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Subsea Sulfate Removal and Low Salinity Plant Membrane Life Prediction for IOR and EOR

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Abstract

Subsea water treatment technology for water injection provides a solution for an optimized water injection strategy on both green and brownfield applications. There are no space and weight constraints on the seabed, which enables simple, flexible, and reliable designs.

A full-scale sulfate removal and low salinity plant designed for seabed operation with minimum maintenance intervention has been in operation for ten months without any chemical cleans. This paper reviews the performance results used to predict the life and longevity of a subsea sulfate removal unit (SRU) for a field application in the North Sea.

The ability to reliably predict the potential risks and serving life of a system is crucial for the success of subsea processing equipment. Results from a test conducted over ten months evaluated the key design parameters such as SRU membrane permeate flux, recovery rate, and analyzed membrane fouling behavior during the test period. Lessons learned from the testing are incorporated into the model for more accurate and reliable membrane life prediction.

Field data was analyzed to extrapolate aging factors that are used in the membrane design projection software. The projection software simulated aging performance of the membrane over the membrane lifespan under subsea operation conditions, and the results were applied to determine operating philosophy, maintenance, and intervention interval for the subsea plant. Lessons learned from this field study were discussed and used as guidelines for the next phase full-scale design and practice.

This novelty field practice establishes a break-through step towards full implementation of subsea seawater treatment and injection for increased oil recovery (IOR) and enhanced oil recovery (EOR) purposes. This firsthand data helps the operators to optimize the operation on the seabed, which minimizes the downtime and demonstrates promising advantages of CAPEX and OPEX saving in the long run.

Introduction

The global petroleum industry is currently dealing with the challenges of declining production for both onshore and offshore oil fields. In addition, operators, governing authorities, and regulatory bodies also expect increasing revenues from oil and gas investments with all HSE regulations fulfilled. Maximizing hydrocarbon recovery in a more efficient, cost-effective, and safe ways is of keen interest around the globe, which drives the development of new injection and production technologies.

Most oil fields face a natural pressure depletion problem that leads to production decline. A natural oil well without special injection technology facilitated can only have limited oil recovery around 10-20% (conventional or unconventional). The exception is if a strong aquifer is present, providing continuous pressure support. To optimize production and oil recovery a ‘secondary’ recovery mechanism is required to maintain pressure and energy in the reservoir, and to sweep oil from injection wells to producers. It is worth noting that waterflooding has become the widely accepted method of secondary recovery.

A waterflood project requires a consistent water source and a high capacity water treatment plant that can support the oil production from the reservoir. It requires treatment of seawater to specified quality to support direct seawater injection or other special injection fluid preparation. Membranes have been used for decades in offshore water injection for sulfate removal and salinity control to reduce the risks of reservoir or pipeline souring and scaling in IOR and EOR operations.

Sulfate Removal

For the implementation of a successful water flood project, it is important to ensure the compatibility between the injection and formation waters. Understanding the chemistry of formation water is vital. A typical incompatibility problem for injection seawater and formation water is sulfate scaling in forms of calcium, strontium, barium, and their combinations. This can happen inside the production facilities and down the reservoir itself. In addition, mineral scale deposition can occur due to supersaturation of calcium carbonate caused by changes in water temperature, pressure, and pH. Moreover, sulfate-reducing bacteria utilizes sulfate in seawater and reduces it into hydrogen sulfide that eventually causes pipeline corrosion. Therefore, topside and subsea sulfate removal plants are required to mitigate such failure risks.

Reducing Salinity

A certain amount of original oil in place (OOIP) is bound to the rock. The ability to change the wettability characteristics of the rock could help unlock immobile oil that could not be possible by water flooding alone. Several techniques are available to influence the wettability and release oil from the rock. Surfactants, polymers, and low salinity water are examples. These techniques are normally referred to as EOR, or tertiary drainage methods (Dake 1978 4.9). One thing all these methods have in common is that they are generally costly to implement.

The SWIT technology enables subsea water treatment and injection of water from the seabed; therefore, it offers a new flexible and cost-effective approach to both IOR and EOR (Hegdal et al. 2020)

Subsea Water Treatment for Injection

Since 2003, a new subsea water treatment technology has been under development. This technology decouples water treatment from topside infrastructure and enables improved water treatment at the seabed for field development projects at any development stage, at water depths ranging from shallow to ultradeep (3000 m).

The system is modularized and can be tailored to varying desired capacities. It can also adapt to different water composition requirements and facilitate a varied treatment process layout. Such flexibility makes in situ adaptation and optimization possible in the field. The subsea treatment facility can be relocated to new locations after the termination of service (Hegdal and Pinchin 2015).

The subsea water treatment technology for sulfate removal or low salinity injection water consists of (Hegdal and Pinchin 2014; Hegdal and Pinchin 2015; Dirdal 2019):

1. The pretreatment module

- For generation of chlorine (EC treatment cells) and water treatment during required residence time
- Sedimentation
- Water treatment by hydroxyl radicals (HRG treatment cell)

2. The ultrafiltration module (UF)
   - Ultrafiltration module is designed to remove all particles sizes above 0.1 micron from the flow
3. Membrane feed pump (FP)
   - To provide required differential pressure (DP) across membrane module
4. Nanofiltration/reverse osmosis (NF/RO) membrane module
   - For sulfate removal and salinity reduction

The subsea water treatment system is qualified and available to the market for fully integrated subsea or hybrid applications.

The pretreatment module, the first stage of subsea water treatment system, has already been installed twice and has a combined operation time of more than three years (end of 2020).

Hegdal and Pinchin 2014; Hegdal and Pinchin 2015; and Dirdal 2019 have extensively discussed results and performance of the module installed at Ekofisk and the full-scale module installed at 220 m water depth for the prototype qualification project.

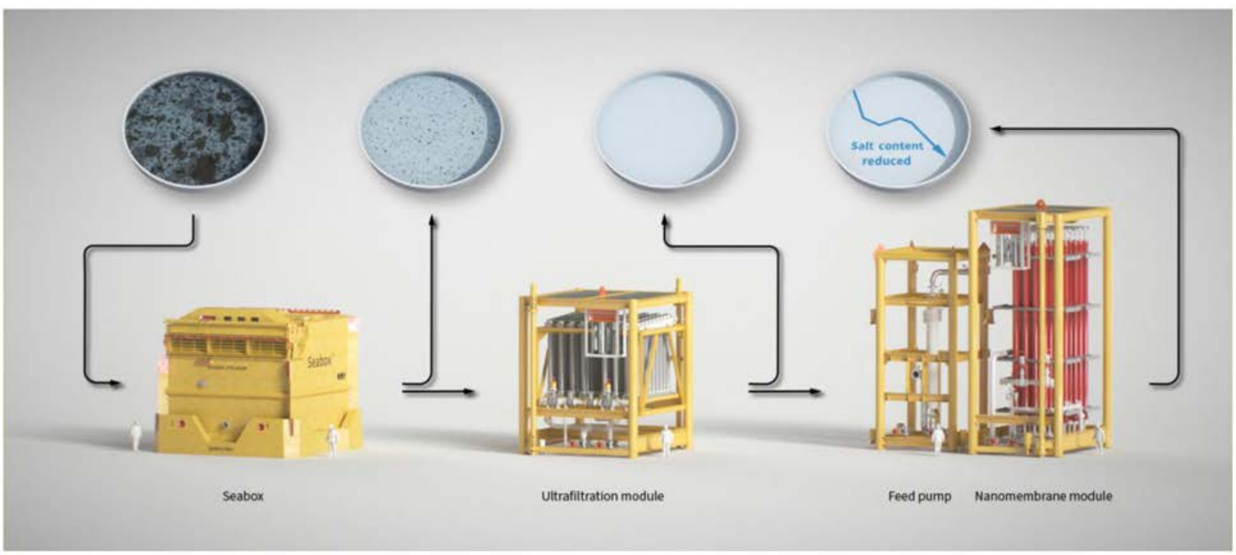

Figure 1—Subsea water treatment technology.

