FINAL OUTCOMES REPORT

Project Title: High Temperature Membranes for SAGD Produced Water Treatment

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Project Description:

Boiler feedwater (BFW) for existing thermal in situ oil sands recovery processes (e.g. CSS, SAGD) are treated using evaporators or lime softening, with Once Through Steam Generators (OTSGs) used for steam production. Typically produced water (PW) is >150°C when extracted from the reservoir but is cooled to <90°C for atmospheric de-oiling and water treatment processes. High pressure and temperature produced water treatment processes have the potential to produce BFW and steam with lower greenhouse gas (GHG) intensity. Low temperature membrane systems are currently used in power generation (at temperatures <60°C) treating boiler feedwater for high efficiency boilers.

Through this project, high temperature reverse osmosis (HTRO) technology tests were performed to determine a range of implementation scenarios and processes that can enable CPF operation at these conditions and generate high quality boiler feedwater compared to incumbent practices, with the goal of commercializing this technology and the potential benefit of reduced GHG emissions.

ERA Funds Received:

$2,500,000.00

Total Project Eligible Costs:

$9,412,752.00

Total Project Ineligible Costs:

$0.00

TRL at Project Initiation:

5

TRL at Project Completion:

8

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LIST OF SELECTED ACRONYMS AND ABBREVIATIONS

Acronym	Description
AER	Alberta Energy Regulator
ASME	American Society of Mechanical Engineers
BPSD	Barrels Per Stream Day
CAPEX	Capital Expenditure
CAPP	Canadian Association of Petroleum Producers
COSIA	Canada’s Oil Sands Innovation Alliance
CPF	Central Processing Facility
CCSI	Carbon Capture Simulation Initiative
CSS	Cyclic Steam Stimulation
GHG	Greenhouse Gas
HEROTM	High Efficiency Reverse Osmosis
HMI	Human Machine Interface
HLS	Hot Lime Softening
HTRO	High Temperature Reverse Osmosis
NF	Nanofiltration
NPV	Net Present Value
OPEX	Operational Expense
OIW	Oil-In-Water
ORF	Oil Removal Filter
OTSG	Once Through Steam Generator
PLC	Programmable Logic Controller
PW	Produced Water
RO	Reverse Osmosis
SAGD	Steam-Assisted Gravity Drainage
SCADA	Supervisory Control and Data Acquisition
TDS	Total Dissolved Solids
TOC	Total Organic Content
TRL	Technology Readiness Level
UF	Ultrafiltration
UHT	Ultra-High-Temperature
WAC	Weak Acid Cation Exchange
WLS	Warm Lime Softening
WTDC	Water Technology Development Centre

1. EXECUTIVE SUMMARY

High temperature (>100°C) and pressure (>atmosphere) boiler feedwater pretreatment has the potential to reduce the greenhouse gas (GHG) footprint and capital cost associated with SAGD central processing facilities (CPFs). High temperature reverse osmosis (HTRO) is one technology that can enable CPF operation at these conditions and generate high quality boiler feedwater compared to current practices. HTRO incorporation into greenfield designs may specifically allow for the use of hybrid-type steam generators that operate at higher steam qualities than once through steam generators (OTSG), which are widely used within the industry. Transitioning to higher steam quality boilers leads to direct GHG reductions at facilities and minimizes steam generator blowdown production. The objective of this project is to determine the technical operating envelope for an HTRO system operating under conditions expected in a full-scale high temperature and pressure CPF process.

High temperature membrane and module development has been conducted at the laboratory scale with model fluids and samples of process water. This work has established the baseline performance of specific materials, components, and module construction aspects under high temperature conditions. The WTDC pilot test, at completion, will be used to map the technical operating envelope of an HTRO system using live process fluids over a range of potential implementation scenarios.

The technical operating envelope focused on the following performance aspects:

- Membrane permeates flux and recovery
- Trans-membrane pressure during operation / permeability
- Permeate quality (organic and inorganic removal)
- Reject quality
- Overall water recovery
- Clean-in-place frequency and method
- Membrane robustness over long-term high temperature exposure and temperature cycles.

The HTRO Pilot test skid enabled several operating configurations to be evaluated that can’t be tested under benchtop or single component (e.g., flat sheet membrane) conditions. Piloting for extended duration at the WTDC helped de-risk the technology and provided important performance information that was incorporated into SAGD CPF process models used as the basis for life cycle cost/benefit estimates to be completed.

High temperature and pressure CPF water treatment plants that incorporate HTRO technology are estimated to reduce the overall GHG footprint by 5-10 percent compared to the standard CPF greenfield design. In addition to GHG benefits, HTRO-based plants are anticipated to reduce the overall land footprint, generate higher quality boiler feedwater that benefit steam generator reliability, and maintain compliance with waste disposal limits defined by the Alberta Energy Regulator (AER) Directive 081. Overall, these impacts are expected to lead to an overall capital cost reduction for greenfield SAGD projects. The benefits of technology utilization for brownfield or debottlenecking projects are currently being assessed by the project partners and show a similar range of benefits to the greenfield project cases.

2. PROJECT DESCRIPTION

2.1 INTRODUCTION

Steam assisted gravity drainage (SAGD) projects increase the temperature of the reservoir to produce bitumen by injecting high temperature steam into the subsurface. Water used to generate high pressure steam is largely made up of recycled produced water that is separated from the production emulsion and treated to a suitable quality for use in a boiler. The majority of SAGD Central Processing Facilities (CPF) actively cool the produced water to temperatures less than 100°C to enable the use of water treatment technologies that treat water to a quality that is acceptable for use in a once-through steam generator (OTSG). Current OTSGs can only operate at steam qualities from 80 to 85%, without the use of technology such as rifled tubes. Cooling the production emulsion below approximately 130°C and utilizing low steam quality boilers directly adds to the GHG footprint of the SAGD process. This project seeks to address both inefficiencies by eliminating active cooling below 130°C and treating to a higher water quality to increase the achievable steam quality.

Water treatment in SAGD CPFs has traditionally been performed using warm lime softening (WLS) or hot lime softening (HLS) followed by weak acid cation exchange (WAC) treatment. This approach removes hardness associated with calcium and magnesium through chemical precipitation such as carbonate or hydroxide solids (in the WLS/HLS) and through surface exchange with sodium ions (in the WAC). Silica is removed through coprecipitation, supplemented by addition of magnesium oxide in the softener. Through this process effluent concentrations of silica are typically between 30 and 50 milligrams per liter (mg/L). Produced water pH and alkalinity are increased from slaked lime (calcium hydroxide) and soda ash (sodium bicarbonate) addition, also in the softener. These processes do not affect the total dissolved solids (TDS) content of the process water and have a limited impact on the organic content.

The water quality produced by this type of treatment train is unable to meet the feed water quality specifications of higher efficiency drum or hybrid-type boilers, which are close or equal to American Society of Mechanical Engineers (ASME) guidelines for industrial water tube boilers. The other predominant water treatment technology in use within the industry is thermal evaporation. Evaporation technologies treat water through a phase separation process that generates a clean distillate, where dissolved non-volatile constituents (salts, oils) are concentrated up in a separate brine stream. Energy input to the system is through a mechanical vapor recompression system. Thermal evaporators are currently used at a smaller portion of CPFs currently compared to WLS/HLS, however, that technology is able to generate much higher quality boiler feedwater that would enable the use of high-efficiency boilers. The capital cost and GHG footprint of that technology tends to limit its adoption as the primary water treatment technology in a SAGD CPF.

Reverse osmosis (RO) is a membrane separation technology that is characterized by removal of dissolved (monovalent) salts from the feed water to produce a low-total dissolved solids (TDS) permeate and a concentrate that contains an elevated concentrations of all dissolved solids that do not pass through the membrane. Typically, 95% or more of dissolved salts are removed from the feed. The TDS (or salinity) buildup on the feed side of the membrane generates an osmotic pressure across the membrane that is opposite of the direction of water flow through the membrane. Therefore, feedwater is required to be supplied at a relatively high pressure (700 kPa to 2 MPa) to an RO system compared to other filtration technology to overcome the osmotic pressure-driven reverse gradient.

Table 1. Pros and cons of HTRO for SAGD boiler feedwater.

Preferred Solution Brief Description	Pros	Cons	Capital Cost (also indicate level of accuracy)
High temperature reverse osmosis of SAGD boiler feedwater	Higher quality boiler feed water enables more water efficient steam generator	Requires redesign of commercially available RO system to operate in high	CAPEX for new facilities would be required for this process.

	Reduced direct and total GHG footprint of a greenfield facility Reduced heat exchanger requirement for greenfield SAGD facility.	temperature and pressure conditions RO process less robust to produced water contaminants than current technologies, which necessitate feed water pretreatment	

Feedwater pressurization represents the largest portion of the overall energy requirement of an RO system. The total power requirement for thermal evaporation, based on desalination applications, is generally 2 to 10 times larger than seawater RO. This difference in the underlying GHG footprint of the two technologies makes RO attractive for development and incorporation into a SAGD CPF process design.

2.2 PROJECT BACKGROUND

The traditional operating temperature profile of a SAGD plant has several trade-offs associated with this approach. Produced water cooling, and reheating, require a relatively large heat exchanger network to implement that leverage a combination of process water-to-process water heat integration and a utility cooling service, such as a glycol chiller circuit. Although OTSGs can utilize a lower-quality feedwater than drum or drum-OTSG hybrid (hybrid) style steam generators, the lower steam quality translates to a higher overall boil feedwater requirement to support the nameplate production capacity of the facility and larger blowdown stream flows. The combination of these two features – large temperature reduction for water treatment and boiler feedwater requirement to support sufficient steam production – lead to larger preheater and steam generator duty requirements.

