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Desalination of Impaired Water Using Geothermal Energy

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ABSTRACT

Membrane distillation (MD) and nanofiltration (NF) are explored as a means to provide high quality water for on-site use at the Tuscarora geothermal power plant in northern Nevada. The plant uses a wet cooling tower, but decreasing flow from the wells providing makeup water necessitates exploration for alternative water or alternative cooling sources. Scenarios are explored to extend cooling water by (1) extracting fresh water from the geothermal brine, (2) upgrading the makeup-water quality to allow for increased cycles of concentration in the cooling tower, or (3) recovering water from the cooling tower blowdown. The preliminary cost analysis indicates that applying NF to extract water from the injection brine is the most attractive option of the scenarios examined. This approach may be useful for other plants as well.

The estimated cost for the NF treatment of the injection brine ranges from $0.63/m^3 to $0.45/m^3 and provides a reduction in the current makeup well flows of 35% to 71%. Savings from the reduction in makeup well pumping and chemical treatment do not fully offset the estimated cost of the proposed treatment systems; the site will have to weigh the cost of these water treatment options versus alternatives in light of the diminishing flows from the existing cooling-water wells. Testing is planned to quantify the performance of the proposed NF and MD technologies and help refine the estimated system costs.

1. Introduction

The National Renewable Energy Laboratory (NREL) leads a multi-disciplinary team that is exploring the use of geothermal energy for water desalination. This three-year project, funded under the U.S. Department of Energy's Geothermal Technologies Office, began in October 2015.

The project team members and roles are shown in Table 1. The project focuses on use of excess or unused thermal energy from existing geothermal power plants for desalination. Typical injection temperature of outlet brine from a geothermal power plant is around 75 °C, which is an excellent temperature match for membrane distillation (MD) if a fraction of that heat can be extracted. Analysis during 2016 established that using geothermal heat from the injection brine of existing geothermal power plants is the most cost-efficient way of accessing low-grade geothermal heat since exploration and well-development efforts have been completed [Akar & Turchi, 2016].

Table 1. Project team members and roles

Organization	Project role
NREL	Project management; techno-economic analysis; opportunity assessment; field testing
Colorado School of Mines	Water characterization; pretreatment and treatment design; field testing
Ormat Technologies	Site host and support
University of California at Riverside	Membrane optimization
Sandia National Labs	MD performance modeling
GE Power and Water	Membrane and system assistance

The site for the project is Ormat's Tuscarora Geothermal Power Plant, located in Elko County, Nevada approximately 60 miles north of Elko in Independence Valley. The plant has an 18 $MW_{e,net}$ (24 MW_{gross}) electric generating capacity. The Tuscarora facility has three production wells, each approximately 4,500-5,000 feet (1,400-1,500 m) deep, with a combined total brine flowrate of 3,127 klb/hr (393.5 kg/s). The geothermal fluid is carried to the power plant facility as liquid brine with 192 psia (13.2 bar) line pressure and 345 °F (174 °C) temperature. Four injection wells inject geothermal fluids back into the reservoir. An additional well is used to inject cooling tower blowdown water into the geothermal reservoir (i.e., not the groundwater aquifer).

Makeup water demand for the cooling tower averages about 1200 gpm (75 kg/s). At present the cooling tower operates at about 2.7 concentration cycles; that is, concentration of dissolved solids in blowdown water is approximately 2.7 times higher than the fresh makeup water. There are two fresh water wells to supply makeup water for the cooling tower. Two wells provide redundancy so that if maintenance is required on one the other is available to supply the necessary water. Also, during periods of high temperature and low humidity, it may be necessary for both wells to be pumped for a short time to meet the demand for cooling water. Water demand varies from season to season with peak demand of up to 1,500 gpm in the summer with an average use of 1,100 gpm in the winter. Flow from these wells has been diminishing, which spurred interest in water reduction/recovery at the site.

In February 2016 the team visited the plant site to collect water samples from the geothermal injection brine, makeup water, and blowdown water from the cooling tower. While on site the team acquired basic system parameters for geothermal production and injection and located potential sites for the treatment/desalination unit during the planned test period. The water samples were subsequently analyzed to characterize water chemistry, scaling potential and minimum injection temperature.

2. Site Water Characteristics

A summary of temperature, pressure and flow rate information for Tuscarora is presented in Table 2. Major anions and cations, total dissolved solids (TDS), total organic carbon (TOC), alkalinity, conductivity and pH values were analyzed from the injection brine, makeup water, and blowdown water samples from Tuscarora. The analysis results for primary anions are presented in Table 3. The geothermal brine TDS is fairly low and would be considered brackish for water desalination. As such, NF or reverse osmosis (RO) would be the likely desalination method of choice. Application of thermal desalination methods at the plant site would be most effective as a polishing step after RO to provide additional water recovery or reduce brine disposal volume. The temperature of the injection brine (74 °C) exceeds that for feedwater in normal RO/NF systems (typically < 45 °C), and the testing explores the potential of "hot NF" at approximately 74 °C as means for extracting fresh water from the injection brine.

Table 2. Production and injection flow parameters at Tuscarora

Tuscarora	Units	Geothermal Brine		Cooling Tower			
		Supply to Plant	Discharge from Plant	Makeup Supply	Water Supply	Water Return	Blow down
Volumetric Flow	gpm	7000	6400	1200	66,000	66,000	450
Mass Flow Rate	klb/hr	3127	3127	600	33,000	33,000	225
Mass Flow Rate	kg/s	394	394	76	4159	4159	28
Pressure	psia	191	158	15	36.5	23.3	481
Temperature	°F	345	165	68	58.7	73.7	73.7
Temperature	°C	174	74	20	15	24	24

Table 3. Geochemistry analysis results of makeup water, blowdown water and injection brine from Tuscarora from samples acquired in February 2016.

Parameter	Unit	Makeup	Injection Brine	Blowdown
pH	-	6.64	6.59	7.30
Conductivity	µS	188	801	1,194
Alkalinity as $CaCO_3$	mg/L	84	260	38
TDS	mg/L	276	696	969
SiO_2	mg/L	90	220	220
TOC	mg/L	0.23	0.52	4.66
Primary Anions				
Chloride	mg/L	8.3	19.9	49.0
Nitrate	mg/L	3.6	< 0.1	15.0
Sulfate	mg/L	12.4	50.1	439
Primary Cations				
Calcium	mg/L	9.6	3.0	37.9
Potassium	mg/L	8.9	15.4	36.6
Magnesium	mg/L	2.4	0.04	9.3
Sodium	mg/L	23.5	127.8	110.6
Sulfur	mg/L	4.4	29.6	124.0
Silicon	mg/L	40.2	94.8	82.8

The injection brine stream is a potential heat source for thermal desalination at geothermal plant sites. However, extracting a portion of this heat (or extracting a portion of fresh water) creates concern for scaling due to decreasing temperature or increasing salt concentration in the injection brine. The scaling potential and the minimum injection temperature are determined by the chemistry of geothermal brine. The chemistry of brine varies and depends on several factors including the geology of the resource, temperature, pressure, and water source. Common forms of scaling found or anticipated at Tuscarora are calcite and silica scaling due to the presence of carbonate ion (CO_3^{2-}) and SiO_2, respectively. Other potential scaling problems can arise from the presence of iron sulfates, iron oxides, clays and other silicates. The team analyzed scaling tendencies and scaling indices of the injection brine for Tuscarora using OLI and Watch 2.4 software (Figure 1).

