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December 30, 2011

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
600 East Boulevard Avenue, Department 405
State Capitol, 14th Floor
Bismarck, ND 58505-0840

Dear Ms. Fine:

Subject: Final Report Entitled "Evaluation of Brackish Groundwater Treatment for Use in Hydraulic Fracturing of the Bakken Play, North Dakota"; EERC Fund 14699

We certify that the Energy & Environmental Research Center (EERC) agreements for this project include the following:

Sponsor	**Award**	**Expended**	
North Dakota Industrial Commission	$110,000	$108,252	
North Dakota Petroleum Council	$10,000	$9616	Phase 1
U.S. Department of Energy	$155,000	$154,886	
Hess Corporation		$3,554,133	Phase 2

Enclosed is the subject final report summary for your review.

If you have any questions or require clarification of any point, please contact me by phone at (701) 777-5050 or by e-mail at bkurz@undeerc.org.

Best regards,

Daniel J Stepan for

Bethany A. Kurz
Senior Research Manager

BAK/kmd

Enclosure

EVALUATION OF BRACKISH GROUNDWATER TREATMENT FOR USE IN HYDRAULIC FRACTURING OF THE BAKKEN PLAY, NORTH DAKOTA

Final Report

Prepared for:

Karlene Fine

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PROJECT SUMMARY

The Northern Great Plains Water Consortium® (NGPWC) is a partnership between the Energy & Environmental Research Center (EERC), the U.S. Department of Energy, and key stakeholders in the north-central region of the United States. The overall goal of the NGPWC is to assess, develop, and demonstrate technologies and methodologies that minimize water use and reduce impacted water discharges from a range of energy technologies. One of the NGPWC's current activities is to evaluate potential sources of water for use in hydraulically fracturing the Bakken oil play of North Dakota. Because of the current high costs for acquisition and transportation of existing water resources in western North Dakota, treatment of nontraditional water supplies may be economically feasible.

To evaluate the feasibility of treating nonpotable groundwater as a means of providing a freshwater supply for hydraulic fracturing in the Bakken play, the EERC teamed with Hess Corporation to conduct a pilot treatment project using reverse osmosis (RO) to treat brackish groundwater from an existing water well screened in the Dakota Formation at a depth of approximately 5500 feet. GE Water Process and Technologies (GE) was contracted to provide a mobile pretreatment and RO system. Agrekko heat exchangers were used to reduce groundwater temperature to desired levels before RO treatment. The project demonstrated greater than 70% treated water recovery and greater than 90% removal of major ions. Over 25 million gallons of brackish groundwater was treated during the demonstration, producing over 17.8 million gallons of high-quality freshwater for use in hydraulic fracturing.

Metal test coupons were installed at various locations during the pilot demonstration to assess corrosion of standard plumbing and heat exchange materials of construction. The corrosion study suggested that stainless steel would be a superior material compared to carbon steel pipe commonly used in the oil field; however, more exotic metals and alloys would not be required.

The success of the pilot project has led Hess to partner with GE to build and operate a full-scale, 1- to 2-million-gallon/day (MGD) RO treatment plant. While the exact costs of the plant are not available to the public, the estimated costs to build and operate a 1.5-MGD (35,700 bpd) RO plant were compiled by the EERC with input from GE. Capital costs associated with construction of the RO plant and associated buildings, land acquisition, well field and pipeline costs, water storage ponds, and concentrate disposal costs were also assessed. Annual operating and maintenance (O&M) costs were also included for the RO plant, well field, and concentrate disposal options. Given the relatively high volume of concentrate that would be produced (15,300 bpd), two different options were considered for disposal: truck transport to an existing commercial injection site and pipeline transport to a dedicated injection site.

The total estimated capital costs for a 1.5-MGD RO plant with concentrate disposal at an existing commercial site were $24.9 million, and O&M was approximately $22.8 million a year. The capital costs for the second option (a dedicated concentrate injection site) were estimated at $38.2 million, and annual O&M was estimated at approximately $1.2 million. Depending on the economic assumptions used, per-barrel costs ranged from $1.28 to $2.95 over a payback period of 3 years or less. When compared to traditional frac water makeup costs, this approach appears viable if the cost savings associated with lower transportation costs and reduced heating costs are taken into account. Given the current pace of Bakken development, coupled with limited access to water, treatment of brackish groundwater sources for use in Bakken fracturing appears economically viable.

EVALUATION OF BRACKISH GROUNDWATER TREATMENT FOR USE IN HYDRAULIC FRACTURING OF THE BAKKEN PLAY, NORTH DAKOTA

BACKGROUND

Water is the most critical limiting resource throughout the world. Sufficient quantities of good-quality water are needed for several competing uses, including energy production, growing and processing high-value crops, industrial manufacturing, and expanding populations. The Northern Great Plains Water Consortium® (NGPWC) is a partnership between the Energy & Environmental Research Center (EERC), the U.S. Department of Energy (DOE), and key stakeholders representing oil and gas companies, power generation utilities, industry, municipalities, and other entities interested in addressing critical water issues in the north-central United States. The primary goal of the NGPWC is to assess, develop, and demonstrate technologies and methodologies that minimize water use and reduce impacted water discharges from a range of energy technologies, including coal combustion, coal gasification, coalbed methane, and oil and natural gas production.

One of the NGPWC's key activities is to evaluate potential sources of water for use in hydraulically fracturing the Bakken Formation (Bakken), located in the Williston Basin of North Dakota, Montana, South Dakota, and Saskatchewan (Figure 1). The Bakken oil play is rapidly

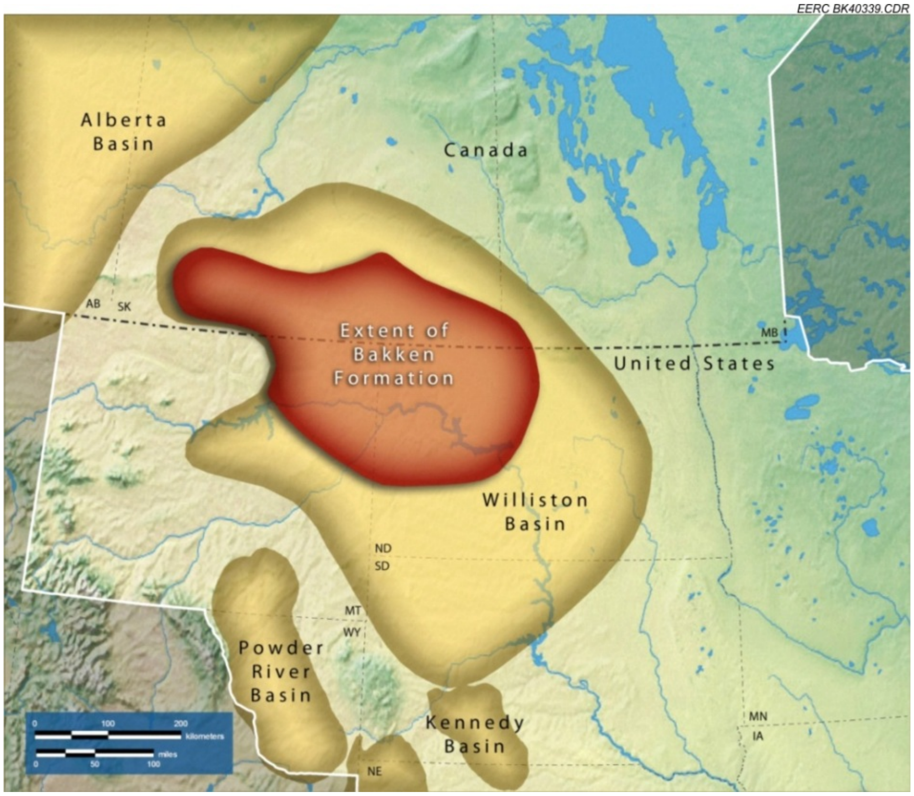


Figure 1. The location of the Bakken Formation within the Williston Basin.

emerging as an important source of domestic oil, with potentially recoverable reserve estimates ranging from 4 to 24 billion barrels (Oil and Gas Journal, 2011). While the hydrocarbon resource within the Bakken is tremendous, the formation is characterized by very low porosity and permeability, which necessitates fracturing to enhance the flow and recovery of oil. Water volumes for fracturing the Bakken range from approximately 20,000 to 115,000 barrels (approximately 840,000 to 5 million gallons), depending on the number of stages in the frac, and, to a lesser extent, differences in varying fracture techniques. More fracturing stages require greater volumes of water. While these volumes of water are not especially high when compared to those needed for municipal and agricultural use within the western portion of North Dakota, there are a limited number of locations from which to obtain the freshwater. For water haulers, the lack of water resources translates to long transportation distances and excessive amounts of time spent waiting in lines at water depots. As a result, water acquisition costs for Bakken oil producers in the region can be quite high. Given the current demand for water resources and the high costs of acquisition and transportation, treatment of nontraditional water supply sources may be economically viable.

One of the first projects conducted by the NGPWC was an assessment of the potential to recover, treat, and recycle fracturing (frac) flowback water from Bakken oil wells (Stepan et al., 2010). The EERC evaluated an array of water treatment technologies, primarily mobile treatment systems that could utilize the high-Btu associated gas generated during the flowback operations to thermally treat frac flowback. However, extremely high dissolved salts in flowback water, combined with a relatively low recovery rate of the flowback water, makes recycling very challenging and, in most cases, economically unattractive.

As part of a continuing effort to evaluate water supply options for oil producers and other industries in the region, the EERC teamed with Hess Corporation to conduct a pilot treatment project using reverse osmosis (RO) to evaluate the technical and economic feasibility of treating brackish groundwater as a water supply source for fracturing. This effort was funded by Hess, DOE, and the North Dakota Industrial Commission Oil and Gas Research Council. The pilot system was in operation from July 2010 through mid-April 2011. The following report discusses the current state of water use practices for Bakken fracturing, summarizes the RO pilot project results, and discusses the feasibility of brackish groundwater treatment for fracturing given the current state of water availability within North Dakota.

CURRENT WATER USE PRACTICES

Fracturing is increasingly being employed by oil producers in western North Dakota to produce the tremendous oil and gas resources of the Bakken Formation. Fracturing entails the injection of water, proppants, and various other chemical constituents at high pressures into reservoir rock in order to increase the permeability of the formation and enhance the flow of oil. Common constituents of frac fluid makeup are shown in Table 1, with water and proppants typically comprising 99.5% of the frac fluid makeup (U.S. Department of Energy, 2009). Frac fluid makeup water typically contains low total dissolved solids (TDS), will be free of bacteria, and be of consistent quality to ensure the ability of individual producers to generate and replicate the desired fracture results.

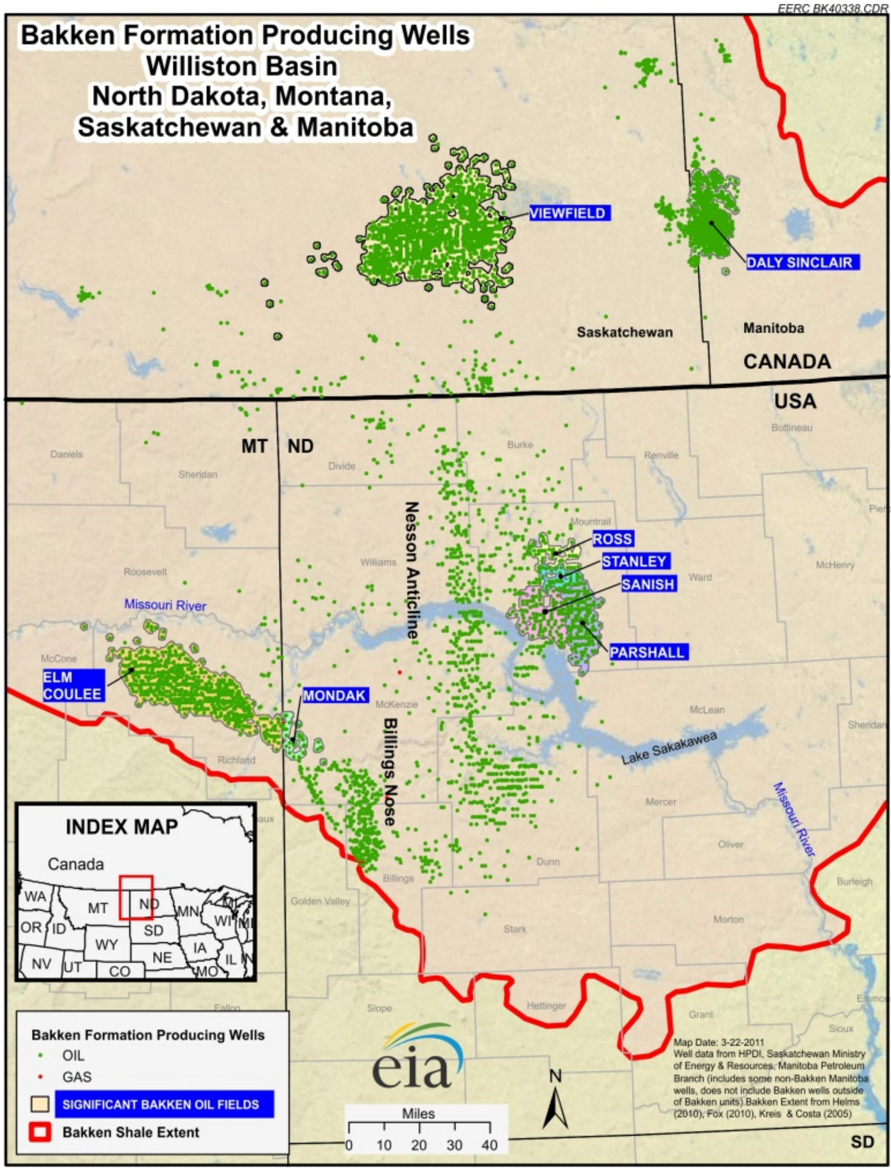
Table 1. Common Constituents of Frac Fluid Makeup

Frac Fluid Component	Purpose
Freshwater	The primary mechanism for delivering the desired proppants and chemicals into the formation; usually high quality.
Proppant	Typically sand or ceramic beads that help keep the fractures open upon release of pressure from the fracturing operation.
Biocides	Reduces the risk of well souring from microbes.
Friction-Reducing Agents	Surfactants that promote frac fluid flow.
Polymers	Forms gels to keep proppants in suspension.
Scale Inhibitors	Reduces scale formation in pipes.
Weak Acids	Helps dissolves minerals that cement formation pore spaces.

In western North Dakota, common freshwater acquisition points for frac fluid makeup are existing water depots and municipalities; however, these have a limited capacity to supply the large demand for water. In response to the increasing demand for freshwater, the North Dakota State Water Commission (SWC) has received numerous permit applications for additional groundwater appropriation for withdrawals at existing water depots as well as permit applications for new water wells. Prescribed permitting procedures require a published public notice, followed by a 30-day comment period. New permit applications are typically contested by environmental groups, which results in significant delays in the overall permitting process. Permits that would normally be issued within a 70- to 90-day period are taking in excess of 9 months.

In addition, SWC is reluctant to permit new allocations from potable groundwater resources for use in the oil industry because of concerns over depletion of the resources and declining hydraulic pressures of bedrock aquifers. With the exception of the Missouri River system, most regional surface waters do not provide a reliable supply of water because of seasonal flow variations. Sufficient flows typically exist only in the spring of the year, during periods of snowmelt.

Given the concerns over mining of groundwater resources, groundwater-permitting issues, and the relative lack of small surface water availability in many areas of the state, SWC is encouraging the oil industry to seek withdrawals from the Missouri River system for use in Bakken development. The Missouri River system, specifically Lake Sakakawea, is a tremendous resource that is located adjacent to many of the Bakken drilling areas (Figure 2). However, several issues arise related to using Lake Sakakawea water, key among them being access to the lake and looming fees for use of the resource. While SWC handles water appropriations from the lake, permission for an easement to a particular point of diversion must be granted by the U.S. Army Corps of Engineers (Corps). This creates additional delays in accessing the resource because having to obtain permission from multiple agencies can slow the permitting process. In addition, it is not yet clear where access to the lake may or may not be allowed so as not to disturb existing cultural sites and/or threatened and endangered species. While the Corps is



Map Date: 3-22-2011
Well data from HPDI, Saskatchewan Ministry of Energy & Resources, Manitoba Petroleum Branch (includes some non-Bakken Manitoba wells, does not include Bakken wells outside of Bakken units).Bakken Extent from Helms (2010), Fox (2010), Kreis & Costa (2005)

Figure 2. The location of the Missouri River system and Lake Sakakawea with respect to Bakken drilling locations (Energy Information Administration, 2011).

studying the potential impacts of increased access to and water use from the lake (estimated to be a multiyear study), it agreed to allow a temporary annual allocation of water from the lake for municipal and industrial (M&I) use for a fee. The Corps recommended that 100,000 acre-feet of water yield be made available from Lake Sakakawea for temporary M&I use over a period of 5 years for an annual fee of $20.91 per acre-foot of yield (U.S. Army Corps of Engineers, 2010).

While water depot and pipeline projects are in the works to improve the availability of freshwater resources for use in Bakken development, in the near-term, there are significant water access issues. The Missouri River system has more than enough water available for Bakken development, but access issues and potential fees associated with this water use remain unresolved. In addition, the Missouri River and Lake Sakakawea are not always adjacent to areas of Bakken drilling; therefore, the high costs associated with long transportation distances may diminish the appeal of the resource.

As part of the EERC study to evaluate the feasibility of fracturing flowback recycling (Bakken Water Opportunities Assessment – Phase 1), cost data for water acquisition were provided by several producers working in North Dakota (Stepan and others, 2010). The reported costs of current water handling for hydraulic fracturing can vary significantly, depending on acquisition and transportation costs (including wait time). Table 2 lists a range of water-handling costs for Bakken frac water as of 2010. The cost to purchase raw water ranged from \$0.25/barrel (bbl) up to \$1.05/bbl (\$5.95 to \$25 per 1000 gallons), and the cost of transporting that water to the fracture location ranged from \$0.63/bbl up to an estimated \$5.00/bbl (\$15 to \$119.05 per 1000 gallons). Transportation costs represented the highest level of variability in water acquisition costs and depended on several factors, including trucking charges, haul distances, and wait time. Trucking charges were reported to range from \$110 to \$150/hr, and the charges that are incurred during wait time are included in the overall transportation costs. The costs for deep well injection ranged from \$0.50/bbl to \$1.75/bbl (\$11.90 to \$41.66 per 1000 gallons). Again, transportation costs are the most significant cost for disposal, and the higher overall transportation costs were associated with long wait times to unload at a disposal facility.

Given the current need for water, coupled with high water acquisition, transportation, and disposal costs, nontraditional options for water supplies, such as desalination of brackish groundwater resources, are worthy of further investigation. As a result of the work conducted during Phase 1 of the Bakken Water Opportunities Assessment, the EERC, with the encouragement of the project sponsor, decided to pursue a pilot project to evaluate the feasibility of treating brackish groundwater.