Maintaining process water at elevated temperatures eliminates much of the heat exchanger duty needs of current SAGD CPFs. This necessitates the use of water treatment technologies that can operate in this environment. High temperature reverse osmosis (HTRO) is designed to generate a high-quality permeate under these process conditions. Higher quality process water allows for the use of higher efficiency steam generators, such as hybrid boilers, to be used in the process. These units generate much less blowdown compared to OTSGs. The extent of boiler blowdown reuse in a traditional SAGD process is not needed in a high temperature-hybrid boiler process that has a lower heat integration demand than traditional SAGD.

The temperature range of most commercially available reverse osmosis membrane systems is 40 to 50°C with high-temperature products being up to 80 to 90°C. The value proposition of an HTRO SAGD process relies on using reverse osmosis membrane technology well above the current temperature limits of these products. This not only requires evaluation and de-risking of membrane material and components, but also system mechanical configuration, setpoints, and cleaning cycles. The WTDC pilot is the key activity to de-risk the system-level challenges associated with this technology and its integration into a SAGD plant.

In 2014, a partnership including Suez, Suncor, CNRL (then Devon) and Alberta Innovates began field piloting of a process to pre-treat produced water to facilitate future low temperature (less than 100°C) reverse osmosis (Gen2). The pre-treatment process that was piloted consisted of coarse and fine de-oiling, along with chemical addition. The objective of the pre-treatment process was to remove free/emulsified oil and dissolved organics to mitigate organic fouling of the reverse osmosis membranes.

The technology readiness level for existing <60°C RO modules is commercial but is only proven in concept (i.e., laboratory and university research) above this temperature. Application of this technology is not commercially operational in Alberta for any oilsands produced water streams. At temperatures above 60°C, the only public RO membrane testing is the above mentioned Gen2 pilot at Mackay River, which completed testing a 2.0-4.5 m^3/hr field pilot in early 2018 (TRL 7 per ERA documentation). The Gen2 process tested a high efficiency reverse osmosis (HEROTM) process at 90°C following treatment from chemically assisted flotation (coarse de-oiling) and ultrafiltration ceramic membranes (fine de-oiling).

During the Gen2 piloting, the project team identified that operation above 100°C would achieve greater GHG benefits and improve on conventional processes capital and operating costs for debottlenecking and green-field implementations through a complementary SAGD CPF process model and CAPEX estimate task. At the same time as the Gen2 pilot, the project team progressed development of HTRO membranes (>100°C) to a prototype development and testing phase (TRL 6 per ERA documentation). These "proof of concept" experiments determined that a membrane element can be specified and fabricated to withstand conditions greater than 100°C when treating SAGD PW. Component compatibility testing was completed in 2016 testing a high temperature element. Flux and salt rejection studies were completed using simulated water.

The project team continued to update SAGD CPF process models and estimates for the environmental, capital, and operational cost benefits of high temperature SAGD CPF configurations. This included energy and water usage, GHG emissions, and waste generation associated with various water treatment technology solutions and CPF configurations. The parameters used are based on actual lab and piloting data developed by the partners throughout the project. The project consisted of two phases with the following scope:

- Phase 1: Continuing from previous flat sheet membrane research, a full-scale commercial membrane and associated module (housing) was developed for bench scale testing at elevated temperatures (100-120°C). The University of Alberta bench scale rig was designed, fabricated, and commissioned to enable this testing. Parallel to this work, a 2.5" diameter membrane test stand at NAIT, and a 4.0" diameter membrane pilot for Firebag Water Technology Development Centre (WTDC) was completed to enable fast progression to Phase 2 testing. Results from the bench scale testing were used to update the SAGD CPF process model HTRO parameters to ensure consistency between experimental data and model forecasting.
- Phase 2 (HTRO membrane module testing): Completion of Phase 1 testing allowed approval to proceed for onsite pilot fabrication for a flowrate of approximately 5 m^3/hr. The host facility was located at the Firebag Water Technology Development Centre (WTDC) operated by Suncor and partner CNRL. The pilot test was executed to de-risk further commercial development of the technology

At the completion of the project, the HTRO membranes completed the demonstration level of deployment (TRL 8).

2.3 PROJECT OBJECTIVES

The objective of the HTRO Pilot was to commercialize an HTRO membrane module capable of operating under conditions that may be encountered when treating SAGD produced water. Particularly, robust and efficient operation at temperatures >100°C and high associated pressure (to prevent flashing) are critical attributes to demonstrate for proving this technology is applicable in the field. The removal of target PW constituents to produce high-quality boiler feed water is a key objective of the project. The technology needs to efficiently and repeatedly produce high quality BFW using a membrane. A membrane to perform this function is not yet commercial, so development of this membrane is the key objective of this project. Following development of this functional membrane, the other key objective was to show the reduced footprint in both land and GHG's to enable lower cost boiler feed water and steam production for oil production.

For Phase 2, the pilot skid was designed to test different levels of pre-treatment prior to being fed to HTRO. Originally, the pilot skid would have been connected to the following feed streams for testing:

- P92 Evaporator Distillate
- P91 WAC Outlet (BFW)
- P91 ORF Outlet (deoiled PW)

Over time, the third feed stream (i.e., P91 ORF Outlet) was no longer considered feasible to test. The pilot operated in two pass (Pass 1 permeate fed directly to the Pass 2 modules to improve overall permeate quality) or two stage (Stage 1 concentrate fed to Stage 2 modules to improve overall system water recovery). Chemical dosing (e.g. acid, base or anti-scalant) was also considered for application to the feed inlet as well as between passes and stages.

2.4 PERFORMANCE/SUCCESS METRICS

The table below lists suggested qualitative technical and economic success metrics for the project. The project will aim to achieve as many success metrics as possible through Phase 1 and Phase 2 of the project.

Table 2. Success metrics.

Metric	**Commercial Target**	**Project Target**	**Actual Project Performance (Physical Testing or Modelled)**
Process Operation at Elevated Pressure and Temperature	Temperature > 120-130°C Pressure > 1500 kPa	Temperature >105-120°C Pressure > 1000 kPa	Membrane component and module testing completed up to 105°C. Safety issues were encountered preventing higher operation, but this was sufficient to demonstrate operation above 100^{oC} continuously.
Permeate Quality	Silica < 10 ppm	Silica 10-20ppm	Target removals achieved for silica and TOC removal in both boiler feedwater polishing and distillate polishing.
Direct + Indirect GHG Reduction (% relative to Base Case SAGD Facility)	10% reduction	5-10% reduction	Preliminary modelling indicates 5-10% total GHG reduction achievable for greenfield; 3-7% for brownfield cases.
Blowdown Disposal	Perform better than D081 requirements	Perform better than D081 requirements	Preliminary modelling indicates exceeding D81 requirements achievable while achieving GHG performance metric.
Facility Capital Cost Reduction (CAPEX)	>25%	>10-15%	Preliminary modelling indicates up to 10% reduction achievable depending on configuration.
Facility Operating Cost Reduction (OPEX)	>5% reduction	NPV neutral	Preliminary modelling indicates NPV neutral or slight improvement.
Facility Footprint Reduction	40% reduction	20-40% reduction	Preliminary modelling indicates 10% reduction achievable depending on configuration.

2.5 TECHNOLOGY RISKS

The principal technical risks when incorporating RO into a SAGD process include:

- Elevated concentrations of constituents (mainly calcium, magnesium, and silica) in produced water and some make-up water sources that have the potential to form scales on the feed side of RO membranes when they become concentrated.
- A complex mixture of dissolved organics that tend to consist of more non-polar species (aromatics, oxygenates)
- The potential for particulate and emulsified oil droplets that may pass through the upstream de-oiling or pre-filtration unit operations.
- SAGD water treatment process operating temperatures are typically between 80 and 90°C.

Among these technical risks, the operating temperature represents the most significant departure from typical operating conditions or design basis of a process utilizing RO. Typical RO membranes for municipal and industrial services have a maximum recommended operating temperature near 50°C. High temperature membranes for specific applications in the food and beverage, pharmaceutical, biotech, and electronics industries have maximum operating temperatures up to 70 to 90°C.

This temperature range partially overlaps the conventional SAGD water treatment temperature range and has no overlap with the target temperature range that is the objective of this project. Increasing the temperature of an RO membrane process is expected to impact both the water flux rate and the separation selectivity through its influence on water (viscosity), solute (ion mobilities), and RO selective layer properties (morphology). In combination these changes are expected to increase overall membrane flux with minimal impact on ion rejection rates.

2.5.1 Technology alternatives considered

Alternatives to the preferred HTRO technology for achieving GHG and CAPEX reductions associated with high temperature operations are summarized in the following table.

Table 3. Pros and cons of alternative technologies for SAGD boiler feedwater.

Alternative solution – brief description	Pros	Cons	Elimination Justification and TRL
Thermal evaporator – Generate high quality boiler feed water using commercially available technology	Enables use of high-efficiency steam generators to decrease BFW requirement and direct GHG intensity production	High CAPEX / OPEX that does not offer same GHG intensity reduction Limited scalability for brownfield or debottlenecking projects	High TRL (9) High CAPEX and process footprint
Alternative steam generator technologies - Direct contact steam generators or similar that operate with low quality BFW	Limited produced water pre-treatment requirement Flue gas water incorporated into steam production benefits overall water requirement	Unproven long-term performance and reliability due to organics and salt content in SAGD PW CO_2 limit in production steam requires post-combustion treatment	Mid TRL (5-6) Technology has limited commercial viability and footprint at this time
Flue gas carbon capture - Direct GHG reduction from post-combustion CO_2 capture and reuse	GHG emission reduction is independent of water treatment	Impacts to steam generator efficiency. High CAPEX associated with bolt-on technology Long-term CO_2 reuse market and sequestration banks	High TRL (7 to 8) Technology is bolt-on with no substantial modification of core water treatment process

3. PROJECT WORK SCOPE

As noted in section 2.2, the University of Alberta bench scale rig was designed, fabricated, and commissioned to better inform pilot design. The final HTRO module was successful at high temperature, and the partners agreed to fund further background de-risking prior to testing at the WTDC.

