AI-SDTC Water Technology Projects

Report Type: Final Technical Report
Reporting Period: Dec 14, 2016 to Mar 31, 2018

Project Title: EOR Produced Water Recycling
Name of Funders: AI and SDTC
AI Project Number: AI 2397
SDTC Project Number: SDTC-2016A-3210

Project Leader: Ben Sparrow
Lead Institution: Saltworks Technologies Inc.
Project Partners: Enerplus Corporation
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Project Start Date: Dec 14, 2016
Project End Date: Mar 31, 2018

Project Budget: $1,500,000
AI & SDTC Funding: $1,000,000

Executive Summary

This project delivered a world's first enhanced oil recovery (EOR) produced water treatment plant for low salinity re-injection to enable recovery of more hydrocarbons. The plant reduced operating costs by reducing polymer consumption. Most importantly, it reduced freshwater withdrawal for make-up and reduced GHGs where trucking and deep well disposal of produced water was required.

Enhanced oil recovery is a low capital investment means to increase oil production by injecting water to displace oil from a reservoir. Injecting water of low salinity and/or with polymer to increase viscosity liberates more oil. EOR operators often recycle produced water for reinjection; however, its salinity rises with re-use due to naturally occurring salts in the reservoir. Higher salinity water tends not to liberate as much oil. When salinity gets too high, the produced water must be disposed. In addition, higher salinity requires more polymer to reach injection viscosity targets. Desalting saline produced water enables re-injection with lower polymer consumption, recycling of water on-site, and increased hydrocarbon production. For a 1,200 m3/day injection well, a plant using the project technology can save as much as $1.9M per year in polymer by desalting the produced water. In this example, the EOR produced water treatment plant's total cost of ownership is approximately $1.2M per year, resulting in $0.7M per year in total savings.

The project technology is Saltworks' Flex EDR Organix, an advancement of electrodialysis, and the second most widely used membrane desalination system in the world. Saltworks re-invented electrodialysis for produced water treatment with the following innovations: patented advanced membranes; a patented membrane-stack design that can operate on high hardness waters common in Alberta without the need for chemical softening; and patented processes and controls for extreme recovery and reliable unattended operation including start, stop, self-clean and self-diagnosis.

The project, supported by Alberta Innovates and SDTC, builds on two years of off-site testing with oil & gas supermajors and a successful 42 day field pilot in an Albertan oil field. The results proved that Flex EDR Organix can lower oil production costs. The technology is a win on many fronts: recycling water in a high-use Albertan application; improving the profitability and competitiveness of Albertan oil; reducing GHGs and preserving the water balance; and helping build a next generation national champion cleantech firm with a technology that has massive export potential.

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1. Introduction

Future Canadian oil production will be costlier and more resource intensive because the "easy" oil has been extracted. Waterflood enhanced oil recovery (EOR) can increase oil yield from certain reservoirs by up to 40%, boosting production. In its simplest form, EOR involves pushing water through an oil reservoir to push out more oil. However, water picks up salt along the way resulting in a saline produced water. EOR can be optimized to liberate more oil by tuning the salinity of injected water and adding polymer to increase viscosity.

Currently, EOR operators recycle produced water as much as possible but salinity rises with re-use. Eventually, the high salinity produced water must be disposed and lower salinity makeup water is needed. Injecting water of low salinity (2,000 to 8,000 mg/L total dissolved solids) and/or with polymer to increase viscosity, stimulates liberation of additional oil from the reservoir. In polymer floods, the amount of polymer consumed to reach an optimal target viscosity increases with salinity: more salty water results in increased polymer costs. For example, a 4,000 m3/day produced water injection site may consume $5-10M in polymer per year. EOR operators currently combine strategies such as adding more polymer to salty produced water, trucking produced water for disposal, extracting make-up freshwater, or sacrificing production.

Canadian innovation is set to change the cost equation for EOR, which the Economist estimates will account for 40% of supermajor oil production moving forward. This project delivered a world's first EOR produced water treatment pilot plant. The project technology will enable recycling of EOR produced water for low salinity injection, which can recover more hydrocarbons. Recycling EOR produced water will also reduce operating costs by reducing polymer consumption. This project advances commercialization of a technology that reduces freshwater make-up withdrawal for EOR injection, reduces GHGs associated with trucking and deep well disposal of produced water, improves hydrocarbon recovery and resulting profitability, and lowers operating costs by reducing polymer consumption.

This report will provide the details on the technical outcomes of this project.

2. Project Description

The project scope is delivery of the world's first enhanced oil recovery (EOR) produced water treatment plant using Saltworks' patented Flex EDR Organix technology. This technology enables recycling of EOR produced water for low salinity re-injection. The project goal is to demonstrate reduced polymer consumption, greater water reuse, reduced water disposal, and improved hydrocarbon recovery.

The project test plan, with support from Alberta Innovates and SDTC, involved off-site testing with supermajors and a successful 42 day field pilot at Enerplus' site in Medicine Hat, Alberta. These tests proved that Saltworks' Flex EDR Organix can lower EOR production costs.

Project objectives were:

- **Task 1:** Design-build and pre-test a 1 m^3/day Flex EDR small scale field pilot plant using the same process and components as future full scale plants. In parallel to this work, off-site smaller scale pilot testing (20L/day) was completed using a fully automated 24 hour operation "micro Flex EDR system" on real produced water samples to de-risk and pre-tune the larger plant. **Task 1 is fully complete.**

- **Task 2:** On site testing of the pilot plant for 42 days to prove treatment objectives and confirm the design basis, operating needs, economics, benefits, and lessons learned for full-scale commercial dispatch. The pilot was originally planned to operate for 60 days at a capacity of 1 m^3/day for a total of 60 m^3 produced water treated. However, Enerplus requested 150 m^3 of produced water be treated in order to provide sufficient volume for their subsequent testing. The pilot was therefore operated at a higher capacity, and reliably treated 150 m^3 over 42 days. Given that the target volume was successfully treated and informative data was obtained, Enerplus deemed the test complete. **Task 2 is fully complete.**

The pilot plant confirmed field performance and economics in-situ under variable daily chemistry and flow rates at the Enerplus EOR facility. Industry requires proof of in-field performance and optimization prior to full-scale implementation. This approach ensured technology development in alignment with and for industry, thereby reducing commercialization risk and building confidence in the technology. Saltworks' existing designs, pilot plant infrastructure, production capability, and talent (engineers, scientists, and field teams) were leveraged for cost effectiveness. In addition, the partner's site and facilities, existing EOR produced water, and operator staff were leveraged, requiring no new infrastructure for the project. Tie-ins and utilities for the pilot plant were required.

3. Progress and Accomplishments

The following table lists the critical tasks and milestones that were achieved over the course of the project and describes the progress made towards each of these tasks, as per the contribution agreement.

Task #	Task Description	Start Date	End Date	Milestones / Deliverables
Task 1				
Task 1.1: Design, build and factory test pilot plant	Design, build, and factory test a 1 m^3/day pilot plant capable of treating EOR produced water or high organic saline waters. Leverage Saltworks' previous pilot plant infrastructure and lessons learned to upgrade the plant to a CSA-certified electrical and Saltworks' high reliability process design.	Dec 14, 2016	June 30, 2017	Containerized, mobile, high quality EOR desalination plant was built with complete automation, self-cleaning, remote monitoring, electrical and controls, CSA-certified and a spare parts plan/kit for high reliability at site.
Task 1.2: Implementation plan	Develop a detailed site implementation and test plan in cooperation with Enerplus. Site tie-in expenses such as valves, utilities, or ground preparation to receive the plant are required. De-risk site implementation by pre-factory testing the pilot plant at Saltworks.	Dec 14, 2016	Aug 31, 2017	Site pilot implementation plan and site preparations were completed in advance of pilot ship date. Pilot plant was tested and ready for field dispatch.
Task 1.3: Flex EDR membrane-stack upgrades	Membrane, stack design and production upgrades for greater resilience and higher capacity performance on produced waters.	Dec 14, 2016	June 30, 2017	Membrane resistance to scaling, gasket robustness and hydraulic capacity of the stack were increased.
Task 1.4: Ongoing bench testing	Ongoing engineering, bench and pilot testing of representative waters in preparation for market roll-out.	Dec 14, 2016	June 30, 2017	24h bench testing a minimum 4,000 L of produced water was conducted on a Saltworks automated bench with the same process and controls as the pilot and future full-scale plants.
Task 1.5: Task 1 reporting & Task 2 implementation plan	Progress reporting	June 30, 2017	Aug 31, 2017	Phase 1 Progress Report was completed.
Task 2				
Task 2.1: Delivery	Pre-test pilot plant prior to dispatch. Deliver, implement and commission pilot plant at the Enerplus site.	Sep 12, 2017	Sep 19, 2017	Pilot Plant > 1 m^3/day was delivered and ready to operate at Enerplus on EOR produced water.

Task #	Task Description	Start Date	End Date	Milestones / Deliverables
Task 2.2: Operation	Operate pilot plant for a minimum of 60 days proving effective treatment of EOR produced water to meet desalination and brine discharge objectives. 60 days is consecutive but not including utility or water supply outages, with downtime for inspections, to confirm reliability. Total operating time shall be 60 days.	Sep 20, 2017	Dec 1, 2017	Completed a successful and reliable operation with average capacity >= 1 m^3/day. Desalted 150 m^3 of EOR produced water to <= 2000 mg/L, proved reduction of polymer addition, and reached injected water viscosity targets for the site. Enerplus required 150 m^3 of produced water be treated in order to provide sufficient volume for their downstream testing. The pilot operated at a higher capacity, treating 150 m^3 in 42 days. Enerplus deemed the test outcome successful and data sufficient and therefore concluded the test.
Task 2.3: Ongoing bench testing and Flex EDR membrane-stack upgrades	Ongoing engineering, bench and pilot testing of representative waters in preparation for market roll-out, as well as upgrades to membrane, stack, and plant systems for successful future commercial roll-out.	Dec 15, 2017	Jan 15, 2018	Bench and/or pilot testing of additional prospective client waters with testing reports were conducted. Further improved the gasket and plate design to increase membrane active area and conducted further membrane longevity testing.
Task 2.4: Design basis & full scale economic analysis	Design basis development for full scale plant (in light of pilot learning) and showing ROI savings of 20% over present methods. Full scale economic and market analysis. Noted this exercise is ongoing throughout the project.	Dec 15, 2017	Feb 28, 2018	Design Basis Memoranda (DBM) and plant economic work-up were completed.
Task 2.5: Reporting	Final project reporting.	Jan 15, 2018	Mar 1, 2018	Phase 2 Progress Report and Final project report have been completed.