Table 2. Water-Handling Costs

	Cost, \$/bbl	Cost, \$/1000 gallons
Acquisition Costs		
Raw Water	\$0.25–\$1.05	\$5.95–\$25.00
Transportation	\$0.63–\$5.00	\$15.00–\$119.05
Disposal Costs		
Transportation	\$0.63–\$9.00	\$15.00–\$214.29
Deep Well Injection	\$0.50–\$1.75	\$11.90–\$41.66
Total Costs	\$2.00–\$16.80	\$47.62–\$400.00

BRACKISH GROUNDWATER RESOURCES

One advantage to utilizing brackish groundwater as a potential water supply is that the region is not limited by a lack of potential resources. Much of the region is underlain by what the U.S. Geological Survey has classified as the Northern Great Plains Aquifer System, a large (approximately 300,000 square miles) regional flow system comprising five major aquifers of varying quality. These aquifers include sandstones of Tertiary and Cretaceous age, carbonate rocks of Pennsylvanian and Mississippian age, and sandstones and carbonates of Cambrian and Ordovician age (Figure 3 and Table 3). The rocks that comprise these aquifer systems were formed by sediment erosion from mountains to the west and subsequent deposition to the east in the Williston and Powder River Basins and adjacent areas (Downey and Dinwiddie, 1988).

Water movement through these systems generally occurs from recharge areas in the southwestern part of the region to the northeast. Recharge occurs where the rocks are exposed at or near the surface in areas that were uplifted as part of the Laramide Orogeny (Bachu and

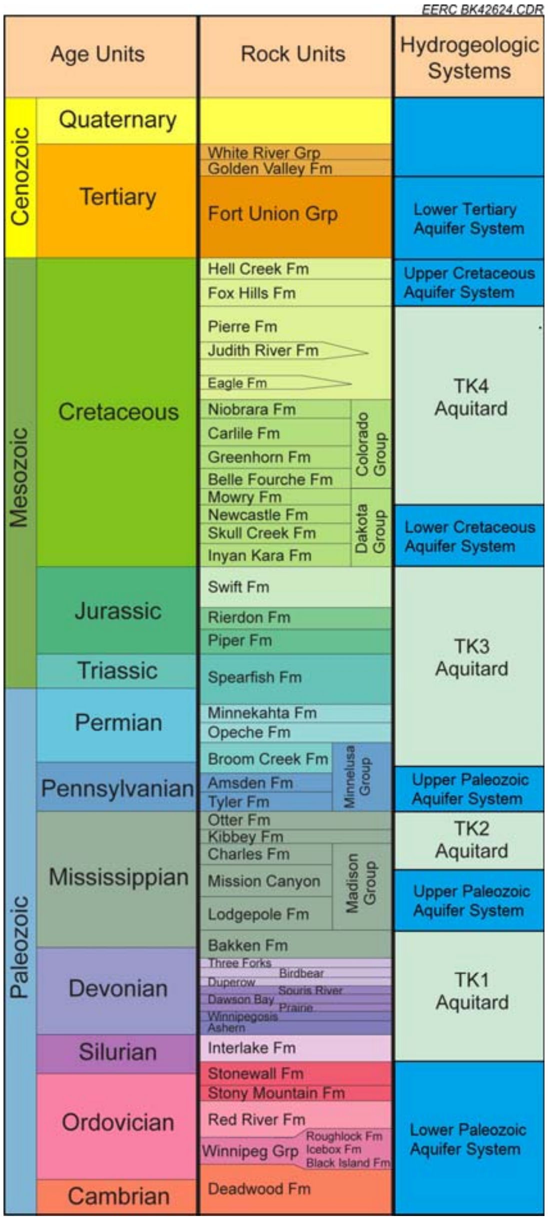


Figure 3. Stratigraphic column showing the age and rock units associated with each of the five aquifer systems within the Northern Great Plains Aquifer System.

Table 3. General Description of Each of the Five Major Aquifer Units Comprising the Northern Great Plains Aquifer System (adapted from Whitehead, 1996)

Hydrogeologic System	Age Unit	General Composition
Lower Paleozoic (Basal Cambrian Aquifer)	Cambrian, Ordovician	Sandstone, shale, limestone, and dolomite; formed in a shallow marine environment.
Upper Paleozoic (Madison Aquifer)	Mississippian, Pennsylvanian	Limestone and dolomite with lesser amounts of clay, chert, and anhydrite; deposited in a marine environment.
Lower Cretaceous (Dakota Aquifer)	Lower Cretaceous	Sandstone; formed in marine, deltaic, and fluvial environments.
Upper Cretaceous	Upper Cretaceous	Sandstone interbedded with siltstone, claystone, and local thin beds of coal or lignite; deposited in a continental environment.
Lower Tertiary	Eocene, Paleocene	Interbedded sandstone, siltstone, claystone, and coal; deposited in a continental environment.

Hitchon, 1996), including the Black Hills, Pryor Mountains, Bighorn Mountains, Beartooth Mountains, and Little Rocky Mountains (Iampen and Rostron, 2000). Because water within these systems moves along very long flow paths and remains in contact with aquifer minerals for long periods of time (sometimes thousands of years [Gerla, 1992]), the water is typically enriched in various chemical species, reflected by moderate to high TDS concentrations. In many parts of the system, TDS concentrations exceed the secondary drinking water maximum contaminant level of 500 mg/L established by the U.S. Environmental Protection Agency (Whitehead, 1996). Figures 4–8 show the approximate extent of each of the five aquifer systems and generalized TDS concentrations of each (no TDS data were available for Figure 4). As a general rule of the thumb, the TDS concentrations are lower adjacent to uplift areas (reflecting recharge of freshwater) and higher in the middle of the Williston and Powder River Basins.

While the quality of the water in many areas of these aquifers is unsuitable for drinking, at many locations it is of a quality suitable for cost-effective treatment. In fact, the water in many areas of the aquifers (mostly excluding the Williston Basin) could be classified as only moderately saline (Table 4). The suitability of any of these aquifers as a water supply source would require a site-specific evaluation, not only to assess water quality, but also to assess aquifer yield, depth, temperature, and sustainability.

DESALINATION TECHNOLOGIES

While many options exist for treatment of brackish groundwater, recent and ongoing improvements in desalination technology have made this an increasingly viable water treatment

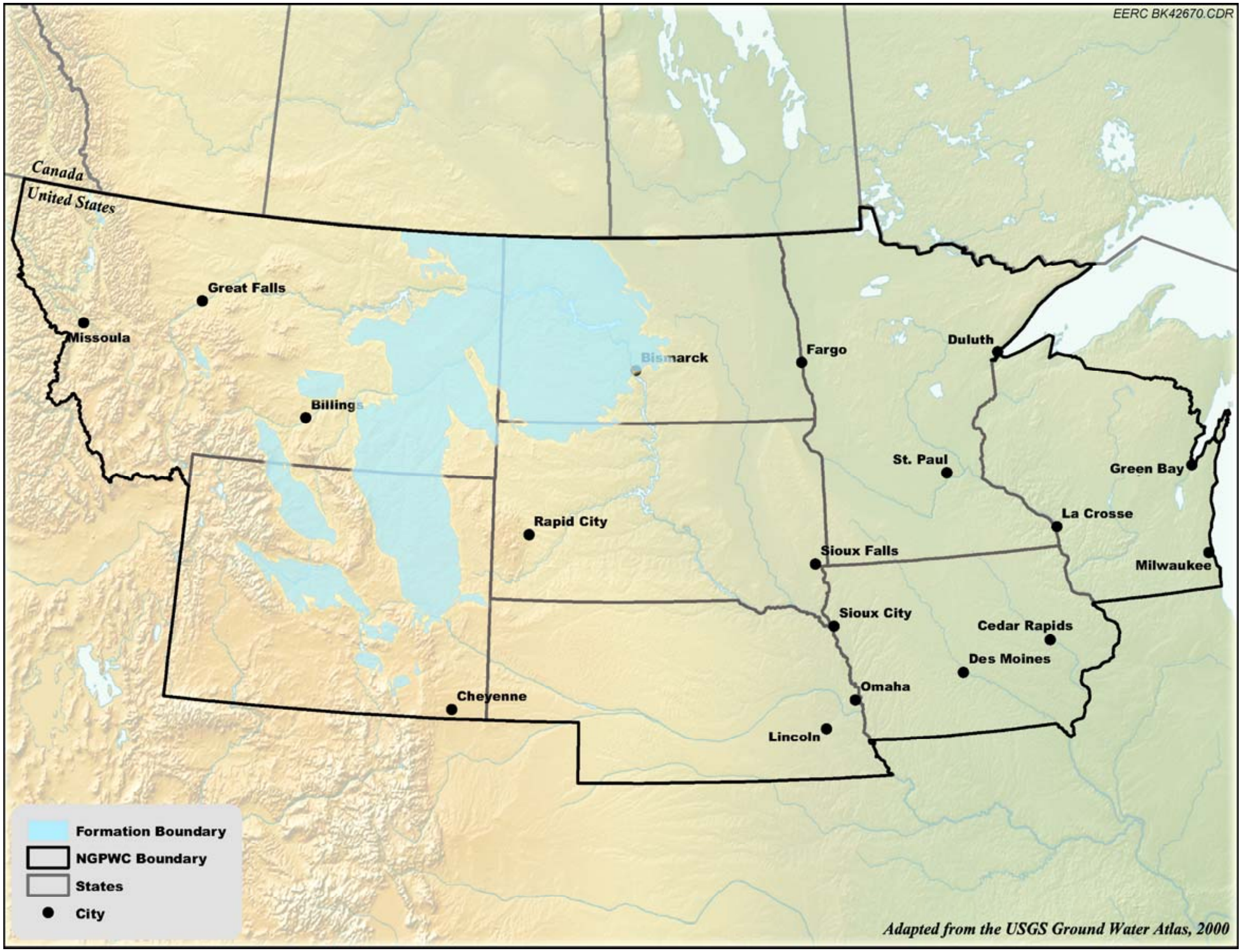


Figure 4. Approximate extent of the Lower Tertiary aquifer system.

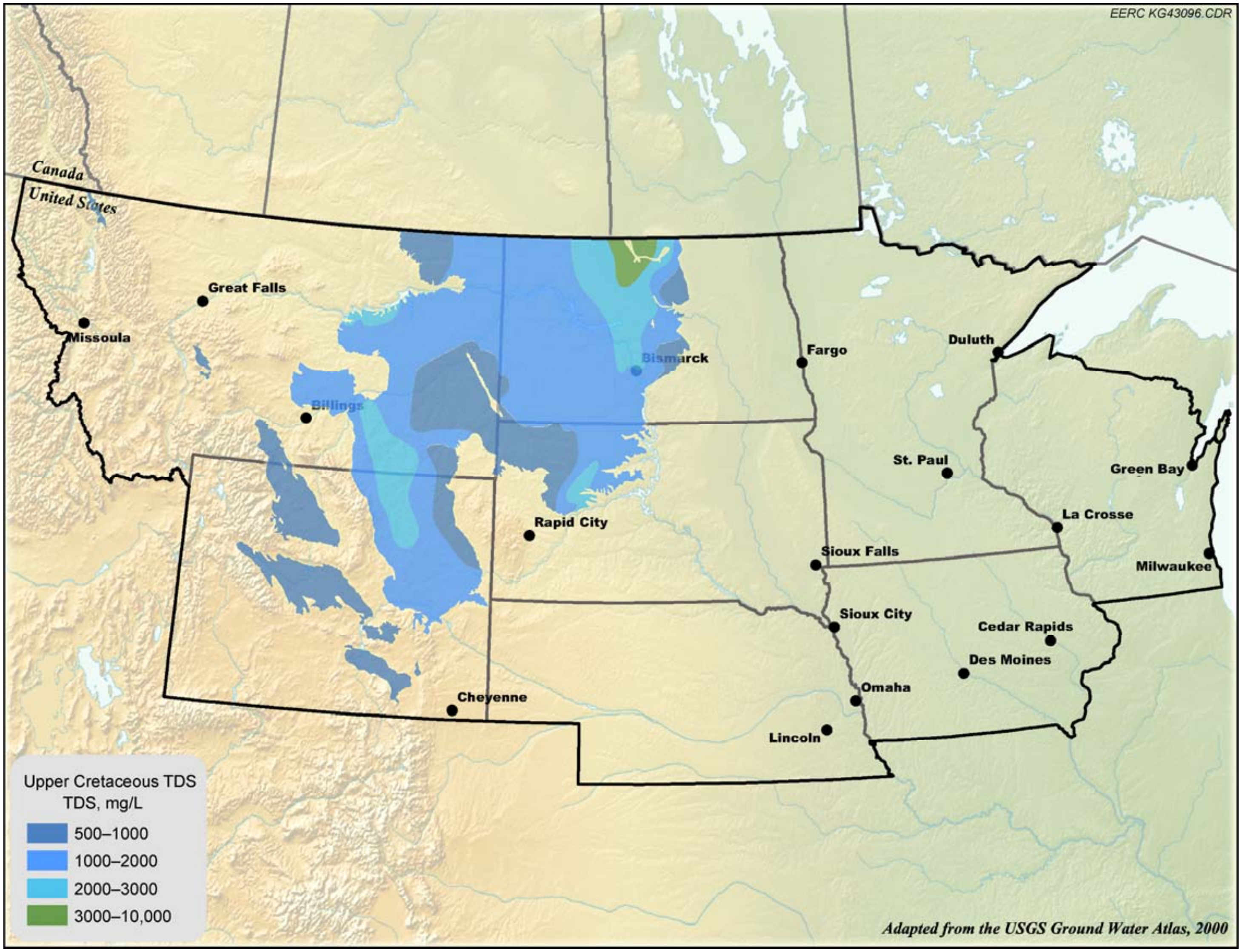
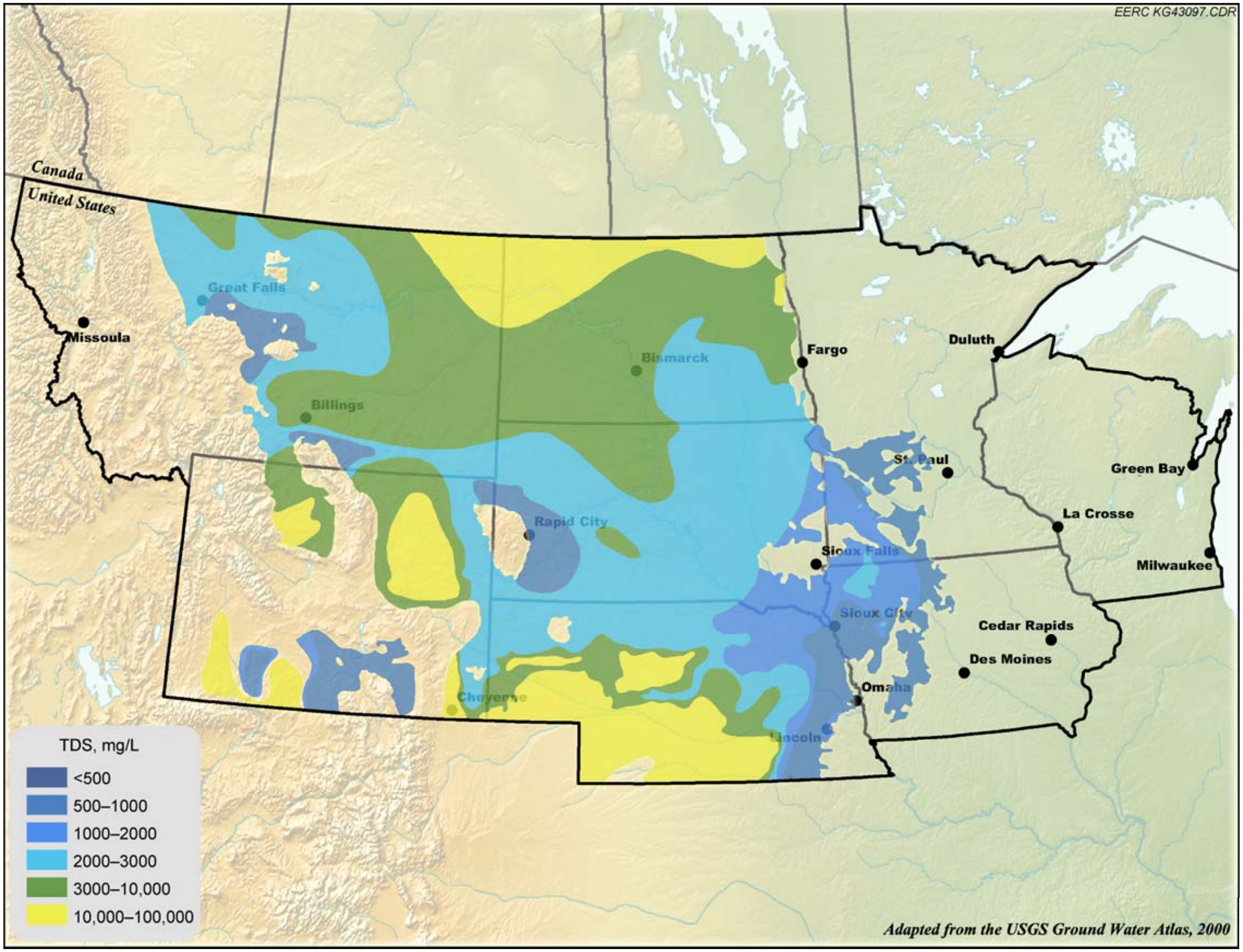
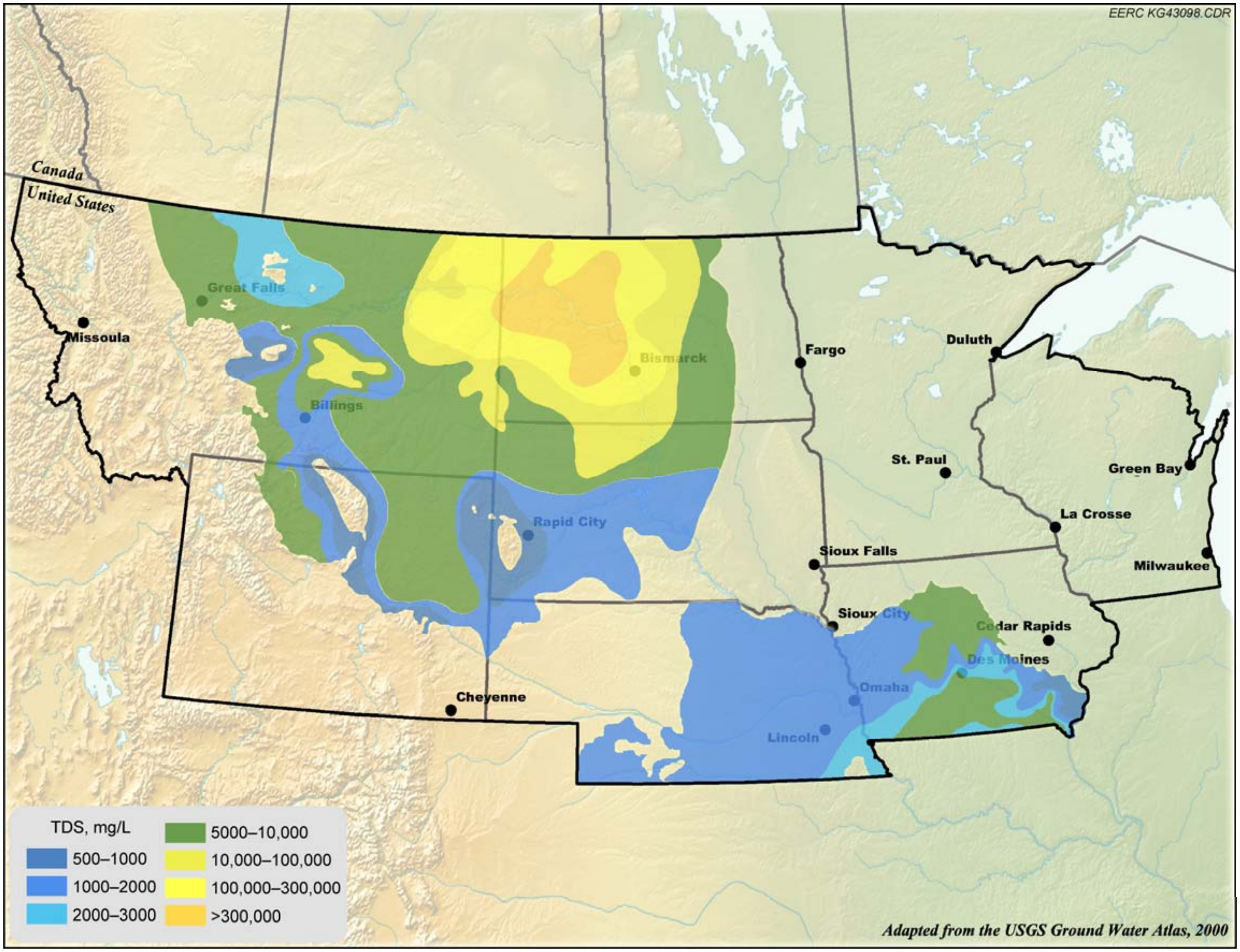


Figure 5. Approximate extent of the Upper Cretaceous aquifer system and generalized TDS concentrations (in mg/L).