At the WTDC, the pilot operated in different modes, depending on the feed stream, permeate quality targets, or the required overall system recovery target:

- Operating mode 1 – Two stage operation with nanofiltration (NF) and reverse osmosis (RO).
- Operating mode 2 – Two pass operation with NF and/or RO.
    - This operating mode can recirculate reject back to the booster pump suction (Mode 2A on PLC), or feed (Mode 2B).
- Operating mode 3 – 1st pass ultrafiltration (UF), followed by 2nd pass NF or RO.

The duration of the pilot's testing stage, originally estimated to be up to 16 weeks, focused on:

- Evaporator Distillate testing of two pass + two stage RO operation with concentrate recycle.
- Boiler Feedwater Polishing testing of two pass + two stage RO operation with concentrate recirculation (per pass).

Membranes were chemically cleaned as required between different feedwater conditions. The skid was able to be inspected when switching between the two different feed streams to inspect metallurgy condition of installed corrosion spools, as well as general skid condition.

Chemical dosing was utilized for membrane performance as recommended by Veolia. Anti-scalant was recommended for dosing for both streams but may not be required for evaporator distillate due to very low levels of fouling and scaling compounds.

3.1 METHODOLOGY / TEST PLAN

Building on previous pilot and bench-scale testing, the principal outcome of the WTDC HTRO system pilot test is the demonstration of a commercial-scale process within the operational setting (i.e., Technology Readiness Level 8). Specific system-level risks addressed by the pilot were:

- Long-term performance for various pre-treatment levels and normal process variability
- Performance maintenance requirements (i.e., membrane cleaning) for various pre-treatment levels
- Component lifetime, particularly for membrane modules, within the SAGD operational environment

The pilot system consists of two pressure vessels that may be configured as multi-stage, multi-pass or pretreat/RO arrangement. A diagram of the pilot system, including sampling locations, is shown in Figure 1.

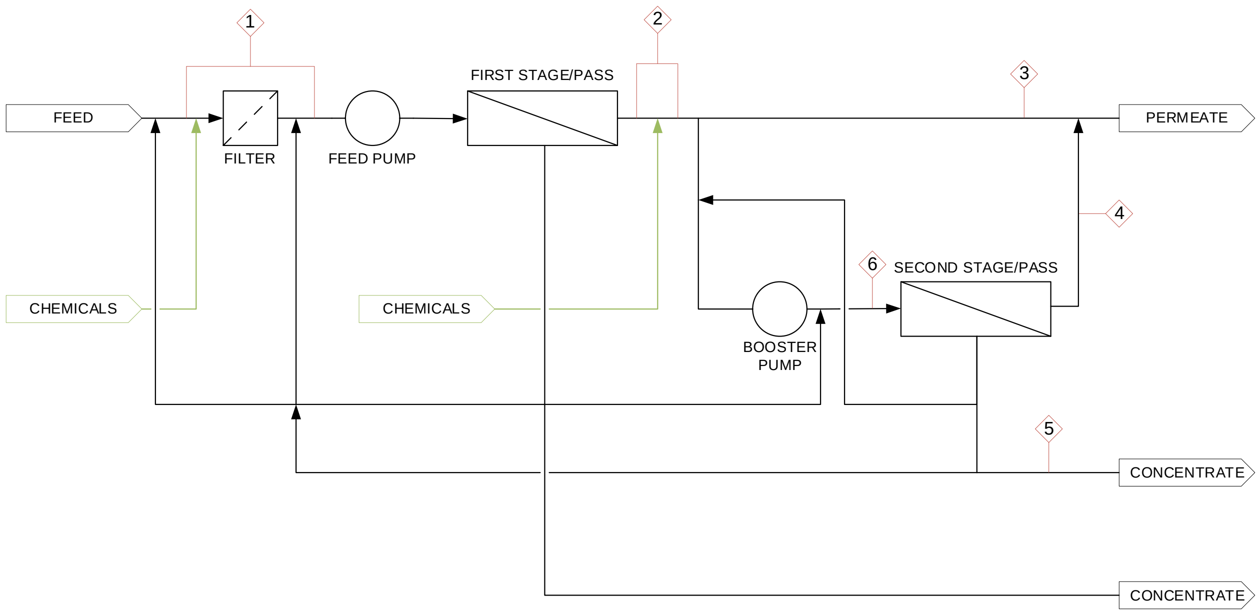


Figure 1. HTRO Pilot system diagram including the two chemical feed points and six sample locations.

Samples 1, 5, and 6 are combined into a common set of instruments using automated valves. Samples 2, 3, and 4 are similarly combined into a different set of common instruments. Samples are cooled before running through the instrumentation and sample collection station.

Pilot feed will be provided from the WTDC supply header system, which ties into multiple locations in the Firebag Plant 91 and 92 processes. Typical properties at the WTDC supply point for the four fluids that will be used in the HTRO Pilot are listed in Table 4. Cooling glycol was connected to the WTDC pilot skid for cooling both inlet fluids, and samples. Low pressure steam was connected to the pilot to allow increases in temperature, to adjust for any low temperature fluid conditions.

Table 4. WTDC Supply Header Fluids.

Supply Header	**Distillate / Blowdown**	**Treated Water**
Tie Point	**TP-02B**	**TP-30B**
Fluid Type	BFW	BFW
Temperature (°C)	85	85
pH (S.U.)	9.1 to 10.4	10 to 10.4
TDS (mg/L)	54 to 309	577 to 1552
Hardness (mg/L as $CaCO_3$)	<0.5 to 1	0.25 to 1
Reactive Silica (mg/L)	0.1 to 3.0	22 to 75
OIW (mg/L)	<0.5 to 2	<0.5 to 2
TOC (mg/L)	34 to 260	330 to 400

Different levels of RO pretreatment may be represented by the range of potential feed water chemistries. Plant 92 evaporator distillate simulates the highest level of pretreatment, including providing a reduced TDS stream that would not be expected present limitations based overall TDS rejection. Blending Plant 91 WAC Outlet into the pilot feed would allow TDS and TOC to be managed in a way to evaluate the specific challenges that those constituents present. Hardness, silica, and oil-in-water (OIW) are elevated in Plant 91 OTSG Blowdown and 91 Oil Removal Filter (ORF) Outlet streams. Utilization of these streams to present specific challenges to the HTRO Pilot system may be performed to evaluate the impact of pretreatment on the HTRO operating envelope and robustness.

Combinations of feed stream blend and HTRO Pilot skid configuration were used to address the pilot objectives. Three different operation modes/configurations are summarized below.

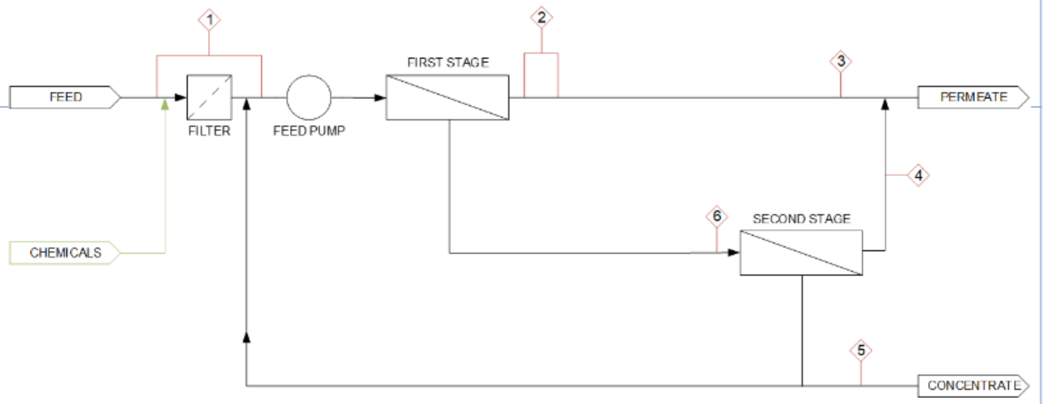
Temperature	90 to 130°C
Feed Water	92 Evap Distillate, 91 WAC Outlet, 91 OTSG Blowdown
Operation Diagram	
Key Performance Indicators	Membrane Flux TDS and Silica Rejection CIP Effectiveness Temperature Robustness

Figure 2. Operating mode: Two-Stage RO with Concentrate Recycle.

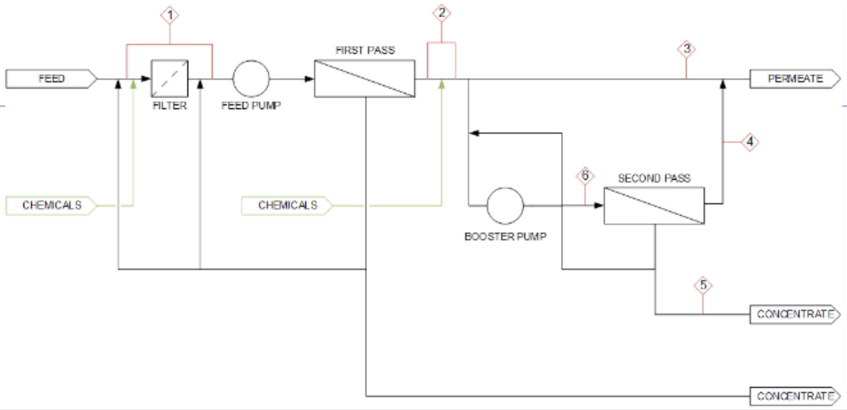
Temperature	90 to 130°C
Feed Water	92 Evap Distillate, 91 WAC Outlet, 91 OTSG Blowdown
Operation Diagram	
Key Performance Indicators	Membrane Flux TDS, Silica, and Hardness Rejection CIP Effectiveness Temperature Robustness

Figure 3. Operating mode: Two-Pass RO with Concentrate Recirculation (Per Pass).

