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Desalination and Water Purification Research
and Development Program Report No. 197

Overcoming Operating Pressure Barrier in High Recovery Membrane Desalination via Hybrid RO-NF Processes



U.S. Department of the Interior
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Technical Service Center
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14. ABSTRACT This Desalination and Water Purification Research Program (DWPR) research project investigated whether hybrid reverse osmosis-nanofiltration (RO-NF) processes might have lower pressure requirements for high recovery desalination than conventional RO processes. We evaluated the operating pressure requirements and concentrate volume reduction in high recovery desalination at a theoretical and bench-scale testing level. We modeled three hybrid RO-NF processes and one conventional RO process. The project found that modeled hybrid RO-NF processes can operate at significantly lower pressure requirements and, consequently, at higher water recovery levels than conventional RO processes, while meeting the same target product water quality. Bench-scale experimental data confirmed the expected reduction in pressure requirements, albeit at suboptimal energy requirements (as the commercial NF membrane had suboptimal NF TDS rejection). The project demonstrated that NF TDS rejection is a critical parameter governing both operating pressure and energy consumption. The present study suggests that further evaluation of single-stage RO-NF operation at pressure-optimal NF rejection (70 - 80%) has merit. Next recommended steps are to investigate the hybrid processes ability to address challenges within feedwater, variable feedwater, and mineral scaling, as well as to explore the benefits of using energy recovery devices.					
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**Prepared for the Bureau of Reclamation Under Agreement No.
R15AC00089**

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**U.S. Department of the Interior
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Denver, Colorado**

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Mission Statements

The Department of the Interior conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

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

Disclaimer

The views, analysis, recommendations, and conclusions in this report are those of the authors and do not represent official or unofficial policies or opinions of the United States Government, and the United States takes no position with regard to any findings, conclusions, or recommendations made. As such, mention of trade names or commercial products does not constitute their endorsement by the United States Government.

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Acronyms and Abbreviations

1-RO	Single-stage RO with a high-pressure feed pump
2-RO	Two-stage RO equipped with RO feed and an inter-stage pump
2-RO-ICD	Two-stage RO with an ICD unit
1-RO-NF	Sequential RO-NF stage with RO feed pump
2-RO-NF	RO-NF with inter-stage pump between the RO and NF stages
C	concentration
CT	conductivity
DWPR	Desalination and Water Purification Research Program
FT	flow
FY	fiscal year
HX	Heat exchanger, Sensors:
ICD	intermediate concentrate demineralization
NF	nanofiltration
NSEC	normalized specific energy consumption
P	pressure
PT	pressure
RO-NF-ICD	RO and NF stages with an ICD unit
Reclamation	Bureau of Reclamation
RO	reverse osmosis
SEC	specific energy consumption
SI	Saturation Index, defined as ratio of activity to solubility ion products of a given mineral TDS.
TDS	total dissolved solids
TR	Calculated at the limit of crossflow thermodynamic restriction.
TT	temperature.
UCLA	University of California Los Angeles
WaTeR	Water Technology Research

Measurements

°C	degree Celsius
gpm	gallons per minute
gfd	gallon/ft ² -day
in	inches
L	liter
mg/L	milligrams per liter
ppm	parts per million
psi	pounds per square inch
psig	pounds per square inch gauge (lb _f /in ² gauge)

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Executive Summary

Problem

Achieving high product water recovery (90 percent or higher) is critical for reverse osmosis (RO) membrane technologies for inland brackish water desalination. Even minor water recovery enhancements can significantly reduce concentrate volumes, which in turn increases fresh water production—and lowers the overall costs of concentrate management.

New methods are needed to alleviate osmotic pressure limits to extend the operating range (and thus applicability) of pressure-driven membrane technologies. Optimizing the pressure for reverse osmosis membranes and nanofiltration rejection rates can minimize energy requirements and maximize high water recoveries.

Water recovery in inland water desalination is often limited due to operating pressure limitations. In reverse osmosis, pressure is applied to overcome the natural osmotic pressure of the feedwater. As fresh water is extracted from the feedwater, the total dissolved solids (TDS) concentration increases in the feed channel. Thus, the osmotic pressure increases as the TDS rises—requiring a higher applied pressure. Since osmotic pressure rises rapidly with water recovery, operating pressure limitations in membrane systems impose an upper limit on the attainable product water recovery. Moreover, high-pressure pumps needed to process high TDS water have a high capital cost.

Objectives

This Desalination and Water Purification Research Program (DWPR) research project evaluated a hybrid reverse osmosis-nanofiltration (RO-NF) process to address operating pressure limitations in high recovery desalination. Hybrid RO-NF processes with higher recovery could reduce concentrate volumes from inland brackish water desalination.

Method and Results

We developed and ran a mathematical model for three conventional RO processes and three hybrid RO-NF processes.

Conventional RO Processes:

- Single-stage RO (1-RO) (Figure ES-1a)
- Two-stage RO (2-RO) (Figure ES-1b)
- Two-stage RO with intermediate concentrate demineralization (2-RO-ICD) (Figure ES-1c)

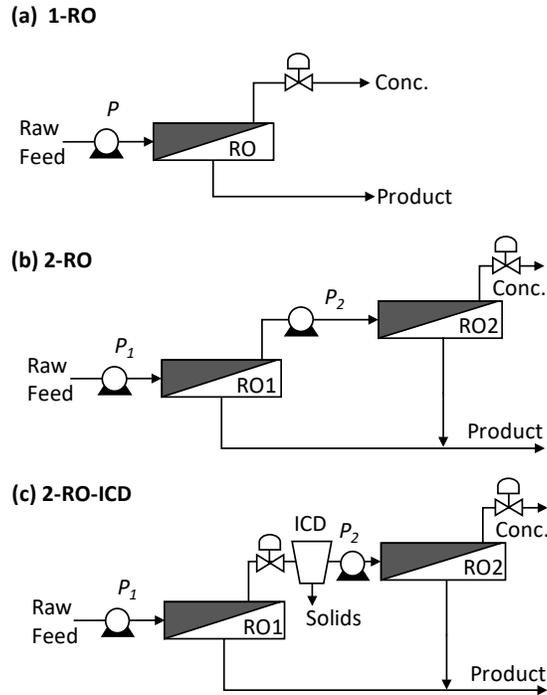


Figure ES-1.—Conventional RO processes modeled.

Hybrid RO-NF Processes

We conducted bench-scale experiments to demonstrate that a hybrid RO-NF membrane system could require lower applied pressure for a given membrane system recovery than a conventional RO system. In the hybrid systems, RO is used to produce water and NF is used to minimize concentrate volumes. The NF permeate returns to the RO feed, thus increasing recovery and reducing the volume of concentrate requiring disposal (Figure ES-2).

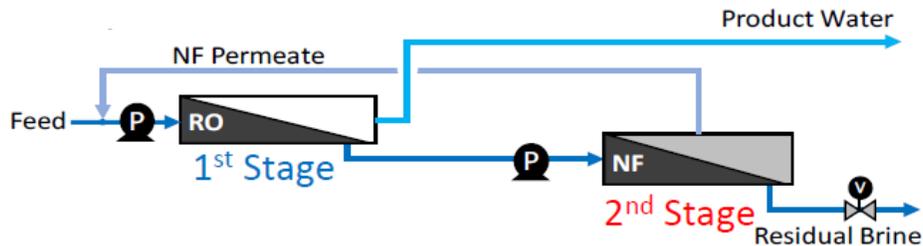


Figure ES-2.—Hybrid RO-NF process.

NF integrated with RO desalting could address the pressure limitations for high recovery found in conventional RO systems. As the NF membranes have a lower salt rejection rate and thus lower osmotic pressure differences, NF could allow operations at lower minimum feed pressures. We modeled three hybrid RO-NF processes:

- Single-stage RO-NF with RO feed pump (1-RO-NF) (Figure ES-3). This process tested a hybrid system without any interstage pumping.

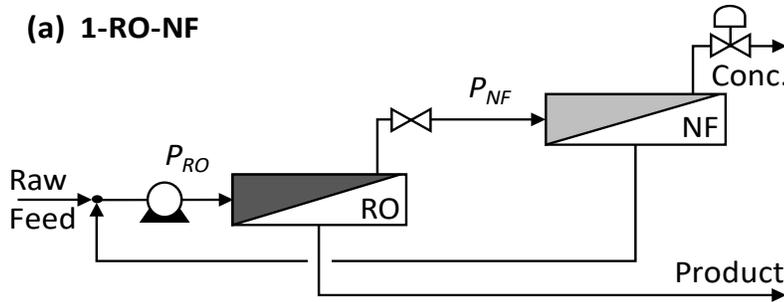


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- RO-NF configuration with an inter-stage pump (2-RO-NF) (Figure ES-4). This process tested a hybrid system with interstage pumping as shown by the red arrow.

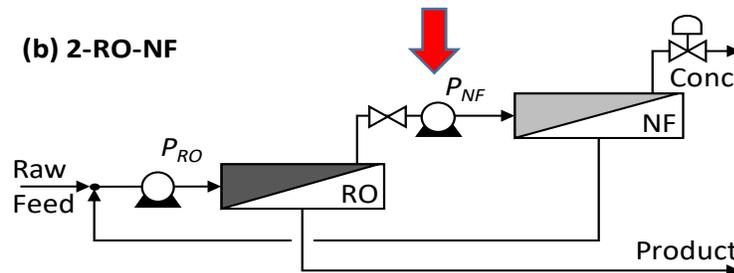


Figure ES-4.—Two stage RO-NF (2-RO-NF) with interstage feed pump.

- RO stage followed by ICD and NF stage to explore optimizing technologies to remove mineral scale precursors (2-RO-NF-ICD) (Figure ES-5). Using ICD helped address the operational limits imposed by antiscalant. ICD reduces the degree of supersaturation of sparingly soluble TDS, such as gypsum, so that the second stage recovery can be pushed higher before the mineral scaling operating limit is reached—thus increasing the overall recovery of the process. To use ICD, the concentrate from the RO needs to be completely depressurized (red arrow in Figure ES-4).

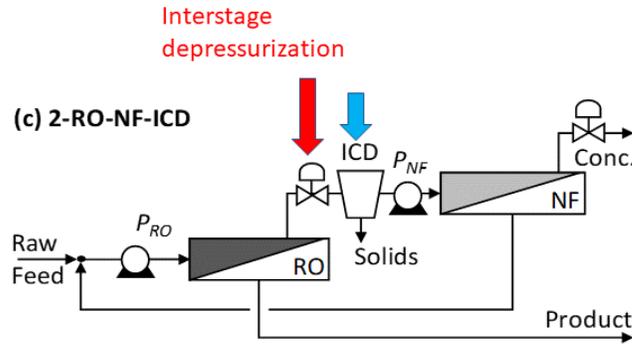


Figure ES-5.—Two stage RO-NF with ICD.

In these experimental runs, we operated both conventional RO and hybrid RO-NF at fixed RO permeate fluxes in the range of 10 to 15 gallons per square foot (ft²) per day (gfd), treating a 3,000 parts per million (ppm) TDS sodium chloride solution.

Figure ES-6 demonstrates the model results, showing that there is an area where an optimal NF rejection rate with an optimal RO pressure that will minimize energy costs and maximize water recovery for the hybrid system (yellow box). The RO and NF stage minimum pressures are optimal when the pressure vs rejection curves are equal (where the curves intersect) for any given overall water recovery. This is referred to as the “pressure optimal” NF rejection point.

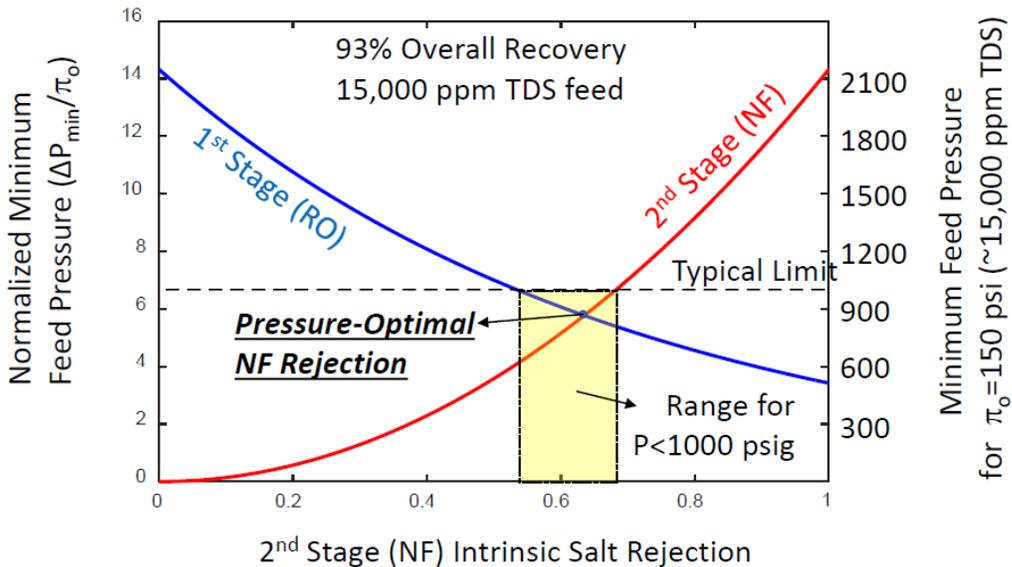


Figure ES-6.—Pressure optimal NF rejection. The yellow box indicates the intersections and the optimal performance area for a hybrid RO-NF based on the model results.

We demonstrated that the pressure and associated energy requirements for hybrid RO-NF processes are highly dependent on the salt rejection of the NF membrane, and that an optimal NF salt rejection exists that minimizes the pressure requirement (i.e., a pressure-optimal NF rejection) and energy requirements (i.e., an energy-optimal NF rejection).

