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Membrane design of a subsea desalination system

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ABSTRACT

For the past several decades, we have seen significant improvements in the desalination industry, mostly intended to increase efficiency and reduce the energy consumption of desalination plants but also to improve the reliability, operability, and longevity of membrane systems. Except for introducing pressure exchanger energy recovery devices, most improvements have been incremental rather than disruptive; in most cases they were small adjustments that made a plant more effective, efficient, or reliable. This paper describes a completely disruptive new method of desalinating seawater: subsea desalination. A patented method combining seawater reverse osmosis (SWRO) membranes with subsea technology is well-proven and has been used extensively in the offshore oil and gas industry for decades. The subsea desalination concept places a membrane desalination plant below sea level, obtaining two very immediate and distinctive benefits: (1) higher and consistent feed water quality and (2) hydrostatic pressure from the column of water that provides all the required pre-membrane pressure. In the paper, we will describe the subsea system design and its advantages, which are substantial and game-changing, explaining how the cost of water can be reduced, reliability improved, and environmental benefits enhanced with such a solution. Specific benefits of the membrane configuration will be discussed, describing the system advantage regarding energy consumption, permeate quality and reduced brine salinity. The paper also presents the set-up and results of subsea field tests where it was proved that the reverse osmosis (RO) membranes performed as predicted by the DuPont WAVE design software.

Keywords: Subsea desalination; Seawater; Reverse osmosis; Desalination economics; Membrane; Field tests

1. Introduction

Norway's oil and gas industry operates entirely offshore. In the early days, they started exploring shallow waters, then moved to platforms connecting deeper waters to the surface. For the past three decades, the Norwegian oil and gas industry has developed a very sophisticated subsea industry, having developed subsea components such as pumps, electrical motors, connectors, transformers, switchgear, umbilical cables and anchor systems, to name a few, designed to work in deep seawaters.

The subsea desalination system patented and promoted by Waterise, a Norwegian company, utilises proven subsea technology developed for oil & gas combined with

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membrane desalination to provide safe and clean access to fresh water in water-stressed regions worldwide.

The majority of the subsea desalination plant consists of elements and parts that are well-known and field-proven in the Subsea oil and gas industry, and Waterise is working with Worley engineers who have long experience and specialist competence in this field [1]. For the membrane design, Waterise has partnered with DuPont Water Solutions to develop the most efficient, effective, and reliable membrane design in the specific conditions of subsea operations [2]. The subsea desalination system has developed according to the DNV best practice [3] and been successfully tested at subsea depth in Norway and in Saudi Arabia [4].

Waterise is positioning their desalination elements at 400+ meters below sea level. This combination of well-known subsea technology and the application of conventional desalination technology provides an innovative solution that addresses the water shortages in many regions globally. This paper describes the benefits of a membrane design in a subsea system with two specific characteristics, (1) cleaner and consistent feed water quality and (2) ambient hydrostatic pressure to provide all the pre-membrane pressure requirements.

The subsea desalination processing system is a modular design where the pumps, prefilters, RO membranes, and control system are inside modules that can be deployed and retrieved from/to the surface location to/or from the subsea template with a vessel. The modules are on top of a subsea template standing on the sea bottom. The subsea template may be mounted on suction anchors if the sea bottom is soft or on a mud mat if the sea bottom is hard. The subsea template contains the manifold piping system of produced permeate and brine.

The brine piping manifold system in the subsea template provides the fluid connection between the modules with the feed seawater inlets, prefilters, and RO-membranes with the modules for the low-head centrifugal circulation pumps and with the brine discharge outlet system.

The permeate piping manifold system in the subsea template provides the fluid connections between the modules containing the RO-membranes' permeate outlets with the modules for the high-head permeate pumps and the permeate transport pipeline to the onshore permeate received location.

The subsea pumps' motors get power through power cables from the onshore variable frequency drives (VFDs). The control system receives low-voltage power through power cables from shore. The communication with the subsea system is done through fibre optic cables. The control room is located onshore location.

The post-treatment of the produced permeate is done on the onshore, terrestrial side. The maintenance and replacement of prefilters and the cleaning/replacement of RO membranes and subsea pumps will be done topside or at the onshore location.

Vessels will be used to retrieve modules from the subsea system's template for maintenance and installation of maintained modules to be put back in production.

The subsea desalination system has full redundancy and will produce the design capacity when any module is retrieved for maintenance.

2. Methods and objectives

2.1. Energy consumption advantage

The subsea desalination system will be located below the sea level. The hydrostatic pressure due to the weight of the seawater column will provide the inlet pressure free of expenditures for energy or equipment costs.