Subsea Application Challenges for Membrane

Commercially available NF and RO membranes are typically spiral wound structured. Such module configuration offers the highest unit surface area, which maximizes the treatment efficiency for modular systems. However, because of the highly compacted filtration unit, spiral wound modules cannot take too much loading on total suspended solids (TSS). Suspended solids and colloidal matter can accumulate in the feed channel and lead position interfaces, which causes fouling problems.

Colloidal particulates fouling and biological fouling are commonly seen on offshore SRU projects. SRU fouling in most cases is reflected by pressure vessel DP increase, which requires frequent chemical cleans to recover the DP to acceptable range. High DP creates extra strain force on the element module, and it can rupture the membrane module and cause leaking when DP overloads on the membrane element in the pressure vessel. Maximum axial pressure loss for a single 8-inch element is 15 psig. For a typical SRU six elements loaded pressure vessel, the maximum allowable pressure drop is 3.45 bar (50 psig).

A typical SRU membrane DP data is shown in Fig. 2 below, which represents a heavy fouling site's operation. It requires cleaning in place (CIP) periodically to reduce the DP of the first stage membrane. In this specific case, cleaning frequency is on average once a month. Differential pressure swings between 1.3 bar to 2.5 bar between cleaning and filtration campaigns. The bottom line is to keep the single pressure vessel DP lower than 3.45 bar. However, in field applications, the membrane needs to be cleaned at an earlier stage to assure cleaning effectiveness when the foulants accumulation is not too severe.

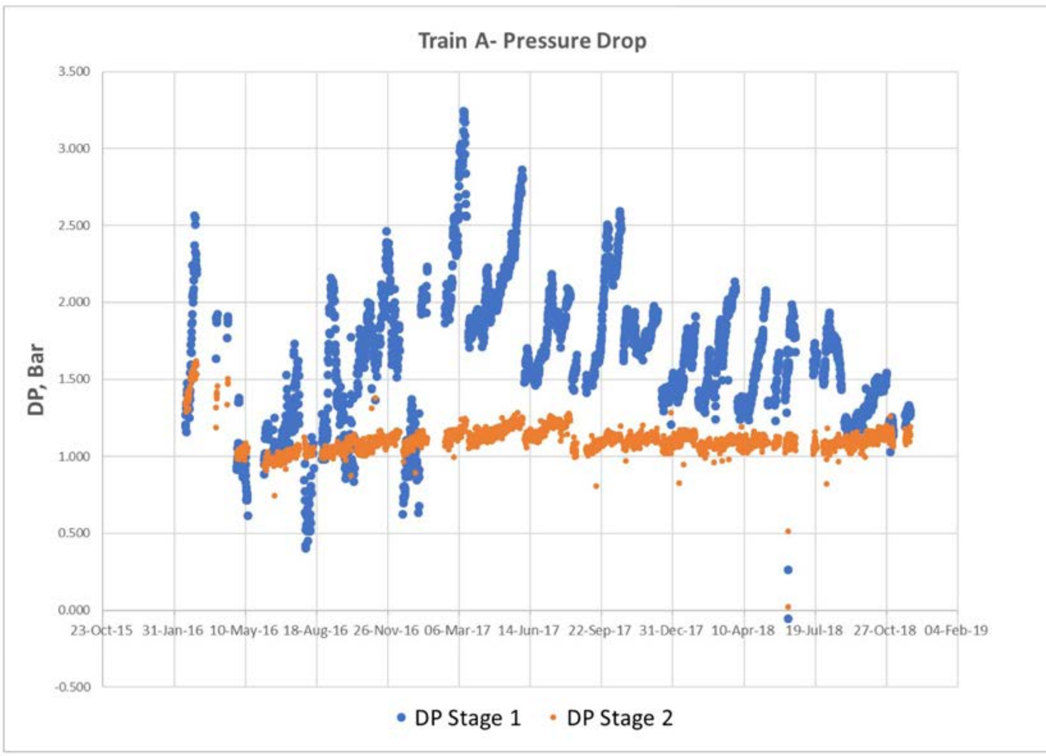

Figure 2—Differential pressure plot for an SRU membrane process on different stages.

Fouling can also impair flow permeability of the membrane and cause feed pressure increase. For sites that experience fouling troubles, DP increase is often the cleaning trigger criteria other than the membrane permeability reduction.

Remote operation in a subsea environment restrains membrane cleaning accessibility. But fouling is a ubiquitous phenomenon for membrane filtration process. Therefore, how to manage fouling on remote control SRU process becomes the main challenge for subsea membrane application. Fouling inhibition and control strategies need to be well considered and evaluated at the system design phase.

Our setup goal for subsea SRU membrane operation is two and a half years without chemical clean intervention, while the total membrane life is expected to be five years. In this study, pilot SRU operation data were collected and analyzed as baseline of aging performance prediction on a membrane to evaluate the viability of setup goals on subsea operation.

Subsea Membrane System Design

Standard top surface SRU design is a two stage membrane treatment process, with the first stage producing 50% of water recovery and the second stage producing 25% of water recovery, overall system recovery is 75%. The high system recovery (75%) is usually driven by the space and weight limitation topside and the need to utilize the energized reject stream to optimize energy consumption and plant economics.

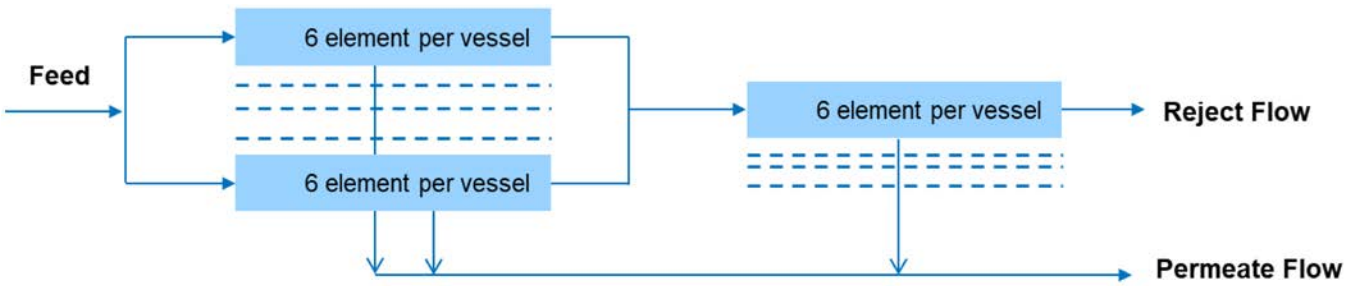

Figure 3—Standard topside SRU design.

Typical flux for SRU membrane is in the range 13-18 GFD. An average flux for the two stage NF design is usually set at 15 GFD. Permeate sulfate requirement for such design is commonly seen between 40-100 mg/L for three years warranty.