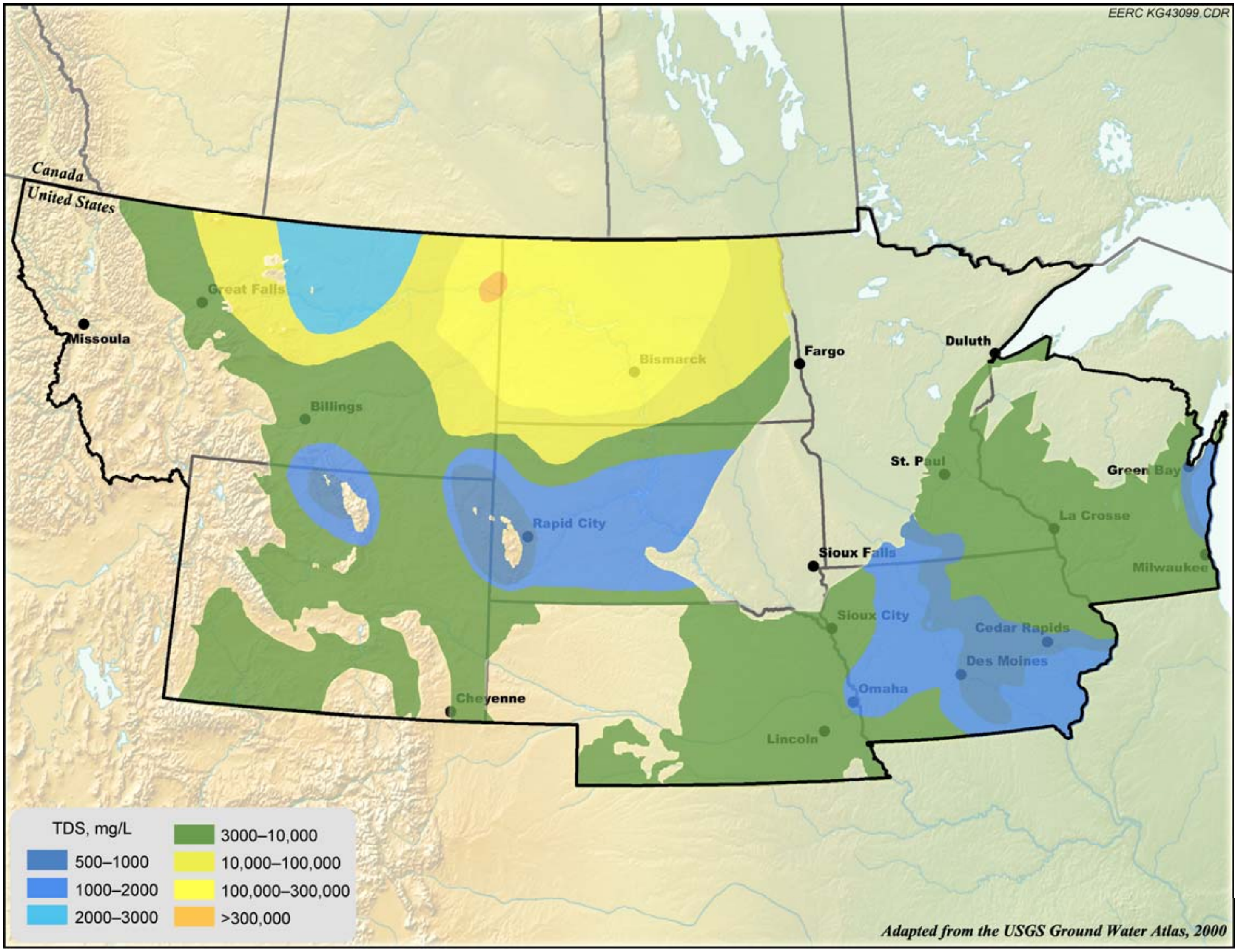
Adapted from the USGS Ground Water Atlas, 2000

Figure 6. Approximate extent of the Lower Cretaceous aquifer system and generalized TDS concentrations (in mg/L).



Adapted from the USGS Ground Water Atlas, 2000

Figure 7. Approximate extent of the Upper Paleozoic aquifer system and generalized TDS concentrations (in mg/L).



Adapted from the USGS Ground Water Atlas, 2000

Figure 8. Approximate extent of the Lower Paleozoic aquifer system and generalized TDS concentrations (in mg/L).

Table 4. Classification of Water Type Based on TDS Concentration (Downey and Armstrong, 1977)

Water Source	TDS Concentration, mg/L
Fresh	<1000
Slightly Saline	1000–3000
Moderately Saline	3000–10,000
Saline	10,000–35,000
Seawater	>35,000

option around the world. Whereas desalination was limited by high costs in recent decades, it is now a cost-competitive option for many communities as available freshwater resources become limited or nonexistent. Because desalination is capable of treating water with varying degrees of salinity, including seawater, brackish ground and surface water, and wastewater, desalination has wide-scale applications across the globe. Since the early 1970s, desalination has gained a foothold in the United States as a practical source of high-quality water supply and is now providing high-quality water for municipal and industrial use.

Desalination can be defined in simple terms as a water treatment process that removes dissolved minerals from water. There are two commonly employed water desalination technologies: thermal (distillation) and membrane. Thermal technologies heat water and collect the condensed vapor to produce distilled water. The most common thermal technology is multistage flash (MSF) distillation (Figure 9), which employs thermal heating and reduced pressure to flash liquid water to vapor in a series of stages, each of which is at a lower pressure.

Thermal desalination is most commonly practiced in areas with abundant fossil fuels to capitalize on cogeneration of power and water, such as in the Middle East. Rarely are thermal

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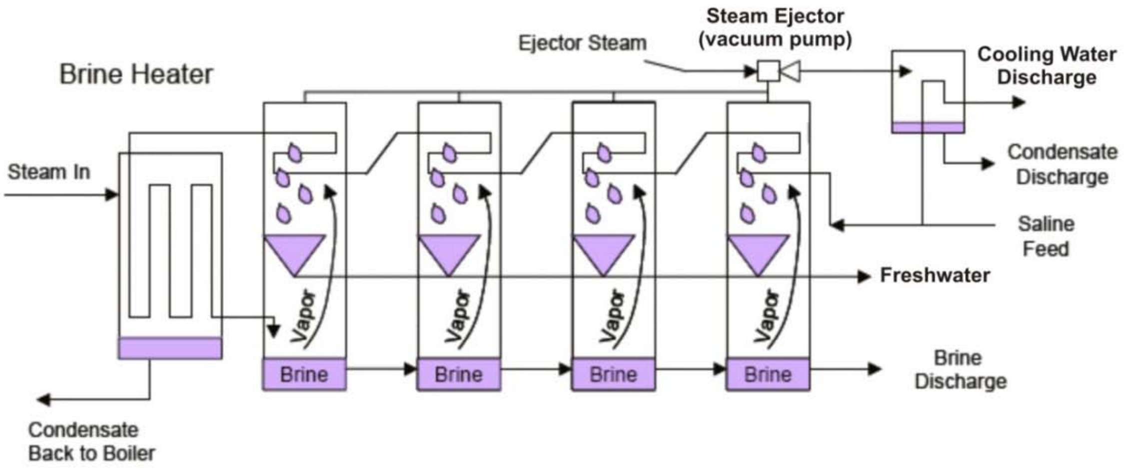

Figure 9. MSF distillation (Miller, 2003).

processes used to desalinate water with less than 10,000 mg/L of TDS; indeed, the vast majority of these applications use seawater as the feed source, which typically has a TDS concentration of 35,000 mg/L. Thermal technologies are generally not cost-effective for low-TDS waters.

Membrane technologies are much younger in development than thermal technologies. Membrane technologies were developed for commercial and municipal water supplies in the 1970s, while thermal technologies have been in practice for over a century. As the name implies, membrane treatment removes dissolved minerals from solution using filtration through a semiporous membrane. The three main types of membrane treatment for dissolved salts include RO, electrodialysis (ED), and nanofiltration (NF).

The International Desalination Association's (IDA) Desalination Yearbook 2011–2012 (IDA, 2011) indicates the global capacity for desalination grew to 77.4 million m^3/day (20.4 billion gallons/day) with 71.9 million m^3/day (19.0 billion gallons/day) of this currently online and 5.5 million m^3/day (1.4 billion gallons/day) of capacity under construction. Figure 10 illustrates that this capacity represents substantial growth over the last decade which is anticipated to continue well into the next. The information in the figure also reveals that while the capacity of thermal desalination plants continues to grow at a steady pace, membrane-based capacity is expanding at an accelerating pace.

The total global desalination output comes from approximately 16,000 desalination plants which vary in size from very small systems producing less than 0.365 million m^3/year (96.4 million gallons/year) of product water to very large systems producing up to 321.2 million m^3/year (84.8 billion gallons/year) (IDA, 2011). The bulk of this capacity is for production of

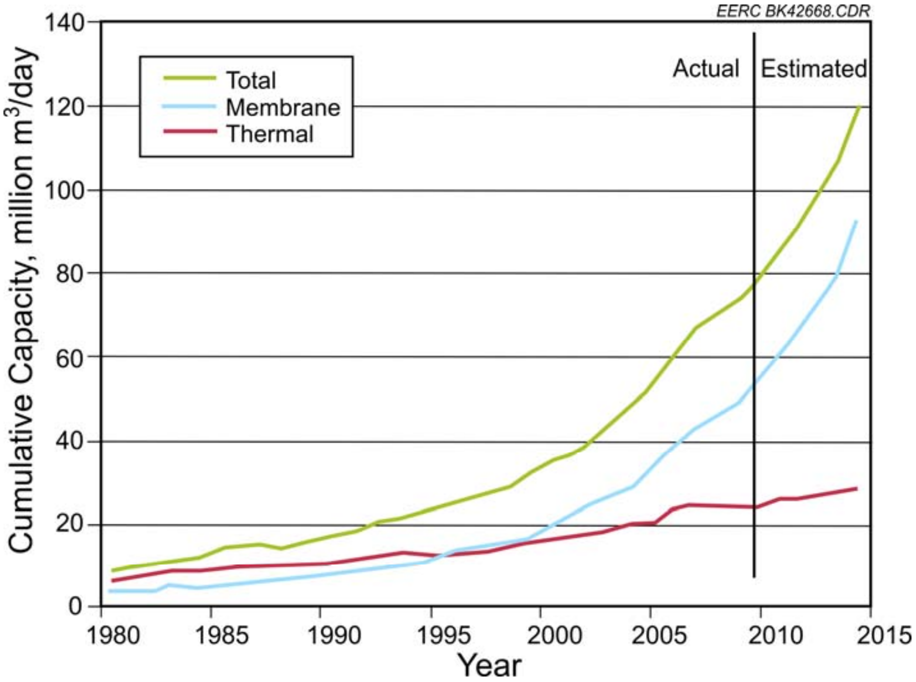

Figure 10. Cumulative worldwide desalination capacity (Birkett, 2010).

municipal supplies. The primary source of feedwater is seawater followed by brackish water as illustrated in Figure 11. The distribution of desalination capacity around the world is illustrated in Figure 12. The figure shows that greater that 53.4% of existing capacity is located in the Middle East, 17% in North America, 10.6% in Asia, and 10.1% in Europe. Africa, Central America, South America and Australia together account for another 9%.

Within the United States, approximately 180 municipal and rural water systems use desalination for part or all of their water supply. Approximately 94% of this capacity is generated using membrane technology. Together, these processing facilities produce over 787 MGD of water for municipal use. Historically, the source water for these desalination plants was seawater, but with advances in RO treatment technology, brackish surface or groundwater sources are increasingly being used.

MEMBRANE TECHNOLOGY

ED is one of the three common membrane processes in desalination and is primarily used to treat brackish water. ED involves the selective movement of ions through a membrane in response to a direct electric current. Electric energy is consumed in proportion to the quantity of salts to be removed. Economics usually limit its application to feedwaters of less than 10,000 mg/L TDS.

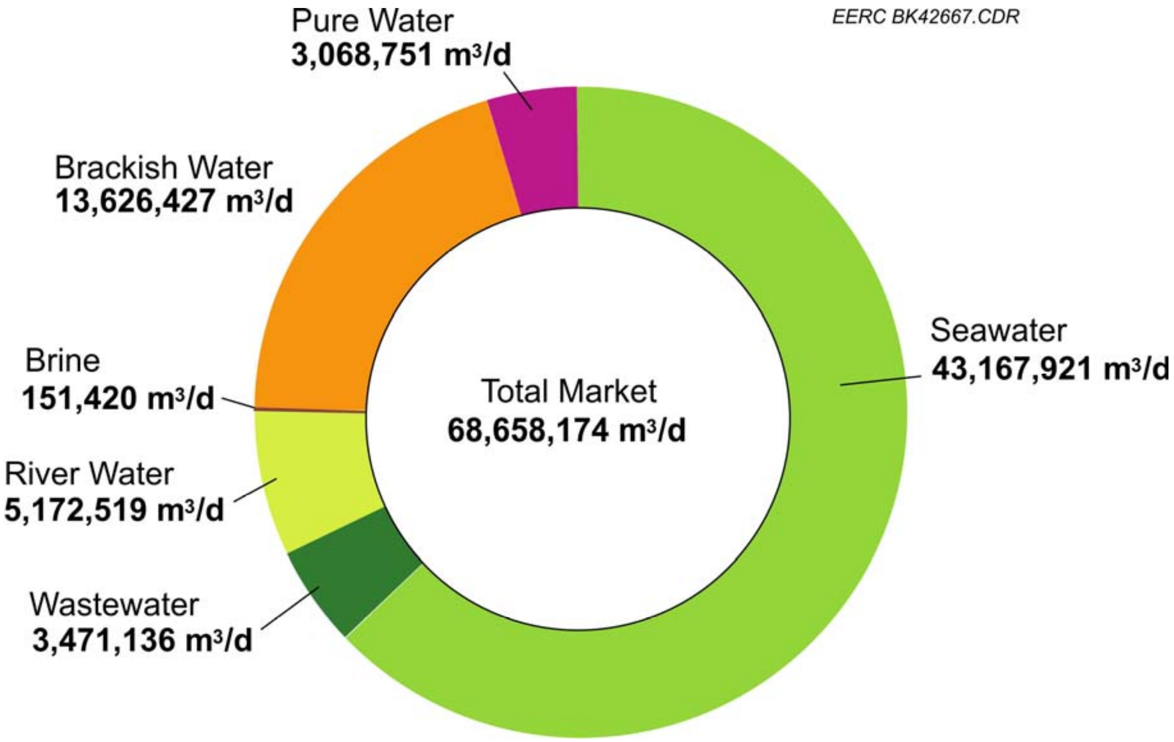

Figure 11. Desalination feedwater sources in the desalination market (DesalData.com, 2011).

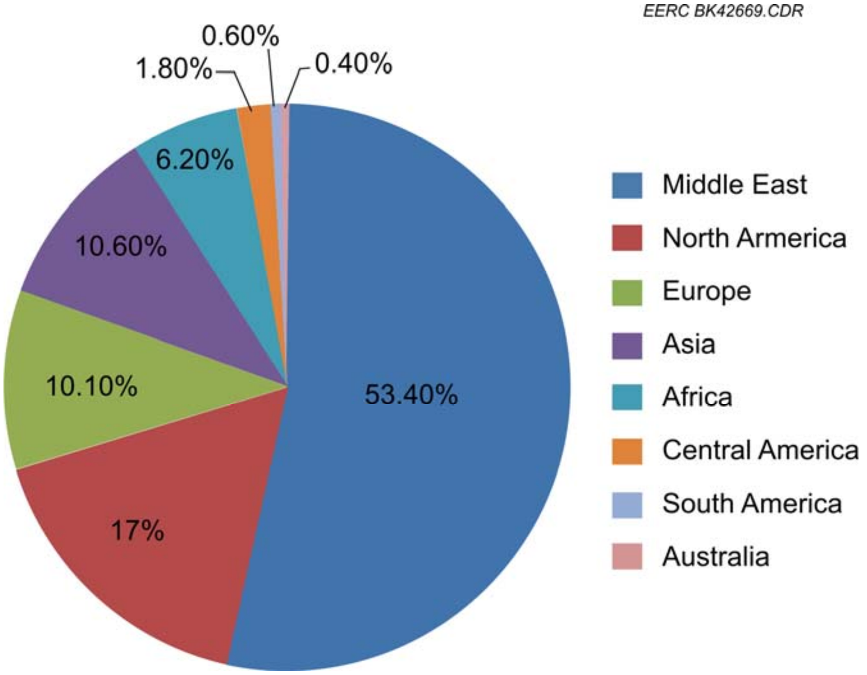

Figure 12. Distribution of desalination capacity (Tinos and Culligan, 2009).

The electrodialysis reversal (EDR) process is based on the same principles of electrochemistry as ED. The fundamental difference is that during the EDR process, the polarity of the cell is periodically reversed, usually 3 to 4 times per hour, to alter the flow of ions across the membrane. This action improves the tolerance of the technology to treat scaling-prone or turbid feedwater. EDR has largely replaced ED in the United States and in some overseas markets. EDR has a permeate recovery capacity and a salt rejection rate of 90% (compared to RO's 75%–85% permeate recovery capacity and 99% salt rejection rate). A significant disadvantage of EDR treatment is the cost, which is approximately twice that of RO (Hanson, 2008).

NF is a membrane process that primarily removes multivalent salt ions (such as calcium, magnesium, and sulfate) from solution, not monovalent ions (such as sodium and chloride), as seen in Table 5. As a result, NF is most commonly used for water softening and for nondesalting applications, such as removal of organic compounds. Given the high concentration of monovalent ions (such as sodium and chloride) in Dakota water, NF is not the best membrane treatment option for producing a low-TDS water.

