs(RejectRatio - 0.6)) ^ 1.55
Else
If RejectRatio > 0.7 Then
TurboEff = TurboEff - (Abs(RejectRatio - 0.7)) ^ 2
End If
End If
End If
Worksheets("Turbocharger ERD Selection").Range("TurboEff") = TurboEff
Boost = (TConcPress + TPermPress - SystemConcPress) * TConcFlow / TFeedFlow *
TurboEff
End If
CalcTurboBoost = 0
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Interstage Turbocharger"
Then
If Worksheets("Summary").OptionButton20 = False Then
Worksheets("Turbocharger ERD Selection").Range("TurboBoost") = Boost
Worksheets("Turbocharger ERD Selection").Range("TurboFeedFlow") = TFeedFlow / 1440
Worksheets("Turbocharger ERD Selection").Range("TurboMinConcPress") =
SystemConcPress 'psi
Worksheets("Summary").InputConcPress = SystemConcPress 'psi
Else
Worksheets("Turbocharger ERD Selection").Range("TurboBoost") = Boost * 6.895 'psi to
kPa
Worksheets("Turbocharger ERD Selection").Range("TurboFeedFlow") = TFeedFlow / 1440 /
(3.785 / 60) 'gpm to L/s
Worksheets("Turbocharger ERD Selection").Range("TurboMinConcPress") =
SystemConcPress * 6.895 'psi to kPa
Worksheets("Summary").InputConcPress = SystemConcPress * 6.895 'psi to kPa
End If
If Worksheets("Summary").OptionButton18 = True Then
If Stage = 2 Then CalcTurboBoost = Boost
End If
If Worksheets("Summary").OptionButton19 = True Then
If Stage = 3 Then CalcTurboBoost = Boost
End If
End If
End Function

Public Function CalcIsoBoost(IConcPress As Double, S1FPress As Double) As Double
'Calc the boost provided by the isobaric device
```

If Worksheets("Summary").OptionButton20 = False Then
IPermPress = Worksheets("Summary").Range("PermPress")
Else
IPermPress = Worksheets("Summary").Range("PermPress") / 6.895 'kPa to psi
End If

IBoost = (IConcPress + IPermPress) * Worksheets("Isobaric ERD Selection").Range("IsoEff")
CalcIsoBoost = S1FPress + IPermPress - IBoost
End Function

Public Function DeltaPressure(InfluentFlow As Double, ConcentrateFlow As Double,
'Calculate the loss in pressure between the feed and concentrate streams. Called often throughout the CalcProjections procedure.

ConcentrateFlow = WorksheetFunction.Max(0, ConcentrateFlow)
FlowAve = (InfluentFlow + ConcentrateFlow) / 2 / 24 / 60 'from gpd to gpm
dpCoef = SpacerThick * -0.000875 + 0.04075
'dp calculated by using the membrane spacer thickness and then validated to hydranautics membranes
DeltaPressure = NElem * dpCoef * FlowAve ^ 1.5 'sends in psi
End Function

Public Function IonicStrength(IonConcentrations() As Double) As Double
'Calculate the Ionic Strength of a flow stream based on the ion concentrations

floatIonStr = 0
For i = 1 To LastIon
If i <> SP_CO2 Then
' ignores CO2 and organics
If i <> SP_Organic Then
floatIonStr = floatIonStr + IonConcentrations(i) * IONS(i).Charge * IONS(i).Charge / IONS(i).MolWt
End If
End If
Next i
' Set some nonzero value just in case to avoid division by zero somewhere.
If floatIonStr < 0.0000001 Then floatIonStr = 0.0000001
IonicStrength = floatIonStr / (2 * 1000)
End Function

Public Function OsmoticPressureCalc(OsConcentrations() As Double, ByVal Temperature As Double) As Double
'Calculate the Osmotic Pressure of a flow stream based on the ion concentrations

PITemp = 0
RT = 0.082054 * (Temperature + 273) ' 14.69 converts answer to psi
RT = RT / 1000 ' convert to moles/l from mm/l
floatDummy = Sqr(**IonicStrength**(OsConcentrations()))

```
For i = 1 To LastIon
' skip CO2
If i <> SP_CO2 Then
' note when Z=0, ActCoef = 1.0 (for SiO2)
z = IONS(i).Charge
If z = 0 Then z = 1
ActCoef = (10 ^ (-0.5 * z * z * floatDummy / (1 + floatDummy))) ^ 0.14
PITemp = PITemp + ActCoef * RT * OsConcentrations(i) / IONS(i).MolWt
End If
Next i
OsmoticPressureCalc = 14.7 * PITemp 'send in psi
End Function
```

Sub PutDataOnSheets()

'After the CalcProjections procedure has finished, print the outputs back to the summary and water quality pages