The project found that modeled hybrid RO-NF processes can operate at significantly lower pressure requirements and, consequently, at higher water recovery levels than conventional RO processes, while meeting the same target product water quality.

Treating the concentrate from an RO process (which has high TDS levels) with an NF membrane increases water recovery. NF membranes allow more TDS to pass into the product water, thereby reducing the osmotic pressure differential that must be overcome to produce product water. For example, at a medium overall recovery rate (50%), the desired NF membrane rejection is 83% and the RO membrane pressure requirement is 33% lower in a hybrid RO-NF system than in a conventional RO system (Figure ES-7).

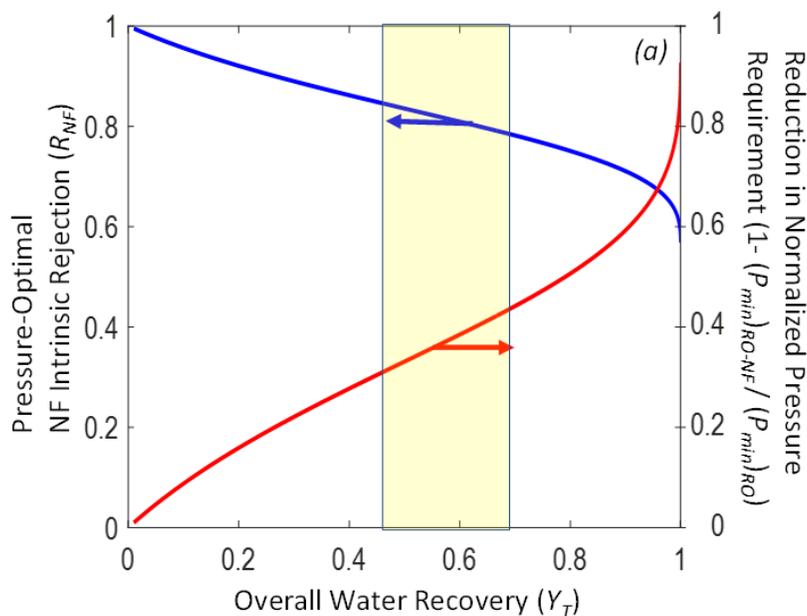


Figure ES-7.—The NF rejection required to minimize the hybrid RO-NF process pressure requirement compared to a conventional RO system. The yellow box indicates the water recovery range from about 50 to 75 percent.

Experimental data confirmed that the RO-NF process, even under suboptimal conditions, could have lower desalination pressures (i.e., the pressure applied in addition the osmotic pressure) than conventional RO.

Conclusions

Limitations from mineral scaling and operating pressures impede high water recovery in conventional RO desalination systems. A hybrid RO-NF approach could lower minimum pressure requirements. High recovery desalination could be used to minimize concentrate volumes. An optimal hybrid RO-NF configuration could minimize required pressure (and corresponding energy requirements) using an NF membrane optimized for TDS rejection. This hybrid system could reduce pressure by 33 to 65 percent over 50 to 90% water recoveries.

An intermediate concentrate demineralization (ICD) technology could be used to help avoid mineral scaling.

The hybrid RO-NF system uses about the same amount of energy as a two-stage RO process, up to a water recovery of about 94%.

Next Steps

Experimental data confirmed that pressure reduction for a given water recovery is feasible with a hybrid RO-NF system. However, additional work is needed to optimize the process and integrate RO with NF for optimal TDS rejections. Recommended next steps include:

- **Consider a range of feedwater qualities.** Provide models and bench-scale testing with feedwater with different ionic compositions. Divalent ions will increase scaling potential and NF membranes have different rejection rates for monovalent and divalent ions.
- **Consider dynamic, variable feedwater qualities.** Provide modeling and bench-scale tests for dynamic source waters. Systems that have feedwater quality that varies over time (e.g., seasonally) require real-time adjustments for optimizing recoveries, operating pressures, and rejection rates.
- **Examine impacts from scaling.** Note that membrane mineral scaling is also a concern, especially at high water recoveries. This concern can be mitigated by adding antiscalant chemicals and integrating ICD technologies to remove mineral scale precursors from primary RO concentrate. While we investigated ICD technologies, this was not a primary focus of this research project.

- **Investigate life cycle costs** at a pilot scale with a wide range of water chemistries.
- **Explore NF membranes with higher rejection rates.** This bench-scale project used NF membranes that did not reach the target values for rejection needed to attain the pressure-optimal levels. The hybrid approach could be further explored to characterize 1-RO-NF with NF TDS rejection that is at or approaching the target value and map the range of possible pressure reductions in high recovery desalination compared to a conventional RO system.
- **Explore the hybrid system at higher recovery rates.** The 1-RO-NF could be used in further experimental operations at high water recovery rates to assess the potential for reducing operating pressures below the operating pressures in a conventional RO system for treating water high in TDS.
- **Assess the impact of pump efficiency and potential energy recovery devices.** Assessing energy use over the range of pump capacities is needed to determine the practical range of desalination capacities. Explore the potential utility of energy recovery devices and the impact of both energy recovery devices and pump efficiencies for 1-RO-NF operation at low recovery (<50%) or with concentrate depressurization and re-pressurization when using the ICD.

1. Introduction

1.1. Project Background

1.1.1. Challenges to Reduce RO Concentrate Volumes

Reverse osmosis (RO) has become the dominant desalination technology due to its relative simplicity, compactness, modularity, and scalability (Greenlee et al. 2009 and Gray et al. 2011). RO water production is pressure driven, which avoids the complexity, relatively larger energy requirements, and high capital costs (e.g., due to material costs of distillation equipment) involved in osmotically- or heat-driven desalination processes (e.g., forward osmosis, membrane distillation, and solar evaporation) (Camacho et al. 2013 and Shaffer et al. 2014). By using electricity for pressure generation, pressure-driven RO desalination has significant deployment flexibility for harnessing renewables (e.g., solar photovoltaic cells and wind turbines), while maintaining consistent operational availability using the conventional power grid as backup power (Ghermandi et al. 2009 and GE Global Research, 2006). Various approaches to reducing RO energy consumption are also well established, such as using energy recovery devices and staged operation with inter-stage booster pumps (Zhu et al. 20009 and Zhu et al. 2010). More importantly, RO desalination has proven commercial success. RO desalination operations and maintenance are supported by diverse and well-established off the shelf supply chain of components and consumables (membrane elements, prefilters, compatible antiscalants, etc.).

Although RO technology has gained a significant share of the desalination market, conventional RO desalination approaches for treating impaired waters (brackish groundwater, agricultural drainage, mine drainage, etc.) at inland locations remain technically and economically challenging (Mccool et al. 2010, Rahardianto 2009, and Rahardianto et al. 2008). At inland locations, minimizing concentrate volume is critical to allow for practical (both technically and economically) concentrate management solutions (e.g., evaporation, deep well injection, etc.). Indeed, “concentrate management solutions leading to concentrate volume minimization for inland brackish water desalination” is one of Reclamation’s DWPR program priorities for fiscal year (FY) 2015.

Increasing RO desalination water recovery reduces concentrate volume. Two major factors, however, typically impose limits on RO water recovery:

- 1) membrane mineral scaling and fouling and
- 2) operational pressure limits from the mechanical limitations of available membrane modules and vessels.

1.1.1.1. Scaling and Fouling

Various approaches are available to overcome the water recovery limit imposed by membrane mineral scaling and fouling. Significant advances in technologies for mitigating membrane mineral scaling have been made (Rahardianto 2009, Rahardianto et al. 2008), including effective feed pretreatment (Rahardianto et al. 2007 and Thompson et al. 2013), optimal antiscalant dosing (Thompson et al. 2013 and Rahardianto et al. 2006), and integration of intermediate concentrate demineralization (ICD) processes to remove mineral scale precursors (Rahardianto et al. 2007 and McCool et al. 2013).

ICD has been shown to be effective in high recovery desalination of agricultural drainage water (e.g., 10,000 parts per million [ppm] total dissolved solids [TDS]) with high gypsum scaling potential, enabling water recovery of up to 90% or higher (McCool et al. 2013). Figure 1 shows how ICD can be incorporated as an intermediate step between two RO stages. ICD reduces the degree of supersaturation of sparingly soluble salts, such as gypsum, so that the second stage recovery can be pushed higher before the mineral scaling operating limit is reached—thus increasing the overall recovery of the process.

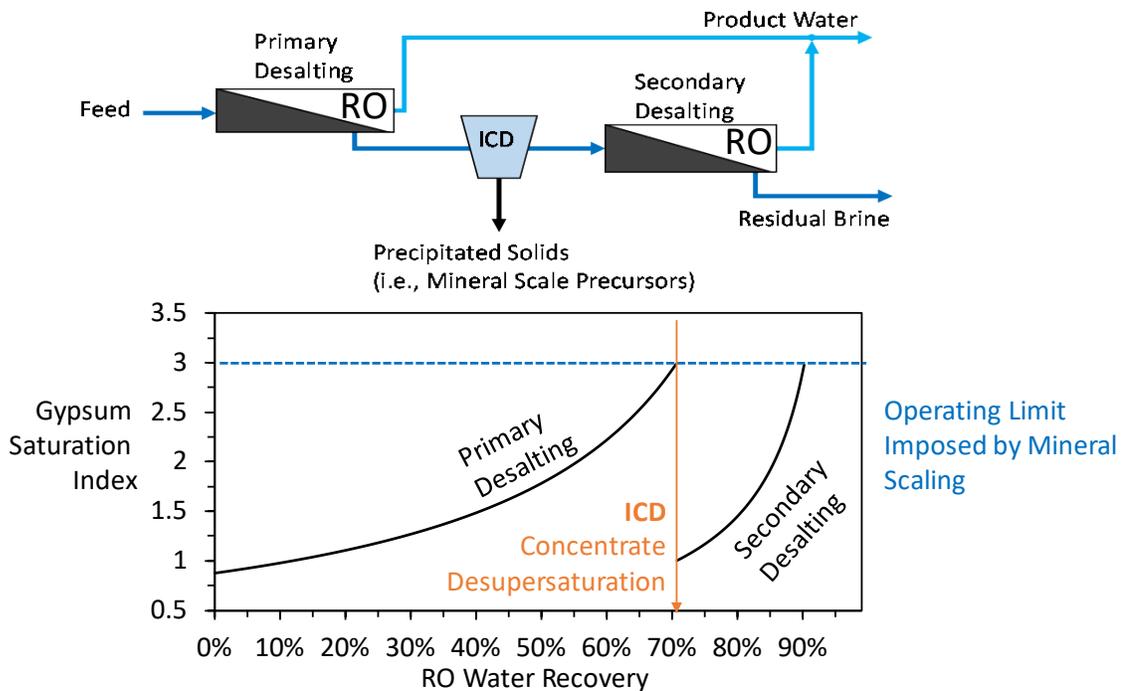


Figure 1.—Gypsum saturation index in membrane concentrate as a function of water recovery in a two-stage desalination process with intermediate concentrate demineralization (ICD). Gypsum saturation index is defined as the ratio of activity to solubility products of the dissolved calcium and sulfate ions.

While this project did not focus specifically on addressing scaling and fouling, we modeled an RO stage followed by ICD process and NF stage to explore optimizing technologies to remove mineral scale precursors (2-RO-NF-ICD).

1.1.1.2. Applied Pressure Limitations

Overcoming the water recovery limitation imposed by operating pressure limits of membrane modules and vessels remains a challenge. Most standard commercial high-pressure RO elements (e.g., seawater RO) are typically rated for operation only up to a pressure of 1,000 pounds per square inch gauge (psig). As shown in Figure 2, the minimum required operating pressure for RO desalination rises quickly above 1,000 psig as water recovery increases.

The minimum applied pressure required to overcome the osmotic pressure and produce permeate along the entire axial direction of the membrane module is defined as the cross-flow thermodynamic restriction. Therefore, at a given pressure, higher overall water recoveries are possible with lower membrane rejection at the typical operating pressure limit of 1,000 psig because the osmotic pressure differential between the feed/concentrate and the permeate is lower.

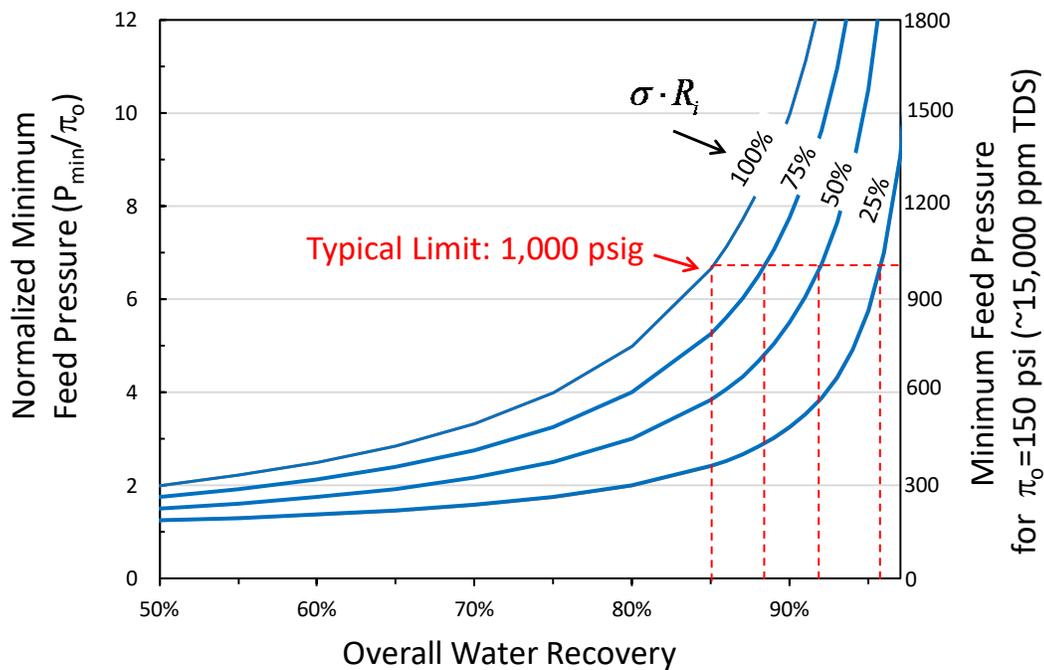


Figure 2.—Minimum required RO/NF feed pressure (normalized to the raw feed osmotic pressure, π_o) as function of overall water recovery at various levels of membrane TDS rejection (R_i) and reflection coefficient (σ).