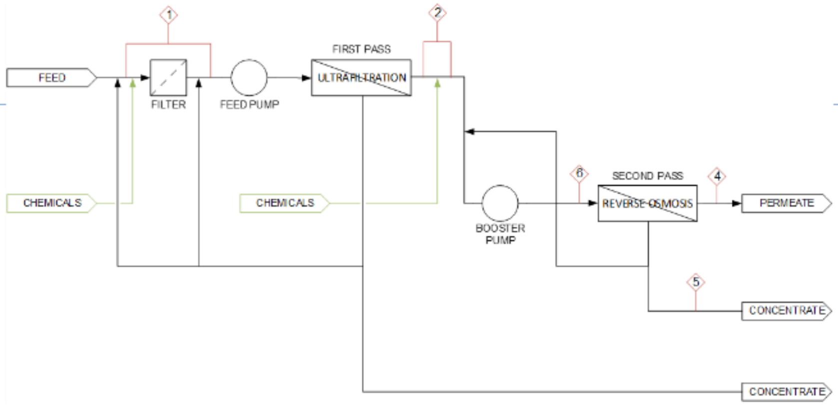
Operating Mode	Ultrafiltration and Single-Stage RO with Concentration Recycle
Temperature	90 to 130°C
Feed Water	92 Evap Distillate, 91 WAC Outlet, 91 OTSG Blowdown, 91 ORF Outlet
Operation Diagram	
Key Performance Indicators	Membrane Flux OIW Removal TDS, Silica, and Hardness Rejection CIP Effectiveness Temperature Robustness

Figure 4. Operating mode: Ultrafiltration and Single-Stage RO with Concentration Recycle.

Table 5. Test matrix.

Feed Water Supply	Pilot Skid Operating Mode		
	2-Stage HTRO w/ Concentrate Recirculation	2-Pass HTRO w/ Concentrate Recirculation	UF to 1-Stage RO w/ Concentrate Recirculation
Distilated/Steam BD	✓	✓	✓
Treated Water	✓	✓	✓
LP Steam BD	✓	✓	✓
Key Performance Indicators	Membrane Flux System water recovery Silica and TDS rejection Robustness at temperature and elevated TOC	Membrane Flux Permeate quality Silica and TDS rejection Hardness removal (Pass 1) Robustness at temperature and elevated TOC	Membrane Flux Silica and TDS rejection Oil removal (UF) Robustness at temperature and elevated TOC

Pilot performance data consisted of process data collection from online sensors and periodic water sample collection for laboratory analysis. WTDC laboratory resources were used to measure a subset of the water parameters of interest. The remaining analyses were conducted at a 3rd party contract laboratory. There were several access points to the process data repository both inside and outside of the WTDC network. The architecture of digital access and data storage into the pilot system is illustrated in Figure 5.

External access was limited to offline data queries to the data historian and read-only views of the pilot skid human-machine interface (HMI). Water quality information from 3rd party and onsite WTDC laboratories are data inputs that would not originate directly from the pilot skid and were stored in the same repository as the online process data.

Process configuration and control through the supervisory control and data acquisition (SCADA) system was located within the WTDC environment, but outside of the skid boundary. Real-time process data was routed to a data historian from the SCADA system. Direct access to individual data acquisition and control components was necessary for calibration and troubleshooting by WTDC operators or 3rd party vendors. This level of access outside of the WTDC environment was not granted.

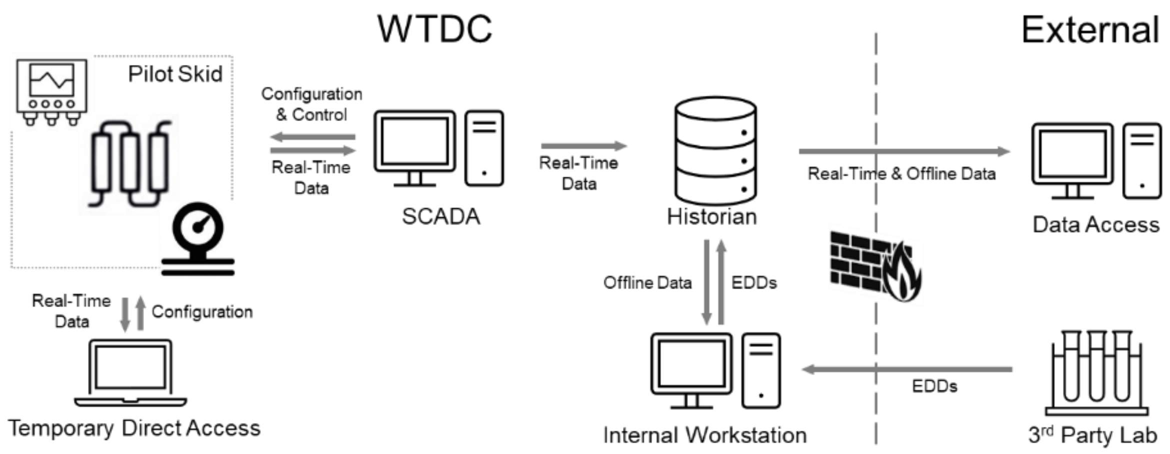


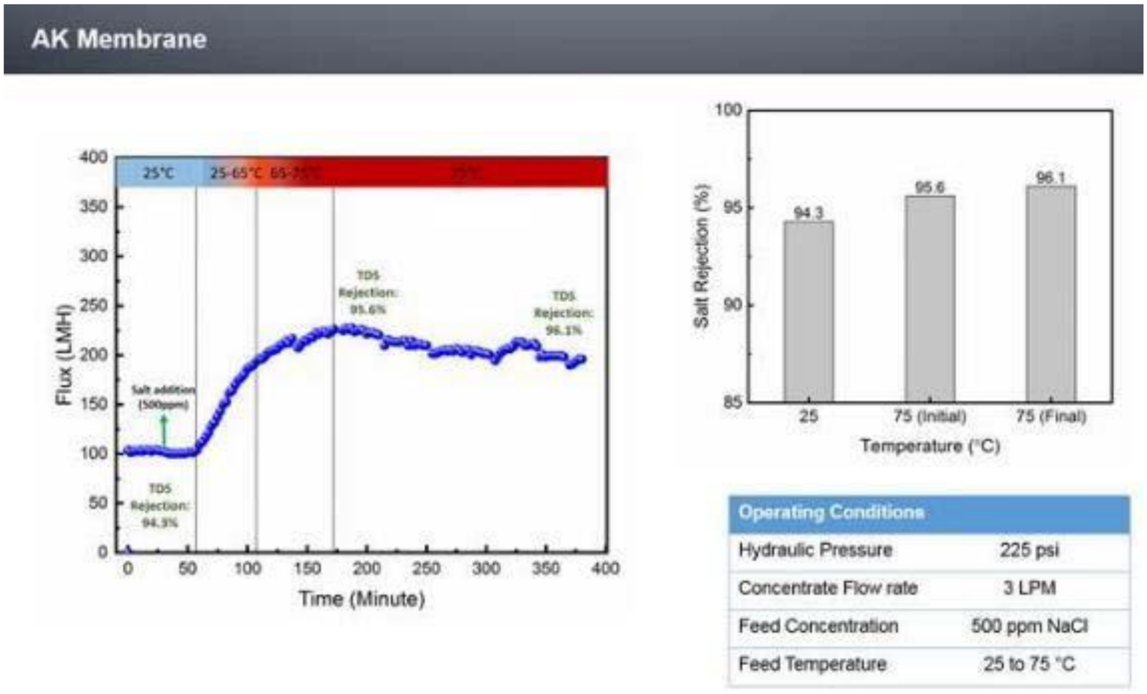
Figure 5. HTRO Pilot digital storage and access architecture.

In addition to these data sources membrane autopsies to elucidate membrane fouling and damage mechanisms under the applied test conditions will be conducted. Visual inspection of other physical components may be conducted to examine wear, scaling, or other potential artifacts of the pilot test.

3.2 PROJECT RESULTS

During the first phase of this project, the University of Alberta and the project partners developed protocols and testing methods for testing of membrane coupons at temperatures lower than 100°C:

- Standardized testing of membrane coupons was performed for the removal of standard solutions developed by Suez to benchmark performance of membrane at various temperatures and conditions (Figure 6).



Operating Conditions	
Hydraulic Pressure	225 psi
Concentrate Flow rate	3 LPM
Feed Concentration	500 ppm NaCl
Feed Temperature	25 to 75 °C

Figure 6. High temperature membrane coupon testing.

- Process modelling of conventional SAGD CPF and HTRO cases were developed in collaboration with third-party subject matter experts and reported at the International Water Conference in 2019 (Figure 7).