In considering the potential challenges and differences in subsea operation, the subsea SRU design takes different approach. Fig. 4 illustrated our prototype subsea SRU membrane system design scheme.

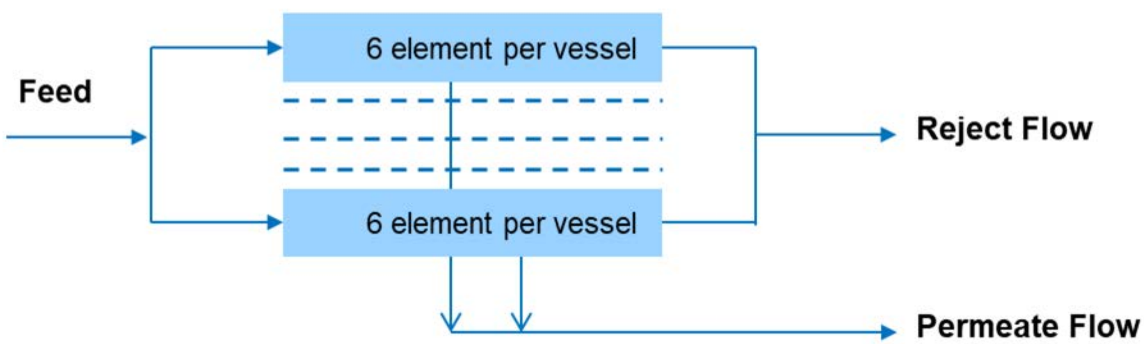

Figure 4—Subsea SRU design.

The subsea system takes a single stage system design. This allows a shorter filtration pass and more flexible system accessibility. Overall single stage system recovery is 50%. Since space and weight are not constrained on the seabed, reduced recovery and flux design provide a conservative scenario for easier fouling control while placing less emphasis on footprint savings.

The focus for subsea SRU systems is to have a simplified, reliable, and robust system that can operate on the seabed maintenance free (i.e no CIP) for several years.

For subsea systems installed in deeper than 350 m water depth, the available hydrostatic head could be used to run the system while in stable operation. This could provide significant power savings depending on the depth of installation. Actual power saving for an application in the North Sea is further elaborated in the case study section.

Full-scale Prototype

Subsea Water Treatment System

A full-scale subsea water treatment module was designed, fabricated, and tested as a pilot project from 2017 – 2020 (Hegdal et al. 2020).

The entire subsea system was qualified according to API 17N (end of 2019) for applications down to 3000 m water depth. However, the system remained in operation until April 2020, for further stress and envelope testing of the UF and NF membranes. In total, the system was in continuous operation for 10 months during the API 17N qualification period and additional stress testing. After which, the system was put in operation once every week for about seven months to refresh and keep the filters and membranes preserved.

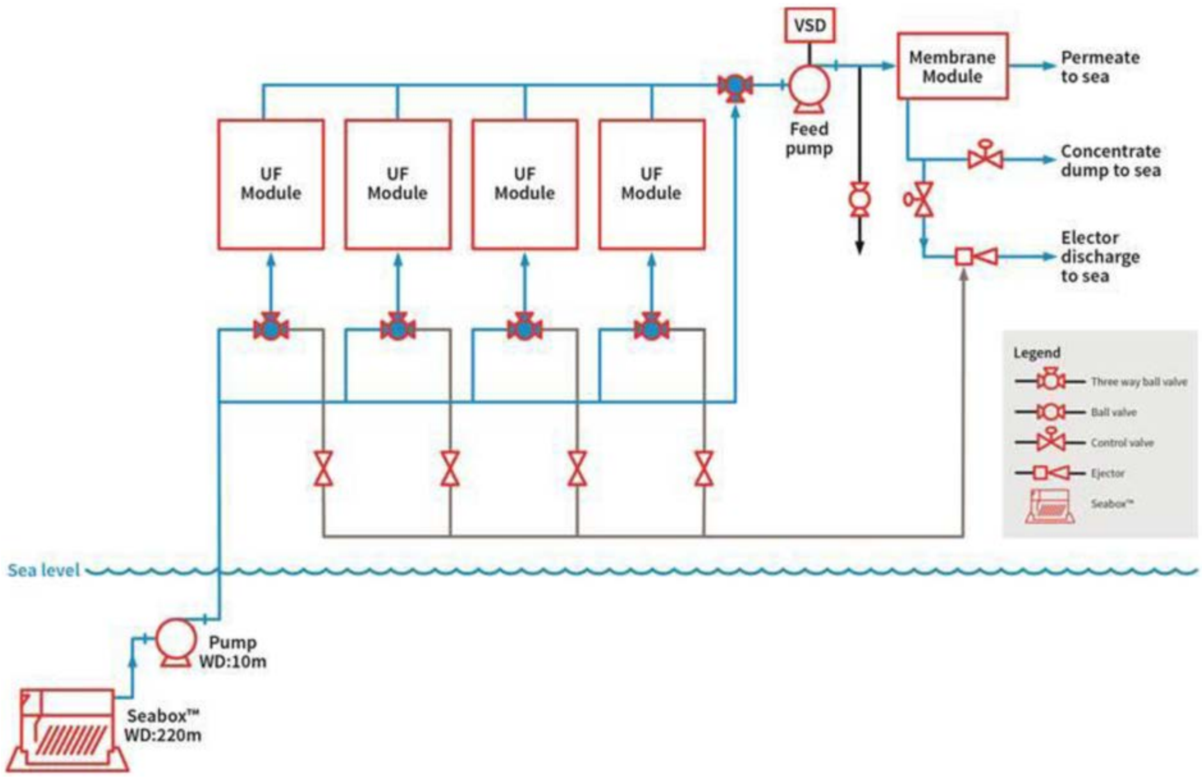

Figure 5—Pilot test set-up show pretreatment module on the seabed at 220 m with the UF, feed pump, and NF modules installed on a quayside.

The process schematics above describes the various treatment processes during the full-scale prototype in Norway. The pretreatment module was installed at 220 m water depth and provided disinfected seawater to the UF modules sitting on the quayside. The filtrate from the UF was then fed into NF treatment processes.

The pretreatment module and its component parts were seen to provide the required quality water over the testing period with 100% availability. Sedimentation and disinfection results have proven to be consistently better than design expectations as recorded in previous test performed in 2018 (Dirdal 2019).

The UF provided further treatment to remove solids and colloidal particles size down to 0.1 microns. The UF module consist of four trains with 36 filter elements in each train.

Analysis of contaminant loading of the raw seawater indicated SDI > 5, with significant increase during certain periods of testing. The pretreatment module treated water quality was typically SDI < 5 while UF filtrate SDI < 1 values were recorded during the test period.

On completion of testing in 2020, the UF filter supplier was consulted for analysis and expected life of the UF filter based on testing results and data collected during the qualification period (Hegdal et al. 2020).

The UF filter transmembrane pressure (TMP) and other process parameters were compared to results received from supplier topside applications using similar filter elements. Based on the result and trends achieved during the subsea qualification program, it could be estimated that a 10-year design life for the UF module is achievable if subsea CIP is implemented after five years of seabed operation.

Subsea maintenance and intervention are further discussed in the case study analysis/review section.

The filtrate from the UF module with an SDI value < 1 was fed to the NF module for sulfate removal. The seawater was dechlorinated upstream the NF module by dosing sodium bi-sulfate into the feed to the NF membrane.

No chemical cleaning was performed during the operation on either the UF or NF module.