RO is a membrane-based technology that employs dynamic pressure to overcome the osmotic pressure of the saline feedwater. RO uses thin, semipermeable membranes (Figure 13) to separate the feed stream into two streams of differing TDS concentration: a low-TDS product (permeate) and a high-TDS brine (concentrate). Pressure forces pure water through a membrane that retains dissolved solids. The retained dissolved solids are rejected from the system in the concentrate stream. The concentrate is disposed of either by introduction into a receiving water Body (ocean), evaporation ponds, or deep well injection into a geologic formation. The permeate is collected as product for beneficial uses.

Table 5. Comparative RO and NF Species Rejection Rates (Bisconer, 1998)

Species	RO, %	NF, %
Sodium Chloride, NaCl	99	0–50
Sodium Sulfate, Na_2SO_4	99	99
Calcium Chloride, $CaCl_2$	99	0–60
Magnesium Sulfate, $MgSO_4$	>99	>99
Sulfuric Acid, H_2SO_4	98	0
Hydrochloric Acid, HCl	90	0
Fructose, MW* 180	>99	>99
Sucrose, MW 360	>99	>99
Humic Acid	>99	>99
Viruses	99.99	99.99
Proteins	99.99	99.99
Bacteria	99.99	99.99

* Molecular weight.

EERC BK33819.CDR

Figure 13. Photo of RO treatment membranes used to desalinize water in El Paso, Texas (Hutchinson, 2007).

For the purposes of this study, RO was deemed the most appropriate and cost-effective technology for treatment of Dakota water. ED and EDR were not considered because of their reduced salt rejection rates and high system cost. As previously mentioned, NF was not considered because of its inability to remove monovalent ions. Figure 14 is a simplified schematic of an RO system.

RO FEEDWATER PRETREATMENT

Pretreatment of the feedwater for a RO plant is required to ensure that constituents present in the raw water supply do not cause plugging, fouling, or damage to the membranes, with a resulting loss of performance and a reduction in output of the facility.

RO Pretreatment Goals

- Biological activity and fouling – Biological fouling is generally not an issue with water from deep aquifers, such as the Dakota, that typically do not contain organic carbon at levels that support biological growth. However, given that the Dakota is a commonly targeted zone for produced-water disposal, residual hydrocarbons may create issues for treatment.

- Iron oxide fouling – Water from deep aquifers often contains dissolved ferrous iron (Fe^{2+}). Reduced iron remains in solution and will be removed by RO membranes; however, if any air is inadvertently introduced into the system, insoluble iron oxide will be formed. Iron oxide will foul the membrane, which requires, at a minimum, system shutdown and cleaning.

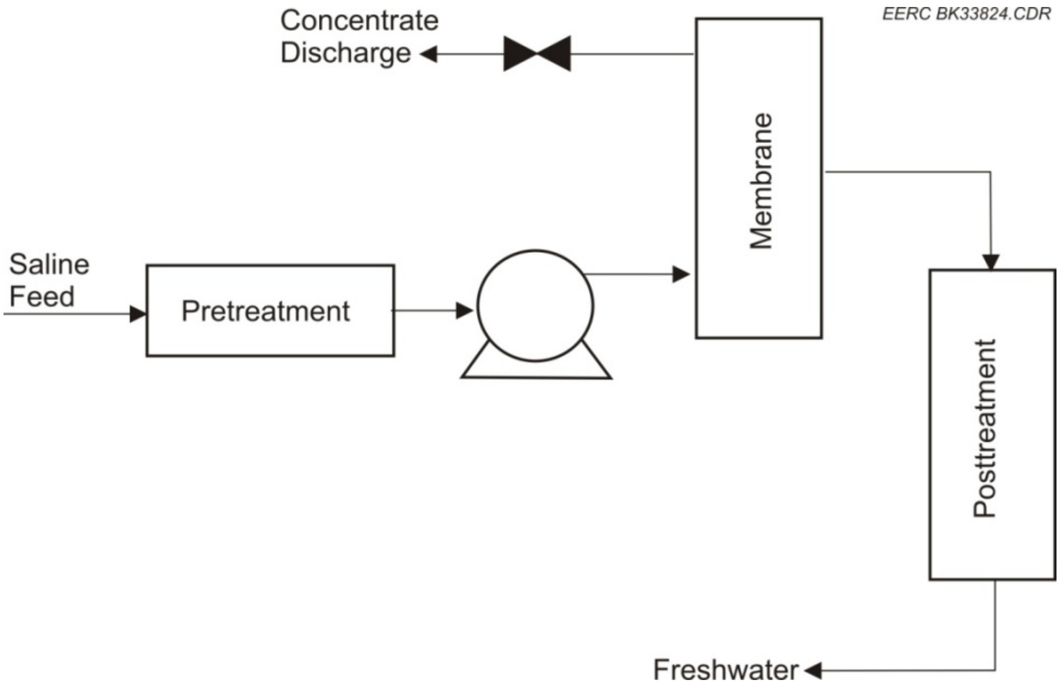

Figure 14. Block diagram of RO system.

There is a very real possibility that the iron fouling will destroy the permeability of the RO membrane, necessitating membrane replacement. Iron oxide formation is prevented by chlorine addition to induce iron precipitation, with subsequent filtration for iron removal prior to RO treatment. Excess free chlorine can damage membranes, so it is removed with the addition of bisulfite.

- Mineral scale – $CaCO_3$ or $CaSO_4$ scale formation occurs when the solubility limit of these compounds is exceeded on the concentrate side of the RO membrane. These scales can foul the membrane, requiring costly cleaning or replacement of RO membranes. Scale prevention can be successfully accomplished by adding antiscaling chemicals to the feedwater after iron removal.

- Silica precipitation – SiO_2 can precipitate out of the concentrate and form scale deposits that are very difficult to remove and may irreversibly damage membranes. Scale prevention can be successfully accomplished by adding SiO_2 antiscaling chemicals to the feedwater.

- Colloidal and particulate fouling – Some particulates and colloids, such as colloidal silica, are effectively removed via sand, cartridge, or stainless steel mesh filtration systems.

Pretreatment Processes

Pretreatment processes appropriate for RO systems include chlorine injection to precipitate iron, a scale inhibitor injection system to prevent scale formation, a fine filtration system to remove suspended solids and iron precipitate, and a cleaning system to periodically perform cleaning of the membranes and piping system.

- Iron oxidation system – Iron oxide formation is prevented by chlorine addition to induce iron precipitation, with subsequent filtration for iron removal. If iron removal is required, the chlorine additive step precedes the filtration step, and the precipitated iron is removed by the filtration system. Systems for storing and introducing these chemicals include bulk and day storage tanks, metering pumps, monitoring and control systems, and safety equipment.

- Fine filtration system – This usually involves the use of sand, cartridge, or stainless steel mesh filters with a 5–10-µm particle-size nominal retention. These filters are designed to prevent total suspended solids (TSS) from damaging either the feed pump or the membranes. Sometimes, the filters are located downstream of the feed pumps, in which case a fine mesh strainer would be included upstream to protect the pump from TSS.

- Scale control system – Most RO systems require adding a scale inhibitor and, perhaps, acid addition, for $CaCO_3$ or $CaSO_4$ scale control in the membrane array, since at least one constituent of the feedwater will often be supersaturated in the concentrate. Silica antiscalants may also be added as necessary. Systems for storing and introducing these chemicals include bulk and day storage tanks, metering pumps, monitoring and control systems, and safety equipment. The antiscalant chemicals are added after the fine filtration system.

- Cleaning system – It is good engineering practice to include a cleaning system in the requirements for a commercially sized RO system. A typical cleaning system consists of one or two tanks, a recirculation pump, a fine filtration device, and control and monitoring instrumentation.

Permeate Treatment

The permeate from RO plants is often blended with a portion of the feedwater to produce a finished water that is less corrosive to metal components in the water system and to increase the finished water yield. The secondary drinking water standard for TDS is 500 mg/L and is often the target to which the blending is aimed, with consideration to concentrations of sulfate, sodium, and perhaps other constituents. Stabilization of the water may require pH adjustment to an 8.0–9.0 range and addition of a low concentration of lime (CaO). The permeate is bacteria- and virus-free and is suitable for distribution after stabilization chlorination.

Concentrate Disposal

The RO system concentrate contains elevated concentrations of the salts contained in the feedwater and must be disposed of in an environmentally acceptable manner. Deep well injection is a common method for disposal of industrial, municipal, and liquid hazardous waste and is increasingly being considered as an option for disposal of desalination plant concentrate (Glater and Cohen, 2003). This method is used quite extensively in the western part of North Dakota for disposal of water produced from oil production. While other methods of concentrate disposal are available, such as evaporation ponds, evaporation/crystallization systems, and/or atomization/ land application, the most cost-effective method of concentrate disposal is likely through deep well injection.

PILOT PROJECT BACKGROUND

Site Description

This project was conducted near Tioga, North Dakota, at an existing site where a groundwater well site is screened in the Dakota Formation (Dakota) at a depth of approximately 5500 feet. The Dakota is part of the Lower Cretaceous aquifer system and is one of the most widespread aquifers in North America. It is present in most states of the Great Plains, from western Iowa to Montana and from the Arctic Circle to New Mexico (Kansas Geological Survey, 1996). In eastern North Dakota, groundwater from the Dakota has been used as a water source for livestock since the beginning of the 20th century, but because of its marginal quality and increased costs associated with treatment and pumping, it has been marginalized as a municipal or industrial water source. However, recent developments in water treatment technologies, coupled with the current water acquisition costs of water for Bakken fracturing, made the economic and technical evaluation of the Dakota's potential as a water supply source for the oil industry a logical endeavor.

The well at the Tioga location provides water that is used as part of a secondary oil recovery operation (waterflood) and is capable of sustaining moderate to high yields. The well has been pumped nearly continuously at a rate of 11,000 to 12,000 bbl per day (320 to 350 gallons per minute [gpm]) for several decades with no measurable impacts to hydrostatic water levels (Hess Corporation, personal communication, 2009); therefore, the additional pumping rate required for the relatively short duration of the pilot project was inconsequential.

Water samples collected from the well revealed that the water chemistry is predominantly sodium chloride in nature, with lesser amounts of sulfate and bicarbonate. TDS average about 8500 mg/L. Specific information on water chemistry is listed in Table 6. Because the Dakota is at such a great depth beneath the surface, the water exits the well at a temperature of approximately 155°F (68°C).

A key issue of concern related to treatment of brackish groundwater (especially when dealing with elevated temperatures) is corrosion of piping, pumps, cooling system components, and other materials that come in contact with the water. Because salinity levels of the formation water are elevated, corrosion could lead to costly equipment failures and corresponding inability to produce permeate at a high rate. Corrosion can be affected by chemical composition, temperature, pH, degree of aeration, flow velocity, and pressure. System-specific testing is helpful to most accurately evaluate corrosion potential. Therefore, the EERC conducted corrosion rate testing of the feedwater and concentrate streams to determine proper heat exchanger, piping, and valve material selection for a full-scale plant.

CORROSION AND SCALE FORMATION MODELING

A two-step approach was used to evaluate the corrosion potential of Dakota water during the pilot study. The first step was to evaluate the corrosion potential of various metals and alloys using computer modeling. The second step was to use the modeling results, coupled with an evaluation of materials likely to be used for a full-scale RO plant, to select corrosion coupons for installation and testing in conjunction with the pilot project. The following section describes the results of the corrosion analysis modeling, which also includes an evaluation of the scaling potential of the water. The results of the field-based testing of metal and alloy coupons are discussed later in this report.

The model-based evaluation of Dakota water was conducted using OLI Systems, Inc., Stream Analyzer and Corrosion Analyzer software to predict the potential for scale formation and corrosion based on the chemistry of the formation water and the predicted RO concentrate chemistry (at 60% recovery).[1] Corrosion rates for 19 metals and alloys were calculated for a water composition representing raw Dakota Aquifer water. Corrosion rates for carbon steel (A212B) and 316 stainless steel were also modeled using water compositions representing RO

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[1] Dr. Robert Cowan wishes to acknowledge and thank OLI Systems, Inc., for allowing his use of the Lab Analyzer, Stream Analyzer, and Corrosion Analyzer software for this project. The software was provided free of charge as part of a 3-month “Friends of OLI” license.

Table 6. Water Chemistry Results for Dakota Aquifer Samples

Analyte	Average Value	Units
Ba	0.11	mg/L
Ca	11.85	mg/L
Cl	4220	mg/L
F	3.9	mg/L
Fe	0.17	mg/L
Mg	2.4	mg/L
Mn	0.04	mg/L
NO_3	<1	mg/L
P, Total	<0.1	mg/L
PO_4	0.94	mg/L
K	14.4	mg/L
Si	16.3	mg/L
Na	3755	mg/L
SO_4	499.5	mg/L
HCO_3	1763	mg/L
Al	<0.1	mg/L
Cu	0.0034	mg/L
Hg	<0.1	µg/L
Pb	0.0024	mg/L
Sr	0.9	mg/L
Temperature (field)	152	°F
pH (lab)	7.8	–
Conductivity (lab)	14.1	mS/cm
Conductivity (field)	13.88	mS/cm
TDS (measured)	8820	mg/L
TDS (calculated)	10,339	mg/L
TSS	14.0	mg/L
Turbidity	2.2	NTU[1]
Alkalinity (as $CaCO_3$)	1445	mg/L
Hardness (as $CaCO_3$)	39	mg/L

[1] Nephelometric turbidity units.

feed and RO reject brine based on water chemistry provided by Hess. The water chemistry was based on an RO recovery rate of 60%, slightly less than the 72% average recovery achieved during the pilot project; however, at the time that the modeling work was conducted, a target recovery had not yet been established for the pilot. Scaling tendencies of all three waters were also calculated using the OLI Systems software. All calculations were performed over a temperature range of 70° to 170°F.

Dakota Aquifer Water Composition

The water chemistry shown in Table 6 was used as the basis for building the water chemistry conditions used in the corrosion calculations. The procedure used was to enter the Dakota Aquifer water analysis results in the OLI Systems Lab Analyzer software and reconcile the charge balance, pH, and alkalinity. The final composition of the water used in corrosion modeling is shown in Table 7.

Scaling Tendency

Scaling tendency is a measure of the likelihood of a dissolved species to precipitate from solution as a solid-phase chemical species. The results of the scaling tendency analysis for Dakota Aquifer water at 152°F are shown in Table 8. Only the 10 highest of the 128 scaling tendency values calculated are given. The results indicate that dissolved solids are likely to precipitate as a scale. A scaling tendency value of 1 indicates the water is supersaturated with respect to that mineral. A scaling tendency below 1 indicates mineral components are present at concentrations below saturation, but at values near 1, scaling may still be of concern. The scaling tendencies shown in Table 8 indicate that fluorapatite ($Ca_5[PO_4]_3F$) and four carbonates, siderite

Table 7. Lab Analysis Values Entered into OLI Lab Analyzer Software and Values after Reconciling Charge Balance, pH and Alkalinity (charge balance adjusted by addition of chloride ion; pH and alkalinity did not require adjustment)

	Input	Calculated	Units	% Diff.
Water	1.00E+06	9.94E+05	mg/L	−0.62
Si	16.3	16.3	mg/L	
Ba	0.11	0.11	mg/L	
Ca	11.85	11.85	mg/L	
Fe	0.17	0.17	mg/L	
Mg	2.4	2.4	mg/L	
Mn	0.04	0.04	mg/L	
K	14.4	14.4	mg/L	
Na	3755	3755	mg/L	
Al	0	0	mg/L	
Cu	0.003	0.003	mg/L	
Hg	0	0	mg/L	
Pb	0.002	0.002	mg/L	
Sr	0.9	0.9	mg/L	
Cl	4220	4390	mg/L	4.03
F	3.9	3.9	mg/L	
NO	0	0	mg/L	
PO_4	0.94	0.94	mg/L	
SO_4	499.5	499.5	mg/L	
HCO_3	1763	1763	mg/L	

Table 8. Scaling Tendency Values for the Ten Minerals Having the Highest Scaling Tendencies for Dakota Aquifer Water at 152°F and pH 8.2 (results valid through full temperature range evaluated [70°–170°F])

Solids Within Temperature Range	Scaling Tendency
Fluorapatite, $Ca_5(PO_4)_3F$	1
Iron(II) Carbonate	1
Manganese(II) Carbonate	1
Strontium Carbonate	1
Calcium Carbonate (calcite)	1
Barium Sulfate	0.624
Copper(II) Hydroxide	0.014
Magnesium Carbonate	0.011
Strontium Sulfate	0.008
Iron(II) Hydroxide	0.007

($FeCO_3$), magnesite ($MgCO_3$), strontianite ($SrCO_3$), and calcite ($CaCO_3$), will form a precipitate or scale unless the chemistry and/or temperature of the water is adjusted. Acid addition and removal of CO_2 through aeration of the water should eliminate the potential for calcite precipitation. The use of other scale inhibitors may be required to prevent fluorapatite precipitation. The apparent molecular composition of the solution suggests that the dominant solid formed would be calcium carbonate. The fact that the scaling tendency for barium sulfate is close to 1 is a potential concern. Barium sulfate scales are often associated with naturally occurring radioactive material (NORM) that can cause difficulties with respect to maintenance, reuse, and disposal of pipes and process equipment. The NORM issue arises because barium (and strontium) scales tend to coprecipitate radioactive radium.

Corrosion Evaluation

The 19 metals and alloys selected to evaluate the corrosion potential upon exposure to Dakota water are listed in Table 9. These include iron (two grades), carbon steel (four grades), stainless steel (four grades), aluminum alloys (two grades), nickel, and six other iron alloys (four Inconel® and two Hastelloy®). These are all of the metals and alloys available in the public database in OLI Systems Corrosion Analyzer software. Unfortunately, there was no option to evaluate titanium. Corrosion rate calculations were performed for flowing water over the velocity range of 0 to 20 ft/s and for every 10 degrees of temperature from 70° to 170°F. Table 9 includes a summary of the corrosion rate range for all of the metals and alloys studied. The lowest rate is always for the condition of 70°C and 0 ft/s. The highest rate is always for 170°C and 20 ft/s.

