



Project Final Report

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1. EXECUTIVE SUMMARY

Saltworks Technologies' CCEMC-supported project, "Waste Heat Driven Water Treatment for Alberta's Oil Sands" was successfully completed. The overall objective of the project was confirming performance and economics of a low cost, low energy, waste-heat-driven water treatment technology – the "SaltMaker" – for treating Steam Assisted Gravity Drainage (SAGD) blowdown wastewater to produce freshwater and solids. The project aims to provide long term economic and environmental benefits by pilot testing the SaltMaker first at Saltworks' Vancouver facility, and then in subsequent projects dispatch a pilot plant to an operating SAGD site. The project's success is demonstrated by a follow-on project now delivering a pilot plant to an operating SAGD site in January 2015 with plans being laid for a larger scale pre-demonstration plant dispatch in 2016/17. Economic and environmental benefits result by increasing water recycling, reducing wastewater, and reducing the cost and greenhouse gas (GHG) impact of blowdown management relative to conventional crystallizers or trucking and deep well disposal.

Saltworks was the project proponent; industry partners included three confidential SAGD operators. The project was funded by Saltworks, CCEMC, NRCan's ecoEnergy II program, NRC-IRAP, and two SAGD operators. The project comprised of three phases: (1) developing a 0.1 m³/day SaltMaker prototype and testing SAGD blowdown; (2) designing and building a 10 m³/day SaltMaker to test commercial scale modules on seawater; and (3) extended testing on SAGD blowdown. Extended testing was performed on a fully integrated 0.3 m³/day pre-demonstration SaltMaker pilot to maximize operation time with the limited supply of SAGD blowdown waters. The 10 m³/day SaltMaker was tested using reconstituted SAGD blowdown water (diluted brine from the 0.3 m³/day SaltMaker). All phases were completed at Saltworks' Vancouver facilities with blowdown waters supplied by oil sands partners, and seawater supplied by Saltworks' fully permitted seawater intake.

In Phase 1, a 0.1m³/day SAGD Multi Effect Concentrator (MEC) SaltMaker prototype was developed and tested on SAGD blowdown waters at Saltworks' Vancouver facility. Two SAGD water sources were tested: (1) Once Through Steam Generator (OTSG) blowdown, and (2) Evaporator blowdown. In total, 3,200L of OTSG blowdown and 450L of evaporator blowdown provided by industry partners were tested. The pilot successfully and reliably produced freshwater and solids from the blowdown wastewaters.

In Phase 2, lessons learned from the prototype were applied to the detailed design and build of a larger, modular 10 m³/day SAGD SaltMaker pre-demonstration pilot also at Saltworks' facility. Commercial scale modules were designed, built and tested on seawater to ensure successful operation. During Phases 1 & 2, a number of important lessons learned were established.

In Phase 3, the project team focused on system refinement based on SAGD operator feedback, incorporation of lessons learned, and long-term duration testing. In an effort to deliver a product most suited for commercial dispatch, Saltworks completed two additional significant scope items at no extra cost to the project: (1) designed and built a new crystallization test bed to refine solids production and extraction; (2) designed and built a new fully integrated 0.3 m³/day pre-demonstration pilot scale plant incorporating all lessons learned and innovations from the course of the project. The improved systems were tested with an additional 28,000L of evaporator blowdown from two industry partners. All industry partners emphasized operational runtime; hence the limited supplied blowdown was tested on the 0.3

m³/day pilot scale machine incorporating all improvements. The 10 m³/day SaltMaker was tested using reconstituted SAGD blowdown water (diluted brine from the 0.3 m³/day SaltMaker)

The CCEMC project proved successful in confirming Saltworks' estimated GHG benefits from the SaltMaker. The energy demand of the SaltMaker (assuming waste heat used for the 80°C thermal source) was ~8 kWh_e/m³ (compared to 41kWh_e/m³ for traditional evaporator-crystallizer systems); representing a potential 81% reduction in GHG emissions. The SaltMaker also replaces trucking the blowdown water off site to disposal wells, saving diesel fuels and GHG emissions in amounts proportional to trucking distances. The differential in electrical energy usage could deliver projected cumulative GHG reductions in Alberta of 555 kilotonnes CO₂e while saving \$945M in total cost of ownership through 2027.

In summary, the project proved performance, economics, and GHG benefits of the SaltMaker technology on SAGD blowdown waters. The project provided a platform for three larger SAGD operators to work with a Canadian innovator to jointly develop and refine a needed SAGD solution. The project has helped advanced the SaltMaker technology which can reduce the cost and environmental impact of SAGD oil sands production, with the resulting potential to increase the oil sands' global competitiveness. The project was a success and the next steps of an on-site SAGD pilot are already being taken with continued support from the original three SAGD operators.

2. PROJECT DESCRIPTION

2.1 Introduction and background

The overall objective of the project was to develop and test a low energy technology for treating highly impaired waters in the Canadian oil sands industry. The technology is a Multi Effect Concentrator (MEC)-SaltMaker that operates on humidification-dehumidification principles producing freshwater and solid salts from oil sands wastewater. It provides a zero liquid discharge (ZLD) alternative to expensive and energy intensive evaporators and crystallizers, or trucking and deep well disposal. The project was broken down into three phases as summarized below:

- **Phase 1:** Develop a 0.1 m³/day prototype and test on Steam Assisted Gravity Drainage (SAGD) oil sands produced water.
- **Phase 2:** Design, build, and commission on seawater a 10 m³/day pre-demonstration pilot to test commercial scale modules.
- **Phase 3:** Extended duration testing on SAGD blowdown waters and system refinement on a fully integrated 0.3 m³/day pre-demonstration SaltMaker to maximize operation time at the request of industry partners. Testing on the 10 m³/day pre-demonstration pilot was also completed.

Phase 1 commenced Oct 29, 2012 and involved the development and testing of a 0.1 m³/day Multi Effect Concentrator (MEC) SaltMaker prototype with industry supplied SAGD blowdown. The 0.1 m³/day prototype is shown in Figure 1. The prototype is a three effect machine consisting of a two-effect MEC unit for concentrating blowdown and a single-effect SaltMaker for producing solids and rejecting the final heat via an air cooled radiator (a more detailed description of the technology is provided in Section 2.2). As part of Phase 1 scope, the MEC and SaltMaker units were integrated (thermal and controls), initially tested on seawater, and then tested with 3,200L of SAGD Once Through Steam Generator (OTSG) blowdown water and 450L of SAGD evaporator blowdown water provided by two project industry partners. Phase 1 was completed March 30, 2013.

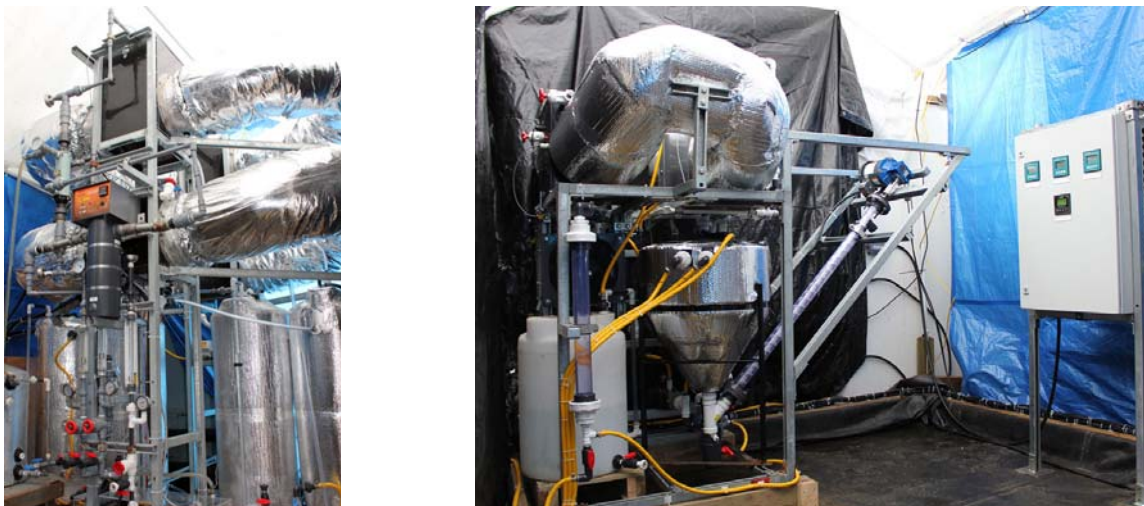


Figure 1: Two Effect MEC (left) and Single Effect SaltMaker (right)

Phase 2 commenced March 31, 2013 and involved the detailed design, build, and initial testing of the 10m³/day SAGD SaltMaker pre-demonstration pilot on seawater with a focus on performance testing modules that would one day form the basis for commercial scale plants. Commercial scale plants would

involve multiples of the same modules. Construction of the 10 m³/day pre-demonstration SaltMaker pilot was completed at Saltworks and testing on seawater was conducted to ensure successful operation. Testing was also completed on re-constituted SAGD wastewaters. Sufficient SAGD fluids could not be supplied for long duration runs on the 10 m³/day SAGD SaltMaker pilot due to its high capacity. This is why Saltworks' seawater intake system was used as the test fluid. Phase 2 was completed April 30, 2014.

Phase 3 commenced May 1, 2014 and involved incorporating all innovations and lessons learned while advancing extended duration testing on SAGD fluids. SAGD operators provided feedback that reliable, continuous solids production and extraction were key success factors for a SaltMaker that would meet the needs of the SAGD industry. In response, Saltworks performed the following additional scope in Phase 3 without an increase to project costs:

- Designed and built a 0.3 m³/day fully integrated pre-demonstration pilot incorporating MEC-SaltMaker learning from Phase 1 learning. The 0.3 m³/day integrated pre-demonstration pilot was commissioned on seawater and then tested with a total 20,000L of evaporator blowdown from two industry partners. The rationale for testing supplied blowdown on this 0.3 m³/day integrated pilot was to maximize operational run-time with the limited blowdown available (at the request of industry partners).
- As part of the project scope, the 10 m³/day pre-demonstration pilot was tested with SAGD fluids reconstituted by diluting the highly saturated brines and solids produced by the 0.3 m³/day integrated pilot.



Figure 2: Evaporator Blowdown (right) and SaltMaker Freshwater (left)

2.2 Technology Description

The SaltMaker is a robust zero-liquid-discharge (ZLD) solution for treating brine or highly impaired waters to produce freshwater and concentrated brine or solids. The SaltMaker was developed ground-up for reliable operation on hyper-saline brines, while also using lower grade waste heat available in SAGD facilities and recycling heat between internal “effects” to reduce electrical energy consumption by up to 81% compared to conventional evaporator-crystallizer-dryer systems, resulting in significant GHG reductions.

The SaltMaker uses a humidification-dehumidification (HDH) cycle to concentrate saltwater and produce freshwater. The use of a humidified air cycle enables operation at temperatures below 90°C and pressures near atmospheric (1 bar). These attributes allow the use of engineered plastics in place of

more costly corrosion resistant metallics, thereby saving capital cost while also reducing scaling risk due to the much lower surface energy of plastics. In addition, evaporation occurs on a non-heated surface, further reducing scaling and enhancing reliability.

Process: The SaltMaker is a thermally driven plant, producing freshwater and a highly concentrated discharge (brine) and/or solids via a multiple-effects HDH cycle. The thermal energy is used to evaporate and condense water in successive “effects”. The latent heat of condensation is recycled as it is downgraded, with each effect operating at 10-15°C lower temperature than the previous one. Each effect produces freshwater and successively concentrates the saltwater. All but the last effect use a closed evaporation air loop to retain heat. The final effect uses the downgraded heat (<40°C) to concentrate brine to solids while rejecting the downgraded heat to atmosphere with an open air stream. The SaltMaker energy requirements are as follows:

- Electrical Requirements: 8-10 kWh per m³ of freshwater removed. Electrical energy can be provided by standard 480 VAC or 600 VAC three phase power.
- Thermal Requirements: 750 MJ per m³ of freshwater removed for four effects, 1,500 MJ per m³ of freshwater removed for two effects.

The SaltMaker design allows the use of multiple “effects” each with their own humidification, dehumidification, and salt extraction subsystems. A simplified process diagram is shown below. It is noted that the diagram describes a four effect SaltMaker with the first three effects being closed air loop and the fourth effect open to atmosphere. In the case of the project, a two effect configuration was used to simulate both waste heat supply at 75-80°C at site and heat rejection to cool glycol on a SAGD site.

