Introduction

In recent years, favorable conditions for Enhanced Oil Recovery (EOR) project development, such as increased costs for identifying and developing new oil reserves, declining production from maturing reservoirs, stringent environmental regulations for produced water management, and heightened oil commodity prices of over $80/bbl, has resulted in a growing interest amongst Operators in water-based EOR technologies. Global water-based EOR recovery potential is approximately 750 billion barrels (Shell 2009). Secondary Improved Oil Recovery (IOR) techniques, such as waterflooding, account for over half of the world's oil production (Idaho National Laboratory 2011). According to Morrow and Buckley (2011), this growth in interest can also be exemplified in the increased number of technical publications and presentations over the past 15 years focused on one type of EOR methodology, Low Salinity Injection (LSI), as set out in Figure 1:
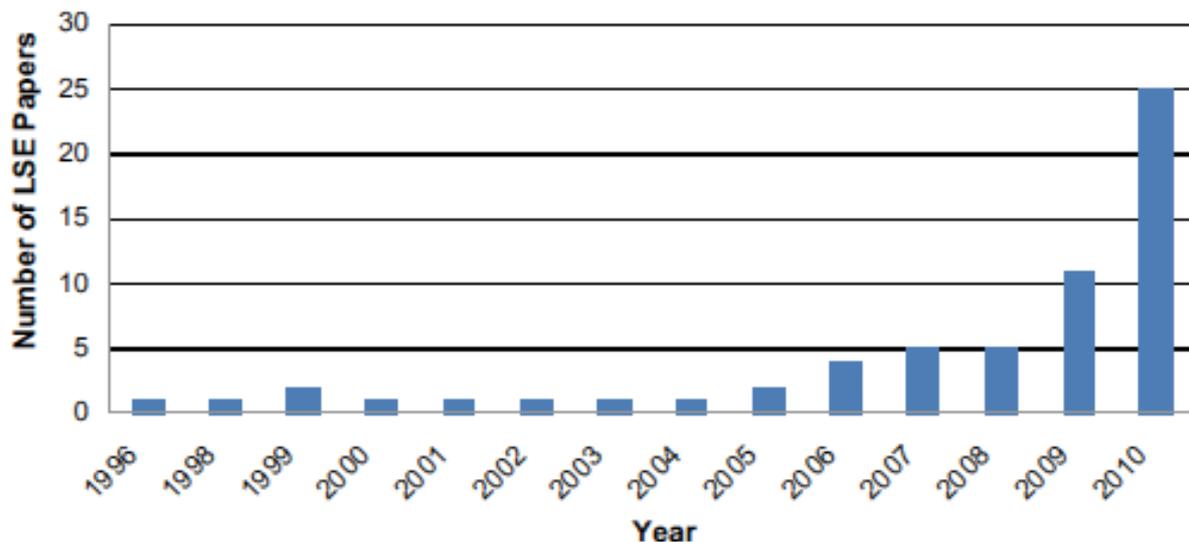

Figure 1 *Number of publications and presentations focusing on the Low Salinity Effect (LSE), the theory governing LSI processes, over time. (Morrow and Buckley 2011).*

Water-based EOR technologies, including LSI, Chemical EOR (CEOR), and steam flooding, require the use of supporting equipment and systems to enable the optimization of oil recovery in light of numerous constraints. As EOR applications become more complex and shift from onshore to offshore environments, these constraints can become increasingly unique. Typically, supporting equipment and systems must be able to:

- Provide consistent treated water quality that is appropriate for the type of EOR process being implemented
- Adapt to changes in influent stream quality
- Address minimal weight requirements
- Address minimal footprint requirements

Technologies typically found in the water treatment industry, such as Reverse Osmosis (RO) and Nanofiltration (NF), hold considerable promise in addressing the challenges found in EOR applications. However, despite their successful demonstration in numerous projects in municipal and industrial markets globally, these and other technologies have limited operational experience in the upstream Oil & Gas Industry. Even fewer have experience offshore.

Current projects offer an opportunity for water treatment technology providers to identify key challenges that will impact not only their designs, but the budget and schedule of a project when it is

implemented. In order to leverage water treatment technologies in the upstream Oil & Gas Industry, without detrimentally impacting the project, pilot tests can be designed to address key constraints that will be encountered on real-world applications.