Task #	Task Description	Status	Comments on Tasks and Milestones
Task 1			
1.1	Design, build, and factory test pilot plant	Completed	Completed ahead of schedule.
1.2	Implementation plan	Completed	Completed ahead of schedule. Site Implementation Plan and Site Preparation was completed.
1.3	Flex EDR membrane-stack upgrades	Completed	Completed.
1.4	Ongoing bench testing	Completed	Completed ahead of schedule.
1.5	Task 1 reporting & Task 2 implementation plan	Completed	Completed.
Task 2			
2.1	Delivery	Completed	Completed ahead of schedule.
2.2	Operation	Completed	Completed ahead of schedule.
2.3	Ongoing bench testing and Flex EDR membrane-stack upgrades	Completed	Completed.
2.4	Design basis & full scale economic analysis	Completed	Completed ahead of schedule.
2.5	Reporting	Completed	Completed.

4. Results and Outcomes

Task 1.1 - Design, build, and factory test pilot plant

- Containerized, mobile, up to 10 m^3/day pilot plant designed and built (exceeds 1 m^3/day plant spec). Plant includes full automation, self-cleaning, remote monitoring, CSA-certified electrical and controls systems, and parts kit.
- Tested full-scale Flex EDR Organix stack in the pilot plant.
- Implemented advanced controls on the pilot plant.
- Completed pilot plant pretreatment skid with up to 10 m^3/day capacity.
- Control system optimized for prefiltration and backwashing.
- Pretreatment consists of: prefiltration for particle removal and for residual oil removal.
- Integrated Flex EDR Organix and Prefiltration factory tested, showing up to 10 m^3/day capacity.
- Raw feed stream 7,000 - 12,000 mg/L total dissolved solids (TDS).
- Product stream TDS target of 1,500 - 2,000 mg/L achieved.

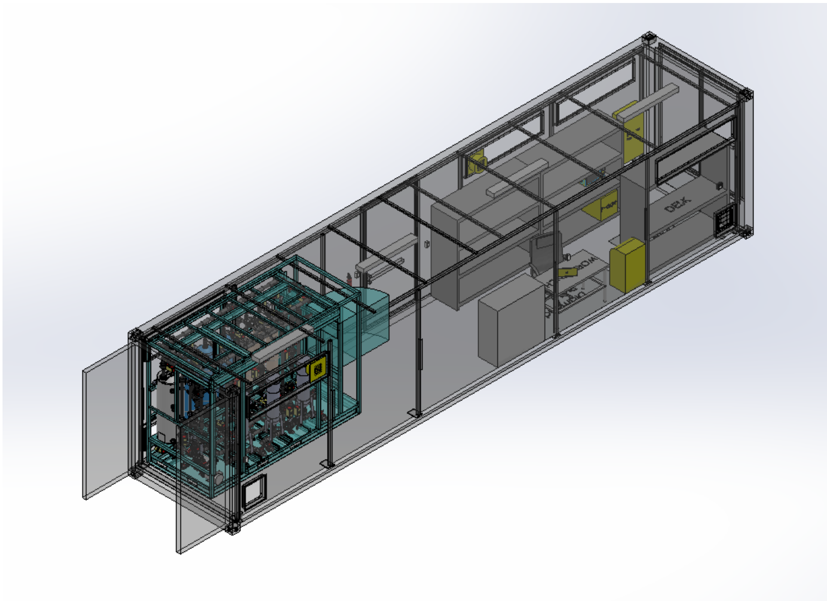


Figure 1. Plant layout design

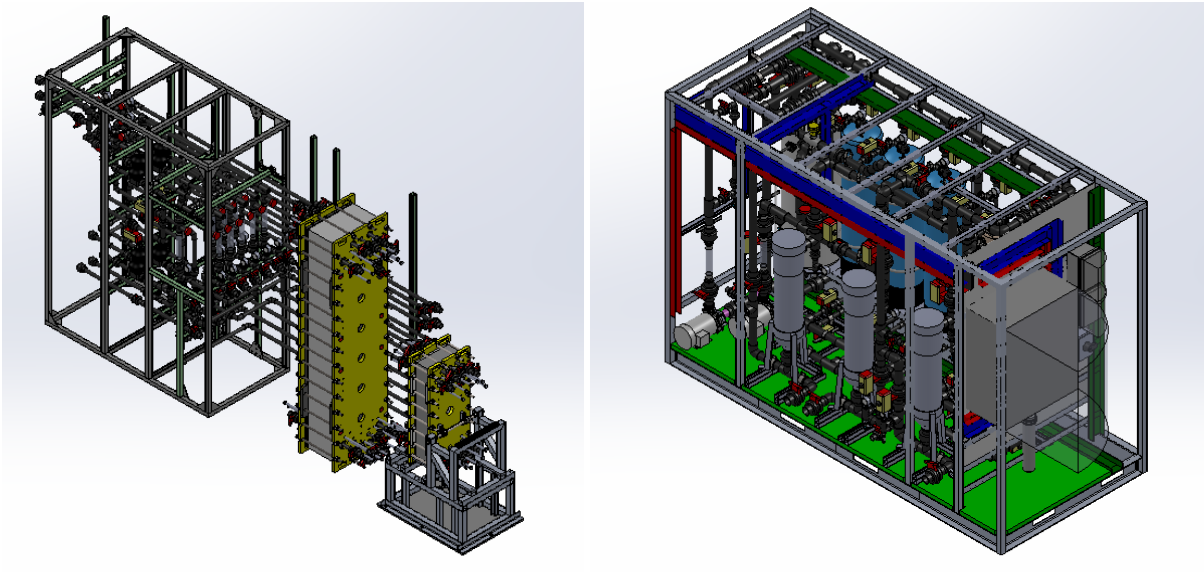


Figure 2. Stack skid design (left) and prefiltration skid (right)

Figure 3. Pilot plant exterior

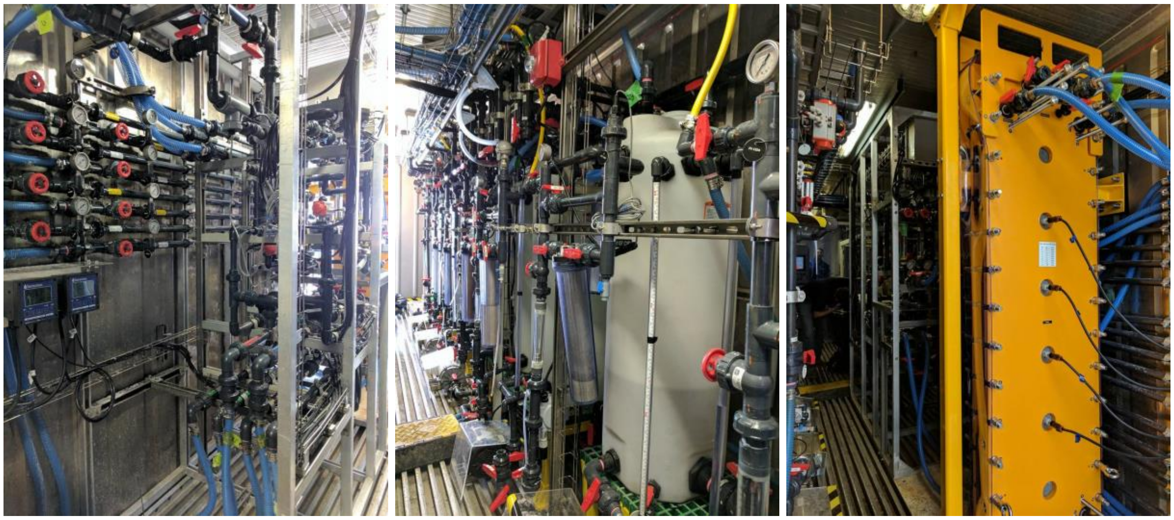


Figure 4. Pilot plant pipework (left), prefiltration (middle), and stack (right)

Figure 5. Pilot plant main AC panel (left), control panels (middle), and air system (right)

Task 1.2 - Implementation plan

Enerplus Pilot Site Implementation Plan and Detailed Test Plan were submitted.

The Enerplus Pilot Site Implementation Plan was developed such that testing would commence upon completion of commissioning. During operations, Saltworks planned for two operators on-site during regular hours. Remote support was also available during off-hours. The plant would shut off if there were any abnormal conditions or alarms detected.

A Test & Sampling Plan was also developed by Saltworks and Enerplus. This plan was followed by the operators to collect samples and perform day-to-day operations. Plant systems had a fully automated Data Acquisition System that measured plant performance based on sensors installed around the plant. Operators checked this system and performed on-site testing daily. Enerplus engineers reviewed the Test & Sampling Plan to ensure the crucial points were bring captured.

Task 1.3 – Flex EDR membrane-stack upgrades

- Increased membrane resistance to scaling by increasing the membrane thickness by 30-50%
- Increased gasket robustness by developing a new gasket design.
- Increased hydraulic capacity of the stack by a factor of 2.

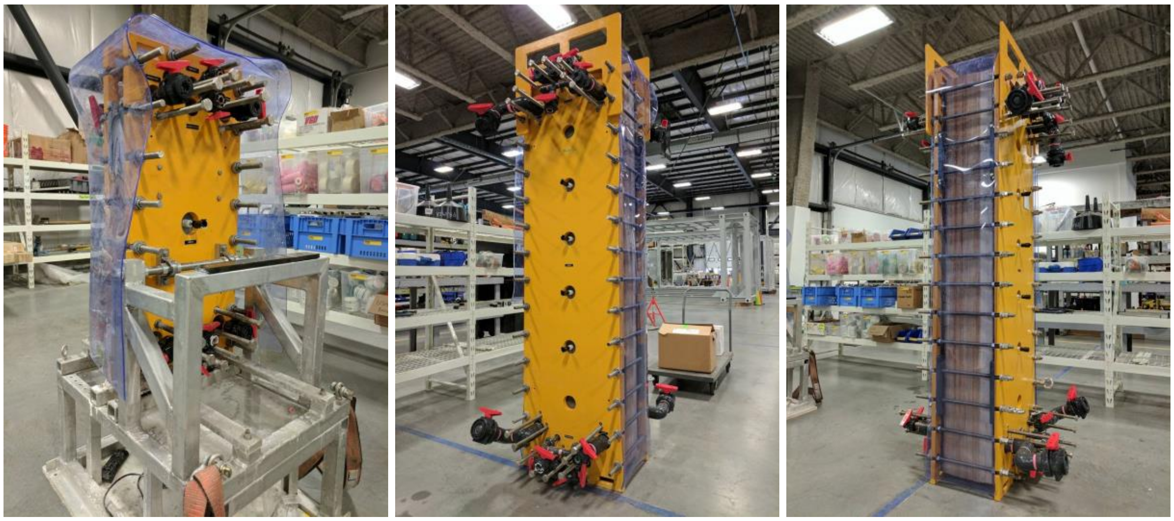


Figure 6. Small capacity stack (left), full-scale capacity stack front view (middle), full-scale capacity stack side view (right)

Both the upgraded full-capacity stack and the small capacity stack were tested in Saltworks' facility. They were installed in the full-scale pilot and used at the Medicine Hat pilot site at Enerplus.