```
If Worksheets("Summary").OptionButton20 = False Then
Range("ByFlow") = GuessBypassFlow 'gpd
Worksheets("Summary").InputBP1Press = Round(BPPress(1), 1)
Range("S1FeedFlow") = TotFeedFlow / 24 / 60
Range("S1FeedPress") = Pressure(1) + Range("PermPress")
Range("S1PermFlow") = S1PermFlow / 24 / 60
Range("S1PermPress") = Range("PermPress") + S1BackPress
Range("S1ConcFlow") = S1ConcFlow / 24 / 60
Range("S1ConcPress") = ConcPress(1) + Range("PermPress")
Range("S1Recovery") = S1PermFlow / TotFeedFlow
Range("S1Flux") = S1PermFlow / StageArea(1)
If NumStages > 1 Then
Range("S2FeedFlow") = Range("S1ConcFlow")
Range("S2FeedPress") = Pressure(2) + Range("PermPress")
Range("S2PermFlow") = S2PermFlow / 24 / 60
Range("S2PermPress") = Range("PermPress") + S2BackPress
Range("S2ConcFlow") = S2ConcFlow / 24 / 60
Range("S2ConcPress") = ConcPress(2) + Range("PermPress")
Range("S2Recovery") = S2PermFlow / 24 / 60 / Range("S1ConcFlow")
Range("S2Flux") = S2PermFlow / StageArea(2)
Else
Range("S2FeedFlow") = 0
Range("S2FeedPress") = 0
Range("S2PermFlow") = 0
Range("S2PermPress") = 0
Range("S2ConcFlow") = 0
Range("S2ConcPress") = 0
Range("S2Recovery") = 0
Range("S2Flux") = 0
End If
If NumStages > 2 Then
Range("S3FeedFlow") = Range("S2ConcFlow")
Range("S3FeedPress") = Pressure(3) + Range("PermPress")
Range("S3PermFlow") = S3PermFlow / 24 / 60
```

```
Range("S3PermPress") = Range("PermPress")
Range("S3ConcFlow") = S3ConcFlow / 24 / 60
Range("S3ConcPress") = ConcPress(3) + Range("PermPress")
Range("S3Recovery") = S3PermFlow / 24 / 60 / Range("S2ConcFlow")
Range("S3Flux") = S3PermFlow / StageArea(3)
Else
Range("S3FeedFlow") = 0
Range("S3FeedPress") = 0
Range("S3PermFlow") = 0
Range("S3PermPress") = 0
Range("S3ConcFlow") = 0
Range("S3ConcPress") = 0
Range("S3Recovery") = 0
Range("S3Flux") = 0
End If
Else
Range("ByFlow") = GuessBypassFlow / 7.48 'gpd to m3/d
Worksheets("Summary").InputBP1Press = Round(BPPress(1) * 6.895, 1) 'psi to kPa
Range("S1FeedFlow") = TotFeedFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S1FeedPress") = Range("PermPress") + Pressure(1) * 6.895 'psi to kPa
Range("S1PermFlow") = S1PermFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S1PermPress") = (Range("PermPress") + S1BackPress) * 6.895 'psi to kPa
Range("S1ConcFlow") = S1ConcFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S1ConcPress") = Range("PermPress") + ConcPress(1) * 6.895 'psi to kPa
Range("S1Recovery") = S1PermFlow / TotFeedFlow
Range("S1Flux") = S1PermFlow / StageArea(1) * 1.697573 'gpf to lmh
If NumStages > 1 Then
Range("S2FeedFlow") = Range("S1ConcFlow")
Range("S2FeedPress") = Pressure(2) * 6.895 + Range("PermPress") 'psi to kPa
Range("S2PermFlow") = S2PermFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S2PermPress") = (Range("PermPress") + S2BackPress) * 6.895 'psi to kPa
Range("S2ConcFlow") = S2ConcFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S2ConcPress") = ConcPress(2) * 6.895 + Range("PermPress") 'psi to kPa
Range("S2Recovery") = S2PermFlow / 24 / 60 / Range("S1ConcFlow") * (3.785 / 60) 'gpm
to L/s
Range("S2Flux") = S2PermFlow / StageArea(2) * 1.697573 'gpf to lmh
Else
Range("S2FeedFlow") = 0
Range("S2FeedPress") = 0
Range("S2PermFlow") = 0
Range("S2PermPress") = 0
Range("S2ConcFlow") = 0
Range("S2ConcPress") = 0
Range("S2Recovery") = 0
Range("S2Flux") = 0
End If

If NumStages > 2 Then
Range("S3FeedFlow") = Range("S2ConcFlow")
Range("S3FeedPress") = Pressure(3) * 6.895 + Range("PermPress") 'psi to kPa
Range("S3PermFlow") = S3PermFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
```

```
Range("S3PermPress") = Range("PermPress")
Range("S3ConcFlow") = S3ConcFlow / 24 / 60 * (3.785 / 60) 'gpm to L/s
Range("S3ConcPress") = ConcPress(3) * 6.895 + Range("PermPress") 'psi to kPa
Range("S3Recovery") = S3PermFlow / 24 / 60 / Range("S2ConcFlow") * (3.785 / 60) 'gpm
to L/s
Range("S3Flux") = S3PermFlow / StageArea(3) * 1.697573 'gpf to lmh
Else
Range("S3FeedFlow") = 0
Range("S3FeedPress") = 0
Range("S3PermFlow") = 0
Range("S3PermPress") = 0
Range("S3ConcFlow") = 0
Range("S3ConcPress") = 0
Range("S3Recovery") = 0
Range("S3Flux") = 0
End If
End If