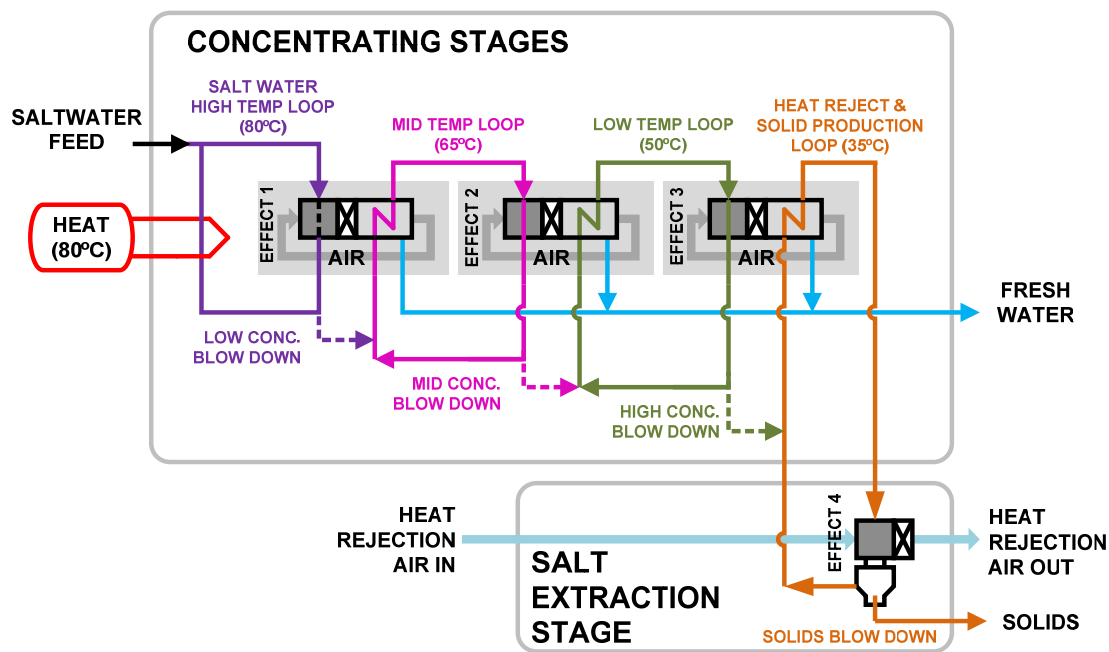


Figure 3: SaltMaker Simplified Process Flow Diagram

All SaltMaker systems incorporate full automation and intelligent self-cleaning operation that measures scaling potential and initiates automated cleaning cycles as required. The details of the cleaning systems are confidential Saltworks’ intellectual property, some of which are patented, are not suitable for

publication in this document. Interested reviewers are encouraged to contact Saltworks directly for details.

Modularity: The SaltMaker is designed for full modularity; everything from individual subsystems to plant packaging is modular. This facilitates future capacity expansion. The modularity of the various components also results in higher quality reliable plants and lower capital and operating costs as described below.

Rapid site dispatch, simple site installation, and flexibility for future plant capacity expansion (Figure 4):

- Modular building blocks based on ISO shipping container dimensions.
- Easy assembly and disassembly allows for Factory Acceptance Testing (FAT) at Saltworks' facility before dispatch.
- Transport and installation using readily available trailers and cranes.
- Plant expansion by adding additional "blocks".



Figure 4: SaltMaker Set (left) and Site Installation (right)

Repeatable manufacturing (Figure 5 to Figure 7):

- SaltMaker sets are built out of modules: fan, evaporation, and heat recovery.
- Each module is mass produced and quality assured for repeatable production.



Figure 5: Evaporation Module (left), Heat Recovery Module (middle), Fan Module (right)



Figure 6: Repeatable Mass Produced: Evaporation Modules



Figure 7: Repeatable Mass Produced: Fan Modules (left), Heat Recovery Modules (right)

Ease of cleaning and replacement (Figure 8):

- Modules slide in and out for easy removal.
- Servicing of modules without confined spaces.
- Modules can be “power washed” and reinstalled.



Figure 8: Assembled Module (left) and Module Removal by Forklift (right)

Balance of Plant: The SaltMaker balance of plant systems are shown in Figure 9 to Figure 12.



Figure 9: Control Room



Figure 10: Thermal Source



Figure 11: Air Compressor and Heat Recovery



Figure 12: Salt Extraction

2.3 Project Goals & Work Scope Overview

Task	Planned Progress	Actual Progress	Comments on Variances
Phase 1			
1.1 Develop, commission and operate prototype-MEC-SaltMaker on Seawater	Baseline performance on seawater	Successfully completed.	No variance
1.2 Treat up to 1,500L of OTSG SAGD blowdown water	Baseline performance on blowdown water from industry partners	Completed. Treated 3,200L of SAGD OTSG blowdown water and 450L of evaporator blowdown water.	Greater volumes of water treated for longer duration runs and potential solids production. Two types of blowdown water treated to test robustness of SaltMaker on different types of SAGD waters.
1.3 Update design, cost and economic assessments based on learning	Phase 1 testing work and analysis complete	Completed a design for a 10 to 100 m ³ /day plant employing commercial scale modules.	Industry partners appreciated development and testing of the future commercial modules, de-risking scale-up. This also shortens commercialization time frames.
1.4 Pre-design and pre-procurement for Phase 2	See Task 2.1	See Task 2.1	See Task 2.1
Phase 2			
2.1 Field unit design and build	Detailed design and review by oil field partner 10 m ³ /day pre-demonstration pilot unit ready for commissioning on seawater	Design and build completed, lessons learned incorporated and reviewed by oil field partner Pre-demonstration pilot ready for commissioning on seawater	Plants' actual capacity close to 25 m ³ /day but insufficient heat and water supply available at Saltworks' Vancouver location.
2.2 Field unit commission and test on seawater	Commissioning and baseline performance on 10 m ³ /day pre-demonstration pilot unit. Phase 2 build / commissioning and analysis complete	Pre-demonstration pilot successfully commissioned and tested on seawater	No variance
2.3 Pre-test and preparations for Phase 3	See Task 3.1	Completed and prepared for Phase 3	No variance

Task	Planned Progress	Actual Progress	Comments on Variances
Phase 3			
Added scope: 0.3 m ³ /day pre-demonstration design, build and test with SAGD blowdown	Complete 0.3 m ³ /day pre-demonstration design, build and testing with 20,000L of SAGD blowdown	Successfully completed, lessons learned applied to future SaltMaker units, including a pilot being dispatched to a SAGD site	Additional scope performed at no cost to project
Added scope: Long duration testing on shipped SAGD blowdown	Test the 0.3 m ³ /day pre-demonstration pilot plant on SAGD oil sands produced water.	Testing complete. Detailed results analysis complete	Saltworks began testing early due to eager customer. Scope of testing work exceeded.
3.1 Site and field unit preparation	Field unit testing ready to start	Pre-demonstration pilot ready for testing. Factory acceptance testing successfully complete.	No variance
3.2 Field unit commission and test on SAGD OTSG blowdown	Performance on 10 m ³ /day pre-demonstration pilot unit with SAGD blowdown water	Completed testing of 20,000L of evaporator blowdown with 0.3 m ³ /day pre-demonstration pilot Completed testing of reconstituted SAGD water on 10 m ³ /day pre-demonstration pilot	Testing performed on 0.3 m ³ /day pre-demonstration pilot to provide longer duration testing at the request of industry partners. Reconstituted evaporator blowdown tested on 10 m ³ /day pre-demonstration pilot. Evaporator blowdown water was tested rather than OTSG blowdown as industry partners indicated evaporator blowdown treatment is a higher priority.
3.3 Machine clean and reporting	10 m ³ /day unit proven on blowdown water and ready for on-site operation at industrial partner SAGD site	SaltMaker operation proven on SAGD blowdown.	No variance. Saltworks proceeding to on-site pilot.

3. EXPERIMENTAL PROCEDURES, METHODOLOGY & MODELLING DETAILS

To monitor performance of the MEC-SaltMaker prototype and pre-demonstration pilot SaltMakers, key operating parameters were recorded and water samples of important process solutions were collected for chemical analysis by an outside third party laboratory. Data was collected with the intent of demonstrating performance of the prototype or pre-demonstration pilot SaltMakers.

4. RESULTS OF EXPERIMENTATION

4.1 Phase 1

The following provides detailed technical test results from the Phase 1 project work.

Integration of MEC and SaltMaker and Operation with Seawater

Prior to the start of the project, Saltworks only operated the MEC and SaltMaker as independent units. As part of the project scope, Saltworks integrated the MEC and SaltMaker units, where the first two effects of the MEC concentrates the source water and the last effect of the SaltMaker produces solids and rejects the heat. The integration of the two units was tested on seawater.

Figure 13 summarizes the successful recycling of the latent heat of condensation, reducing the net thermal energy input. The 1st effect has a temperature of near 80°C, representing the readily available waste heat available from SAGD operations, with the heat cascading down to the final effect temperature of approximately 30°C, which is rejected via an air cooled radiator.

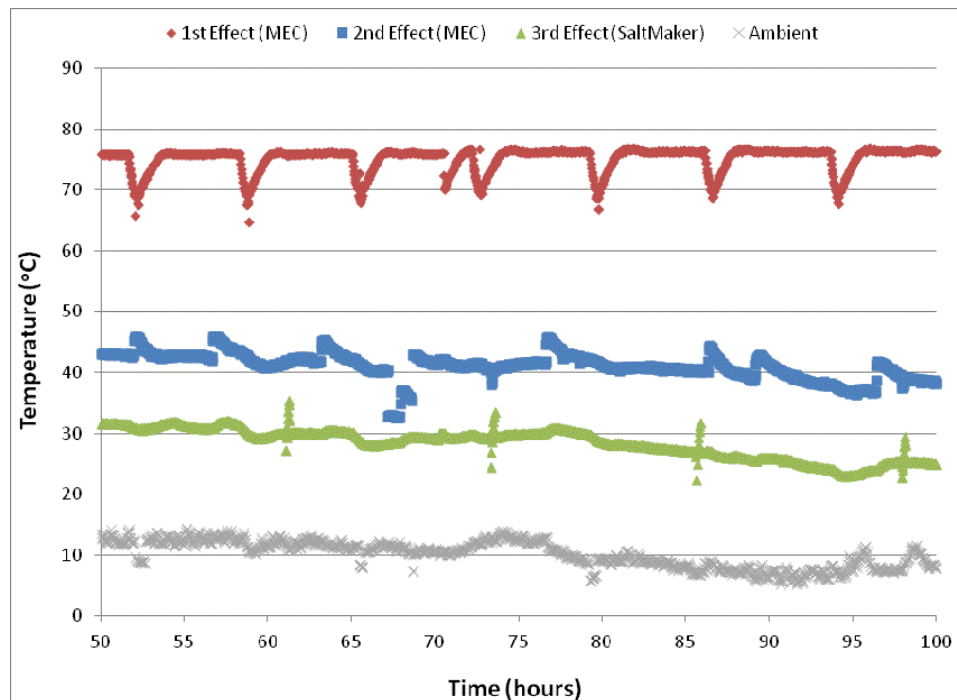


Figure 13: Recycling of Heat Through Each of the Effects - Seawater

During operation of the integrated MEC-SaltMaker, freshwater is produced and seawater is successively concentrated in each of the effects. Figure 14 shows the increase in conductivity of the seawater in each effect.

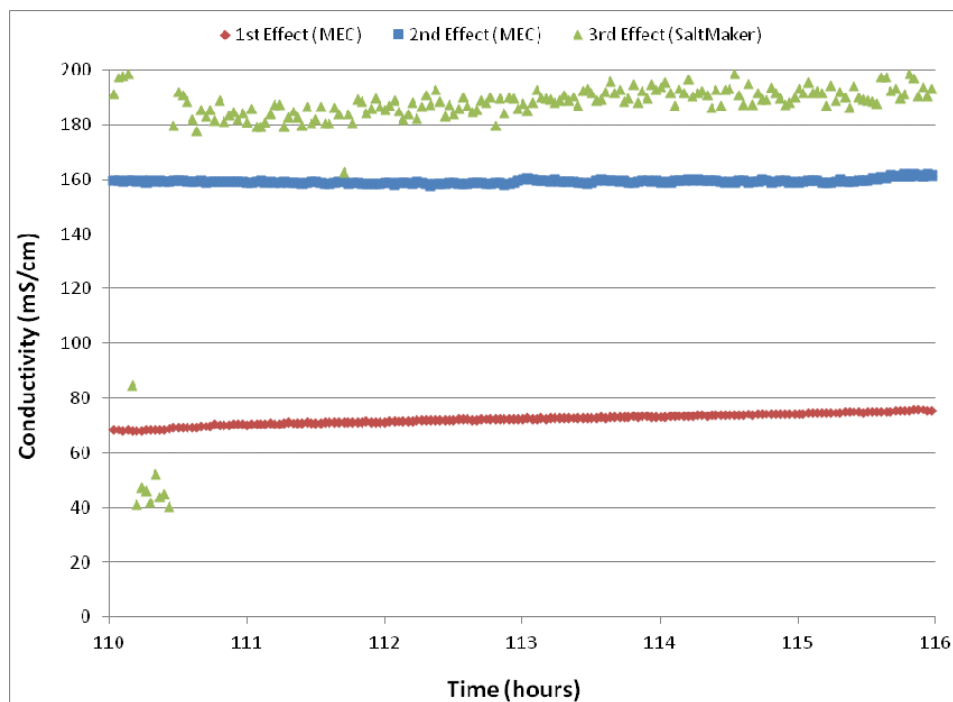


Figure 14: Conductivity of Seawater in Each Effect

The integrated MEC-SaltMaker operated for 800 hours, processing 3,500L of seawater. Freshwater and solid salts from seawater were produced during the testing. Table 1 summarizes the analytical results which show that the freshwater was of extremely low total dissolved solids (TDS) concentration (<5 mg/L). The salts produced during the test were analyzed using x-ray diffraction (XRD) and the results revealed that it consisted mostly of halite (sodium chloride) with some gypsum (calcium sulfate) (Figure 15).