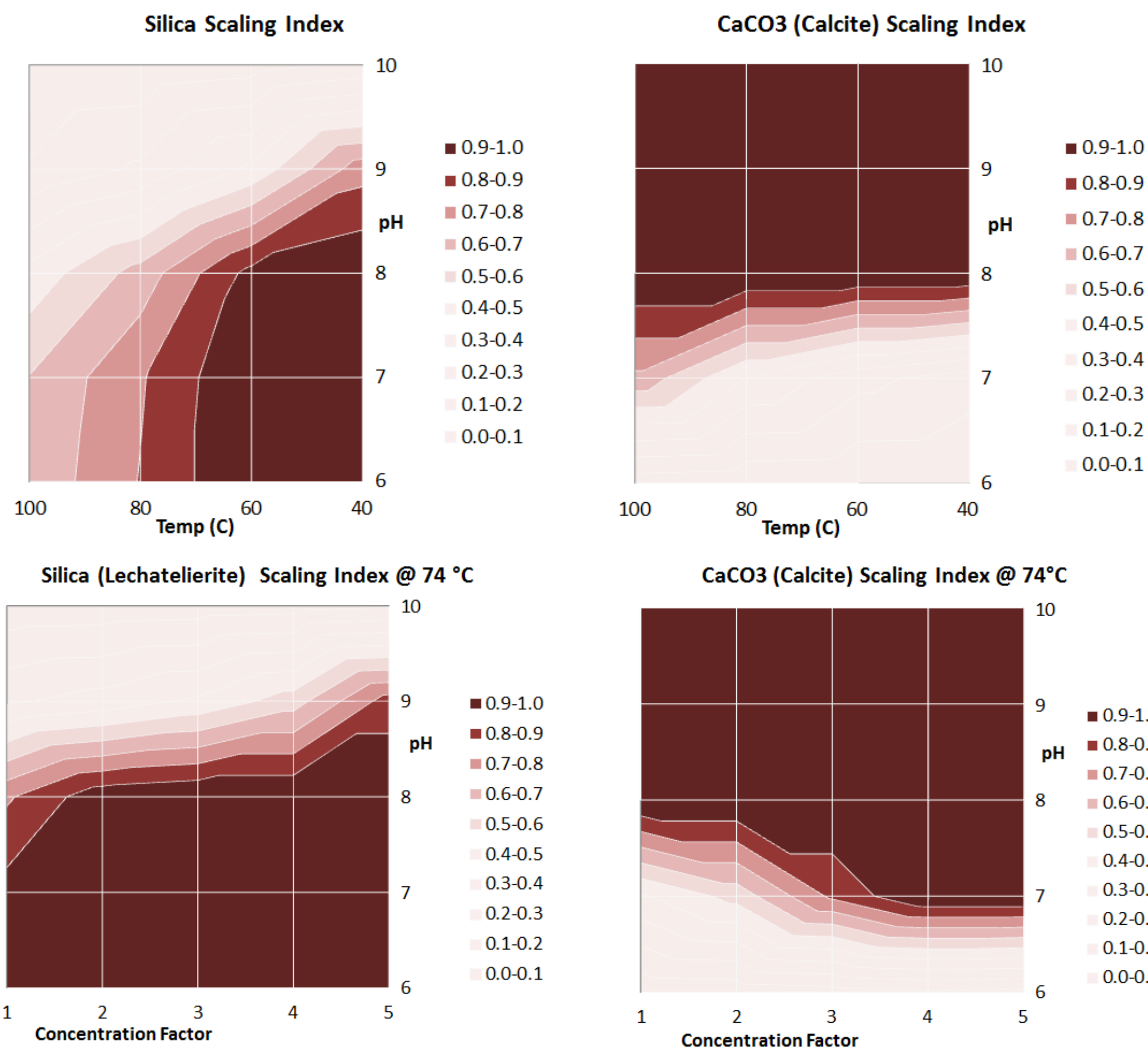

Figure 1. Scaling tendency indices for silica (left column) and calcite (right column) for the injection brine at Tuscarora as a function of temperature (top row) or concentration factor (bottom row). Existing conditions: T = 74 °C, pH = 6.6, Conc. factor = 1. Scaling potential increases as the index approaches unity. (OLI Software)

Scaling tendency estimates from both software packages provided similar results. The analysis suggests that the primary scaling concern as the injection brine temperature is lowered or concentration is increased (due to water extraction) is from silica. The results further suggest that lowering the injection brine temperature below about 70 °C or concentrating the brine could lead to silica scale concerns.

3. Laboratory Testing of Membranes

3.1 MD Membranes

Membrane testing was carried out at the Colorado School of Mines with candidate MD membranes from the following vendors:

- 3M (St. Paul, MN),
- Aquastill (Sittard, Netherlands),
- Celgard (Charlotte, NC),
- CLARCOR Industrial Air (Overland Park, KS),
- GE Osmonics Corporation (Hopkins, MN) and
- Pall Corporation (Port Washington, NY).

Aquastill and CLARCOR are the only companies that market their membranes specifically for MD applications. The membrane material and properties as reported by the manufacturer are summarized in Table 4. Most of the active-layer materials considered for MD are represented. Ethylene chlorotrifluoroethylene is a novel material developed by 3M. Membrane properties varied significantly: pore size ranged from 0.05 to 0.79 micron, thickness ranged from 25 to 305 micron, and porosity ranged from 41 to 85%.

The membranes were tested in a modified Sepa acrylic flow cell (Sterlitech, Corp.) having a membrane area of 136 cm^2 and flow channel dimensions of 145-mm long, 94-mm wide, and 2.5-mm deep. The same diamond spacer was used in the feed and distillate channel. This spacer had a hydrodynamic angle of 70°, a filament diameter of 2.3 mm and a mesh width of 10.8 mm. Feed and distillate temperature were set to 60 °C and 20 °C, respectively. Equal flow rates of 1.6 L/min, corresponding to an average channel velocity of 13 cm/s, were set for feed and distillate. Because of the similar channel geometry, flow velocity and spacer, the pressure drop along the distillate and feed channels should be very similar. As a result, co-current operation was preferred, to assure a similar pressure differential along the membrane. NaCl was added to the feed solution to allow for checking membrane integrity and calculating rejection. Three liters of 1 g/L NaCl was used for the feed, and three liters of deionized water for the distillate.