Set s = Worksheets("Water Quality")

nCol = Range("AdjFeed").Column
Pcol = Range("ROPermeate").Column
Bcol = Range("BlendedROPermeate").Column
Ccol = Range("ROConcentrate").Column
Pcol1 = Range("S1Permeate").Column
Ccol1 = Range("S1Concentrate").Column
Pcol2 = Range("S2Permeate").Column
Ccol2 = Range("S2Concentrate").Column
Pcol3 = Range("S3Permeate").Column
Ccol3 = Range("S3Concentrate").Column
CRow = Range("ROFeed").row

' Sodium -Na
CRow = CRow + 1
i = SP_Na
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Potassium -k
CRow = CRow + 1
i = SP_K
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
```

```
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Calcium -Ca
CRow = CRow + 1
i = SP_Ca
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Magnesium -Mg
CRow = CRow + 1
i = SP_Mg
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Strontium -Sr
CRow = CRow + 1
i = SP_Sr
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)
```

```
' Barium -Ba
CRow = CRow + 1
i = SP_Ba
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Aluminum - Al+++
CRow = CRow + 1
i = SP_Al
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Ferric Iron - Fe+++ (as Fe)
CRow = CRow + 1
i = SP_Fe3
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Boron - B+++
CRow = CRow + 1
i = SP_B
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
If BlendedPermConc(i) < s.Range("B2Pass") Then
s.Range("B2PPower") = 0
```

```
s.Range("B2PPowerMax") = 0
End If
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Ammonia - NH4 (as NH4)
CRow = CRow + 1
i = SP_NH4
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Hydrogen Ion - H
‘run the CO2toPH procedure to calculate the pH of each stream based on the CO2 and total
carbon. This assumes CO2 concentration is the same for all flow streams.
PermConc(SP_CO2, 1) = FeedIons(SP_CO2)
ConcConc(SP_CO2, 1) = FeedIons(SP_CO2)

CRow = CRow + 1
CO2toPH Istr(1), Temperature, FeedIons(SP_HCO3), FeedIons(SP_CO2),
FeedIons(SP_CO3)
HPlus(1) = HPlusCalc
HCO3(1) = HCO3Calc
CO3(1) = CO3Calc
CO2(1) = CO2Calc
CO2toPH Istr(2), Temperature, ConcConc(SP_HCO3, 1), ConcConc(SP_CO2, 1),
ConcConc(SP_CO3, 1)
HPlus(4) = HPlusCalc
HCO3(4) = HCO3Calc
CO3(4) = CO3Calc
CO2(4) = CO2Calc
CO2toPH Istr(5), Temperature, PermConc(SP_HCO3, 1), PermConc(SP_CO2, 1),
PermConc(SP_CO3, 1)
HPlus(5) = HPlusCalc
HCO3(5) = HCO3Calc
CO3(5) = CO3Calc
CO2(5) = CO2Calc
CO2toPH Istr(3), Temperature, ConcConc(SP_HCO3, 2), CO2(4), ConcConc(SP_CO3, 2)
'Send 1st stage concentrate data to 2nd stage perm, concentrate
HPlus(6) = HPlusCalc
```

```
HCO3(6) = HCO3Calc
CO3(6) = CO3Calc
CO2(6) = CO2Calc
CO2toPH Istr(6), Temperature, PermConc(SP_HCO3, 2), CO2(4), PermConc(SP_CO3, 2)
HPlus(7) = HPlusCalc
HCO3(7) = HCO3Calc
CO3(7) = CO3Calc
CO2(7) = CO2Calc
CO2toPH Istr(4), Temperature, ConcConc(SP_HCO3, 3), CO2(6), ConcConc(SP_CO3, 3)
'Send 2nd stage concentrate data to 3rd stage perm, concentrate
HPlus(8) = HPlusCalc
HCO3(8) = HCO3Calc
CO3(8) = CO3Calc
CO2(8) = CO2Calc
CO2toPH Istr(7), Temperature, PermConc(SP_HCO3, 3), CO2(6), PermConc(SP_CO3, 3)
HPlus(9) = HPlusCalc
HCO3(9) = HCO3Calc
CO3(9) = CO3Calc
CO2(9) = CO2Calc
If NumStages = 1 Then ConcConc(SP_CO2, NumStages) = CO2(4)
If NumStages = 2 Then ConcConc(SP_CO2, NumStages) = CO2(6)
If NumStages = 3 Then ConcConc(SP_CO2, NumStages) = CO2(8)
CO2toPH Istr(1 + NumStages), Temperature, ConcConc(SP_HCO3, NumStages),
ConcConc(SP_CO2, NumStages), ConcConc(SP_CO3, NumStages)
HPlus(2) = HPlusCalc
HCO3(2) = HCO3Calc
CO3(2) = CO3Calc
CO2(2) = CO2Calc
TotPermConc(SP_CO2) = (CO2(5) * CalcPermFlow(1) + CO2(7) * CalcPermFlow(2) +
CO2(9) * CalcPermFlow(3)) / TotPermFlow
CO2toPH Istr(8), Temperature, TotPermConc(SP_HCO3), TotPermConc(SP_CO2),
TotPermConc(SP_CO3)
HPlus(3) = HPlusCalc
HCO3(3) = HCO3Calc
CO3(3) = CO3Calc
CO2(3) = CO2Calc
CO2toPH Istr(9), Temperature, BlendedPermConc(SP_HCO3),
BlendedPermConc(SP_CO2), BlendedPermConc(SP_CO3)
HPlus(10) = HPlusCalc
HCO3(10) = HCO3Calc
CO3(10) = CO3Calc
CO2(10) = CO2Calc


