FWT Field Pilot Unit (FPU): Design, Build, Trial
Alberta Innovates 2398-1

Public Final Report
Submitted on December 31st, 2019

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FORWARD WATER TECHNOLOGIES

1. PROJECT PARTNERS

The lead consortium partner was Terrapure Environmental. They provided a site suitable for waste water handling. Terrapure also provided general labor and some mechanical services for FWT as an in-kind contribution. They have concluded that $141,000 of in-kind was provided to support the project.

A. EXECUTIVE SUMMARY

An NMe_3/CO_2 forward osmosis (FO) membrane brine concentrator commercial scale pilot (plate capacity of 15000 L/d_{feed}) was tested in the desalination of waste waters from oil and gas production activities. Pretreatment was limited to basic 5 micron particle bag filtration. The salinity concentration of the wastewater where stable operation occurred was doubled from 3660 to 7890 ppm total dissolved solids (TDS) which corresponded to a 55% volume reduction in single pass mode. However, tracking specific ions such as chloride, which is less likely to form a precipitating salt complex, indicated a > 70% volume reduction. Average pilot performance characteristics at a steady state performance for 4 h are as follows: water flux of 3.6 L/m^2h at 10^oC (when adjusted for temperature dependence is equivalent to 11.1 L/m^2h) and Outlet Water Stream (OWS) quality of < 300 mg/L total dissolved salts (TDS). The thermal energy required by the forward osmosis (FO) pilot was on average 139 kWh_{th}/m^3_{OWS} and for periods where OWS flow was maintained and low conductivity values were recorded, the power requirement reached values of 74 kWh_{th}/m^3_{OWS}, which is substantially lower than reported comparative thermolytic draw FO technologies of 180 to 275 kWh_{th}/m^3_{OWS} and notably lower than processes that involve direct evaporation where thermal energy inputs can exceed 600 kWh_{th}/m^3.

The strong impact of temperature on membrane flux rates was unexpected and not previously observed. This can be overcome by warming feed solutions or by adding additional membrane surface area as required. Although the tested wastewaters were sourced from oil and gas operations in Alberta, more challenging waste streams and longer-term operational studies are required for continued evaluation.

B. LIST OF TABLES AND FIGURES

C. INTRODUCTION

The extensive use of water in energy recovery operations remains essential. For example, relying on hydraulic fracturing to stimulate production of oil and natural gas from shale formations leads to a tremendous demand on fresh water resources. As much as 7,000 to 30,000 m^3 of water can be required per well during the development and stimulation phase, which is often taken from ground or surface water sources. Subsequently, the stimulation of the well results in the production of large volumes of high salinity frac-flowback and co-produced water (the mixture of both streams referred to subsequently as "produced water"). Global oil and gas produced water volumes have decreased per barrel of oil over the last decade as efficiencies have been improved; however, the increase in overall hydrocarbon yield per well has led to an increase in the total amount of water used. Furthermore, the chemicals added to the frac fluids to enable higher production, along with the salinity of the produced water stream, cause concern about the impacts of hydraulic fracturing activities on water resources in the environment. Methods of managing these produced water streams include disposal through wastewater treatment facilities into fresh water streams, deep well injection, reuse with dilution in hydraulic fracturing operations, and desalination. Desalination may be required for beneficial use of the produced water for further extraction processes or to enable surface discharge. As the concentration of these streams is typically between 70,000 and 250,000 mg/L total dissolved solids (TDS), only evaporative desalination technologies are typically capable of treating these streams to the lower salinity levels required for surface discharge. Commercially available evaporation technologies include mechanical vapor compression ("MVC", sometimes also referred to as mechanical vapor recompression, or "MVR") evaporators, as well as open cycle evaporation techniques that evaporate water to the air rather than producing a fresh water stream. An additional proposed evaporation technique is membrane distillation, however challenges in the stability of this process have made wide scale adoption difficult. Commercially available evaporative desalination technologies have been perceived as having prohibitive cost and complexity by the oil and gas industry, delaying or preventing their use.

Alternatively, the use of membrane processes could be considered as an approach to overcome the thermal inputs required by evaporative methods. The most well-established process, reverse osmosis (RO) has severe limitations for these applications. Reverse osmosis typically relies on applied pressure to push feed water through a membrane that selectively rejects dissolved ions, which rapidly demands high driving pressure as the TDS moves to 3-4% wt. Moreover, due the increasing pressure needs, high equipment design, and energy inputs, the RO process is impractical above 5-7% wt TDS and not suited for the applications under consideration here. One other proposed method for reducing the cost of desalination is the use of an osmotically driven membrane process known as forward osmosis (FO). In this process, a solution consisting of specially selected solutes (often called the "draw solution") is used to provide a solution with a lower chemical potential energy of water than the feed stream to be treated. Forward Water Technology's process uses a revolutionary "two-phase" draw solute, trimethylammonium bicarbonate, that functions as a switchable or changeable additive in FO. The switchable property derives from its ability to shift between its salt form and two volatile gases – trimethylamine (TMA) and carbon dioxide as shown in Figure 1 below. FWT's process relies on three straightforward unit operations (refer to Figure 2): 1) forward osmosis, 2) draw solute removal and 3) draw solution regeneration. Once FO is complete the draw solute is switched into the two gases via the use of heat and either reduced pressure and/or a sweep gas, leaving behind fresh water.