Membrane performance was measured for flux and thermal efficiency. Thermal efficiency is the ratio of the convective heat transfer to the total convective and conductive heat transfer through the membrane and is an important metric for MD systems. A thermal efficiency of unity (i.e., vapor convection but no conduction) would be the ideal case for an MD membrane. There should be a strong correlation between the water flux and the thermal efficiency.

Table 4. Membrane characteristics as provided by the manufacturers

Manufacturer	Model Number	Active layer	Support Material	Nominal Pore Size (µm)	Thickness (µm)	Porosity (%)
3M	0.2 micron	PP	No	0.59 [2]	110	85
	0.45 micron	PP	No	0.79 [2]	110	85
	ECTFE	ECTFE	No	0.43 [2]	46	67
Aquastill	0.3 micron	PE	No	0.3	76	85
Celgard	2400	PP	No	0.043	25	41
	2500	PP	No	0.064	25	55
CLARCOR	QL218	ePTFE	PP	0.45	254-305	70-85 [1]
	QL822	ePTFE	PP	0.45	127-203	70-85 [1]
	QP952	ePTFE	P	0.45	150-300	70-85 [1]
	QP955	ePTFE	P	0.1	127-305	70-85 [1]
	QP961	Oleophobic ePTFE	P	0.05	76-203	70-85 [1]
	QM902	ePTFE	No	0.45	-	70-85 [1]
Osmonics Corp.	PP22	PP	No	0.22	150	70
	TS22	PTFE	PP	0.22	175	70
	PVDF	PVDF	No	0.4	160	-
Pall Corp.	0.2 micron	PTFE	LDA[3]	0.2	179-246	-
	0.45 micron	PTFE	LDA[3]	0.45	191-257	-

P: polyester; PP: polypropylene; PE: Polyethylene; ECTFE: ethylene chlorotrifluoroethylene; PVDF: polyvinylidene difluoride; ePTFE: elongated polytetrafluoroethylene

[1] Estimate of manufacturer; [2] Bubble Point Pore Diameter; [3] non-woven polypropylene

Figure 2 summarizes the results for thermal efficiency and water flux for the tested membranes; desirable membranes fall in the upper right corner of the plot. The 3M membranes and the CLARCOR QM902 membrane exhibited the highest fluxes and demonstrated the highest thermal efficiencies at well over 50%. The 3M ECTFE had the highest thermal efficiency of 59.5%, almost tenfold better than the lowest performing membrane. An examination of the membrane property data indicates that flux and thermal efficiency correlate positively with nominal pore size and porosity. The relationship with membrane thickness is biased by the thin Celgard membranes having poor performance, while the other membranes show an inverse relationship between flux and thickness, as one might suspect.

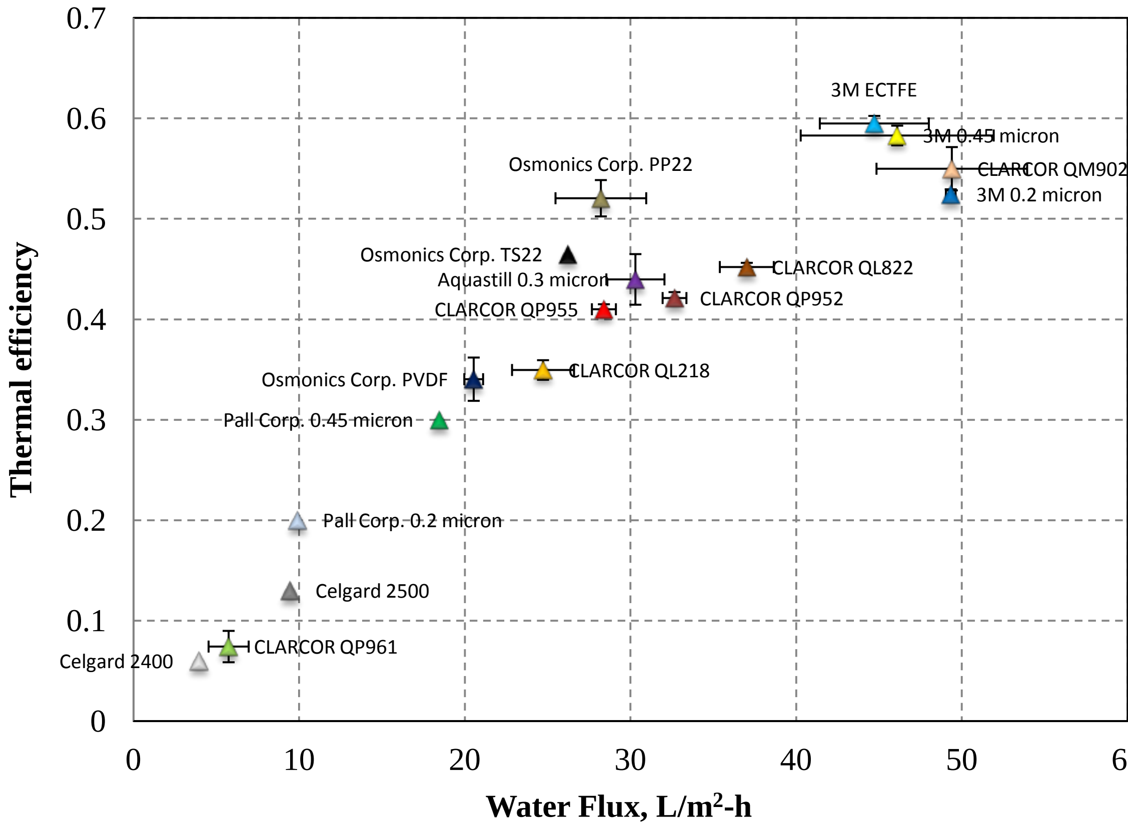

Figure 2. Thermal efficiency versus water flux for the different membranes. Feed and distillate temperature of 60 and 20 °C respectively. Feed and distillate flow rate of 1.6 LPM. Feed concentration of 1 g/L NaCl. Standard deviation is based on three different samples.

3.2 NF Membranes

In addition to the analysis and selection of MD membranes, the team examined NF membranes that would be applicable as pretreatment to protect the MD system from silica scaling or potentially as primary treatment. Aside from equilibria constraints, silica scaling can be kinetically prevented if the time spent in the treatment system is less than the induction time for silica colloid formation. An advantage of NF compared to MD is that evaporation is not required and much higher single-pass water recoveries can be obtained. As a result, silica can be rejected and concentrated much more with NF without scaling the membrane because the time spent in the system for single pass is only seconds, which is typically smaller than the induction time for silica colloid formation (minutes to several hours).

An ideal NF membrane for this application would have high water flux and high silica and TDS rejection. Four different membranes were tested for this application: GE's NFDK and ROSE, and Dow-Filmtec's NF245 and NF90. NFDK and NF245 are typical NF membranes. ROSE is a high-temperature reverse osmosis membrane and NF90 is a very tight NF membrane, almost comparable to an RO membrane. All membranes were pre-compacted with a 2000 mg/L NaCl solution at 300 psi (20 bar) for four hours to assure stable operation. Subsequently, the membranes were tested at 150 psi (10 bar) to match the pressure of the injection brine.