s.Cells(CRow, nCol).Value = HPlus(1)
s.Cells(CRow, Ccol).Value = HPlus(2)
s.Cells(CRow, Pcol).Value = HPlus(3)
s.Cells(CRow, Ccol1).Value = HPlus(4)
s.Cells(CRow, Pcol1).Value = HPlus(5)
s.Cells(CRow, Ccol2).Value = HPlus(6)
s.Cells(CRow, Pcol2).Value = HPlus(7)
```

```
s.Cells(CRow, Ccol3).Value = HPlus(8)
s.Cells(CRow, Pcol3).Value = HPlus(9)
s.Cells(CRow, Bcol).Value = HPlus(10)

' Bicarbonate -HC03
CRow = CRow + 3
i = SP_HCO3
s.Cells(CRow, nCol).Value = HCO3(1)
s.Cells(CRow, Ccol).Value = HCO3(2)
s.Cells(CRow, Pcol).Value = HCO3(3)
s.Cells(CRow, Ccol1).Value = HCO3(4)
s.Cells(CRow, Pcol1).Value = HCO3(5)
s.Cells(CRow, Ccol2).Value = HCO3(6)
s.Cells(CRow, Pcol2).Value = HCO3(7)
s.Cells(CRow, Ccol3).Value = HCO3(8)
s.Cells(CRow, Pcol3).Value = HCO3(9)
s.Cells(CRow, Bcol).Value = HCO3(10)

' Carbon Dioxide - CO2 (calc'd)
CRow = CRow + 1
i = SP_CO2
s.Cells(CRow, nCol).Value = CO2(1)
s.Cells(CRow, Ccol).Value = CO2(2)
s.Cells(CRow, Pcol).Value = CO2(3)
s.Cells(CRow, Ccol1).Value = CO2(4)
s.Cells(CRow, Pcol1).Value = CO2(5)
s.Cells(CRow, Ccol2).Value = CO2(6)
s.Cells(CRow, Pcol2).Value = CO2(7)
s.Cells(CRow, Ccol3).Value = CO2(8)
s.Cells(CRow, Pcol3).Value = CO2(9)
s.Cells(CRow, Bcol).Value = CO2(10)

' Carbonate - CO3 (calc'd)
CRow = CRow + 1
i = SP_CO3
s.Cells(CRow, nCol).Value = CO3(1)
s.Cells(CRow, Ccol).Value = CO3(2)
s.Cells(CRow, Pcol).Value = CO3(3)
s.Cells(CRow, Ccol1).Value = CO3(4)
s.Cells(CRow, Pcol1).Value = CO3(5)
s.Cells(CRow, Ccol2).Value = CO3(6)
s.Cells(CRow, Pcol2).Value = CO3(7)
s.Cells(CRow, Ccol3).Value = CO3(8)
s.Cells(CRow, Pcol3).Value = CO3(9)
s.Cells(CRow, Bcol).Value = CO3(10)

' Bromide -Br
CRow = CRow + 1
i = SP_Br
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
```

```
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
If BlendedPermConc(i) < s.Range("Br2Pass") Then
s.Range("Br2PPower") = 0
s.Range("Br2PPowerMax") = 0
End If
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Chloride -Cl
CRow = CRow + 1
i = SP_Cl
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
If BlendedPermConc(i) < s.Range("Cl2Pass") Then
s.Range("Cl2PPower") = 0
s.Range("Cl2PPowerMax") = 0
End If
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Fluoride -F
CRow = CRow + 1
i = SP_F
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Sulfate -SO4
CRow = CRow + 1
i = SP_SO4
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
```

```
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Nitrate -NO3
CRow = CRow + 1
i = SP_NO3
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Phosphate - PO4 (as PO4)
CRow = CRow + 1
i = SP_PO4
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' Hydroxide -OH
CRow = CRow + 1
s.Cells(CRow, nCol).Value = 10 ^ -14 / HPlus(1)
s.Cells(CRow, Ccol).Value = 10 ^ -14 / HPlus(2)
s.Cells(CRow, Pcol).Value = 10 ^ -14 / HPlus(3)
s.Cells(CRow, Ccol1).Value = 10 ^ -14 / HPlus(4)
s.Cells(CRow, Pcol1).Value = 10 ^ -14 / HPlus(5)
s.Cells(CRow, Ccol2).Value = 10 ^ -14 / HPlus(6)
s.Cells(CRow, Pcol2).Value = 10 ^ -14 / HPlus(7)
s.Cells(CRow, Ccol3).Value = 10 ^ -14 / HPlus(8)
s.Cells(CRow, Pcol3).Value = 10 ^ -14 / HPlus(9)
s.Cells(CRow, Bcol).Value = 10 ^ -14 / HPlus(10)