The NF pilot skid contains 15 pressure vessels, each holds six pieces of 8-in. elements in it. After the completion of the test run, selected lead and tail position elements were returned to membrane supplier for autopsy evaluation.

SRU NF Membrane Pilot Results and Analysis

The SRU NF pilot test lasted for six months continuously with two segmented stages. The first stage test lasted four months long with design subsea permeate flux. The second stage test lasted about two months long with permeate flux at 42 - 60% greater than the design subsea flux rate. Pilot design treatment production flow is 60 m^3/h in the first stage and average production flow is 93.5 m^3/h. Total accumulative continuous operation is six months (4,320 hours) at designated test conditions.

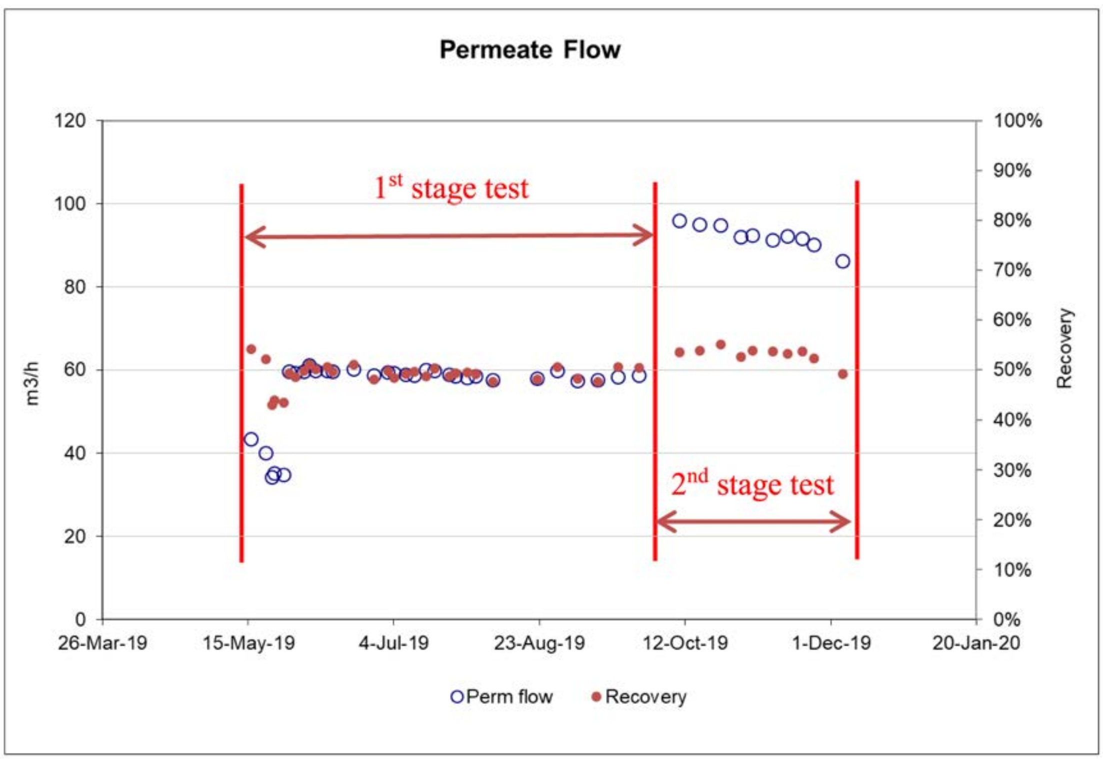

Figure 6—Pilot SRU system permeate and recovery plot.

Operation data and treated permeate water sulfate concentration were plotted in Fig. 7 and Fig. 8. The beginning four months of the operation demonstrated a very stable performance and operation conditions at subsea design operation flux and 50% recovery. Feed pressure and permeate flow rate are constant in the first four months. Fig. 7 plotted the normalized permeate flow rates, which normalizes the impact from temperature, net driving pressure, and water quality changes. The normalized permeate flow tracks the true membrane permeability changes over time. There is an instant reduction on the permeate flow during the first week's operation due to membrane surface conditioning from ocean organic matter adsorption (Suwarno, S. et al.2016). After this quick developing stage, the flow change slowed down in the later operation. Normalized flow was maintained above 25 m3/h in the beginning four months. The second stage test was conducted at raised flux rates for two months. Flux rate was 42 - 60% greater than the design subsea flux rate. The purpose of this higher flow operation is to evaluate membrane performance at more challenging conditions. Further reduction on the normalized permeate flow was observed for second stage, which indicates this is an unfavorable operation zoom to run subsea SRU.

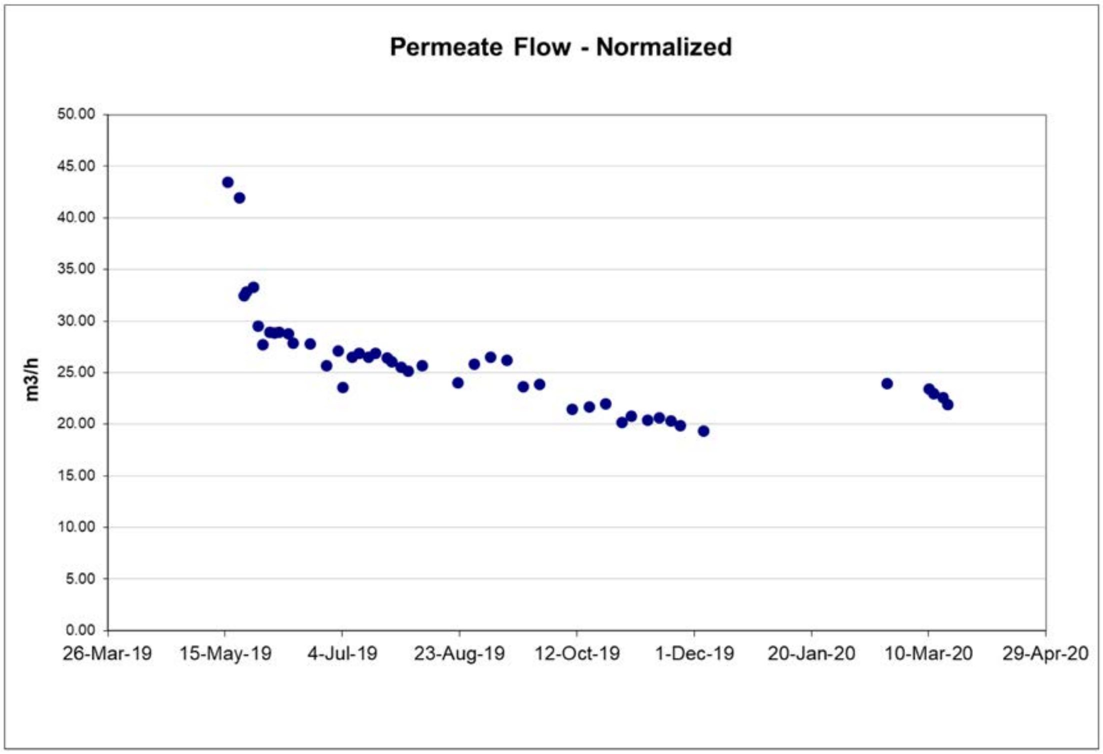

Figure 7—Pilot SRU system normalized permeate flow plot.