Membranes were tested at 90 mg/L SiO_2 at 20 °C to simulate the makeup water and 220 mg/L SiO_2 at 74 °C to simulate the injection brine. Test solutions start from Na_2SiO_3. These solutions have very high pH and are adjusted to the target pH with HCl, resulting in a residual concentration of NaCl that can be used to monitor salt rejection via solution conductivity measurements. The NaCl concentration will be two times the molarity of SiO_2 concentration, which for 90 mg/L silica is 3 mM NaCl and for 220 mg/L silica is 7.3 mM NaCl. From Figure 3 (left) it is clear that the NFDK and NF245 membranes have significantly higher water fluxes than the RO or NF90 membranes, as expected. NaCl salt rejection is lower, but deemed to be acceptable for this application (Figure 3, right).

Rejection of silica was relatively low for the NFDK and NF245 membranes (less than 20%) while the NF90 and RO membranes demonstrated high levels of silica rejection (Figure 4). Overall, the NF90 had the best combination of silica rejection and water flux. For the NF90 membrane, the increase in temperature from 20 °C to 74 °C increased the water flux by up to a factor of three (Figure 3) despite the higher silica level with little detrimental impact to silica rejection (Figure 4).

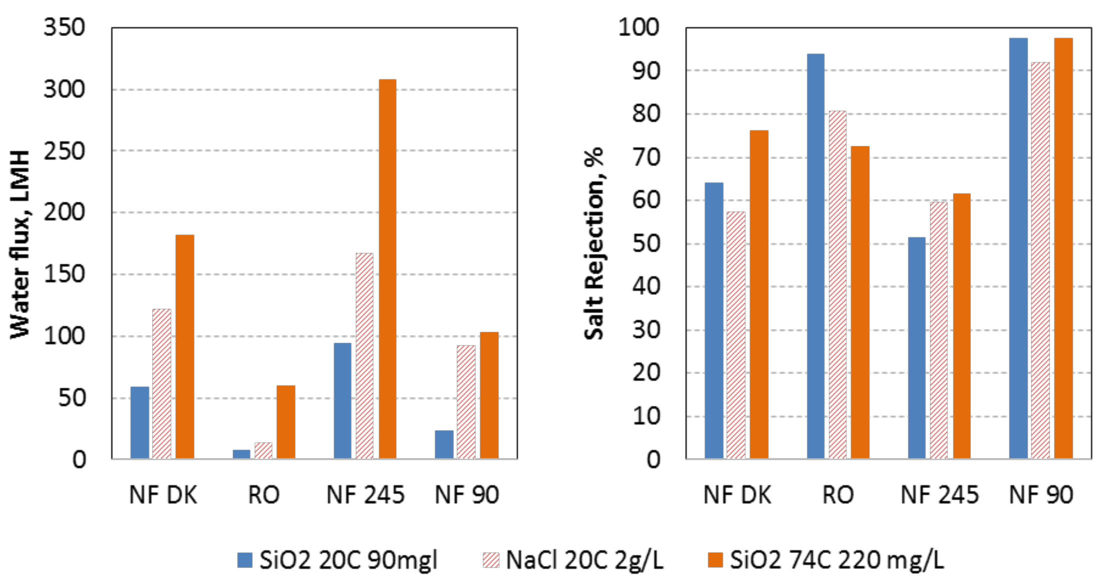

Figure 3. Water flux (left) and NaCl rejection (right) for NaCl solution and two silica/NaCl solutions at two different temperatures. Tests run at 150 psi to match the injection brine pressure. The NaCl pre-compaction test was operated at 300 psi. Cross flow was 1 LPM and membrane area 139 cm^2.

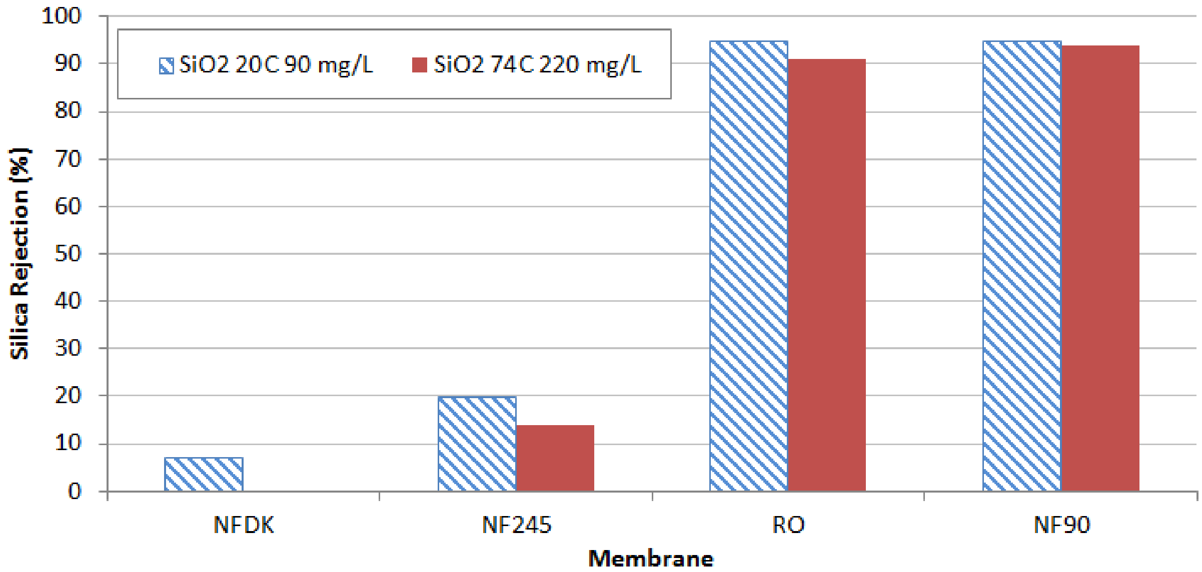

Figure 4. Silica rejection for simulated Tuscarora makeup water (blue stripes) and Tuscarora injection brine (red bars). Tests run at 150 psi to match the injection brine pressure. The NaCl pre-compaction test was operated at 300 psi. Cross flow was 1 LPM and membrane area 139 cm^2.

Based on the above, NF90 was identified as the best membrane in terms of water flux and silica rejection. However, NF90 is not available in high-temperature spiral wound elements. Based on its composition, the membrane itself should resist the temperature (as evidenced by its silica rejection at high temperature, Figure 4). According to the manufacturer, the limitation lies in the materials and the glue of the membrane module, which are only rated to 45 °C.