' Silica (as SiO2)
CRow = CRow + 3
```

```
i = SP_SiO2
s.Cells(CRow, nCol).Value = FeedIons(i)
s.Cells(CRow, Ccol).Value = ConcConc(i, NumStages)
s.Cells(CRow, Pcol).Value = TotPermConc(i)
s.Cells(CRow, Bcol).Value = BlendedPermConc(i)
s.Cells(CRow, Ccol1).Value = ConcConc(i, 1)
s.Cells(CRow, Pcol1).Value = PermConc(i, 1)
s.Cells(CRow, Ccol2).Value = ConcConc(i, 2)
s.Cells(CRow, Pcol2).Value = PermConc(i, 2)
s.Cells(CRow, Ccol3).Value = ConcConc(i, 3)
s.Cells(CRow, Pcol3).Value = PermConc(i, 3)

' TDS (in ppm)
CRow = CRow + 2

' PH
CRow = CRow + 2
s.Cells(CRow, nCol).Value = Worksheets("Water Quality").Range("pH_input")
s.Cells(CRow, Ccol).Value = -Log(HPlus(2)) / Log(10#)
s.Cells(CRow, Pcol).Value = -Log(HPlus(3)) / Log(10#)
s.Cells(CRow, Ccol1).Value = -Log(HPlus(4)) / Log(10#)
s.Cells(CRow, Pcol1).Value = -Log(HPlus(5)) / Log(10#)
s.Cells(CRow, Ccol2).Value = -Log(HPlus(6)) / Log(10#)
s.Cells(CRow, Pcol2).Value = -Log(HPlus(7)) / Log(10#)
s.Cells(CRow, Ccol3).Value = -Log(HPlus(8)) / Log(10#)
s.Cells(CRow, Pcol3).Value = -Log(HPlus(9)) / Log(10#)
s.Cells(CRow, Bcol).Value = -Log(HPlus(10)) / Log(10#)

' Osmotic Pressure (estimated psi)
CRow = CRow + 1
If NumStages = 1 Then i = 2
If NumStages = 2 Then i = 3
If NumStages = 3 Then i = 4
s.Cells(CRow, nCol).Value = OsmoticPressure(1)
s.Cells(CRow, Ccol).Value = OsmoticPressure(i)
s.Cells(CRow, Pcol).Value = OsmoticPressure(8)
s.Cells(CRow, Bcol).Value = OsmoticPressure(9)
s.Cells(CRow, Ccol1).Value = OsmoticPressure(2)
s.Cells(CRow, Pcol1).Value = OsmoticPressure(5)
s.Cells(CRow, Ccol2).Value = OsmoticPressure(3)
s.Cells(CRow, Pcol2).Value = OsmoticPressure(6)
s.Cells(CRow, Ccol3).Value = OsmoticPressure(4)
s.Cells(CRow, Pcol3).Value = OsmoticPressure(7)

' Ionic Strength
CRow = CRow + 1
s.Cells(CRow, nCol).Value = Istr(1)
s.Cells(CRow, Ccol).Value = Istr(i)
s.Cells(CRow, Pcol).Value = Istr(8)
s.Cells(CRow, Bcol).Value = Istr(9)
s.Cells(CRow, Ccol1).Value = Istr(2)
```

```
s.Cells(CRow, Pcol1).Value = Istr(5)
s.Cells(CRow, Ccol2).Value = Istr(3)
s.Cells(CRow, Pcol2).Value = Istr(6)
s.Cells(CRow, Ccol3).Value = Istr(4)
s.Cells(CRow, Pcol3).Value = Istr(7)

Range("FinalPermTDS") = Worksheets("Water Quality").Range("BlendedTDS")
Range("PrintS1FeedTDS") = Worksheets("Water Quality").Range("FeedTDS")
Range("PrintS1PermTDS") = Worksheets("Water Quality").Range("S1PermTDS")
Range("PrintS1ConcTDS") = Worksheets("Water Quality").Range("S1ConcTDS")
If NumStages > 1 Then
Range("PrintS2FeedTDS") = Worksheets("Water Quality").Range("S1ConcTDS")
Range("PrintS2PermTDS") = Worksheets("Water Quality").Range("S2PermTDS")
Range("PrintS2ConcTDS") = Worksheets("Water Quality").Range("S2ConcTDS")
Else
Range("PrintS2FeedTDS") = 0
Range("PrintS2PermTDS") = 0
Range("PrintS2ConcTDS") = 0
End If
If NumStages > 2 Then
Range("PrintS3FeedTDS") = Worksheets("Water Quality").Range("S2ConcTDS")
Range("PrintS3PermTDS") = Worksheets("Water Quality").Range("S3PermTDS")
Range("PrintS3ConcTDS") = Worksheets("Water Quality").Range("S3ConcTDS")
Else
Range("PrintS3FeedTDS") = 0
Range("PrintS3PermTDS") = 0
Range("PrintS3ConcTDS") = 0
End If
End Sub

