PERFORMANCE AND CHARACTERISTICS OF REVERSE OSMOSIS MEMBRANES

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ABSTRACT

This paper discusses the performance and characteristics of desalination membranes used in treatment of water for industry and potable use. In this study, a recent advance have been made in spiral wound reverse osmosis membrane elements which make them particularly well suited for desalting high TDS water, such as found in Red Sea and Arabian Gulf. This paper presents the results of the operational performance of RO units in Al-Yosr plant, Hurghada, Red Sea, Egypt.

The rate of decline of productivity for a period 48 months was examined and described by simple power law function. The evaluation of the solvent and salt permeability coefficients with the time of operation is quantified. The results show the recovery, pressure and conductivity across the membrane for 365 days test run. Also, the results show the effect of chemical additives and operational parameters on the performance of the membrane during the cleaning. Based on such individual RO module data (one year) the product flow rate and Total Dissolved Solids (TDS) performance is calculated and RO module replacement ratio can be estimated.

Key Words

Desalination, spiral wound reverse replacement, module replacement, permeate and performance.

INTRODUCTION

Two trade associations oriented toward desalination technology organizes a conference each year and publishes the technical proceedings, namely the International Desalination Association (IDA), the American Desalination Association (ADA)- formally known as the National Water Supply Improvement Association (NWSIA). The National Water Research Institute (NWRI) has also organized conference and published their proceedings, Also the American Water Works Institute (AWWI) publishes a monthly journal which often times includes paper pertaining to desalination technology.

Modern research and development of membrane desalination technology is now more than four decades old. An industry offering a wide range of competitive products has developed over the years to meet the drinking water demands of the 21st century. Advancements in membrane materials and other aspects of this technology have lowered overall operating costs, which will ultimately reduce the cost of implementing public water quality improvement programs.

Spiral wound elements are normally used in high flow applications [1, 2]. RO membrane is tested in a quality control test loop before it is shaped under specific conditions [3]. There are computer models that can simulate the performance of membranes based on feed water characteristics of treatment system. In some tests of membrane an experimental error may be increase due to additional handling and also variations of swatch bench testing may be significant [4]. The fouling film detected on the surface of RO membranes, which is responsible about the decline of RO performance [5]. Membranes generally operate based on three principles and they include *(a) Filtration, (b) Diffusion, and (c) Adsorption.* Each membrane process utilizes varying degrees of principle to properly function [6]. The operation and maintenance of membrane is very important and normally controlled and monitored by Supervisory Control and Data Acquisition (SCADA) computer software. The primary operation and maintenance factors by SCADA include the following:

1 - Operating pressure — *2 - Flux rate*
3 - Rejection percentage — *4 - Recovery percentage*
5 - Fouling — *6 - Concentration Polarization*
7 - Chemicals — *8 - Temperature*
9 - Turbidity (1 NTU) — *10- pH*
11 - Electrical conductivity — *12 - Silt density index (SDI)*

But the membrane life affect by the following factors:

(l) Hydrolysis, (2) Operating pressure, (3) Bacterial attack,

(4) Chemical degradation, and (5) Fouling.

The basic governing equations of the product transport and salt flux through the membrane for steady state, assuming diffusive flow and neglecting leakage, are expressed as [9, 10]:

$$F_w = A\,(\Delta P - \Delta\pi) \quad (1)$$

$$F_s = B\,(C_t - C_p) \quad (2)$$

Where the permeability coefficient A and B are defined as:

$$A = D_w c_w V/(RTL) \quad (3)$$

$$B = D_s c_s/(Lc) \quad (4)$$

Over their operating time, the membranes compact resulting reduced the flow capacity. This phenomenon is refereed to as "membrane flux decline" which is expressed as a Membrane Flux Retention Coefficient (MFRC), i.e.

$$MFRC = Q_{pt}/Q_{pi} \quad (5)$$

The relationship between Q_{pt} (permeate flow rate at time t) and Q_{pi} (permeate flow rate at initial setup) has been proposed by power law function [11, 12] and given by:

$$Q_{pt} = Q_{Pi}\, t^{-m} \quad (6)$$

The Salt Reduction Factor S.R.R and rejection percent are calculated for the membrane as follow [13]:

$$S.R.F. = (C_f/C_p) \quad (7)$$

= ppm in feed water / ppm in product, and

$$\%\ Rejection = [\,1 - (1/S.R.F.)\,] \times 100 \quad (8)$$

The goal of this paper is to describe the performance characteristics of spiral wound elements of membrane, in particular the long term's performance of RO units. Also, RO module performance curve versus time can be illustrated.