Bridging Water Treatment Technologies with EOR Applications

In Southeast Asia, two projects are pioneering the use of customized water to improve oil recovery in offshore applications. These projects are described in two cases, as follows:

Case 1. In the South China Sea, a sandstone reservoir commenced oil production in 2001. Using conventional water injection to maintain pressure within the reservoir to improve oil recovery efficiency, crude oil production reached its peak in 2005 and declined over the next three years. Two CEOR injection techniques utilizing combinations of Surfactant and Polymer (SP) and Alkaline, Surfactant, and Polymer (ASP) chemistries are currently being studied to determine their potential to enhance oil recovery from the field.

Sandstone reservoirs are typically considered favorable candidates for CEOR programs relative to carbonate reservoirs due to their wettability and texture. Numerous pilot and commercial scale technologies have been tested in this lithology as a result (Alvardo 2010). In a CEOR program, alkaline, surfactant, and polymer are mixed in water to create an injectant "cocktail," whose properties will enhance its ability to sweep Original Oil in Place (OOIP) more efficiently than a water-based flooding technique could alone. Each chemical component serves a different intended purpose. Alkaline is used to catalyse saponification reactions with the organic acids of oils within a reservoir's formation water, generating natural surfactants that mobilize the oil. The deployment of surfactant chemicals will minimize interfacial tension between oil and water, thereby stimulating oil movement. Polymer will increase the viscosity of the injection fluid, improving its ability to displace oil within a reservoir. When used in combination with one another, the beneficial effects of CEOR injection can be amplified. For example, when alkaline is combined with surfactant chemistry, alkaline will help prevent manufactured surfactants from adhering to reservoir rock, increasing the overall efficiency of the CEOR application (Henthorne 2012).

In order for a chemical cocktail to work successfully and honour the specifications required in the Case 1 sandstone field, the injection water source, seawater, must be treated using technology from the water treatment industry to achieve a composition that will enhance its effectiveness in the reservoir. Two programs are being considered in this field. One technique utilizes ASP, and the other SP chemistry. Seawater treatment requirements, prior to chemical mixing within these regimes, are set out in Table 1:

Parameter	Units	Case 1: ASP Injection	Case 2: SP Injection
Total Dissolved Solids (TDS)	mg/L	5,000	15,000 – 25,000
Calcium	mg/L	< 10	< 100
Magnesium	mg/L	< 10	< 100
Sulphate	mg/L	< 10	< 100
Salinity	mg/L	-	22,000 with or without produced water blend

Table 1 *Case 1 CEOR project treated water requirements.*

Besides satisfying the treatment requirements set out in Table 1, water treatment technologies must also address unique, site-specific constraints. Water treatment technologies must be able to:

- Provide either water quality in Case 1 or Case 2, using a common set of treatment infrastructure

- Respond to water quality impacts associated with produced water reinjection facilities currently used on site
- Produce consistent water quality, with or without the influence of produced water
- Demand minimum weight requirements
- Demand minimum footprint requirements

Case 2. At another location in the South China Sea, a field comprised of layers of shallow sandstone and shale has been in production for over 30 years. While the field originally utilized gas injection to recover crude oil, waterflooding operations began in 2011 to improve production. Recently, CEOR injection using a combination of ASP chemistry has been under investigation to determine its viability in enabling Operators to maximize recovery from the maturing field.

Similar to the Case 1 field, the prevalence of high-permeability sandstone in the Case 2 field renders it a potential candidate for a CEOR program. However, in this project, only one injection scenario is currently under consideration. This scenario entails providing ASP chemistry to the reservoir using treated seawater as the injection fluid. Seawater treatment requirements are set out in Table 2:

Parameter	Units	Case: ASP Injection
Total Dissolved Solids (TDS)	mg/L	20,000 – 30,000
Calcium	mg/L	< 5
Magnesium	mg/L	< 5
Sulphate	mg/L	< 5