For RO and NF membranes the effect of temperature and pressure stress are related [Valentin 2010] and reducing the pressure can allow a membrane to run effectively at higher temperature. The NF90 elements are rated up to 600 psi (approx. 41 bar). Given that the pressure of the injection brine is only 150 psi (10 bar), it is anticipated the element could withstand the higher temperatures at Tuscarora. This will be evaluated in future testing. Ultimately, the core membrane could be packaged in a module that is rated to the higher temperature.

The temperature stability of the existing NF90 product was tested under laboratory conditions by subjecting it to increasing temperatures from 40 °C to 70 °C. After 10 h of operation at each temperature, an integrity test was performed at 40 °C. The water flux after operation at 60 °C dropped 25% compared to 50 °C, but remained stable after testing at 70 °C. The salt rejection increased slightly after 60 °C, which indicates that the membrane was slightly compacted by the high temperature, but it remained functional. Single-element water recoveries of over 50% were obtained at high temperatures. This means three elements in series could achieve 90% water recovery.

3.3 Membrane Selection Conclusions

The team reviewed and tested 17 different membranes believed to be suitable for the proposed MD field test. This list included at least one representative of the different types of membranes that have been proposed for MD systems. The membranes were evaluated based on water flux, thermal efficiency, salt rejection, and cost. Almost all the membranes rated highly for salt rejection, with 15 of 17 membranes showing rejection levels greater than 99.8%. Based on flux and thermal efficiency, the best performing membranes were CLARCOR's QM902 and three offerings from 3M: denoted as 0.2 micron, 0.45 micron, and ECTFE. None of these membranes uses a backing for support, which is one reason they perform well in flux tests; however, this design comes at the expense of physical toughness and unsupported membranes tend to be less robust. The highest rated membrane with a support was CLARCOR's QL822.

Price was more difficult to assess, as the vendors were reluctant to provide specific quotes. Prices in the range of \$50 to \$100 per m^2 are expected based on the data that were received and prior experience. 3M indicated their ECTFE membrane is approximately twice the cost of their 0.2 micron membrane. Based on the combination of flux and thermal performance, cost, and expected durability, the team selected 3M's 0.2 micron, Aquastill's 0.3 micron and CLARCOR's QL822 as the primary candidates. The 3M product was chosen as the preferred material and a sample was shipped to Aquastill for evaluation of fabrication into spiral-wound modules.

The team selected Dow-Filmtec's NF90 nanofiltration membrane for pretreatment of the incoming makeup water and injection brine streams at Tuscarora. This membrane will be subjected to high operating temperatures when used on the injection brine. We believe the NF90 will be suitable at the 74 °C injection brine temperature because the system pressure is much lower than the element's rated value of 600 psi. Comparison with a Wagner diagram [Valentin, 2010] and limited-duration laboratory testing supports this assertion.

4. System Configurations

Analysis of the conditions at Tuscarora led to proposed system configurations that include NF with or without an MD stage, as well as an MD-only design. In the first option (Figure 5), the geothermal injection brine passes through an NF unit (NF-1) that rejects a high percentage of large ions and compounds such as silica, sulfates, and phosphates. A high percentage of smaller ions such as chlorides will pass through the NF system; however, the water composition at Tuscarora is dominated by silica and sulfate species such that the permeate will have low TDS. Based on the manufacturer's performance software (DOW ROSA version 9) and laboratory testing we anticipate NF-1 will be able to reduce the TDS of the injection brine from approximately 700 to less than 20 ppm. This reduction would produce permeate water with lower TDS than the current makeup water and allow for higher cycles of concentration in the cooling tower. However, the permeate from NF-1 will be hot (~74 °C) and cooling will be necessary. The configuration in Figure 5 shows a fin-fan air-cooler. Intermittent operation could allow the system to operate only during periods of low ambient temperature (e.g., overnight) thus allowing for a smaller air cooler.

The second option is NF-treatment of the makeup water to remove silica and allow for higher cycles in the cooling tower. This configuration is shown in Figure 5 as NF-2. In this scenario NF-2 runs at high recovery (85%) to produce a very low TDS stream for the cooling tower and a reject stream that is high in silica and other solids. Figure 5 shows an optional silica recovery process [Bourcier et al., 2009]. An MD-only configuration (Figure 6) assumes heat from the injection brine drives an MD unit that treats blowdown water or some other impaired water source. A fourth variant considered MD in conjunction with NF. Overall, the cases included:

(1) "Hot NF" of injection brine to provide additional cooling tower makeup water,

(2) NF of the incoming makeup water to reduce TDS and increase cycles of concentration in the cooling tower (with an option for silica recovery),

(3) MD-only system using heat from the injection brine, and

(3b) Options (1) and (2) integrated with MD to simultaneously cool the NF-1 permeate while recovering high quality distillate from the NF-2 reject stream.

5. Preliminary Cost Estimates

5.1 Cost Methodology

In the late 1990s and early 2000s the Bureau of Reclamation developed a decision support tool to provide preliminary size and cost estimation for drinking water treatment processes. This tool evolved into the Water Treatment Estimation Routine (WaTER) [Wilbert et al., 1999]. The team downloaded and updated the WaTER spreadsheet with 2016 cost indices and used this tool for the preliminary cost exercise. Dow's Reverse Osmosis System Analysis (ROSA) software [Dow 2017], which includes the NF90 membrane within its library, was used to size the NF treatment units. The balance of plant and O&M costs were taken from WaTER. CSM's own spreadsheet-based MD performance and cost model was used for MD projections [Hickenbottom et al., 2017]. The procedure that was used to develop cost estimates for the application at Tuscarora is outlined in Table 5, and an example of the system cost results is presented in Table 6.

Table 5. Cost estimation methodology and tools

(1) Conceptual process schematics developed and mass and energy balances calculated with Engineering Equation Solver (EES), see Figure 5 and Figure 6
(2) Initial system sized based on site-specific constraints and technology assumptions: • 43 kg/s water required for evaporation in the cooling tower, • no more than 4% extraction of water from injection brine, • representative NF recovery rates (50% to 85%), • representative gain output ratio (GOR) for MD (1.5).
(3) NF and MD system performance based on several methods, which were used to update the required NF and MD system sizes: • Laboratory tests with surrogate water and NF90 and Aquastill MD membranes • Dow ROSA performance software • Bureau of Reclamation's WaTER spreadsheet • CSM MD-performance model
(4) System costs estimated using: • Bureau of Reclamation's WaTER spreadsheet • ASPEN • EconExpert webtool
(5) Annualized cost of water based on: • 8% interest rate for debt financing, 20 year project life, fixed charge rate = 0.1019
(6) Cost of water treatment was compared to potential savings in water and water treatment versus the current system

Table 6. Preliminary cost analysis for NF-treatment of the injection brine sized for permeate flow of 250 gpm and 500 gpm.