MEMBRANE CHARACTERISTICS

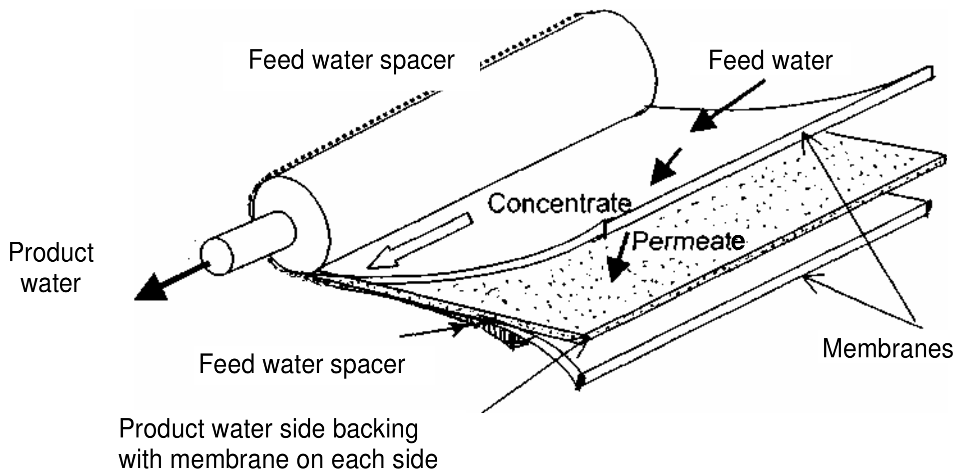
In this study spiral type of reverse osmosis modules are used which occupies the smallest space of all the systems available today. The spiral wound modules are constructed from two layers of semi-permeable membrane (aromatic polyamide) of thin film composite (TFC) which are made into a sandwich with a highly micro porous but incompressible backing material inside. The sandwich is wound spirally around a plastic pipe (central pipe) like Swiss roll but with an open weave spacer placed in between to separate adjacent membrane surfaces (20.32 cm diameter by 1 m long) as shown in figure 1(a). Each element contains approximately 27.9 m^2 (300 ft^2) of membrane area and a gap 0.79 mm feed channel spacer. Elements are joined in series by 15 cm long interconnections with up to six elements and installed in a pressure vessel 6.5 m long and 20 cm diameter, as shown in Figure 1(b). The feed water stream flows axially through the channels between the spiral windings. Water permeates through the membrane and flows radially inside the membrane layers towards the central product tube, which passes through one end of the pressure vessel. In this end the concentrated water is outlet without a significant pressure drop inside the pressure vessel.

The Fluid System Corporation (FSC) has developed spiral wound elements that display sufficiently high salt rejection (99.6 %) and work under high pressure up to 83 bar. RO membranes are effective in removing Total Dissolved Solids (TDS) in any feed water and up to 40,000 mg/l (ppm) [6]. RO membranes can be distinguished from other membranes based on bore sizes around 0.0005 microns [8] and is so small that it functions primarily by diffusion instead of filtration and adsorption. The specifications of spiral wound module under considerations are given in Table 1.