Table 1. Seawater and Freshwater Produced by MEC-SaltMaker Water Chemistry

Parameter (mg/L)	Seawater	Freshwater
pH	7.68	6.74
Total Dissolved Solids	26700	<5
Total Hardness (as CaCO ₃)	4920	4
Bicarbonate (as CaCO ₃)	109	6
Carbonate (as CaCO ₃)	<1	<1
Bromide	49.9	0.06
Nitrate-N	1.71	0.126
Chloride	15200	12.7
Sulphate	2310	1.4
Silica (reactive)	3.52	<0.01
Calcium	306	<0.05
Iron	<0.5	<0.01
Magnesium	1010	0.89
Manganese	<0.05	0.004
Phosphorus	<2.5	<0.05
Potassium	302	0.4

Parameter (mg/L)	Seawater	Freshwater
Sodium	8540	6.8
Aluminum	0.05	0.017
Arsenic	0.038	0.0008
Barium	0.017	<0.0001
Boron	3.0	0.038
Cadmium	0.0018	0.00022
Lithium	0.139	0.0003
Molybdenum	0.008	<0.0001
Strontium	6.23	0.0030
Titanium	0.68	<0.001
Uranium	0.0024	<0.00001
Vanadium	0.058	<0.0005
Zinc	0.29	0.023

^a Only significant parameters summarized in the above table. All other parameters were at or less than the laboratory detection limit.

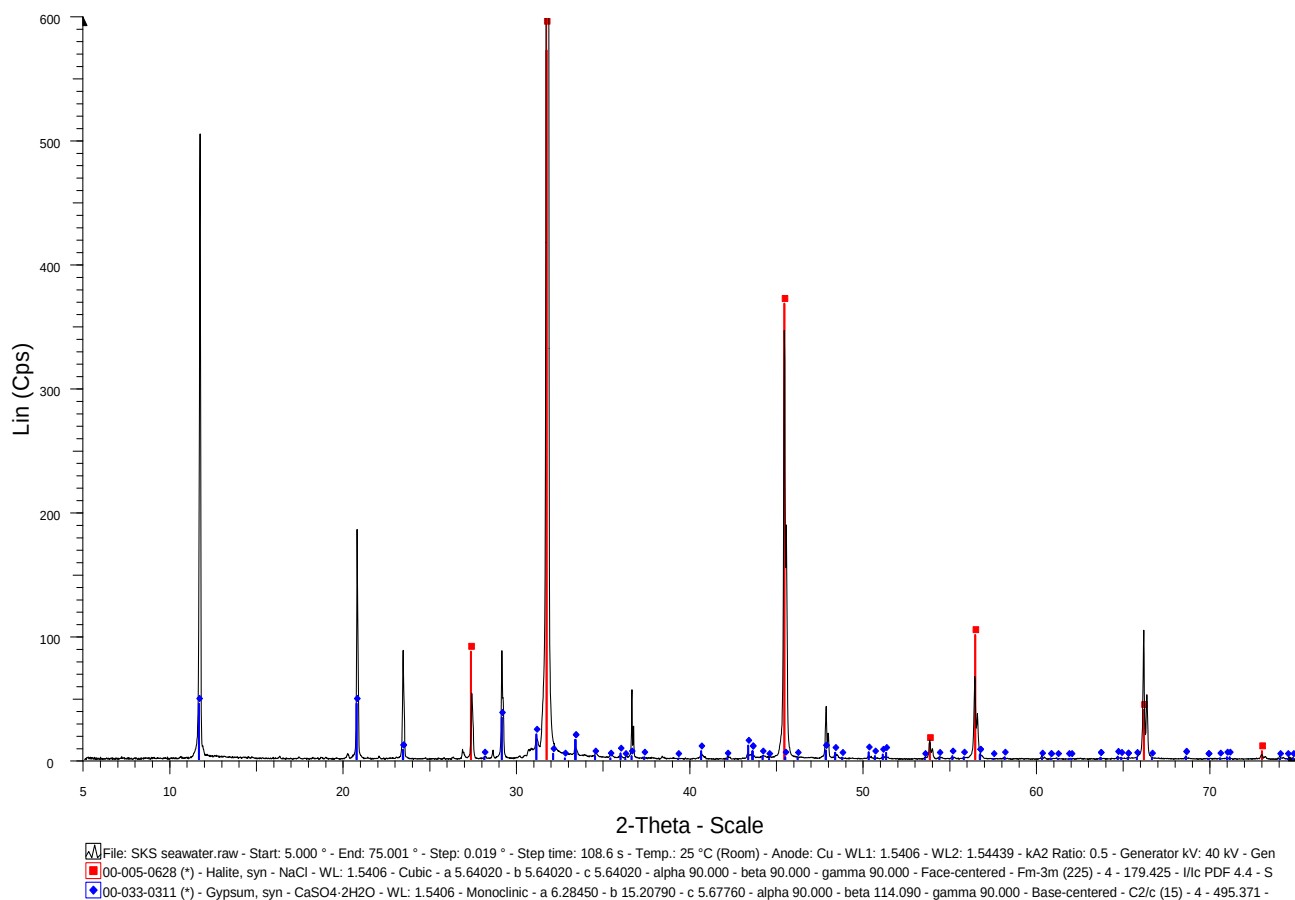


Figure 15: Seawater Salts XRD Identification Results

0.1 m³/day MEC-SaltMaker Testing with OTSG Blowdown Water

Saltworks completed the treatment of 3,200L of OTSG blowdown water provided by a SAGD Industry partner. The OTSG blowdown water was tested with the 0.1 m³/day MEC-SaltMaker prototype. However, due to limited blowdown volume, the first two effects of the MEC were operated with seawater and the final third effect was operated with OTSG blowdown water. The three effect operation demonstrated the recycling of thermal energy for energy efficiency treatment of SAGD waters. The MEC-SaltMaker is still fully and thermally integrated with the 1st effect operating at 70-80°C and the heat cascading down to the final 3rd effect of the SaltMaker.

Figure 16 summarizes the successful recycling of the latent heat of condensation, from approximately 70-80°C in the 1st effect down to approximately 50°C in the 3rd SaltMaker effect operating with seawater in the 1st and 2nd effect and OTSG blowdown in the 3rd effect.

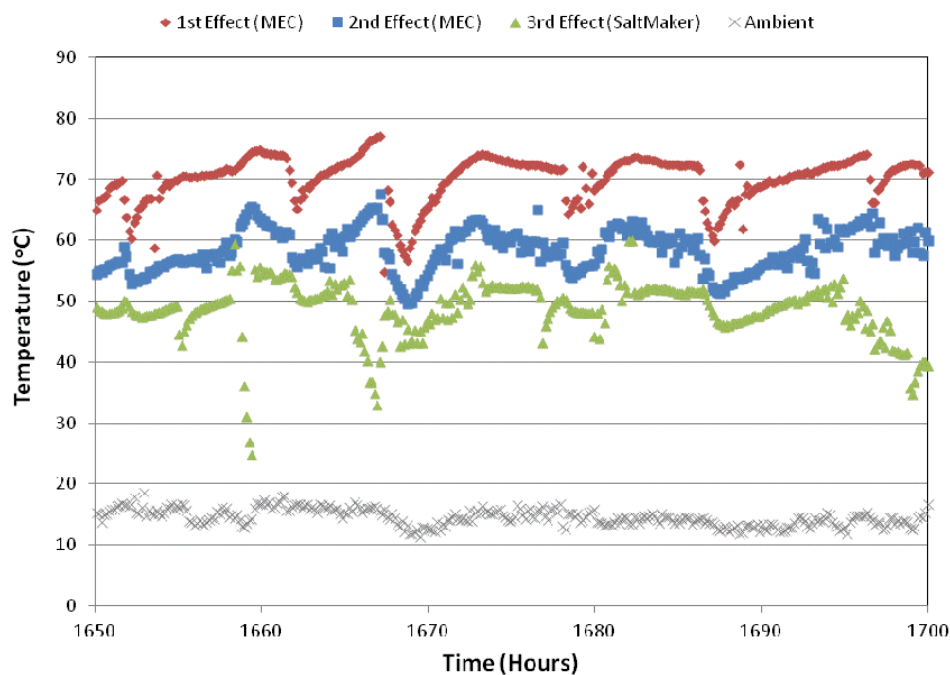


Figure 16. Recycling of Heat Through Each of the Effects - OTSG Blowdown

The 0.1 m³/day MEC-SaltMaker prototype operated for 1800 hours (75 days) to treat the 3200L of OTSG blowdown water producing freshwater with TDS <200 mg/L (Figure 17).



Figure 17: OTSG Blowdown Water (right bottle) and SaltMaker Freshwater (left bottle)

The conductivity of the untreated OTSG blowdown water was 35mS/cm. The MEC-SaltMaker prototype concentrated the blowdown water to a high of just over 350mS/cm in 600 hours. It is noted that the fluctuations in conductivity readings, especially after 600 hours, is due to the self cleaning cycles, using hot water wash/flush, causing a dilution in the brine, and is also due to interference of the water chemistry (highly scaling and high in organics) on the conductivity probes.

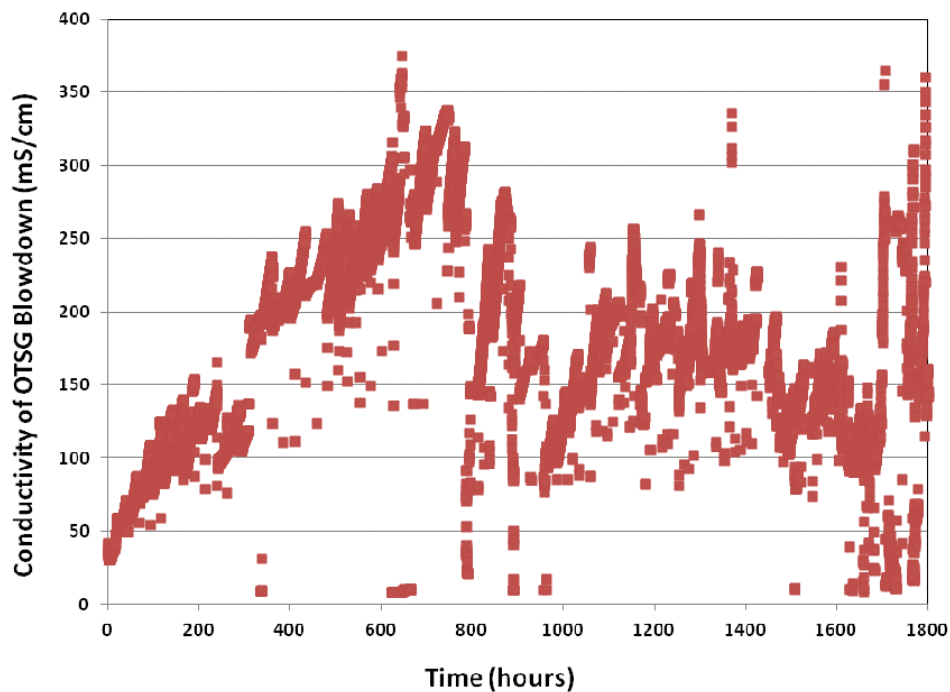


Figure 18: Conductivity of SaltMaker Brine Operating on OTSG Blowdown Water

Near the end of the test run, samples were collected from the brine and the freshwater and sent to a laboratory for analysis. Approximately 20 kg of solid salts were produced.



Figure 19: Solids Produced from SAGD Blowdown

Table 2 shows that the freshwater was of extremely low salt content with a total dissolved solids (TDS) concentration of 158 mg/L and low organics, as represented by Total Organic Carbon (TOC) of 6.2mg/L. The TDS of the brine was 182,000 approximately 10x concentrated from the untreated OTSG blowdown. Due to confidentiality agreement with industry partner, the raw untreated OTSG blowdown water chemistry is not provided but the TDS was ~20,000 mg/L..