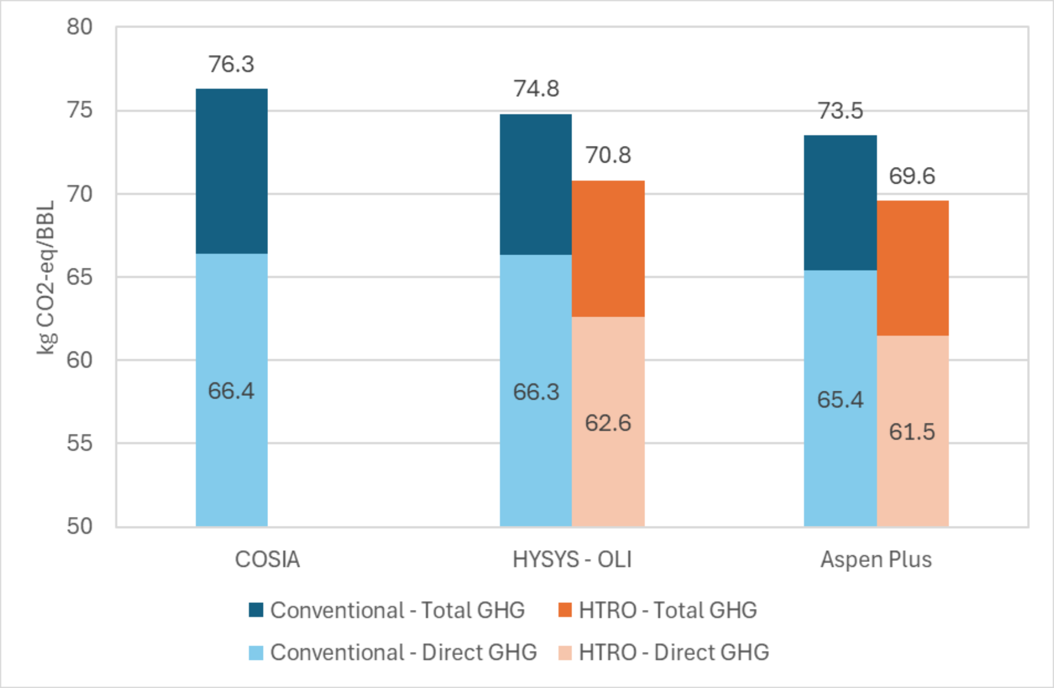
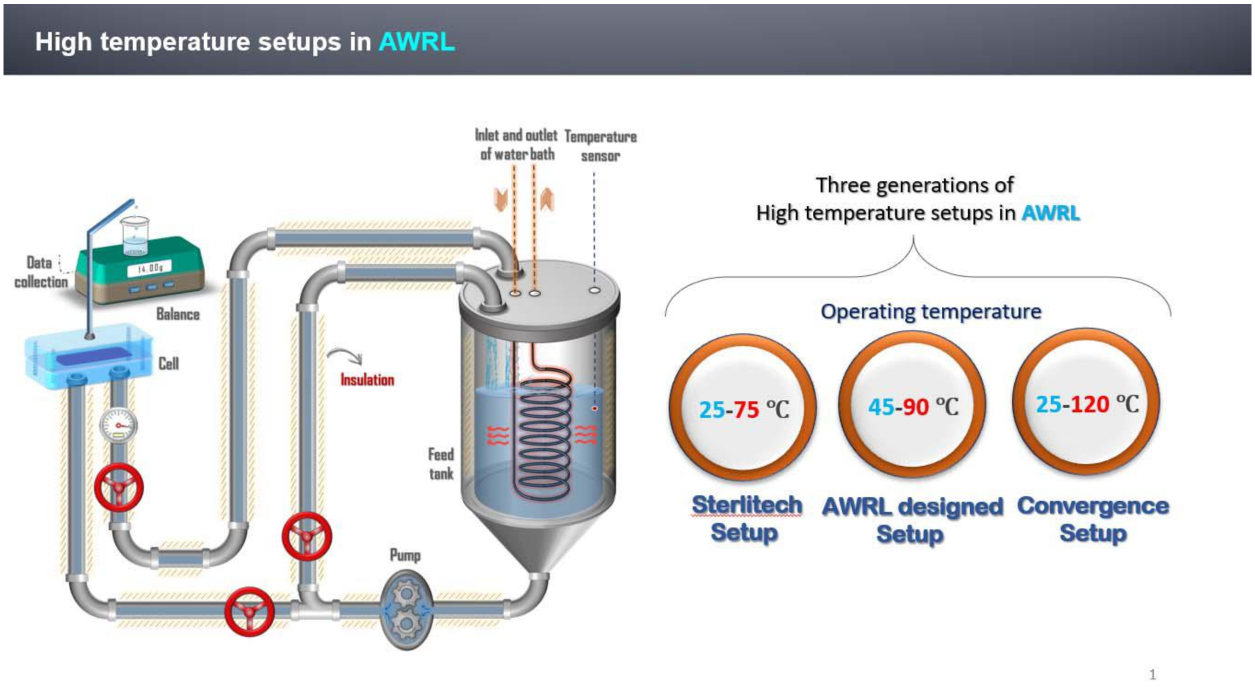


Figure 7. SAGD CPF Process Model total and direct GHG estimate comparison for conventional and HTRO process designs.

- Based on the results of preliminary flat sheet tests and technology integration models a test rig design for spiral-wound membrane elements was refined by all project partners to develop a testing rig suitable for operation at up to 120°C (Figure 8).



High temperature setups in AWRL

Three generations of High temperature setups in AWRL

Operating temperature

25-75 °C	45-90 °C	25-120 °C
Sterlitech Setup	AWRL designed Setup	Convergence Setup

Figure 8. Progression of development of testing setups.

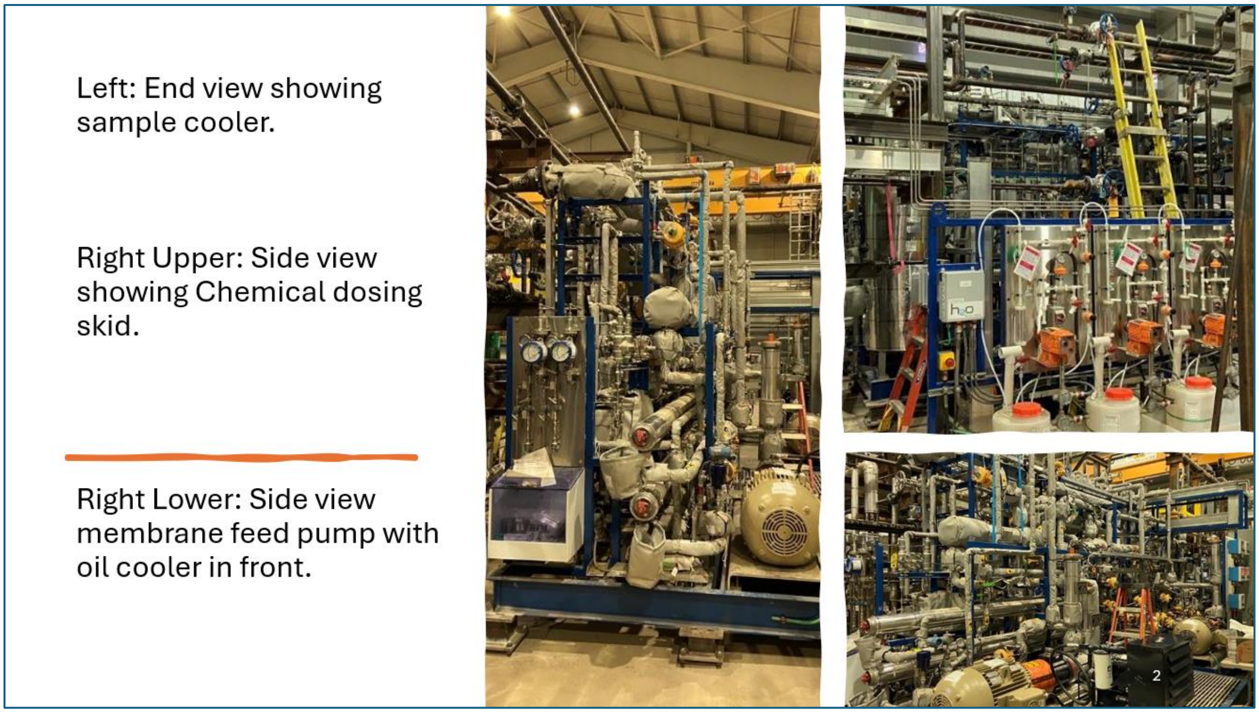
Parallel to the tests at the University of Alberta, the mechanical and operational performance of standard constructed and high temperature constructed membranes at high temperatures were evaluated at NAIT. The testing was conducted with synthetic fluids at temperatures up to 113°C and two different pH levels (9.5 and 10.5). Overall results showed that:

- During heating time, a decline in salt rejection was observed.
- The rate of water permeation through the membrane increased with the feed water temperature.
- Feed solution at a pH of 9.5 had a better salt rejection (>95%) compared to pH of 10.5 (>90%).
- No significant physical damage was observed except discoloration in all of the membranes, either standard or high temperature constructed elements regardless of the condition of the test.

The preliminary results provided a benchmark for comparison with future membrane developments.