Table 2 *Case 2 CEOR project treated water requirements.*

Despite the favorable permeability of sandstone reservoirs compared to carbonate lithology, oil recoverability can be reduced, if injection fluid chemistry is not properly managed. Injection fluids whose constituents react with ASP or other chemicals found in formation water can catalyse precipitation chemistry. Solid material that forms during this process, or scale, can block pore pathways and the subsequent oil recovery that can be achieved. In the Case 2 project, water treatment equipment must address this constraint, by being able to remove hardness to very low levels, minimizing the potential for scale formation. Overall, water treatment technologies used in this application must be able to:

- Provide injection water with ultra-low hardness, to prevent scaling within the reservoir
- Provide robust equipment that produces consistent treated water quality from seawater whose quality can vary
- Demand minimum weight requirements
- Demand minimum footprint requirements

Developing and Piloting Water Treatment Technologies for Offshore EOR Projects

The Case 1 and Case 2 EOR projects indicate there are numerous unique constraints that water treatment technologies must be able to address, ranging from the ability to provide robust, flexible treatment infrastructure that produces a consistent treated water quality, to requirements for minimal weights and footprints to render technologies suitable for offshore applications. Pilot studies can be designed to investigate the capabilities for which water treatment technologies are known, such as their ability to provide efficient hardness treatment, in tandem with their ability to address other project-specific constraints.

Project Background. In 2012, a pilot study was designed and implemented to investigate the potential for a proprietary design that leverages the capabilities of Reverse Osmosis (RO) and

Nanofiltration (NF) technologies, to achieve unique treatment objectives apparent in the Case 1 and Case 2 EOR projects. These treatment objectives included the ability to produce a range of water quality chemistries, including ultra-low hardness/high salinity, and low salinity injection water.

RO and NF are membrane-based technologies accepted in many industries as robust, reliable, and cost-effective water treatment devices. There is over 43 million m^3/day of ionic separation capacity, including RO and electrodialysis, and over 19 million m^3/day of membrane installation capacity globally (IDA 2011, Furukawa 2008). However, despite this extensive experience, only a small portion of it can be found in oil and gas facilities (Henthorne 2012).

Experimental Design. To evaluate the potential for the proprietary RO/NF-based technology to overcome unique challenges apparent in EOR applications, a phase-based pilot study was designed to achieve specific objectives according to Key Performance Indicators (KPI).

Phase 1a. The proprietary RO/NF technology was evaluated based on its ability to respond to changing seawater quality and permeate set points, particularly for hardness and TDS. This would be done to portray field conditions in which seawater quality varies and then impacts the permeate quality, as well as to mimic changing membrane performance, over time. Objectives and KPI included:

- Objective 1: Demonstrate the ability to change and control output salinity and hardness levels from the blended permeate of RO and NF test units at various set points
- KPI: Response to changes in a set point within a specified time; response to a change in seawater quality within a specified time of 20 minutes; stabilization of output salinity within ±150 mg/L of the set point within the specified time

Phase 1b. The proprietary RO/NF technology was evaluated based on its ability to produce a wide range of treated effluent qualities using the same baseline water treatment infrastructure. This would be done to portray project conditions in which treated injection water quality requirements change over the lifetime of EOR program, such as that under consideration in the Case 1 field. Objectives and KPI included:

- Objective 2: Demonstrate the ability to operate with various types of RO and NF elements to produce different water qualities suitable for different injection purposes
- KPI: Ability to achieve new blend permeate quality set points; ability to achieve projected salt rejection of new RO and NF membranes; ability to achieve projected flows of new RO and NF membranes

Phase 2. The need for ion selective NF products for the upcoming water-based EOR projects required verification these products were suitable for duty.