Table 2. SaltMaker Brine and Freshwater Chemistry

Parameter (mg/L)	SaltMaker Brine	SaltMaker Freshwater
pH	8.80	6.88
Total Dissolved Solids	182,000	158
Total Organic Carbon	7,540	6.2
Bicarbonate (as CaCO ₃)	2,210	13
Carbonate (as CaCO ₃)	14,000	<1
Chloride	103,000	82.0
Sulfate	2,620	10.3
Reactive Silica	265	0.2
Calcium	39.5	1.98
Sodium	73,600	52.5

Figure 22, below, shows the XRD analysis of the OTSG blowdown salts indicating that the salts were mostly NaCl and CaCO₃.

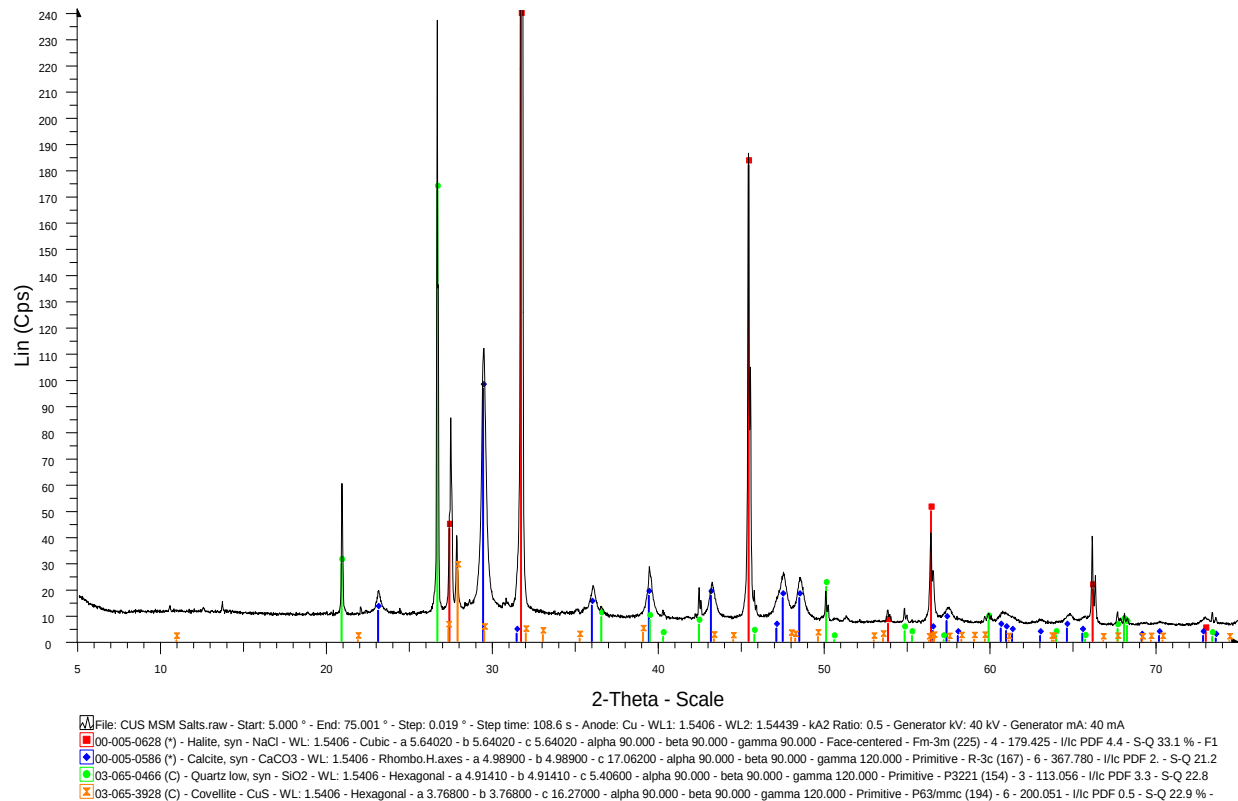


Figure 20: SaltMaker Produced Salts Operating on OTSG Blowdown XRD Identification Results

Upon completion of the test, the SaltMaker was inspected for scaling and plugging. There were no visible signs of scale build up or plugging of the various SaltMaker components after 1800 hrs of operation. The machine was also easily cleaned using a typical commercially available pressure washer.

0.1 m³/day MEC-SaltMaker Testing with Evaporator Blowdown Water

Saltworks completed the treatment of 450L of evaporator blowdown water provided by another industry project partner. The evaporator blowdown water was tested with the same 0.1 m³/day MEC-SaltMaker prototype, cleaned thoroughly after the OTSG blowdown testing. The prototype was also operated with seawater in the 1st and 2nd effects and evaporator blowdown water in the 3rd effect, again due to limited sample water. The MEC-SaltMaker is still fully thermally integrated with initial 1st effect operating at 70-80°C and the heat cascading down to the final 3rd effect of the SaltMaker.

Figure 21 summarizes the successful recycling of the latent heat of condensation, from approximately 70-80°C in the 1st effect down to approximately 30-50°C in the 3rd SaltMaker.

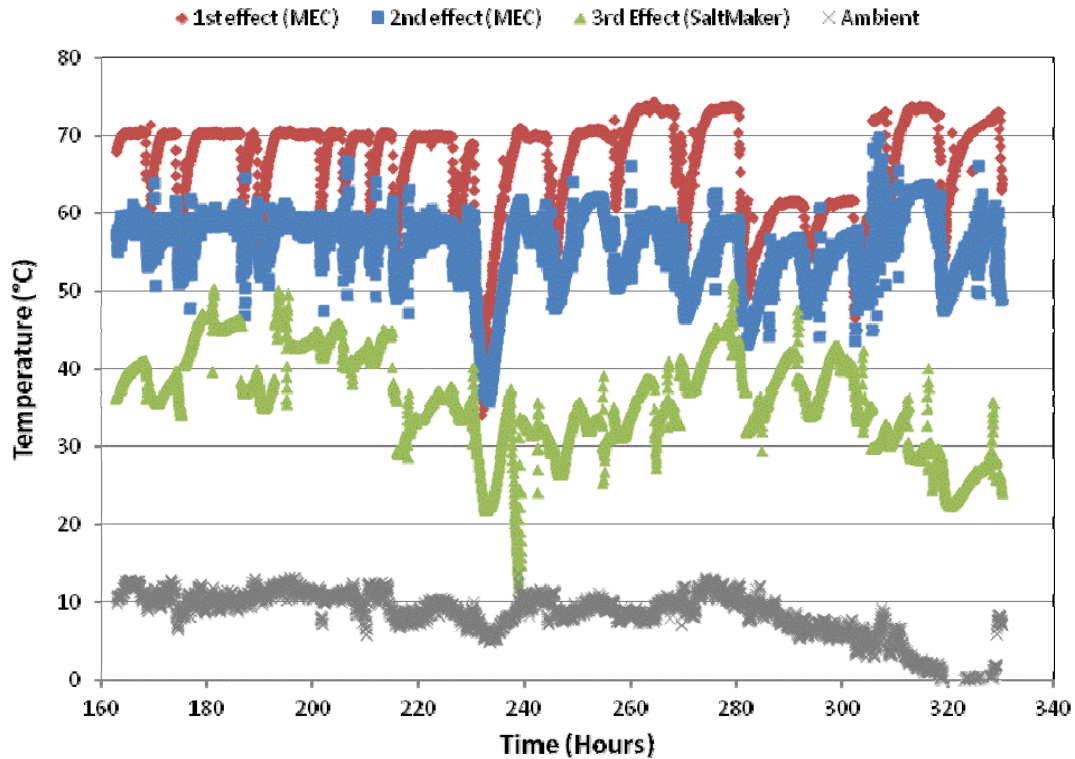


Figure 21: Recycling of Heat Through Each of the Effects - Evaporator Blowdown

Since the evaporator blowdown is very concentrated ($>200,000\text{mg/L TDS}$), it is near the saturation limit and salts formed readily. The evaporator blowdown, however, maintained its water-like characteristic while operating in the SaltMaker and salts did not stick to tanks (Figure 22). Plugging did occur in the packing material. The packing material used in the MEC-SaltMaker prototype was film fill and it quickly plugged with solids (Figure 23).

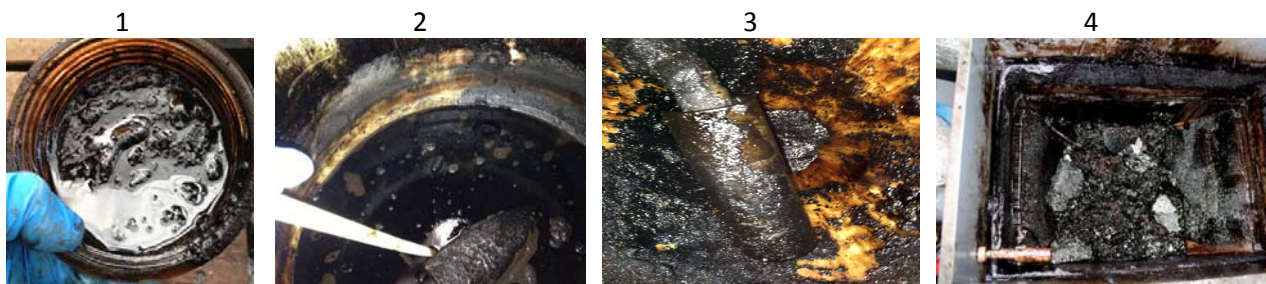


Figure 22: Sand and Sludge (1), "Water-Like" Brine (2), Non-Sticky Solids (3), Hung Up Solids (4)

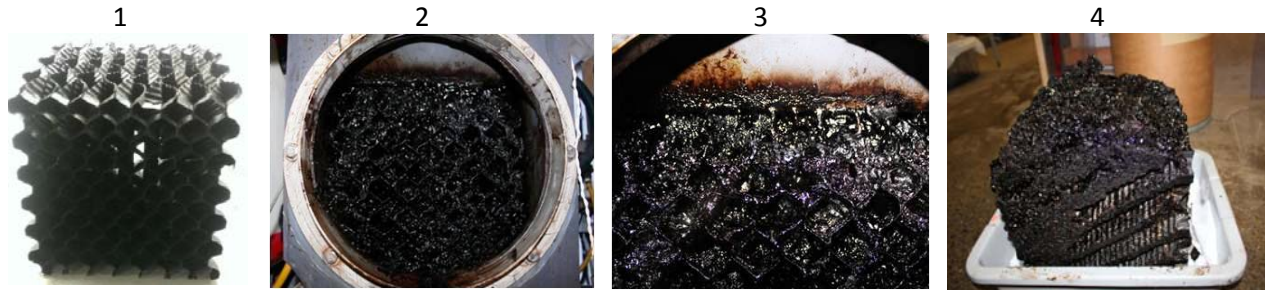


Figure 23: New Film Fill Packing (1) and Clogged Film Fill Packing (2, 3, 4)

The film fill packing was then replaced with splash fill packing. The new splash fill packing material provided reliable operation when used in conjunction with the MEC-SaltMaker pilot's automated hot water wash/flush system (Figure 24).



Figure 24: New Splash Fill Packing (left), Reliable Operation on >400,000mg/L TDS Blowdown (right)

The 0.1 m³/day MEC-SaltMaker pilot operated reliably for 500 hours (21 days) to treat the 450L of evaporator blowdown water producing freshwater with TDS <5 mg/L (Figure 25).



Figure 25: Freshwater Produced from Treatment of Evaporator Blowdown

The conductivity of the untreated evaporator blowdown water was between 150 to 250mS/cm. The MEC-SaltMaker prototype concentrated the blowdown water to a high of 400mS/cm. As with the OTSG blowdown testing, the fluctuations in conductivity readings are due to the self cleaning cycles, using hot water wash/flush, and interference from the water chemistry.