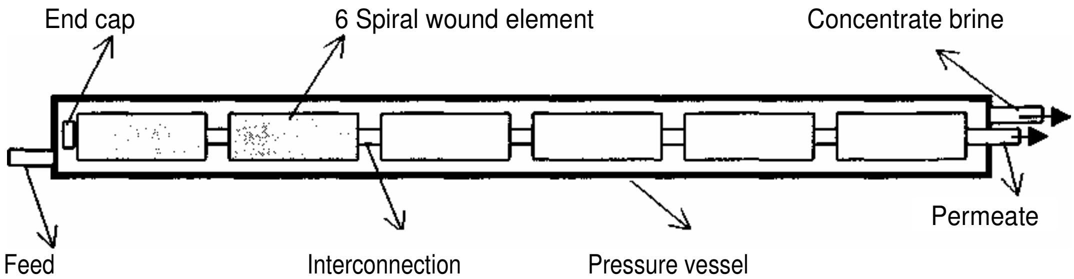
Table 1: Spiral wound specifications

Parameters	Value
TFC membrane module	2282
Membrane length	40" (101.6 cm)
Membrane width	8" (20.32 cm)
Membrane area	300 ft^2 (27.9 m^2)
Membrane drained weight	40 lb (18.1 kg)
Design rejection	99.4 %
Design permeate flow rate	5000 U.S. gpm (19.0 m^3/d)
Maximum operating pressure	1000 psi (69bar)
Allowable operating - cleaning pH range	4-11, 2.5-11
Allowable feed water temperature	1 to 45 °C
Turbidity	1 NTU
Slit density index (SDI)	5

<u>Test condition:</u> 32800 mg/l NaCI solution (isosmotic to ASTM seawater), 800 psi (55.2 bar), 7% recovery, 25 °C and pH 5.7. Data are collected on each element after 30 minutes of operation at this condition.



(a) Direction of Flow in Spiral Module



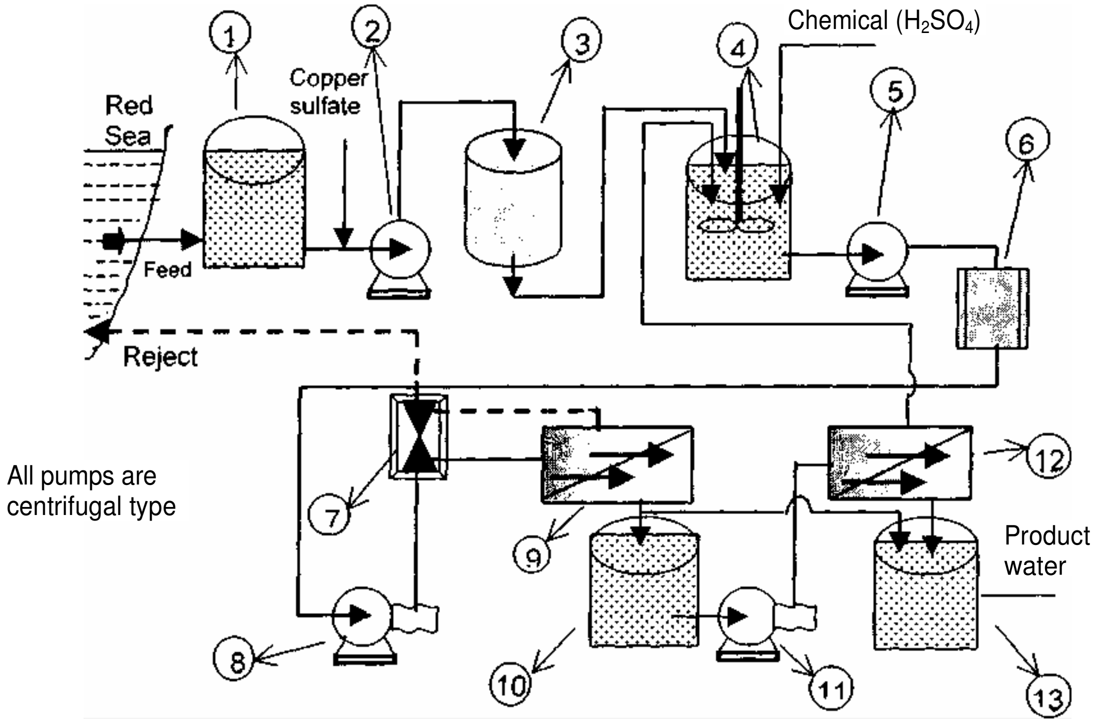
(b) Section in Module Pack assembly

Figure 1. Spiral Wound Membrane Module

TEST SYSTEM DESCRIPTION

Ongoing long-term tests of the TFC (thin film composite) membrane are being conducted at Hurghada city located in Red Sea coast, Egypt. The RO process in Al-Yosr seawater reverse osmosis plant consists of two stages. The first stage RO produces 4800 m^3/day with 500 ppm of TDS and 30% recovery. The product of first stage is fed to the second stage and produces 3450 m^3/day with 100 ppm of TDS and 80% recovery.