- Objective 3: Demonstrate and assess the performance of a specialized NF technology in various pass configurations
- KPI: Ability to reject calcium, magnesium, sulphate, sodium, and chloride at the permeate streams of various passes; ability to respond to different feed pressure requirements; ability to recover water in various passes

Methods. The pilot study was conducted at the Bureau of Reclamation's Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, New Mexico, USA. A customized, containerized RO/NF system was designed and delivered to the site. The pilot system operated in a feed recirculation loop, in which permeate and concentrate lines were recombined in an external tank and re-fed through the two independent systems. Seawater was simulated by adding conventional salts to high-purity RO permeate according to the Brumewicz artificial seawater recipe

(Brumewicz 1970). A comparison of this water quality with that anticipated in the Case 1 field is set out in Table 3:

| Constituent | Units | Simulated Seawater | Case 1 Field | |
			Measured	Balanced
Temperature	°C	20 - 35	22 - 31	22 - 31
pH	-	7.5-8.5	8.2	8.2
Turbidity	NTU	<1	-	-
Total Hardness as Ca and Mg	mg/L	1,628	1,514	1,514
Chlorides	mg/L	18,938	-	-
Total Dissolved Solids	mg/L	34,099	33,830	34,618
Total Suspended Solids	mg/L	<1	10	10
Sulphate	mg/L	2,436	2,950	2,500
Calcium	mg/L	387	352	352
Magnesium	mg/L	1,241	1,162	1,162
Sodium	mg/L	10,505	10,240	10,796
Potassium	mg/L	380	485	485
Carbonate	mg/L	function of pH	24.3	24.3
Bicarbonate	mg/L	147 at pH 8.3	143	143

Table 3 *Comparison of simulated seawater quality and expected seawater quality in the Case 1 field.*

A five micron cartridge filter was provided to remove any potential solids or debris in the feed water, prior to downstream RO and NF treatment. The biocide 2,2-dibromo-3-nitrilopropionamide (DBNPA) and phosphonate-based antiscalent were utilized to limit biological fouling and scaling potential, respectively. In addition, the pilot unit was equipped with a Clean in Place (CIP) system for membrane cleaning, in case it was required.

The membrane treatment equipment was outfitted with a proprietary controls system that would modify the operating set points of the RO and NF systems in response to water quality. Water quality was monitored using online instrumentation and verified through laboratory testing utilizing standard testing procedures developed specifically for each analyte.

Results and Discussion. Pilot testing revealed the proprietary RO/NF-based system was able to achieve its objectives according to its KPI.

During Phase 1a, the proprietary controls system successfully demonstrated its ability to stabilize system performance rapidly in response to a conductivity step point step change. The RO/NF system was able to be stabilized to within ±150 mg/L of this set point in several minutes, a significant improvement from the 20-minute timeframe designated in the KPI. The equipment response to a 10% change in seawater salinity, over time, is set out in Figure 2:
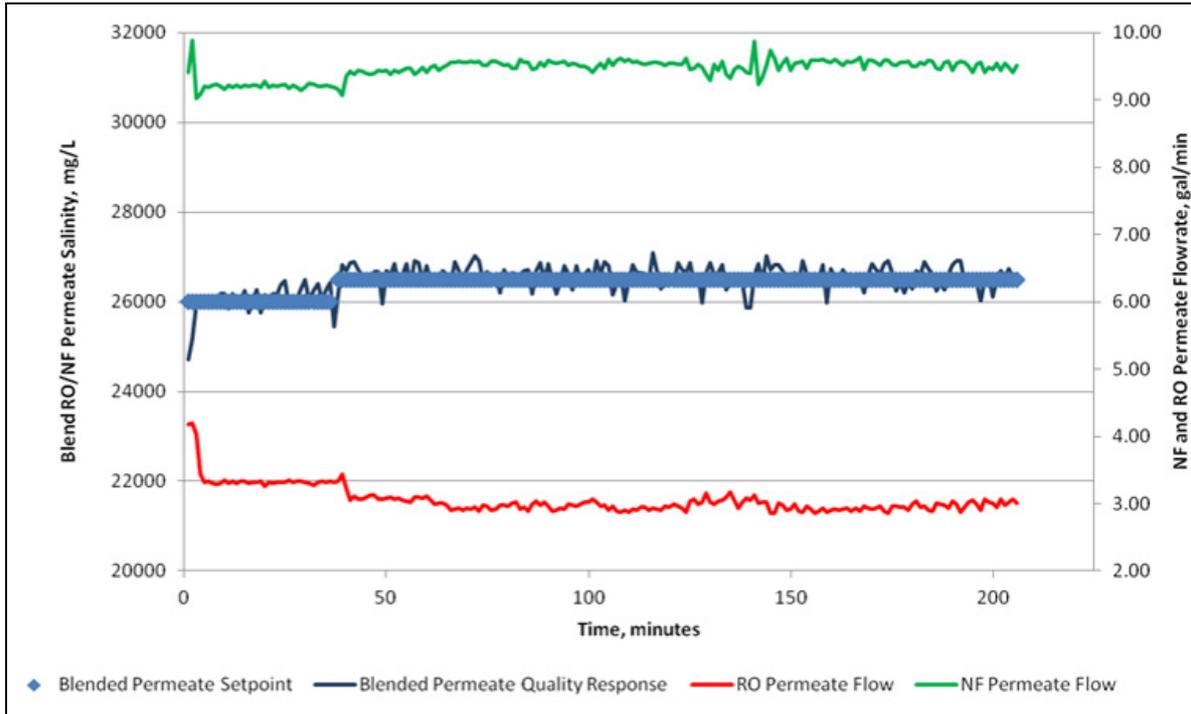
Figure 2 *Equipment response to a 10% change in salinity set point.*