Public Sub CO2toPH(ByVal IonStr As Double, ByVal Temperature As Double, ByVal '
' Returns new distrbution of carbonates and new pH based TotalCarbon coming in, CO2,
' HCO3 and CO3 Concentrations
' Carbonate Equilibria data using Stumm and Morgan, Aquatic Chemistry
' pages 120-121 and 148-150
' Linear Regression analysis of Stumm and Morgan data for K1 and K2 versus temperature
' Estimation of Activity Change as Ionic strength from Stumm and Morgan, p 149.
' Inputs are CO2, HCO3, and CO3
' Outputs are pH and new distribution of HCO3 and CO3 to fit new pH

'DEAL WITH ZERO VALUES
If HCO3c = 0 Then
CO3c = 0
CO2c = 0
HPlusCalc = 10 ^ (-7) ' PH SET AT 7
Exit Sub
End If

' first correct K1 and K2 for temperature, using Excel derived equation

pK1 = -0.007 * (Temperature + 273) + 8.4454
```

```
pK2 = -0.0101 * (Temperature + 273) + 13.368

' now correct for ionic strength
pK1 = pK1 - 0.5 * Sqr(IonStr) / (1 + 1.4 * Sqr(IonStr))
pK2 = pK2 - 2 * Sqr(IonStr) / (1 + 1.4 * Sqr(IonStr))

K1 = 10 ^ (-pK1)
K2 = 10 ^ (-pK2)

' First get the total carbon figured out
TotalCarbon = CO3c / 60.0092 + HCO3c / 61.0171 + CO2c / (12.0111 + 2 * 15.9994) ' 2
meqs/mol for CO3, others 1 to 1
If HCO3c <= 0 Then HCO3c = 0.001639 ' minimum 0.1 ppm = .1/61

'Very high pH case
If CO3c / 2 > HCO3c Then ' very high ph ~10.33
HPlusCalc = K2 * HCO3c / (CO3c / 2)
Else ' Do it normally with CO2/HCO3 ratio
HPlusCalc = CO2c / (HCO3c * 0.82 * 10 ^ (6.3))
End If

' Now have the pH, figure out the new distribution of carbonates
' keeping CO2 constant and changing the CO3/HCO3 ratio as needed.
MF_HCO3 = 1 / (HPlusCalc / K1 + 1 + K2 / HPlusCalc) ' Stumm and Morgan, alpha1, p 120
MF_CO3 = 1 / (HPlusCalc ^ 2 / (K1 * K2) + HPlusCalc / K2 + 1)
MF_CO2 = 1 / (1 + K1 / HPlusCalc + (K1 * K2) / HPlusCalc ^ 2)

' now reassign CO2, HCO3, and CO3 based on calculated distrbutions
HCO3Calc = TotalCarbon * MF_HCO3 * 61.0171 ' 1 meq = 1 mmole so no change needed
CO3Calc = TotalCarbon * MF_CO3 * 60.0092 ' 1 meq = 0.5 mmoles or 1 mmole = 2 meq!
CO2Calc = TotalCarbon * MF_CO2 * (12.0111 + 2 * 15.9994)
End Sub
```

Module 1

```
Sub CheckInputs()
'Stop the code if the user needs to revise any inputs
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Interstage Turbocharger"
Then
If Worksheets("BWRO Flow Balance").Range("NumStages") = 2 Then
If Worksheets("Summary").OptionButton9 = True Then
Ans1 = MsgBox("You have selected to have both a Booster Pump and an Interstage
Turbocharger after Stage 1. Do you want to continue?", vbYesNo, "ERROR!!")
If Ans1 = 7 Then
End
End If
End If
If Worksheets("Summary").OptionButton11 = True Then
Ans2 = MsgBox("You have selected to have both a Booster Pump and an Interstage
Turbocharger after Stage 1. Do you want to continue?", vbYesNo, "ERROR!!")
```

```
If Ans2 = 7 Then
End
End If
End If
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") = 3 Then
If Worksheets("Summary").OptionButton18 = True Then
If Worksheets("Summary").OptionButton9 = True Or
Worksheets("Summary").OptionButton11 = True Then
Ans3 = MsgBox("You have selected to have both a Booster Pump and an Interstage
Turbocharger after Stage 1. Do you want to continue?", vbYesNo, "ERROR!!")
If Ans3 = 7 Then
End
End If
End If
End If
If Worksheets("Summary").OptionButton19 = True Then
If Worksheets("Summary").OptionButton10 = True Or
Worksheets("Summary").OptionButton11 = True Then
Ans3 = MsgBox("You have selected to have both a Booster Pump and an Interstage
Turbocharger after Stage 2. Do you want to continue?", vbYesNo, "ERROR!!")
If Ans3 = 7 Then
End
End If
End If
End If
End If
End If

If Worksheets("BWRO Flow Balance").Range("ERDType") = "Turbocharger" Then
If Worksheets("Summary").OptionButton17 = False And
Worksheets("Summary").OptionButton18 = False And
Worksheets("Summary").OptionButton19 = False Then
MsgBox ("Please select where the turbocharger is located before calculating.")
End
End If
End If