The subsea desalination system will not have high-pressure pumps pressurizing the feed seawater up to the required feed pressure used in terrestrial desalination plants employing RO membranes. Instead, the subsea desalination plant uses low-head centrifugal pumps to circulate the feed seawater through the feed inlets, the prefilters, and the RO membranes and then circulate the produced brine through the discharge outlet system.

The pressure drops from feed seawater inlets to brine discharge outlets are low over the open circulation flow loop. The pressure drop over the prefilters is the largest contributor to the pressure loss. The prefilters will operate under excellent conditions at the deep-water location, resulting in a very low-pressure drop. In general, the quality of seawater in the feed will be stable and excellent. This is because most biological activity occurs below the epipelagic zone, where there is less light and, consequently, less marine life. This results in fewer problems in the system due to fouling.

Using subsea desalination, we can avoid the energy and pressure losses that occur with larger, more complex terrestrial pre-treatment systems. These systems often must filter shallow, near-coast seawater that varies in quality. Boosting the seawater to the desalination plant often causes a significant pressure drop, and using high-head pumps to move the water through the piping system at the terrestrial level can also lead to inefficiencies. Finally, Subsea desalination avoids the inefficiencies associated with recovering energy from the brine.

Each RO pressure vessel will contain two RO membrane elements in series, resulting in a minimal pressure drop. This is about one-third of the pressure loss experienced in terrestrial plants, which usually have seven or eight RO membrane elements in series and require less osmotic pressure.

The high-head centrifugal permeate pumps located downstream of the RO pressure vessels permeate outlets produce differential pressure through the reverse osmosis membranes. The permeate pumps decrease the pressure at the RO pressure vessels permeate outlets to create sufficient net driving pressure (NDP) to produce the permeate from the RO membranes in the system. The suction pressure created by the permeate pumps is typically a few bars above the vacuum to ensure sufficient net positive suction head (NPSH) for the permeate pumps. The depth of the subsea desalination system will be sufficient to allow total permeate production over the lifetime of the RO membrane elements and prefilter elements.

The high-head centrifugal permeate pumps' outlet pressure will be approximately equal to the ambient seawater pressure at the location of the subsea desalination system. The high-head centrifugal permeate pumps will only pump the produced permeate.

The main part of the subsea energy consumption is pumping the permeate out of the RO membranes with the high-head centrifugal permeate pumps. The minor parts of the energy consumption are due to the low head centrifugal pumps to run the circulation flow from feed flow inlets to the brine discharge outlets, the minor pressure loss in the permeate transport pipeline to shore, and the onshore energy consumption due to post-processing of the permeate to the customer's specifications.

The total energy consumption will be approximately 40% less for an equal-capacity terrestrial RO desalination plant. The subsea energy consumption per cubic meter of produced permeate will typically be 2.1 kWh/m^3 for a 50 000 m^3/d capacity subsea desalination system located 5 km from shore at 400+ m depth with feed seawater from the Red Sea. The total energy consumption, including the permeate's onshore post processing, is 2.3 kWh/m^3.

2.2. Permeate water quality advantage

Located over 400 m below sea level, this subsea site offers a consistently high-quality seawater feed with a stable temperature. The subsea deep-water ambient seawater temperature is cooler and more stable than the feed seawater in terrestrial desalination plants. These conditions are advantageous concerning the quality of the produced permeate from the RO-membrane elements.

In the subsea desalination system, using two RO-membrane elements in series per RO pressure vessel results in higher quality permeate compared to the typical terrestrial RO pressure vessels which have about seven or eight RO membranes in series. The hydrostatic pressure due to the weight of the seawater column provides the feed seawater pressure without expenditure of costs for energy or pumping equipment. Therefore, operating the subsea desalination system at a decreased recovery is possible, compared to the typical terrestrial desalination system with, say, seven or eight RO elements in series, without compromising overall energy efficiency.

The advantages due to cooler temperature and the benefit of only two RO-membrane elements in series per RO pressure vessel will provide lower total dissolved solids (TDS), that is, less salinity in the permeate.

The subsea desalination system will be configured with the type of RO membranes that provide the best overall performance to permeate quality, energy consumption, and maintenance costs at the specific location of the subsea desalination plant. RO membrane elements from DuPont, such as the FilmTec™ SW30HRLE, SW30XLE and FilmTec™ Seamaxx™ RO membrane element types, will all benefit from the advantages described here. The advantages are further defined by comparing the subsea desalination system and a typical terrestrial desalination system in section 3.2 – Significant improvement in permeate water quality.

2.3. Brine advantage

The subsea desalination system will be operated at low recovery with only two RO elements in series per pressure vessel. This provides the advantage of having a discharge brine flow containing less total dissolved solids (TDS). The brine salinity discharged from the subsea desalination plant is 1.3 times higher than the salinity of the feed seawater. The brine salinity from the typical terrestrial desalination plant will be 1.7 times higher than the salinity of the feed seawater.