At the 1,000 psig pressure limit, a brackish water with TDS of 15,000 milligrams per liter (mg/L), for example, is limited to a maximum desalination recovery of 85% (assuming 100% TDS rejection), even with RO operations that approach the thermodynamic limit.

Relying on membranes alone to handle pressures beyond the 1,000 psig pressure limit is not feasible. Specialized ultra-high-pressure RO modules, capable of operating up to 2,300 psig, are available in niche markets (e.g., treating dumpsite leachate). However, using these membranes can be undesirable due to increased

costs of RO modules and vessels, as well the associated piping, pump equipment, and exotic materials costs. Furthermore, the current generation of high water permeability RO membranes has already enabled RO desalting operations at pressures approaching the thermodynamic limit (i.e., minimum applied pressure) (Gray et al. 2011, Zhu et al. 2009 [Thermodynamic restriction], and Zhu et al. 2010). Therefore, further RO membrane permeability improvements are not expected to provide significant reductions in membrane operating pressure requirements Zhu et al. 2009 [Costs].

1.1.2. Need to Reduce Applied Pressure

New methods for reducing the required applied pressure in pressure-driven, membrane-based desalting are needed to enhance water recovery above the pressure-imposed water recovery limit of conventional RO desalination. Even small enhancements in water recovery can significantly reduce concentrate volumes. This, in turn, directly affects the capacity requirements and overall costs of concentrate management and/or disposal solutions. For example, the ability to increase water recovery from 85 percent to 90 to 95 percent can reduce concentrate volume by 33 to 67 percent (Figure 3).

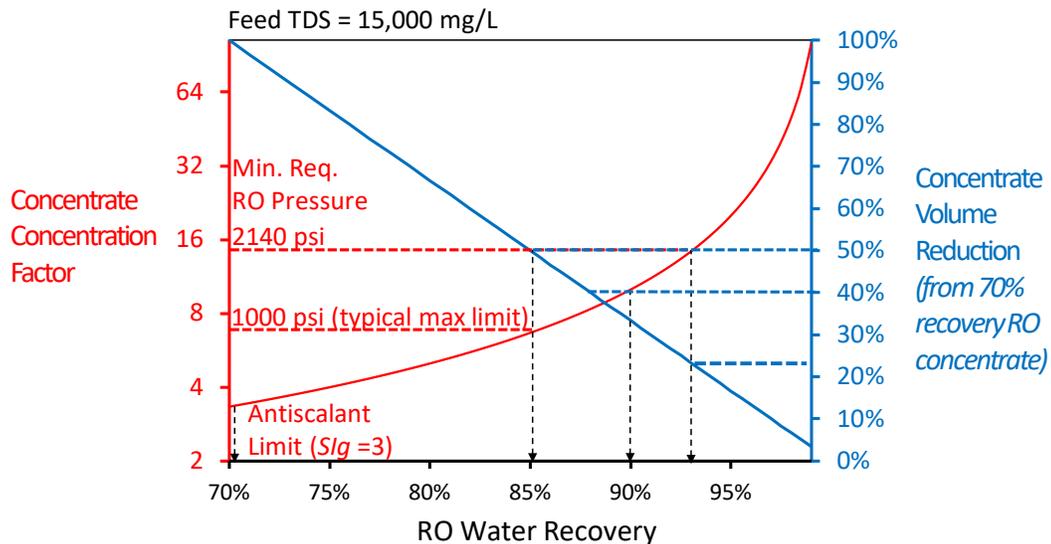


Figure 3.—Incremental increases in RO water recovery above 70 percent recovery reduce concentrate volume (compared to RO operations at 70 percent recovery) and where antiscalant use is limited to the condition of $SI_g=3$ for the mineral scalant of concern.

1.2. Project Overview

1.2.1. Objectives and Tasks

This project investigated the theoretical potential of hybrid RO-NF processes to have lower pressure and energy requirements for high recovery desalination than conventional RO processes.

The project developed fundamental principles for process design and optimization of RO-NF processes for high recovery desalination.

The project modeled three hybrid RO-NF processes and three conventional RO process and provided laboratory, proof-of-concept data for the hybrid RO-NF process.

Specific project tasks included:

- a) Developing a model and analysis framework to predict process performance and develop process design and optimization strategies
- b) Generating experimental data for RO-NF proof-of-concept through bench-scale testing

1.2.2. Overall Approach and Concepts

The project developed the theoretical modeling and analysis framework for process design and optimization, assessed pressure and associated energy requirements, and provided laboratory proof-of-concept demonstration of RO-NF integration as an approach for enhancing water recovery above the pressure-imposed water recovery limit of conventional RO processes. The project results support the hypothesis that hybrid RO-NF processes can operate at significantly lower pressure requirements—and, consequently, at higher water recovery levels than conventional RO processes—while meeting the same target product water quality.

A simple example of such processes is a two-stage RO-NF process with and without intermediate concentrate demineralization (ICD) to remove scale between the RO and the NF stages (Rahardianto et al. 2007 and McCool et al. 2013). To achieve product water quality targets while maximizing water recovery, NF permeate is recycled to the RO feed. While NF permeate recycle leads to partial dilution of the RO feed (which reduces the overall feed osmotic pressure), it also increases the feed flow rate—leading to increased pumping energy requirements (Figure 4).

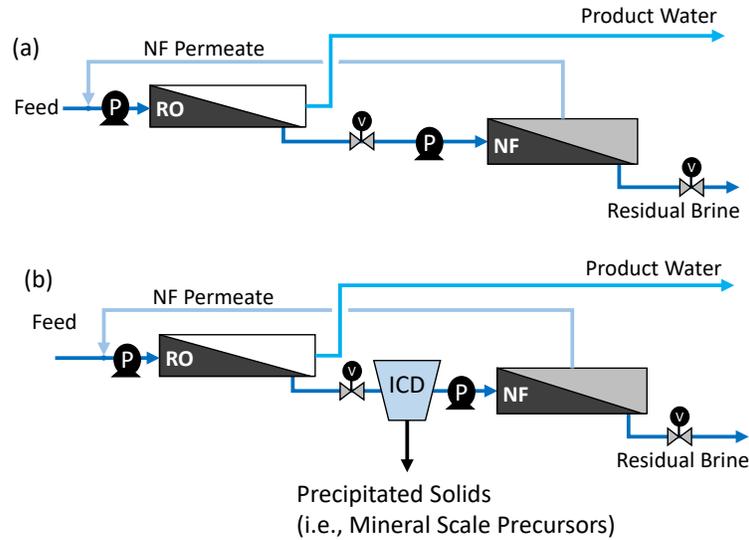


Figure 4.—Two-stage hybrid RO-NF process with and without intermediate concentrate demineralization (ICD, for scale precursors removal). P: pump; V: pressure throttling valve.

In this example, the first-stage RO process produces water, while the second-stage NF process reduces the final process concentrate volume by desalting concentrate from the first-stage RO. The produced water from the NF process is returned to the RO feedwater.

The required applied pressure of the two-stage RO-NF process is lower than the pressure required for a conventional two-stage RO process because of the significantly lower NF TDS rejection rate, which results in a lower second-stage concentrate osmotic pressure.

1.2.3. Overall Method

The project sought to develop process models of hybrid RO-NF processes for general assessments of overall process capabilities (i.e., feasible operating domain as governed by thermodynamics), comparing various RO-NF process configurations and process units (e.g., ICD, inter-stage pumping), as well as comparing with conventional RO. As previously demonstrated for conventional RO (Zhu et al. 2009 [Thermodynamic restriction] and Zhu 2010), process analysis that considers operation up to the thermodynamic limit provides critical insight regarding technical feasibility, operating configuration and optimal operational domain (including pressure and associated energy requirements, flux, and achievable target permeate quality).

Process modeling considered the case of three hybrid RO-NF processes:

- single-stage RO-NF (1-RO-NF, with RO feed pump,
- RO-NF configuration with an interstage pump (2-RO-NF, and
- RO stage followed by ICD and NF stage (2-RO-NF-ICD).

The process model was used to:

- Identify the fundamental parameters (e.g., Y_{RO} , Y_{NF} , R_{NF} , and σ_{NF}) that govern operating pressures and energy consumption. These parameters can be used to optimize operating pressures.
- Determine optimal desalination process configurations.
- Compare RO-NF and conventional RO energy requirements. We modeled these processes to predict RO-NF process performance (e.g., flow, pressure, and energy requirements).

Results from the modeling and analysis component of the project guided the experimental portion of the project. Bench-scale, laboratory tests were conducted for proof-of-concept to generate data for a single-stage RO-NF process. We evaluated the RO-NF processes' performance to assess two factors over a range of water recovery of the individual RO and NF stages and NF TDS rejection:

- a) whether NF integrated with RO could reduce operating pressure requirements, and
- b) the impact of process integration on specific energy consumption (SEC).

The bench scale tests used synthetic NaCl solutions, a spiral-wound membrane desalination system (2.5 x 40-inch elements; 4 gallons per minute [gpm] feed capacity; and 1,000 pounds per square inch [psi] maximum pressure) at the University of California Los Angeles (UCLA) Water Technology Research (WaTeR) Center.

2. Technical Approach and Methods

The technical approach of the project involved process modeling and comparing the experimental characterization of a hybrid RO-NF process to conventional RO processes.

First, we developed a mathematical process model to characterize the operations of RO-NF processes. The model was then used to compare the minimum pressure and associated energy requirements for RO-NF processes with conventional RO. Using a reconfigurable RO system, we conducted bench-scale tests with a single-stage RO-NF process configuration and compared these performance results to a conventional single-stage RO process. We compared the experimentally observed trends in pressure requirements and energy use for the hybrid RO-NF process with those predicted by the RO process model.

2.1. Mathematical Process Model

To achieve high recoveries, we need to address the challenges involved in recovery limits imposed from osmotic pressure. In reverse osmosis, pressure is applied to overcome the natural osmotic pressure of the feedwater (pure water to salt water). As product water is extracted from the feedwater, the concentration of total dissolved solids (TDS) increases in the feed channel. Thus, the osmotic pressure increases as the TDS concentration level rises—requiring a higher applied pressure. Since osmotic pressure rises rapidly with water recovery, operating pressure limitations in membrane systems impose an upper limit on the attainable product water recovery.

We developed process models for hybrid RO-NF processes, extending the approach for conventional RO operating at the limit of crossflow thermodynamic restriction (Zhu et al. 2009 [Thermodynamic restriction] and Zhu 2010). The crossflow thermodynamic restriction is the minimum operating pressure required to produce permeate along the entire axial direction of the membrane. In deriving the process models, we considered flow and TDS balances for conventional RO and RO-NF processes (see the process flow diagram depicted in **Figure 5**). The energy requirements for hybrid RO-NF and conventional RO processes depend on pump placements in the process. A pump between membrane systems is used in this two-stage process and uses the residual pressure from the first membrane process as the feed to the second is a single stage process.

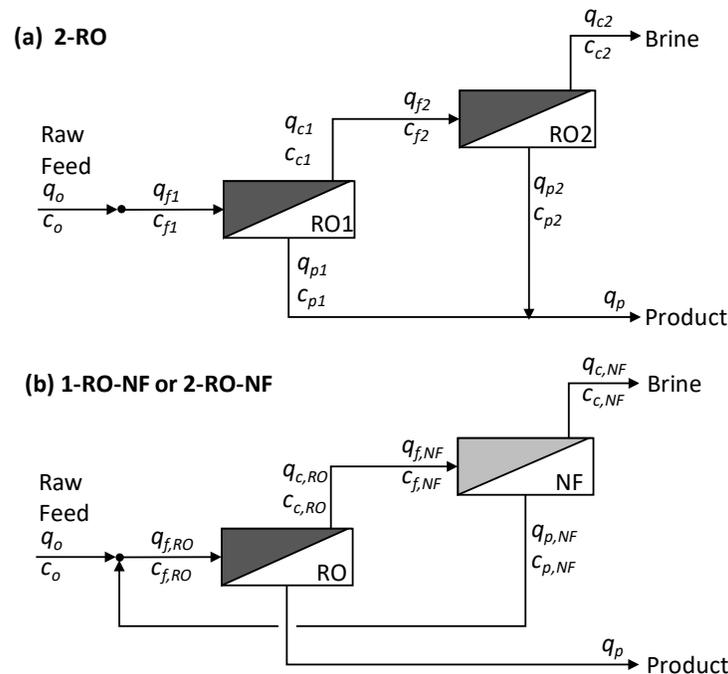


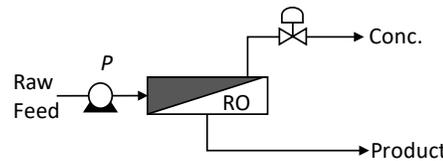
Figure 5.—Flow rates (q) and concentration (c) of major process streams in (a) a conventional 2-stage RO (2-RO) and (b) a hybrid 1-stage RO-NF (1-RO-NF) or a hybrid 2-stage RO-NF (2-RO-NF) process. Nomenclature: q - volumetric flow rate, c -TDS concentration. Subscripts: o - raw water, f - feed, c - concentrate, p - permeate.