$$[Me_3NH][HCO_3] \rightleftharpoons Me_3N_{(g)} + CO_{2(g)} + H_2O$$

Figure 1. "Switchable" formation and decomposition of trimethylammonium bicarbonate. The salt formed on the left side of the equation acts as the forward osmosis draw solute

A semi-permeable membrane is used to employ this difference in potential energy (manifested by an osmotic pressure gradient) to spontaneously dewater the feed stream by means of water permeation through the semi-permeable membrane, into the draw solution, which becomes dilute. A secondary process is then used to re-concentrate the draw solution, producing water with substantially less TDS

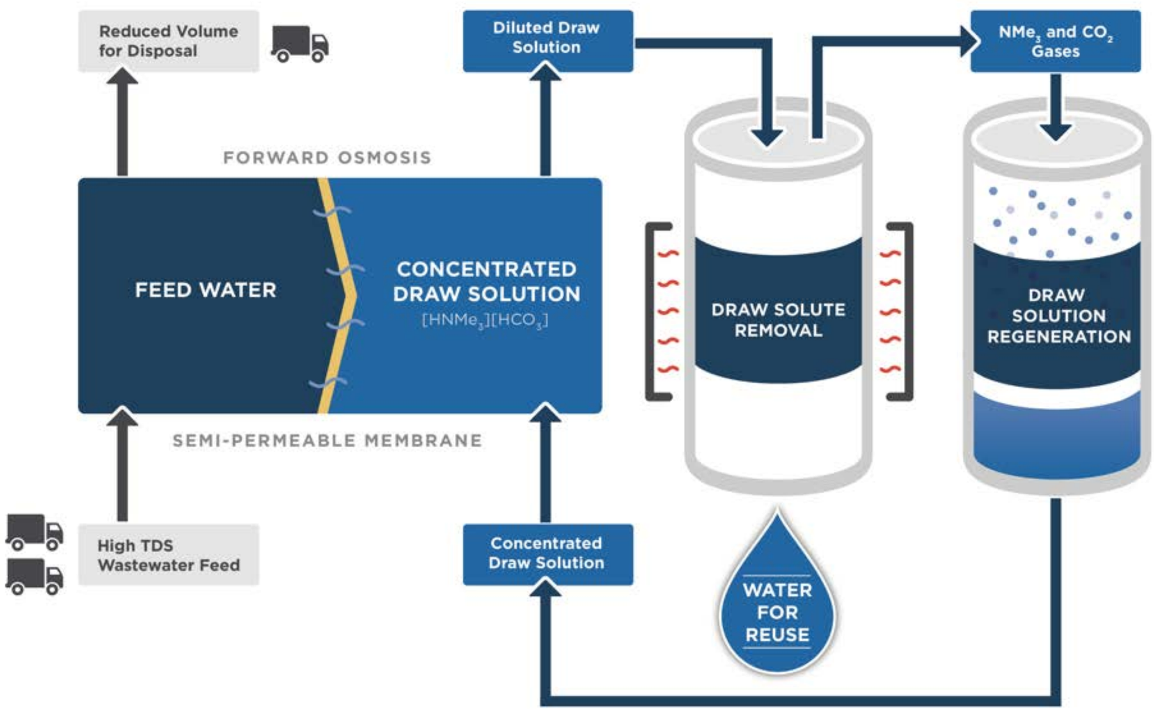

Figure 2. High level FWT process flow diagram.

compared to the feed. The energy or fuel resource requirements of the secondary process may be less than those of conventional alternatives such as reverse osmosis (RO) or evaporation, and fouling and scaling phenomena in the FO membrane system may be substantially reduced. The primary objective of this study was to experimentally investigate the scalability of performance of an NMe_3/CO_2 FO desalination process and its ability to treat or desalinate wastewater feeds from the industrial production of extracted hydrocarbons. Previous estimates of the energy required for the separation and re-concentration of the NMe_3/CO_2 draw solution were based only on modeling, along with several methods for thermal integration and smaller scale engineering demonstrations. Here, we report experimental findings from the testing of a fully integrated, steady state NMe_3/CO_2 FO process. For this study, a frame work mounted pilot comprising the FO membrane system, draw solution recycling system, heating subsystems consisting of a sump mounted stab-in electrical heater, chiller, instruments, and automated controls (designed and fabricated in conjunction with Zeton Engineering) was delivered to the field pilot location in Airdrie, Alberta. The feedwater treated by the pilot system was water from refinery operations (water 1) and a produced water sourced (water 2) by Terrapure Environmental (TE).[1] Importantly TE is an aligned partner for FWT in that they have a robust business across Canada with over 50 operational sites including 7 Alberta based facilities that are focused on waste recovery, reuse, value creation through recovery, and minimizing overall final waste disposal. TE's direct involvement on this project will allow them to understand how the technology could cooperatively fit into their operations and aid in achieving their own sustainability driven business goals. As a result of their on-going activities TE was able to provide waste water that is commonly produced and has known costs for disposal and thus represents strong commercial possibilities. The requested wastewater was delivered by trucks and selected by TE, without input by FWT or prior treatment. Pilot testing was conducted over a period of six weeks with only daily (8 hr) operation, inclusive of start-up and shut down time.

Key to this installation was determining that the scale up of the process itself was feasible including the large-scale use of trimethylamine, what the eventual operational costs could be expected with full commercial adoption and what capital expenses would be required.