During Phase 1b, RO and NF membrane elements successfully demonstrated the ability to produce water qualities required for different types of CEOR programs. The ability of the membranes to mimic expected performance from manufacturer projections is an indicator of this, as illustrated in Figure 3:
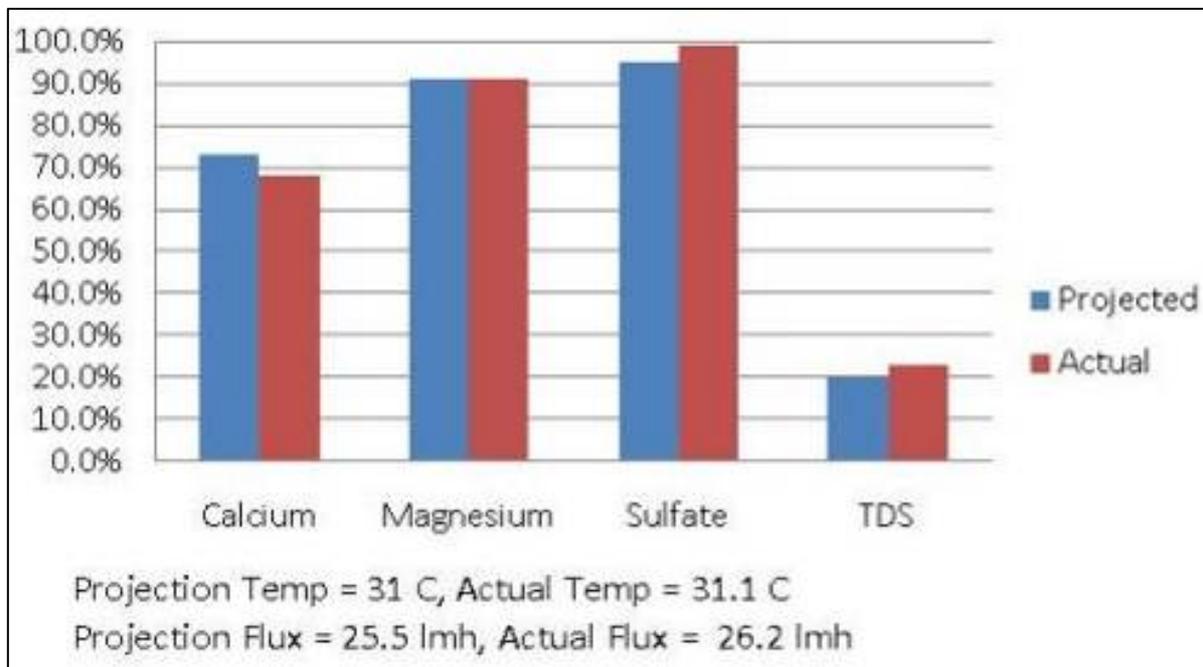

Figure 3 *Proprietary NF membrane performance compared to manufacturer projections. The NF equipment aligned with performance expectations within several percentage points.*