We first modeled three conventional RO process configurations as shown in Figure 6.

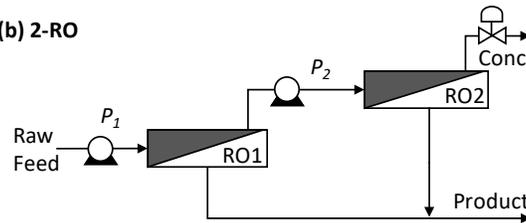
- Single-stage RO (1-RO) (Figure 6a)
- Two-stage RO (2-RO) (Figure 6a),
- Two-stage RO with intermediate concentrate demineralization (2-RO-ICD) (Figure 6a)

An intermediate pump is used in the conventional 2-RO stage process, which allows 2-RO to operate at two pressure levels and thus save energy. No intermediate pumps are used in the conventional 1-RO stage.

(a) 1-RO



(b) 2-RO



(c) 2-RO-ICD

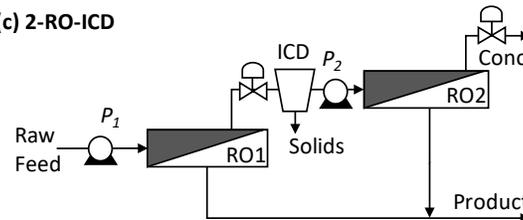


Figure 6.—Diagram identifying pumping and throttling locations in major process streams of (a) a 1-stage RO (1-RO), (b) 2-stage RO (2-RO), (c) 2-stage RO process with ICD (2-RO-ICD) or a 2-stage RO-NF (2-RO-NF). P-pump/valve outlet pressure, ICD-intermediate concentrate demineralization.

Using ICD in conventional 2-stage RO process requires depressurizing the first stage concentrate, and then re-pressurizing the ICD-treated concentrate with a second pump from the atmospheric level (instead of using the concentrate pressure from the first-stage RO, which does not require a second pump). Therefore, as complete depressurization and re-pressurization of first-stage RO concentrate with an ICD has about the same pressurization requirements as two separate 1-RO processes arranged in series, the 2-RO-ICD is expected to need more energy than a combined 2-RO process (which does not require a complete de-pressurization and re-pressurization process).

We modeled three configurations of the hybrid RO-NF-processes as shown in Figure 7:

- Single-stage RO-NF (1-RO-NF) (Figure 7a)
- Two-stage RO-NF (2-RO-NF) (Figure 7b)
- two-stage RO-NF with ICD (2-RO-NF-ICD) (Figure 7c)

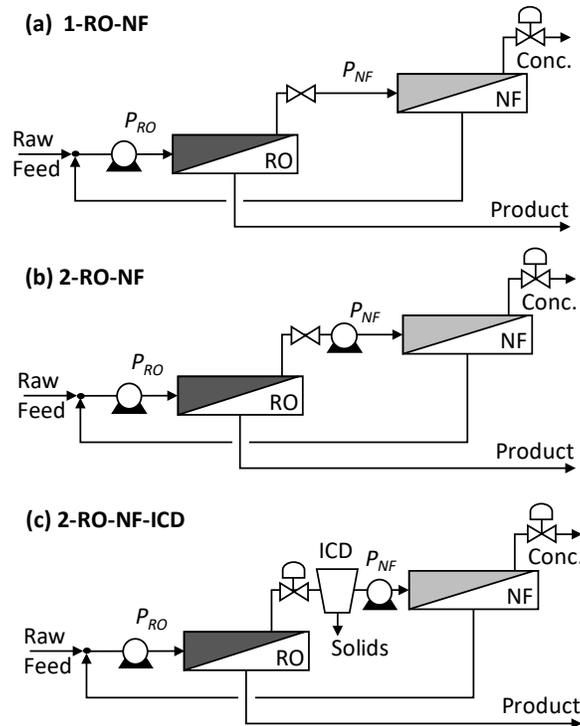


Figure 7.—Diagram identifying pumping and throttling locations in major process streams of (a) 1-stage RO-NF (1-RO-NF), (b) 2-stage RO-NF (2-RO-NF), (c) 2-stage RO with ICD (2-RO-ICD) or a 2-stage RO-NF (2-RO-NF). P-pump/valve outlet pressure, ICD-intermediate concentrate demineralization.

In all of the hybrid RO-NF processes, the RO stage produced water and the NF stage treated the RO concentrate. NF permeate was recycled to the RO feed, thereby lowering the osmotic pressure of the RO feed relative to the raw feed. In conventional 2-RO, the required second stage pressure is always higher than the first stage. For the hybrid RO-NF processes (with no ICD), however, under certain circumstances, the required first-stage RO pressure may be larger than the required second-stage NF pressure due to lower NF TDS rejection (which results in a lower osmotic pressure difference between the NF feed and product). When the required first-stage RO pressure is higher than the second-stage NF pressure, an intermediate depressurization (i.e., via a throttling valve) may be required to avoid operation of the NF at a pressure that would generate more product water than recommended.

2.1.1. Water Recovery in Conventional RO and Hybrid RO-NF Processes

The overall recovery (Y_T) for either the hybrid RO-NF or conventional RO is defined as **Equation 1**:

$$\text{Equation 1. } Y_T = q_p / q_o$$

Where:

q_p is the total product water flow rate

q_o is the raw feed water flow rate

For a conventional two-stage RO (i.e., 2-RO), the water recovery for the first (Y_1) and second (Y_2) stages are shown in **Equation 2**:

$$\text{Equation 2. } Y_{RO1} = q_{p1} / q_{f1}, Y_{RO2} = q_{p2} / q_{f2}$$

Where:

q_{p1}, q_{p2} is the permeate rate of the individual stages

q_{f1}, q_{f2} is the permeate and feed flow rates of the individual stages.

The relationship between the water recovery in individual stages and the overall water recovery can be deduced from flow balances balance to give **Equation 3**:

$$\text{Equation 3. } Y_T = 1 - (1 - Y_{RO1})(1 - Y_{RO2})$$

For the special case of $Y_{RO1} = Y_{RO2}$, the overall water recovery is given by

Equation 4:

$$\text{Equation 4. } Y_T = 1 - (1 - Y_{RO1})^2$$

For both hybrid single- (1-RO-NF) and two-stage (2-RO-NF) pumping in hybrid RO-NF processes, the individual RO and NF water recoveries are defined as shown in **Equation 5** :

$$\text{Equation 5. } Y_{RO} = q_p / q_{f,RO}, Y_{NF} = q_{p,NF} / q_{f,NF}$$

Where:

Y is water recovery for RO or NF

q_p is the total product water flow rate

q_f is the feed water flow rate

variable subscripts, RO and NF, are used to denote the individual values for each process, RO or NF.

Note that, for RO-NF processes, product water is only produced by RO, while NF treats the RO concentrate and generates permeate that is recycled into the RO feed. Based on flow balance of RO-NF processes, the overall water recovery for both single- (1-RO-NF) and two-stage (2-RO-NF) pumping in hybrid RO-NF processes is given by **Equation 6**:

$$\text{Equation 6. } Y_T = \frac{Y_{RO}}{1 - Y_{NF} \cdot (1 - Y_{RO})}$$

Where:

Y_T is the total system recovery

Y_{RO} is the RO recovery

Y_{NF} is the NF recovery

2.1.2. Salt Rejection

In this study, it is assumed that the RO membranes provide complete salt rejection ($R_{RO}=1-c_p/c_o=1$). Salt rejection by the NF membrane stage is assessed based on the Spiegler-Kedem-Katchalsky (SKK) model (Zhu et al. 2009 [Thermodynamic restriction] and Zhu 2010) as shown in **Equation 7**:

$$\text{Equation 7. } R_{i,x} = 1 - \frac{1 - \sigma_x}{1 - \sigma_x \cdot F}, \quad F = \exp\left(-\frac{(1 - \sigma_x)}{k_{s,x}} \cdot j_x\right)$$

Where:

$R_{i,x}$ is TDS rejection

$$R_{i,x} = 1 - c_{px} / c_{mx},$$

in which c_{px} and c_{mx} are the local permeate and concentrate near the membrane at axial location x along the membrane element concentrate channel length, respectively

σ_x is the local membrane solute reflection coefficient

$k_{s,x}$ is the local solute membrane permeability coefficient

j_x is the local permeate flux

For NF, k_s is large so $F \approx 0$ and thus $R_{i,x} \approx \sigma_x$.

In this study, for NF, a reasonable approximation is to consider σ_x as constant along the membrane channel and that concentration polarization as negligible. In this ideal case, the intrinsic salt rejection for NF (R_{NF_i}) approaches the NF membrane reflection coefficient as expressed in **Equation 8**:

$$\text{Equation 8. } R_{NF_i} \approx \sigma_{NF}$$

Given that the intrinsic rejection is not directly measurable, the observed NF TDS rejection is typically used to characterize NF performance, which can be defined as **Equation 9**:

$$\text{Equation 9. } R_{NF} = 1 - c_{p,NF} / c_{f,NF}$$

Where:

R is rejection

c is salt concentration

The relationship between the and nominal TDS rejection can be derived from a one-dimensional differential mass balance along the length of the NF concentrate channel, yielding **Equation 10**:

$$\text{Equation 10. } R_{NF} = 1 - \frac{\ln(1 - (1 - R_{NF}) \cdot Y_{NF})}{\ln(1 - Y_{NF})}$$

Where:

Y is recovery

2.1.3. Minimum RO Pressure Requirement

In conventional RO processes, the pressure required for each RO stage is governed by the RO concentrate osmotic pressure as given by the following inequality expressed in **Equation 11**:

$$\text{Equation 11. } p_{RO} \geq \pi_{c,RO}$$

Where:

p_{RO} is the RO pressure requirement

$\pi_{c,RO}$ is the osmotic pressure in the concentrate

The crossflow thermodynamic restriction imposes a minimum required RO feed pressure $p_{RO,min} = \pi_{c,RO}$ for producing water over the entire axial length of the RO membrane train of elements. Given the reasonable assumption that the osmotic pressure is approximately proportional to concentration ($\pi \propto c$), the minimum pressure ($p_{RO,min}$), for a membrane with complete TDS rejection, as function of RO water recovery (Y_{RO}) and RO feed osmotic pressure (π_f) is given by

Equation 12:

$$\text{Equation 12. } \frac{p_{RO,min}}{\pi_f} = \frac{c_{c,RO}}{c_{f,RO}} = \frac{1}{1 - Y_{RO}}$$

Therefore, for a single-stage RO (1-RO), the RO recovery and feed osmotic pressure are equivalent to the overall water recovery (Y_T) and the raw water osmotic pressure (π_o). Accordingly, the minimum pressure is then given by **Equation 13**:

$$\text{Equation 13. } \frac{(P_{RO,\min})_{1-RO}}{\pi_o} = \frac{1}{1-Y_T}$$

For a two-stage RO (2-RO), the minimum pumping pressures at the entrances of the first (RO₁, i.e., RO feed pump) and the second (RO₂—the intermediate pump) stages are given by **Equation 14**:

$$\text{Equation 14. } \frac{(P_{RO1,\min})_{2-RO}}{\pi_o} = \frac{1}{1-Y_{RO1}}, \quad \frac{(P_{RO2,\min})_{2-RO}}{\pi_o} = \frac{1}{1-Y_T}$$

For RO-NF processes, the minimum feed pressure for the RO membrane stage depends on the NF and RO water recovery rate (Y_{NF} , Y_{RO}), NF nominal TDS rejection (R_{NF}), and raw water osmotic pressure (π_o). This minimum feed pressure can be derived based on flow and TDS balances on first-stage RO, yielding **Equation 15**:

$$\text{Equation 15. } \frac{(P_{RO,\min})_{RO-NF}}{\pi_o} = \frac{1-Y_{NF}(1-Y_{RO})}{(1-(1-R_{NF})\cdot Y_{NF})\cdot(1-Y_{RO})}$$

Substituting **Equation 6** into **Equation 15** yields **Equation 16**:

$$\text{Equation 16. } \frac{(P_{RO,\min})_{RO-NF}}{\pi_o} = \frac{(1-Y_{NF})}{(1-(1-R_{NF})\cdot Y_{NF})\cdot(1-Y_T)}$$

Note that the nominal NF TDS rejection is a function of both the NF TDS rejection and water recovery as per **Equation 10**.