A schematic diagram of RO Al-Yosr plant is shown in Figure 2. The feed saline water from Red Sea flow by gravity to *intake feed tank (1)* through three large PVC pipes (10 m below sea level). This tank provided with screen to prevent fish and other trash to enter the system. A Copper sulfate is added to the water's tank to control algae and other bio-growth, then pumped to *multi media filters (sand filters* - 3) by *centrifugal pumps (2).* The output from the filter is accumulated in *mixing tanks* (4), then sulfuric acid is added to lower pH to approximately 6.4 and Sodium hexameta sulfate is also added to the water as antiscalent to prevent scale formation in RO membrane. The *vertical turbine pumps (5)* suck the clear water from the mixing tanks and discharge to *cartridge filters (6),* to prevent the particles larger than 5 microns to enter the membrane, and feed directly to *high pressure pumps (8).* The *high pressure pumps (8)* (P = 47 bar, Q_f = 192 m^3/hr each) are used to pump water to the *first stage membranes (9).* The 1st stage RO units consist of 4 banks and each bank contains 20 pressure vessels. The feed saline water under high pressure is made to flow across the membrane surface, part of this feed passes through membranes, which removes the majority of the dissolved solids and then accumulates in *transient tank (10).* The remainder with the rejected salt still at high pressure recovered in a *turbocharger (7)* then discharges to the Red Sea beach by brine pump. The turbochargers use the pressure from the concentrate stream to drive turbine, which boosts the pressure from H. P. pump of 1st stage from around 47 bar to around 67 bar.



NO.	Item	No. of units	No.	item	No. of units
1	Feed tank	1	8	H. P. Pump (1st stage)	4
2	Intake Pumps	3	9	Membranes (1st RO)	4 banks x 20
3	Multi Media Filters	12	10	Transient tank	1
4	Mixing tanks	2+1 (standby)	11	H. P. Pump (2nd stage)	4
5	Feed Pumps	3+1 (standby)	12	Membranes (2nd RO)	4 banks x 7
6	Cartridge Filters	28+4 (standby)	13	Produced water tank	1
7	Turbochargers	4			

Figure 2. Schematic Diagram for the RO Process in AL-Yosr Plant

The product of first stage RO is combined from all membranes and lead to transient tanks. If the 1st stage RO permeate increase above 500 ppm, the 2nd stage units have the capacity to treat approximately 4/5 of the 1st permeate to adjust the product salinity. In the 2nd stage RO four multistage centrifugal pumps (2 stage H. P. pumps, pressure 22 bar and capacity 40 m /hr each) are used to pump water to the *second stage membrane (12).* The 2nd stage RO units consist of 4 banks and each bank contains 7 pressure vessels (tubes) which are connected in the following manner: The first 4 tubes are in parallel (first path), The reject of these paths is fed to the second path through 2 tubes in parallel. The concentrated from the above 2 tubes is fed to the final path in the last tube.

The product from each 2nd stage units (100 PPM of TDS - 144 m^3/hr capacity with 80% overall recovery rate) and the surplus from 1st stage banks is combined and piped to *product water tank* (*13*) or holding tank. The final permeate (4800 m^3/day -150 ppm of TDS) is sterilized with calcium hypochlorite and pH is adjusted between 7-8.5 (neutral) by adding lime, and then the product is fed to the local water supply system for distribution to the end users.

Instrumentation and Data Collection

The plant is provided with graphic flow process panel with indicator to show which equipment is operating on standby or shut down. The pumps should always protected by low-pressure switch, which shut down the pump. The indicator panel includes various display units that measure pressure, flow rate, pH, TDS, and turbidity. The product water (permeate) quality can be continually monitored by conductivity meter which is connected to the plastic tubes to sampling rack and controlled by valves. The operating data for RO train are recorded in full scales treatment system under various long terms operating conditions. In addition to above, individual RO membrane performance must be checked to select the RO membrane to be replaced.