D. PROJECT DESCRIPTION

Technology Description

FWT's continuous process addresses the challenge of difficult to treat wastewater by way of a revolutionary "two-phase" draw solute, trimethylammonium bicarbonate, [TMAH][HCO_3], that functions as a switchable additive in FO. The switchable property derives from its ability to shift between its salt form and two volatile gases – trimethylamine (TMA), a readily available low-cost industrial amine made at commodity scale, and carbon dioxide (CO_2). In applying this material from a process perspective, FWT relies on three straightforward unit operations; 1) forward osmosis, 2) draw solute removal and 3) draw solution regeneration. More specifically, FWT uses the salt form of the draw materials as powerful osmotic agent to create a solution that pulls only water across a membrane from the wastewater feed and into the draw solution. Once FO is complete the draw solute is switched back into two gases (TMA and CO_2) via the use of heat, leaving behind fresh water. The gases are captured and recycled to generate a fresh draw solution and can be cycled repeatedly in a closed loop process. Overall, the process is low energy, has no consumable materials, uses only off the shelf capital equipment, and provides clean water from waste streams otherwise discarded or treated using massive amounts of thermal energy.

[1] Water 1 - Wastewater created from a thermal (steam) water separation from oil in a re-refining process located in North Vancouver; Water 2 - Water collected as produced water from oilfield production well located in Alberta.

The basic structure of this project was to:

1. Establish pilot specifications and design
2. Fabrication of equipment and delivery to trial site
3. Field installation, operational validation, and demonstration

More specifically, the project scope was designed to significantly expand the capabilities of the existing FWT engineering skid (1 m^3/day Micro-pilot Unit) to a commercial scale and extrapolate feasible scale up capacity to 500 m^3/day for the treatment of high TDS wastewater streams. Following the conclusion of this project, a channel partner will be engaged, and Canadian manufacturers will be selected for their suitability to support a full commercial scale approach.

Updates to Project Objectives

FWT required a specific window to operate the trial. For strictly budgetary reasons, operations were planned for late spring to end of summer to avoid sub-zero temperatures. Winterizing equipment or operating indoors was not feasible solely from a cost perspective. Typically, cold weather operations can be achieved for desalination process with off the shelf design considerations. This includes (but is not limited to) the installation of equipment in an enclosed space that can be heated and/or include heat line tracing on all water containing lines and equipment. One specific challenge would be to ensure the membrane process is performed at a minimum temperature of 10^{o}C and preferably above 15^{o}C. To achieve this condition would require heating the feed liquids prior to the membrane process. Overall, this would add to the energy demands of the system but needed heat could be readily calculated. Moreover, needed heat could be provided from the exiting OWS as opposed to being used to preheat the DDS inflow to the stripper. Equipment could be readily designed to have this as a process option for cold weather operations and reverted to the current arrangement for more typical warm weather processing with minimal additional capital needs.

Three major mis-configurations became apparent once the equipment was delivered to site. Piping had been assembled with a sealant not tolerant to the draw solution per design specifications. As many of the threaded joints would be exposed to TMA containing fluid streams, and with the possible risk of TMA leakage being a major concern, all joints along the fluid paths needed to be cleaned and have the qualified sealant applied and then be reassembled and leak tested. Secondly, key heat exchangers along the stripping and absorption pathways were massively undersized and required replacement. This short coming became apparent only after the initiation of a hot water test where the warping of the downstream plastic piping occurred leading to observable failures. Subsequently new heat exchangers needed to be sourced and installed and damaged piping required replacement. Furthermore, pumps installed for two critical operations were not designed for outdoor use and were not in working condition following equipment delivery. The net result was that experimental time was reduced from 3 months to 4-5 weeks. Critical data necessary to meet project objectives was obtained using wastewater supplied by Terrapure, both of which were sourced from on-going oil and gas processing operations. However, additional operational time would've provided more robust data sets to have been collected over the 3 month period and would have also allowed for a frac-based waste (flow back or produced) to be evaluated.

Program Specific & Success Metrics

Metric	Ideal target	Minimum requirement	Achievements to date**
CapEx	$4k/m^3$ capacity	$7k/m^3$ capacity	$10-15k/m^3$ capacity
OpEx	$4/m^3$ feed	$12/m^3$ feed	$15-20/m^3$ feed
Outlet Water Quality	<100 ppm TDS	<4000 ppm TDS	<500 ppm TDS
Treating 1000 m3 at first site (Power Requirements)*	<50 kWh_{th}/m^3 feed	70 kWh_{th}/m^3 feed (60 kWh_{th}, 10 kWh_e)	72 kWh/m^3 feed (60 kWh_{th}, 12 kWh_e)
Continuous Operation	7-10 d @24/hr/d	3 days @ 24 h/day	8 h

Table 1 Original KPI's from project application

**During operation it became apparent that it more valuable to report the energy demand by amount of clean water produced (OWS volume). The means that for an assumed volume reduction of 50% these targets are increased by 2x from these initial goals.*

** Date of initial application to the program funders. It was also anticipated that improvements in these metrics would be recognized through scale up efficiencies, but demonstration of that result was still required.

The above table represents the intended performance targets for the technology. With the elimination of the capital expenditures noted in Section F (below), and assuming first time engineering is viewed as a one-time expense, current major equipment estimates at full scale surpass the minimum requirement target of $7,000 /m^3 of capacity at > 400 m^3 or larger design scale. Moreover, it is projected that the capital expectation will be reduced by as much as 40% relative to the minimum requirement and operational costs will be in the range of the ideal target of Table 1.