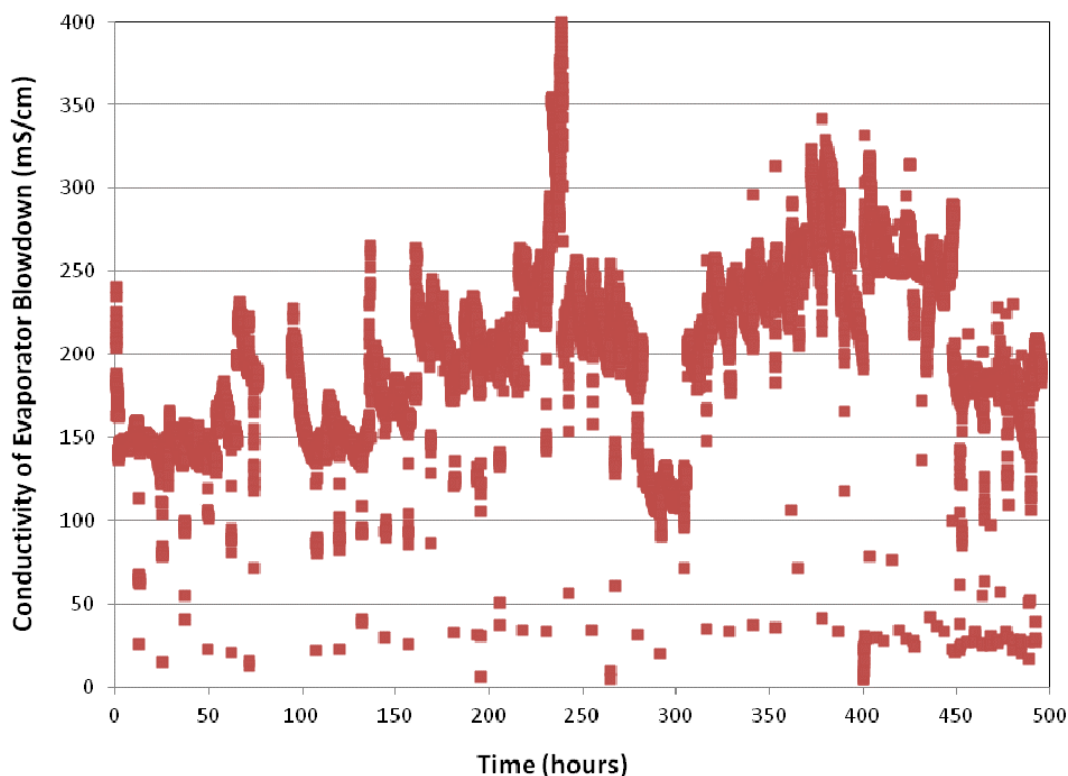


Figure 26: Conductivity of SaltMaker Brine Operating on Evaporator Blowdown Water

The MEC-SaltMaker prototype reliably produced solids from the evaporator blowdown, when concentrated to 400,000 mg/L (Figure 27). Near the end of the run, samples were collected from the SaltMaker brine and the SaltMaker freshwater and sent to a laboratory for analysis.

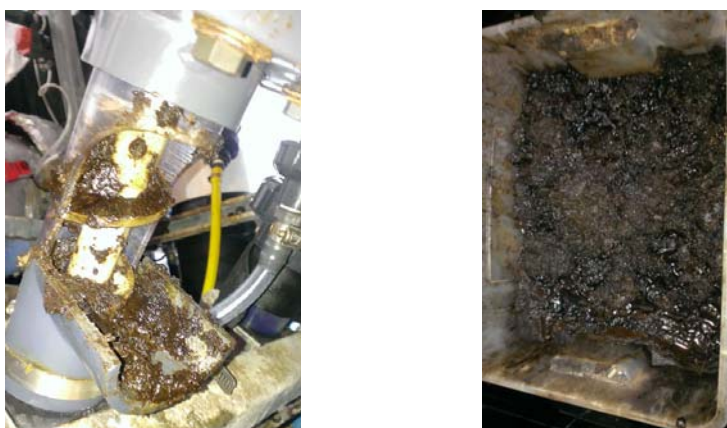


Figure 27: Reliable Solids Extraction (left) and Solids Produced from Evaporator Blowdown (right)

Table 3 summarizes the analytical results, showing that the freshwater had extremely low total dissolved solids (TDS) concentration of <5 mg/L. The organics was elevated, as represented by TOC of 84mg/L. The elevated organics in the freshwater is likely due to volatile organics, which blow over into the freshwater. The TDS of the blowdown was concentrated ~2x.

Table 3. Raw Evaporator Blowdown, SaltMaker Brine and Freshwater Chemistry

Parameter (mg/L)	Raw Evaporator Blowdown	SaltMaker Brine	SaltMaker Freshwater
pH	9.5-11.5	10.3	7.02
Total Dissolved Solids	90,000 - 300,000	406,000	<5
Total Organic Carbon	15,000 - 50,000	43,400	84.2
Calcium	10 - 400	14	<0.05
Chloride	5,000 – 150,000	149,000	6.51
Sodium	15,000 – 150,000	138,000	4.6
Sulfate	500 – 15,000	3,700	<0.5
Reactive Silica	100 – 25,000	103	-

4.2 Phase 2

Design, build, and testing of the 10m³/day SAGD SaltMaker pre-demonstration pilot was completed in Phase 2. The detailed design and construction incorporated lessons learned from Phase 1 of the CCEMC project. Pictures of the 10m³/day SAGD SaltMaker pre-demonstration pilot build are shown below.



SaltMaker Pipe Skid



SaltMaker Modules



SaltMaker Salt Extraction Skid



Electrical Panel (left) & Pumps (right)



SaltMaker Balance of Plant



SaltMaker Built into ISO Shipping Containers

Figure 28: 10m³/day SAGD SaltMaker Pre-Demonstration Pilot Construction Completion

Upon completion of the 10m³/day SaltMaker construction, the pre-demonstration pilot plant was commissioned and tested on seawater. As shown in Figure 29, the data demonstrates that the SaltMaker consistently produced freshwater with conductivity <1 mS/cm while operating on seawater with conductivity >40 mS/cm. The data demonstrated that the 10 m³/day pre-demonstration pilot SaltMaker was operating as designed and built.

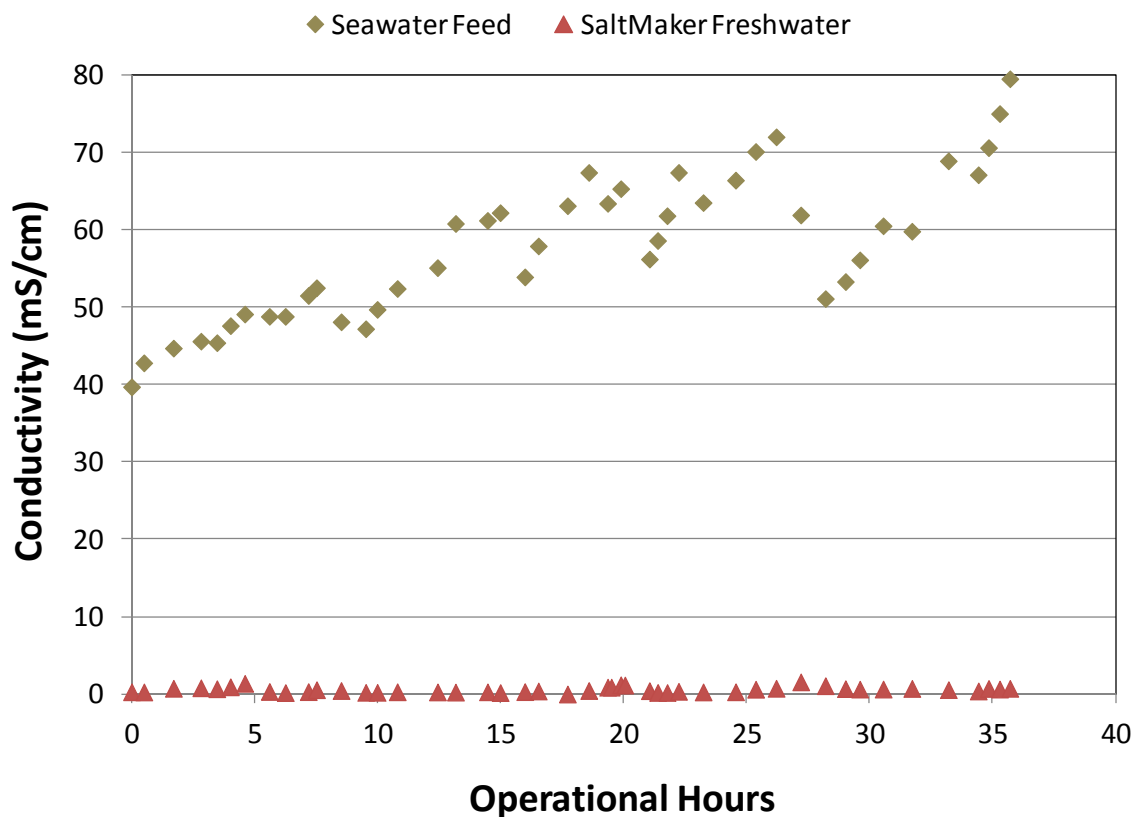


Figure 29: 10 m³/day SaltMaker Commissioning on Seawater

4.3 Phase 3

Phase 3 scope was expanded at Saltworks' cost to incorporate all lessons learned and innovations from the project. The focus was to extract maximum value from the extended testing on real SAGD blowdown

water, while maximizing test time. A total of 28,000L of evaporator blowdown water was tested in this phase of work. The test results showed that the now fully integrated SaltMaker (MEC + SaltMaker; hereinafter simply referred to as “SaltMaker”) pre-demonstration pilot plant reliably operated with 80°C heat 24-7 on SAGD evaporator blowdown and consistently produced freshwater for reuse in SAGD facilities and solids for low volume disposal at Class II landfills.

Phase 3 project work was driven by SAGD operator feedback to develop a reliable, low cost, and energy efficient SaltMaker that would meet the needs of the entire SAGD industry. Industry partners identified reliability and continuous solids production and extraction as key success factors. This is primarily due to their aversion to crystallizer technology and their downtimes which prevent treatment of blowdown waters, adding costs and operational issues with managing the blowdown.

As such additional scope was added to Phase 3 without an increase to project costs. The additional scope is summarized below:

- Build of a smaller scale 0.3 m³/day fully integrated SaltMaker pre-demonstration pilot incorporating the improvements from lessons learned during the Phase 1 MEC-SaltMaker (hereinafter simply referred to as “SaltMaker”) testing. A total of 20,000L of evaporator blowdown was tested on the 0.3 m³/day SaltMaker pre-demonstration pilot. It is noted that industry feedback was that operational run time was of the utmost importance with the limited available evaporator blowdown. Therefore, the decision was taken to operate the smaller scale 0.3 m³/day SaltMaker pre-demonstration pilot with the 20,000L of evaporator blowdown provided by two industry partners.
- Testing of the 10 m³/day pre-demonstration pilot was also completed on reconstituted SAGD waters and wastewaters, in addition to the previous seawater tests.

0.3 m³/day Pre-Demonstration SaltMaker Pilot

A fully integrated three effect 0.3 m³/day pre-demonstration pilot was built for long term continuous 24/7 testing at no additional cost to the CCEMC project (Figure 30). Testing on 20,000L of evaporator blowdown showed that the 0.3 m³/day pre-demonstration pilot reliably operated 24/7 on 80°C heat and produced freshwater for reuse in SAGD facilities and solids for low volume disposal at Class II landfills. The SAGD partner selected to run with only two of three effects due to a desire to accept heat from their warm glycol waste heat loop (75-85°C) and reject heat to their cool glycol loop (40-50°C); providing a temperature difference suitable for only two of three effects. Increasing the number of effects increases the volume of freshwater produced per unit of thermal energy added. However, each effect requires a 10-15°C temperature difference, as the recycled thermal energy is downgraded at each effect. Given the SAGD partner’s request for an output temperature of 40-50°C, a two effect system is required. The pre-demonstration pilot incorporated all lessons learned from the Phase 1 MEC-SaltMaker prototype testing into a fully functional and automated unit. A total of 20,000L of evaporator blowdown was tested on the 0.3 m³/day SaltMaker pre-demonstration pilot. The evaporator blowdown was provided by two SAGD industry partners.

Both industry partners indicated that there was limited supply of the evaporator blowdown and recommended that run time to demonstrate reliability of the fully integrated 0.3 m³/day pre-demonstration pilot was more important than short duration runs on the 10 m³/day pre-demonstration pilot. Therefore, the decision was taken to operate the smaller scale 0.3 m³/day SaltMaker pre-demonstration pilot with the 20,000L of evaporator blowdown provided by the two industry partners: 12,000L from Industry Partner #1 and 8,000L from Industry Partner #2. The 10 m³/day pre-

demonstration pilot was nevertheless operated on SAGD wastewaters collected from berms and reconstituted waters produced by re-dissolving the 0.3 m³/day SaltMaker brine and solids.