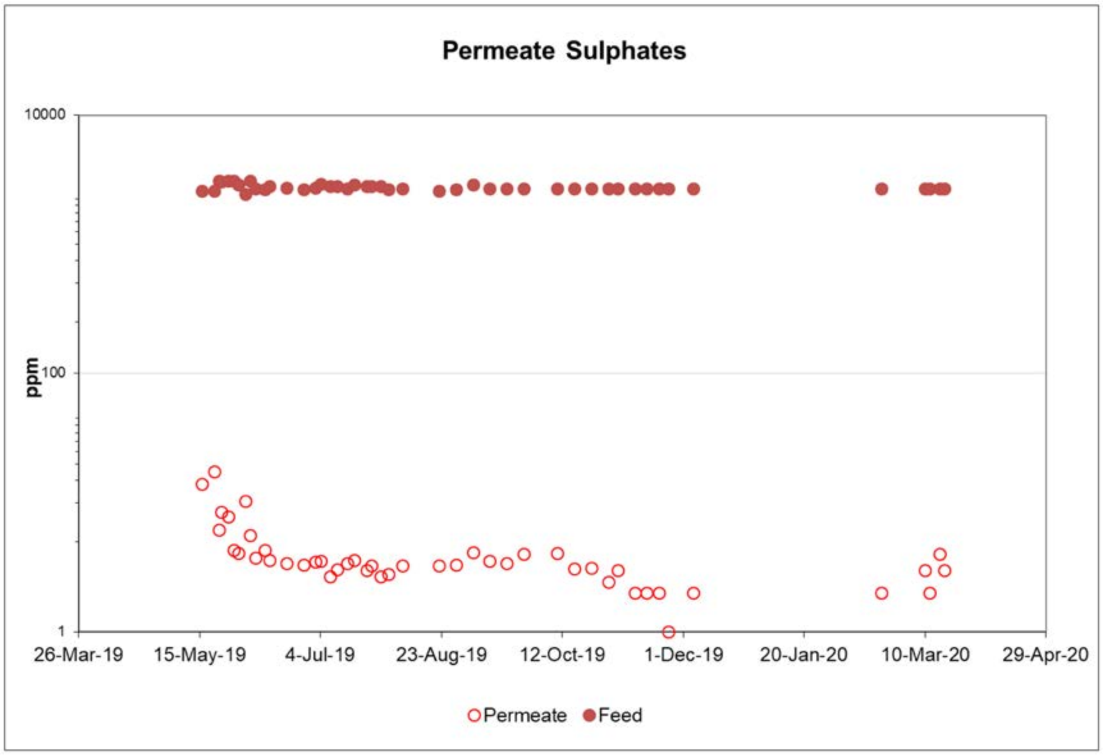

Figure 8—Pilot SRU system permeate sulfate plot.

The average sulfate concentration in the feed water was at 2800 mg/L. Fig. 8 tracks the pilot SRU permeate sulfate concentration during the nine month test. After the first week of operation, permeate sulfate was stable and maintained below 5 ppm.

The SRU pilot was successful as the TRL 4 qualification objective was achieved. The treatment goal of stable operation without chemical clean was achieved. Valuable operation data was collected and applied to guide full treatment facility designs with aging predictions.

SRU Fouling Analysis and Aging Predictions

Two characteristics of fouling behaviors were monitored in this pilot test: differential pressure increasement pace and membrane permeability reduction speed.

For a six element per pressure vessel layout, the maximum allowable DP of an 8-in. membrane system is 3.45 bar. Fig. 9 tracks the DP development data for the first six months pilot. DP started from 0.35 bar, went up to 0.5 bar in the first four months operation at the subsea design flux rate. DP stayed in a very stable region in between 0.4 bar and 0.5 bar for the second stage operation with 42 – 60% increase in subsea design flux rate.

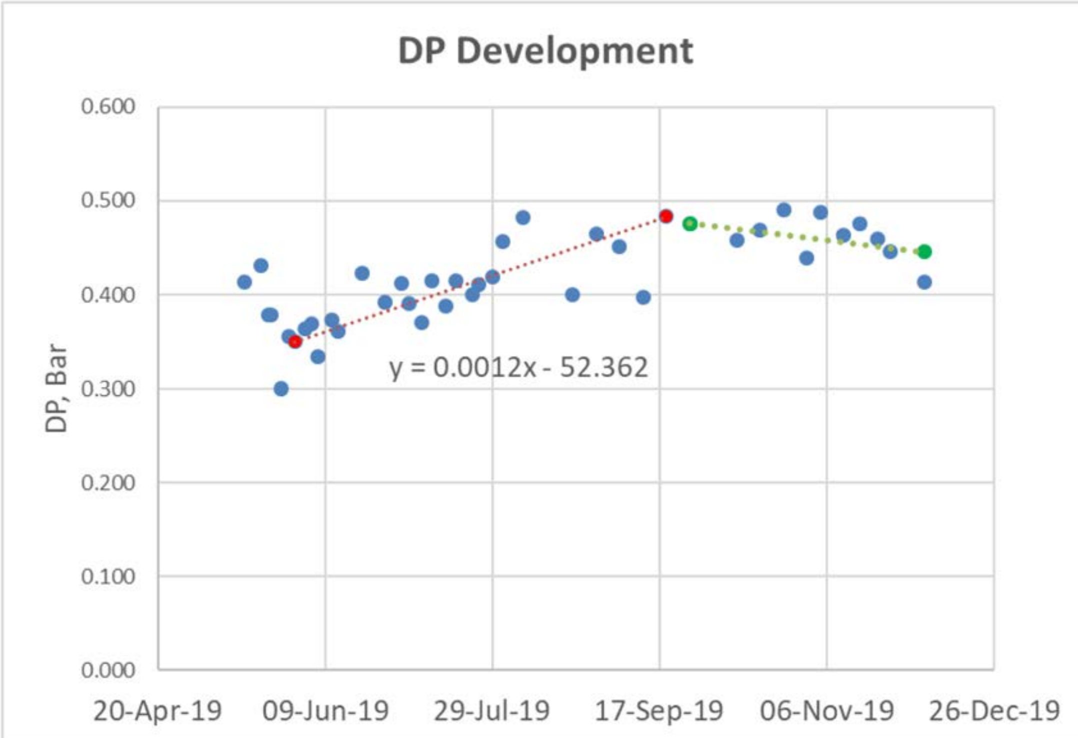

Figure 9—DP development plot for the six months operation at 10.5 GFD, 50% recovery and higher flux condition.

We take the worst scenario observed in this pilot test, which is the beginning four months of operation, and run an aging trend analysis on DP. The DP increasing speed ratio was calculated to be 0.0012 (Fig. 9). In the later higher flux operation condition, DP stabilized in certain way that the absolute DP readings showed a decreasing pattern.

If we take this increasing ratio and apply two and a half years (912.5 days) aging timeline, the predicted DP after two and half years of operation is 1.5 bar, which is well below the maximum limit of 3.45 bar. Extrapolating further, the membrane may be operated for 5.75 years before reaching the maximum DP limit of 3.45 bar. This aging analysis on DP assumes that the DP increasing rate is a fixed number, which would not change overtime.

Fig. 10 shows NF membrane water transport coefficient development trend for the six months pilot. The fouling analysis avoided the first two week's preconditioning zoom, and only took account the stable operation regions. Water transport coefficient reduced about 17% for the first stage operation and 19% reduction for the second stage operation (two months). Water transport coefficient characterizes the membrane water permeability. If we take the first stage operation condition water transport coefficient development trend, the extrapolated one-year membrane permeability change will be 51%. Some sensitivity analysis may be required on water transport coefficient trend and therefore should be interpreted in conjunction with information from the prediction tool and the retuned elements autopsy results. Based on the calculated water transport coefficient some increase pumping capacity will be required to compensate flow loss to achieve five years operation with one or two CIPs performed.