E. METHODOLOGY

The project was set in to 3 major parts: set design criteria, fabricate the equipment and install and operate the final equipment using wastewater sourced from industrial operations.

Design Criteria

FWT relied on bench testing analysis and several experimental results from the engineering scale pilot located in Sarnia, Ontario. The effort in the design phase (Task 1 Report) led to the final design requirements.

The table below records general feed and effluent characteristics that were used to as an input to FWT's design criteria. The table includes the Parameter, the Parameter Value, an explanation as to why the parameter was important for design consideration:

Table 2 – Design constraints for final equipment

Parameter	Value / Description	Explanation
Feed Criteria		
Flow (feed)	15 m^3/day	Based early information from Zeton, a flow rate of 15 m^3/day is achievable with FWT's budget
Temperature	20-25 °C	Water processed in lab and pilot has been in temperature controlled facilities, change in feed water temperature vs other process parameters had not been explored
pH	3-10	The FO process pH is limited to the membrane specification. Several experiments have been conducted to demonstrate that a pH between 2 and 10 is functional
TSS	Up to 16,000 ppm	TSS is important for membrane function. While FO membranes are more resilient than RO membranes, TSS loads will impact flux and membrane fouling.
TDS Content as Sodium Chloride	Up to 10%	TDS content impacts the process efficiency and the maximum effective water removal possible by the process
Hardness	Minimal scaling hardness assumed	
Effluent Targets		
Target Volume Reduction	50%	
Target TMA in Effluent	100 ppm as N or; 50 ppm	Ensures that direct sewer discharge (or surface release) will be permissible
Target TMA in Concentrate	100 ppm as N	The target TMA in the concentrated reject stream will be determined during the pilot with the operation of a secondary stripping column.

Figure 3: Engineering skid used for some design parameter setting for field unit

Other considerations for membrane selection, energy requirements, outlet water stream (OWS) quality, brine and draw stripping column design and absorber needs were also considered. Once this was collated into a design package the second phase (Task 2) of the project was initiated.

Equipment Fabrication

FWT considered several vendor options for the fabrication of the final equipment. Ultimately Zeton Engineering was selected as this vendor offered several advantages. Primarily, they offered a fixed price to deliver final equipment and have the in-house capability to make design considerations in parallel to fabrication. This allowed this manufacturer to have quicker timelines than more traditional fabricators and also can make design improvements as they become apparent during construction. The design effort lead to the CAD illustration in Figure 4.

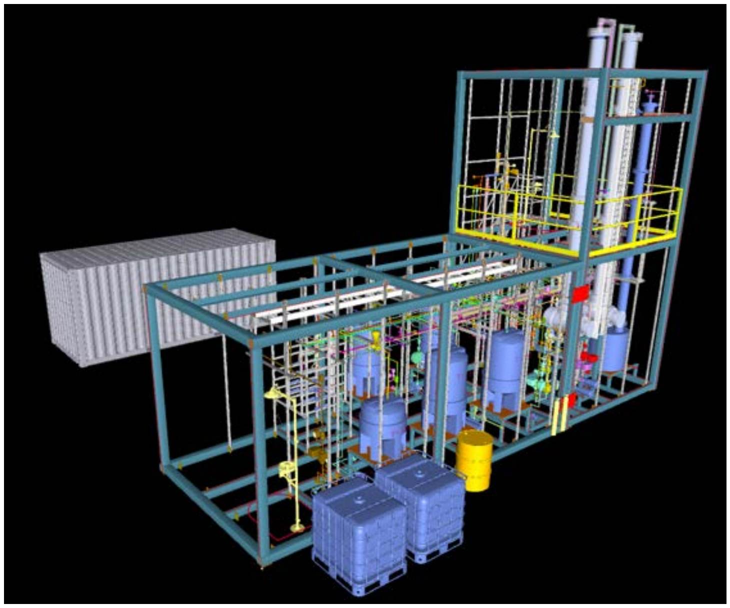

Figure 4 CAD illustration of field unit design as first draft by Zeton Engineering.

Final equipment was completed on schedule and factory acceptance testing (FAT) illustrated that the basic construction was adequate. However, the FAT could only partially confirm operational performance and final commissioning on-site was required. Equipment was loaded and shipped to site in early June 2019, as anticipated.

Commissioning and Operation

Prior to equipment arrival in Airdrie AB, the specific site had been prepared for installation. All rental equipment (rig mats, tankage, electrical supply preparation, etc.) had been completed by the delivery date. Once equipment was in-place and connected, commissioning was initiated on schedule. However, this effort immediately identified two major flaws in construction and one minor issue of consequence. As noted, pipe sealant that was TMA tolerant was not used (as per design requirement) and heat exchangers were of an inappropriate size (under sized). The latter issue was only apparent when hot water was used in commissioning (not possible during FAT) and the undersized heat exchangers enabled hot water (> 90^{o}C) to travel through to the PVC piping leading to deformation of the pipe. These two issues required significant equipment re-work and led to delays and resulted in experimental time being reduced to 4-5 weeks.

Once re-work had been completed and final commissioning demonstrated the equipment was suitable for operation, the work plan was put into place to treat waste water streams sourced by Terrapure. While FWT did not have immediate control over the specific characteristics of the waste, Terrapure selected wastewater streams that would have significant commercial impact if successfully treated.

Figure 5 Final equipment installed in Airdrie AB post commissioning.