The results of the corrosion analyses were compiled in plots showing the corrosion rate in mils per year (mpy) versus the water flow velocity. Figure 15 shows an example of the model-predicted corrosion rate of carbon steel (212), stainless steel (316), and Hastelloy C-276. It should be noted that these are semi-log plots that show corrosion rates over a range of four orders of magnitude. The carbon steel exhibited a moderate corrosion rate and would be

Table 9. Range of Corrosion Rates Calculated for All 19 Metals and Alloys Studied

Metal or Alloy Name	Lowest Calculated Corrosion Rate (mpy) (velocity = 0 ft/s; temperature = 70°F)	Highest Calculated Corrosion Rate (mpy) (velocity = 20 ft/s; temperature = 170°F)
Fe (zone refined)	0.051	0.278
Fe (pure)	0.051	0.278
Carbon Steel A212B	0.102	2.799
Carbon Steel A216	0.102	2.799
Carbon Steel G10100 (generic)	0.102	2.709
Carbon Steel 1018	0.102	2.732
Stainless Steel 304	0.104	0.275
Stainless Steel 316	0.018	0.096
Stainless Steel Alloy 254SMO (alloy 254, vlx954)	0.011	0.075
10% Cr Stainless Steel	0.073	0.346
Aluminum 1199 (pure)	0.066	16.890
Aluminum 1100	0.065	16.811
Ni	0.021	0.230
Superalloy Inconel 600™	0.005	0.019
Inconel Nickel Chromium Alloy 625	0.004	0.008
Superalloy Inconel 690™	0.004	0.018
Incoloy 825®	0.004	0.009
Hastelloy Alloy C-276	0.004	0.008
Hastelloy C-22	0.004	0.008

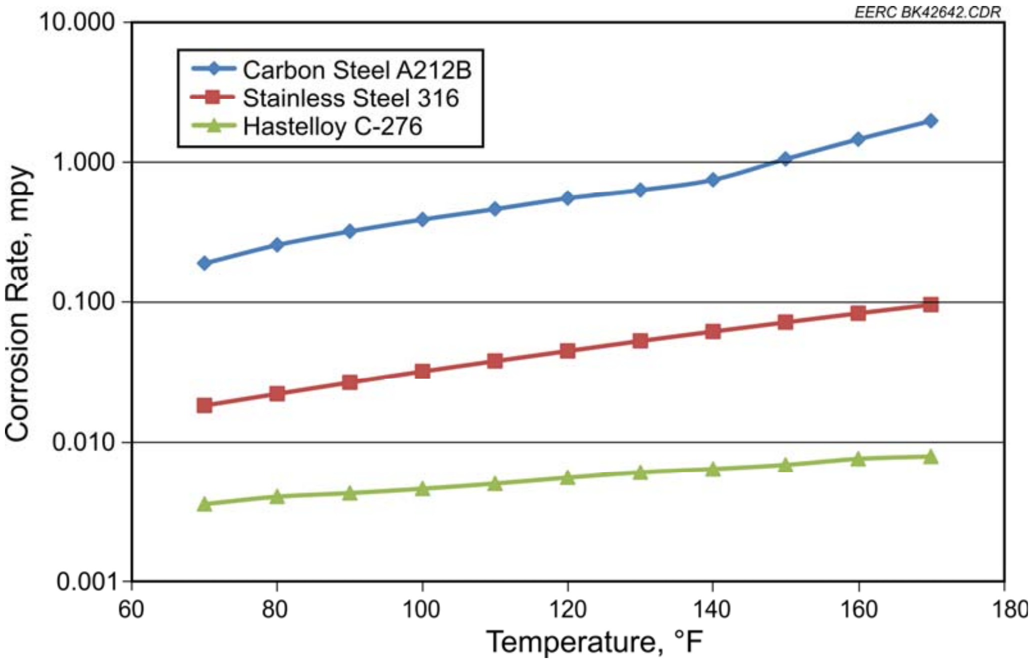


Figure 15. Predicted corrosion rates of carbon steel (A221B), stainless steel (316), and Hastelloy C-276 by raw Dakota water.

acceptable for use under certain conditions. The stainless steel had a very low rate of corrosion and should be acceptable for use over the full range of conditions for which calculations were performed. The Hastelloy C-276 alloy exhibited an even lower rate of corrosion and would certainly be suitable for use with Dakota water; however, the additional cost of the alloy over stainless steel may prohibit its use.

It is interesting to note that while the stainless steel and Hastelloy C-276 (as well as most other alloys evaluated) showed very little variation in the predicted corrosion rate as a function of flow velocity, the carbon steels that were evaluated were highly influenced by the flow velocity over the range of temperatures evaluated (Figure 16). This may be of significance if interest in using water from the Dakota increases since carbon steel pipes are commonly used in North Dakota's oil and gas operations.

The acceptability of the calculated corrosion rate depends on the material and the application. For example, to evaluate the severity of the carbon steel corrosion rates calculated using the OLI software, a comparison of corrosion rates was made to guidelines developed by Boffardi (2010) and Puckorius (2003) for open and closed recirculating cooling water systems (Tables 10 and 11). The modeled corrosion rates for carbon steel ranged from negligible to severe, depending on the temperature, velocity, and application. More specifically, the lowest rate of corrosion for Carbon Steel A212B was found to be 0.102 mpy for a velocity of 0 ft/s and a temperature of 70°F. This is considered to be negligible corrosion for an open recirculating cooling water system and mild corrosion for a closed recirculating cooling water system. The highest rate of corrosion for Carbon Steel A212B was found to be 2.799 mpy for a velocity of 20 ft/s and a temperature of 170°F. This is considered mild for open recirculating cooling water systems and severe for closed recirculating cooling water systems.

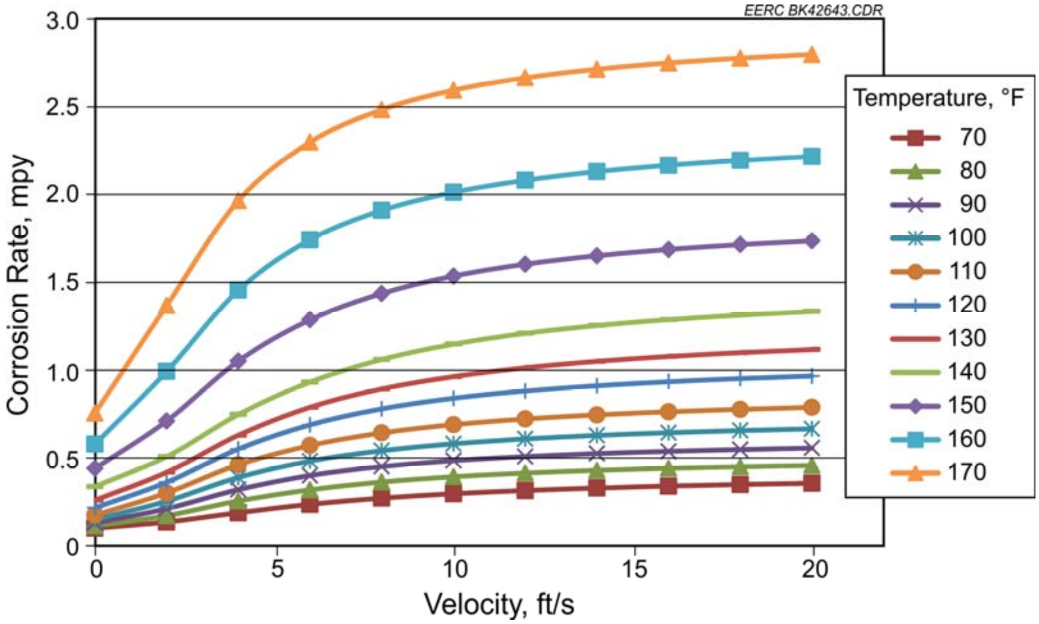


Figure 16. Predicted corrosion of Carbon Steel A212B by Dakota water over a range of temperatures and flow velocities.

Table 10. Quantitative Classification of Carbon Steel Corrosion Rates for Open Recirculating Cooling Water Systems

Description	Corrosion Rate, mpy
Negligible or Excellent	Less than or equal to 1
Mild or Very Good	1 to 3
Good	3 to 5
Moderate to Fair	5 to 8
Poor	8 to 10
Very Poor to Severe	>10

Table 11. Quantitative Classification of Carbon Steel Corrosion Rates for Closed Recirculating Cooling Water Systems

Description	Corrosion Rate, mpy
Excellent	Less than or equal to 0.2
Good	0.2 to 0.5
Moderate	0.5 to 0.8
Poor	0.8 to 1
Very Poor to Severe	Greater than or equal to 1

Within these systems, stainless steel corrosion is more simply classified in both systems as acceptable for rates less than 0.1 mpy or unacceptable for rates greater than 0.1 mpy. In these systems, pitting of any metal is considered unacceptable.

Based on the results of the corrosion analyses and the corrosion rate classification of the various materials, the metals were ranked into five groups, as shown in Table 12. Corrosion rates vary over 4 orders of magnitude, with the lowest rates being <0.004 mpy for Alloys C-22, C-276, 625, and 825 and the highest rates being near 16.8 mpy for Aluminum 1100 and Aluminum 1199. It should be noted that the corrosion rates were calculated for an environment containing no dissolved oxygen.

Table 12. General Classification of Metals and Alloys Based on the Calculated Corrosion Rates with Dakota Water

Excellent	Alloys C-22, C-276, 625, and 825 Alloys 600 and 690
Very Good	Alloy 254SMO and Stainless Steel 316
Good	Fe (pure), Fe (zone refined), Ni, Stainless Steel 304, and 13% Cr stainless steel
Fair	Carbon Steel 10100,1018, A216, and A212B
Very Poor/Unacceptable	Aluminum 1100 and 1199 (pure)

These results, along with information on the price and availability of metals for use in heat exchangers, as well as knowledge on standard material use in the oil field were used to help guide in the selection of corrosion test coupons. Selected corrosion test coupons were subsequently installed at the RO treatment pilot project site for field testing. Those results are discussed later in this report.

Corrosion and Scaling Analysis for Anticipated RO Concentrate (at 60% recovery)

Additional corrosion calculations were performed based on a predicted brine (concentrate) composition of Dakota water after treatment with RO at 60% recovery. These data were much less detailed than that used for the raw Dakota water analysis discussed above. No scaling or corrosion analyses were done for RO permeate.

The same methodology used to evaluate the raw Dakota water was used to evaluate the anticipated RO concentrate. The water analysis results were entered into the OLI Systems software and reconciled with respect to electroneutrality, pH, and alkalinity (Table 13). The scaling tendency values were also calculated and are shown in Table 14. The resulting apparent molecular composition of the water was obtained and used to calculate corrosion rates for two metals (316 stainless steel and Carbon Steel A212B) over the temperature range of 70° to 170°F and water velocities of 0 to 20 ft/s.

Table 13. RO Concentrate Water Analysis and Reconciliation

	Input	Calculated	Unit	% Diff.
Water	1.00E+06	9.91E+05	mg/L	−0.88
Si	81	81	mg/L	
Ca	26.2	26.2	mg/L	
Mg	4.5	4.5	mg/L	
K	22.5	22.5	mg/L	
Na	6777	6777	mg/L	
Cl	7875	8203	mg/L	4.16
SO_4	972	972	mg/L	
HCO_3	2772	2772	mg/L	

Table 14. Scaling Tendency for RO Concentrate (minerals with 5 highest values) (values are valid over the temperature range evaluated [70°–170°F])

Tendency	Scaling
Calcium Carbonate (calcite)	1
Calcium Carbonate (aragonite)	0.514
Calcium Carbonate Monohydrate (vaterite)	0.130
Sodium Bicarbonate (nahcolite)	0.010
Calcium Sulfate Dehydrate (gypsum)	0.003

The only reconciliation required for the RO concentrate was the addition of a small amount of chloride ion in order to obtain electroneutrality (Table 15). Scale formation with calcium carbonate minerals in the concentrate is possible even at the temperature of the water analysis, 25°C, as evidenced by the scaling indices given in Table 15. Because the simplified water analysis did not include strontium, barium, or fluoride, the analysis could not identify a potential for the formation of the other scale minerals identified for the more detailed Dakota Aquifer water.

Table 15 contains the lowest and highest calculated corrosion rates for both carbon steel and stainless steel. As would be expected, the results suggest that the RO concentrate would be more corrosive to Carbon Steel A212B and 316 stainless steel than the raw Dakota water. While the corrosion rate of 316 stainless steel was very similar between the raw Dakota water and RO concentrate, the predicted corrosion rate of Carbon Steel A212B was considerably higher with the RO concentrate, particularly with increasing flow rate and at higher temperatures. These rates suggest that Carbon Steel A212B would be unacceptable for use with the RO concentrate except at the lowest flow rate and temperature conditions. The rates predicted for 316 stainless steel suggest that it would be acceptable for use with the RO concentrate at 60% recovery.

MOBILE RO TREATMENT SYSTEM

After evaluating several mobile technology treatment system providers, Hess selected General Electric (GE) Water and Process Technologies as the preferred pilot system provider. GE's MobileRO® is a mobile RO water treatment system, consisting of two semitrailers and several skid-mounted components, including all the hardware and electronics necessary to monitor the system operation and performance. Given the quality of the feedwater at the pilot project site, GE estimated that, at full capacity, the system would be capable of producing approximately 160 gpm of permeate at a 75% recovery rate. Because the system contains two independently operated filter arrays, it could also be operated at reduced capacity, equivalent to approximately 80 gpm of permeate at a 75% recovery rate. The mobile system contained all necessary prefilters, the antiscalant treatment system, controls, piping, valves, and instrumentation. All operations associated with the mobile RO unit were the responsibility of GE personnel for the duration of the pilot test.

Table 15. Range of Corrosion Rates Calculated for Carbon Steel A212B and S316 Stainless Steel by the Anticipated RO Concentrate

Metal or Alloy Name/Water	Lowest Calculated Corrosion Rate, mpy (velocity = 0 ft/s; temperature = 70°F)	Highest Calculated Corrosion Rate, mpy (velocity = 20 ft/s; temperature = 170°F)
Carbon Steel A212B	0.184	7.919
316 Stainless Steel	0.018	0.096

SITE PREPARATION

In order to prepare the site for the pilot project, several activities were conducted, including the following:

- Installation of the RO treatment and pretreatment units.
- Installation of the feedwater cooling system and heat exchangers.
- Construction of a lined and covered pond for storage of the treated water (RO permeate).
- Installation of five 400-barrel tanks that are used to store the feedwater, excess permeate (if needed), and RO concentrate (the RO concentrate tank is designed to meet saltwater storage standards).
- Installation of the necessary piping to connect the system components.
- Installation of the electrical power supply and necessary connections.
- Construction of a truck-loading station that is used to transport the RO permeate to fracturing locations within the Bakken play.
- Installation of corrosion coupon test racks to evaluate the corrosivity of the feedwater, permeate, and concentrate on various metals and metal/alloys.

One of the challenging aspects of the pilot project was the cooling of the feedwater, which exited the production well at a temperature of approximately 155°F (68°C), down to the required 90°F (32°C) prior to membrane treatment during the summer months, when temperatures can exceed 90° or 100° and humidity can be high. In fact, the pilot project cooling system did not provide sufficient cooling capacity during a couple of the hottest days of the summer, resulting in system shutdown during the afternoon hours. While the high feedwater temperature was an inconvenience with respect to the RO membranes, the heat from the water can also be a potential resource, given that the desired temperature of the fracturing fluid prior to injection is approximately 80°F (27°C). During the winter months, the cost to heat the fracturing fluid prior to injection is considerable and can sometimes exceed $150,000 or more to heat the water required for one well fracturing (Hess Corporation, personal communication, 2010). Therefore, heat exchangers were installed by Aggreko at the pilot project site to partially cool the feedwater using the RO permeate, which exited the system at approximately 90°F (32°C), and, in turn, to heat the permeate prior to use as frac water makeup.

As previously mentioned, because of the potential corrosivity of the feedwater and RO concentrate, in situ corrosion testing was conducted as part of the pilot test. A total of six test racks, each equipped to hold either three or five test coupons, were installed at various locations in the treatment train of the RO system. The location of the test racks as well as a generalized layout of the pilot-scale RO system is depicted in Figure 17. Groundwater from the Dakota

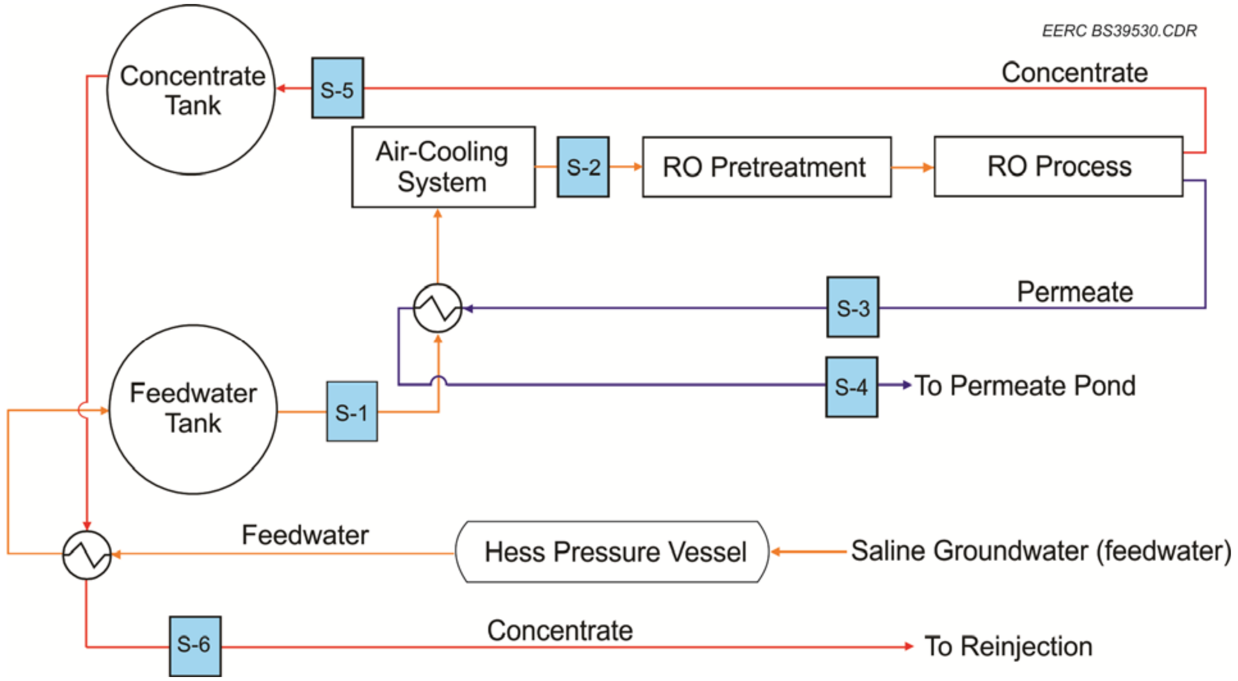


Figure 17. Flow diagram with corrosion test rack locations.

Aquifer was pumped from the well to a surge tank (pressure vessel). Water was routed from the surge tank to a 400-bbl feedwater tank where it was stored prior to entering the cooling, pretreatment, and RO systems. The first corrosion coupon test rack (S-1) was installed to evaluate feedwater corrosivity just prior to cooling. The first step in the cooling process was a tube-and-shell heat exchanger between the hot feedwater and the RO permeate, followed by an air-cooled system with foggers. The temperature of the hot feedwater from the storage tank prior to cooling was approximately 125°–130°F. After passing through the cooling system, the feedwater was lowered to a temperature of approximately 80° to 90°F. The second corrosion coupon test rack (S-2) was installed at this point in the system to evaluate the corrosivity of the cooled feedwater before undergoing pretreatment. Prior to entering the RO trains, the water underwent pretreatment via sand filtration and granulated activated carbon adsorption to remove suspended solids and dissolved organics, respectively. It was very important to remove any organic carbon from the feedwater, since this can result in membrane fouling. The water was then routed through one of the two RO treatment trains. Upon exiting the RO membranes, the permeate was routed back through the heat exchangers to help cool the feedwater, prior to storage in the lined and covered pond. Corrosion test racks were installed to evaluate the permeate upon exiting the system (S-3) and following heat exchange with the permeate (S-4). The concentrate was routed to a 400-bbl storage tank prior to blending with raw Dakota water for injection into existing waterflood operations. The corrosion potential of the concentrate just after exiting the RO system was evaluated at location S-5. In addition to evaluating the corrosivity of the concentrate at 80° to 90°F, a titanium plate and frame heat exchanger was installed at the site and coupled with the feedwater to heat the concentrate up to approximately 115° to 120°F (S-6). This evaluation was conducted to assess the corrosivity of the concentrate in the event that it be used in a heat exchanger as part of the cooling system for future applications.