Task 1.4 - Ongoing bench testing

We performed bench testing on 4000L of EOR produced water supplied by Enerplus for approximately 2 months using our standard bench testing infrastructure (full automation, data logging, and Saltworks "micro" Flex EDR stack with our ion exchange membranes). We obtained the following results and observations:

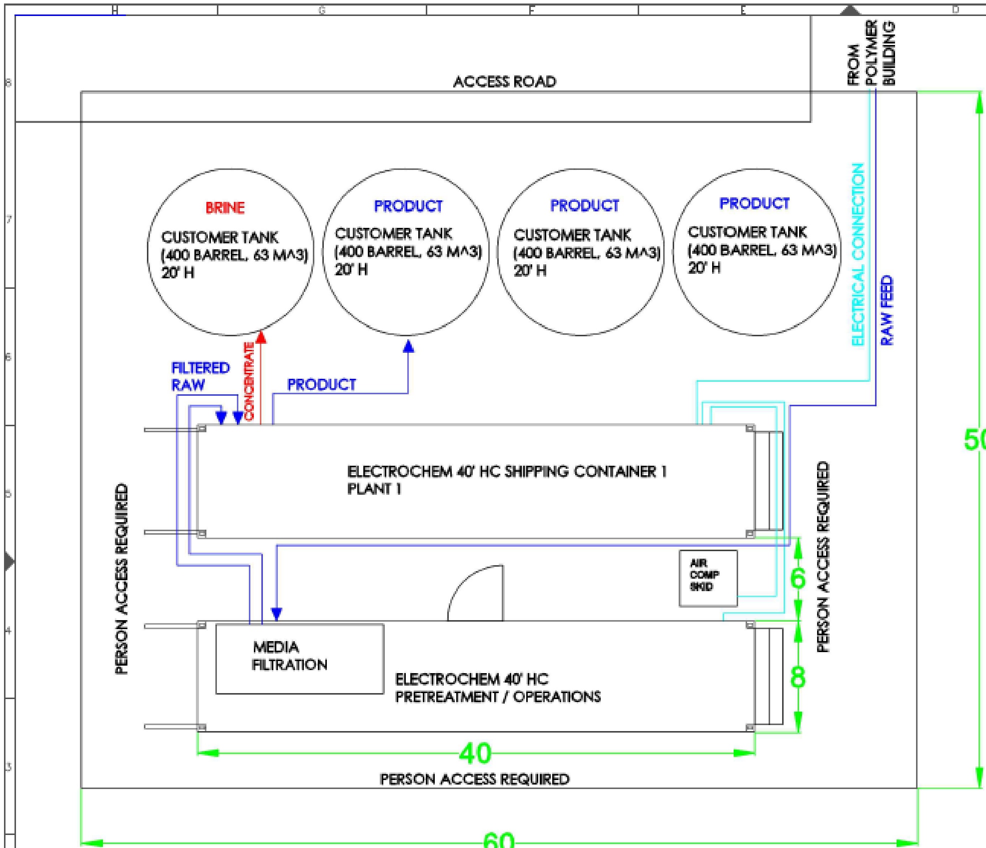
- Demonstrated 24/7 reliable desalination of EOR produced water from 7,000 - 12,000 mg/L TDS to 1,500 - 2,000 mg/L TDS.
- Optimized cleaning processes and controls
- Confirmed performance of prefiltration
- Optimized chemical dosing requirements to mitigate scaling risk
- Reduced energy consumption
- Compared cost benefits testing of desalinating to lower TDS. Results showed that best economics was to desalinate to 1,500 to 2,000 mg/L TDS.

Figure 7. EOR bench testing station (left and right)

After 2+ months of bench testing, the stack was opened and the membranes were inspected and tested. The inspection showed no damage and no irreversible membrane scaling or fouling. Characterization of membrane performance also confirmed no degradation in performance

Task 1.5 - Task 1 reporting & Task 2 implementation plan

A detailed site General Arrangement Drawing (GAD) for site implementation was developed (see following figure). The plant consists of two 40' ISO shipping containers. One contains the primary plant with the stack, tanks, pumps, electrical and controls. The second has the prefiltration unit and an operator/storage area. There is an independent air compressor skid.



PILOTSITE REQUIREMENTS	
ELECTRICAL REQUIREMENTS	120/208 VAC, 3PH, 60 HZ REQUIRED ELECTRICAL FEED SIZE: 125-200 A OPERATING DRAW: < 90 A/ 30 kW TYPICAL
INTERNET CONNECTIVITY	HIGH SPEED LANDLINE INTERNET CONNECTION WITH FIREWALL PROVISIONS FOR REMOTE MONITORING AND ASSISTANCE. 3G/4G CONNECTIVITY AS BACKUP (SOLID SIGNAL REQUIRED, MIN 3 BARS)
PLANT INLET	2" PIPE CONNECTED TO SALTWORKS FEED PUMP
TREATED WATER (OUTLET)	TO TANK
BRINE DISCHARGE	TO TANK
LAYOUT/FOOTPRINT	2 X 40' HC SHIPPING CONTAINERS AND DISCHARGE TANKS ESTIMATE 60' X 50'
NATURAL GAS	NOT REQUIRED
NITROGEN	CUSTOMER TO SUPPLY NITROGEN REQUIRED FOR ANAEROBIC CONDITIONS
FEED TANK	CUSTOMER TO PROVIDE DISCHARGE TANKS AS PER FLOW REQUIREMENTS
OTHER	NON-POTABLE WASHDOWN WATER
	BACK UP CLEAN, DRY, INSTRUMENT COMPRESSED AIR RECOMMENDED
	FORKLIFT (RATED FOR 3,000 LBS) AND CRANE REQUIRED FOR SITE SETUP

NOTES:

- DRAFT REQUIREMENTS
- DIMENSIONS ARE IN FEET
- CAPACITY TO BE CONFIRMED POST BENCH TRIAL
- THE FULL 200A POWER MAY NOT BE REQUIRED. HIGHER CAPACITY REQUIRES HIGHER CURRENT, LOWER CAPACITY REQUIRES LOWER CURRENT
- CUSTOMER TO PROVIDE DISCHARGE TANKS AND PRESSURIZED FEED (2-10 PSI INLET)

ITEM	DIMENSIONS, L X W X H (FT)	APPROX DRY WEIGHT (LBS)
PLANT 1 CONTAINER	40 X 8 X 9.5	30,000
OPERATIONS/MEDIA FILTER CONTAINER	40 X 8 X 9.5	15,000
TREATED WATER TANK (MIN 10 M^3)	PROVIDED BY CUSTOMER	
CONCENTRATED BRINE TANK (MIN (1-2 M^3)		

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LTR	DATE	DESCRIPTION	REV. BY:
2	21–JUL–17	UPDATED TANKS PER DISCUSSION AND SITE	–
–	–	–	–
–	–	–	–
–	–	–	–

TITLE: ELECTROCHEM PILOT PLANT 1 EOR
PROJECT: ELECTROCHEM EOR | CUSTOMER: – | REVISION: 2
PREPARED BY: DM | DATE: 21–JUL–2017 | DWG. NO: –
CHECKED BY: – | DATE: – | JOB/CO NO: –
APPROVED BY: – | DATE: – | SHEET: # OF #

Task 2.1 – Delivery

(Pilot plant pre-tested prior to dispatch. Delivered, implemented, and commissioned pilot plant at Enerplus' site)

Per discussion with Enerplus the following plant modifications were applied in preparation for site deployment:

- Upgrades were made to tanks and piping to make them airtight to resist oxidation. A nitrogen blanket was required to keep process fluid anaerobic by displacing oxygen with nitrogen on the headspace of 4 tanks.
- Installed pressure sensors and upgraded control system to compensate and correct for the effects of the nitrogen blanket system.
- Updated plant automated self-cleaning systems and chemical dosing based on learnings from bench testing.

All plant subsystems including electrical/mechanical/plumbing were pre-tested prior to site dispatch. The plant arrived at site on September 19th, 2017.

Figure 8: Pilot Plant Unloading at Site

Task 2.2 – Operation

Saltworks completed a successful and reliable field pilot test on EOR produced water supplied by Enerplus at their Medicine Hat, Alberta facility. The pilot was originally planned to run for 60 days at 1 m3/day, treating a total of 60 m^3. However, Enerplus required treating 150 m^3; the volume needed for their own subsequent testing. Additionally, 150 m^3 was the maximum volume that would fit in their three onsite storage tanks reserved for the treated produced water (see figure below; note the fourth storage tank for holding the Flex EDR output brine). Saltworks pushed the pilot to run at over 1 m^3/day with actual capacity varying between 1 and 5 m3/day depending on operating parameters. The higher capacity operation informed process tuning and optimization, generated additional data, and provided further insight into operating limits. The pilot reliably treated 150 m^3 over 42 days running 24/7. Enerplus was satisfied with the treated water output, achieving the target volume, and the quantity and quality of data collected, thus they concluded the testing in order to transfer the treated water to their downstream process and offboard the pilot.

Figure 9: Containerized Flex EDR Organix Pilot Plant

Figure 10: Pilot Plant Site

The objectives were:

- Desalt produced water to improve hydrocarbon recovery and reduce polymer consumption for EOR;
- Operate Flex EDR Organix pilot plant under field conditions and meet all site safety requirements; and
- Inform full scale plant development with a field pilot; tracking performance, reliability, chemical consumption and energy use.

Figure 11 shows a simplified process flow diagram (PFD) of the overall process.

