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Independent testing of commercially available, high-permeability SWRO membranes for reduced total water cost

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ABSTRACT

Energy remains the major operating expense when producing desalted water by seawater reverse osmosis (SWRO). Recent advances in membrane materials and highly efficient energy recovery devices have drastically reduced the energy required to desalinate seawater over a wide range of system capacities. This study tests the performance of novel, commercially available, high-permeability membranes (including nanocomposite membranes) over an extended period of time. Tests were carried out utilizing a 125 m^3/day SWRO system with independently verified continuous power monitoring. The desalination subsystem utilizes a staged membrane configuration and a low flux—low recovery design to minimize the overall energy consumption, reduce potential fouling, and reduce membrane cleaning. The specific power required to desalinate water to produce potable water having total dissolved solids below 400 mg/L was consistently below 2.0 kWh/m^3 for feedwater temperatures above 20 ℃ using commercially available high pressure pumps and energy recovery devices.

Keywords: SWRO; High permeability membrane; Nanocomposite membrane

1. Introduction

The major operating expense when producing desalted water by seawater reverse osmosis (SWRO) is energy consumption. The desalination process requires the major proportion of energy utilized by SWRO. Recent advances in membrane materials and efficient isobaric energy recovery devices have brought down the amount of energy required to produce potable water from seawater over a wide range of system capacities. The well-cited Affordable Desalination Collaboration (ADC) achieved an energy consumption of 1.58 kWh/m^3 using commercial, off-the-shelf technologies at their demonstration facility located in Port Hueneme, California. This was achieved utilizing the DOW SW30XLE-400i membrane at a recovery of 42% and an average flux of 10.2 L/m^2/h for seawater having an average total dissolved solids (TDS) concentration of 35,390 mg/L and average feedwater temperature of 15 ℃ [1].

Campbell Applied Physics has developed the advanced seawater reverse osmosis (ASWRO) desalination system which incorporates a system engineering approach to desalting of seawater at a total energy of <2.6 kWh per cubic meter of fresh water (for intake seawater salinity <40 PSU) designed for the small- to

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Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012, Barcelona, Spain medium-scale market. Key system requirements which had an impact on reverse osmosis process parameters was the need to design modules having a production capacity of 1,000 m^3/day, specific energy requirement for desalination subsystem to be <1.8 kWh/m^3 over a range of feedwater temperatures and salinities, maximize membrane life and minimize CIP requirements. A demonstration unit designed to produce 125 m^3/d of drinking water to meet California's drinking water standards and WHO drinking water quality guidelines was built in 2010.

A number of membrane manufacturers offer high-performance seawater membranes to choose from. This paper describes our ongoing experience with the testing of various types of membrane elements and configurations. The results of these tests will feed the selection process for element type and configuration for commercial systems. The selection process is based on minimizing the component of total water cost which is associated with the choice of membranes both in terms of capital cost as well as operating cost per cubic meter of water produced over the useful life of the project.

2. Materials and methods

Pacific Ocean water is delivered periodically to the test site via tanker truck and stored onsite in large tanks. The initial salinity of the water varied between 37 and 38 PSU. The electric conductivity and feedwater temperature during the two test periods are shown in Figs. 1 and 2. The permeate and brine streams from the desalination unit are recombined in these storage tanks, and as can be seen in the figures below, the salinity of the feedwater being desalinated increased considerably through the test period reaching TDS concentrations of over 41,000 mg/L. Since the water is stored in above-ground tanks, since commissioning in May 2010, the feedwater temperatures ranged from 11 to 36 °C. Step changes in feedwater temperature and electric conductivity are due to new consignments of seawater.

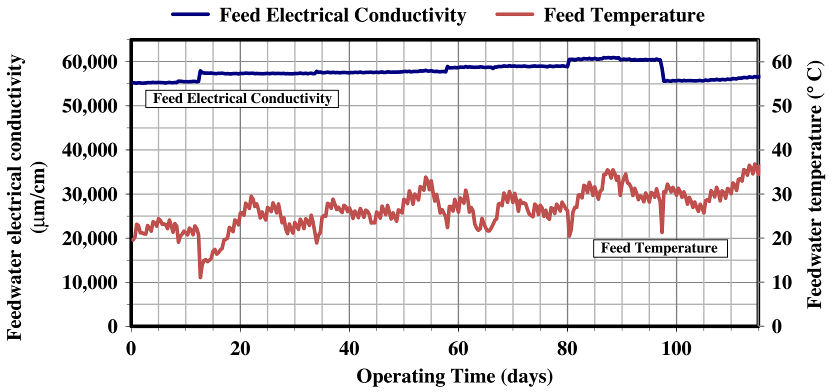

Fig. 1. Feedwater temperature and electrical conductivity over Test Period 1.