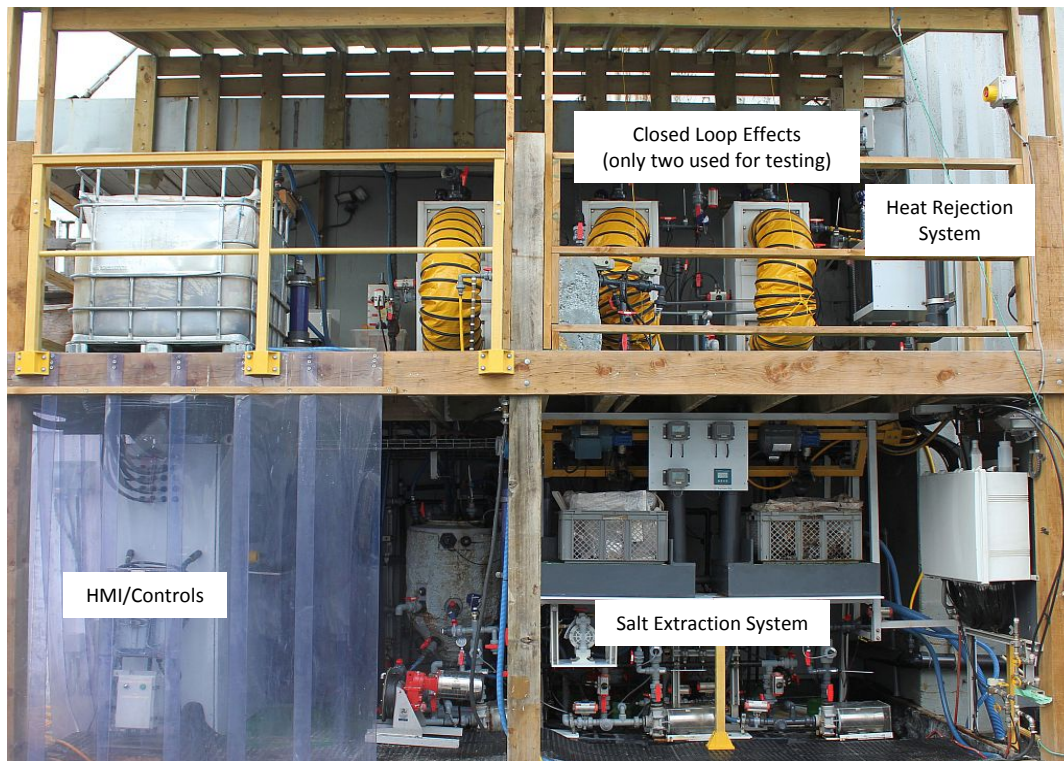


Figure 30: Fully Integrated 0.3 m³/day Pre-Demonstration SaltMaker Pilot

0.3 m³/day Pre-Demonstration Pilot Testing Results

Testing of the 0.3 m³/day pre-demonstration pilot testing showed:

- Reliable Operation: 100% reliable 24/7 operation on evaporator blowdown;
- Energy Efficiency: Use of 80°C heat that is recycled two times and confirmed heat balance;
- Freshwater Quality: Produced of freshwater with total dissolved solids < 100 mg/L; and
- Solids Production and Extraction: Produced and extracted solids from SaltMaker that is suitable for disposal at a Class II landfill.

Reliable Operation: Industry Partner #1 provided 12,000 L of evaporator blowdown water which was reliably operated on the 0.3 m³/day pre-demonstration pilot SaltMaker for 2,600 hours (108 days). The SaltMaker pilot produced freshwater with total solids <500 mg/L and concentrated the brine to 400,000 mg/L total solids. Solids were also produced (please see Solids Production section).

- Figure 31 shows the freshwater conductivity and total solids from operating the pre-demonstration pilot on the 12,000L of evaporator blowdown. The conductivity and the total solids of the SaltMaker freshwater was < 1mS/cm and <500 mg/L, respectively. There were two incidences of loose fittings that contaminated the freshwater with brine, which were subsequently fixed. Otherwise, the pilot operated 24/7 reliably.
- Figure 41 shows the brine conductivity (Effect 2 and Effect 3) and total solids (Effect 3). The data shows that the pre-demonstration SaltMaker pilot concentrated the brine from an initial conductivity of 75 mS/cm (total solids of 150,000 mg/L) and reached steady state solids saturation at ~225 mS/cm (total solids of 400,000 mg/L) after 1,000 hours of operation. The data

also shows that the conductivity of Effect 3 brine is greater than Effect 2 brine, demonstrating the successful concentration of the brine through the two effects.

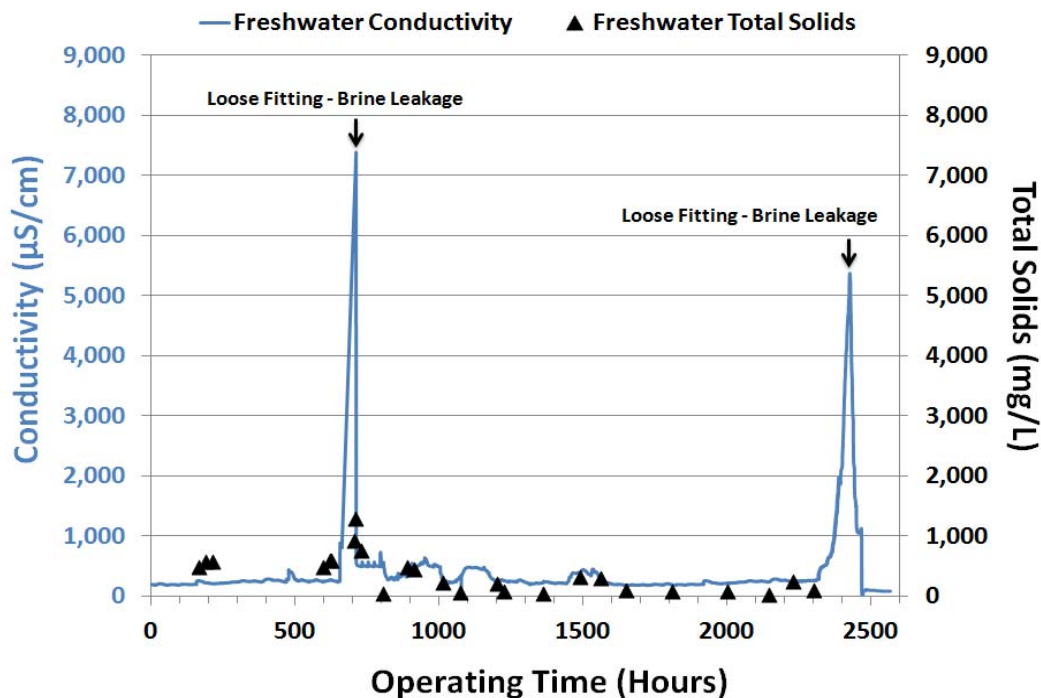


Figure 31: Industry Partner #1 - SaltMaker Freshwater Conductivity and Total Solids

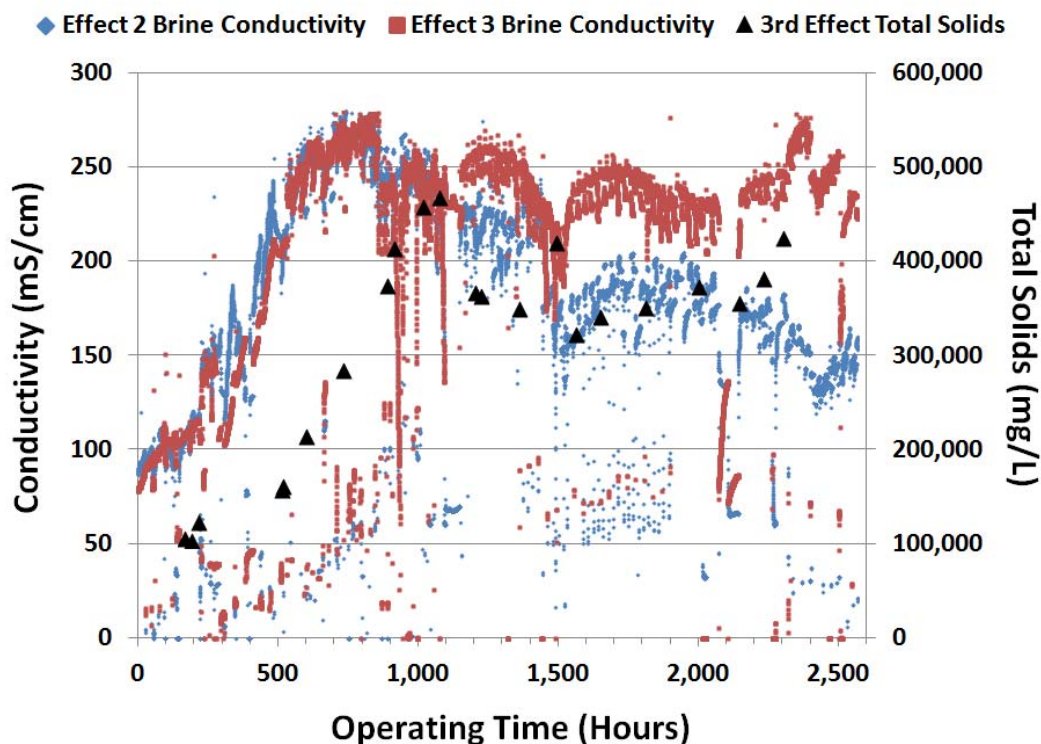


Figure 32: Industry Partner #1 - SaltMaker Brine Conductivity and Total Solids

Industry Partner #2 provided 8,000L of evaporator blowdown water which was reliably operated on the 0.3 m³/day pre-demonstration pilot SaltMaker for 1,400 hours (58 days). The SaltMaker pilot produced freshwater with total solids <200 mg/L and concentrated the brine to 400,000 mg/L total solids. Solids were also produced (please see Solids Production section).

- Figure 42 shows the freshwater conductivity and total solids from operating the pre-demonstration pilot on the 8,000L of evaporator blowdown. The conductivity and the total solids of the SaltMaker freshwater was < 0.2 mS/cm and <200 mg/L, respectively. There was one incident of a faulty valve that contaminated the freshwater with brine, which was subsequently fixed. Otherwise, the pilot operated 24/7 reliably.
- Figure 34 shows the brine conductivity (Effect 2 and Effect 3) and total solids (Effect 3). The data shows that the pre-demonstration SaltMaker pilot concentrated the brine from an initial conductivity of 50 mS/cm (total solids of 100,000 mg/L) and reached steady state solids saturation at ~225 mS/cm (total solids of 400,000 mg/L) after 1,000 hours of operation. The data also shows that the conductivity of Effect 3 brine is greater than Effect 2 brine, demonstrating the successful concentration of the brine through the two effects.

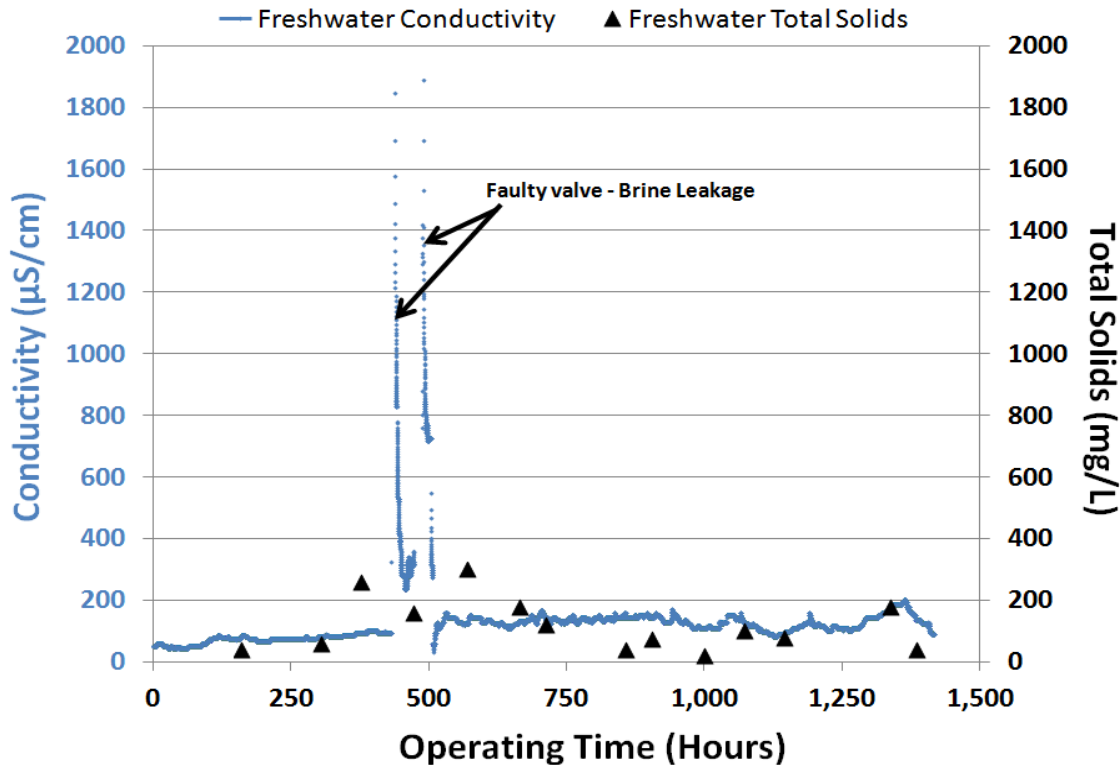


Figure 33: Industry Partner #2 - SaltMaker Freshwater Conductivity and Total Solids