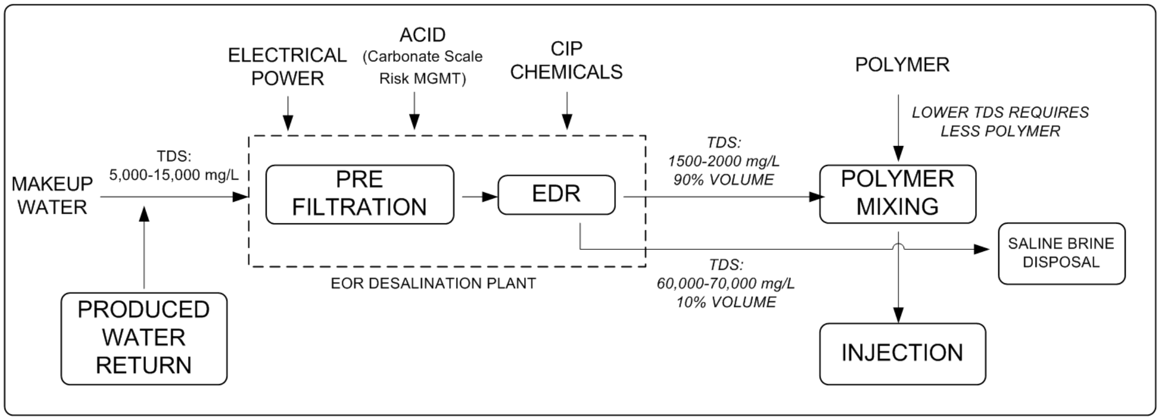


Figure 11: Simplified Pilot Plant PFD

Key results were:

- Polymer savings estimated at approximately 50%, exceeding the cost of water treatment.
- Treated water required less polymer to reach target viscosity for injection.
- Reliably desalted 150 m^3 of produced water from 7,000-8,000 mg/L TDS to 1,700-2,000 mg/L .
- Achieved freshwater recovery of up to 93.5%.

Figure 12: Produced water and treated water samples

Figure 13 shows the produced water, treated water and brine volumes over the duration of the pilot and Figure 14 shows the % reduction of ions in the treated water vs. produced water.

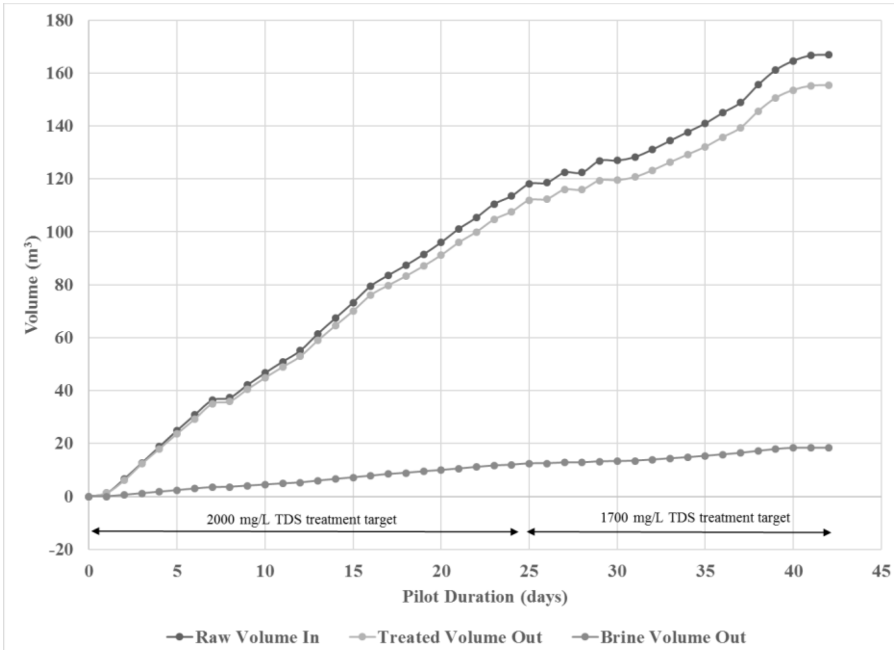


Figure 13: Raw volume, treated volume and brine volume over the duration of the pilot

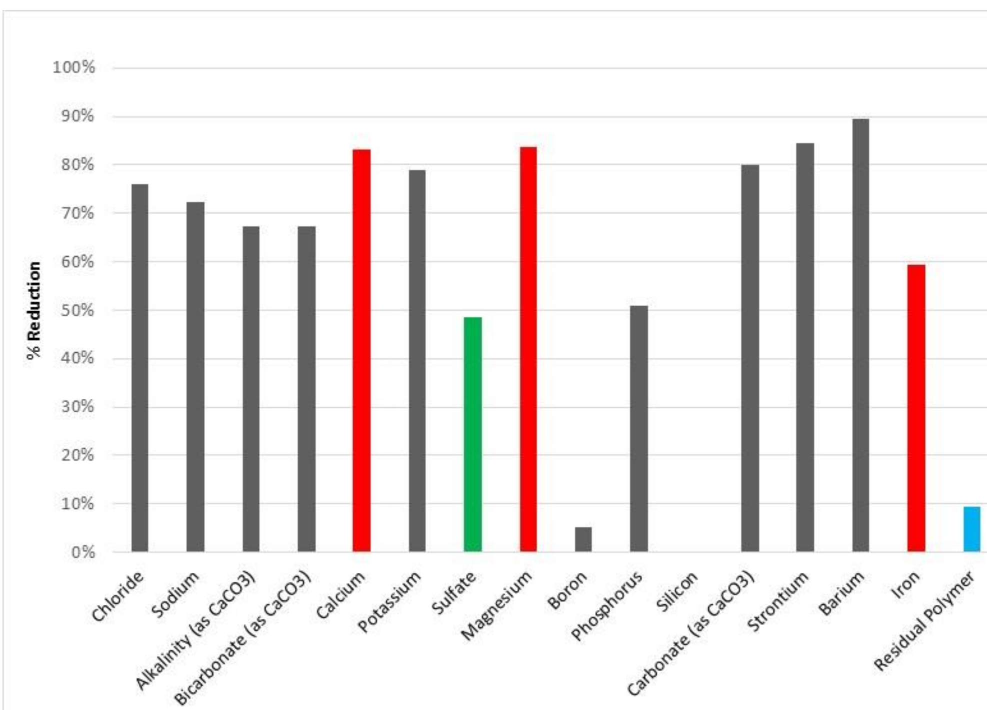


Figure 14: % reduction of TDS, Ions and Residual Polymer in the treated water vs produced water

Produced water with oil-in-water concentrations up to 1000 mg/L was reliably desalinated - as shown in Figure 15. The result proved that Flex EDR Organix can operate reliably without extensive pretreatment for hydrocarbons. Figure 16 shows the results of reliable and continuous operation, except when issues were caused upstream and out of Saltworks' control.

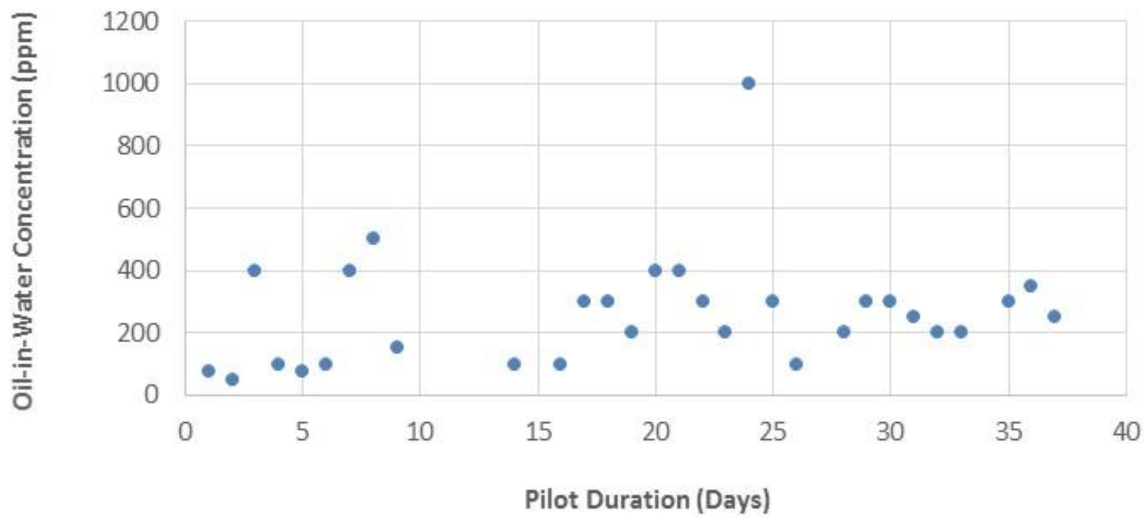


Figure 15: Pilot operated with Oil-in-Water concentrations varying from 50-1000 ppm

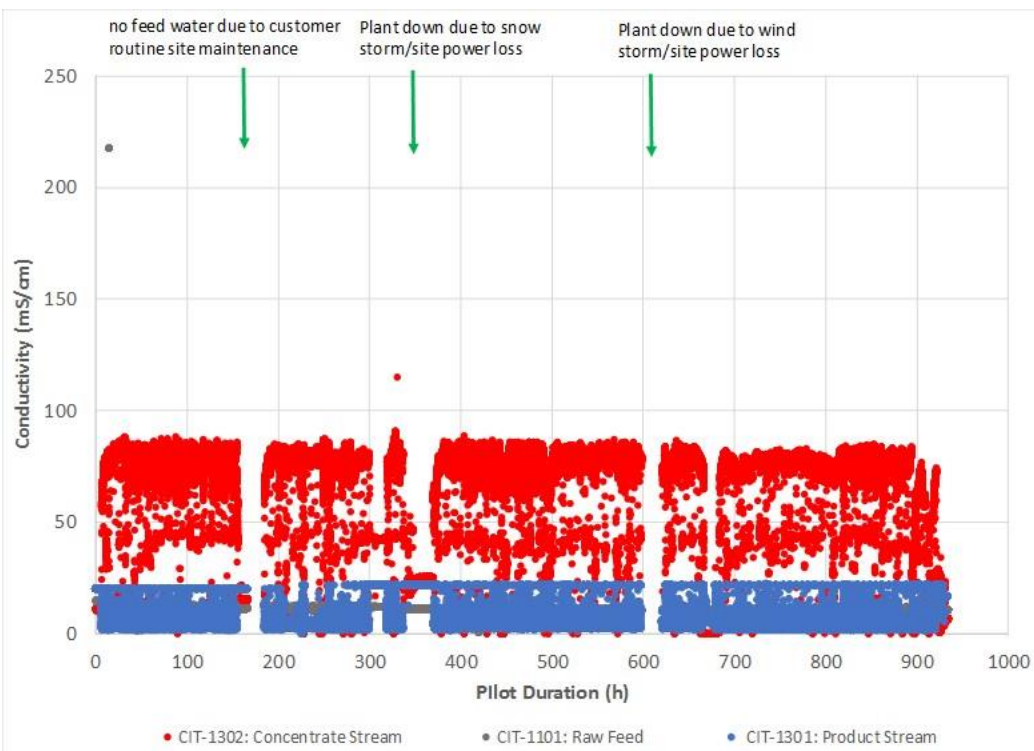


Figure 16: Reliable Flex EDR Organix Operation on Produced Water

Viscosity of the desalted produced water increases, which reduces the polymer requirements (lower operating costs) and increases oil recovery. Figure 17 shows the lab scale results for comparison of polymer compositions made with produced water and treated water. Treated water consumes less polymer to reach the target viscosity - data suggests 50% polymer savings. This offsets and exceeds the cost of water treatment.

