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# Pilot-scale study on the reverse osmosis treatment of oil sands tailings pond water: Impact of pretreatment on process performance

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## HIGHLIGHTS

- This pilot study investigated the use of reverse osmosis (RO) to treat recycle water.
- The impact of different pretreatments on the RO performance was studied.
- RO permeate fluxes normalized to 25 °C of 31 to 52 L/m$^2$·h were recorded.
- The two configurations resulted in low total dissolved solids and dissolved sodium.
- Clean-in-place procedures were not required for both treatment configurations.

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## ABSTRACT

The oil sands industry has recently focused on both reducing their freshwater usage and maximizing the reuse of process water. This study is one of the few pilot-scale investigations reporting the ability of reverse osmosis (RO) to treat recycle water (RCW) from an oil sands facility. Two distinct treatment trains were assessed to evaluate the impacts of pretreatments on the RO performance. Treatment train 1 consisted of coagulant addition, ceramic ultrafiltration (CUF), antiscalant, and a single-pass RO system operated at natural pH, while the treatment train 2 included softening, coagulant addition, CUF system, weak acid cation ion exchange, antiscalant addition, and an RO system operated at alkaline pH. RO permeate fluxes normalized to 25 °C of approximately 31–39 L/m$^2$·h at 72% recovery and 38–52 L/m$^2$·h at 85% recovery were recorded for treatment trains 1 and 2, respectively. At these conditions, the two treatment trains resulted in total dissolved solids lower than 18 mg/L, while the dissolved sodium concentrations were below 7 mg/L. During the pilot tests, clean-in-place procedures were not required for both treatment configurations, highlighting the effectiveness of the pretreatment steps to reduce the RO membrane foulants.



## 1. Introduction

The oil sands in Alberta, Canada, are one of the largest oil deposits in the world [1]. With increased development of the oil sands resource, the oil sands companies have recently focused on reducing their freshwater usage and reusing their process waters. Typical constituents of recycle water (RCW), also known as oil sands process-affected water, include suspended and dissolved solids, organics, inorganic compounds, and trace metals [2]. As water is recycled, dissolved ions accumulate in the RCW from ore extraction chemicals and oil sands ores, some of which are of marine origin and highly saline. The concentrations of total dissolved solids (TDS) in tailings pond water can reach values as high as 2470 mg/L [3]. As such, TDS and salinity are one of the most critical constituents in RCW as their concentrations have increased at a rate of 75 mg/L per year during the last two decades [2]. Water softening is also a water management objective. The addition and buildup of water hardness, due to polyvalent cations, such as calcium and magnesium and to a lesser extent, aluminum and iron, in the RCWs are detrimental for optimum water recovery [4].

Several treatment options have been used to treat RCW, including physico-chemical processes, adsorption, advanced oxidation processes, biological treatment, and membrane filtration, among other technologies [5–9]. Biodegradation is potentially an economical, energy-efficient and environmentally sound approach for tailings water reclamation. However, previous studies have shown that naphthenic acids (NAs), one of the organic compounds of concern present in RCW [10], are persistent toward biodegradation because of their extensive cyclical molecular structures [11]. Biofilm reactors have a great potential to be

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used for RCW treatment. Endogenous population of microorganisms in RCW can readily form biofilms, which are able to degrade and remove NAs and other organic contaminants [12]. In terms of membrane filtration, synthetic polymeric and ceramic membranes have been used for the removal of oil, suspended solids, dissolved solids, and other contaminants from RCW [4,9,13]. Nanofiltration (NF) has been applied for the treatment of RCW, particularly for water softening and NA removal [4]. Pretreatment methods such as coagulation–flocculation–sedimentation, with and without coagulant and coagulant aids were found to improve the desalination of RCW for both NF and reverse osmosis (RO) membranes [9]. Alpatova et al. [13] reported that 1 kDa ceramic ultrafiltration membranes were suitable for the removal of inorganic and organic compounds from RCW, resulting in membrane permeates meeting the requirements for high pressure-driven membrane processes.

Although efforts have been made to assess individual technologies to remove or degrade specific constituents of RCW, a strategy to treat and manage the various streams of RCW has not been proposed so far. This study is one of the few pilot-scale investigations assessing the performance of RO membranes to treat RCW. In this study, two distinct treatment trains were assessed to evaluate the impacts of pretreatments on the RO performance. Treatment train 1 consisted of coagulant addition, ceramic ultrafiltration (CUF), antiscalant, and a single-pass RO system and was designed to provide minimal pretreatment in front of the RO system. Treatment train 2 was designed to provide a high level of pretreatment in front of the RO system and consisted of softening, coagulant addition, CUF system, weak acid cation (WAC) ion exchange, antiscalant addition, and an RO system. The goal of this study was to produce fit-for-purpose water for several purposes such as bitumen extraction, boiler make-up water for upgrading, steam assisted gravity drainage (SAGD) operations, or for release into the environment. Other objectives of this pilot-scale study were to determine the optimum ranges for operating parameters that impacted the RO system performance, including permeate flux and maximum sustainable recovery rates, and to evaluate the membrane fouling caused by RCW under the different treatment configurations.