PILOT TEST OPERATION AND PERFORMANCE

The pilot project system began operation on July 21, 2010, at a permeate flow rate of 80 gpm and 50% permeate recovery. Higher permeate recovery rates were not achievable until GE performed system modifications on August 3, 2010, at which time the recovery rates increased to approximately 70%. GE continued to operate the RO system at a flow rate (80 gpm of permeate production) to be consistent with the truck hauling cycle demands and maintain a more constant, steady operation. The permeate produced from the system was used for fracturing the Bakken, and the concentrate was blended with the waterflood injection system feedwater.

The RO system continued to operate at a permeate flow rate of 80 gpm with 70% permeate recovery until September of 2010, when the system was shut down to make alterations to the permeate holding pond, to address electrical issues at the truck loading station, and to winterize the site. Based on GE operational logs, from July 21, 2010, through September 6, 2010, a total of 6,084,700 gallons of groundwater was processed through the RO system, resulting in approximately 4.26 million gallons of permeate and approximately 1.83 million gallons of concentrate. Although no flow measurements were recorded during the shutdown period, GE did operate the RO system approximately 1 hour each day to prevent membrane fouling.

After the necessary system modifications were made, GE began continuous operation of the RO system on November 29, 2010, and as of April 13, 2011, had processed approximately 19 million gallons of Dakota Aquifer water. Continuous operation of the system was only stopped during three short periods:

- January 1, 2011
- February 25, 2011, through February 28, 2011
- March 22, 2011, through March 25, 2011

GE personnel observed lower flow rates (Figure 18), lower operating pressures (Figure 19), and higher permeate conductivity (Figure 20) when operating RO Train 1. Because of those conditions, GE primarily operated RO Train 2 throughout the demonstration and only occasionally operated Train 1 in order to mitigate membrane scaling. The cause of the operational differences between the two trains is unknown. Train 1 was operated for approximately 39 days, resulting in the treatment of 5.5 million gallons, and Train 2 was operated for approximately 88 days, resulting in the treatment of approximately 13.5 million gallons. Feed water temperature was monitored during operation and is shown in Figure 21. The feed water temperature ranged from 62° to 95.0°F and averaged 81.3°F during continuous operation (November 29, 2010, through April 13, 2011).

Feedwater flow rates were lower while Train 1 (103 gpm) was operated compared to Train 2 (124 gpm). Resulting permeate flow rates were also impacted, averaging 73 gpm on Train 1 compared to 90 gpm on Train 2. Permeate conductivity also showed a difference, averaging 585 microseimens per centimeter (µS/cm) on Train 1 and 395 µS/cm on Train 2.

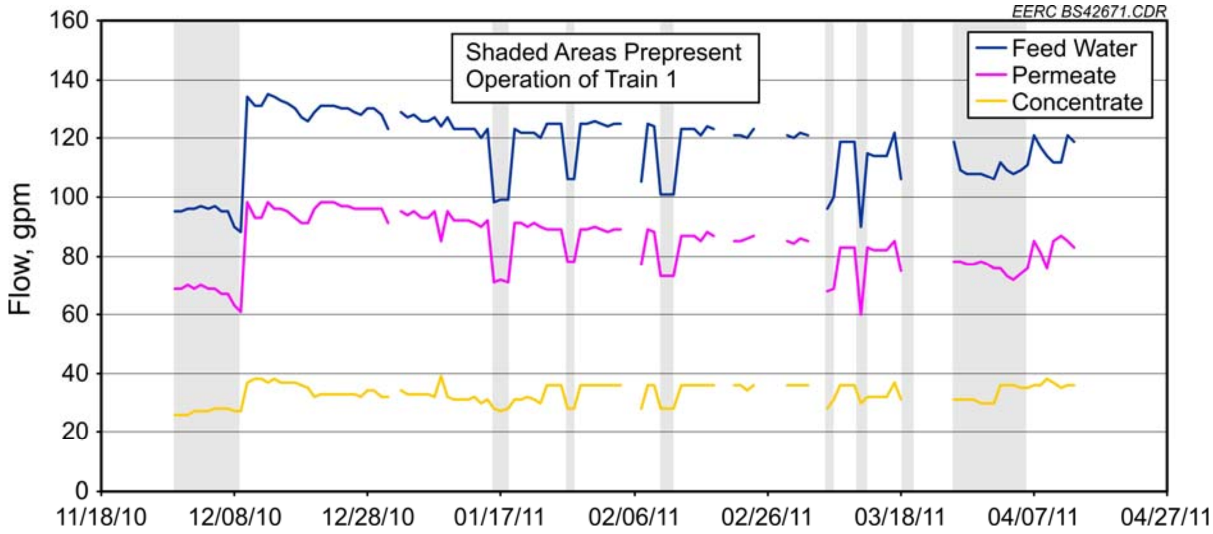


Figure 18. Pilot-scale RO system flow rates.

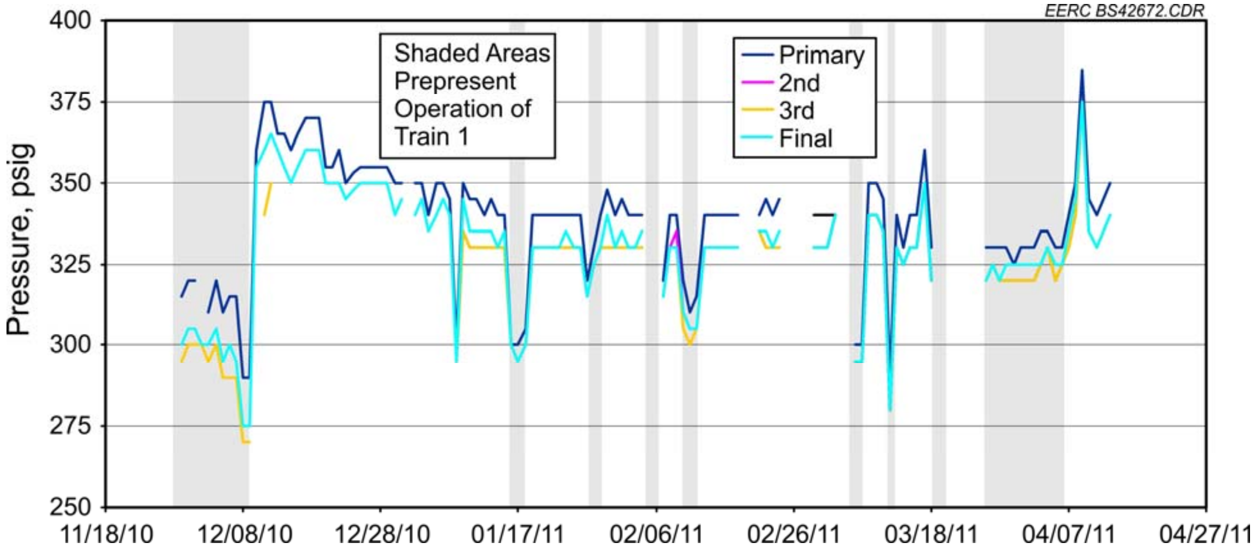


Figure 19. Pilot-scale RO system operating pressures.

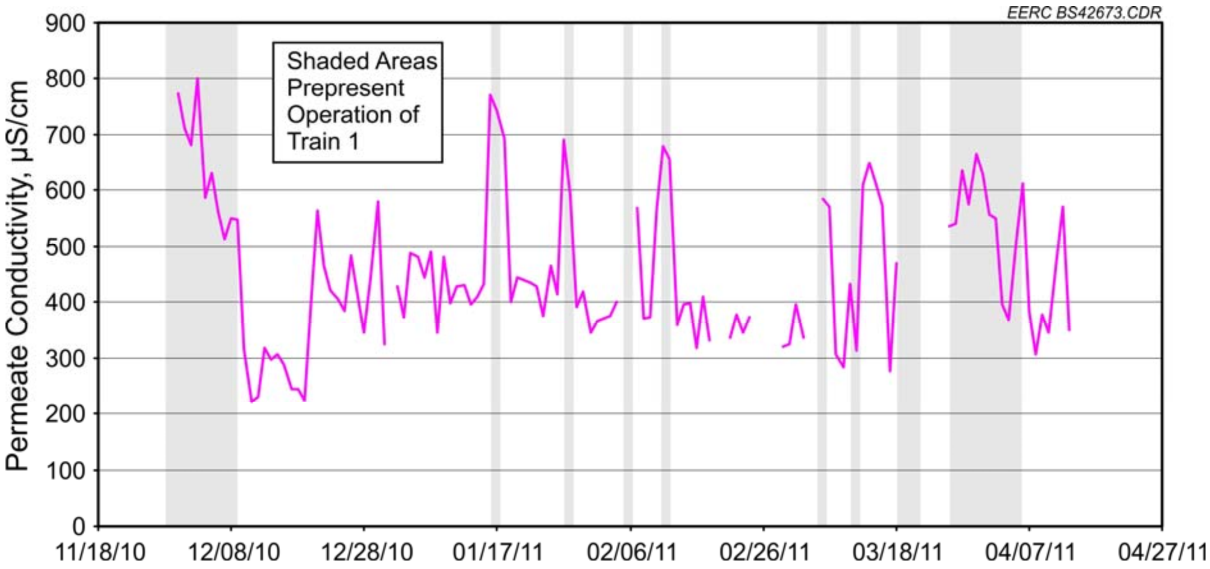


Figure 20. Pilot-scale RO system permeate conductivity.

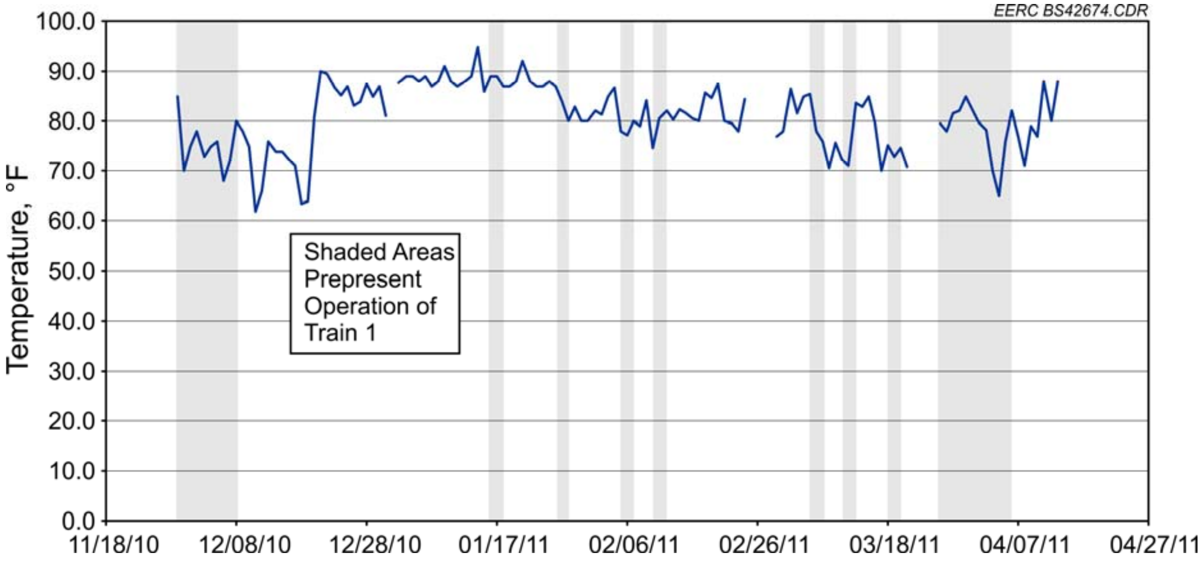


Figure 21. Pilot-scale RO system feedwater temperature.

As expected, the RO permeate was very high quality, and all major chemical constituents, except iron (Fe), were below Environmental Protection Agency secondary drinking water standards. As shown in Table 16, there was a 97% reduction in TDS concentration along with a 96% reduction in conductivity. Most major chemical constituents in the feedwater were reduced by greater than 90%. Alkalinity was reduced by 94%, and pH was measured at 6.06 in the permeate. Iron was measured at higher levels in the permeate than in the feedwater. However, the analytical techniques used to measure the iron concentrations are less susceptible to interferences with clean water than with the brackish feedwater, and one could argue that the data are inconclusive with respect to iron. RO treatment did not appear to remove any total organic carbon (TOC).

Given the issues with Train 1 operation, system performance was analyzed solely based on the operation of Train 2. Permeate recovery rates remained relatively consistent, averaging nearly 72% over the current operating period. Throughout the testing period, membrane cleaning was not deemed necessary, and no scaling was observed. GE personnel credited the low-turbidity feedwater for the lack of membrane fouling. GE performed backwash operations on a once-a-week basis as preventive maintenance. Since pressure readings did not indicate the need for more frequent backwashing, this frequency appeared to be sufficient to maintain desired operational pressures. GE records also indicated that once the system was stabilized, the feedwater conductivity was consistently around 14,000 µS/cm, and the permeate averaged 700 µS/cm. Figure 22 is a plot of conductivity of Train 2 during continuous operations.

Each treatment train consisted of 30 RO elements, and each element was nominally 365 square feet of surface area. This equates to each treatment train consisting of 10,950 square feet of surface area. By dividing the daily flow rate by the surface area of the treatment train, a flux rate in gallons per square foot per day (gfd) was calculated. A summary of permeate flux is presented in Table 17 and graphically shown in Figure 23. A regression of this data indicates that the flux would likely stabilize at approximately 15 gfd.

Additionally, flux was plotted against temperature and pressure differential as presented in Figures 24 and 25, respectively. As expected, the flux decreases with decreasing temperatures but not significantly over the range of temperatures experienced during the pilot test. Differential pressure also did not greatly influence the system flux over the range from 5 to 15 psig. In both cases, the flux maintained nominally between 14 and 16 gfd for the observed range of temperature (60º to 95°F) and differential pressure (0 to 20 psi).

Table 16. Summary of Water Analysis Results (units in mg/L unless otherwise noted)

Analyte	Feedwater (S-1)	Permeate (S-4)	Concentrate (S-5, S-6)*	% Reduction
Ca	15.8	3.0	44.4	81
Na	3300	103	10,750	97
K	9.9	<1	42.8	>90
Cl	3710	130	13,200	96
SO_4	456	<5	1460	>99
NO_3	<0.1	<0.1	0.14	–
HCO_3	1220	74	3820	94
Ba	<0.5	<0.1	<1	–
F	3.57	0.14	12.8	96
Fe	<0.5	0.66	<1	–
Mg	2.6	<1	7.9	>62
Mn	<0.25	<0.05	<0.5	–
P, total	<0.1	<0.1	0.96	–
Si	17.2	<1.1	56.3	>94
Cu	<0.25	<0.05	<0.5	–
Sr	0.98	<0.1	2.92	>90
Temperature (field), °F	127	110	96, 118*	
pH (lab)	7.4	6.2	7.8	
pH (field)	7.32	6.06	7.55	
Conductivity (lab), µS/cm	13,600	568	37,700	96
Conductivity (field), µS/cm	15,400	610	41,500	96
Total Dissolved Solids (calculated)	8230	280	27,800	97
Alkalinity (as $CaCO_3$)	1220	74	3820	94
Hardness (as $CaCO_3$)	50.2	7.49	144	85
Total Organic Carbon	5.9	4.9	7.1	17

* Because the water chemistry results from Racks S-5 and S-6 were not significantly different, they were averaged in this column, with the exception of temperature, which is listed separately for Racks S-5 and S-6, respectively.

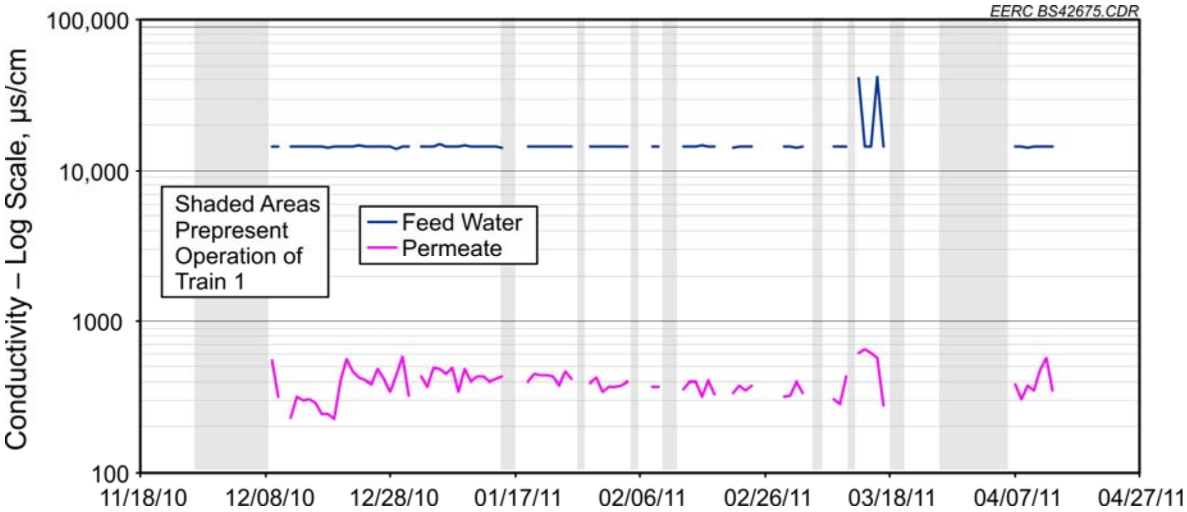


Figure 22. Treatment Train 2 feedwater and permeate conductivity.

Table 17. Summary of Flux Calculations

Treatment Train	Minimum, gfd	Maximum, gfd	Average, gfd
Train 1	11.57	17.23	13.51
Train 2	14.73	17.75	16.29

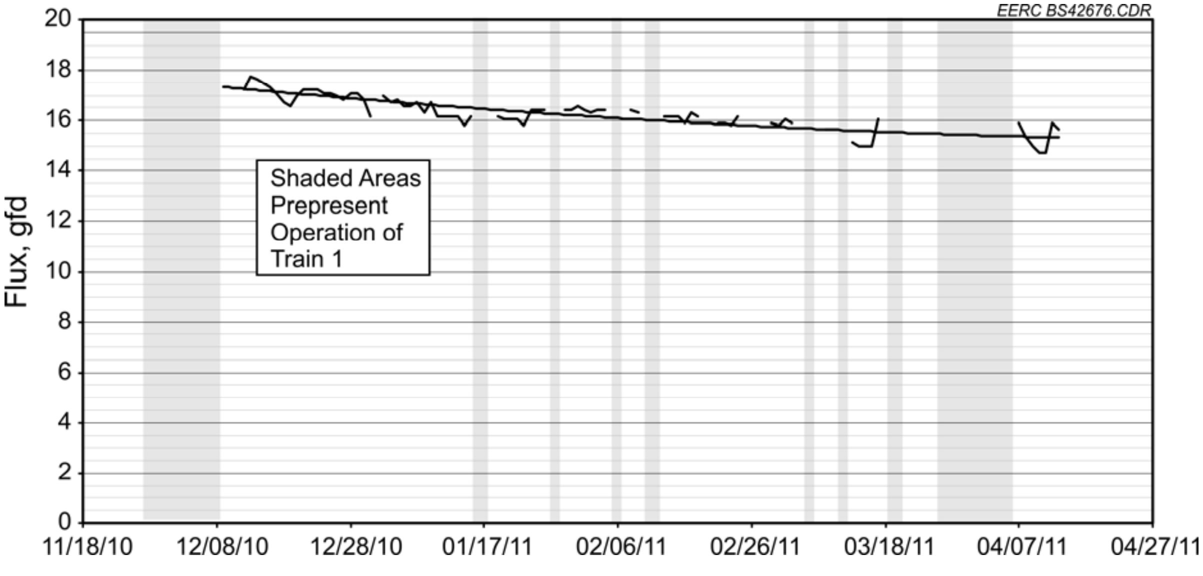


Figure 23. Treatment Train 2 flux versus time.