No chemicals will be injected into the feed water to the subsea desalination system during operation. RO membrane cleaning will be performed annually onshore, where cleaning outlet fluids will be discharged according to the rules and regulations. Hence, the brine discharge flow from the subsea desalination plant will only contain the natural ions of the ambient feed seawater.

The brine reject flow produced by the subsea desalination system will be discharged nearby the subsea desalination process system 400+ m below sea level. The brine discharge system will be located at, say, 50+ meters from the subsea desalination process system. The brine discharge will have several brine discharge outlet nozzles with sufficient space between each other to provide the required dispersion by the environmental agencies. Each brine discharge outlet nozzle will provide sufficient velocity to ensure the mixing the discharged brine with the ambient seawater downstream of the nozzle outlet to prevent any local brine concentration.

The environmental impact of the low-salinity brine discharge at the subsea deep-water location will be less than the high-salinity discharge at a shallow water location near the coast of the typical terrestrial desalination system.

There is no excessive RO membrane brine outlet pressure to choke or recover in the subsea desalination system. The low-head centrifugal circulation flow pumps only provide the pressure to keep the circulation flow running from the feed seawater inlets, through the prefilters, through the RO membranes, and then send the produced brine through the brine discharge outlet system. There is no energy left to recover from the brine discharge flow. No energy recovery system is needed.

2.4. Design for longevity

The subsea desalination system is designed for longevity due to the inheritance of design and operating principles from the subsea oil and gas industry where the design life is 25–30 y with minimum or no need for maintenance during the lifecycle.

Accordingly, the subsea template with the manifold piping system will not be retrieved to the surface during the subsea desalination system's lifetime. The brine discharge outlet system and the permeate transport pipeline will not be recovered either during the lifetime of the subsea desalination system. The subsea valves on the template will last for the subsea system's lifetime. This method has been successfully proven in the subsea oil and gas industry.

The valve actuators on the template valves can be retrieved to the surface location if needed. This will eventually be done (if required) by a remotely operated vehicle (ROV). The subsea remotely operated valve actuators are electrically powered from shore. The remotely operated actuator can also be manipulated with the ROV. Some subsea valves are only used during installation or retrieval (when the ROV is available) and do not need remotely operated actuators. These subsea valves will be manipulated by the ROV only.

The permeate production is done in the filter modules where the prefilter elements and RO membranes are located. The subsea intervention campaign is set up to retrieve one (or more) filter modules, replace the spent prefilter element assemblies with new prefilter element assemblies, and, if necessary, clean the RO membranes. The maintenance campaign is completed when all filter modules have been serviced.

The subsea pumps are in modules for the low-head brine centrifugal circulation pumps and in modules for the high-head centrifugal permeate transport pumps. The subsea pumps are robust and reliable. The system will have one standby pump of each type. The standby pumps will be rotated in and out of production at regular intervals during subsea desalination system operation to ensure the integrity and health of all pumps. When pumps are scheduled for maintenance, a similar approach as for the filter modules will be applied.

2.5. Reliability design

When designing the modules, reliability is prioritized. The subsea desalination system has redundancy built into every major component, ensuring a highly dependable system.

The filter module maintenance is performed during a maintenance campaign. The maintenance campaign is triggered either by the increased pressure drop over the prefilters or by the increased pressure drop over the RO membranes, where the pressure drop limit will be set to balance the cost of energy, marine intervention and cost of the replacement RO and cartridge elements. When the filter module is in maintenance, the system can operate at its total production capacity.

The subsea pumps are equipped with instruments and sensors that will provide the necessary monitoring of eventual degradation to proactively schedule the maintenance before failure occurs. When a subsea pump is retrieved for maintenance, there will still be enough pumps in operation to provide the permeate design flow rate.

There is also redundancy designed into the control system with respect to power supply and electronic components. The electrical actuators can also be retrieved for maintenance without removal of the valve body. The valves are designed for the full lifetime of the system without any leaks or ingress of sea water or brine to the permeate.

The strategy behind the high reliability system is not limited to having redundant units, but also includes actions in advance of faults that may be detected. The traditional maintenance philosophies are as follows:

- Corrective: Based on fault/repair action.
- Preventive: Periodic actions on assets for avoiding faults.
- Predictive: Based on sensors and field analysis, treat to act before failures.

Modern maintenance philosophies are driven by production planning interventions not only according to the forecasting failure but also focusing on fine tuning for better production ratios. The predictive strategy based on sensors for forecasting is mixed with the historical information of the process production and employee expertise to arrange a parallel plan for fine tuning services.