2.1.4. Minimum NF Pressure Requirement

In RO-NF processes, the required feed pressure to ensure water productivity along the entire length of a series of NF elements is given by **Equation 17**:

$$\text{Equation 17. } p_{NF} \geq \pi_{c,NF}$$

At the limit of cross-flow thermodynamic restriction, the minimum required NF feed pressure ($P_{NF,min}$) is governed by the salinity of the NF concentrate ($c_{c,NF}$) relative to NF feed ($c_{f,NF}$), the NF reflection coefficient (σ_{NF}), and nominal NF TDS rejection as shown in **Equation 18**:

$$\text{Equation 18. } \frac{P_{NF,min}}{\pi_{f,NF}} = \sigma_{NF} \cdot R_{NF} \cdot \frac{c_{c,NF}}{c_{f,NF}}$$

Because NF is fed with the RO concentrate and the NF permeate is recycled to the RO feed, $c_{f,NF}$ depends on both the RO recovery and the NF TDS rejection. From flow and TDS balances on the second-stage NF the following expression for the minimum feed pressure to the second-stage NF in the RO-NF processes can be derived by using **Equation 19**:

$$\text{Equation 19. } \frac{(P_{NF,min})_{RO-NF}}{\pi_o} = \sigma_{NF} \cdot R_{NF} \cdot \frac{1 - Y_{NF} (1 - Y_{RO})}{(1 - Y_{NF})(1 - Y_{RO})}$$

Combining **Equation 6** with **Equation 19** yields **Equation 20**:

$$\text{Equation 20. } \frac{(P_{NF,min})_{RO-NF}}{\pi_o} = \frac{\sigma_{NF} \cdot R_{NF}}{1 - Y_T}$$

2.1.5. Optimal Operating Pressure in RO-NF Process

Based on the minimum RO (**Equation 16**) and NF (**Equation 20**) feed pressures in RO-NF processes, the following relationship indicates that the minimum second-stage NF feed pressure in RO-NF approaches that of conventional-single stage RO process, $(p_{RO,min})_{1-RO}$ (i.e., **Equation 13**) at the limit of complete NF TDS rejection as shown in **Equation 21**:

$$\text{Equation 21. } \frac{(P_{NF,min})_{RO-NF}}{\pi_o} = \frac{1}{1 - Y_T} > \frac{(p_{RO,min})_{RO-NF}}{\pi_o} \text{ for } \sigma_{NF} \cdot R_{NF} \rightarrow 1$$

The minimum NF feed pressure $(p_{NF,min})_{RO-NF}$ at complete NF TDS rejection is higher than in the upstream minimum RO feed pressure $(p_{RO,min})_{RO-NF}$. At the other extreme of zero NF TDS rejection, the opposite condition exists so that the $(p_{RO,min})_{RO-NF}$ is equivalent to that of conventional-single stage RO process, $(p_{RO,min})_{1-RO}$ (i.e., **Equation 13**) as shown using **Equation 22**:

$$\text{Equation 22. } \frac{(P_{RO,\min})_{RO-NF}}{\pi_o} = \frac{1}{1-Y_T} > \frac{(P_{NF,\min})_{RO-NF}}{\pi_o} = 0$$

for $\sigma_{NF}, R_{NF} \rightarrow 0$

The above suggests that an optimal NF TDS rejection (R_{NF_i} , where $R_{NF_i} \approx \sigma_{NF}$ by **Equation 8**) exists that minimizes the feed pressure requirements for NF and RO stages. This optimum occurs when the minimum feed pressure requirements for RO and NF in NF-RO processes are the same, as shown in **Equation 23**:

$$\text{Equation 23. } (P_{opt})_{RO-NF} = (P_{RO,\min})_{RO-NF} = (P_{NF,\min})_{RO-NF}$$

Thus, by combining **Equation 15** with **Equation 19** to satisfy the equality in **Equation 23**, it can be shown that the optimal $R_{NF_i} = \sigma_{NF}$ depends only on the NF water recovery as given by **Equation 24**:

$$\text{Equation 24. } Y_{NF} = \frac{1 - R_{NF_i,opt} \cdot R_{NF}(R_{NF_i,opt}, Y_{NF})}{1 - (1 - R_{NF}(R_{NF_i,opt}, Y_{NF})) \cdot R_{NF_i,opt} \cdot R_{NF}(R_{NF_i,opt}, Y_{NF})}$$

2.1.6. RO Specific Energy Consumption

Energy requirements for RO and RO-NF processes can be expressed in terms of the specific energy consumption (SEC), defined as **Equation 25**:

$$\text{Equation 25. } SEC = \frac{\text{Energy Consumption}}{\text{Water Productivity}}$$

RO/NF energy consumption is dependent on the raw water osmotic pressure (π_o), hence it is convenient to normalize the SEC (i.e., NSEC) as a dimensionless energy consumption expressed as **Equation 26**:

$$\text{Equation 26. } NSEC = \frac{SEC}{\pi_o}$$

For an RO/NF stage, the NSEC at the limit of cross-flow thermodynamic restriction (tr) can be determined based on the feed (q_f) and product (q_p) volumetric flow rates, minimum feed pressure (p_{min}), and pump efficiency (η_p) as shown in **Equation 27**:

$$\text{Equation 27. } NSEC_{tr} = \frac{1}{\pi_o \cdot q_p} \left(\frac{q_f \cdot p_{\min}}{\eta_p} \right)$$

To simplify the analysis, an ideal pump can be assumed ($\eta_p = 1$). The NSEC at the limit of cross-flow thermodynamic restriction (tr) can be determined for single-stage RO (1-RO), two-stage RO (1-RO) and two-stage RO with ICD (2-RO) by combining **Equation 27** with **Equation 13** and **Equation 14**, respectively. Thus, for a conventional single-stage RO (1-RO) as shown in **Equation 28**:

$$\text{Equation 28. } (NSEC_{tr})_{1-RO} = \frac{1}{Y_T \cdot (1 - Y_T)}$$

and for a conventional two-stage RO as shown in **Equation 29**:

$$\text{Equation 29. } (NSEC_{tr})_{2-RO} = \frac{1}{Y_T} \left(\frac{1}{1 - Y_{RO1}} + \frac{1}{1 - Y_{RO2}} - 1 \right)$$

NSEC is lowered with $Y_{RO1} = Y_{RO2}$ (Zhu et al. 2009 [Thermodynamic restriction] and Zhu 2010), leading to the relationships for conventional 2-RO as shown in **Equation 30**:

$$\text{Equation 30. } (NSEC_{tr})_{2-RO} = \frac{1}{Y_T} \left(\frac{2}{(1 - Y_T)^{1/2}} - 1 \right)$$

The 2-RO-ICD operation needs to de-pressurize and re-pressurize for the ICD between the first and second RO stages, which increases the energy requirements as defined in **Equation 31**:

$$\text{Equation 31. } (NSEC_{tr})_{2-RO-ICD} = \frac{2}{Y_T (1 - Y_T)^{1/2}}$$

2.1.7. RO-NF Specific Energy Consumption

To determine the NSEC at thermodynamic restriction (tr) for RO-NF processes, it must be recognized that the feed pressure of the RO stage maybe higher or lower than feed pressure of the NF stage, depending on the TDS rejection and NF water recovery relative to the optimal values (i.e., **Equation 24**). When $p_{RO,\min} \geq p_{NF,\min}$ in 1-RO-NF and 2-RO-NF, $p_{NF,\min}$ in the NF stage can only be achieved by

depressurizing the RO concentrate from $p_{RO,\min}$ to $p_{NF,\min}$. Thus, under such a condition in which $p_{RO,\min} \geq p_{NF,\min}$, an inter-stage pump is not required.

When $p_{RO,\min} < p_{NF,\min}$, the entire 1-RO-NF process must be operated at $p_{NF,\min}$, while 2-RO-NF process enables operation at $p_{RO,\min}$ and $p_{NF,\min}$ for the respective RO and NF stages. For 1-RO-NF-ICD operations, the requirement for depressurization of the first-stage RO concentrate for ICD enables decoupling of the RO and NF stages and thus the process train can be operated independently at $p_{RO,\min}$ and $p_{NF,\min}$, respectively. Given the above, **Equation 27**, **Equation 15** and **Equation 19** can be combined to determine the energy requirements at thermodynamic restriction (*tr*) for a single-stage RO-NF (1-RO-NF) as given in **Equation 32**:

$$\text{Equation 32. } (NSEC_{tr})_{1-RO-NF} = \begin{cases} \frac{1}{Y_{RO}} \cdot \left(\frac{p_{RO,\min}}{\pi_o} \right) & \text{if } p_{RO,\min} \geq p_{NF,\min} \\ \frac{1}{Y_{RO}} \cdot \left(\frac{p_{NF,\min}}{\pi_o} \right) & \text{if } p_{RO,\min} < p_{NF,\min} \end{cases}$$

and for the two-stage RO-NF (2-RO-NF) process, the energy requirements at *tr* is given by **Equation 33**:

$$\text{Equation 33. } (NSEC_{tr})_{2-RO-NF} = \begin{cases} \frac{1}{Y_{RO}} \cdot \left(\frac{p_{RO,\min}}{\pi_o} \right) & \text{if } p_{RO,\min} \geq p_{NF,\min} \\ \frac{1}{Y_{RO}} \cdot \left(\frac{p_{RO,\min}}{\pi_o} + (1 - Y_{RO}) \cdot \left(\frac{p_{NF,\min}}{\pi_o} - \frac{p_{RO,\min}}{\pi_o} \right) \right) & \text{if } p_{RO,\min} < p_{NF,\min} \end{cases}$$

With the implementation of ICD, the first-stage RO and second-stage NF feed pressures are decoupled. Following **Equation 27**, the energy requirements for the 2-RO-NF-ICD process is simply the sum of the energy requirements for the individual first-stage RO and second-stage NF as given by **Equation 34**:

$$\text{Equation 34. } (NSEC_{tr})_{2-RO-NF-ICD} = \frac{1}{Y_{RO}} \cdot \left(\frac{p_{RO,\min}}{\pi_o} + (1 - Y_{RO}) \cdot \frac{p_{NF,\min}}{\pi_o} \right)$$

2.2. Bench Scale Experiments

2.2.1. Design

We developed and tested reconfigurable RO system with a feed capacity of 2.5 gallons per minute (gpm) was developed to operate both in a conventional single-stage RO and a hybrid RO-NF configuration. The system could operate with a single pressure vessel or up to a series of six pressure vessels. Each pressure vessel could accommodate a single 2.5 x 40-inch element). The permeate flow rates from up to two individual pressure vessels could be measured simultaneously. While the system was designed to operate up to 1,000 psig; however, the available brackish water RO and NF membrane elements used in the project had maximum operating pressures of 600 psig. Experiments were conducted over a permeate flux range of 10 to 15 gallons per square foot per day (gfd), water recovery of up to 90 percent, and feed pressure of up to 315 psig.

2.2.2. Source Water

All experiments were conducted using synthetic 3,000 mg/L NaCl solutions, prepared as 100-liter (L) batches by dissolving technical grade NaCl TDS in deionized water inside a large polypropylene tank. This feed solution salinity was selected to mimic the TDS of typical brackish groundwater. A 0.2 micron filter was fitted in the RO system to ensure removal of impurities from the raw feed before entering the RO vessels.

2.2.3. Set Up

The reconfigurable RO system (Figure 8) was composed of two major units: a pretreatment and pumping unit and an RO membrane unit. In some experiments, the system was configured as a conventional single-stage RO system with a feed pump (1-RO) containing 5 RO elements in series (Figure 9). The system was also configured as a hybrid RO-NF system with feed pump delivering inflow to four RO elements in series, followed by 2 NF elements in series (Figure 10). The main RO pump was a positive-displacement plunger Cat Pump Model 351 with a NEMA Premium Efficiency motor, connected to a Baldor VS1MX variable frequency drive to allow feed flow rate control.

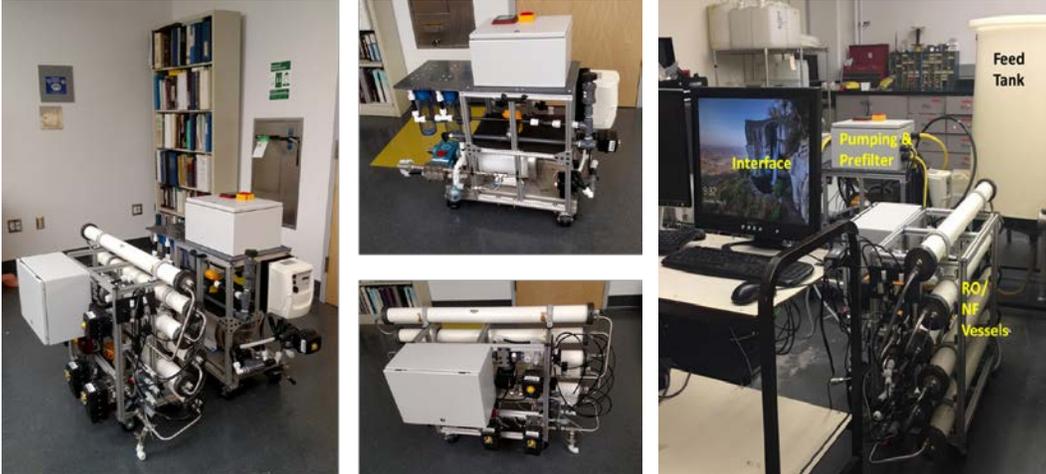


Figure 8.— UCLA mini-mobile-modular (M3v2) system for evaluation of spiral-wound RO/NF membrane-based water desalination.