If Worksheets("Summary").Range("Recovery") = 0 Then
MsgBox ("Error: Please input the correct system recovery.")
End
End If

If Worksheets("Summary").Range("NVesselsS1") = 0 Then
MsgBox ("Error: Please input the correct number of stage 1 vessels.")
End
End If

If Worksheets("Summary").Range("NumS1Elements") = 0 Then
MsgBox ("Error: Please input the correct number of stage 1 elements.")
End
```

```
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") > 1 Then
If Worksheets("Summary").Range("NVesselsS2") = 0 Then
MsgBox ("Error: Please input the correct number of stage 2 vessels.")
End
End If
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") > 1 Then
If Worksheets("Summary").Range("NumS2Elements") = 0 Then
MsgBox ("Error: Please input the correct number of stage 2 elements.")
End
End If
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") > 2 Then
If Worksheets("Summary").Range("NVesselsS3") = 0 Then
MsgBox ("Error: Please input the correct number of stage 3 vessels.")
End
End If
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") > 2 Then
If Worksheets("Summary").Range("NumS3Elements") = 0 Then
MsgBox ("Error: Please input the correct number of stage 3 elements.")
End
End If
End If

If Worksheets("Summary").Range("FPEfficiency") <= 0 Then
MsgBox ("Error: Please input a feed pump efficiency in box 7.")
End
End If

If Worksheets("BWRO Flow Balance").Range("NumStages") = 1 Then NVesselsLastStage =
Worksheets("Summary").Range("NVesselsS1")
If Worksheets("BWRO Flow Balance").Range("NumStages") = 2 Then NVesselsLastStage =
Worksheets("Summary").Range("NVesselsS2")
If Worksheets("BWRO Flow Balance").Range("NumStages") = 3 Then NVesselsLastStage =
Worksheets("Summary").Range("NVesselsS3")
If Worksheets("Summary").OptionButton20 = True Then
ConcFlow = (Worksheets("Summary").Range("FeedFlow") -
Worksheets("Summary").Range("PermFlow")) / 0.003785 / 1440 'm3/d to gpm
Else
ConcFlow = (Worksheets("Summary").Range("FeedFlow") -
Worksheets("Summary").Range("PermFlow")) / 1440 'gpd to gpm
End If
If ConcFlow / NVesselsLastStage < 10 Then
MsgBox ("Error: Concentrate flow is less than 12 gpm per vessel. Please revise system
design.")
```

```
End
End If

If Worksheets("Summary").OptionButton20 = True Then
If Worksheets("Summary").Range("Flux") > 34 Then
MsgBox ("Error: Flux should be less than 34 lmh.")
End
End If
Else
If Worksheets("Summary").Range("Flux") > 20 Then
MsgBox ("Error: Flux should be less than 20 gfd.")
End
End If
End If

If Worksheets("Summary").OptionButton20 = True Then
If Worksheets("Summary").Range("Flux") < 8 Then
MsgBox ("Error: Flux should be less than 8 lmh.")
End
End If
Else
If Worksheets("Summary").Range("Flux") < 5 Then
MsgBox ("Error: Flux should be greater than 5 gfd.")
End
End If
End If

If Worksheets("Water Quality").Range("Temp_C") > 45 Or Worksheets("Water
Quality").Range("Temp_C") < 2 Then
MsgBox ("Error: Water temperature should be between 2 and 45 degrees C. Please adjust the
temperature on the Water Quality page to continue.")
End
End If

If Worksheets("Water Quality").Range("pH_input") > 10 Or Worksheets("Water
Quality").Range("pH_input") < 2 Then
MsgBox ("Error: Feed water pH should be between 2 and 10. Please adjust the pH on the
Water Quality page to continue.")
End
End If

If Worksheets("BWRO Flow Balance").Range("ERDType") = "Interstage Turbocharger"
Then
If Worksheets("BWRO Flow Balance").Range("NumStages") = 1 Then
MsgBox ("Error: There can not be an interstage turbocharger in a 1 stage system. Please
revise configuration.")
End
End If
End If

If Worksheets("Summary").OptionButton24 = True Then
```

```
If Worksheets("Summary").Range("ROBoostPress") = 0 Then
MsgBox ("If you want to include an RO Inlet Booster Pump in the 'System Design' box,
please enter the RO Booster Pump Pressure.")
End
End If
End If

If Worksheets("Summary").OptionButton9 = True Or
Worksheets("Summary").OptionButton11 = True Then
If Worksheets("Summary").Range("BP1Press") = 0 Then
MsgBox ("If you want to include a Booster Pump after Stage 1, please enter the Booster
Pump 1 Boost Pressure in the 'Pressure Control' box.")
End
End If
End If

If Worksheets("Summary").OptionButton10 = True Or
Worksheets("Summary").OptionButton11 = True Then
If Worksheets("Summary").Range("BP2Press") = 0 Then
MsgBox ("If you want to include a Booster Pump after Stage 2, please enter the Booster
Pump 2 Boost Pressure in the 'Pressure Control' box.")
End
End If
End If