The Waterise maintenance plan of the subsea desalination system is based on total productive maintenance (TPM), maintaining, and improving the effectiveness of production through assets, employees, and processes that maximize equipment availability.

Waterise has implemented the latest technologies for maintenance purposes. The fourth generation of maintenance systems is the cornerstone of Waterise's plan, which is based on implementing expert systems for a clear and real understanding of the status and availability of its assets.

3. Results and discussion

3.1. Energy consumption reduced by 40%

The energy consumption advantage of the subsea desalination system is described in section 2.1 – Energy consumption advantage. Fig. 1 presents the Waterise subsea desalination system energy consumption per cubic meter of produced permeate of 2.1 kWh/m^3 for a 50,000 m^3/d capacity subsea desalination system located 5 km from shore at 400+ meter depth feed seawater from the Red Sea. The post-treatment of the permeate will require 0.2 kWh/m^3. The total energy consumption of the subsea desalination system including the onshore post processing of the permeate is 2.3 kWh/m^3, as shown at the bottom of Fig. 1.

The energy consumption of a terrestrial plant is shown in the upper part of Fig. 1. The intake and pre-processing will consume 0.3–0.6 kWh/m^3 to produce the permeate. The energy consumption is partly due to the long pipeline and/or pipes of the inlet system to locate the intake at a location that provides feed sea water of sufficient quality. Another reason for the energy consumption is the pre-filter system that must expect feed sea water of poorer quality than the subsea desalination plant. The capacity must be sufficient to handle algae blooms or high turbidity events such as those caused by silt and dirt from the shore during rainfalls. The feed sea water quality is in general poorer with large quality variations requiring a more extensive pretreatment system to get the required quality to enter the reverse osmosis system, which impacts the energy consumption.

The terrestrial plant will require 2.7–3.1 kWh/m^3 in the reverse osmosis system of the desalination plant. The filtered feed sea water is pumped at high pressure. The discharge brine will be of high pressure that will mostly be recovered with energy recovery devices (ERDs). Still the energy loss is significant in the process to pressurize the feed and recover the discharge pressure, as compared to subsea desalination systems that do not require energy recovery.

The post processing at the terrestrial desalination plant will also require an energy consumption of 0.2 kWh/m^3 for the produced permeate.

The comparison between the subsea desalination plant with 2.3 kWh/m^3 and a modern, energy efficient terrestrial desalination plant with 3.2 kWh/m^3 yields the result that the terrestrial desalination plant requires 40% more energy per m^3 of produced permeate.

3.2. Significant improvement in permeate water quality

Fig. 2 provides more details on the advantages described in sections 2.1 – Energy consumption advantage, 2.2. – Permeate water quality advantage and 2.3. – Brine advantage. The first advantage is the cool and stable feed sea water temperature at the deep-water location of approximately 21°C, where the terrestrial feed sea water temperature is approximately 31°C. The second advantage is that the ambient feed sea water pressure is sufficient to provide the necessary inlet pressure. Therefore, it is not necessary to design the plant to achieve high recovery by configuring each pressure vessel with many RO-membrane elements to be energy efficient.

The top of Fig. 2 presents the typical RO membrane configuration per RO pressure vessel for a terrestrial desalination system. The feed seawater has a temperature of 31°C and a total dissolved solids (TDS) content of 40,104 mg/L at the inlet side on the top, the left side of Fig. 2. There are seven FilmTec™ SW30XLE-440 RO membrane elements by DuPont in the pressure vessel. The DuPont Water Solutions Water Application Value Engine (WAVE) is used to predict the permeate and brine quality. Each of the seven boxes in the upper-pressure vessel in Fig. 3.B is an RO-membrane element. The upper number in each box represents the feed TDS in mg/L of the specific RO membrane element. The lower number in each box represents the permeate TDS in mg/L that flows into the permeate tube and then out of the pressure vessel. The total dissolved solids (TDS) content of the feed water increases for each RO-membrane element in the series of RO-membrane elements. It can also be seen that the permeate TDS increases for each RO-membrane element. The last RO-membrane element has a feed flow TDS of 68,742 mg/L and produces permeate with a TDS of