Phase 2: WTDC Testing

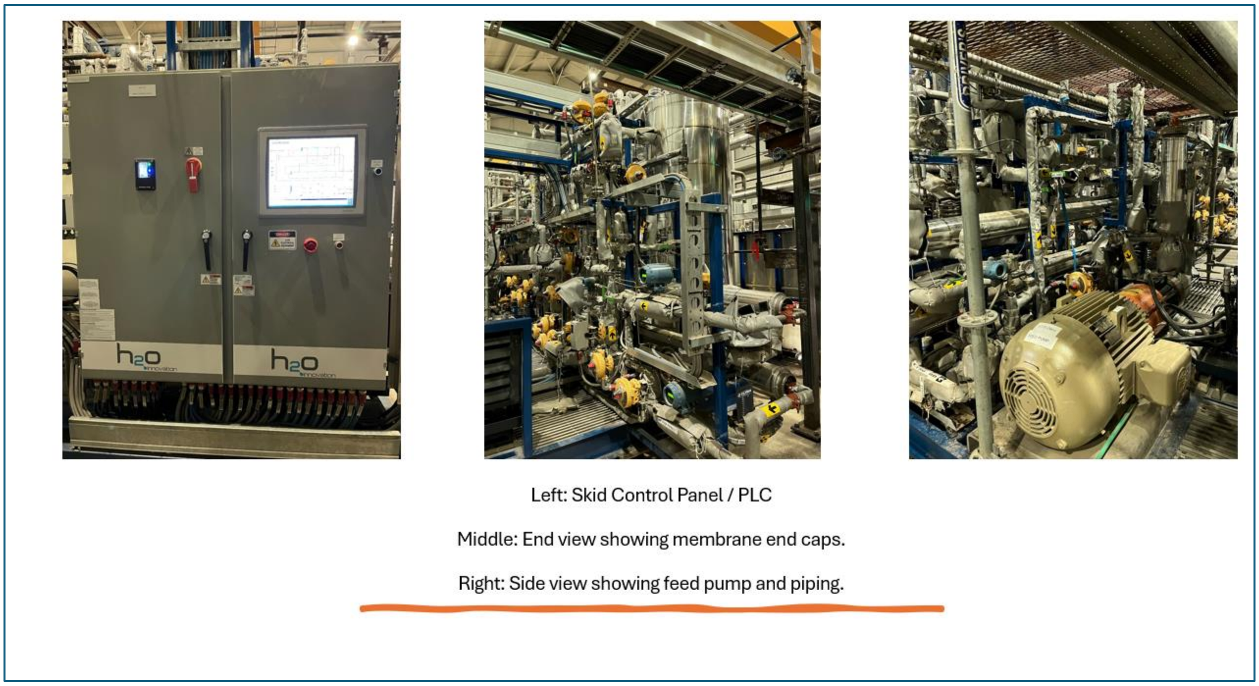
The HTRO pilot skid was successfully installed within the Firebag WTDC for testing. Images are shown below showing connections and components.



Left: End view showing sample cooler.

Right Upper: Side view showing Chemical dosing skid.

Right Lower: Side view membrane feed pump with oil cooler in front.



Left: Skid Control Panel / PLC

Middle: End view showing membrane end caps.

Right: Side view showing feed pump and piping.

Initial commissioning runs were performed using HTRO membranes on evaporator distillate feed at low pressure and flux until confident to progressively operate towards higher pressures and temperatures. Focus initially was on obtaining high quality distillate organics removal over production volume (i.e. lower flux and recovery) to observe organics removal, and identify if one or two passes were sufficient to reject the majority of organics. These tests were performed both with and without anti-scalant.

First stage permeate initially showed good TOC removal, but performance was not as successful on the second stage. Silica removal trended positively, with stable pressure measurements. Through a number of improvements in both membrane installation and operation, overall organics removal was able to be achieved with significant silica removal, and high recovery.

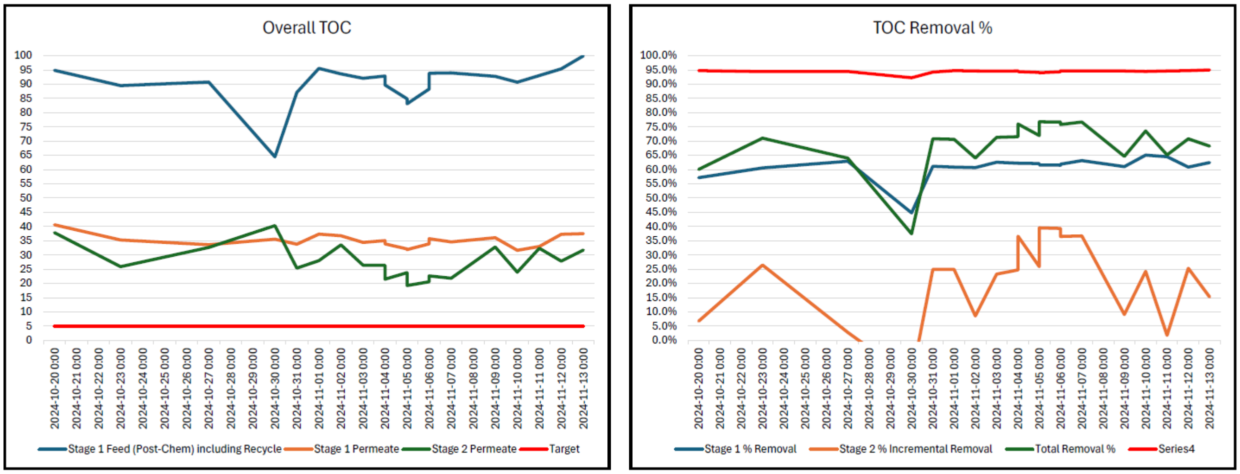


Figure 9. TOC removal.

Following successful polishing of evaporator distillate organics, the feed to the pilot was changed to allow boiler feedwater (BFW) from the Firebag plant to be polished for silica and organics. This system was operated successfully at existing process temperatures of 85-90^{o}C, and also successfully operated at temperatures up to 105^{o}C. Above this temperature, issues were encountered with the system.

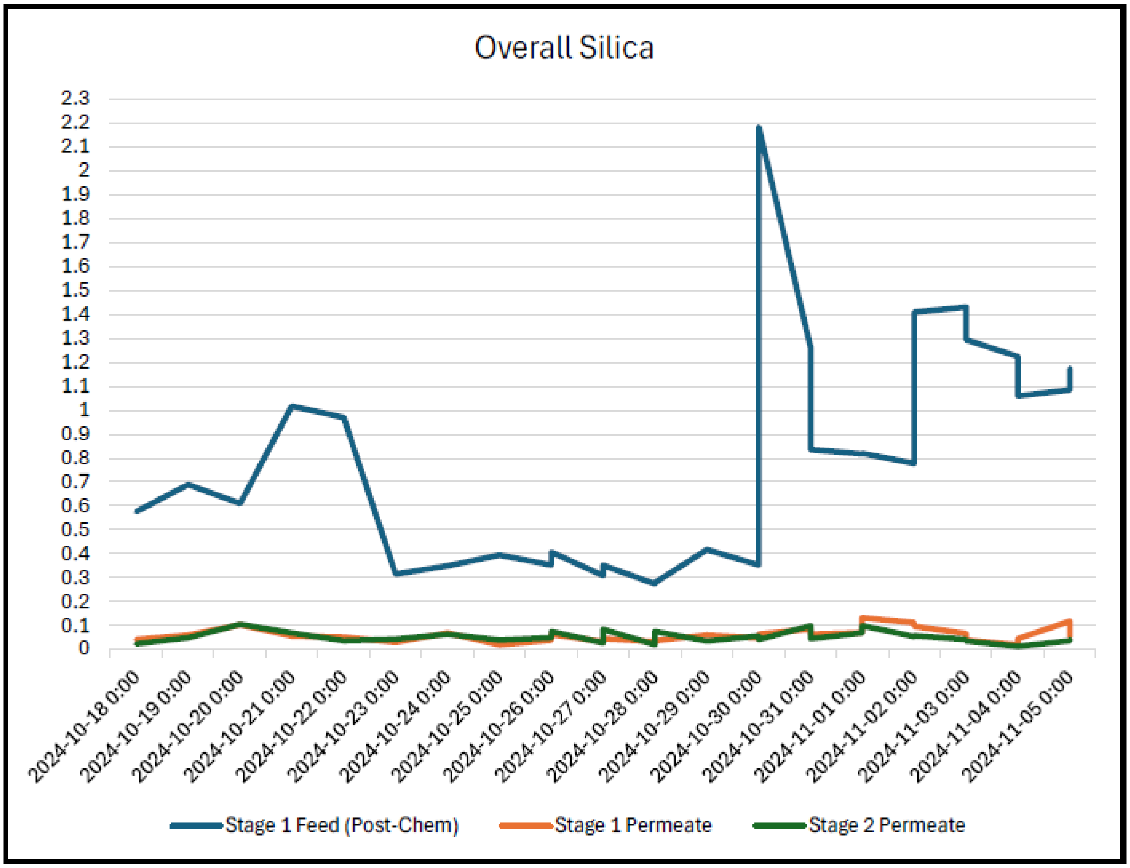


Figure 10. Silica removal.

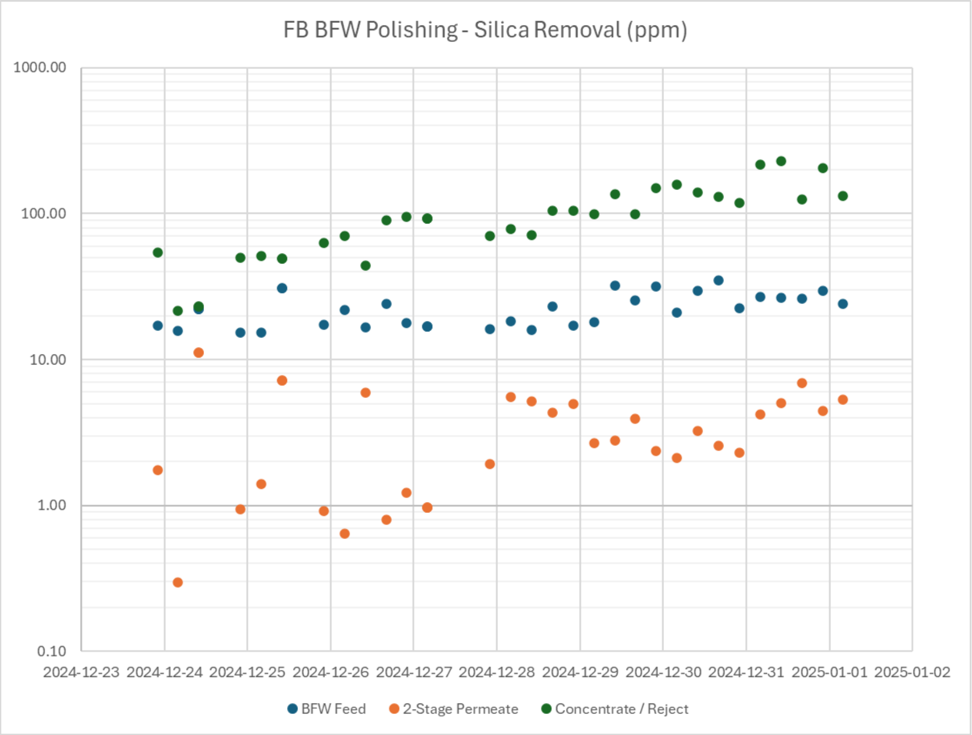


Figure 11. FB BFW Polishing - Silica removal.