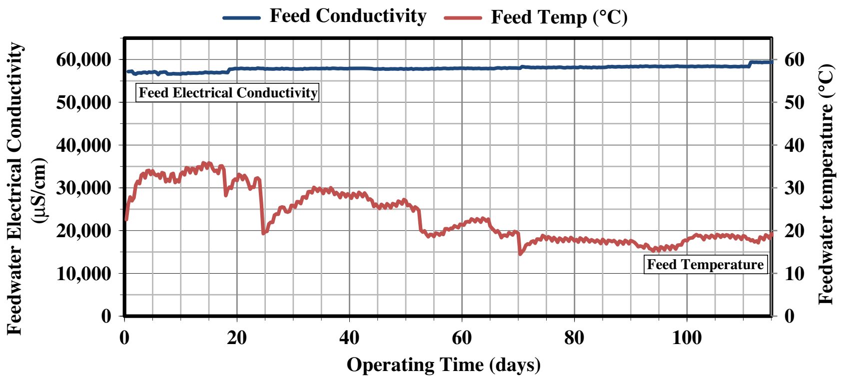

Fig. 2. Feedwater temperature and electrical conductivity over Test Period 2.

Pretreatment of the demonstration system consists of coarse filtration (which simulates the use of indirect seawater intake methods having an SDI < 4), oxidation, micro screening, and finally oxidant removal.

The high pressure (HP) loop is made up of three main components: a HP pump, energy recovery device (ERD), and pressure vessel assembly. A Danfoss APP8.2 axial piston HP pump is employed in the demonstration unit. Internal moving parts of the APP pump are lubricated by seawater feed.

The ERD utilized in the system is a Danfoss iSave21, which consists of an isobaric pressure exchanger, a HP positive displacement booster pump, and an electric motor integrated into a single device. The booster is of the vane type (fixed displacement) in which flow is proportional to the number of revolutions of the driving shaft enabling flow control. Coupled to this shaft is the pressure exchanger enabling simultaneous flow control of both the pressure exchanger and booster pump using the variable-frequency drive (VFD-)controlled electric motor preventing over spin [2]. Both the Danfoss iSave21 and the APP8.2 pumps are standard, commercially available, off-the-shelf products and are equipped with variable frequency drives.

The pressure vessel assembly is equipped with two parallel side-ported pressure vessels which hold seven 8-inch SWRO membranes.

The objective of the design phase was to evaluate the effect on process economics of the major design parameters (system recovery rate and average system flux) over a variety of feedwater salinities and temperatures while meeting the system criteria mentioned above. A low permeate flux of 10–11 L/m^2/h together with a system recovery rate of 36% were chosen after evaluating capital and operating costs for various configurations over the lifetime of the project.

The membrane configuration uses a hybrid membrane inter-stage design (HID) which consists of two or more different types of membranes of different permeate flux to reduce the lead to tail element flow imbalance by placing a low flux element in the lead position/s followed by high flux elements [3]. Since 2008, a number of commercial seawater desalination facilities have been operating by utilizing the HID successfully with considerable cost savings [4]. The decreased flux through the first element reduces the potential for colloidal and biological fouling of this lead element as well as reducing feed pressure requirements substantially.

Table 1
Membrane configuration and element properties for TFC membranes utilized during Test Period 1

Element position		1	2	3–7
Permeate flow rate	m^3/d	23	34	41.6
Membrane area	m^2	37.16	37.16	37.16
Stabilized salt rejection	%	99.80	99.70	99.70
Stabilized boron rejection	%	93	88	87

Table 2
Membrane configuration and element properties for TFN membranes utilized during Test Period 2

Element position		1	2–7
Permeate flow rate	m^3/d	28	47
Membrane area	m^2	33.91	33.91
Stabilized salt rejection	%	99.85	99.75
Stabilized boron rejection	%	93	88

The demonstration system employed two HID membrane configurations: Polyamide thin-film composite (TFC) membranes and thin-film nanocomposite (TFN) membranes. The membrane configuration and properties are given in Tables 1 and 2. The TFN membranes incorporate nanoparticles within the polyamide layer which are reported to increase permeability and "alter surface properties potentially related to fouling" while maintaining salt rejection [5]. TFC and TFN membranes were tested during Test Period 1 and Test Period 2, respectively.