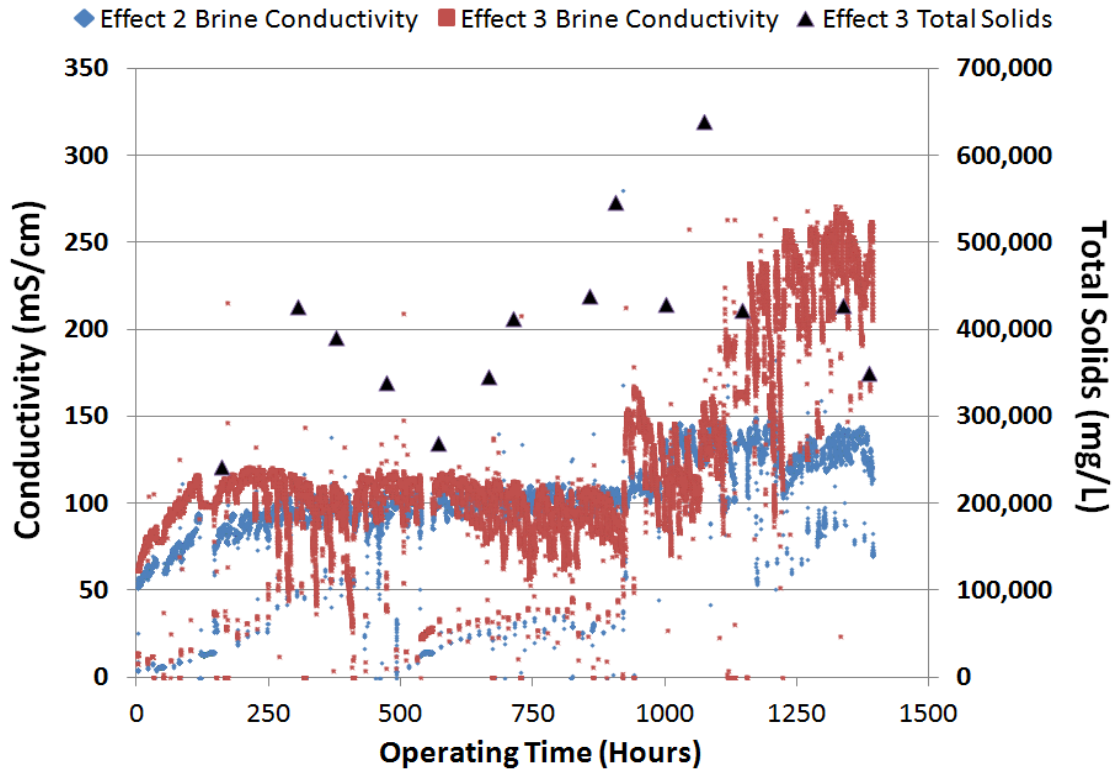


Figure 34: Industry Partner #2 - SaltMaker Brine Conductivity and Total Solids

The 0.3 m³/day pre-demonstration SaltMaker pilot's automated cleaning system was effective in preventing scaling and fouling of the heat exchangers and packing during operation with the 20,000L of evaporator blowdown waters. This resulted in reliable continuous operation. During the pilot, a stringent inspection cycle was followed and the machine's cleaning systems "tuned" to prevent scaling and fouling. Regular inspections were scheduled to ensure reliability of machine. The inspections revealed no scaling or fouling of the heat exchangers or packing throughout the testing period (Figure 35). Automated hot washes using the SaltMaker's freshwater was carried out daily. Full-scale SaltMakers can carry out automated washes as needed, depending on the water source treated.



Figure 35: Inspection of Heat Exchanger (left), Effect 2 Packing (middle) and Effect 3 Packing (right)

Energy Efficiency: Testing of the 20,000L of evaporator blowdown waters with the 0.3 m³/day pre-demonstration SaltMaker pilot showed that it can operate on medium grade waste heat from SAGD facilities for energy efficiency. The SaltMaker is a thermally driven plant, producing freshwater and highly concentrated discharge or solids via a multiple-effects humidification-dehumidification (HDH)

cycle. Medium grade heat (i.e., 80°C), which is readily available from SAGD plant's glycol loop can be used to evaporate and condense water in successive "effects". The latent heat of condensation is recycled as it is downgraded, with each effect operating at approximately 15°C lower temperature than the previous one. Each effect produces freshwater and successively concentrates the saltwater (as shown in Figure 32 and Figure 34).

The data in Figure 36 shows that the pre-demonstration SaltMaker pilot operated on a heat source of 80°C. The temperature profiles from each effect (2 and 3) show cascading and recycling of the latent heat of condensation in two effects through to a final rejection temperature of 43°C, emulating the glycol cooling loop temperatures common in SAGD operations.

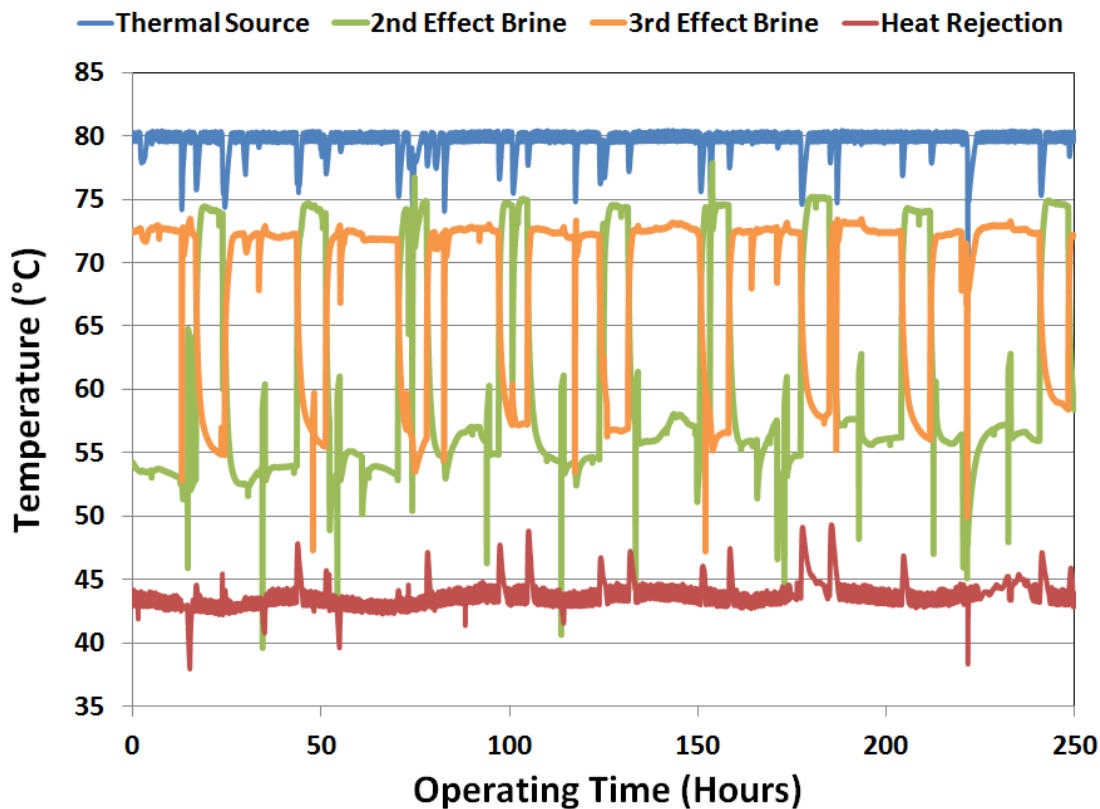


Figure 36: Pre-Demonstration SaltMaker Pilot Multiple Effect Recycling of Heat

Freshwater Quality & Saturated Brine: The pre-demonstration SaltMaker pilot demonstrated the production of freshwater that could be reused in the SAGD plant and a highly concentrated brine. In addition to the 24-7 monitoring via DAQ and daily manual checks, periodic water samples were extracted and sent to a third party lab for analysis. This data is included in Table 4. The table shows the as received raw water quality and the SaltMaker freshwater and brine. As shown by the data:

- The quality of the freshwater was 73 mg/L TDS. There was some TOC present (292 mg/L), likely light organics/hydrocarbons that were blown over into the condensed water.
- The brine was concentrated to 547,000 mg/L TDS (concentrated 5.5 times)

Table 4. Detailed Analytical of SaltMaker Freshwater and Brine

Parameter (mg/L)	Raw Evaporator Blowdown	SaltMaker Brine	SaltMaker Freshwater
pH	9.5 - 11.5	9.23	7.44
Total Dissolved Solids	90,000 - 300,000	413,000	55.6
Total Suspended Solids	50 - 30,000	2,152	<2
Total Hardness (as CaCO ₃)	35 - 1,500	3,960	1.00
Total Organic Carbon	15,000 - 50,000	60,500	133
Alkalinity	25,000 - 70,000	81,400	43.0
Calcium	10 - 400	1,580	0.313
Chloride	5,000 - 150,000	137,000	11.9
Magnesium	1 - 5	3.70	<0.05
Silica (Reactive)	100 - 25,000	379	0.317
Sodium	15,000 - 150,000	140,000	12.5
Sulfate	500 - 15,000	2,490	2.57

Solids Production and Extraction: The 0.3 m³/day pre-demonstration SaltMaker pilot reliably produced and extracted solids for the evaporator blowdown water provided by both industry partners. The solids for both test runs were very similar to each other, brown to dark brown with a sticky consistency, almost similar to a mixture of fine salt and tar resembling a sticky “putty” (Figure 46).



Figure 37: SaltMaker Extracted Solids - "Tar Like" and Sticky

The testing also included characterization of the extracted solids for suitability of disposal at a Class II non-hazardous landfill. The parameters analyzed were leachable BTEX, leachable metals, pH, flash point, and no free liquids (paint filter test). The results from the analytical testing showed that the SaltMaker extracted solids met all the applicable regulatory requirements for disposal at a Class II Landfill.

10 m³/day Pre-Demonstration Pilot Testing Results

The 10 m³/day pre-demonstration pilot was tested with SAGD fluids reconstituted by diluting the highly saturated brines and solids produced by the 0.3 m³/day pre-demonstration pilot. Exemplar test data is provided in Figure 38 and Figure 39.