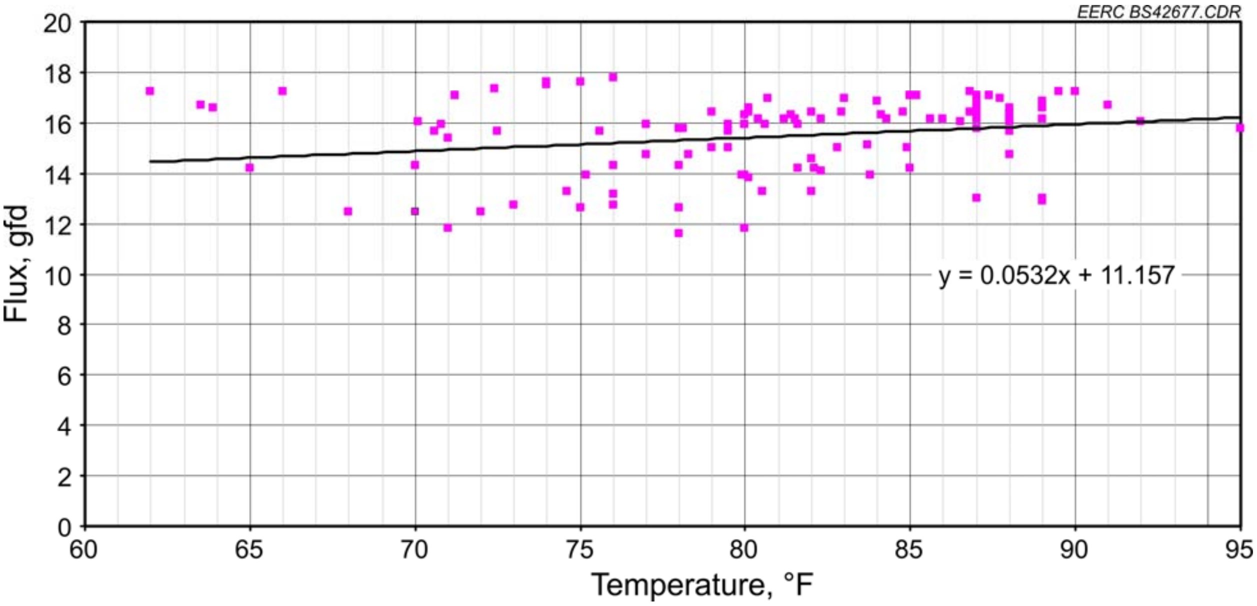


Figure 24. Flux versus temperature.

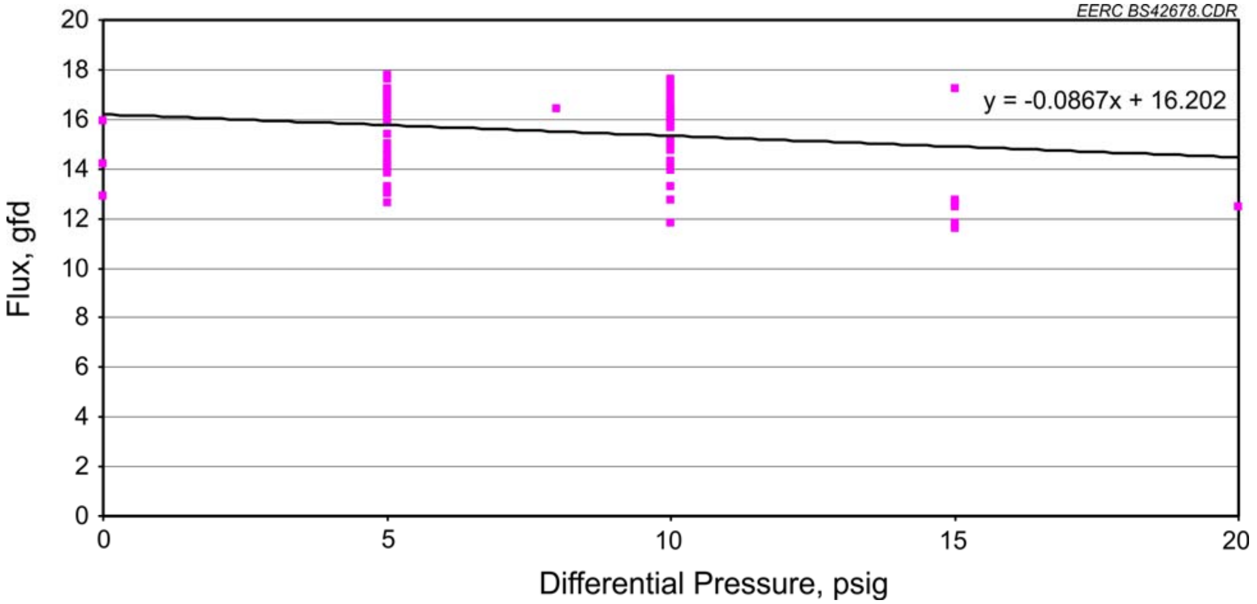


Figure 25. Flux versus pressure differential.

FIELD-BASED CORROSION TESTING

Shortly after start-up of the system, six corrosion test racks were installed at the subject site. Based on corrosion modeling results presented earlier, the test coupons selected for evaluation included four standard materials: carbon steel (API 5LX42), stainless steel (316L), copper–nickel alloy (CDA706), and titanium (Ti), as well as a more exotic alloy, Hastelloy C276, that is a nickel–molybdenum–chromium wrought alloy characterized by versatile corrosion resistance. The coupon racks were constructed of ¾-inch Schedule 80 PVC (polyvinyl chloride) pipe which has an internal diameter of 0.722 inches. The type of test coupon and operating conditions for each rack are included in Table 18. The discharge from Racks S-1, 2, 3, and 4 were manifolded together and plumbed to discharge into the feed tank. Figure 26 is a photograph of Rack S-2, a five-place corrosion test rack assembly. The discharge from Racks S-5 and S-6 were plumbed to discharge into the reject tank. During the installation and testing of the racks, EERC personnel were unable to attain enough water flow through Racks S-3 and S-4 to maintain desired corrosion test conditions. This was caused by insufficient water pressure on the influent side of the rack to overcome the pressure at the discharge point. While the test racks could have been relocated, it would have entailed shutting down the system. Since permeate corrosivity was expected to be minimal, no test coupons were installed in Racks S-3 and S-4.

Table 18. Corrosion Rack Description

Rack No.	Rack Material	Number of Coupons	Coupon Order	Fluid	Fluid Design Temperature	Observed Temperature
S-1	CPVC[1]	5	Ti C276 316L CDA706 API 5LX42	Feedwater	155°F (68°C)	127°F (53°C)
S-2	PVC	5	Ti C276 316L CDA706 API 5LX42	Feedwater	90°F (32°C)	80°F (27°C)
S-3	PVC	3	No coupons	Permeate	90°F (32°C)	–
S-4	CPVC	3	No coupons	Permeate	130°F (54°C)	110°F (43°C)
S-5	PVC	3	Ti 316L API 5LX42	Concentrate	90°F (32°C)	96°F (36°C)
S-6	CPVC	3	Ti 316L API 5LX42	Concentrate	155°F (68°C)	118°F (48°C)

[1] Chlorinated PVC.

Figure 26. Photograph showing the installation of corrosion test Rack S-2.

Following installation of the corrosion test racks, water was allowed to flow through the racks for several weeks to flush the system prior to coupon installation, as recommended by the test rack manufacturer. Sample flow rates through the coupon racks varied between 0 corrosion and 5 gallons per minute, corresponding to a flow velocity in the coupon racks between 0 and 3.92 ft/s (0 and 1.19 m/s).

The test coupons were installed in the racks in the order shown in Table 19, which represents their anticipated resistance to corrosion from most to least. This was done to minimize the potential of corrosion from one test coupon influencing the corrosion rate of subsequent test coupons. The only notable issue observed during coupon installation was the presence of a black residue on the Rack S-1 flowmeter and coupon holders. This residue was later determined to be a form of hydrocarbon, although detailed testing to determine the exact nature and source of the residue was never conducted.

On November 9, 2010, the corrosion racks and associated piping were retrieved to prevent any damage occurring from freezing temperatures. The corrosion coupons were removed from their respective racks, visually inspected, photographed, and allowed to dry overnight.

Upon retrieval, the corrosion coupons from Rack S-1 (127°F feedwater) were covered in the same black coating that appeared on the coupon holder and the flowmeter during the August 26, 2010, site visit. Coupons removed from Rack S-2 (80°F feedwater) also exhibited a slight black coating. The black residue was not observed in any of the other test racks. As previously mentioned, a sample of the black residue was collected, and some preliminary testing indicated that it was a type of hydrocarbon. Additional testing of the residue to determine its exact composition has not been conducted.

Table 19. Comparison of Measured and Predicted Corrosion Rates

Rack	Fluid	Coupon	Metal	Measured Corrosion Rate, mpy	Predicted Corrosion Rate, mpy	Temperature and Flow Rate for Predicted Rate[2]
S-1	Feedwater, 127°F	Ti-2	Titanium	0.0968	NA	
S-1	Feedwater, 127°F	C276	Hastelloy	0.0472	0.0061	130°F, 4 ft/s
S-1	Feedwater, 127°F	316L	Stainless steel	0.0724	0.0525	130°F, 4 ft/s
S-1	Feedwater, 127°F	CDA706	Copper–nickel	0.7528	NA	
S-1	Feedwater, 127°F	API 5LX42	Carbon Steel	1.2684	0.631	130°F, 4 ft/s
S-2	Feedwater, 80°F	Ti-2	Titanium	0.0639	NA	
S-2	Feedwater, 80°F	C276	Hastelloy	0.0402	0.00407	80°F, 4 ft/s
S-2	Feedwater, 80°F	316L	Stainless steel	0.0590	0.0219	80°F, 4 ft/s
S-2	Feedwater, 80°F	CDA706	Copper–nickel	2.2485	NA	
S-2	Feedwater, 80°F	API 5LX42	Carbon steel	1.9256	0.256	80°F, 4 ft/s
S-5	Concentrate, 96°F	Ti-2	Titanium	0.0542	NA	
S-5	Concentrate, 96°F	316L	Stainless steel	0.0601	0.0319	100°F, 4 ft/s
S-5	Concentrate, 96°F	API 5LX42	Carbon steel	2.0864	1.10	100°F, 4 ft/s
S-6	Concentrate, 118°F	Ti-2	Titanium	0.0716	NA	
S-6	Concentrate, 118°F	316L	Stainless steel	0.0501	0.0449	120°F, 4 ft/s
S-6	Concentrate, 118°F	API 5LX42	Carbon teel	2.0249	1.65	120°F, 4 ft/s

[1] Corrosion rate units on the figures at mm/year. To convert mm/yr to mil/yr multiply by 39.37 mil/yr/mm/yr.

[2] Figures only show values for every 20° of temperature change but calculations were performed at 10° intervals.

Not available – this metal was not available in the OLI Corrosion Analyzer public database.

An initial visual corrosion assessment revealed that, in each case, the carbon steel (API 5LX42) and the copper–nickel, if present, showed significant corrosion, while the stainless steel, Hastelloy (if present), and the titanium coupons did not show visible corrosion although a slight scale was present.

Once the coupons were dry, they were individually weighed (without cleaning), placed in individual glass vials, and sent to the supplier of the corrosion coupons, Metal Samples Company (MSC), for postexposure analysis. MSC cleaned and weighed the coupons in accordance with ASTM International Standard G-1, provided the EERC with a corrosion analysis, and then returned the coupons upon completion of the analysis. MSC results are shown in Table 19.

With an initial and final weight, the corrosion rates for the respective metal coupons were calculated using the following equation:

$$CR = (K \times W)/(A \times T \times D) \qquad \text{[Eq. 1]}$$

Where:

CR = Corrosion rate (mils per year)
K = Conversion constant (3.45×10^6)
W = Mass loss (g)
A = Surface area (cm^2)
T = Exposure time (hours)
D = Density (g/cm^3)

Results from MSC (Table 19) clearly show that the carbon steel and copper–nickel coupons corroded significantly more than the titanium, Hastelloy, or stainless steel samples, although even the higher corrosion rates are not considered to be excessive by industry standards. Interestingly, it appears that the more susceptible metals (carbon steel and copper–nickel) were protected somewhat from corrosion by the black substance that was present in the feedwater and coated the coupons in Rack S-1 (127°F feedwater).

For comparison, the predicted corrosion rates, calculated at a flow velocity of 4 ft/s and fluid temperatures close to what was measured in the field, are also listed in Table 19 and shown graphically in Figure 27. While all of the predicted corrosion rates were lower than the observed corrosion rates, the modeling calculations did a good job of predicting the observed corrosion rates for both 316L stainless steel and API 5LX42 carbon steel. The modeling calculations substantially underpredicted the observed corrosion rates for Hastelloy C276 for the two conditions tested, feedwater at 80° and 127°F. For the hot feedwater (Rack S-1), this may again be a result of the black coating that formed on the test coupons.

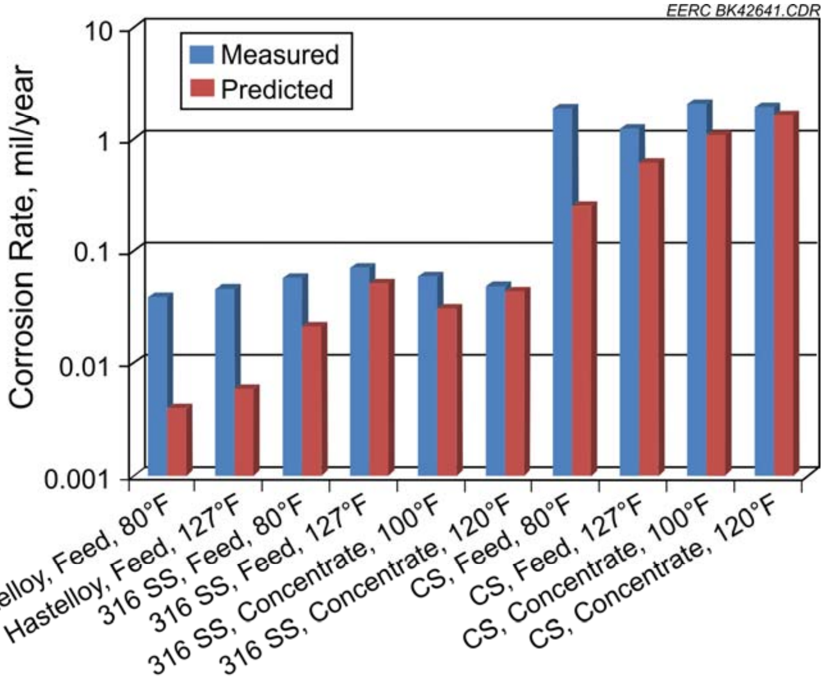


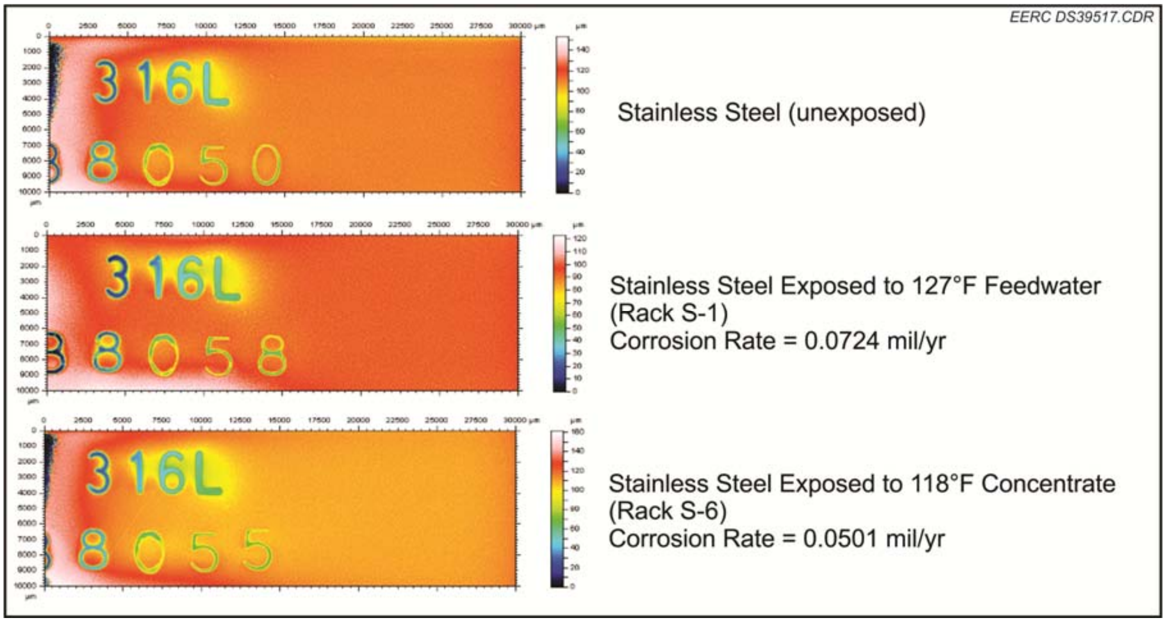
Figure 27. Comparison of measured and predicted corrosion rates.

A surface analysis of select coupons was performed at the EERC using a Nanovea PS-50 optical profilometer. The profilometer measures the height of the sample surface in relation to a fixed optical assembly, with a horizontal detection limit of 0.1 µm and a vertical detection limit of 5 nanometers. Six corrosion coupons were analyzed for comparison: carbon steel and stainless steel coupons from Rack S-1 (127°F feedwater), carbon steel and stainless steel coupons from Rack S-6 (118°F concentrate), and unexposed carbon steel and stainless steel coupons. The resulting profilometer images provide a graphical comparison of corrosion between carbon steel and stainless steel in different water streams and are shown in Figures 28 and 29, respectively. It should be noted that the color height scales associated with each coupon are specific to that coupon and do not represent a common datum. More clearly explained, the profilometer scans a sample, and the deepest measured point on that sample is assigned the zero datum, and all other heights measured are referenced to that sample-specific zero datum.

As seen in Figures 28 and 29, the carbon steel exhibited more pitting corrosion than did the stainless steel (especially in Coupon No. 10 from Rack S-1). Figure 30 shows a more detailed projection of a highly corroded section of the carbon steel coupon from Rack S-1 (Coupon No. 10), illustrating the high degree of pitting observed for the carbon steel coupon.

Of all materials tested, the carbon steel and copper–nickel coupons exhibited higher rates of corrosion in all of the water streams than did the titanium, Hastelloy, and stainless steel coupons. With that said, the most severe corrosion observed for carbon steel was around 2 mpy.

This corrosion rate may not be considered excessive if it occurred evenly on the surface of a material; however, that does not appear to be the case, as localized pitting was observed and may be of concern in a long-term application.