Phase 2 of pilot testing demonstrated the ability of the membrane technology to reliably recover water within various passes, amongst other capabilities. Membrane performance trends are given in Figure 4:
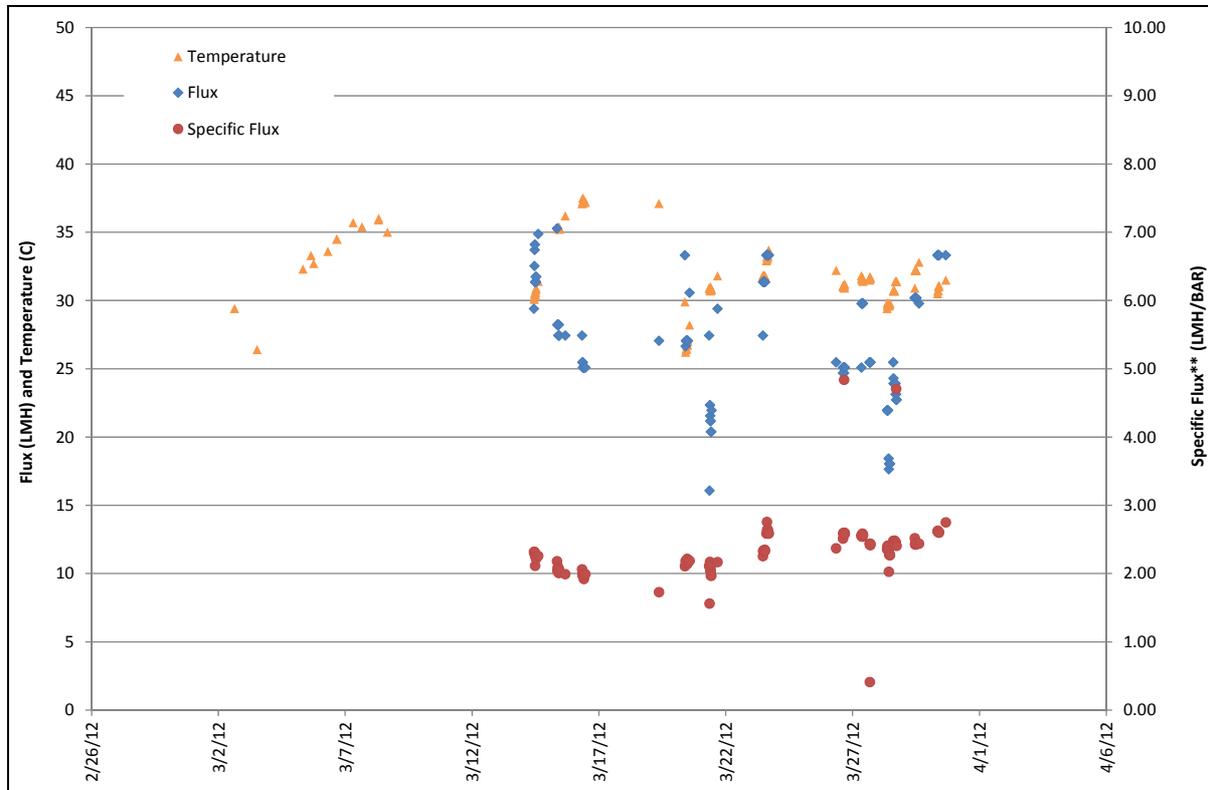

Figure 4 *Proprietary NF performance trends over time.*

As Figure 4 suggests, the proprietary NF membrane was able to achieve consistent performance within various passes of its design, over time. This condition would be required to enable water quality requirements to be achieved in CEOR projects, such as those in the Case 1 and Case 2 fields.

Conclusions

Growing interest in EOR development provides an opportunity for water treatment equipment providers, whose designs are uniquely positioned to address a range of challenges apparent in both onshore and offshore projects. While many water treatment technologies have limited operational experience in the Oil & Gas Industry, designing and implementing pilot studies that address specific constraints apparent in real-world projects will enable the capabilities of these systems to be leveraged to enhance their applicability to these projects. Successful testing of a proprietary RO/NF design that addressed constraints apparent in the Case 1 and Case 2 CEOR projects confirmed new technologies can be designed to address challenging issues that arise in offshore EOR applications.

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