## 2. Materials and methods

### 2.1. Recycle water

RCW from the Canadian Natural Resources Limited (CNRL) Horizon operation was used as feed water for this pilot study. The RCW was drawn from a header of the main hydrocyclones of the CNRL cooling water recycle system. A storage tank of 60 $m^3$ was used to collect the RCW flowing from the header. The RCW in the storage tank was constantly recirculated in order to prevent the settling out of solids and avoid the separation of hydrocarbon materials. Selected key water quality parameters of untreated RCW are given in Table 1.

**Table 1**
Selected water quality parameters of untreated RCW.

| Parameter | Unit | Value |
|---|---|---|
| pH | – | 8.1 ± 0.1 |
| Total suspended solids (TSS) | mg/L | 215 ± 280 |
| Total dissolved solids (TDS) | mg/L | 1963 ± 265 |
| Chloride | mg/L | 460 ± 41 |
| Bicarbonate | mg/L as $CaCO_3$ | 870 ± 26 |
| Total hardness | mg/L as $CaCO_3$ | 48 ± 5 |
| Total organic carbon (TOC) | mg/L | 43.6 ± 10.9 |
| Oil and grease | mg/L | 27 ± 4 |

RCW: recycle water.

### 2.2. Pilot facility

The water treatment pilot facility was located on CNRL Horizon site, adjacent to 99A plant, which is on the north side of the site, next to a tailings pond, in Fort McMurray, Alberta. As shown in Fig. 1, two distinct treatment trains were tested to treat RCW. The treatment train 1 consisted of aluminum sulfate addition followed by a CeraMem® CUF system and a single pass RO operated at a neutral pH (Fig. 1a). The CUF system consisted of two banks of ceramic membranes operated in parallel. Each bank contained two CUF elements operated in series. The CUF system was operated in dead-end mode with a constant reject waste stream. The RO system was operated in a three-stage, single pass configuration with the goal of achieving the maximum possible recovery (Fig. S1 included in the Supplementary Material). The primary obstacles in operating the RO system were the mineral scaling and organic fouling [14]. Scaling was mitigated through the use of antiscalants (Hydrex 4102; Veolia Water Technologies), pH control, and chemical cleaning [15,16], while organic fouling was mitigated by the occasional application of biocide (Nalco Permaclean PC-11) to prevent biological growth and by chemical cleaning [17]. The treatment train 1 tests were carried out from November 2nd to December 12th, 2012.

The treatment train 2 included a softening equipment (Multiflo™) followed by a CeraMem® CUF system (Fig. 1b). The Multiflo™ system consists of a series of reaction tanks followed by a crystallization tank with an integrated mixing system that facilitated the precipitation of hardness-causing ions in the feed water and crystallization of the solids generated. Crystalline solids were then settled using a lamella plate clarifier, also integrated into the Multiflo™ system. A portion of the settled solids were recycled to the front of the softening system to seed the precipitation process. The effluent from the softening system was then treated using a CUF system. CUF filtrate was further treated using weak acid cation (WAC) ion exchange system consisting of two vessels operated in series to further reduce hardness-causing cations to low levels. Resin Lewatit CNP 80 and a linear feed velocity of approximately 4.7 m/h were used in this pilot study. The WAC vessels were sized to last the entire duration of the piloting period, such that on-site regeneration was not required. Immediately upstream of the RO system, antiscalant (Hydrex 4102; Veolia Water Technologies) was dosed (10 mg/L) as a safeguard against performance excursions of upstream softening processes. The operational target pH of RO influent was 10.5 to 10.7, which ideally maintained organic compounds and silica in a soluble state so they did not foul the membrane surface as well as assisted in controlling the biological growth [18]. The trials for treatment train 2 were carried out from December 28th, 2012 to February 9th, 2013.

Treatment trains 1 and 2 used the same CUF pilot system and configuration. Titania membrane elements (CeraMem® FE-S2S-0100TO-D00-00) with a nominal average pore size of 0.1 μm were used. The membrane element length and diameter were 864 and 144 mm, respectively, while the membrane active surface area per element was 10.7 $m^2$. The same three-stages, single pass RO pilot system was used in both treatment trains (Fig. S1). However, different RO elements were used, specifically designed for the low scaling, high pH feed water produced from the treatment train 2. The pilot RO system consisted of a three-stage design with fiberglass pressure vessels, containing three 102 mm (4 in.) diameter, 1016 mm (40 in.) long elements. The RO elements were polyamide thin-film composite (DOW Filmtec LC4040 for treatment train 1 and OPUS 4040 for treatment train 2) with membrane element active surface areas of 8.7 and 7.3 $m^2$, respectively. The specifications and operational settings of the RO units are summarized in Table S1 and S2, respectively. The process equipment, including Multiflo™ softening system, chemical dosing systems, and CUF system was supplied by Veolia Water Technologies. Chemically enhanced backwashes (CEBs) and clean-in-place (CIP) procedures were conducted using caustic soda, sodium hypochlorite and citric acid, according to the membrane manufacturer's recommendations.