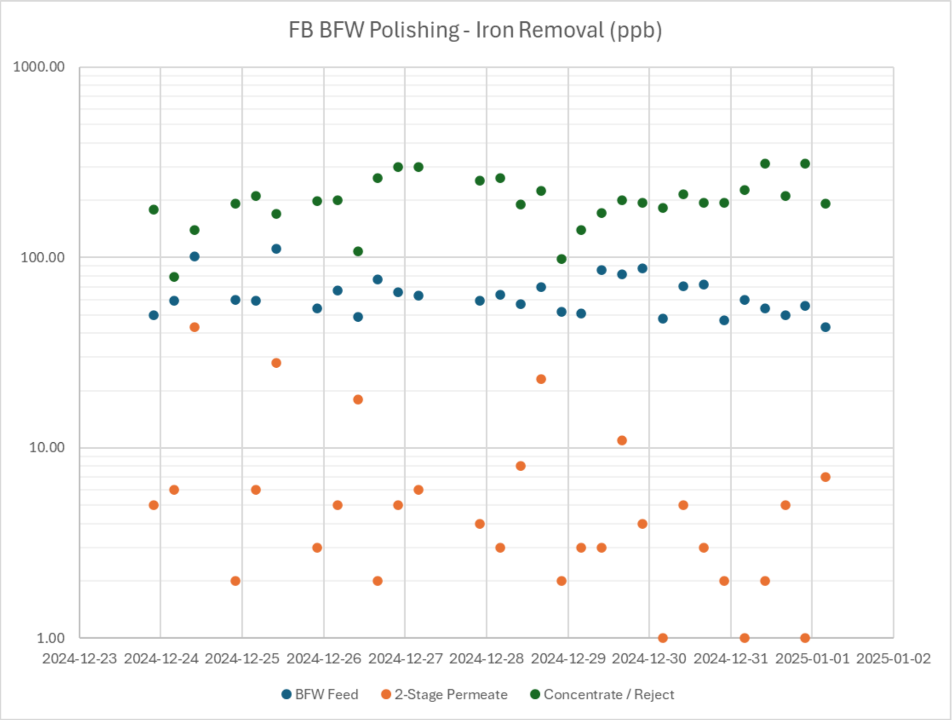


Figure 12. FB BFW Polishing - Iron removal.

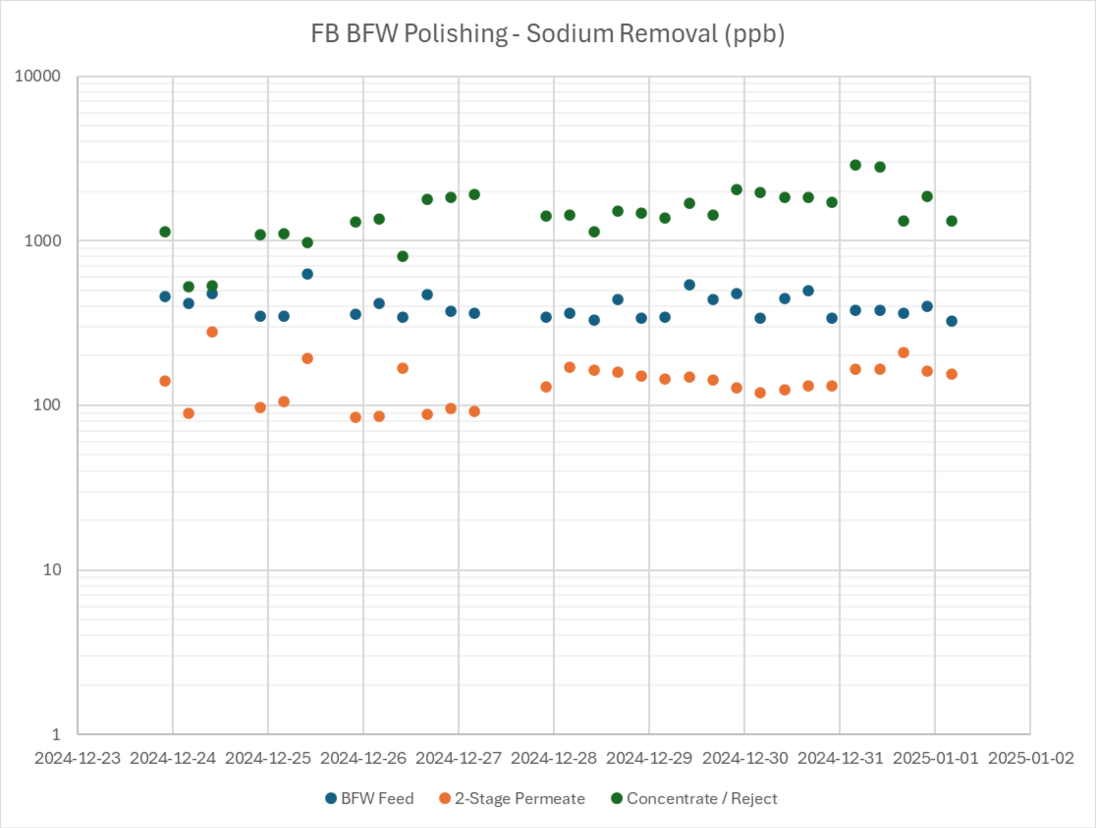


Figure 13. FB BFW Polishing - Sodium removal.

4. COMMERCIALIZATION

CNRL and Suncor represented two producers interested in the development of this technology to provide an overall benefit to the oil and gas industry in Alberta. Widespread adoption of technology traditionally occurs following an ‘early adopter’ de-risking technology, and Suncor and CNRL intend to be such early adopters. CNRL and Suncor supported this Project as this technology has the potential for a step change in developing existing assets in an environmentally and economically responsible manner. This type of technology is applicable for greenfield deployment, but it is more likely the first commercial installation would be a debottleneck project to further prove commercial potential before larger scale implementation. Example CPF configurations of the current conventional SAGD water treatment technology, an HTRO-based greenfield CPF, and a brownfield/debottlenecking configuration using HTRO are illustrated in Figure 14.

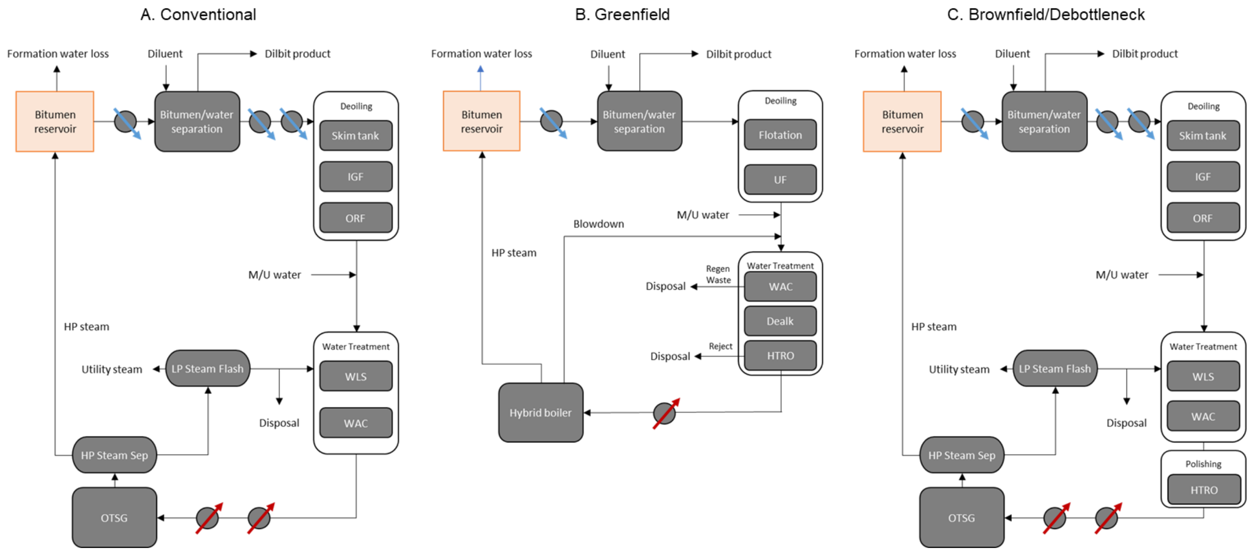


Figure 14. SAGD CPF (A) conventional, (B) greenfield, and (C) brownfield/debottleneck configurations.

Export of the technology to other market segments in Alberta, as well as other provinces is a realistic outcome from successful commercialization. End users of HTRO technology could include food processing (e.g. dairy & vegetable proteins, sugar concentration/fractionation/clarification, UHT pasteurized juices/teas), industrial hot process condensate, boiler condensate treatment, evaporator blowdown treatment and pharmaceutical sterile water production.

The project results will be shared after completion through various industry bodies that both companies are members of including CAPP, COSIA and the Water Technology Development Centre (WTDC), and opportunities to participate in later stages of the Project will be given to other SAGD producers in Alberta through these industry bodies. Members of these industry bodies represent the majority of SAGD producers in Alberta.