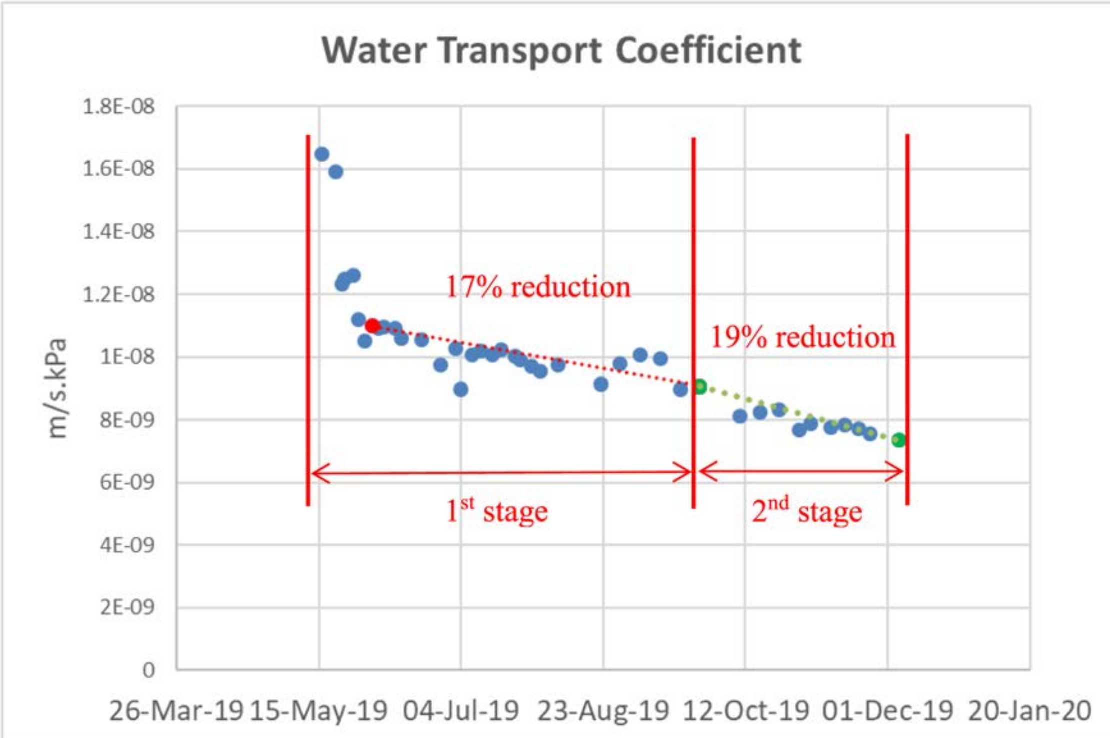

Figure 10—Water transport coefficient development plot for the six months operation at 10.5 GFD, 50% recovery and higher flux condition.

Lead and tail elements were removed from the site after ten months of operation and sent back to membrane manufacture's lab for re-evaluation. We saw almost unchanged performance on these two returned elements. Membrane flow rates even gained a little (2%) on each module. After autopsy, we saw a mild fouling coating layer on the membrane surface, which seems to be mostly hydrophilic in nature of organic substances coating. Extrapolating this average flow loss percentage into a year span, we get 0% permeate flow loss per year on membrane aging factor on flow.

Table 1—Return evaluation at standard wet test condition

Standard Re-Test Performance Data							
SERIAL NUMBER	Original Wet-Test Data		Re-Test			% Change From Original Wet-Test	
	MgSO4 Rejection (%)	Flow (GPD)	MgSO4 Rejection (%)	Floe (GPD)	dP (psi)	Salt Passage (%)	Flow (GPD)
NANO-SW-SUBSEA (S/N 1215572)	99.7%	9,500	99.6%	9,648	5.0	47%	2%
NANO-SW-SUBSEA (S/N 12155657)	99.7%	9,779	99.6%	9.936	5.9	33%	2%

NF Projection and Actual Pilot Data Comparison

Projections were run with real site data and ion analysis using the membrane suppliers web program. Since the typical subsea design flux and 50% recovery operation condition is the qualification target, our projection checks and evaluations were mainly focused on these operational conditions.

Two data points were taken as emphasized examination: stable operation point at the beginning and the last operation point at the end of first four months pilot. The beginning stable point is on the date May 29, 2019. The ending date of this test condition is September 26, 2019. Projections were run at these two collected data points. The beginning stable operation site data matches well on ion concentration and pressure predictions. Table 2 compares the actual and projected permeate stream ion concentrations on the date May 29, 2019.

Table 2—Actual ion concentration vs. projected permeate ion concentration on the May 29, 2019 (date)

Ion concentration, mg/L	Feed	Perm-Actual	Perm-Projected
Ca	389	172	171.8
Mg	1258	160	157.4
Na	10300	9380	9081.1
K	529	433	435.7
HCO3	136.8	52.32	49.6
SO4	2659	2.92	3.0
Cl	19712	15883	15146.6

For the initial four months of operation, the feed pressure had about 6% increase from the starting point. To fit the four months aging pressure, the fouling factor on flow decline needs to be set at 0.91, which corresponds to 28% per year of flow decline. Pressure projection results with and without aging are listed in Table 3.

Table 3—Aging projection fitting actual data

	Actual	Projected-no aging	Projected-aging	Flow aging factor	Note
2019/05/29	16.2	16.8	N/A	N/A	Beginning
2019/09/26	17.2	16.5	17.1	28% per year	After 4 months operation

The above analysis on flow change using different methods yielded three flow decline percentage. Table 4 listed all the extrapolation results on annual flow reduction prediction.

Table 4—Annual flow decline percentage derivation results based on different evaluation methods

Evaluation method	Water transport coefficient as typical subsea flux rate	Element flow loss at std wet test	Software fitting decline
Annual flux decline	51%	0%	28%

The evaluation methods gave an annual flux decline percentage of between 0% - 51%. Therefore, 28% (slightly higher than average) of flux decline per year fouling factor was selected for subsea water treatment project applications. From the above fouling development analysis, DP increase is managed and kept under control for two and a half years of operation without CIP. A five-year operational life is achievable based on the analyzed and calculated DP development. The flow loss may be compensated by increasing feed pump pressure to achieve required permeate flow rate. Depending on the water depth, such increased pressure across the NF membranes may be provided by the feed pump (for shallow water) or by the injection pump (best alternative energy wise) at greater water depths. For subsea applications, the 28% flux decline will be applied when sizing the pump to provide the required pressure margin to compensate any flow loss. In addition to the increase in pump pressure, one or two CIPs may be required for fouling control to mitigate flow loss. The DP and flow loss information has been applied in the case study section for an application in the North Sea.

Case Study

The subsea water treatment technology enables water treatment and injection from the seabed and thus represents innovative 'tools' that provide operators with a distributed and flexible solution based on retrievable modules when it comes to new field development or optimizing existing fields.

Applications currently under considerations are fully integrated subsea water treatment systems for low sulfate and low salinity water with capacity of 100,000 bpd or more at water depths between 50 and 3000 m for fields in various parts of the world (e.g Gulf of Mexico [GoM], North Sea, Offshore Asia, Offshore West Africa).