Performance testing of the demonstration unit has been ongoing since May 2010 to ensure that the system can continuously meet design specifications and performance goals in regard to product water quality and quantity, energy use, reliability, noise levels, and pretreatment efficacy over the long term. Specific periods of testing since commissioning have been carried out under the guidance and supervision of an independent expert to validate and monitor the results.

A supervisory control and data acquisition (SCADA) system continuously monitors a number of process parameters of importance for automated system operation and system performance assessment.

Specific energy requirements for the desalination subsystem reported below include the power requirements solely for the HP pump and the iSave ERD. The power requirements for these two components were obtained as the multiple of motor voltage and current. This power is divided by the permeate flow rate to obtain specific power consumption. Independent testing showed that the value obtained for power consumption from the VFD voltage and current was not accurate. Tests were carried (Itron Quantum Q1000 power meter) out to obtain a correction factor for both devices to obtain accurate power readings from the voltage and current values logged by the SCADA system. It must be noted that the value given does not include the energy required by the intake pump which feeds the pretreatment system and provides a suction pressure to the HP pump and ERD of 1.7 ± 0.2 bar.

3. Results

The HP seawater flow rate from the iSave unit is dependent on the iSave rpm. The feedwater flow to the membranes from the iSave unit was calculated by multiplying the iSave motor speed (rpm), which is logged by the SCADA system, with the rated flow rate specified per rpm tested for the particular unit. This flow rate is added to the measured flow rate passing through the APP pump to obtain the membrane feed flow rate.

Due to the large fluctuations in feedwater temperature, the normalization of data with respect to projected process conditions was required to monitor membrane performance. Data were normalized to a feedwater temperature of 25 ℃ and seawater having a TDS concentration of 35,000 mg/L. The following tables and figures give a picture of performance of the demonstration desalination system utilizing the two membrane configurations tested.

3.1. Results from Test Period 1 utilizing polyamide thin-film composite membranes

See Table 3 and Figs. 3–6.

3.2. Results from Test Period 2 utilizing thin-film nanocomposite membranes

See Table 4 and Figs. 7–10.

Table 3
Performance parameters for testing of demonstration system utilizing polyamide TFC membrane configuration

Test duration	115 days
Feedwater electrical conductivity	57,758 ± 1,620 μS/cm
Feedwater temperature	22.3–31.2 ℃
Permeate flow	5.3 ± 0.1 m^3/h
System recovery	35.1 ± 0.4%
Feed pressure at 25 ℃ and EC of 55,880 μS/cm	45.0 bar
Average feed pressure over range of test	45.5 ± 1.7 bar
Pressure differential at start & end of test period	Start = 0.7 bar, end = 0.74 bar
Permeate pressure	0.03 ± 0.01 bar
Permeate electrical conductivity	627 ± 116 μS/cm
Specific energy requirement—HP pump	1.63 ± 0.06 kWh/m^3
Specific energy requirement—iSave ERD	0.23 ± 0.01 kWh/m^3
Specific energy requirement—HP pump + iSave	1.86 ± 0.06 kWh/m^3

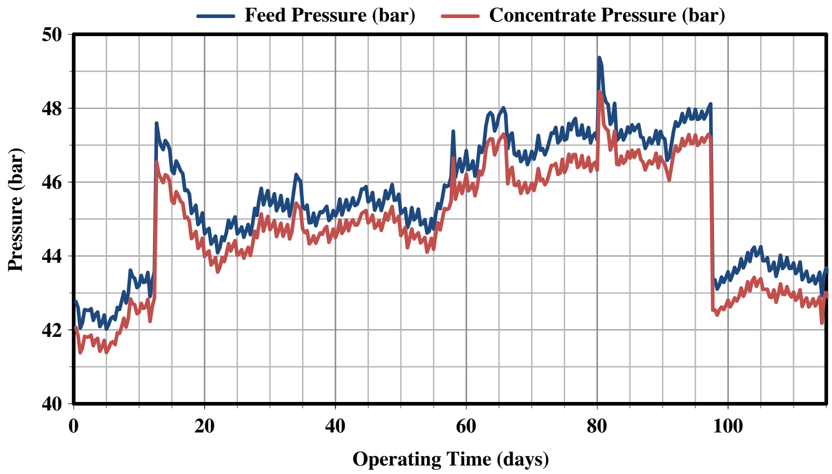

Fig. 3. Feed and concentrate pressure.