	Capacity = 250 gpm		Capacity = 500 gpm	
Cost Category	Basis	Cost	Basis	Cost
Membranes	1,115 m^2	15,000	2,230	30,000
Membrane Vessels	5	44,000	10	88,100
Unit enclosure/structural	64 m^2	126,324	107 m^2	212,800
Electrical		129,711		203,500
Instruments & controls		126,000		126,000
Pumps		7,230		14,500
Piping		40,600		81,200
Prefilters		10,300		18,500
Membrane cleaning equip.		64,900		64,900
Permeate holding tank	1300 m^3	213,000	2600 m^3	315,000
Permeate cooler		98,000		159,200
Training and startup		68,000		68,000
Site work		34,600		69,100
Total Direct Capital Cost		**977,700**		**1,450,800**
Indirect Costs				
Interest during construction	5%	48,900	5%	72,500
Contingency	6%	58,400	6%	86,700
Engineering and Project Mgmt	12%	116,800	12%	173,300
Working Capital	4%	39,100	4%	58,000
Total Installed Cost		**1,241,000**		**1,841,000**
O&M Costs				
Electricity		33,800		66,800
Labor		89,400		89,400
Membrane replacement		5,700		17,100
Parts, chemicals, prefilters		12,200		23,800
Insurance and lab fees		16,400		17,800
Annual Values				
Annual capital recovery		126,400		187,600
Annual O&M		157,700		214,900
Annual water production	m^3	447,600		895,200
Water cost	$\$/m^3$	0.63		0.45

5.2 NF System Size and Costs

Water extraction from the injection brine was limited to 250 gpm (4% of total flow) based on guidance from Ormat. A calculation at twice that rate was made to assess the sensitivity of cost to system capacity; however, reservoir analysis would be necessary to determine if such an extraction rate is sustainable.

NF-treatment of the makeup water was initially sized at 0.6 MGD (417 gpm or 2,270 m^3/day) – a scale that assumed processing almost half of the makeup water flow. The sizing data were used in WaTER to estimate the cost per cubic meter of the low-TDS permeate. Figure 7 highlights the cost of permeate for different cases.

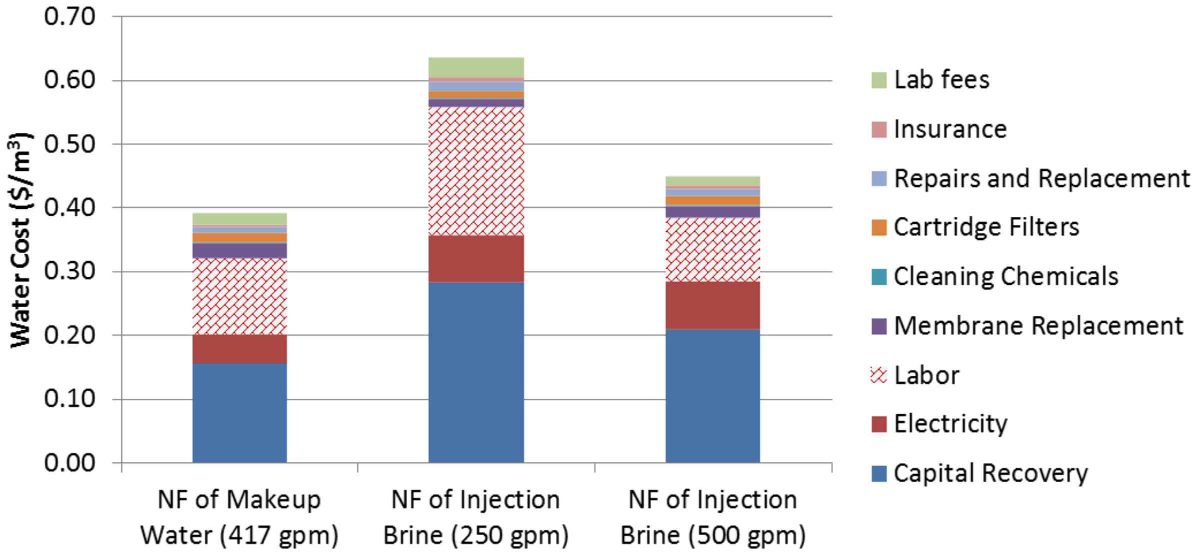

Figure 5. Overall estimated cost of water for NF treatment of the makeup or injection brine flows. MD costs for a comparable flow rate of distillate (250 gpm) was estimated at $1.60/m^3 and was considered noncompetitive.

5.3 MD System Size and Costs

The MD scenario extracts heat from the injection brine while distilling water from a water source such as a brackish well or the cooling tower blowdown (Figure 6). For comparative purposes the size and cost of an MD system that could produce 250 gpm was estimated and compared to the NF options depicted in Figure 7. Based on CSM's MD cost model [Hickenbottom et al., 2016 and 2017; Bush et al., 2016], the cost of water from the MD system was estimated as $1.60/m^3, which is almost threefold higher than the estimated NF-permeate costs at similar capacity (~$0.63/m^3). Given the good quality water produced by the NF treatment, MD was not deemed to be a competitive option in this application.

In the specific case of Tuscarora, where the objective is to produce low-TDS water for cooling tower makeup, an MD design is not competitive with the NF-based options for two reasons: (i) the quality of water required for cooling tower makeup is achieved with NF without the need to deploy full desalination and (ii) the amount of thermal energy needed to produce such a large amount of desalinated water exceeds that available in the injection brine. An MD deployment would be more suited for applications where a lesser amount of high-quality desalinated water is required; for example, providing demineralized water for mirror washing in a geothermal/solar-thermal hybrid plant, providing demineralized water for hybrid spray cooling at an air-cooled plant, or providing lab-quality water for onsite analytical or maintenance activities. These applications also consume lesser amounts of water than a cooling tower, which is more aligned with the capabilities of the technology given the available heat source from the injection brine. These concepts are being investigated in the ongoing project.

5.4 Project Economics at Tuscarora

The above estimated cost of treated water for the Tuscarora site can be combined with cost information for the existing makeup water at the site to address the net cost of deploying the proposed technology. Providing additional makeup water or providing additional cycles of concentration will offset the pumping and treatment of cooling tower makeup water from the site's declining makeup water wells. Table 7 lists the cost associated with pumping and treatment of makeup water under the current configuration based on information from Ormat. Four candidate alternative cases are shown. The estimated costs for three of these cases were shown in Figure 7. One additional alternative, *NF of all Makeup Water*, represents a larger size for the NF of makeup water design.

The analysis assumes that the cooling tower heat duty remains unchanged at the equivalent water evaporation rate of 688 gpm (43 kg/s), which corresponds to about 100 MW_{th}. Providing low-TDS water to the cooling tower allows the tower to run at higher cycles, thereby reducing blowdown and makeup water flow rates. The cycles of concentration is calculated by matching the hypothetical blowdown composition of the new cases to the concentration of TDS and silica in the current blowdown water.

Under these assumptions, Table 7 indicates that the cycles of concentration can be increased from 2.67 to a range of 3.5 to 10 depending on the scenario. The greatest level of water savings occurs under the *2x Injection Brine NF* case, where it is assumed that as much as 8% of the water can be extracted from the injection brine. (Note that a 4% extraction limit was imposed by Ormat based on a preliminary assessment of reservoir conditions.)