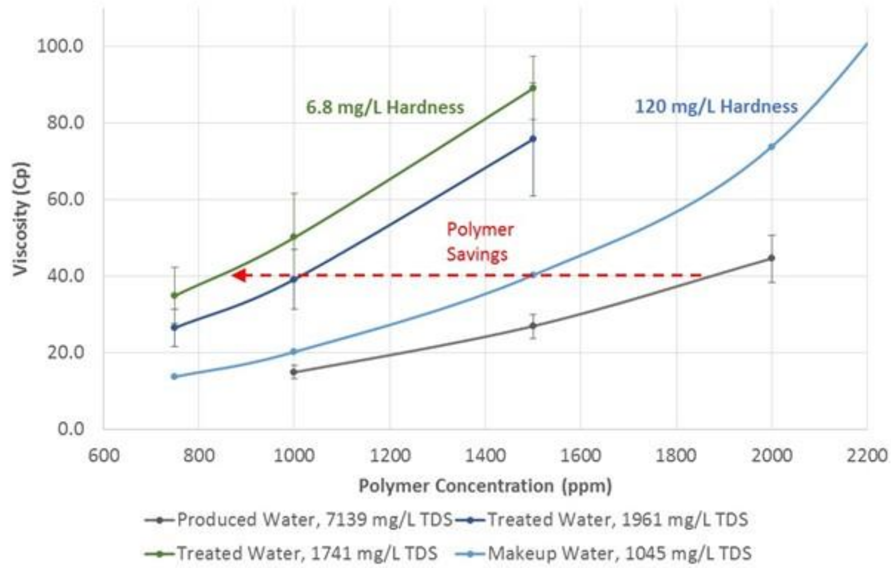


Figure 17: Polymer savings when using treated water

The residual polymer is reactivated, increasing the viscosity of treated water without adding any more polymer. Figure 18 shows that the viscosity of the treated water was higher than the produced water, when no polymer was added, proving residual polymer reactivation.

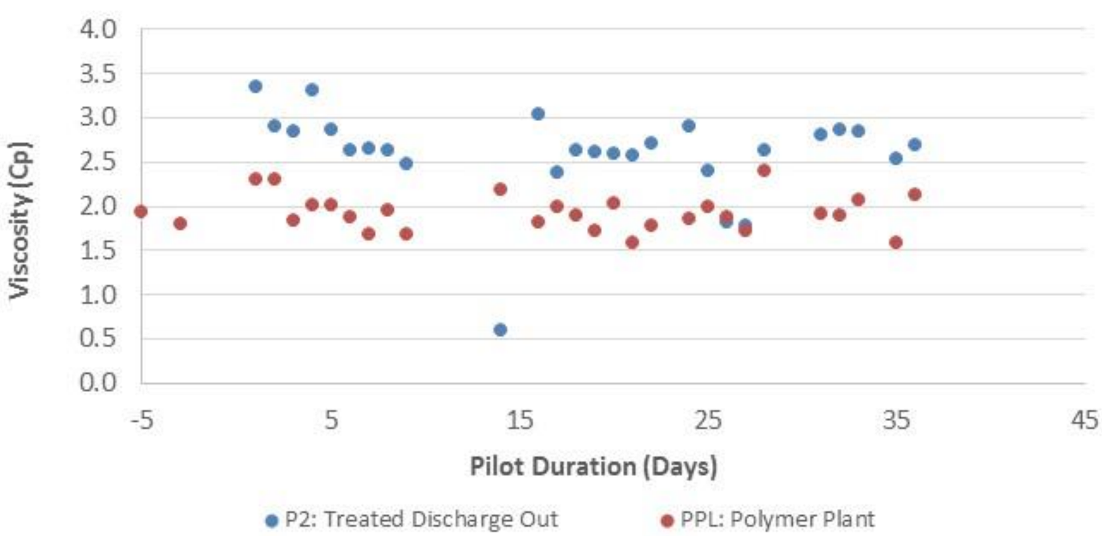


Figure 18: Residual Polymer Reactivation

Task 2.3 – Ongoing bench testing and Flex EDR Organix membrane-stack upgrades

We performed further testing on the membrane stacks after the Enerplus pilot. The results were:

- Further improved the gasket and plate design resulting in a 15% increase in membrane active area.
- Advanced further automated cleaning systems and controls by testing different clean-in-place (CIP) solutions.
- Completed further membrane longevity testing by running the stacks used in Enerplus on simulated produced water over extended time periods and confirmed no performance degradation.

We were also engaged by another Calgary oil & gas company seeking to desalinate EOR polymer flood produced water for their European assets. This company's produced water is ~25,000 mg/L TDS and they are seeking to desalinate to a target of 1,000 to 2,000 mg/L. The ultimate required treatment capacity is up to 20,000 m^3/day of produced water. Their additional objectives include:

- Reducing chemical polymer costs by reducing the salinity of the produced water; and
- Minimizing produced water disposal volume due to capacity constrained injection wells.

Saltworks has started initial desktop study work with this customer.

Task 2.4 - Design basis & full scale economic analysis

A design basis memorandum was developed for a 1200 m^3/day commercial demo plant. This includes the Process Train, General Arrangement drawings, energy / utilities consumption and other details required for the design of the full scale plant.

See Appendix A for Full Scale Economic Analysis.

Task 2.5 - Reporting

A detailed report was prepared for Enerplus with the pilot testing results, lessons learned, optimization plans and path forward for full scale operation.

Setbacks, Issues and Lessons Learned

Task	Setback/issue/challenges	Mitigation
Task 1.1 - Design, build, and factory test pilot plant	Clogging and poor flow of the media in the pre-treatment system.	Solved by rinsing and screening media to remove fine dust.
Task 1.2 – Implementation Plan	From discussions and test plan reviews with Enerplus, preventing oxygen from contacting the influent water is crucial for the test. The standard way to achieve this is to apply nitrogen gas in the water tanks. However, pilot plant water tanks were not designed to be sealed and would leak nitrogen gas. H2S release from influent water is also a risk that needs to be addressed.	Tanks were modified, sealed, and tested under typical nitrogen blanket pressures. Level controls were updated to correct for the additional pressure applied to the tanks. Sealing and placing the tanks under nitrogen pressure reduced the risk of H2S gas leakage. Multi-gas personal monitors were sourced for persons operating the plant on site.
Task 1.3 – Flex EDR membrane-stack upgrades	Supplier quality issues with membrane raw materials.	Increased level of QA/QC of receivables from supplier.
Task 1.4 - Ongoing bench testing	Chemical dosing can change water chemistry.	Understand the chemistry change and its effect on EDR performance. Consider use of alternative chemicals that do not change water chemistry or performance.
Task 2.2 – Operation	(1) Media filter differential pressure was not significant enough to detect when a filter requires backwash. (2) Oil in water was highly variable in the feed water, timers in (1) were not adequate to react to changing conditions. (3) Variation in the TDS of treated water discharge samples (4) Loss of performance following an unexpected power outage without shutdown flush of the system. (5) Reliability/accuracy of low TDS measurements in the field affected setpoint tuning (6) Higher chemical consumption than small scale testing	(1) Switched to timer operation for backwash frequency. (2) Investigate oil in water sensor for pre or post filter to provide feedback (3) Full scale plant design to include processes and controls to provide consistent treated TDS concentrations. (4) Complete a clean-in-place wash prior to startup (5) Utilized external lab results. Better field methods or equipment needed for quick tuning. (6) Larger system losses and different water chemistry. Further optimizations can be done with pipework changes.

5. Relevance and Benefits

Project success should result in three notable environmental benefits:

- Land disturbance and waste associated with oil & gas development would be minimized while net energy efficiency is improved, since technology will enable existing operations to extract 40% more oil, rather than developing new, more distant wells.
- Positive impacts on water will be achieved. By desalting and recycling produced water, less freshwater is withdrawn and less wastewater is disposed. Rivers and surface water are often used for oil & gas injection, and trucked to sites. By reducing freshwater withdrawal, aquatic ecosystems are better protected: river water resource levels are maintained for aquatic life and public enjoyment, as well as reduced fish habitat disturbance and pollution risk associated with truck mounted pumping machinery. The pilot results show that oil and gas produced water can be recycled. The technology at Enerplus alone would result in 420,000 m^3 per year of water recycling with plans for future expansion. Water savings by recycling produced water vs withdraw freshwater and dispose waste, lower O&G freshwater demand and extraction from aquatic ecosystems. By 2030, the number of active EOR water treatment plants by Saltworks are estimated to be 152 in Alberta and 68 in the rest of the world. This results in water savings of 63M m^3/yr in Alberta and 28M m^3/yr in the rest of the world.
- Reduced GHGs may also result where produced water is transported for disposal, as the technology not only applies to EOR but also to other produced waters. GHG reduction potential for a single EOR water treatment plant (capacity of 1200 m^3/day) in Alberta that would otherwise transport water for disposal is estimated to be 1.35 kt CO2e/yr.

The project will also provide immediate economic benefits to Albertan and Canadian EOR operators, demonstrating a scalable technology to reducing operating costs while beneficially recycling water. The pilot plant developed by the project will travel to many operator sites after the project to further build the market, including applications outside of EOR. This will provide high value export related jobs and tax revenue for Canadians, in addition to enhancing the competitiveness of our oil industry while preserving precious water supplies.