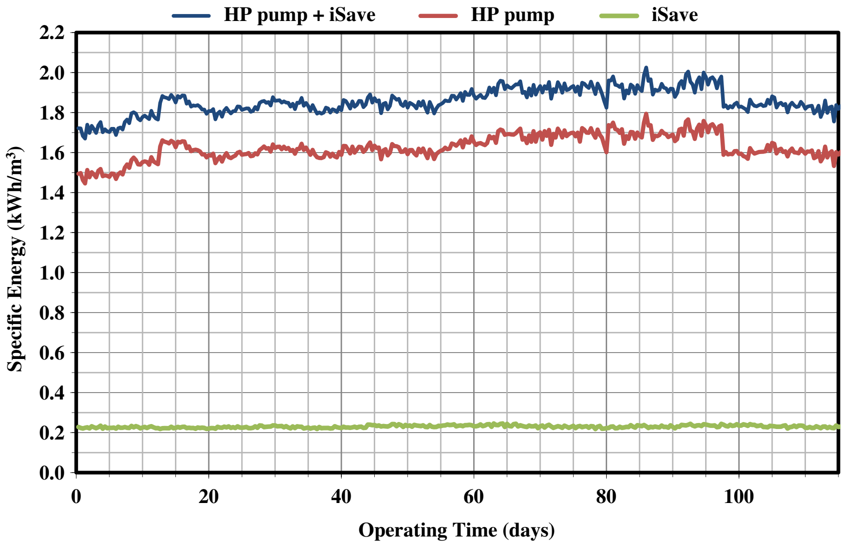

Fig. 4. Specific requirement for the iSave ERD, HP pump, and iSave + HP pump.

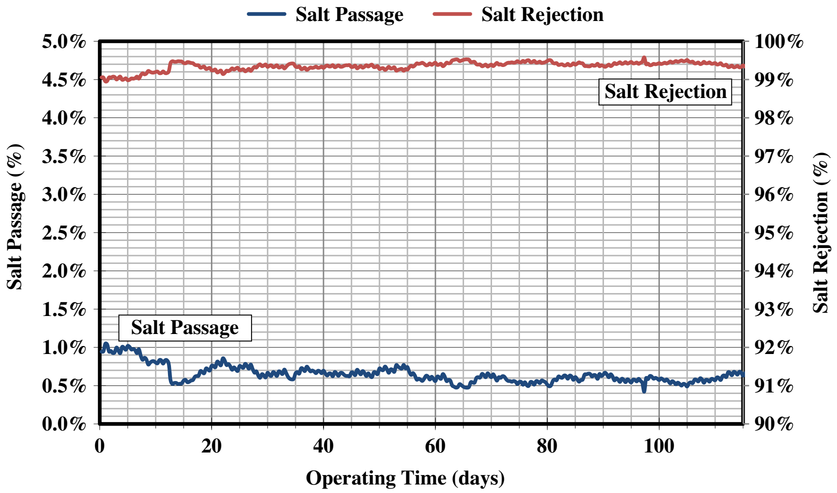

Fig. 5. Normalized salt passage and salt rejection.

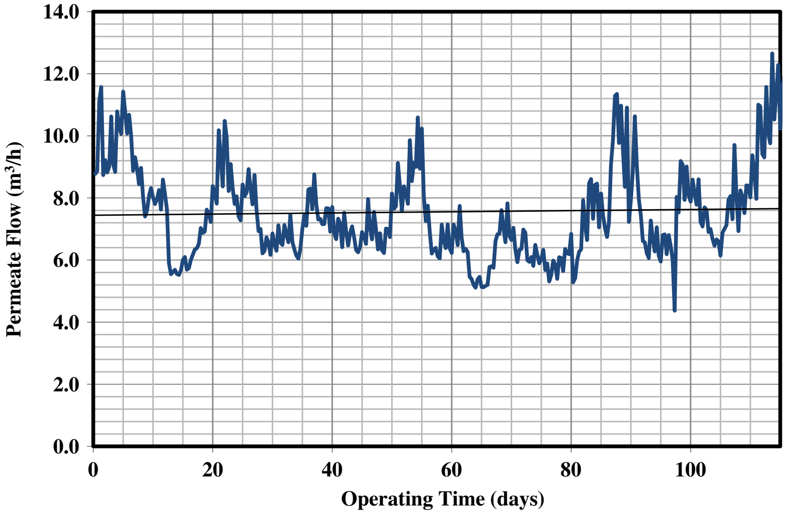

Fig. 6. Normalized permeate flow.