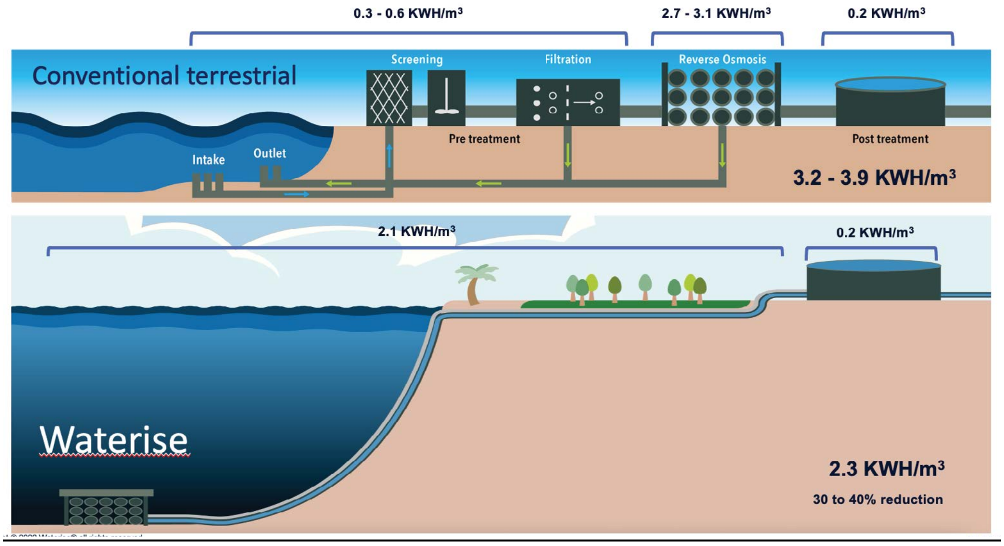

Fig. 1. Comparison of the energy consumption kWh/m³ of produce permeate.

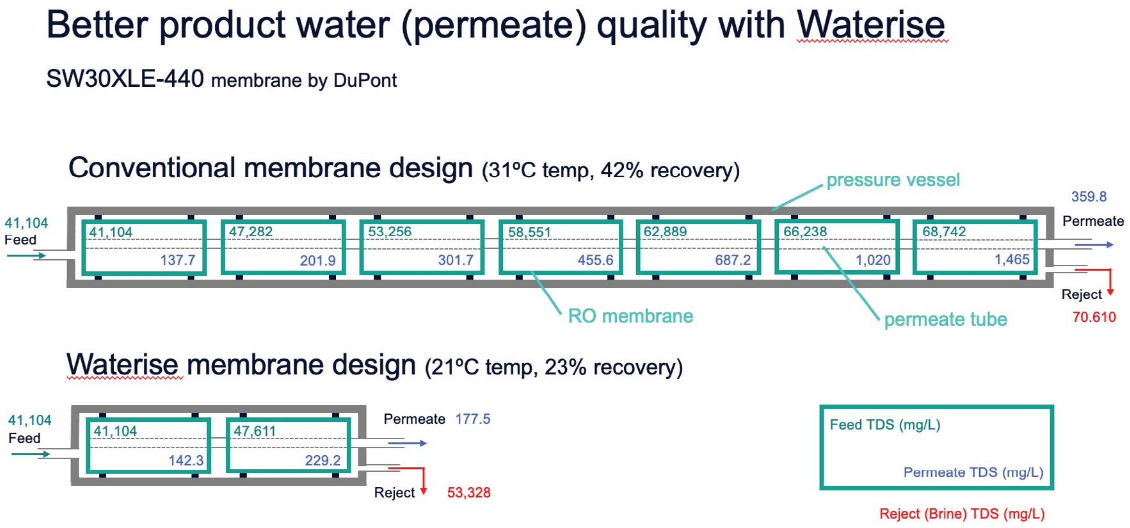

Fig. 2. Comparison of the terrestrial and subsea RO-membrane configurations.

1,465 mg/L. The combined permeate outlet downstream of the terrestrial pressure vessel yields permeate with a total dissolved solids (TDS) content of 359.8 mg/L. The discharge brine reject flow has a Total Dissolved Solids (TDS) content of 70,610 mg/L.

The ambient feed pressure advantage of the subsea system provides the opportunity to use only two RO-membrane elements in the subsea pressure vessel as shown at the bottom of Fig. 2. This is because there is no energy penalty from decreased recovery. The stable, cooler deep-water temperature is also an advantage with respect to the permeate quality.

The bottom of Fig. 2 presents the RO membrane configuration per RO pressure vessel for a subsea desalination system. The feed seawater has a temperature of 21°C and a total dissolved solids (TDS) content of 40,104 mg/L at the inlet side on the bottom, left side of Fig. 2. There are two FilmTec™ SW30XLE-440 RO-membrane elements by DuPont in the pressure vessel. The DuPont Water Solutions WAVE software predicts the permeate and brine quality. Each of the two boxes in the upper-pressure vessel in Fig. 3.B is an RO-membrane element. In this case, the last (second) RO-membrane element has a feed flow TDS of 47,611 mg/L and produce permeate with a TDS of 229.2 mg/L. The combined permeate outlet downstream of the terrestrial pressure vessel yields permeate with a total dissolved solids (TDS) content of 177.5 mg/L. The discharge brine reject flow has a total dissolved solids (TDS) content of 53,328 mg/L. The results from the DuPont Water Solutions WAVE prediction tool for the subsea and terrestrial desalination plant cases are shown in Fig. 1 are summarized in Table 1.