The case study presented in this paper is based on work performed for a major operator in the North Sea for a green field development project. The operator defined HSE, sustainability, value, digitalization, and industrialization as strategic drivers for the company going forward. Therefore, a subsea water treatment and injection solution fits all these drivers, enabling unmanned field developments and reduces the need for service consumables and hazardous chemicals.

Design basis for the application to be considered is as follows:

Table 5—Basis of design for a project in the North Sea

Design data	Values
Total water injection (WI) capacity, i.e. treated water	9 000 m3/d
Maximum particle size	95 wt% < 20 μm
Sulfate content level injected in reservoir	< 20 mg/l
Water depth at location	385 m
Distance from host platform to subsea location	Approx. 29 km
Operational water injection pressure	330 bara (at wellhead)
Operational temperature	6 - 9°C

The subsea water treatment modules were designed in close cooperation with a major subsea system integrator to ensure proper interface between the water treatment modules (i.e Pretreatment module, UF, and NF modules including control system) and the membrane feed pump, water injection pump, FP, WI control system, power distribution system, and flow base supplied by the system integrator.

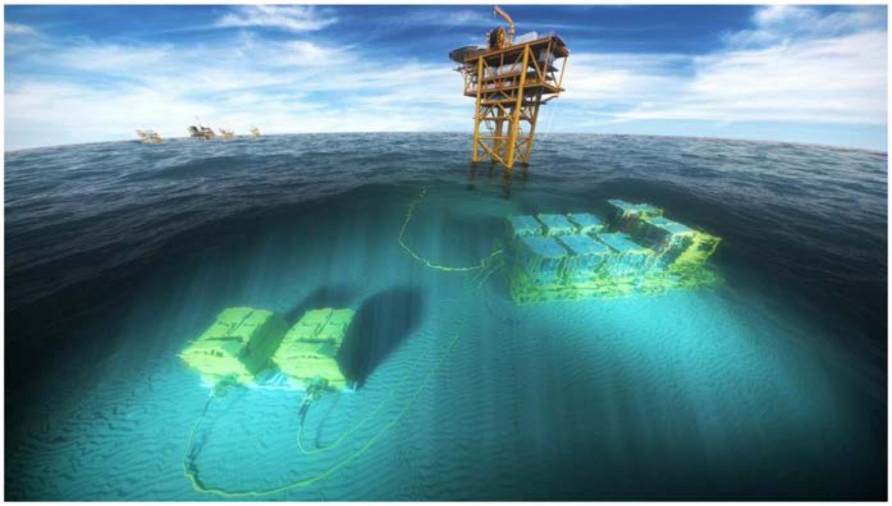

Figure 11—Case study subsea seawater treatment station.

The design parameters for the UF and NF modules were as tested and established during the pilot project that achieved TRL 4 status in December 2019, and proved that long-term reliable subsea operation of UF and NF modules is achievable when both modules are fed with right quality of water from the pretreatment module.

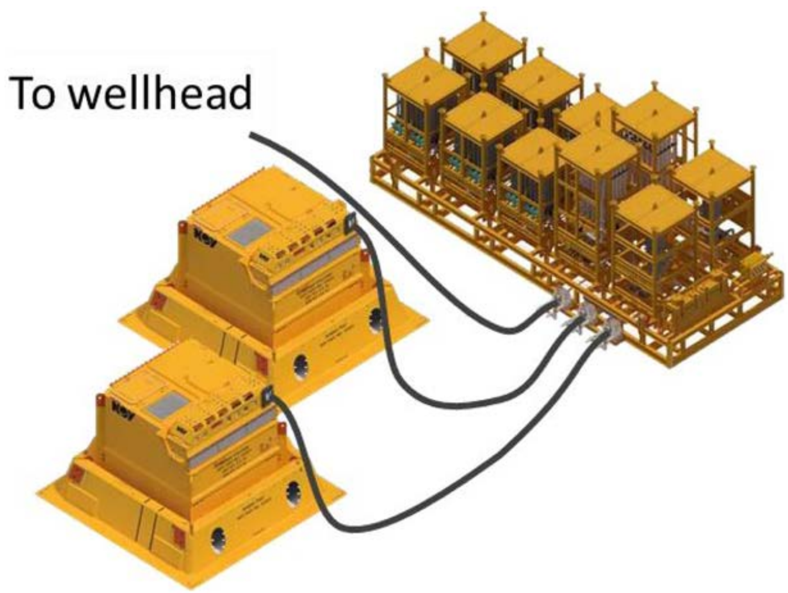

Figure 12—Draft schematic of case study subsea water treatment and injection system.

To ensure a cost-effective water treatment and injection solution, the layout above consisting of two pretreatment modules, six UF modules, one FP, two NF modules, and one WI pump was proposed to meet the operator's requirements

When compared to a traditional topside water treatment plant providing the same duty, the above facility would provide a continuous power saving of approximately 2 MW, which amounts to 17,520 MWh per year. This assumes that for a subsea water treatment solution, the water does not have to be lifted to the topside facility for treatment, no requirement to pump 29 Km through a pipeline to injection well location (as for this specific project), and that the subsea system will utilize the available hydrostatic head in the NF filtration process during steady state operations.

Since this system is installed on the seabed at 385 m depth, it is possible to lower the injection pump suction pressure, thereby generating the NF osmotic pressure by sucking with the injection pump rather than developing the required feed pressure with the feed pump. In theory, this will increase efficiency and lower power requirement by approximately 50%. Reducing the power requirements of the system will decrease the carbon footprint related to operation significantly.

NF SRU Full-scale Design and Performance Prediction

The membrane supplier projection software was used to predict the behavior of the membranes using derived fouling factor from the pilot study.

Feed water analysis input for the projections was the same as the pilot feed sample analysis. The design production flow rate was at 9000 m3/day and the design temperature was 4°C. The system recovery was set at 50%. Flux decline per year fouling index was set as previously selected 28%.

Two operation scenarios were assumed in this performance prediction. Scenario one assumes one CIP was performed at year 2.5, which recovered half of the flow loss on the fouled membrane. The resumed flow performance and aging behavior for the latter two and a half years followed the pattern before the cleaning. Scenario two assumes no CIP performed for five years span. This creates a worst-case situation on pressure prediction, but it assumes the membrane fouling rate is a fixed number over years. The predicted feed pressure and permeate sulfate concentrations were plotted in Fig. 13 for two cleaning operation scenarios.