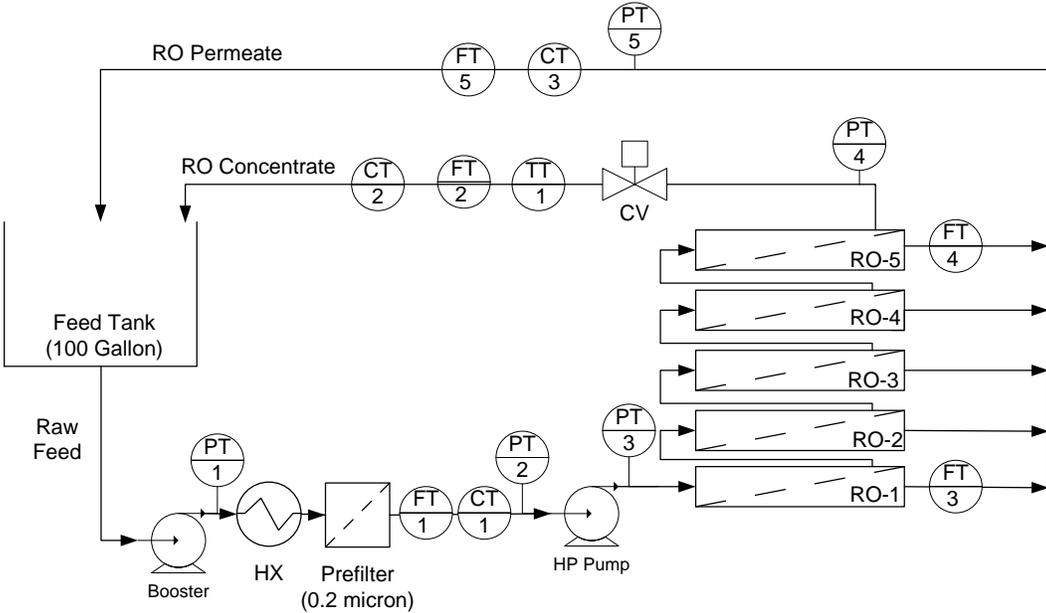


Figure 9.—Process flow diagram of the experimental single-stage conventional RO system (1-RO). HX: Heat exchanger, Sensors: PT- pressure, FT- flow, CT- conductivity, TT- temperature.

To counter the effect of water heating (due to pumping) in the recycle loop, a plate-and-frame heat exchanger (HX) coupled with a water chiller was installed in the raw feed water stream to maintain water temperature at 21 to 22 degrees Celsius ($^{\circ}\text{C}$).

Data acquisition and control were accomplished using National Instruments cRIO-9074 Compact RIO Controller interfaced with a PC.

2.2.4. Bench-Scale Desalination Experiments

We conducted experiments over a range of RO permeate flux (10-15 gfd) for each process configuration (1-RO or 1-RO-NF). Each experiment involved determining the pressure requirements of 1-RO or 1-RO-NF in desalting a 3,000 mg/L TDS feed water over a total recovery (Y_T) range of 40 to 90 percent at a fixed RO permeate flux. Specifically, the system was operated at a successively increasing overall water recovery, starting from about 40 percent and ending at a high level of about 90 percent, while maintaining a constant RO permeate flux. The 90 percent recovery rate was achieved by adjusting the feed flow rate and pressure. At each water recovery, the feed flow rate and pressure were adjusted to maintain a constant flux, and the system was allowed to stabilize for at least 30 minute before pressure, flow rate, and conductivity data were recorded. RO feed flow range was 0.8 to 2.5 gpm, and the RO feed pressure range ranged from 160 to 360 psig.

3. Results and Discussion

3.1. Analytical Process Summary

We used the process models detailed in **Section 2.1** to:

- assess the effect of NF rejection on RO-NF pressure requirements (Equation 15-Equation 19) relative to conventional RO (Equation 13-Equation 14),
- identify the NF rejection that will minimize the pressure requirement (i.e., “pressure-optimal NF rejection”) as per Equation 24,
- assess the theoretical maximum reduction in pressure requirement of RO-NF relative to conventional RO,

- assess the energy requirements of the RO-NF processes (Equation 32-Equation 34) relative to conventional RO (Equation 28-Equation 31) at the pressure-optimal NF rejection (Equation 24), and
- evaluate the effect of NF rejection on the RO-NF energy requirements (Equation 32-Equation 34).

We ran bench-scale experiments, operating both conventional RO and RO-NF at fixed RO permeate fluxes in the range of 10 to 15 gfd. Experimental data for flow, pressure, and conductivity were collected to determine the normalized feed pressure at each RO permeate flux level (10 to 15 gfd). We then compared these data to the minimum required normalized feed pressure predicted by Equation 13 for conventional RO and Equation 15 or Equation 19 for RO-NF. The normalized feed pressure data were used to estimate the energy requirements under an ideal pumping condition (i.e., $\eta_p = 1$) using Equation 35

$$\text{Equation 35. } NSEC = \frac{1}{Y_{RO}} \left(\frac{P_f}{\pi_o} \right)$$

The results were compared to the NSEC at the thermodynamic restriction under the same process operating conditions (NF salt rejection, NF and RO water recovery, and overall water recovery) using Equation 28 and Equation 32.

3.2. Optimal Hybrid RO-NF Systems Can Be Determined

In hybrid RO-NF processes, the RO stage produces water while the NF stage treats the RO concentrate to reduce the volume of concentrate. Because the NF feed will be retreated in the RO process, NF can be operated with higher TDS passage than RO, lowering the concentrate osmotic pressure and thus NF feed pressure requirements.

As there is a high degree of TDS passage through the NF stage, the NF permeate must be recycled to the RO feed to produce water. Recycling the NF permeate to the RO feed dilutes the TDS concentrations in the RO feed, thereby reducing the RO feed osmotic pressure below the raw water osmotic pressure. The amount that the TDS in the RO feed can be reduced by (and thereby the amount that the osmotic pressure can be lowered by) depends on the NF membrane rejection rate. Therefore, the lower the NF TDS rejection rate, the more TDS passes to the NF permeate, which in turn also decreases the osmotic pressure in the NF stage.

Thus, an NF membrane with a higher TDS rejection rate (i.e., lower TDS passage into the permeate) will result in a higher quality NF permeate. Recycling this higher quality permeate into the RO feed lowers the RO feed's osmotic pressure and, in turn, lowers the required minimum RO applied feed pressure. However, higher NF TDS rejection would also increase the trans-membrane osmotic pressure difference—and thus increase the minimum required feed pressure of the NF stage. Therefore, one would expect that an optimal NF TDS rejection rate would generate the lowest minimum pressure requirements for the RO and NF stages in RO-NF processes. Indeed, as shown in Figure 11, estimates for the minimum required pressures for RO and NF stages at overall water recovery levels of $Y_T=53\%$ and $Y_T=95\%$ (assuming equal NF and RO stage recovery, i.e., $Y_{RO}=Y_{NF}$) clearly indicate the existence of a pressure-optimal NF TDS rejection (at 83% for $Y_T = 53\%$ and 68% at $Y_T=95\%$). At this optimal condition, both RO and NF stages in RO-NF processes have the same minimum pressure requirements.

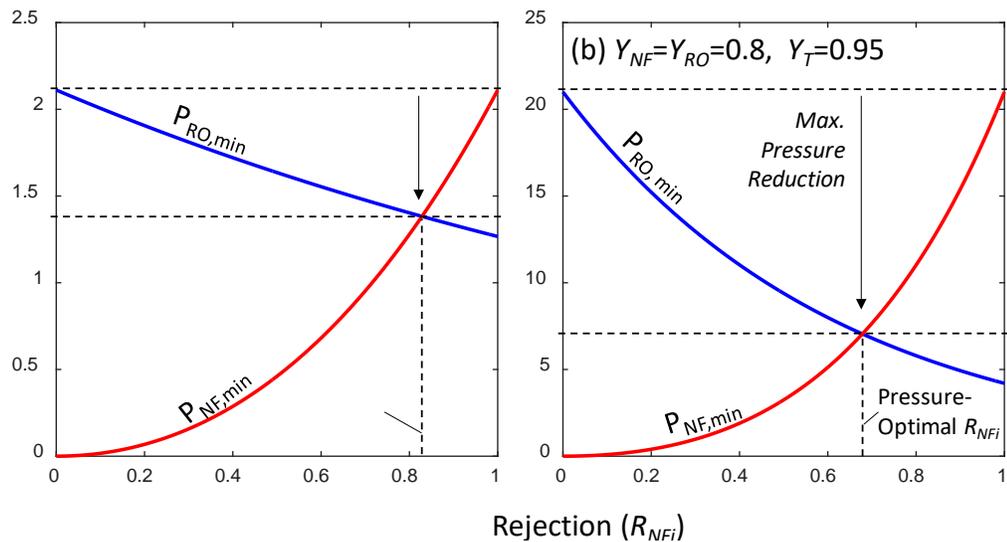


Figure 11.—The dependence of the normalized minimum pressure requirement (i.e., at the crossflow thermodynamic restriction) of RO and NF stages in a hybrid RO-NF process on NF TDS rejection at two illustrative levels of overall water recovery of (a) $Y_T=53\%$ and (b) $Y_T = 95\%$.

3.3. NF Rejection Rates Drive the Optimal Recovery Rates

Per Equation 24 as plotted in Figure 12, the pressure-optimal NF TDS rejection is only a function of the NF water recovery (Y_{NF}), not RO recovery (Y_{RO}), and is related to the overall recovery by Equation 6. As shown in Figure 13, the pressure-optimal NF TDS rejection decreases with increasing overall water recovery.

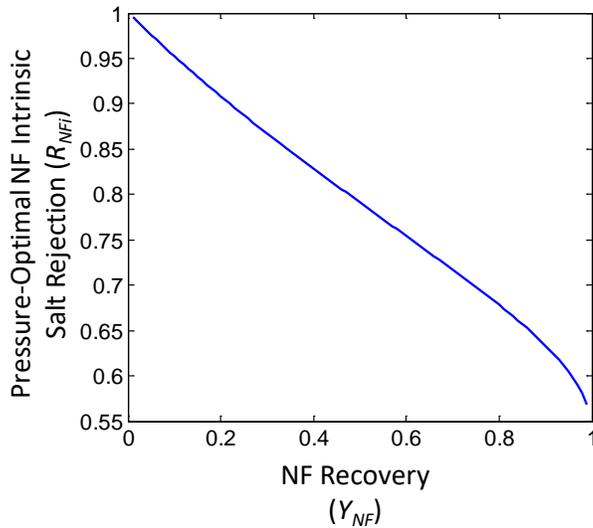


Figure 12.—The pressure optimal NF salt rejection, which would lead to the lowest RO and NF pressure requirements, on the NF stage water recovery for hybrid RO-NF desalting.

The more salt within the feedwater, the later pressure limits will be reached. Using an RO concentrate (which has high salts) with an NF membrane increases water recovery, thereby reducing pressure (and related energy requirements), and lowering the requirements for higher rejections in the NF membrane. For example, at a medium recovery rate (50%), the NF membrane rejection requirements are 83% and the RO membrane pressure requirements are 33% lower in a hybrid RO-NF system than in a conventional RO system (Figure ES-2). Clearly, the NF salt rejection rate is a critical parameter governing the maximum reduction of the optimal (i.e., minimum) pressure requirement of RO-NF processes (see Figure 13).

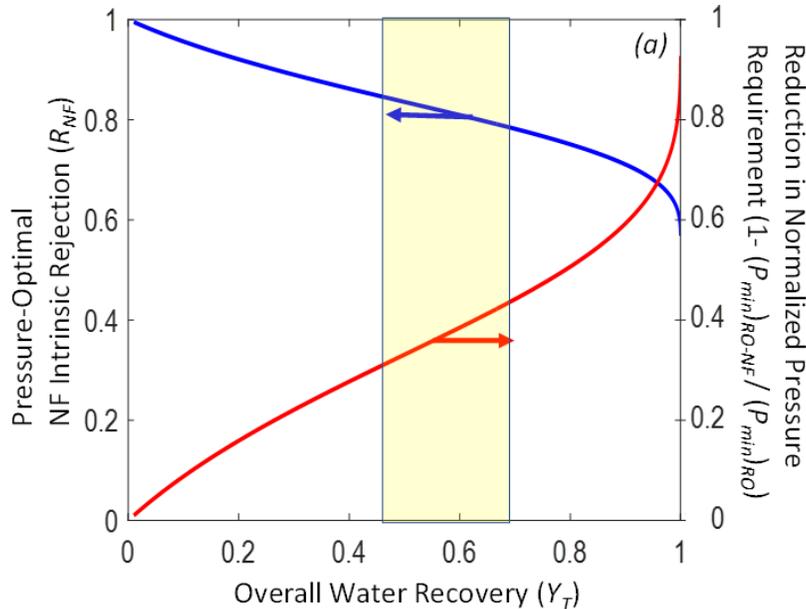


Figure 13.—The NF rejection required to minimize RO/NF pressure (i.e., in a hybrid RO-NF process and the associated reduction in pressure requirement relative to a conventional RO desalting. The yellow box indicates the water recovery range from about 50 to 75 percent.

3.4. Energy Requirements Depend on the NF Rejection Rate

The NF rejection, which governs the minimum pressure requirements of RO-NF processes, also has a significant impact on the energy requirements, expressed as $NSEC_{tr}$. NF rejection is at the optimal pressure when the minimum pressure requirements for RO and NF are equivalent. In other words, as shown in Figure 13 for 1-RO-NF, the pressure-optimal NF rejection is the transition point to change from the RO pressure requirements governing the minimum pressure requirement to the NF rejection requirements. This transition point for 1-RO-NF, is also observed in the energy requirements, as shown in Figure 14a. For 1-RO-NF, the lowest energy requirements for NF rejection (i.e., energy-optimal NF rejection) also occur at the pressure-optimal NF rejection (Figure 14a).

The pressure-optimal and energy-optimal NF rejection levels are similar for both 1-RO-NF with 2-RO-NF configurations (Figure 14a and Figure 14b). However, the pressure-optimal and energy-optimal NF rejection levels for 2-RO-NF-ICD are very different than those for 1-RO-NF and 2-RO-NF. The analysis demonstrates that the 2-RO-NF process configuration has lower energy requirements than other RO-NF processes. The energy requirements for RO-NF processes without ICD are significantly higher than a conventional RO process without ICD, except in the region close to the pressure-optimal NF TDS rejection.