F. PROJECT RESULTS

Equipment Design and Capital Expense Projections (CapEx)

FWT provided both the basic design criteria and design input to the fabricator for the first time scale up of the FWT process. In doing so, some conservative assumptions were made – particularly with respect to the chiller capacity and need for a brine stripping process. Had the decision been to reduce or eliminate these processes it may have potentially led to a non-functional pilot and both laboratory experiments and engineering projections (by Zeton and Hatch Engineering as well as FWT) had indicated these unit operations may have been required. A summary of project CapEx cost savings is provided in Table 3. With the elimination of chiller demand and brine stripping, the table below illustrates the current projection of installed capital expense as well as illustrating the deceased costs /m^3 as scale increases. There will be additional opportunities for equipment cost reduction including construction of a repetitive reference design but to date those savings remain speculative.

Scale (volume feed)	Vendor Quote Pre-Pilot (+/- % not included)	Modified Projected CapEx	$/m³ capacity	Comment
15 m^3/d	$1,300,000	$780,000	$52,000	Includes 1st time engineering
50 m^3/d	$2,748,400*	$1,649,040	$32,980	Includes 1st time engineering
> 250 m^3/d	$2,236,691**	$1,324,014	$5,368	Design cost separate

Table 3: Current and projected capital expenses for various scales of treatment capacity *Zeton Engineering; ** HATCH Engineering Phase 1 design proposal at +/- 50% and does not include indirect expenses

Operational Results & Key Results

Previous studies had assessed the specifics of the thermolytic draw processes under evaluation in this study.[2] Their conclusions led to two main observations: Firstly, when evaporation is compared to an ammonium-based draw (as opposed to the TMA used in the FWT process), evaporation is expected to require 6 times the amount of energy under ideal conditions. Secondly, it was reported that TMA would have a 40% energy improvement when compared to ammonia. The ammonia system had been previously commercialized and scaled to at least 50 m^3/d with commercial claims of scaling to > 600 m^3/d in Chinese based jurisdictions. The available peer reviewed studies of the 50 m^3/d performance have reported that NH_3 driven systems consume 275 kWh/m^3_{OWS} but commercial reports claim to be as low as 180 kWh/m^3_{OWS}. The change in energy may be related to the scale that the measurement was obtained at, however the commercially quoted values are difficult to verify. Practical observations of these power requirements had not been proven at any substantial scale for TMA, which was a key focus of this study. Furthermore, while third party modeling of the TMA system had indicated a positive outcome, direct and non-theoretical measurements had not been possible. FWT focused on collecting direct electrical input measurements and simply comparing those to the predicted or anticipated values. This focus allowed FWT to eliminate all assumptions required in theoretical models and provide an actual power demand for the thermolytic TMA based system. Over the 6 key dates of operation where operation was unaffected by extraneous circumstances and including all start-up needs, daily average power needs ranged from 139 to 275 kWh/m^3_{OWS} for the thermal component only (the electrical needs for other equipment such as pumps and valving requirements were negligible). In determining these values, the overall process control was observed to have a large number of variables that were all impactful to the other conditions or operational settings. For example, the flow rate used in one sub-process, such as flow rate of OWS out of the system, would impact the sump temperature of the stripper column as new cooler feed was added to make up for the outflow; this in turn would cool the column temperature and lead to a lower flow rate of OWS. The general observation that the overall process was highly interdependent made establishing

[2] Boo, C.; Khalil, Y.; Elimelech, M.; Performance evaluation of trimethylamine-carbon dioxide thermolytic draw solution for engineered osmosis, J. Membr. Sci., 473 (2015) 302-309

steady state across multiple sub-processes very challenging from a manual control viewpoint. Nonetheless, steady state was achieved and over a course of 4 hours and energy values were maintained at 74 kWh/m^3_{OWS}. This is expected to be the value for long term continuous operation since the higher daily averages included start-up input, requiring all cooled process waters to be reheated upon daily turn-on.

Using the determined steady-state value, together with provincial commercial electrical utilities costs (7.5 to 8.5 ¢/kWh) and daily measured energy averages, the energy cost for operation in Alberta would range from \$5.55 to \$6.29/m^3_{OWS}. Based on this analysis and a small increase for material make-up due to possible loss of TMA, operational costs should fall in to the region of \$8 – 10/m^3_{OWS} if all energy input is supplied as electrical. If thermal sources such as natural gas or waste heat are used, this cost could be reduced to as low are \$5 - 7/m^3_{OWS}. If expressed in the manner of the original proposed targets, which reflect the feed volume and assumed a 50% volume reduction, these values would drop by a factor of 2 (summary provided in Table 4).

	Goal (Feed based Volume)	Goal (OWS based Volume)	Achieved (OWS based Volume)
Thermal Demand/m3	70 kWh	140 kWh*	74 kWh
Operational Cost/m3	\$12	\$24*	\$8 - 10
Capital Cost/m3	\$7,000	\$7,000	\$5,000 - \$6,000

Table 4 : Summary of project KPI goals and outcome.

**Base case used to develop original targets assumed a 50% volume reduction. Thus, for every 2 m^3 of feed, 1 m^3 of OWS would be require thermal stripping.*

Although positive, these outcomes are only valid if the OWS water quality is high and the reduction in fugitive TMA can be shown. Analysis of the various water streams showed that OWS can reach very low concentrations of TDS (Table 5 lower chart). The OWS tested in Trial 1 was of reasonable quality and would be suitable for industrial re-use. Of note and as seen in Table 5, was that the Water 1 brine concentration did not increase, indicating that waste concentration did not occur. This is believed to be associated with sampling time interval since flux values during the run were consistent with Water 2 and were typically 3-4 L/m_2h at the colder temperatures. Given the reduction in observed in the OWS COD level, FWT has assumed the reported Brine Concentrate TDS is in error for Water 1.