The bottom rows of Table 7 highlight the net annual cost and potential makeup well flow rate reduction for the four NF scenarios. NF treatment of the raw makeup water has the lowest cost, but also the least savings in makeup water consumption. Because it provides a new source of water, NF of the injection brine yields the greatest savings in makeup water flows. None of the scenarios cover the cost of the NF system on the basis of makeup water pumping and chemical treatment savings alone. The next step is to assess the cost of alternatives, such as prospecting and drilling for additional fresh water or conversion to dry cooling, as well as refine the NF system cost/benefit analysis, to determine the most cost-effective solution for addressing the decreasing flows from the existing makeup water wells.

6. Conclusions

Three basic water-treatment scenarios and one variant for production of low-TDS water for the Tuscarora cooling tower have been explored in this preliminary cost assessment:

(1) NF of injection brine,
(2) NF of the tower makeup water to reduce TDS and increase cycles of concentration in the cooling tower,
(3) MD-only treatment that processes blowdown or an additional impaired water source, and
(3b) Options (1) and (2) integrated with MD to simultaneously cool the injection brine permeate while recovering high quality distillate from the makeup water NF-rejection stream.

Table 7. Current and estimated future flows from the Tuscarora makeup wells for different water-recovery/treatment scenarios. Potential savings based solely on reduced pumping and chemical treatment costs for the existing makeup water. Annualized NF costs taken from WaTER (for example, see Table 6 for NF of injection brine cases).

	Units	Current Configuration	NF of Makeup Water	NF of Injection Brine	NF all Makeup Water	2x Injection Brine NF
Cooling Tower feed from makeup well	gpm	1100	450	710		320
TDS	mg/L	276	276	276		276
Silica	mg/L	90	90	90		90
Cooling Tower feed from NF2	gpm		417		764	
Feed to NF2	gpm		491		899	
TDS	mg/L		15.4		15.4	
Silica	mg/L		3.2		3.2	
Cooling Tower feed from NF1	gpm			250		500
TDS	mg/L			23.3		23.3
Silica	mg/L			5.4		5.4
Cooling Tower feed total	gpm	1100	867	960	764	820
TDS	mg/L	276	150.6	210.2	15.4	121.9
Silica	mg/L	90	48.3	68.0	3.2	38.4
Required Evaporation rate	gpm	688	688	688	688	688
Blowdown flowrate	gpm	412.5	180	273	77	133
Calc'd Cycles of Concentration	-	2.67	4.83	3.52	9.99	6.19
Blowdown TDS	mg/L	736	728	741	154	755
Blowdown Silica	mg/L	240	233	239	32	238
Makeup well water consumption	gpm	1,100	941	710	899	320
Makeup water cost	$	-	-	-	-	-
Pumping Costs	$/yr	$ 81,000	$ 69,261	$ 52,282	$ 66,186	$ 23,564
Makeup water chemical treatment cost	$/yr	$ 198,360	$ 81,147	$ 128,032	$ -	$ 57,705
Makeup water Total Cost	$/yr	$ 279,360	$ 150,409	$ 180,314	$ 66,186	$ 81,268
Annualized NF system cost	$/yr	$ -	$ 292,000	$ 284,100	$ 402,000	$ 402,500
Net annual savings (additional expense)			$ (163,049)	$ (185,054)	$ (188,826)	$ (204,408)
Net makeup well water savings	gpm		159	390	201	780

Either NF-based design (Cases 1 and 2) supplies suitable cooling tower water at a lower cost than an MD system, and the NF technology is suitable as a primary treatment option because of the composition of the makeup water and injection brine at Tuscarora. The annualized net cost of each NF-based system is similar, ranging from $163,000 to $189,000 per year over a 20-year project life. Savings in flowrate from the current makeup wells ranges from 159 to 390 gpm (14% to 35%) depending on the scenario. An additional scenario explored extracting more water from the injection brine with a larger NF system. This design was predicted to reduce makeup well flow by 71% at an annualized net cost of $204,000. However such a design removes 8% of the water from the injection brine, which would need to be evaluated to determine if such a rate is sustainable. An MD-only system cost is projected at $1.60/m^3 for a 250 gpm (0.36 MGD) system, which is not competitive with the NF designs for augmenting the cooling tower water. The low-TDS in the source waters and the relatively low water-quality requirements for cooling tower water negated the value of MD and meant that NF treatment was sufficient at this site.

On the basis of this preliminary cost analysis, NF as primary treatment is a preferred alternative for the Tuscarora site. This technology can produce acceptable water quality for the desired application at a water cost of about $0.40/m^3 to $0.63/m^3. NF treatment is a commercial technology, but some embodiments at Tuscarora would employ NF at conditions outside of its normal usage by directly treating the 74 °C, 10 bar injection brine stream. The permeate would be air-cooled prior to blending with the existing makeup water. Silica recovery as a by-product is an option that has been identified but not fully evaluated for the Tuscarora site.

Planned future work under this project will test hot-NF on surrogate injection brine. Laboratory testing has identified the preferred membranes and expected performance, which fed into the preliminary assessment provided here. The planned tests will acquire operational data on the membranes and illustrate and quantify the potential of the NF process for direct use on geothermal brines. The next stage of the research and analysis will include:

- Optimizing the operating schedule and cooling options to reduce cost associated with the holding tank and air cooler for water produced from NF of the injection brine
- Refining system sizing and soliciting vendor quotes to improve cost projections
- Comparing the NF/MD options with an air-cooling retrofit or prospecting and drilling for additional makeup water as alternatives