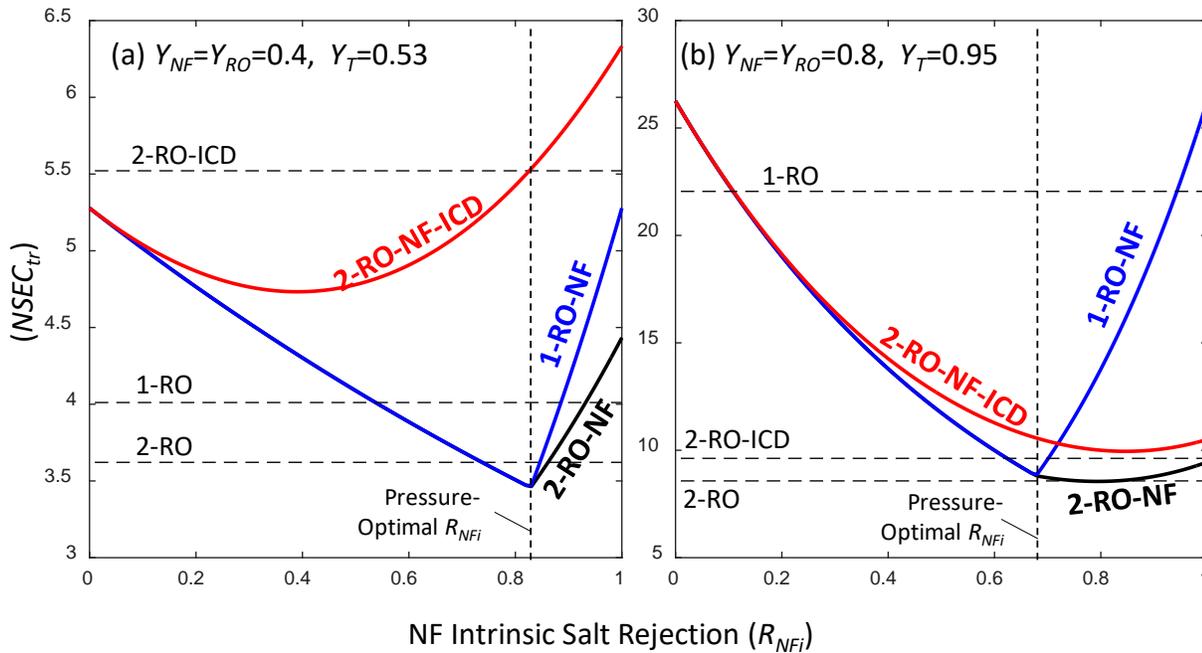


Figure 14.— Energy requirements for NF TDS rejection for three different hybrid RO-NF process configurations at two overall water recovery levels of (a) $Y_T=53\%$ and (b) $Y_T=95\%$. The energy requirements for conventional RO processes (dotted lines) are shown for comparison.

As shown in Figure 15, 1-RO-NF and 2-RO-NF have essentially the same minimum energy requirements and similar or slightly lower energy requirements than 2-RO-NF over a wide range of water recovery rates. This suggests that the inter-stage pump in 2-RO-NF does not lead to lower energy requirements than 1-RO-NF., if operated at the pressure-optimal NF TDS rejection—unlike conventional 2-RO, which does require less energy than a conventional 1-RO stage process. Therefore, for RO-NF processes operated with NF membranes with pressure-optimal rejection rates, there are no significant energy savings for two-stage pumping. Thus single-stage pumping is sufficient (e.g., 1-RO-NF). Adding ICD (e.g., for 2-RO-NF-ICD), the energy requirements are similar to conventional 2-RO-ICD at the pressure-optimal NF TDS rejection rate. However, for 2-RO-NF-ICD, the pressure-optimal TDS rejection rate is not necessarily energy optimal.

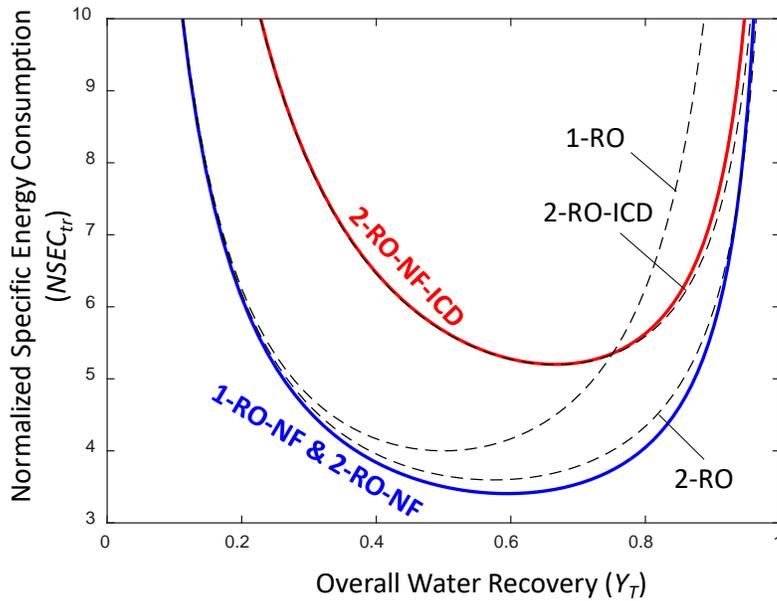


Figure 15.—Energy requirements for three hybrid RO-NF process configurations at pressure-optimal conditions for NF TDS rejection compared to energy requirements for conventional RO processes (dotted lines).

Direct comparisons of the relative energy requirements between RO-NF with conventional RO processes, at the pressure-optimal NF salt rejection rates, over a wide range of total water recovery are given in Figure 16 through Figure 19. Based on these results, it can be concluded that 1-RO-NF is the both the simplest and most energy efficient RO-NF configuration, with energy requirements similar or slightly lower (by <10%) than conventional 2-RO for up to an overall water recovery rate of 94% (Figure 16), at which point the energy requirement grows significantly higher than 2-RO. Using ICD significantly increases energy requirements, but the difference in energy requirements decreases at high recovery rates (Figure 17). The ratio of the normalized specific energy consumption (NSEC) (at the limit of cross-flow thermodynamic restriction) for 2-RO-NF-ICD is about the same as conventional 2-RO-ICD up to about 80% water recovery rates (Figure 18) and only up to 10% higher at 95% water recovery. This trend suggests that 2-RO-NF and conventional 2-RO have similar energy requirements for most practical applications.

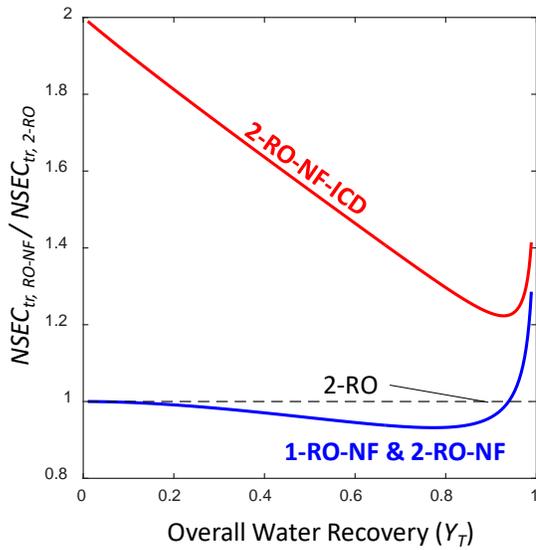


Figure 16.— Energy requirements for hybrid RO-NF processes compared to conventional two-stage RO with ICD (2-RO-ICD.) (dotted line). Conventional 2 stage RO water recovery is shown as a dotted line.

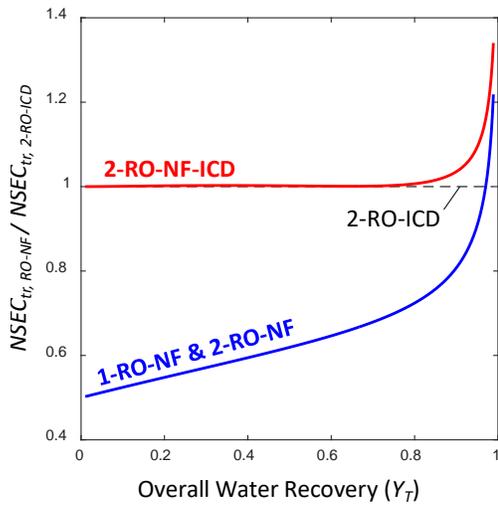


Figure 17.— Energy requirements for the hybrid RO-NF processes compared to conventional two-stage RO with ICD (2 RO-ICD) (dotted line). Conventional 2 stage RO water recovery is shown as a dotted line.

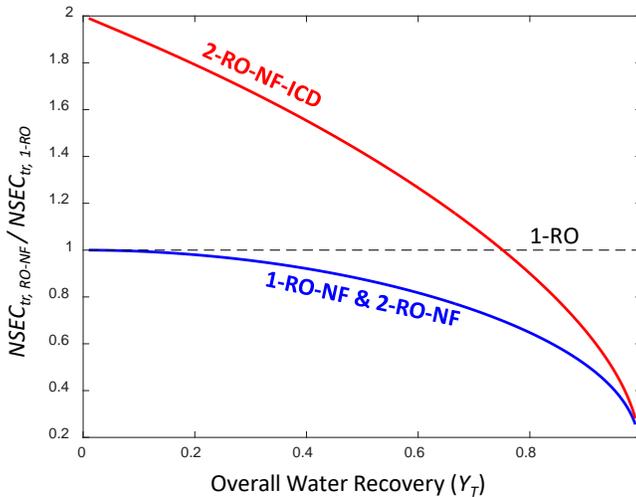


Figure 18.— Energy requirements for hybrid RO-NF processes compared to conventional single-stage RO (dotted line).

The impact of NF salt rejection on the minimum energy requirements for 1-RO-NF, 2-RO-NF, and 2-RO-NF-ICD are shown in Figure 19 through Figure 21. The general trend is that the energy requirements for both 1-RO-NF and 2-RO-NF increase as the NF rejection diminishes to zero (i.e., no salt removal) or is at 100% (i.e., complete salt removal) and are lowest at or near the pressure-optimal NF rejection. It is noted that the case of recycling NF permeate, when NF rejection is zero (i.e., no salt removal by NF), is essentially equivalent to partial RO concentrate recycling. It is noted that for NF rejection of 75%, the energy requirements are within 5% of the pressure-optimal condition. The situation is different for 2-RO-NF-ICD where the pressure- and energy-optimal conditions are not similar with concentrate depressurization and re-pressurization. Nonetheless, operating at or close to the pressure-optimal conditions ensures that the hybrid 2-RO-NF-ICD requires about the same amount of energy as conventional 2-RO-ICD processes.

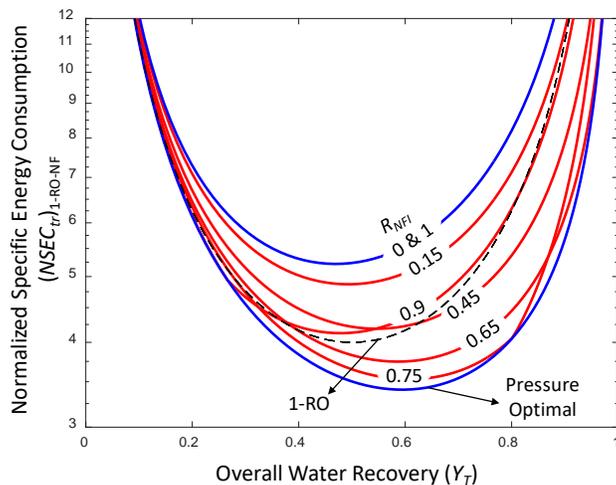


Figure 19.—Effect of NF salt rejection on energy requirements of a 1-RO-NF process as function of overall water recovery.

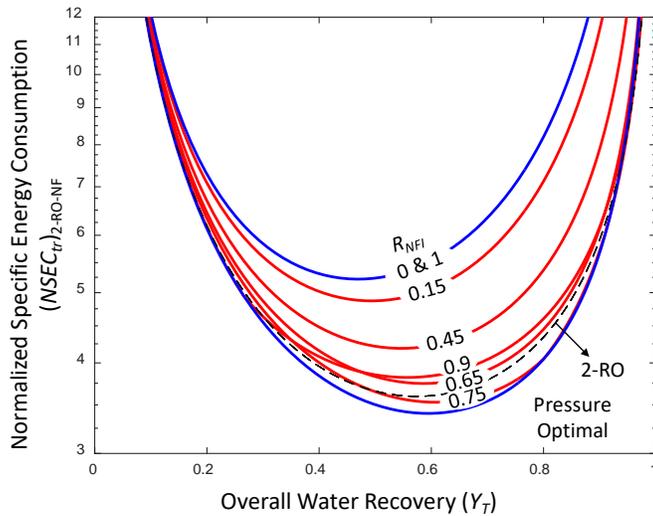


Figure 20.— Effect of NF salt rejection on energy requirements for a 2- RO-NF process as function of overall water recovery.

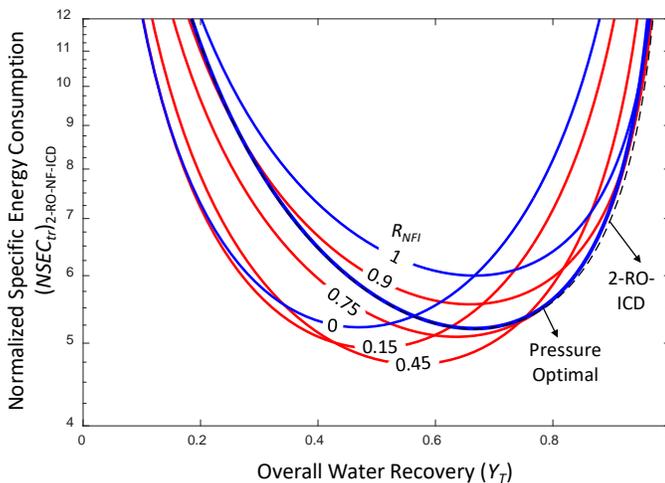


Figure 21.— Effect of NF salt rejection on energy requirements for a two-stage RO-NF process with ICD as function of overall water recovery.