Concentrations of total (kjeldah) nitrogen in the brine concentrate and feed water were determined to assess the amount of TMA lost from the system. Important to note is that estimating the expected TKN value in the brine concentrate requires an accurate determination of the concentration factor. Ions where complete rejection can be ascertained served as markers for concentration factors. Thus where the OWS is near or at detection limits for select ions (Ca, Mg, As, Fe, Mg, Se) and thus void in the OWS, concentration analysis can be used to estimate actual concentration factors of the resultant brine concentrate when compared to the same ions in the feed. From this approach, the average concentration factor is 3.75 (approximately a >70% volume reduction) and led to the projection of approximately 4500 ppm TKN nitrogen to be in the brine concentrate compared to the reported value of 3700. This suggests that for Water 1 there was no significant loss of TMA into the brine due to reverse salt flux. Importantly, the TDS measurements in which the entire TDS content is calculated using conductivity, as opposed to gravimetric analysis, made the complete ion content very difficult assess. Therefore, the reported TDS values are an inaccurate indicator of concentration factor estimates. The low residual nitrogen in the OWS and absence in the brine above the concentration factor increase indicate very little TMA has exited the system. This is also seen in Water 1 although the TDS change reflects the non-ideal steady state results.

Water 1	Feed (mg/L)	OWS (mg/L)	Brine Concentrate (mg/L)
TDS	7336	2422	6944
COD	273000	22000	297000
TKN*	Not detected	Not detected	Not detected

Water 2	Feed (mg/L)	OWS (mg/L)	Brine Concentrate (mg/L)
TDS	3660	162	7980
COD	133000	18400	263000
TKN	1200	0.89	3700
Total Hardness	103.8	<7	474.8
Arsenic	0.009	<0.004	0.037
Boron	114	13.8	275
Iron	9.03	<0.12	27.8
Manganese	0.348	<0.02	1.11
Selenium	0.0152	0.0083	0.0576

Table 5 Summary of OWS Quality a) Water 1 – Refinery Water and b) Water 2 – Process Water. *Detection limit for TKN was 0.9 mg/L

Water 2 results indicate that very clean OWS can be produced. The results in terms of clearing Chemical Oxygen Demand testing (COD) were an unintended benefit and was not expected. While there were light hydrocarbons in the OWS, over 90% and 85% of the COD was cleared by the FO process making the OWS easily polished using simple carbon bed skids.

G. KEY LEARNINGS

As FWT approached the initial design for the plant two perspectives were taken. The operational success of the final design needed to be high confidence. That is, the plant had to operate in a manner that the process was competed, and clean water production was achieved. Secondly, as FWT had studied the designs of competitors, in particular that of Oasys Water, similar unit operations were included to ensure process success. FWT uncovered that several of the capital components can be eliminated as they are not required for the specific draw FWT is relying on. These sub-systems differences are;

1. Waste brine stripping not required
2. Absorber column size reduction
3. Chiller size reduction (or elimination)
4. Outlet water polishing not required

In operating the FWT FPU it became apparent that because of the membranes used and due to the nature of using TMA, a significant portion of the capital equipment was not required for successful operations. Specifically, there was minimal fugitive TMA as reverse salt flux (RSF) had been eliminated through the use of Aquaporin ***Inside***™ membranes. FWT had originally anticipated that there would be a loss of TMA from the membrane process and that TMA would cross the membrane boundary into the concentrating waste water brine. Laboratory work indicated that this could be at a high enough level that recovering that lost material would need completed or operational costs would be problematic. As such, a brine stripper system was included in the FPU design and was a "conventional" feature of the Oasys Water design. The fact that no significant RSF (almost nil) was observed means that this entire process path can be eliminated in future. This includes 2 pumps, a full-size column, heating capacity and all supporting tubing and piping will not be included in future designs. FWT anticipates this change alone will be at least a 20% reduction in major equipment costs.

Another impactful capital change is the reduction of size and design for the absorber. Substituting a correctly sized heat exchanger for cooling the stripped TMA and CO_2 gases allows for a much smaller absorber column to be used, which also provides an option for reduced capital. Furthermore, the heat exchanger was so effective that the cooling demand originally planned for is also not required and the chiller can be reduced or eliminated and replaced with ground water sourced cooling. Together, FWT is estimating that capital costs can be reduced by as much as 40% or more. The near elimination of TMA make-up, nil requirement for brine stripping, and the reduction of the cooling demand leads to reduced operational expenses. As such, these learnings both positively affect the target KPI's of the original project goals.

Differences between the OASYS design and the proposed FWT system design is illustrated in Figures 6 and 7, where the re-treatment of both OWS and brine in the OASYS design creates a considerably more complex flow path.