The subsea permeate total dissolved solids (TDS) content is predicted to be 177.5 mg/L. This is half of the predicted total dissolved solids content (TDS) of 359.8 mg/L from the terrestrial plant considering the same type of membranes.

3.3. Brine salinity only 1.3 times the salinity of seawater

The feed seawater total dissolved solids (TDS) content is 41.104 mg/L in the example shown in Fig. 1 where the results from the DuPont Water Solutions Water WAVE software tool are shown in Table 1 for the subsea and terrestrial desalination systems.

The subsea discharge brine total dissolved solids (TDS) content is predicted to be 53,328 mg/L. The terrestrial discharge brine total dissolved solids content (TDS) is expected to be 70,610 mg/L.

The subsea brine total dissolved solids (TDS) content is 1.3 times the feed seawater total dissolved solids (TDS) content. For comparison, the terrestrial desalination plant yields brine with 1.7 times the feed water salinity.

The subsea desalination system has a lower environmental impact because it produces less saline brine and discharges it at a deep-water location. This means there is less effect on the flora at depths of 400 m or more, as no corals or other plants live there due to the lack of light.

3.4. Very high plant availability when combining (1) feed water quality with (2) built in redundancy and (3) subsea production system philosophy

The availability estimate includes the scheduled downtime and the unscheduled downtime for the subsea desalination process system and the terrestrial post-treatment system.

The downtime due to feed sea water quality issues is eliminated. The deep-water location of the intakes prevents the impact by algae blooms, jellyfish, petroleum spillage, and other issues often seen at surface level. There is therefore no annual downtime due to permeate non-compliance because of the high-quality sea water feed.

The unscheduled downtime is caused by unforeseen equipment failure. The equipment failure estimates are based on supplier information and the OREDA Handbook [5].

The system availability of 98.2% presented in Fig. 3 is the product of the availability of the subsea seawater RO (SWRO) desalination system (including the onshore power system) and the availability of the terrestrial post treatment system. The calculation methodology is based on the equations provided by OREDA (commonly used for availability calculations), where availability is the product of the equipment components' availability. The availability will decrease with the increased number of components. The drop in availability due to the product of equipment components availability is countered with hot stand-by equipment components in the system. The hot standbys will increase

Table 1
Comparison of permeate and brine quality for the subsea and terrestrial desalination plant

		Subsea	Terrestrial
Permeate total dissolved solids (TDS)	mg/L	177.5	359.8
Brine total dissolved solids (TDS)	mg/L	53,328	70,610

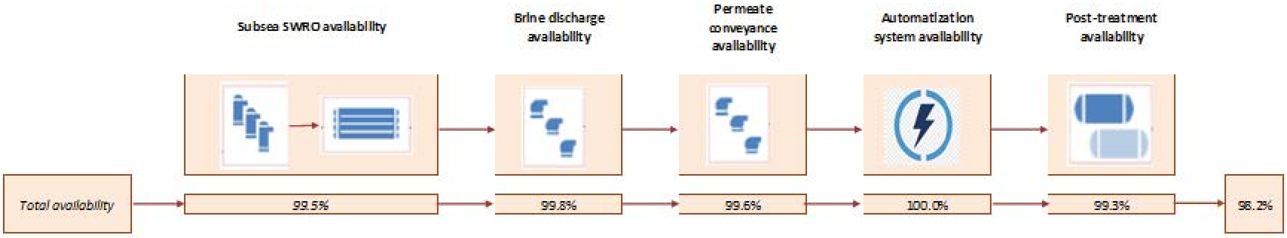

Fig. 3. System availability calculation.

availability because the eventual failure of a component does not impact the performance of the system.

The subsea desalination system has redundancy in each equipment component. The Waterise maintenance plan of the subsea desalination system is based on the Total Productive Maintenance (TPM) plan. The unscheduled downtime due to mechanical failures is significantly decreased.

4. Subsea field tests

The subsea desalination system has been tested in four test campaigns in Boknafjorden, Norway, from August 2020 to June 2021. The feed sea water at the test depth between 420–480 m in Boknafjorden has a feed seawater salt content of 35.1 ppt and a temperature of 7.6°C. A fifth test campaign was performed in the Red Sea outside Jeddah, Saudi Arabia, February 2022. There the feed sea water salt content was 40.6 ppt with a temperature of 21.7°C at the test depth. This paper shows the results from the fourth test campaign in Boknafjorden in June 2021 where the subsea demonstration test rig was operated continuously for 73 h.