Referring to the EOR case, the economic benefits are four fold:

1) Polymers to increase injected water viscosity represent a cost to operators. Recycling of the polymer and increasing the viscosity of the reinjection fluid can reduce operating costs. Polymer costs \$3.3/kg. For a 1,100 m^3/day Flex EDR Organix plant that recycles polymer, \$4/m^3 can be saved by recycling. At the Flex EDR total cost of treatment of \$2-3/m^3, operators can reduce polymer costs by over 50%.
2) Reduced freshwater withdrawal and water license or service payments through increased recycling.
3) Expectation to produce additional oil from fixed asset through low salinity injection, as has been proven the case in public information released by BP.
4) For locations that need to truck the wastewater for disposal, there is a large cost associated. Trucking the wastewater for disposal can cost \$60-125/m^3. Flex EDR Organix can treat the produced waters on-site for \$2-3/m^3, providing significant cost savings. Operators will witness an immediate economic benefit by reducing their offsite trucking and disposal costs.

Flex EDR will benefit Alberta and Canada by reducing the cost and environmental impact of the O&G industry, thereby increasing its global competitiveness. The proposed project could affect a step change in commercialization, production, high skill job creation, tax revenue, environmental benefits, and competitive position.

The project will directly lead to job creation benefits in Canada, with four new immediate positions at Saltworks as a result of this project, backfilling positions where Saltworks will apply its top talent to commercialization of the EOR solution. Saltworks will continue to hire technical employees to support the design, development, implementation, operation and maintenance of the technology. Commercialization of the technology will amplify the job creation benefits, leading to even more Canadian jobs to support the dispatch and operation of the technology across Canada and worldwide.

Total Number of Eligible Recipient's (ER) Full Time Equivalent (FTE) Employees and/or contractors working at Project Start	65
Number of ER's FTE Employees and/or contractors working **on the AI-SDTC Project (including staffing related to marketing and commercialization of the technology)** at Project Start	21
Current total number of ER's FTE Employees and/or contractors	89
Current number of ER's FTE Employees and/or contractors working **on the AI-SDTC Project (including staffing related to marketing and commercialization of the technology)**	45
Net number of new FTEs AI-SDTC funding has created since Project inception	6
Approximately how many FTE employees and/or contractors do you expect to hire **(related to the AI-SDTC Project (including staffing related to marketing and commercialization of the technology)** in the next 24 months?	5

6. Overall Conclusions

After two years of off-site testing with supermajors and a successful pilot test at the Enerplus site, we proved that Saltworks' Flex EDR Organix offers strong potential to lower oil production costs for polymer/waterflood enhanced oil recovery (EOR). This was accomplished with the support of Alberta Innovates and SDTC. Table 1 shows the results from the off-site and on-site pilots. Next steps include further pilot testing and design-build of a future commercial 1200 m^3/day plant.

Table 1: Results from off-site and on-site pilot testing

Metric	Ideal target	Minimum requirement	Achievements
TDS reduction (assumes ~8,000 mg/L feed)	TDS <2,000 mg/L	TDS <3,500 mg/L	Bench testing and pilot testing results show treated water TDS of 2,000 mg/L
Plant availability	90%	80%	Off-site pilot demonstrated >90% availability. Pilot plant at Enerplus demonstrated 89% availability. Downtime was primarily caused by upstream factors outside our control such as extreme weather conditions and no availability of feed water upstream.
Polymer use reduction through desalination (lower TDS = less polymer consumption)	>50%	>40%	Pilot operation proved 50% polymer savings
Recovery rate	85%	75%	Recovery of 93.5% achieved during pilot testing.
Energy consumption	<10 kWh/m^3	<12 kWh/m^3	Energy consumption for the pilot includes the Stack Energy and the Balance of Plant (BoP) Energy. The stack energy for the pilot was ~5kWh/m^3 and the BoP was ~12kWh/m^3. It is expected that the BoP does not scale-up linearly and so energy consumption for the full-scale plant is expected to be lower. Total energy consumption at full scale (Stack + BoP) is estimated at 5-7.5 kWh/m^3.
Return on Investment / Total cost of ownership	ROI > 20% (polymer savings pay for capital + operating cost + 20% return)	ROI > 0%	Economic modeling based on results to date show that an ROI > 20% is achievable and can be further improved. Noted that most oil firms required ROI > 20% for investment decisions.

7. Communications Plan

Conferences

We will be presenting at the following technical conferences in 2018. We will be discussing this project more fully in the Improved Oil Recovery Conference (Oklahoma). For the other conferences, presentation topics will vary but all will discuss Flex EDR Organix technology and its capabilities, and highlights/economics for this project:

- Improved Oil Recovery Conference (Society of Petroleum Engineers) – Tulsa, Oklahoma
- UltraPureWater (Global Water Intelligence) – Austin, Texas
- 2nd International Congress on Water in Industrial Processes – Santiago, Chile
- Mine Water Solutions 2018 (MWH / Stantec) – Vancouver, BC
- 2018 Qingdao International Water Conference – Qingdao, China
- 2018-09 IMWA Mine-South Africa
- International Mine Water Association 2018 Conference – Pretoria, South Africa

Other events

Saltworks is hosting a "Water Technology Forum" in Vancouver where we will present on various technologies and projects, including this project. This event is organized by Saltworks and we have also invited three other water technology companies to present: Marabex, BQE Water, and Boydel. Attendees include engineering procurement construction (EPC) firms and end-users from mining and oil & gas.

Media releases

The following media releases area planned for 2018:

- Article in WaterWorld magazine (print and online), "Desalting Adds Value," that discusses the project in some detail – May, 2018
- Saltworks press release (on our website) that briefly discusses the project work – May, 2018
- WaterTechOnline.com article discussing Flex EDR Organix – June, 2018

Customers

Cenovus Energy and BP are investors in Saltworks. Two supermajors have also completed two years of offsite EOR research and testing with us. All are interested in the project results. We have also recently been engaged by another Alberta oil & gas company seeking to desalinate their waterflood/polymer EOR produced water for their European assets; initial desktop work is underway. Lastly, Saltworks continues to develop its oil & gas customer funnel with inquiries from firms in Alberta, Europe, Argentina, and China, and we will highlight the project work with these potential customers.

8. Scientific Achievements

Presentations given at scientific meetings, public events and media appearances: SPE Improved Oil Recovery Conference, April 14-18, 2018, Tulsa Oklahoma (paper accepted for presentation)
Publications (draft, submitted and published): Proceedings for the SPE Improved Oil Recovery Conference, April 14-18, 2018, Tulsa Oklahoma (to be published after the conference).
Project-related IP generated during the project:

IP Type	Country	App. No.	Filing Date	Status	Patent Title
Patent	Canada US China Australia	2,649,873 8,137,522 200980123945.X 2009261893	2009.0121	Issued and active	Method, Apparatus and Plant for Desalinating Saltwater using Concentration Difference Energy
Patent	Canada US	2748567 8,317,992	2011.08.05	Issued and active	Modular apparatus for a Saltwater Desalinating System and method for using same
Patent	Canada US Australia	2812825 9227857 2011288890	2011.08.05	Issued and active	Apparatus for Compression of a Stack and for a Water Treatment System
Patent	Canada	2812805 2844706 2844708	2011.10.04	Issued and active	Resilient Ion Exchange Membranes
Patent	Canada US Australia	2826364 9227857 2012308061	2012.09.14	Issued and active	Method, Apparatus and System for Desalinating Saltwater
Patent	Canada	2812825	2012.09.14	Issued and active	Produced Water Desalination for Enhanced Oil Recovery
Patent	Canada Canada US US	2863060 2866300 9199203 9636642	2013.04.17	Issued and active	Ion Exchange Membranes based on Polymerizable Ionic Surfactants
Patent	Canada US US China EU	2858238 9416239 9662647 allowed allowed	2013.09.27	Issued and active	Acrylamide-Based Crosslinkers from Acrylic Acid and Isocyanates
Patent	Canada US China	2859381 Office action allowed	2014.03.25	Issued and active	Ion Exchange Membrane Selectively Permeable to Specific Ions
Patent	Canada	2896022	2014.03.06	Issued and active	Multivalent Ion Separating Desalination Process and System
Patent	Canada	2893345	2014.04.24	Issued and active	Hybrid Electrochemical Softening Desalination System and Method
Patent	Canada	2893708	2014.11.06	Issued and active	Removal of Ammonia from Ammonia-containing water using an Electrodialysis Process.
Patent	Canada US	2935262 Office action	2016.04.07	Issued and active	Electrodialysis Process and Apparatus for Multivalent Ion Desalination

APPENDIX A: Full Scale Economic Analysis.

Refer to Slide 15 for Full Scale Economic Analysis.

An Advanced Electrochemical System for EOR Produced Water Desalination and Reduced Polymer Consumption

Derek Mandel – Director of Technology, Flex EDR
Ben Sparrow – CEO
Saltworks

Overview

- Reliably desalinated produced water using EDR for reuse in polymer flood EOR

- Pilot plant operated in southern Alberta oil field, treating 150 m^3

- Polymer savings scale to a 20% Return on Investment

Flex EDR pilot plant at site in southern Alberta, Canada

Background: Lower Polymer Costs by Desalinating Produced Water

- Polymer costs can be very high ($2-10M/year for 1,000-4,000 m^3/day site)
- High salinity produced water often poorly suited for reinjection
- Desalinating produced water may offer:
  - Reduced make-up polymer costs
  - Improved water reuse and balance
  - Reduced water disposal volume and costs
  - Polymer reuse during reinjection