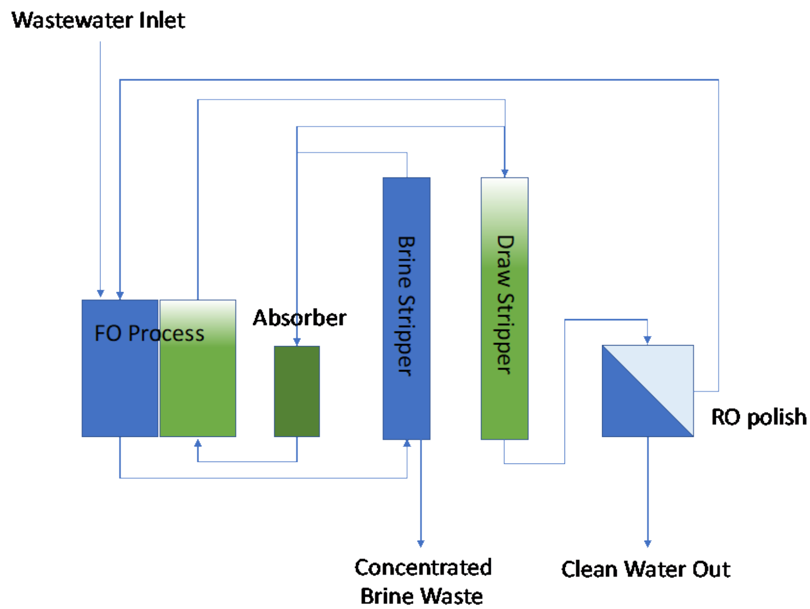

Figure 6. Process flow required by OASYS Water as a result of fugitive draw materials (NH_3)

Areas in the process design identified as requiring further engineering improvements were related to the dilute draw stripper column and sump design. Specifically, sump layout/sizing and improved column temperature control need to be re-considered. In term of sump design, the stab-in heater element was located in the upper section of the reservoir. As these heater elements must always remain submerged, this required maintaining a sump level of > 80% and even minor changes in water out flow from the sump

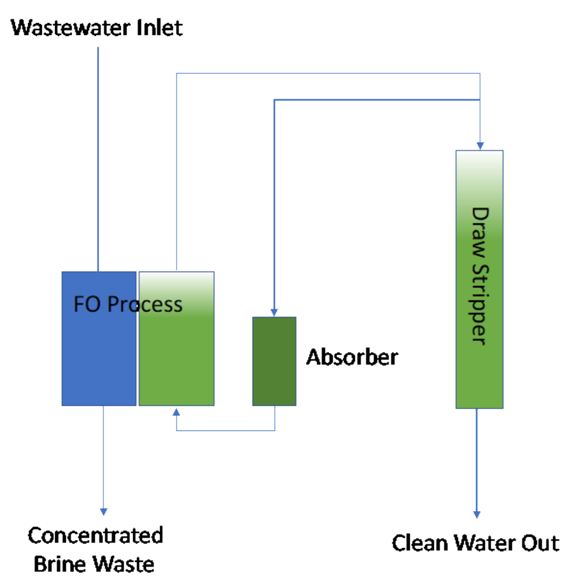

Figure 7. Process flow required by Forward Water. Several unit operations have been eliminated by comparison to Figure 6. This is a direct result of observations that very little or no TMA draw materials

crossed the membrane and that the stripping operation can generate exceptionally clean water. See Table 5.

would lead to automatic heater shut down. This required immediate require user intervention and often led to a sudden cooling spike within the column disrupting steady state operations. The column itself would also benefit from further temperature control, especially with the addition of a rectifier sections at the highest point in the column. This would allow all water to be removed from the gaseous outlet (only emitting CO_2 and TMA) and the evolving gases would be cooler as they then enter the absorber system.

During operation, it became apparent that the design improvements could draw on CO_2 scrubbing processes that rely on widely available high molecular weight amines. In future, FWT will seek engineering design groups with this type of experience.

Significant learning also came from issues around the membrane process. One learning was that the membrane materials are robust in terms of contamination of the feed streams. Although each feed was pretreated with a simple 5-micron sock filter step, no other pretreatment steps were taken. In running the feeds as otherwise received, in addition to the main task of desalination, the Aquaporin materials were also capable of rejecting high COD loadings. In one case, over 90% of the COD load was rejected even though the feed began with over 200,000 ppm COD. This is an encouraging result but also underscores the advantage of forward osmosis, which is known to have fewer fouling issues compared to other membrane processes such as reverse osmosis.

One identified performance issue was the impact of temperature on flux rate. The membrane process is significantly less effective at fluid temperatures under 15^{o}C and was evidenced by a reduced flux. FWT will need to be cautious on how to deploy these products in colder regions. Warming the feed materials or using the exchanged heat from the dilute draw stripping column outlet prior to the membrane step could resolve the issue. Other alternatives that allow for more accessible membrane surface area would also alleviate the problem as would feed recirculation.

H. OUTCOMES AND IMPACTS

Project Outcomes and Impacts

The broadly successful outcome of the demonstration shows that the proprietary technology can be successfully scaled and meets the needed criterion for commercialization in terms of cost and quality. This was held in doubt by the water treatment industry which is often skeptical about radical new technological approaches.

Clean Energy Metrics

Nature Bank initially completed a life cycle analysis at the onset of the project and confirmed the assumptions that FWT had originally advanced. The net result was that if FWT entered the market in western Canadian oil and gas provided the advantages it forecasted, over 12kT/yr of CO_2 could be eliminated from current practices and up to 45M m^3 of wastewater could be returned for re-use or other purposes. For this field trial, FWT needed to ensure that the energy inputs into the system met the expectations of this study. As described below the overall energy demand has been met, the clean water metrics have been achieved so the impact of the technology is valid if it enters the market as assumed.