Stainless Steel (unexposed)

Stainless Steel Exposed to 127°F Feedwater
(Rack S-1)
Corrosion Rate = 0.0724 mil/yr

Stainless Steel Exposed to 118°F Concentrate
(Rack S-6)
Corrosion Rate = 0.0501 mil/yr

Figure 28. Profiler images of select stainless steel coupons.

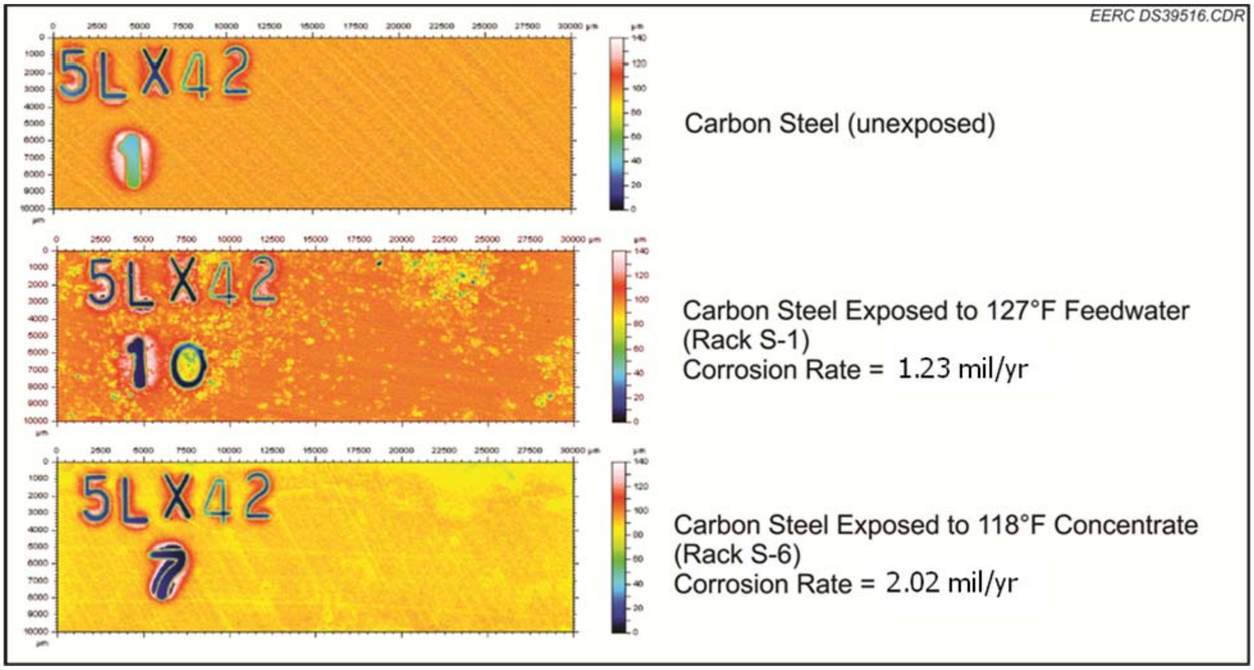


Figure 29. Profiler images of select stainless steel coupons.

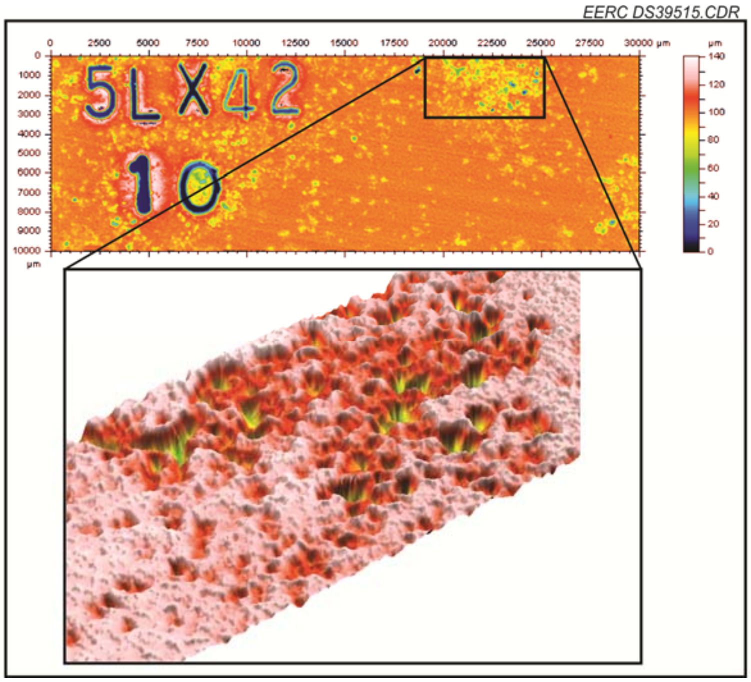


Figure 30. Profiler image of carbon steel coupon zoomed in to pitted area.

Corrosion results do indicate that stainless steel should withstand contact with the respective feedwater and concentrate streams quite well. Therefore, investment in more exotic (and expensive) materials such as Hastelloy and titanium are likely not warranted for use in the full-scale facility.

ECONOMIC EVALUATION

As summarized in earlier sections, the pilot-scale RO system was operated continuously from November 29, 2010, through April 13, 2011. Over this period, approximately 19 million gallons of Dakota Aquifer water was processed to produce approximately 13.6 million gallons of permeate (average 71.6% recovery rate). Operation of the pilot system was intended to continue throughout the summer of 2011 but because of several issues that hampered continuous operation, the system was not operated beyond April 2011, except to prevent scaling by periodically circulating permeate water.

Although the pilot RO system experienced periodic interruptions, it provided valuable technical and economic information regarding design and operation of a full-scale system. These included the operation of modular RO systems in extremely cold and hot climates, identification of water-handling issues, and issues of logistical coordination with oil field operations. Unfortunately, the intermittent operation of the pilot system made it difficult to estimate full-scale operation and maintenance (O&M) costs based on the pilot-scale operation.

Based on conversations with Hess personnel during operation of the pilot system, Hess was sufficiently confident in the technical and economic viability of the RO system to proceed with the design and bidding of a full-scale 1- to 2-MGD RO treatment facility.

A comparison of the estimated costs of freshwater for frac makeup from three different sources was performed by Hess and included 1) water from a 1-MGD RO plant (per barrel cost included capital and operating expenses); 2) water from existing municipal, commercial, or private sources; and 3) water from the planned Western Area Water Supply (WAWS) system, a pipeline project coupled with expansion of Williston's water treatment plant that is currently being constructed in northwestern North Dakota. Hess's internal evaluation included costs for heating and transportation of the water.

Based on this internal evaluation, Hess determined that the water produced from its own RO plant was cost-competitive and logistically favorable compared to the current means of acquiring frac make-up water. As a result, Hess, jointly with GE, is proceeding with plans to construct a full-scale RO system. The economic details of this contractual arrangement were not made available for inclusion in this report.

RO Treatment Plant Costs

In the absence of actual bid data, the EERC made an effort to quantify the capital and O&M costs associated with a full-scale RO plant similar in size to that being constructed by Hess and GE. Estimates for equipment-only capital cost and O&M were provided by GE for a full-scale RO plant producing up to 1.5 MGD of treated water for use as a frac make-up water.

GE's estimates of capital showed that an RO system with a treated water capacity of 1.5 MGD would have an equipment-only capital cost of approximately \$3.5 million. This capital cost does not include site construction or infrastructure development-related activities. A series of assumptions summarized in Table 20 were made to estimate the remaining costs to construct a 1.5-MGD RO plant. The methodology to calculate each cost was based on an assumed percentage of the equipment-only capital cost. Using this method, the total cost to construct a 1.5-MGD RO plant is estimated at approximately \$15.75 million, not including land acquisition costs, the cost of providing feed water to the RO system, and the cost of RO concentrate disposal.

The estimated annual O&M cost for operating the RO system, provided by GE, was approximately \$1,000,000 not including the cost of RO concentrate disposal.

Production Well Costs

In addition to the capital costs for the RO plant, costs were estimated for the groundwater extraction well field. Based on the EERC's experience in groundwater extraction wells completed in the Dakota Aquifer, five wells completed to a depth of 5500 ft would be required to provide the RO plant demands. At an estimated cost of \$1.5 million for each well (\$7.5 million total) and assuming an additional 10% of the total well field cost for the pumps and associated infrastructure, the total estimated cost for the water extraction system to provide water to the RO plant would be approximately \$8.25 million.

The O&M cost associated with the groundwater extraction operation was based primarily on the cost of electricity to run the pumps. Assuming a 30-kW pump in each of five wells operating for 7872 hours (328 days) a year and an electrical cost of \$0.08/kWh, the electricity cost would be approximately \$95,000.

Brine Disposal Costs

Two different brine disposal options were considered:

1. Truck transportation to an existing commercial injection site
2. Pipeline transport to a dedicated injection site.

The cost for disposal of RO concentrate was based on personal communications with service companies in the Williston Basin that provide injection and disposal services. Based on these conversations, the cost for disposal is estimated to be \$1.75 per bbl. Assuming 1.5 MGD of RO permeate (at 70% RO recovery), the volume of RO concentrate for disposal would be approximately 643,000 gpd or 15,300 bbl/day, which equates to approximately 211 million gpy or 5 million bbl per year (assuming 90% plant availability). At the previously stated cost of \$1.75 per bbl for injection, the annual injection-only cost would be \$8.7 million a year.

Table 20. Cost Estimate Assumptions – 1.5-MGD RO Plant

Description	Direct Labor as % of Process Equipment	Material as % of Process Equipment	Labor Cost	Material Cost	Total Direct Cost
Process Equipment	10.0	100.0	$350,000	$3,500,000	$3,850,000
Site Preparation (clearing, grading)	2.8	0.5	$96,250	$17,500	$113,750
Site Improvement	10.0	15.0	$350,000	$525,000	$875,000
Concrete	10.0	5.4	$350,000	$189,000	$539,000
Structural Steel – Platforms, Racks and Supports	6.0	15.0	$210,000	$525,000	$735,000
Building – Steel, Cladding, Interior and HVAC	5.0	10.0	$175,000	$350,000	$525,000
Underground Piping	8.0	12.0	$280,000	$420,000	$700,000
Aboveground Piping	8.0	12.0	$280,000	$420,000	$700,000
Electrical – MCC, Wiring, Lighting	6.5	12.5	$227,500	$437,500	$665,000
Instrumentation	5.5	12.7	$192,500	$444,500	$637,000
Insulation	7.5	5.0	$262,500	$175,000	$437,500
Painting	3.0	1.7	$105,000	$59,500	$164,500
Proratables	8.0	2.0	$280,000	$70,000	$350,000
Total Direct Costs			**$3,158,750**	**$7,133,000**	**$10,291,750**

Construction Equipment	% of Direct Labor Cost	Total Indirect Cost
Rental or Purchase	10.0	$315,875
Service Labor	3.0	$94,763
Fuel, Oil, Supplies	10.0	$315,875
Overhead and Indirects		
Salaried	10.0	$315,875
Contractor Profit	10.0	$315,875
Office Hourly	6.0	$189,525
Field Hourly	5.0	$157,938
Temporary Construction Facilities	5.0	$157,938
Payroll Burdens and Benefits	32.0	$1,010,800
Small Tools and Consumables	7.0	$221,113
Other Indirects	2.0	$63,175
Total Indirect Costs		**$3,158,750**

Continued . . .

Table 20. Cost Estimate Assumptions – 1.5-MGD RO Plant (continued)

	% of Total Direct and Indirect Costs	
Engineering/Design Services	10.0	**$1,345,050**
Construction Engineering	1.0	134,505
Project General Management	2.0	269,010
Total Engineering and Management Services		$1,748,565
Escalation (material – 1 yr)	2.0	$142,660
Summary		
Total Direct and Indirect Cost		$13,450,500
Total Engineering and Management Services		$1,748,565
Escalation		$142,660
Total Project Costs		**$15,341,725**

The total cost of disposal must also include the cost of trucking the RO concentrate to the injection facility. This cost was estimated to be approximately $11.9 million a year based on the following assumptions:

- 30-mile one-way haul to the injection site
- Three hours per round trip at $150 an hour
- 26,315 round trips annually (190 bbl hauled each trip)

Using these volumes and costs, the annual total cost for RO concentrate disposal by the truck transport method is estimated to be approximately $20.7 million.

Given the cost of RO concentrate disposal by truck transport method, it is feasible that a dedicated pipeline and injection well field would be more cost-effective. Assuming a pipeline cost of $1 million dollars per mile and a distance of 10 miles to the injection well field, the cost of the pipeline would be approximately $10 million. Using the same per well cost stated in the groundwater extraction discussion of $1.5 million, assuming two injection wells, and adding 10% for injection pumps and infrastructure, the total estimated cost for an injection well field would be approximately $3.3 million. The total cost for a dedicated pipeline and injection well field is then estimated to be $13.3 million. In this scenario, the $13.3 million cost would be added to the total capital cost, and the $20.7 million O&M cost for RO concentrate disposal would be reduced to the cost of operating the injection pumps (approximately $75,000).

The O&M cost for the dedicated pipeline scenario was estimated based on the cost of electricity to run the pumps. Assuming a 60-kW pump in each of two wells operating for 7872 hours (328 days) a year and an electrical cost of $0.08/kWh, the electricity cost would be approximately $75,500 per year.

Land Acquisition

Assuming that the site area is not currently owned a land acquisition cost was included and estimated based on the following assumptions:

- Required land area: 160 acres
- Price per acre of land: $1500

Using these assumptions the estimated cost for acquiring land for the site is $240,000.

Permeate and Concentrate Storage

It is necessary to also include storage facilities for the permeate and concentrate produced during system operation. Each pond (permeate and concentrate) was sized with a 5-day capacity. This resulted in a permeate and concentrate pond volume of approximately 7,500,000 and 3,200,000 gallons, respectively. The following assumptions were made to calculate the estimated product storage capital costs.

- Excavation: 50,000 cubic yards at $2.00 per cubic yard

- Liner: 130,000 square feet at $4.00 per square foot
- Pond cover: 100,000 square feet at $1.50 per square foot
- Security fence: 1900 linear feet at $25 per linear foot
- Contingency: 25% of total cost

Using these assumptions the estimated cost for the total storage facility (permeate and concentrate storage) was approximately $1,021,875.

Total costs associated with a 1.5-MGD RO plant, showing the two RO concentrate disposal options summarized in Tables 21 and 22. In addition to a summary of the estimated costs, a calculated cost per bbl of treated water for each component is provided. O&M costs per bbl were directly calculated by dividing the line item cost by the annual volume of treated water produced (11,714,192 bbls). Deriving a per bbl cost for the capital cost items required assumptions to be made regarding the financing of capital costs. For these calculations the entire capital cost is assumed to be borrowed and the following financial assumptions were made:

- Interest rate: 5%
- Term: 3 years

As shown in Tables 21 and 22 the cost per bbl of treated water for the truck transportation disposal is $2.63 per bbl and the cost for the dedicated pipeline and injection well field is $1.28.

When compared to the average water acquisition costs for traditional sources (water depots and pipeline), which range from $0.63 to $1.26 (Hess, personal communication), the total estimated costs for option one during the first three years ($2.63/bbl) are high. However, when compared to the costs savings achieved from reduced transportation costs and reduced heating costs as a result of heating the permeate, the costs become quite competitive (Hess, personal communication). The second option, at $1.28/bbl appears quite viable, even without accounting for the cost savings associated with reduced transportation and heating costs. In each instance, the water costs are reduced substantially after the 3-year capital costs payback period.

Table 21. Total Cost Summary – 1.5-MGD RO Plant with Truck Transportation Disposal

	Cost	Cost per bbl
Capital Costs		
Land Acquisition	$240,000	$0.01
Groundwater Extraction Well Field	$8,250,000	$0.25
RO Plant	$15,750,000	$0.47
Permeate and Concentrate Storage	$1,021,875	$0.03
Total Capital Cost	**$24,853,600**	**$0.76**
Annual O&M Costs		
Groundwater Extraction	$95,000/yr	$0.01
RO Plant Operation	$1,000,000/yr	$0.09
RO Concentrate Disposal	$20,700,000/yr	$1.77
Total Annual O&M Cost	**$21,795,000/yr**	**$1.87**

Table 22. Total Cost Summary – 1.5-MGD RO Plant with Dedicated Pipeline Disposal

	Cost	Cost per bbl
Capital Costs		
Land Acquisition	$240,000	$0.01
Groundwater Extraction	$8,250,000	$0.25
RO Plant	$15,341,725	$0.47
Permeate and Concentrate Storage	$1,021,875	$0.03
RO Concentrate Disposal Well Field	$13,300.000	$0.41
Total Capital Cost	**$38,153,600**	**$1.17**
Annual O&M Costs		
Groundwater Extraction	$95,000/yr	$0.01
RO Plant Operation	$1,000,000/yr	$0.09
RO Concentrate Disposal	$75,000/yr	$0.01
Total Annual O&M Cost	**$1,170,000/yr**	**$0.11**

The per-barrel costs determined above were based on an economic model most representative of the RO plant capital costs being financed by a third party. An alternate means of determining per-barrel costs was also considered. This alternative assumed producer-deployed capital and a 15% internal rate of return (IRR) over a 3-yr period. A simplistic spreadsheet model was used to determine the per barrel costs for both scenarios using the capital and O&M costs provided in Tables 21 and 22. A 40% income tax rate was used, and it was conservatively assumed that the plant and all associated equipment fully depreciated in 3 years. The resulting payback period was 2.3 years. Given these assumptions, the per-barrel value (or acquisition costs) of the water was $2.95/bbl for the commercial disposal well and $1.75/bbl for the dedicated pipeline and injection well field. While the costs are higher than those determined using a 5% interest rate, they are still economically competitive with other options when the cost savings associated with reduced transport and lower heating costs are taken into account. As with the previous scenario, it appears economically advantageous to invest in a dedicated pipeline and injection well field.

CONCLUSIONS

While water resources in the western part of North Dakota are not necessarily scarce, especially considering the resources in Lake Sakakawea and the Missouri River system, current access to water is limited. This creates a unique environment where unconventional water acquisition methods, such as treatment of brackish groundwater resources, are economically competitive with conventional approaches. This project demonstrated an approach that may be economically competitive with water acquisition from traditional resources. Two of the factors driving the costs of frac makeup water are transportation, including the time that water haulers spend waiting in line at water depots, and costs of heating the water to the desired 80°F temperature for fracturing. The demonstrated approach provided a substantial reduction in both transportation and heating costs by considering both a dedicated on-site water hauling station and by utilizing the relatively high-temperature groundwater to preheat the permeate. When these costs were taken into account, this project demonstrated that RO treatment of groundwater from the Dakota Aquifer may be economically feasible compared to existing approaches.

RO treatment of nonpotable groundwater was demonstrated to be technically feasible with pretreatment to remove suspended solid and organic matter, coupled with the use of heat exchangers to reduce water temperature. One of the greatest expenses of this type of RO treatment system is associated with concentrate disposal, especially when a commercial disposal well is utilized. The economic assessment suggested that if a dedicated injection well field were constructed, the disposal costs could be reduced substantially and this approach would become economically competitive, even without accounting for the reduced transportation and heating costs.

Given the high demand for frac makeup water in western North Dakota and the widespread nature of brackish groundwater formations, like the Dakota, this approach may be economically and technically feasible for other producers and/or other industries in the region. While case-by-case assessments will likely be needed, it is encouraging to know that this resource is available and may be economically competitive.

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