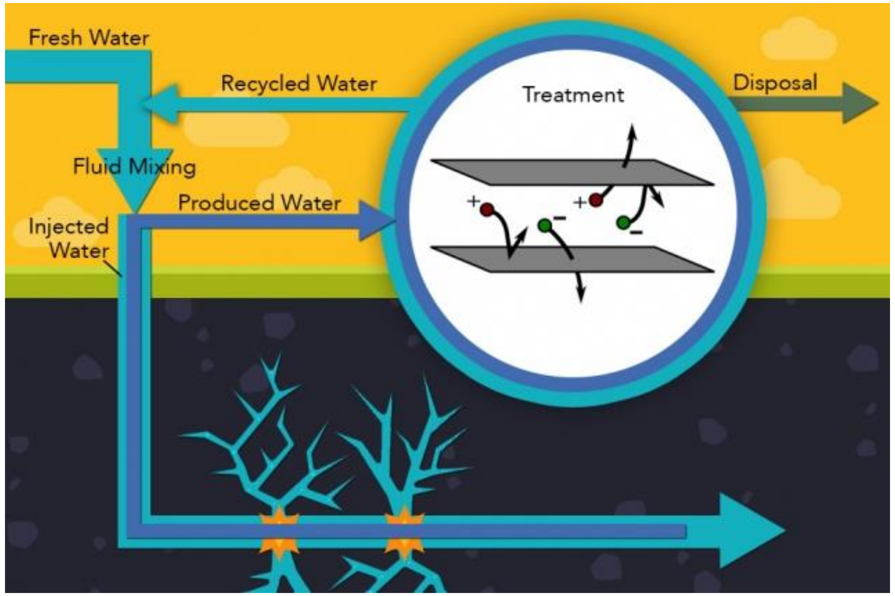


Image Credit: Jose-Luis Olivares, MIT

Background: Produced Water Treatment Technology

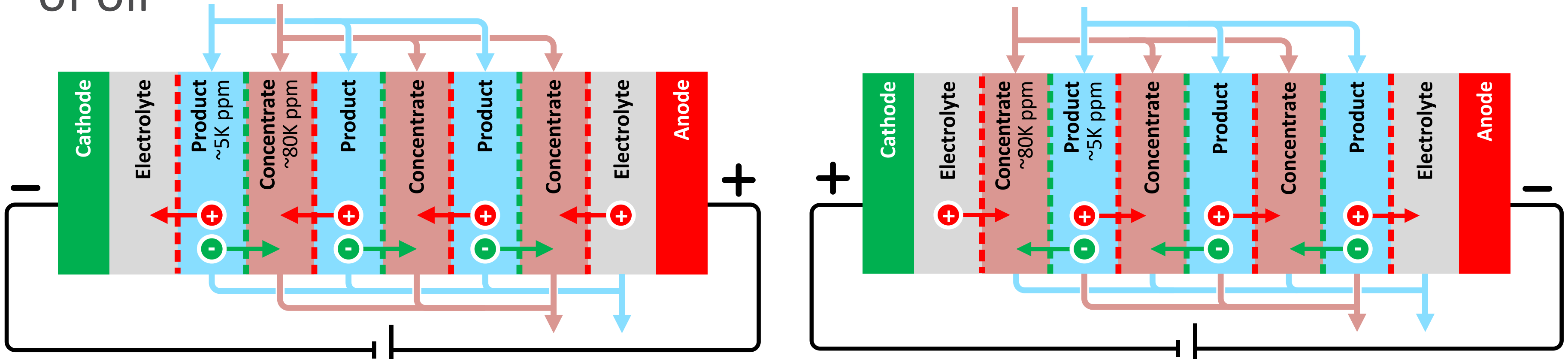
- Reverse Osmosis (RO)
  - Pros:
    - Low cost solution
    - Readily available membrane technology
  - Cons:
    - Conventional membranes swell and break in the presence of oil and solvents
    - Extensive pretreatment may be required

Background: Produced Water Treatment Technology

- Evaporators
  - Pros:
    - Withstand high oil and organics concentrations
    - Capable of Zero Liquid Discharge (ZLD)
  - Cons:
    - 10-20 fold greater total cost of ownership than membrane systems

Background: Produced Water Treatment Technology

- Electrodialysis Reversal (EDR)
  - Pros:
    - Low cost membrane solution, comparable to RO
    - May selectively remove divalent ions based on their charge
    - Self cleaning via hydraulic and ionic reversal
  - Cons:
    - Conventional membranes swell and break in solutions with high concentrations of oil



EDR Stack Configuration and Reversal Operation – Forward Mode (left) and Reverse Mode (right)

Improving EDR with Saltworks IonFlux Ion Exchange Membranes

- IonFlux Ion Exchange Membranes for EDR
  - Novel, highly cross-linked polymer composition improves resistance to oils, solvents and acids/bases.
  - High selectivity to multivalent ions

Membrane production

Ionflux Ion Exchange Membrane

Comparing Produced Water Treatment Options

Treatment Technology	Total Cost of Ownership /m³ Inlet*	Oil Resistance
Reverse Osmosis	Pre-treatment risk + $2-5	Low
Electrodialysis Reversal (EDR)	Pre-treatment risk + $2-6	Low
Evaporators	$30-40	High
Electrodialysis Reversal with IonFlux Membranes (Flex EDR)	$2-6	High

*estimate includes CapEx + OpEx, $USD

Pilot Operating Conditions

Flex EDR Stack
The assembly of ion exchange membranes

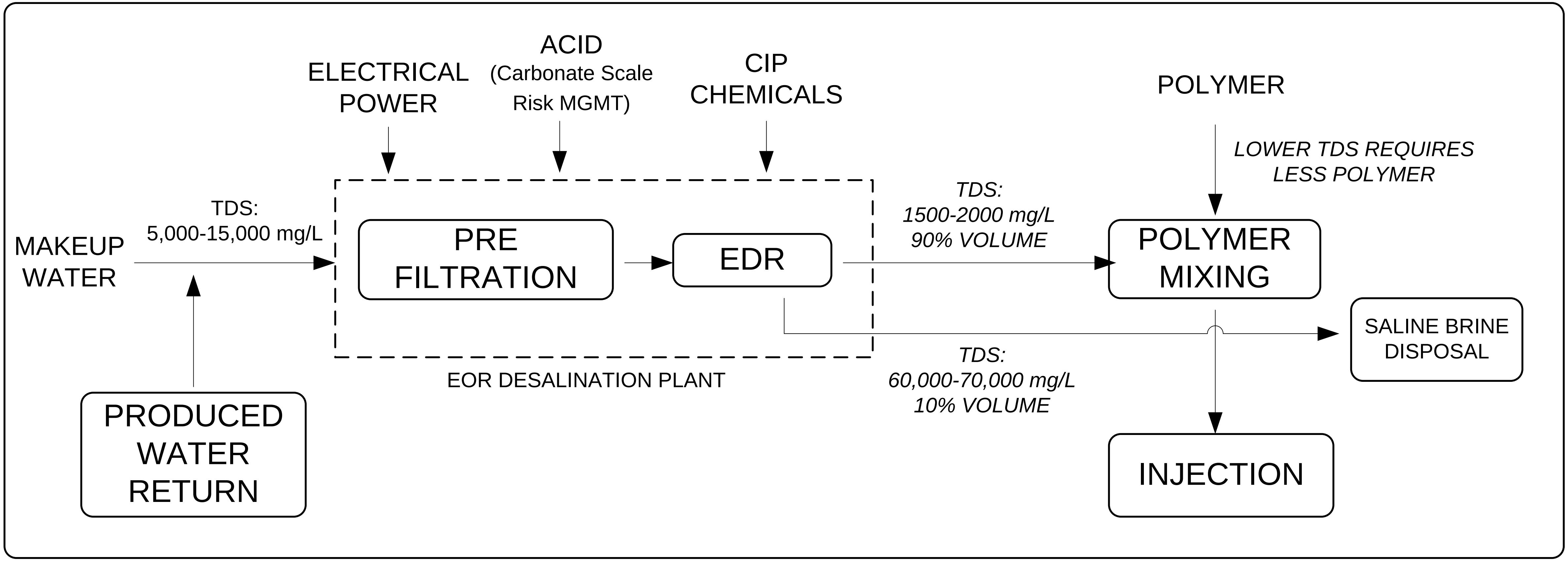
	Flex EDR Fit	Pilot Operating Conditions
Inlet TDS	5,000-25,000 mg/L	7000-8000 mg/L
Treatment Target TDS	500-3000 mg/L	1500-2000 mg/L
Recovery	Chemistry dependent, typical 85-95%	90%
Oil in water concentration	Tested up to 1000 ppm Not limited yet Ideally Remove >C10	50-1000 ppm

Pilot Operating Conditions

- 2-5 m^3/day (prefiltration capacity)
- 24/7 automated operation with self cleaning cycles
- Flow rate only used 15% plant capacity

  (40 out of 300 potential membranes)
- Current density (salt flux): 40-200 A/m^2
- System held under anaerobic conditions (Nitrogen blanket)

Pilot Process Flow Diagram: Flex EDR System Setup



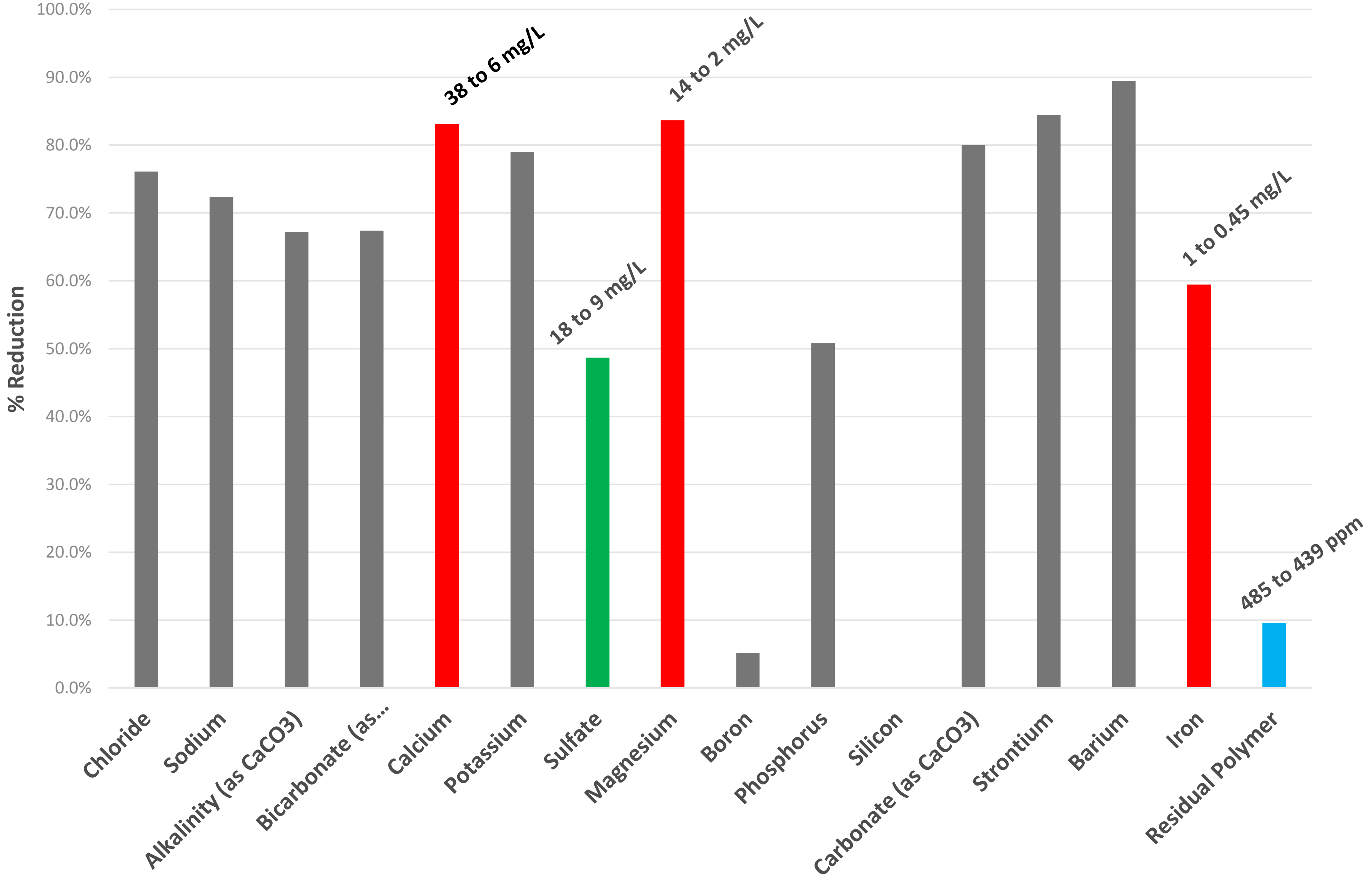
Pilot Results: Water Chemistry Comparison of Produced and Treated Water