It was Forward Water's understanding that the conclusions of the initial report relied on several factors related to calculating the overall carbon footprint with one essential being related to power demands. Given that FWT has shown the power requirements are a fraction of that originally proposed, capital needs have been reduced, and that draw chemical make-up is now known to be minimal, there is a fair expectation that the anticipated GHG impact will be improved.

Program Specific Metrics

The values in Table 4 indicate that for the proposed KPI's that the project was successful in meeting those targets. The originally formulated KPI's were developed from the perspective of other types water treatment technologies that meet the commercial needs or have been demonstrated in the field. This allowed FWT to compare its results in a "as good as" manner. With the results exceeding those original KPI's, FWT is in an excellent position to make high confidence statements about commercial outcomes.

I. BENEFITS

Economic

The major outcome of the project was to demonstrate feasible scalability of the process both from an operational and cost perspective. This was accomplished as KPI metrics were met or exceeded. Post project undertakings will include communication to stake holders and commercial roll out activities such as trade conference presentations. Any commercial traction will lead to the increasing in direct FWT support hires. With the potential to address wastewater issue in western Canadian oil and gas production the potential to open an Alberta based office or partner with an Alberta based distributor will be considered.

Environmental

As water handling and re-use regulations expand, FWT will provide end users or services companies with the potential to meet those tightening regulatory requirements. The demonstration of the scalability of the technology and the conclusion that less overall energy is required will allow Forward water to exceed the GHG and water savings projections originally established at the on-set of this work. Those original projections are included below for reference.

Projected water annual savings by 2025 from roll-out estimates in Canada only;

Projected 2025 Installed Base*	50 m3/day	500 m3/day
In Service Units	13	14
Unit Utlization	75%	75%
Total Annual Water Savings (m3)	266,903	958,125
Grand Total m3/yr in 2025		1,225,028

Total annual impact on GHG reductions by 2025 from roll out estimates in Canada only;

Projected 2025 Installed Base*	50 m3/day	500 m3/day	2025 Annual Total
In Service Units	13	14	
Unit Utlization	75%	75%	
Total Annual Diesel Reduction (L)	314,236	3,384,098	3,698,334
Total Annual GHG Reduction (kT)	0.78	12.11	12.89

Social

As with meeting tightening water regulatory demands for water re-use, the social partnerships that manufacturing and other industrial activities have with their communities would be improved through a better waste water treatment option. This includes the reduction in transportation leading to reduced overall mileage and hence reduce the number of traffic related accidents and injuries.

Building Innovation Capacity

With the aid of Alberta Innovates, FWT is seeking a suitable partner for advancing the pilot plant even further which includes process optimization via items such as column design as well as miniaturization of the current foot print, weatherization, and containerization leading to a commercial reference design. In making these considerations FWT has approached both NAIT and SAIT to understand if there can be a mutual benefit. Organizations such as COSIA would also be considered. If these partnerships can be established, then the spin off benefits such as training of HQP would occur.

J. RECOMMENDATIONS AND NEXT STEPS

FWT will leverage the results of this project to provide far more accurate and convincing business models for the water treatment industry. This is enabled due the far better ability of assess capital and operation expenses from what amounts to a “real world” evaluation of the processes. Currently, FWT already has early introductions to service providers such as its partner Terrapure but also groups such as Schlumberger and Tervita who could adopt the technology to serve their clients. International adoption is also already under way in the Netherlands, India, United Sates and Singapore. The adoption and sales cycle is expected to be up to 24 months but lead clients could be in a position to consider first contracts within 6 months. In particular, in India where water resources are under extreme focus Goldfinch Pvt, a water treatment engineering company may become a licensed distributor and supplier in Q1 2020.

K. KNOWLEDGE DISSEMINATION

Upon completion of the project, FWT has used media releases with its partners to promote the success of the commercial scale pilot. In addition, FWT has presented the result at two conferences specifically focused on waste water and sustainability (i3 Clean Tech – Singapore; World Water Tech – Los Angeles). Both events resulted in business connections requiring follow up including the summary that this report has resulted in. Alberta Innovates has also used the completion of the project to introduce FWT to potential partners within the energy sector in Alberta. Discussions with NAIT and SAIT are on-going.

L. CONCLUSIONS

The key objective for this project was to illustrate the scalability of the thermolytic forward osmosis process Forward Water is commercializing. Prior to this project the engineering community typically had reservations about the scalability and effectiveness of the technology.

An NMe_3/CO_2 forward osmosis (FO) membrane brine concentrator commercial scale pilot (plate capacity of 15000 L/d_{feed}) was tested in the desalination of waste waters from Oil & Gas production activities. Overall a > 70% volume reduction was observed and an OWS quality reached < 300 mg/L TDS with minor amounts of light hydrocarbons. The thermal energy required by the FO pilot was on average 139 kWh_{th}/m^3_{OWS} and for periods where OWS flow was maintained and low conductivity values were recorded, the power requirement reached values of 74 kWh_{th}/m^3_{OWS} which is substantially lower than reported comparative thermolytic draw FO technologies of 180 to 275 kWh_{th}/m^3_{OWS}.

In addition, there are ample avenues to further improve the process that were not particularly obvious prior to this effort. Notable are 2 main areas for improvements; stripping column design improvements that draw on amine-based CO_2 capture technology and artificial learning studies to maximize process controls efficiencies. The later avenue could be an effective collaboration between academic groups and FWT. Lastly, the redesign of a small foot print containerized reference design for commercial roll out is required to enter the treatment market. However, FWT will need to have a confirmed commercial interest prior to committing to that type of deliverable.