The above analysis indicated that 1-RO-NF provides the simplest yet energy efficient hybrid RO-NF process. Thus, we used a 1-RO-NF system to compared pressure reduction in RO-NF configurations to conventional 1-RO systems. As shown in Figure 22 under the present bench-scale experimental conditions (permeate flux of 10 to 15 gfd, feed flow rate of 0.8 to 2.5 gpm), the pressure-optimal NF TDS rejection rate (for NaCl) ranged from 66 to 85%. The actual NF NaCl rejection of the available commercial NF element was determined to be significantly lower—ranging from 20 to 45%. It was therefore expected that the pressure requirement would be below the optimum. Based on the experimental conditions, it was predicted that the minimum normalized feed pressure requirement (i.e., at the limit of thermodynamic restriction) for the

1-RO-NF process (Figure 23) would be about 5 to 17% lower than 1-RO. Similar reductions of about 5 to 12% was observed for the normalized feed pressure of 1-RO-NF at a permeate flux of 12 to 14 gfd, albeit at much higher normalized pressure. The difference between the normalized feed pressure at 12 to 14 gfd compared to the feed pressure at the thermodynamic restriction appeared to decrease significantly at high recovery. This suggested that, at lower recovery, membrane permeability will have a significant impact on pressure requirements.

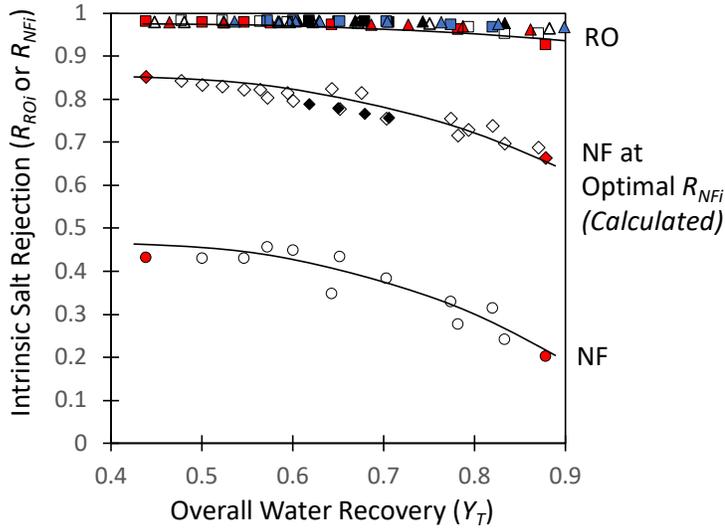


Figure 22.— Salt rejections of RO and NF observed during the experimental runs. The pressure-optimal NF salt rejections were calculated based on the experimental conditions (permeate flux of 10 to 15 gfd, water recovery level of up to 90%, and pressure of up to 315 psig).

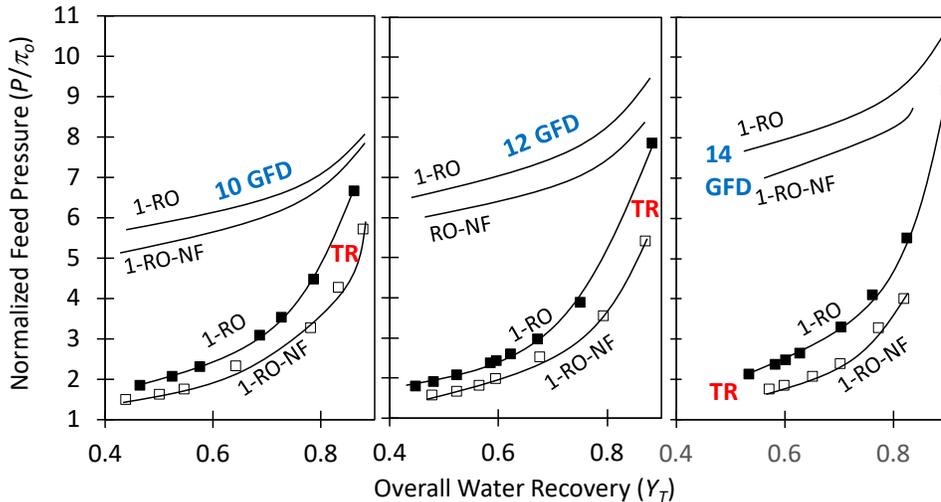


Figure 23.—Experimental data comparing feed pressure requirements of single-stage RO-NF with conventional single-stage RO at various RO permeate flux (10 to 14 gfd) and at thermodynamic restriction (TR). The pressure requirements at thermodynamic restriction (TR) were calculated based on the experimental RO-NF and RO operating conditions (permeate flux of 10 to 15 gfd, water recovery level of up to 90%, and pressure of up to 315 psig).

RO-NF operations at the limit of thermodynamic restriction are predicted and revealed at the tested experimental conditions to have slightly higher energy requirements than 1-RO (Figure 24). The experimental NSEC for 1-RO-NF at RO permeate flux 12 to 14 gfd, however, was greater than predicted at 20 to 60% higher than for the 1-RO process. This trend is attributed to the lower RO recovery per pass in 1-RO-NF (i.e., given $Y_{RO} < Y_T$) than in 1-RO (i.e., where $Y_{RO} = Y_T$). This behavior is not surprising given the NF permeate recycling to the RO feed, coupled with suboptimal NF TDS rejection (i.e., with respect to the NF rejection needed for lowering the required NF pressure). Nonetheless, the general trends revealed by the SEC data, at various fixed permeate flux (10-15 gfd) and at thermodynamic limit, are consistent with observations regarding the performance of the 1-RO configuration as in the present and previous studies (Zhu et al. 2009 [Thermodynamic restriction] and Zhu 2010).

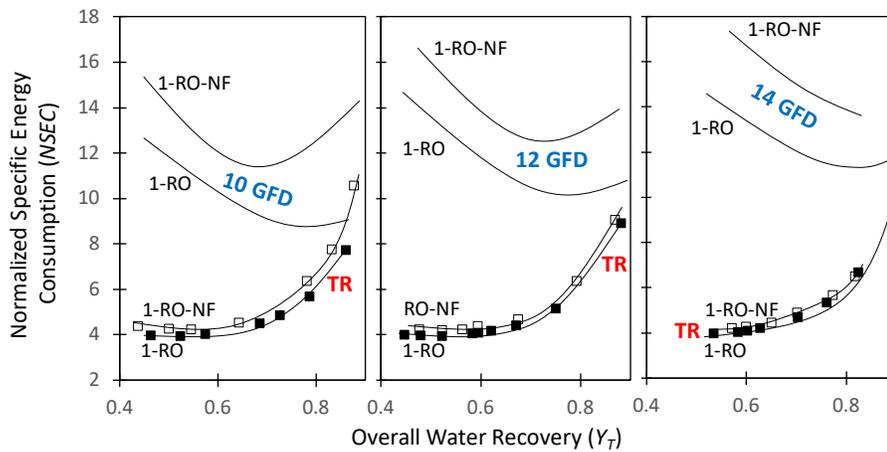


Figure 24.— Experimental energy requirements for RO separation for a single-stage RO-NF with conventional single-stage RO for permeate flux in the range of 10 to 14 gfd at thermodynamic restriction (TR). Energy requirements at TR were calculated based on the experimental operating conditions (permeate flux of 10 to 15 gfd, water recovery level of up to 90%, and pressure of up to 315 psig).

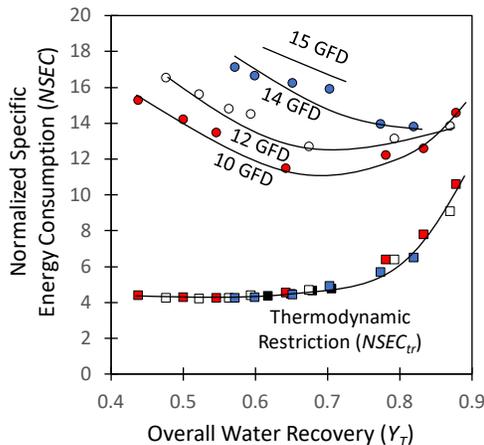


Figure 25.— Energy requirements for a single-stage hybrid RO-NF process at various RO permeate flux compared to the calculated energy requirements at the crossflow thermodynamic restriction (TR).

4. Conclusions and Next Steps

4.1. Conclusions

1-RO-NF provides the simplest yet most energy efficient RO-NF process relative to conventional RO. A theoretical proof-of-concept demonstrated that a single-stage RO-NF (1-RO-NF) process (i.e., without an inter-stage ICD pump or energy recovery device) can have significantly lower operating pressure requirements—about 33 to 65% less than a conventional single-stage RO process over an overall water recovery rate ranging from 50 to 95% (Figure 26). Experimental data confirmed that the RO-NF process could still have lower pressure requirements than conventional RO, even under suboptimal conditions.

We found that optimal NF rejection levels can maximize reducing operating pressure (i.e., the pressure-optimal NF rejection). The minimum energy requirements are relatively close (within 8%) to a conventional two-stage RO (2-RO) with intermediate pump up to an overall water recovery of 94%.

We demonstrated that the pressure and related energy requirements for hybrid RO-NF processes are highly dependent on the NF TDS rejection and that optimal NF rejection levels exist that minimizes pressure requirements (i.e., “pressure-optimal NF rejection”) and energy requirements (i.e., “energy-optimal NF rejection”). For operation at pressure-optimal conditions, the pressure and associated energy requirements for the hybrid 1-RO-NF are nearly identical to the hybrid 2-RO-NF, indicating that there is no significant benefit for having an inter-stage pump in RO-NF processes. Guidelines for selection of the target NF TDS rejection are given in Table 1.

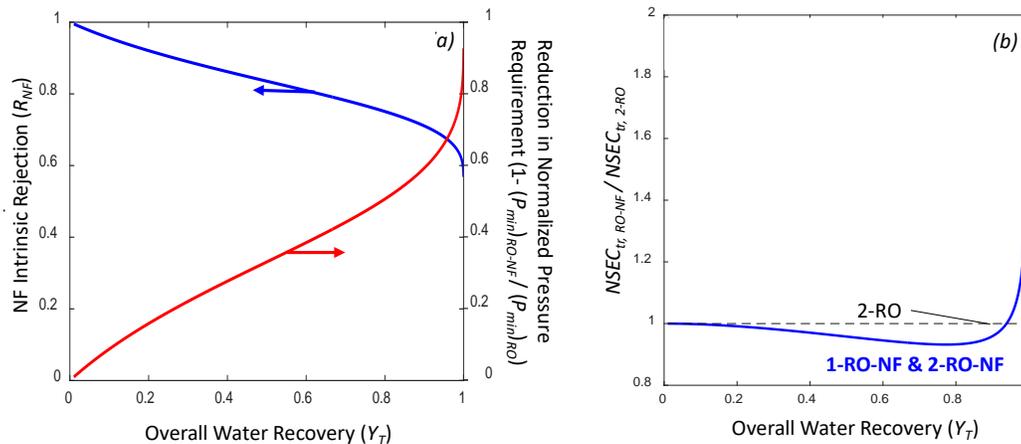


Figure 26.—(a) RO-NF processes with pressure-optimal NF salt rejection significantly reduce pressure requirements while (b) using similar energy levels as conventional two-stage RO up to a water recovery rate of around 24%.

Table 1.— Recommended pressure-optimal NF membrane salt rejection in RO-NF processes at various overall water recovery ranges.

Overall Recovery Range (Y_T)	Recommended NF Rejection*
15-30%	91%
30-50%	86%
50-75%	80%
75-85%	75%
85-95%	71%

* Calculated $Y_{RO} \approx Y_{NF}$

4.2. Recommended Next Steps

Recommendations include:

- **Consider a range of feedwater qualities.** Provide models and bench-scale testing with feedwater with different ionic compositions. NF membranes have different rejection rates for monovalent and divalent ions.
- **Consider dynamic, variable feedwater qualities.** Provide modeling and bench-scale tests for dynamic source waters. Systems that have feedwater quality that varies over time (e.g., seasonally) require real-time adjustments for optimizing recoveries, operating pressures, and rejection rates.
- **Examine scaling.** Note that membrane mineral scaling is also a concern, and can be overcome via antiscalant chemical addition, as well as integrating ICD technologies to remove mineral scale precursors from primary RO concentrate. While we investigated ICD technology, this was not a primary focus of this research project.

- **Investigate life cycle costs** at a pilot scale with a wide range of water chemistries.
- **Explore NF membranes with higher rejection rates.** This bench-scale project used NF membranes that did not reach the target values for rejection needed to attain the pressure-optimal levels. The hybrid approach could be further explored to characterize 1-RO-NF with NF TDS rejection that is at or approaching the target value and map the range of possible pressure reductions in high recovery desalination compared to a conventional RO system (see Table 1).
- **Explore the hybrid system at high recovery rates.** The 1-RO-NF could be used in further experimental operations at high water recovery rates to assess the potential for reducing operating pressures below the operating pressures in a conventional RO system for treating water high in TDS.
- **Assess the impact of pump efficiency and potential energy recovery devices.** Assessing energy use over the range of pump capacities is needed to determine the practical range of desalination capacities. Explore the potential utility of energy recovery devices and the impact of both energy recovery devices and pump efficiencies for 1-RO-NF operation at low recovery (<50%) or with concentrate depressurization-re-pressurization when using the ICD.

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