Throughout the testing process, the subsea demonstration test rig remained suspended from the umbilical, connected to the winch on the topside vessel. The rig hung at a depth and vertical distance of 50 m above the sea bottom.

The left photo in Fig. 4 presents the subsea demonstration test rig on the deck of the vessel before deployment into the sea. The winch, the umbilical and the umbilical sheave are also shown in the foreground. The mid photo in Fig. 4 presents the subsea demonstration test rig hanging under the sheave from the umbilical immediately before deployment to the test depth. The right photo in Fig. 4 shows the subsea demonstration test rig.

The Subsea Demonstration Test Rig has topside and subsea main equipment.

The topside main equipment is the umbilical winch, the umbilical sheeve, the topside control station, and the topside end of the permeate water hose, filling up produced permeate water to the sampling bucket. The umbilical contains the power cables, the communication cable and the permeate water hose.

The subsea main equipment is a cartridge pre-filter, a RO membrane, a pressure vessel, one high-head transport pump to create the suction pressure and lift the permeate to the surface, and one low-head circulation pump to circulate seawater through the RO membranes, and the necessary piping, valves, pressure sensors and flow meters to direct and monitor the flow of permeate and seawater through the system. Additionally, it also contains a canister to house all the electronics, for example, sensor controllers, fiber optic modem.

The tests have been conducted with the DuPont™ FilmTec™ Seamaxx™ 440 and SW30XLE-440 RO membranes mounted into the RO membrane pressure vessel.

The system is cleaned and primed with fresh water from the municipal waterworks before the deployment to sea and test start. Fig. 5 presents the typical start of a subsea test. The first half hour of the test the primed fresh water is pumped out of the subsea demo rig during the period before 17:00 in Fig. 5. The primed fresh water from the municipal waterworks was measured with the conductivity instrument (Hach) immediately upstream the outlet of the hose before 17:00.

In Fig. 5 the produced permeate arrived at the outlet of the hose approximately 30 min after the start of the pumps at 17:00. The conductivity peak can be seen at 17:00.

The permeate conductivity measured with the conductivity meter (Hach) located immediately upstream the outlet of the hose then dropped rapidly down from 904 to 223 µS/cm at 17:30. Thereafter, the permeate conductivity dropped further down to 214 µS/cm after 5 h of operation. Then the conductivity slowly decreased to approximately 200 µS/cm during the two last test days (not shown in Fig. 5).

The decrease in conductivity shown after 17:00 in Fig. 5 during the first hours and days is expected when starting up the system with new RO-membranes. Initially, before the start-up, the water at the permeate side of the membrane surface is salty due to the preservation fluid and also due to diffusion of salts through the membrane surface. After start-up, the convection of water becomes the dominant flow mechanism through the membrane surface. The diffusion of salts through the membrane surface becomes significantly less than the convection of water. Some of the reduction in conductivity is due to flushing the salty water out of the permeate side of the system, and some may be to the stabilization if the RO-membrane.

Fig. 6 presents the pressures along the stream from upstream the prefilter at the left side (pf), through the prefilter (p2), through the retentate side of the RO-membrane

Fig. 4. Photos of the subsea demonstration test system.

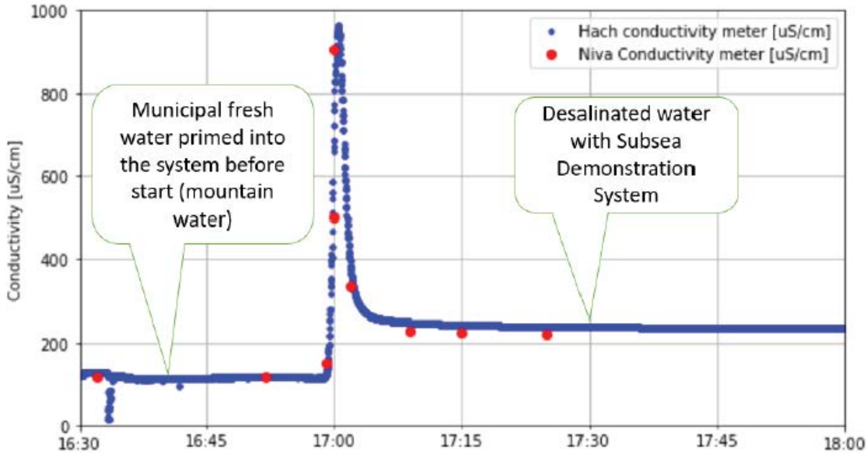

Fig. 5. Permeate conductivity immediately upstream the topside outlet during the first hours of the test.