The table below indicates the current technology readiness level (TRL) for HTRO technology and the expected TRL at completion of the project.

Table 6. Technology Readiness Level (TRL) Self-Assessment.

TRL 3 Experimental Proof of Concept Demonstration	**TRL 4** Technology Development & Validation	**TRL 5-6** Prototype Development & Testing	**TRL 7** Near Commercial Pilot Demonstration	**TRL 8** Commercial-Scale Field Demonstration	**TRL 9+** Commercial Implementation and Market Rollout
Complete	Complete	Current HTRO TRL Level (Project Start)		HTRO TRL Level at Project Completion	HTRO TRL Level following sharing of Project Results

5. LESSONS LEARNED

Overall, the development and execution of this pilot was successful in highlighting the potential use of membrane for boiler feedwater production in SAGD process at high temperatures up to 105°C. Challenges were encountered with understanding the most effective modes and conditions of membrane operation, but these were overcome to successfully operate the skid in polishing silica and organics. The early closure of the WTDC as decided by project funders and partners did affect the available runtime and test plan, but the main test plan targets were completed as planned.

While successful at this scale, there are still challenges with commercialization of membrane technology such as this at high temperatures. Further work is planned, and the current test skid has been removed from the WTDC and is planned to be re-installed at a new facility to continue de-risking this technology.

6. ENVIRONMENTAL BENEFITS

6.1 EMISSIONS REDUCTION IMPACT

GHG emission reduction is the primary benefit of this project. BFW for existing SAGD processes is treated using evaporators or lime softening, with OTSGs used for steam production. Typically, PW is >150°C when extracted from the reservoir but is cooled to <90°C for atmospheric de-oiling and water treatment processes. While most of this energy is recovered through heat exchange, high pressure and temperature produced water treatment processes have the potential to produce BFW and steam with lower GHG intensity based on process modelling and testing performed for this project.

Process models of SAGD CPFs were initially developed using a combination of Aspen Plus®, Aspen HYSYS®, and OLI Flowsheet: ESP to evaluate the overall GHG footprint, water use efficiency, and equipment size for greenfield SAGD-HTRO configurations compared to conventional technology. For both workflows, a CPF base case simulation was first developed based on an industry accepted standard plant design (i.e., COSIA Base Case) as well as a greenfield HTRO flowsheet matching the flow diagram shown in Figure 14B.

Modelling and testing have indicated that adopting HTRO technology will reduce total GHG's per ton of produced oil by 5.3% compared to a baseline WLS process. Subsequent phases of greenfield SAGD CPF process models that accounted for a range of produced water chemistry, make-up water chemistry, and added evaporator-based CPFs as a secondary benchmark demonstrated that the total GHG reduction of an HTRO-based greenfield project is in the 5 to 10% range compared to currently used SAGD CPF technology. The reference plant design used in the modelling is representative of the majority of central process facility designs that are currently operating in the Athabasca oil sands. Further total GHG gains may be achieved through increased GHG reductions from the Alberta electricity grid that directly impact the indirect GHG footprint.

Pilot testing confirmed that the technology has the ability to operate under high temperature and pressure conditions. Further work is ongoing to assess how to integrate membrane treatment operations into future assets and reduce, replace or supplement existing warm lime softener evaporator-based processes to potentially reduce future emissions.

6.2 OTHER ENVIRONMENTAL IMPACTS

A HTRO membrane-based treatment system would have several advantages over conventional unit operations currently installed in SAGD CPF's based on the technical-economic analyses completed:

- Under select conditions reduce make-up water input and wastewater disposal up to 40%.
- Reduce land disturbance by up to 10% due to plant footprint reduction, with further reduction dependant on process selection and configuration.
- Ability to polish existing SAGD boiler feed water (BFW) to potentially operate steam generation units at high steam quality and reduce blowdown quantities in existing facilities.

7. ECONOMIC AND SOCIAL IMPACTS

In terms of market opportunity and adoption, in a capital constrained environment debottlenecking of facilities is of high value to producers. CNRL and Suncor see potential to deploy this technology for debottlenecking opportunities within existing plants. For example, where existing evaporator or WLS processes are limiting plant capacity, a small modular membrane-based process may unlock the ability to produce more produced water for steam generation, with low capital and operating expense compared to conventional expansion.

The expected economic benefits that HTRO can provide can be judged using CAPEX and OPEX estimations developed by the project partners, which indicate a potential CAPEX reduction between 10-

17% (dependant on process configuration and scale), and a neutral to slightly positive improvements tor OPEX.

Modelling of high temperature membrane technology for the purposes of conceptual CPF design has shown improved CAPEX and OPEX per produced barrel, which results in improved cost competitiveness for oilsands development and ongoing operations. Modelling was developed to compare a high temperature flowsheet to existing SAGD projects proposed for sanctioning to illustrate that the proposed flowsheet is suitable to current market conditions required for financial break-even, and enhances returns due to lower footprint, CAPEX and OPEX costs. Commercialization of HTRO technology may allow development of more modular SAGD facilities, which could enable smaller scale in situ development. This would be beneficial to all producers, either in accessing 'remote' stranded oil sands assets with thermal technology, or allowing smaller producers to scale up from small modular facilities with more favorable economics. Currently, smaller producers are restrained in deploying new technology due to the high cost of entry, and scale of production required to achieve returns on investment. Modular central processing facilities may be a key tool in removing these barriers, and improving diversification of the installed SAGD thermal producer base. All of the developments above would positively impact the province through efficient extraction of resources, improved GDP and tax revenues, as well as increase to royalty revenues.

Full-scale development of HTRO technology created full-time and part-time jobs not only through collaboration with institutions, but also through project development, execution and reporting. The majority of work for this project took place within Alberta, hosted at the Water Technology Development Centre (WTDC) at Suncor's Firebag facility, directly employing a number of part-time and fulltime employment positions in pilot construction and operation. As a result of successful piloting, the value of local expertise developed at the WTDC will be highly valued by current and future employers. Export of the technology to other Albertan market segments, as well as other provinces is a realistic outcome from successful commercialization (see section 4).

8. SCIENTIFIC ACHIEVEMENTS

8.1 PUBLICATIONS, CONFERENCE PRESENTATIONS AND PARTNERSHIPS

Perdicakis, B., McGregor, M., Gerbino, AJ., and Petersen, M. 2019. High Temperature Reverse Osmosis Membrane SAGD Process Design Assessment. Published at the 2019 International Water Conference (Paper # IWC 19-61), Orlando, Florida, United States of America.

Khorshidi B., Bhinder A., Thundat T., Pernitsky D., Sadrzadeh M. (2016). Developing high throughput thin film composite polyamide membranes for forward osmosis treatment of SAGD produced water. Journal of Membrane Science. 511: 29-39.

Sadrzadeh M., Pernitsky D., McGregor, M. (2018). Nanofiltration for the Treatment of Oil Sands-Produced Water. InTech. Doi: 10.5772/intechopen.74086.

Northern Alberta Institute of Technology (NAIT) HTRO HTRO Pilot test - NAIT – High Temperature Testing Facility supported by COSIA (Project Administrators CNRL and Suncor).

Gen3 Program – Joint Industry Project (JIP) under which HTRO R&D was conducted by Devon (CNRL), Suncor and GE (Suez).

9. OVERALL CONCLUSIONS

A membrane based high pressure and temperature produced water treatment process was successfully tested on different SAGD produced water fluids in a field pilot. This technology was shown to have the potential to produce BFW and steam with lower greenhouse gas (GHG) intensity.

Through the project, high temperature reverse osmosis (HTRO) technology tests were performed to determine a range of implementation scenarios and processes that can enable CPF operation at these conditions and generate high quality boiler feedwater compared to incumbent practices, with the goal of commercializing this technology and the potential benefit of reduced GHG emissions.

Further work will continue to determine the next steps and testing required to further allow future decisions to be made for deployment of the technology.

10. NEXT STEPS

Following the Project, further development of commercial-scale production based on forecasted market size may be required. Emissions Reduction Alberta will be important in this stage to assist in marketing Project results to the oilsands industry as a whole, and to prove that a reasonable market exists for large scale membrane production. This may then allow economies of scale to be developed if widespread adoption of the HTRO membrane technology can be achieved. It is anticipated this could be the main barrier to adoption of the HTRO membrane into new or existing facilities, i.e., market understanding of the potential capital, operating and environmental (GHG) benefits of using the technology developed.

11. COMMUNICATIONS PLAN

To assist in distribution of results following the trial, the project partners currently support groups such as COSIA, whose role is to disseminate information on technology projects that improve environmental performance. Contribution of results is proposed from the project partners to COSIA, as well as participation in conferences and workshops with other oilsands partners in open forums to allow knowledge transfer to the industry as whole. Publication of results in industry journals, as well as applying to present at the International Water Conference (IWC) is also proposed.

While no specific new intellectual property was generated during the pilot testing phase at the WTDC, there is likelihood that IP may be generated following further analysis of the data from the pilot testing data. In this case new IP and licensing, if applicable, would be proposed to be shared between the project partners, and going forward, if commercialized made available through reasonable commercial terms to benefit other Albertan firms.

12. LITERATURE REVIEWED

During the planning phases of the project, the following references were reviewed:

Alberta Energy Regulator. (2019). Directive 081 - Water Disposal Limits and Reporting Requirements for Thermal In Situ Oil Sands Schemes.

Khorshidi B., Bhinder A., Thundat T., Pernitsky D., Sadrzadeh M. (2016). Developing high throughput thin film composite polyamide membranes for forward osmosis treatment of SAGD produced water. Journal of Membrane Science. 511: 29-39.

Sadrzadeh M., Pernitsky D., McGregor, M. (2018). Nanofiltration for the Treatment of Oil Sands-Produced Water. InTech. Doi: 10.5772/intechopen.74086