Table 4
Performance parameters for testing of demonstration system utilizing nanocomposite membrane configuration

Test duration	115 days
Feedwater electrical conductivity	57,920 ± 560 μS/cm
Feedwater temperature	17.2–29.4 ℃
Permeate flow	5.2 ± 0.1 m^3/h
System recovery	35.4%
Feed pressure at 25 ℃ and EC of 57,330 μS/cm	45.1 bar
Average feed pressure over range of test	45.9 ± 1.4 bar
Pressure differential at start/end of test period	Start = 0.8 bar, end = 1.7 bar
Permeate pressure	0.04 ± 0.01 bar
Permeate electrical conductivity	576 ± 184 μS/cm
Specific energy requirement (Avg)—HP pump	1.60 ± 0.1 kWh/m^3
Specific energy requirement (Avg)—iSave ERD	0.23 ± 0.01 kWh/m^3
Specific energy requirement (Avg)—HP pump + iSave	1.82 ± 0.11 kWh/m^3

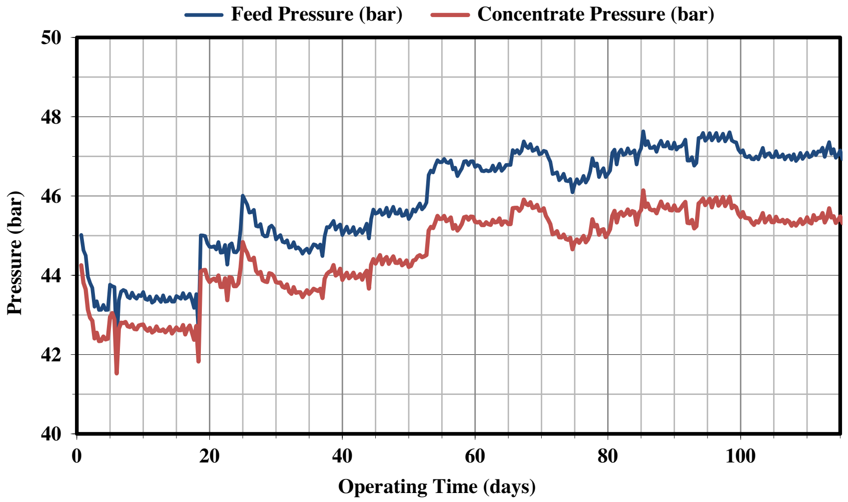

Fig. 7. Feed and concentrate pressure.

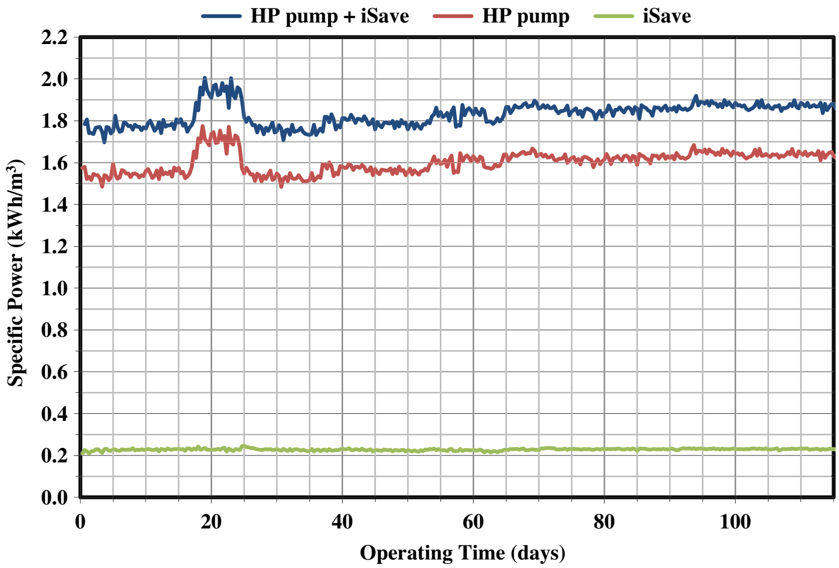

Fig. 8. Specific energy requirement for iSave ERD, HP pump, and iSave + HP pump.