If Worksheets("Summary").OptionButton27 = True Then
If Worksheets("Water Quality").Range("FeedTDS") < 20000 Then
MsgBox ("Error: 2nd Pass should only be included for feed water with greater than 20,000
mg/L TDS")
Worksheets("Summary").OptionButton26 = True
End
End If
End If

If Worksheets("Water Quality").Range("FeedTDS") > 10000 Then
If Worksheets("Membrane Database").Range("S1Application") = "BWRO" Then
MsgBox ("Error: A SWRO membrane should be used with this water source. Please decrease
the feed TDS or select a SWRO membrane.")
End
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") > 1 Then
If Worksheets("Membrane Database").Range("L24") = "BWRO" Then
MsgBox ("Error: A SWRO membrane should be used with this water source. Please decrease
the feed TDS or select a SWRO membrane for stage 2.")
End
End If
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") > 2 Then
MsgBox ("Error: A SWRO system design can only include 2 stages.")
End
End If
```

```
End If

If Worksheets("Water Quality").Range("FeedTDS") < 3000 Then
If Worksheets("Membrane Database").Range("S1Application") = "SWRO" Then
MsgBox ("Error: A BWRO membrane should be used with this water source. Please increase
the feed TDS or select a BWRO membrane.")
End
End If
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Turbocharger" Then
MsgBox ("Error: Turbocharger upstream of 1st stage membrane is not a typical BWRO ERD
configuration. Please choose a different ERD option.")
End
End If
If Worksheets("BWRO Flow Balance").Range("ERDType") = "Pelton Wheel" Then
MsgBox ("Error: Pelton Wheel ERD is not a typical BWRO configuration. Please choose a
different ERD option.")
End
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") > 1 Then
If Worksheets("Membrane Database").Range("L24") = "SWRO" Then
MsgBox ("Error: A BWRO membrane should be used with this water source. Please increase
the feed TDS or select a BWRO membrane for stage 2.")
End
End If
Else
MsgBox ("Error: A BWRO system design must include a minimum of 2 stages.")
End
End If
If Worksheets("BWRO Flow Balance").Range("NumStages") > 2 Then
If Worksheets("Membrane Database").Range("R24") = "SWRO" Then
MsgBox ("Error: A BWRO membrane should be used with this water source. Please increase
the feed TDS or select a BWRO membrane for stage 3.")
End
End If
End If
End If

If Worksheets("Summary").CheckBox2 = True Then
If Worksheets("Water Quality").Range("BypassTDS") = 0 Then
MsgBox ("Error: If there is bypass flow, please enter the desired permeate TDS on the Water
Quality page.")
End
End If
If Worksheets("Water Quality").Range("FeedTDS") > 20000 Then
MsgBox ("Error: Bypass flows are not calculated in this program for feed TDS greater than
20,000 mg/L.")
End
End If
End If
If Worksheets("Summary").OptionButton1 = True Then
'manual projections
```

```
If Worksheets("Summary").Range("S1FeedFlow") = 0 Then
MsgBox ("Error: Please enter in the projections information in the 'Projections Summary'
box.")
End
End If
If Worksheets("Summary").OptionButton15 = True Then 'English units
If Abs((Worksheets("Summary").Range("FeedFlow") -
Worksheets("Summary").Range("ByFlow")) / 1440 -
Worksheets("Summary").Range("S1FeedFlow")) /
Worksheets("Summary").Range("S1FeedFlow") > 0.1 Then
MsgBox ("Error: Stage 1 Feed Flow in the 'Projections Summary' box should be equal to the
Feed Flow in the 'Flow Information' box.")
End
End If
If Abs((Worksheets("Summary").Range("S1PermFlow") +
Worksheets("Summary").Range("S2PermFlow") +
Worksheets("Summary").Range("S3PermFlow")) * 1440 -
Worksheets("Summary").Range("PermFlow")) /
Worksheets("Summary").Range("PermFlow") > 0.1 Then
MsgBox ("Error: The total permeate flow in the 'Projections Summary' box should be equal
to the Permeate Flow in the 'Flow Information' box.")
End
End If
Else 'Metric units
If Abs((Worksheets("Summary").Range("FeedFlow") -
Worksheets("Summary").Range("ByFlow")) / 86.4 -
Worksheets("Summary").Range("S1FeedFlow")) /
Worksheets("Summary").Range("S1FeedFlow") > 0.1 Then
MsgBox ("Error: Stage 1 Feed Flow in the 'Projections Summary' box should be equal to the
Feed Flow in the 'Flow Information' box.")
End
End If
End If
If Worksheets("Summary").Range("FeedPress") +
Worksheets("Summary").Range("ROBoostPress") >
Worksheets("Summary").Range("S1FeedPress") Then
MsgBox ("Error: Please enter the correct Stage 1 Feed Pressure.")
End
End If
End If
End Sub
```

Advancing the Science of Water Reuse and Desalination




WATEREUSE RESEARCH

1199 North Fairfax Street, Suite 410
Alexandria, VA 22314 USA
(703) 548-0880
Fax (703) 548-5085
E-mail: Foundation@WateReuse.org
www.WateReuse.org/Foundation