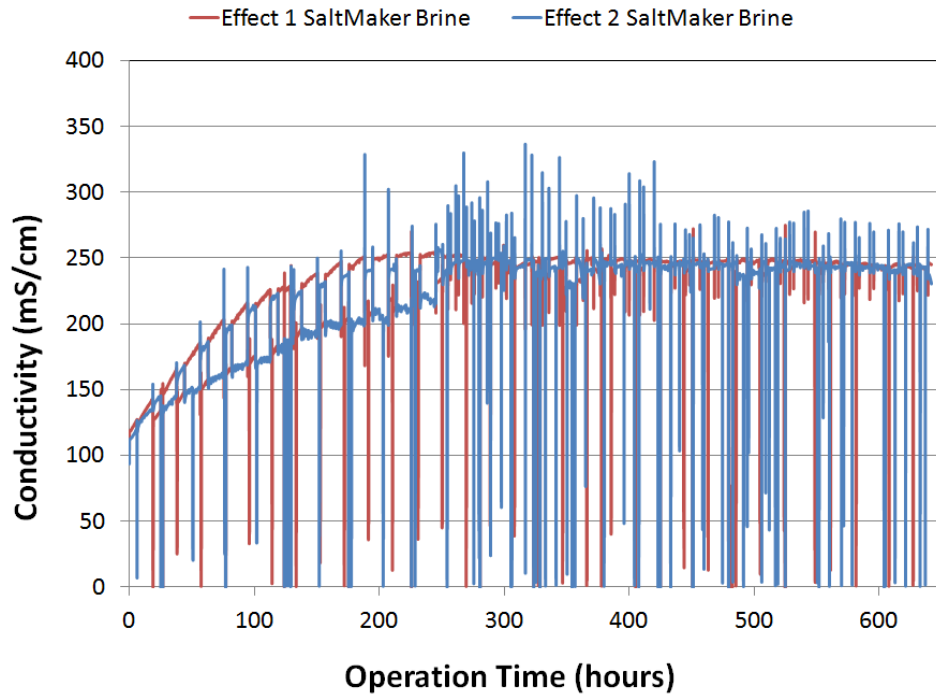


Figure 38: 10 m³/day SaltMaker Results - Brine

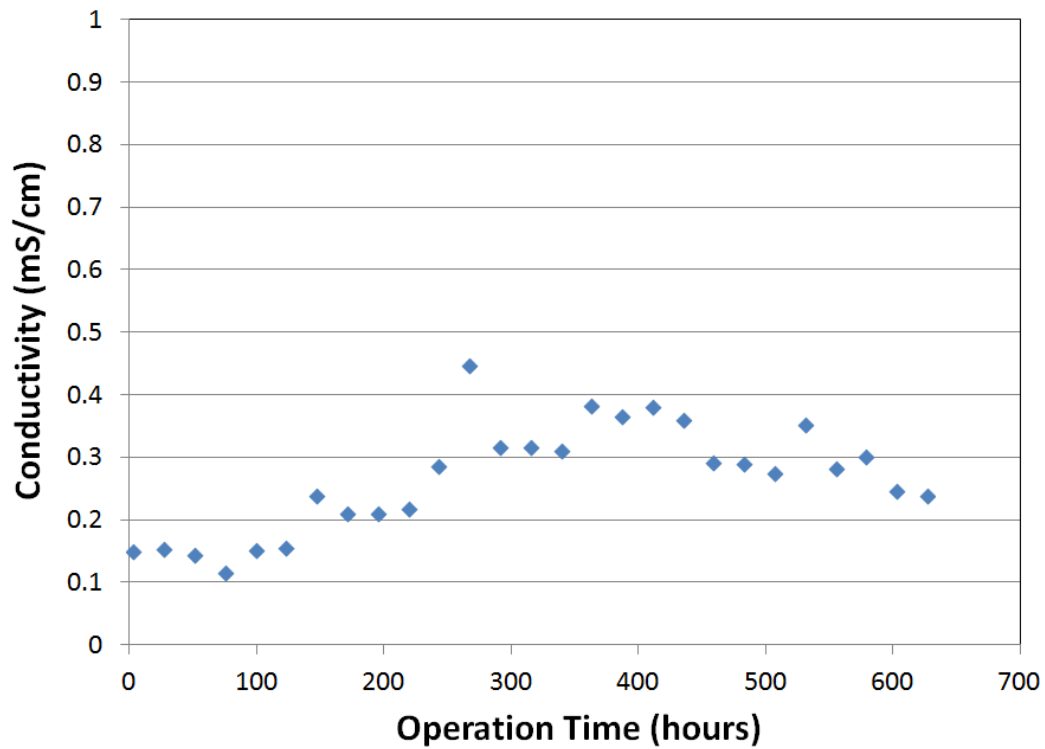


Figure 39: 10 m³/day SaltMaker Results - Freshwater

5. GREENHOUSE GAS & NON-GHG IMPACTS

6.1 Qualitative Discussion about GHG Benefits

The CCEMC project proved successful in confirming Saltworks' estimated GHG benefits from the SaltMaker. The pilot used electrically heated hot freshwater at 65-80°C as the thermal source. This was to simulate use of waste glycol heat on site. As such, the electricity required for piloting at Saltworks' facility was higher than a field plant. However, the actual energy demand (assuming waste heat used for the 80°C thermal source) was ~8 kWh_e/m³ (compared to 41kWh_e/m³ for evaporator-crystallizer systems); representing a potential 81% reduction in GHG emissions. If trucking and deep well disposal is used, diesel fuel is saved in amounts proportional to trucking distances. Deep well disposal is becoming more costly and challenging, in addition to not returning the water for re-use. For analysis purposes, GHG benefits are based on a reduced electrical power comparison to a crystallizer. Trucking distances vary widely and the future availability of deep wells is questionable; they are already tapering off due to regulatory or geological limits.

While the initial market is the replacement of crystallizers, future growth and market penetration involves the replacement of evaporators; an expensive and energy inefficient incumbent technology. The differential in electrical energy usage could deliver projected cumulative GHG reductions in Alberta of 555 kilotonnes CO₂e while saving \$945M in total cost of ownership through 2027.

6.2 Quantification of Expected Annual GHG Benefits

The pilot testing program confirmed GHG benefit estimates. These benefits are calculated on an annual basis until 2027 (10 years after planned commercialization date as a result of this project) and shown in Figure 49, below, and Table 7.

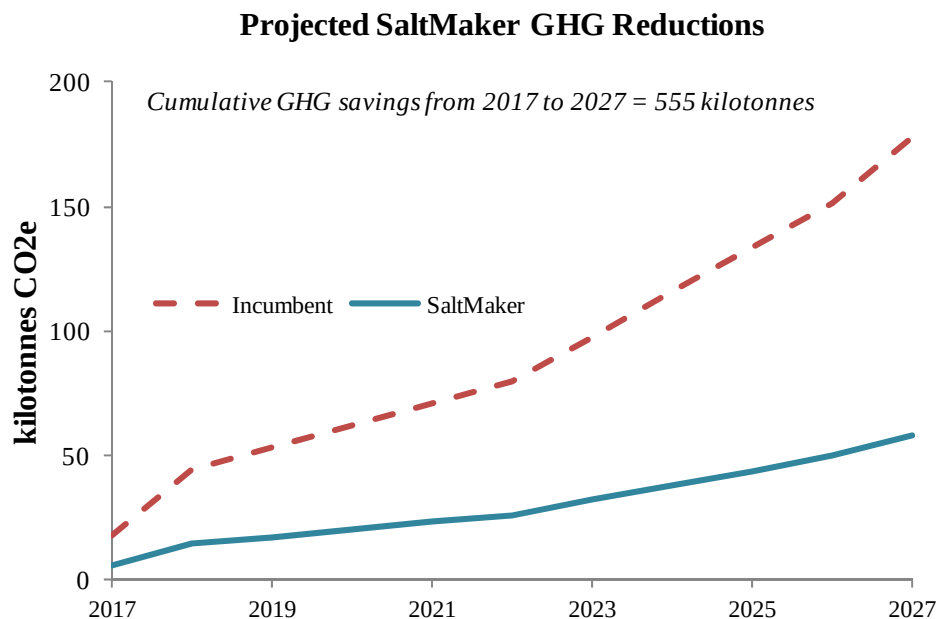


Figure 40: SaltMaker Projected GHG Benefits

Table 5. Projected SaltMaker GHG Benefits in Alberta

Table 5: Projected Saltmaker GHG benefits in Alberta				
Alberta GHG reduction estimates				
Oil sands cumulative production 2012-2030 (bbl/day) ¹		SAGD: 2.5M / surface mining: 0.9M		
Average production capacity added per year (bbl/day) ²		SAGD: 138,889 / surface mining: 50,000		
GHG tonnes (per MWhe) ³		0.65		
SAGD: 1 bbl of bitumen produced generates: 3 bbl produced water; 0.33 bbl blowdown; and requires 0.67 bbl basal aquifer make-up water. Surface mining: 1 bbl of bitumen produced requires treatment of 0.67 bbl basal aquifer water encountered in mine depressurization. ⁴				
Technology	Evaporator	Evaporator-crystallizer-dryer		SaltMaker
Energy consumption normalized to freshwater output (kWh_e/m ³) ⁴	22	41		8
Total cost normalized to freshwater output (\$/m ³) ⁴	\$20.00	\$47.00		\$7.00
Annual GHG reductions for typical 30,000 bbl/day SAGD / surface mining facility				
Application	Technology	Energy consumption (GWh_e / yr)	GHG emissions (kT CO ₂ e / yr)	Cost of Ownership (CapEx & OpEx)
SAGD produced water	Evaporator	86.2	56.0	\$ 78.3 M
	SaltMaker	31.3	20.3	\$ 19.6 M
	<i>Savings</i>	<i>54.8</i>	<i>35.7</i>	<i>\$ 58.8 M</i>
SAGD blowdown	Evap-crystallizer-dryer	22.6	14.7	\$ 25.9 M
	SaltMaker	4.4	2.9	\$ 3.9 M
	<i>Savings</i>	<i>18.2</i>	<i>11.8</i>	<i>\$ 22.1 M</i>
Overall Alberta market (2017-2027)				SaltMaker
Estimated Saltworks Alberta SAGD market penetration by 2027				50%
Cumulative GHG reduction (kT CO ₂ e)				555
Cumulative Total Cost of Ownership savings				\$ 945 M
Cumulative GHG equivalent carbon credit savings @ \$15/tonne				\$ 8.3 M
Cumulative GHG equivalent carbon credit savings @ \$40/tonne				\$ 22.2 M
1: “Crude Oil Forecast, Markets & Transportation”, Canadian Association of Petroleum Producers, June 2013				
2: Linear addressable market growth				
3: Marginal grid emission factor (Alberta Environment, 2011)				
4: From data provided by industry partners				

In addition to the benefits to Alberta, as listed in Table 7 above, the SaltMaker technology can be applied worldwide to a variety of industries such as oil & gas produced water, brackish municipal water, refining, mineral mining and smelting, chemical processing, and food & beverage. The SaltMaker can reduce GHG emissions, water use, and wastewater across these industries worldwide.

6.3 Discussion about Non-GHG Benefits

The SaltMaker improves reliability of crystallizers through the use of a low temperature solids production and extraction process, engineered plastics, non-boiling heat transfer, and automated self-cleaning systems. This reliability has been proven through the CCEMC project. The increased reliability will improve the reliability of SAGD oil sands production and increase operator safety.

The SaltMaker uses two waste sources (wastewater and waste heat) to produce freshwater for reuse throughout operations. This will decrease the water demand of the oil and gas industry. In addition, utilizing the water produced from the SaltMaker will decrease production costs for oil and gas operators. An outline of additional SaltMaker benefits is shown in the table below.

Table 6. SaltMaker Additional Benefits

Benefit	SaltMaker Operation
Reduction of environmental footprint and reduce land disturbances	The main objective of the SaltMaker is low cost, low energy, waste minimization and water recycling. Currently, waste is trucked off-site and injected into deep wells or energy intensive incumbent technologies are used. The SaltMaker replaces these practices, employing the waste heat available at every SAGD site.
Improved reliability and safety of O&G water treatment	The SaltMaker improves reliability of crystallizers through the use of a low temperature solids production and extraction process, engineered plastics, non-boiling heat transfer, and automated self-cleaning systems.
Reduce water use / increase water recycling	The SaltMaker produces freshwater from a wastewater previously disposed. The freshwater can be reused throughout on-site operations.
Improved operational efficiency of O&G production	The SaltMaker replaces more expensive and unreliable conventional crystallizers. It may one day also replace evaporators. With increased water recycle, SAGD operators can maximize steam production and therefore oil production. They can also remove a key and expensive bottleneck: liquid waste disposal.

6. OVERALL CONCLUSIONS

The project was successful in meeting its objective of confirming performance and economics of a low cost, low energy, waste-heat-driven water treatment technology – the “SaltMaker” – for treating Steam Assisted Gravity Drainage (SAGD) blowdown wastewaters to produce freshwater and solids. A total of four plants ranging from prototypes to pilots were developed, refined and tested. The combination of test results from a final and refined 0.3 m³/day pre-demonstration pilot plant that operated for over six months continuously, combined with results from a 10 m³/day pre-demonstration pilot plant consisting of commercial scale modules operated on seawater formed the basis for the economic analysis. The economic analysis was submitted to partner SAGD operators and accepted as evidenced by their continued support and on-site piloting. The economic analysis is confidential due to pricing and competitive matters. Readers may contact Saltworks directly for consideration of an economics section from the SAGD operator report. The plants ran reliably, without any safety or environmental incidents. Freshwater and solids were continuously produced and extracted using an 80°C thermal source similar to that available in SAGD sites. The solids were tested and confirmed safe for permanent disposal at a Class II (non-hazardous) landfill.

7. SCIENTIFIC ACHEIVEMENTS

The project helped the SaltMaker's marketing and awareness in the water treatment industry. Vicki Lightbown, project specialist at Alberta Innovates-Energy and Environment, highlighted the SAGD SaltMaker system in a paper, *"New SAGD Technologies Show Promise of Reducing Environmental Impact of Oil Sand Production."*

Saltworks and the SaltMaker were also featured in a recent Canadian Association of Petroleum Producers (CAPP) commercial, which showcased the CCEMC supported technology.

8. COMMUNICATION PLAN

Sample oil and gas conferences Saltworks is interested in attending and presenting the project results in 2015 are listed below.

- COSIA Water Conference
- Offshore Technology Conference
- International Desalination Association (IDA) Oil and Gas

The project has also formed the foundation of Saltworks' SAGD case study. This case study will be posted on Saltworks' website, distributed at conferences and workshops worldwide, and help form Saltworks' marketing material. The case study will outline non-confidential results, findings, economics, and detailed lab analytics from Saltworks' successful SAGD pilot project. The work will also be disseminated at landfill, mining, and shale oil & gas related conferences.

9. ACKNOWLEDGMENTS

Saltworks Technologies Inc. acknowledges and thanks Climate Change and Emissions Management (CCEMC) for their support on this project and Natural Resources Canada, Sustainable Development Technology Canada, and Industrial Research Assistance Program for their support on other projects related to the background technology.

Recipient Organization

Saltworks Technologies Inc.

Title

Low severity ZLD using OTSG water

GHG Emission Reductions (ERs): 2011–2050

2011	0
2012	0
2013	0
2014	0
2015	0
2016	0
2017	6
2018	0
2019	0
2020	0
2021	0
2022	0
2023	0
2024	0
2025	0
2026	0
2027	0
2028	0
2029	0
2030	0
2031	0
2032	0
2033	0
2034	0
2035	0
2036	0
2037	0
2038	0
2039	0
2040	0
2041	0
2042	0
2043	0
2044	0
2045	0
2046	0
2047	0
2048	0
2049	0
2050	0

Please Refer to ERA's Website For the Quantification Methodologies
<https://www.eralberta.ca/calculating-ghg-emissions-reduction/>