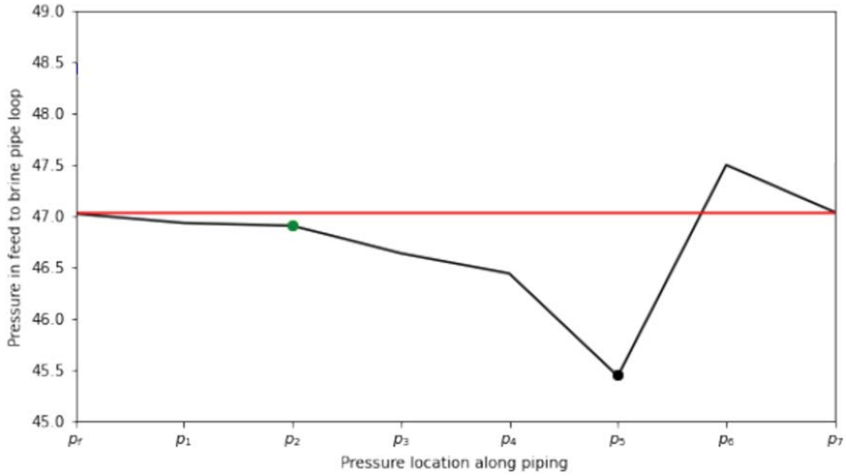

Fig. 6. Pressures along the flow path of the feed inlet and brine outlet flows.

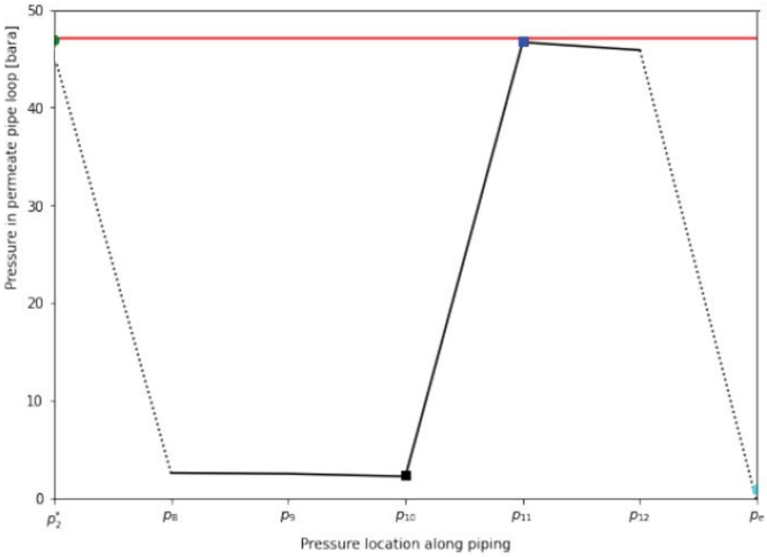

Fig. 7. Pressures along the flow path of the permeate flow.

(p3), through the brine pump (p4), through the brine outlet pipe (p5), and out the discharge outlet (p6).

Fig. 7 presents the pressures along the stream from the RO-vessel, out of the RO-vessel's permeate outlet (p8), through the permeate pump upstream (p10) and downstream (p11) and through the umbilical hose up to the topside outlet of the hose.

The absolute pressure (p8) immediately downstream the RO-vessel's permeate outlet is approximately 2 bara and is slightly above the permeate pump's required NPSH limit.

The pressure differences, shown in Figs. 6 and 7, over the RO-membrane cartridge were as expected when compared with the predictions from the DuPont WAVE software.

The DuPont™ FilmTec™ SW30XLE RO-membrane provides somewhat better permeate quality at somewhat increased pressure difference relative to the DuPont™ FilmTec™ Seamaxx™ 440 RO membrane as expected. The conductivity measurement results were in good agreement with the DuPont WAVE modelling software.

5. Conclusion

A design for a subsea membrane offers a compelling benefit to its customers – a positive impact on the environment (without the use of chemicals), less demand for land, and the possibility of lower costs with improved reliability, safety, and security.

But in addition to these, the subsea system provides other benefits:

- The membrane design operates at reduced pressure and recovery, utilizing the natural hydrostatic pressure to supply pre-membrane pressure.
- Large reduction in energy consumption, adding to significant positive changes for the environment.
- Permeate quality advantage, which in most cases can meet the most stringent water quality requirements and eliminate the need for a second pass.
- Connected to low recovery is that brine salinity is only 1.3 times the salinity of seawater, which reduces the risk of impacting the marine ecosystem and facilitates dilution.
- The combination of favorable raw water quality with built-in redundancy and the subsea production system philosophy delivers high reliability and low maintenance.
- The plant's location at approximately 400+ m below sea level adds safety and natural security to the plant.

The performance of the RO membrane was found to be in line with expectations when tested in a subsea desalination system and operated at great depths, as predicted by the DuPont WAVE software tool.

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