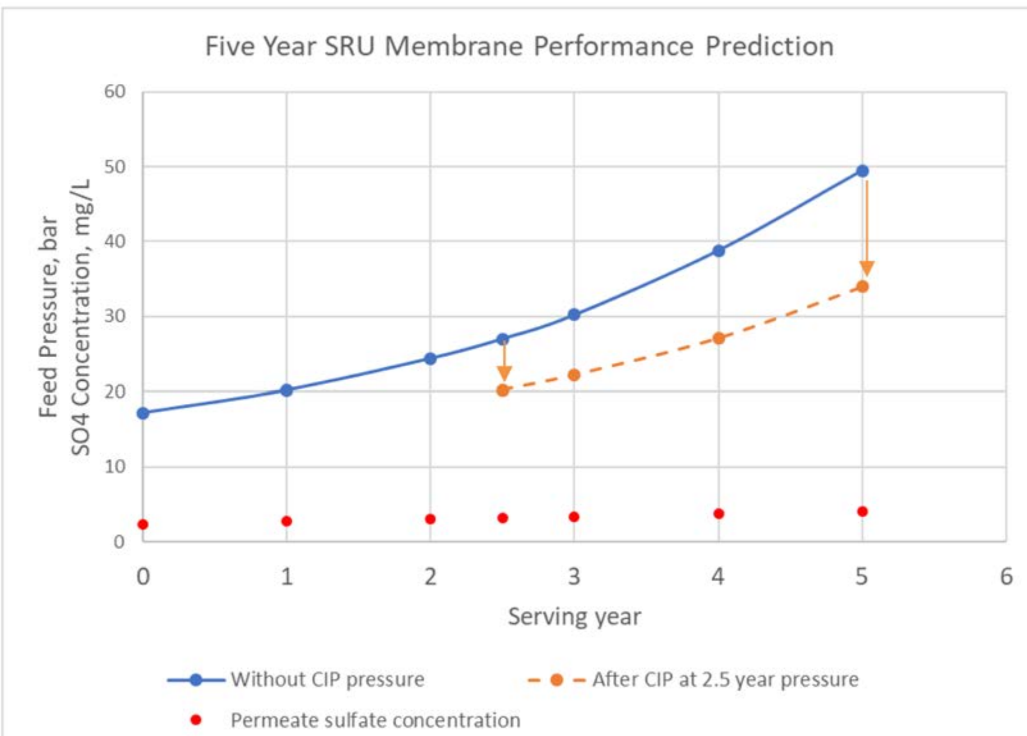

Figure 13—NF membrane case study system aging performing prediction.

The above trend defines the initial feed pressure (18 bar) required for the NF operation. For the scenario without CIP, there is a gradual increase from the initial startup pressure to 50 bar over a five-year period.

This increase in pressure over time should compensate for the expected flow loss over the five-year membrane life. Another fouling control mechanism included in this design is ability to perform CIP. If CIP is performed after two and a half years, the estimated increase in the feed pressure over the five year lifetime will be approximately 94%, compared to the 178% increase in feed pressure from the worst-case scenario without CIP.

It is important to note that for both scenarios (i.e operations with or without CIP) there is a 44% increase in feed pressure during the first two and a half years. Therefore, the flow decline effect is more pronounced as the membranes ages further after two and a half years in operation.

However, the projected sulfate concentration remains consistently below 5 mg/l over the five-year period which is within the 20 mg/l requirement defined by the operator.

Therefore, by performing CIP after two and a half years in operation, the membrane feed pump will be dimensioned to provide approximately 40 - 50 bar to compensate the flow loss during the five-year design life of the membranes before the membrane module is retrieved and replaced.

Intervention and Maintenance Philosophy

The main principle for maintenance is that equipment should remain in service for as long as possible, consistent with the availability requirements and system downtime constraints. Thus, the number of components that are replaced on a purely time-based schedule as opposed to condition-based replacement are minimized.

The optimization of the subsea water treatment and injection system operational availability depends on the ability to perform maintenance actions rapidly and cost-effectively. This, in turn, requires the hardware design to facilitate such actions. The system design intent is to provide sufficient redundancy to enable active equipment to run to failure without compromising output.

Continuous remote monitoring of the subsea water treatment system performance will be used to indicate the need for corrective or preventive maintenance activities. The operator will be informed of all relevant aspects of SWIT performance. This system provides a means of monitoring condition, health, and performance of equipment and operation through data trending and analysis.

The actual interval will depend on condition monitoring data. The following inspection and maintenance intervals are expected for the various modules, based on system performance and supplier recommendations for the individual sub-components. No maintenance is required on the pretreatment module and foundation structure. Periodic inspections will be performed when maintenance is performed on the other modules.

Table 6—Estimated intervention intervals for the subsea water treatment system

Description	2.5 years	5 years	10 years	30 years
Pretreatment module and foundation				X
Removable Treatment Unit		X		
Ultrafiltration Module		CIP*	X	
Nano membrane Module	CIP*	X		

* Subsea CIP envisaged after two and a half years of nano membrane module operation and five years after UF module operation.

Chemical cleaning in place

The system design uses filtered water from downstream of the UF modules to alternately backwash all individual UF modules. The backwash flow and rejection of wastewater is achieved using an ejector driven by the NF concentrate flow.

After many years of operation, based on the information from prediction software, it may be necessary to perform chemical cleaning of the modules to achieve the design life. The system is designed with the possibility to perform chemical cleaning of the UF and NF modules on the seabed if required. For this specific application with a 29 Km step out, the approach will be to utilize an inspection, maintenance, and repair (IMR) vessel with facilities for chemical cleaning. No chemical is discharged to sea or the injection well. Used chemicals are returned to CIP tanks on the vessel. Dilute concentrations of alkaline or acidic solutions (e.g citric acid, sodium hydroxide) is required for CIP.

For other projects with relatively shorter step out, CIP may be performed via the umbilical. In such a case, there would be no need for a vessel to perform CIP.

Another alternative considered for CIP is the innovative subsea chemical storage and injection system (SCSI). It can replace topside chemical storage or chemical injection from an IMR vessel. This technology is designed for both continuous and intermittent injection of chemicals to allow for operation at any water depth and at any location.

Therefore, depending on the project specifics, the most suitable cost-effective method for performing CIP will be chosen.

Conclusion

The subsea water treatment technology now qualified (TRL 4) and ready for use presents new ways of developing fields and optimizing existing assets to reduce cost and emissions while enhancing recovery.

A full-scale sulfate removal and low salinity plant designed for long term seabed operation without maintenance has been in operation for ten months without any cleaning or intervention.

Data from the pilot plant is used to determine the optimal maintenance and intervention intervals for an application in the North Sea. For such a system subsea, the preferred operational mode will be to run the system to its maximum pressure capacity. With adequate condition monitoring, there would be advance warning on future failures to ensure enough time to organize module replacement.

The expected intervention interval for the treatment unit (TU) replacement is every five years. There is no maintenance required for the stillroom or foundation structure.

Based on information derived from the pilot project, the expected lifetime of the UF modules is 10 years while performing CIP every five years.

The expected intervention interval for replacement of the NF modules is five years with CIP performed in two and a half years.

The ability to perform CIP based on condition monitoring of the system will significantly reduce OPEX cost. In addition, utilizing the hydrostatic head to drive the NF process during steady state operation will also reduce emissions and carbon footprint from the entire field.

Nomenclature

API	American Petroleum Institute
bpd	Barrels per day
CFD	Computational Fluid Dynamics
CIP	Cleaning in Place
DP	Differential Pressure
EC	Electrochlorinator
EOR	Enhaned Oil Recovery
FP	Feed Pump
GFD	Flux (Gallons / ft2 / day)
GoM	Gulf of Mexico
HRG	Hydroxyl Radical Generator
IMR	Inspection, Maintenance, and Repair
IOR	Increased Oil Recovery
NF	Nanofiltration
MW	Mega Watt
OOIP	Original Oil In Place
ppm	parts per million
RO	Reverse Osmosis

SDI	Silt Density Index
SRU	Sulfate Removal Unit
SRB	Sulfate Reducing Bacteria
SSTI	Subsea Seawater Treatment and Injection
TDS	Total Dissolved Solids
TMP	Transmembrane Pressure
TRL	Technology Readiness Level
TSS	Total Suspended Solids
TU	Treatment Unit
UF	Ultrafiltration
WI	Water Injection

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