Parameter	Raw Feed	ElectroChem C Discharge	ElectroChem Treated Discharge P = 1,300 mg/L TDS	ElectroChem Treated Discharge P = 2,100 mg/L TDS
Units:	mg/L	mg/L	mg/L	mg/L
pH	7.83	7.48	6.98	6.91
Total Dissolved Solids	7,500	69,000	1,310	2,100
Total Hardness (as CaCO3)	144	1,500	21.50	26
Alkalinity (as CaCO3)	2,500	7,200	400	820
Aluminum	<0.10	0.25	-	0.024
Antimony	<0.010	<0.025	-	<0.0005
Arsenic	0.040	0.15	-	0.023
Barium	1.24	8.8	-	0.130
Beryllium	<0.0010	<0.0025	-	<0.00005
Bicarbonate (as CaCO3)	2,500	7,200	400	815
Boron	10.18	9.50	-	9.66
Bromide	15.40	210	-	-
Cadmium	<0.0002	<0.0005	-	<0.00001
Calcium	38.50	461	4.50	6.49
Carbonate (as CaCO3)	<5	<5	<1	<1
Chloride	2,550	35,500	490	610
Chromium	<0.010	<0.025	-	0.004
Cobalt	<0.0010	<0.0025	-	0.0001
Copper	<0.010	<0.025	-	0.001
Fluoride	0.90	3.50	0.24	<0.03
Hydroxide (as CaCO3)	<5	<5	<1	<5
Iron	1.11	1.89	0.45	0.45
Lead	<0.0010	<0.0025	-	0.00026
Lithium	1.06	50	-	0.388
Magnesium	14.50	169	2.00	2.38
Manganese	0.04	0.23	0.01	0.010
Mercury	<0.0000019	<0.00001	-	<0.0000019
Molybdenum	<0.002	<0.005	-	<0.001
Nickel	0.020	<0.025	-	0.021
Nitrate (as N)	<0.05	<0.5	<0.005	0.105
Nitrite (as N)	<0.05	<0.5	<0.005	<0.01
Phosphorus	6.10	35.50	0.56	3.00
Potassium	20.00	250	3.00	4.20
Selenium	<0.010	<0.025	-	<0.0005
Silicon	6.00	4.60	5.90	6.20
Silver	<0.004	<0.01	-	<0.005
Sodium	2,550	24,650	450	705
Strontium	5.00	56.00	-	0.778
Sulfate	18.50	155	9.00	9.5
Thallium	<0.0004	<0.0010	-	<0.00002
Tin	<0.0010	0.0070	-	0.002
Titanium	<0.02	0.0700	-	0.008
Uranium	<0.0002	<0.0005	-	0.0001
Vanadium	<0.02	<0.05	-	0.004
Zinc	<0.10	<0.25	-	<0.005

Parameter	Produced Water	Flex EDR Treated	Flex EDR Brine
Units:	mg/L	mg/L	mg/L
pH	7.83	6.91	7.48
Total Dissolved Solids	7,500	2,100	69,000
Total Hardness (as CaCO3)	144	26	1,500
Calcium	38.50	6.49	461
Chloride	2,550	610	35,500
Iron	1.11	0.45	1.89
Magnesium	14.50	2.38	169
Sodium	2,550	705	24,650
Strontium	5.00	0.778	56.00
Sulfate	18.50	9.5	155

Pilot Results: Water Chemistry Comparison of Produced and Treated Water

Produced and Treated Water



Project Economics: Waterflood viscosity vs. Polymer Concentration

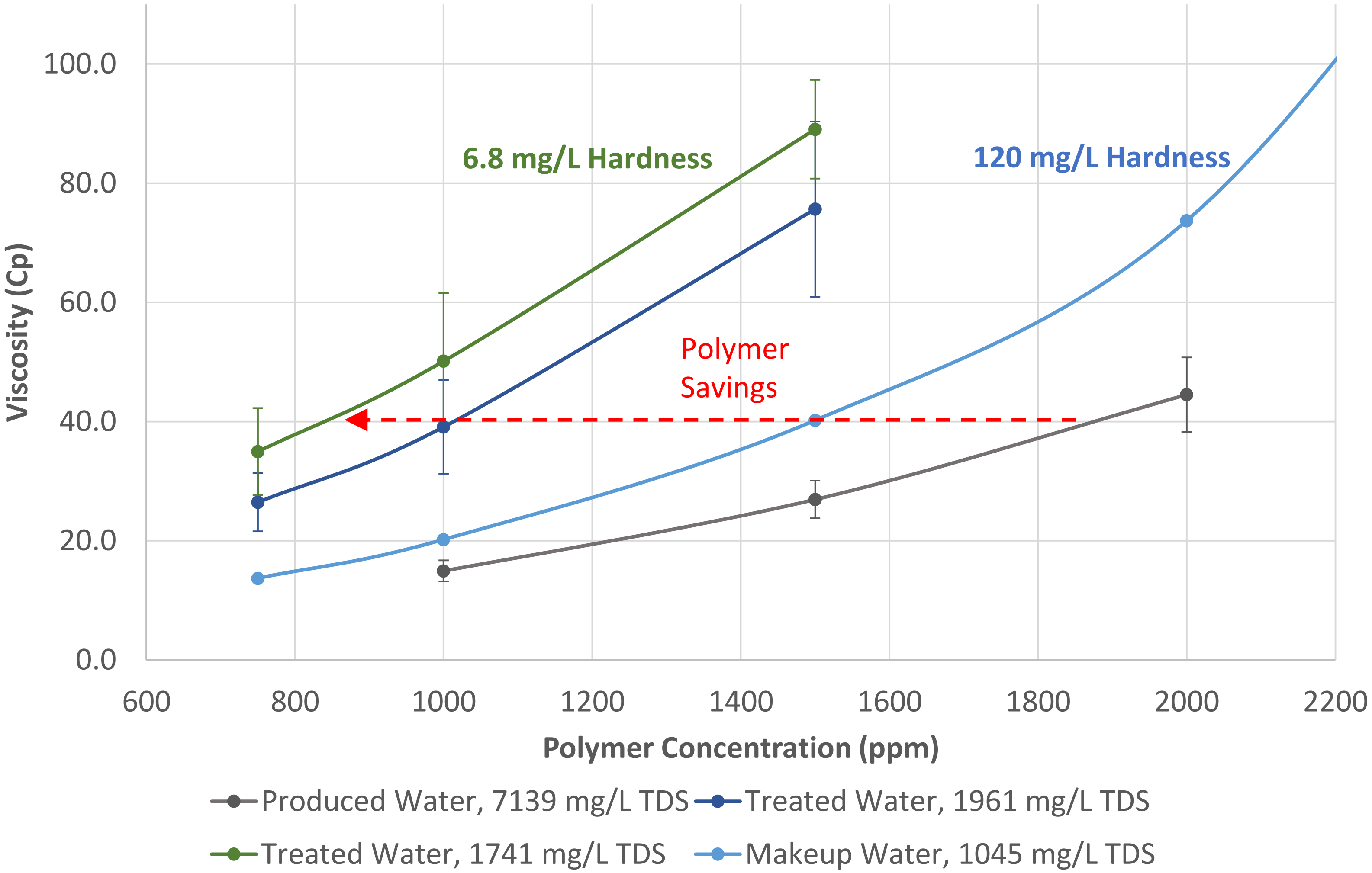
- Higher injected water viscosities can be achieved at lower polymer concentrations if

(1) a lower TDS water source is employed

or

(2) if the produced water is desalinated to a lower TDS.

- The data suggests **<u>50-65% polymer savings.</u>**



Project Economics: Costs for Treating Produced Waters at Different TDS Concentrations

Input TDS (mg/L)	Outlet TDS (mg/L)	TDS Removed (mg/L)	CapEx* ($ USD /m³)	OpEx* ($ USD /m³)	Total Cost of Ownership* ($ USD /m³)
7000	1500	5500	$0.60-0.75	$1.15-1.75	$1.75-$2.50
12000	1500	10500	$0.80-0.95	$1.20-2.00	$2.00-$2.95
20000	1500	18500	$1.10-1.25	$1.30-2.5	$2.40-$3.75

*Assumptions have been made regarding energy cost, chemical cost and inlet chemistry, which vary by region. Every case is unique.

Project Economics Summary

- Pilot results project up to 65% savings on ongoing polymer costs
- Potential for up to 20% return-on-investment

Next Steps: Scale-Up

- Proceeding to scale-up to 1000 m^3 / day demo plant
- Investigate economics with additional pilots:
  - Offshore EOR produced water
  - Higher TDS inlets
  - Non-polymer water flood EOR

Acknowledgements

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ALBERTA INNOVATES

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TECHNOLOGIES DU DÉVELOPPEMENT DURABLE CANADA

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