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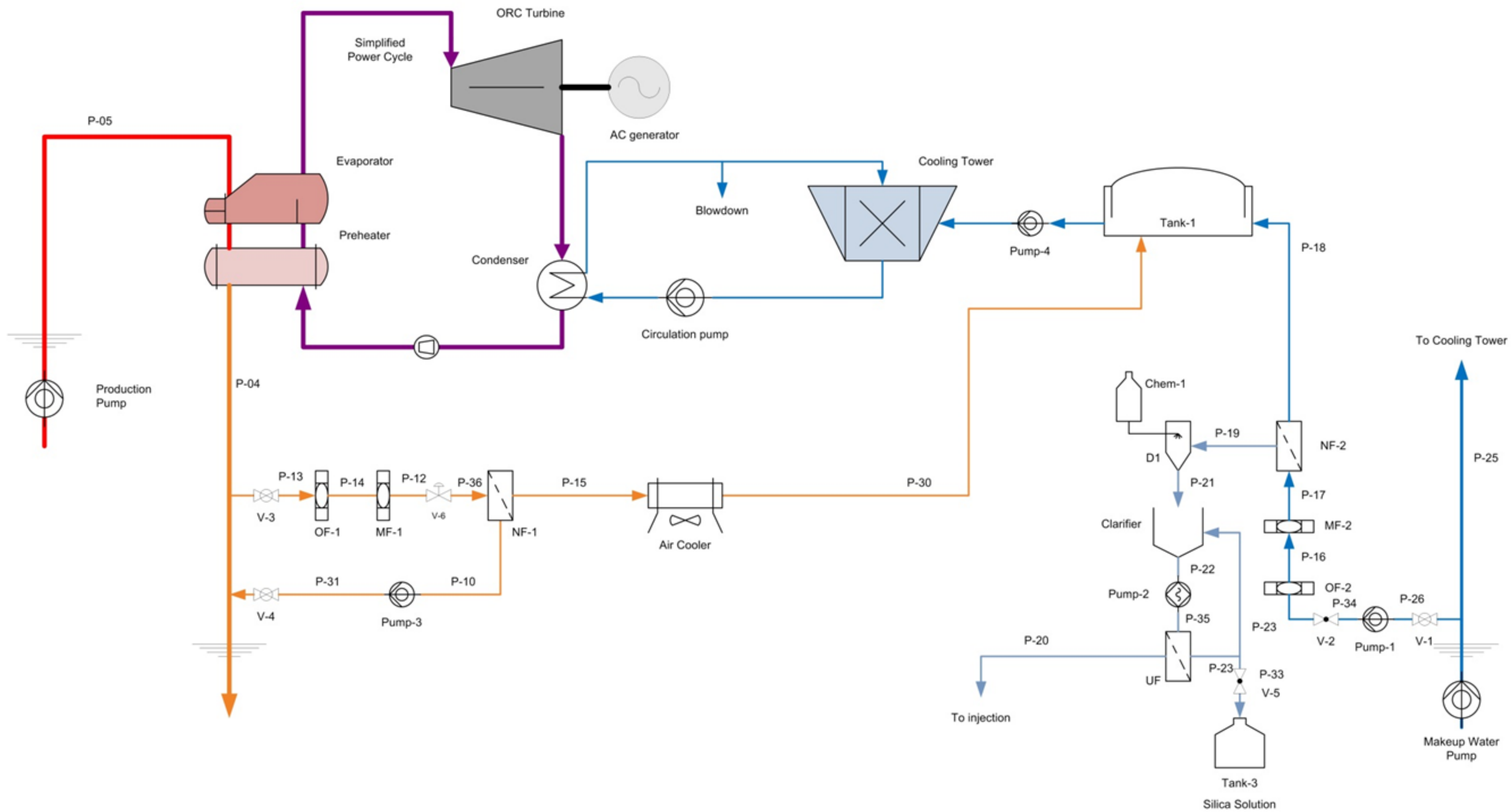

Figure 6. Process flow diagram for two different NF options to produce or save makeup water. NF-1 represents a "hot" NF treatment of the injection brine to recover additional low-TDS water. NF-2 represents treatment of the makeup water to remove silica and allow for increased cycles of concentration in the cooling tower. Optional silica recovery as a by-product is shown.

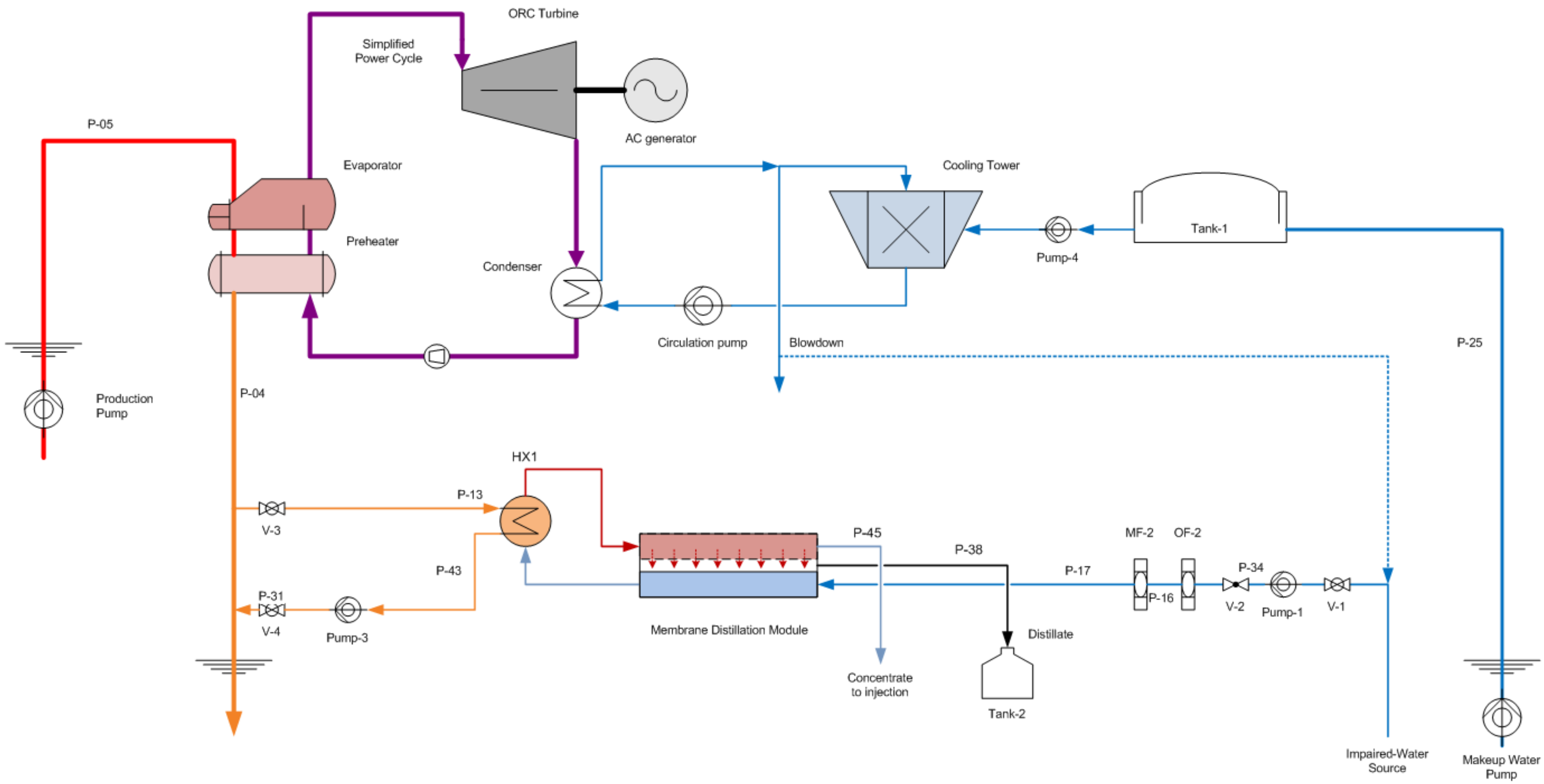

Figure 7. Process flow diagram using only MD with heat taken from the injection brine and treating water from the cooling tower blowdown or other impaired water source.