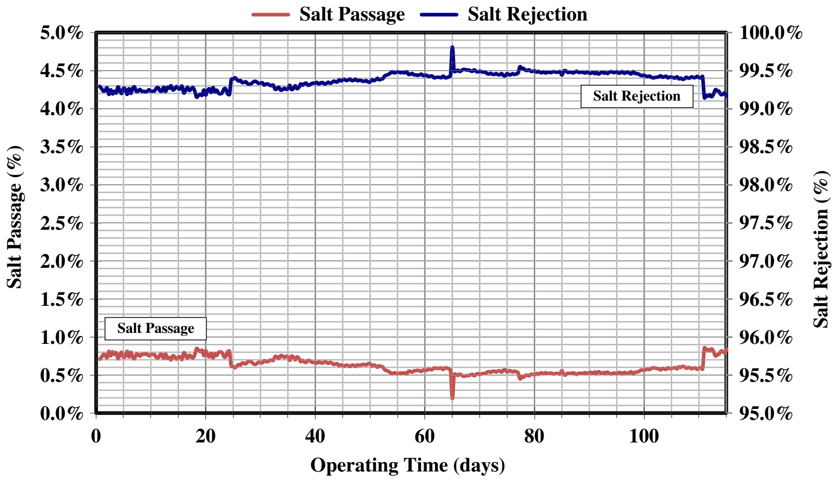

Fig. 9. Normalized salt passage and rejection.

4. Conclusion

Results from ongoing tests of a one-eighth scale demonstration system show that low specific energy requirements consistently less than 2.0 kWh/m^3 are possible using standard off-the-shelf components over a range of feedwater temperatures. The TFN membrane configuration had a slightly lower average specific energy consumption than the TFC membrane configuration when comparing results—1.82 ± 0.11 kWh/m^3 for the TFN membranes vs. 1.86 ± 0.06 kWh/m^3 for the TFC membranes. The results are not directly comparable because of the wide range of feedwater temperature during the two test periods.

Membrane selection will be carried out to minimize the component of total water cost which is affected by the selection of membrane type (manufacturer, element performance metrics) and configuration (type and combination of types of elements) for particular site feedwater conditions. The results for specific energy from test data will be utilized to project energy costs over the lifetime of the project discounted to present value. Trends in membrane fouling and the effect of fouling on element replacement rate and cleaning requirements are very specific to feedwater quality and pretreatment efficacy; and although such testing gives an indication of membrane susceptibility to fouling given a feedwater quality and pretreatment

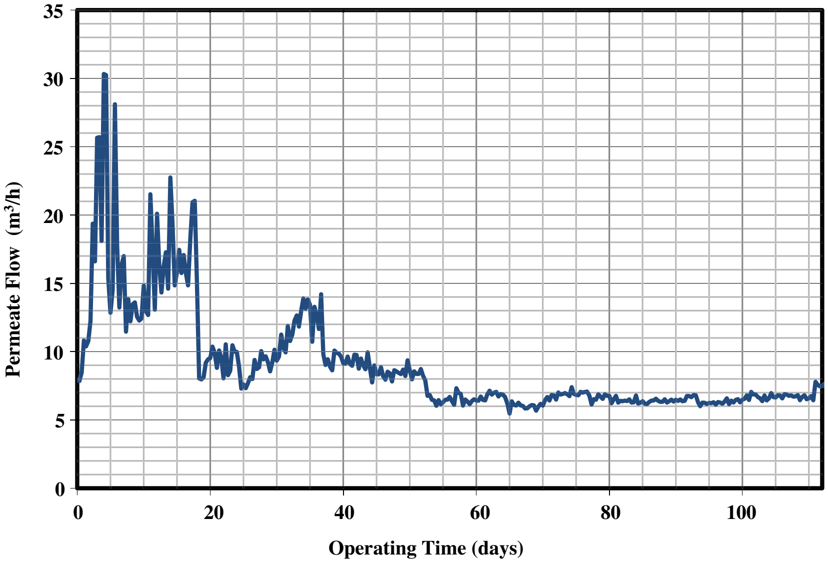

Fig. 10. Normalized permeate flow.

setup, this remains a project specific component of the total water cost.

In the selection process, besides the performance evaluations, practical considerations including the method of connection between membrane elements where there is a possibility of feed–permeate leakages through pinched o-rings, the ease of loading and unloading of elements, and the diameter of the permeate tube need to be examined. Other considerations related to commercial interest in the choice of membrane type and configuration particular to a membrane manufacturer include terms of credit, the cost of delivery to assembly site and project site (for replacement elements), the point at which there is a transfer of ownership during delivery (who bears the liability of loss), membrane manufacturer acceptance criteria for inherent variations in membrane performance, replacement policy for nonconforming elements, warranty, the lead time to delivery, and the accessibility of manufacturers' field service personnel.

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