To control and monitor the processes in each stage, the RO plant is operated from a control room, which includes switches for electrical actuators, chemical metering pump on/off motor control switches. Operational data, over a period of 365 days starting from 1st January 1997, were collected from 1st RO unit, which installed in 3rd of November 1993. The data obtained included feed pressure, conductivity, temperature, pH, and flow rates of the water feed and product. The TDS is monitored on a continue basis in order to balance the mix of first and second stages permeate required to produce clean, potable water.

RESULTS AND DISCUSSION

In November 1993 the TFC spiral wound elements (model 2822) were installed and work under high-pressure operation of 67 bar. Testing began after installation, the average results of water product (Q_P), recovery rate (%Y) and membrane flux retention coefficient (MFRC) during 4 years of running time are given below in Table 2 for one pressure vessel.

Table 2: Water product, recovery rate and membrane flux retention coefficient

Item	**Installation 3/11/1995**	**1994**	**1995**	**1996**	**1997**
Running time (days)	1-58	59 - 424	425-790	791-1156	1157-1522
Product water Q_p	3.86	3.632	3.26	2.72	2.16
Recovery rate %Y	33%	30%	29%	27%	26%
MFRC	1	0.94	0.84	0.72	0.56

The membrane flux retention coefficient (MFRC) is calculated by Eq. (5) and the recovery is the percentage of product water and is defined as: flow of product water divided by the flow of feed water, i.e., $y = [Q_p / Q_f] \times 100$.

From the above table the RO performance naturally deteriorates with time and part of RO modules installed is subjected to replacement in order to maintain the plant performance. Based on the pervious data the relationship between Q_{pt} (permeate flow rate at time t) and Q_{pi} (permeate flow rate at initial setup) has been proposed by power law function (Eq. 6) and given by the following relation after calculation the constants:

$$Q_{pt} = 3.86\ t^{-0.036} \qquad m^3/hr \tag{9}$$

The time in the above equation is by days and it is noted that the above relation can describe the decline in productivity of the plant reasonably well.

The results show the seawater at intake averages 43,000 ppm TDS and the reject brine more than 60,000 ppm TDS. The salt concentration in water from the first stages is reduced to an average of 600-700 ppm when the membrane cartridges are first installed. However, the salt concentration in this water rises slowly as the membranes begin to deteriorate. The chemical analyses of feed and product water for Al-Yosr RO plant are made and given below in Table 3:

Table 3. Chemical analysis of seawater and product water

Item	Water Analysis		Remarks
	Feed	Product	
Calcium	550	4.0	mg/L
Magnesium	1570	12	mg/L
Sodium	13000	140	mg/L
Potassium	800	10	mg/L
Ammonia	0.0	0.0	mg/L
Carbonates	1.0	3	mg/L
Bicarbonates	135	40	mg/L
Sulfates	3700	2	mg/L
Chlorides	23370	240	mg/L
Nitrates	1.6	0.0	mg/L
Fluorine	2.5	0.0	mg/L
Silica	0.0	0.0	mg/L
TDS	43130	451	ppm
pH	8.3	7.7-8.2	Unit.
Conductivity	96000	900	ns/cm
Carbon dioxide	1.5	12	mg/L
Chlorine	-	1.5	mg/L

Figure 3 shows the results for permeate TDS across the membrane for a 365-day of operating time (test run). The results indicated that no membrane damage or fouling occurred during that period. Also, the TDS of product is slightly increased and affected by cleaning time of membrane time and shout down of the plant; it is appeared in the region of sharp fluctuating of the curve.

Figure 4 illustrates the decline of product rate as function of tested time of the year 1997, this may be due to hydrodynamic conditions of the feed flow at the vicinity of the membrane blocking of the feed spacer mesh structure would further impair surface by the fouling deposit. In Figure 5, the feed water temperature against running tested time of year 1997, the temperature is going up in summer up to 31 °C which increase the productivity this due to elasticity of membrane material and increase in the size of porous. The relation between temperature and productivity is linear [7].

In normal operation, mineral scale, biological matter, colloidal particles, and insoluble organic constituents can foul the membrane in reverse osmosis elements. Deposits build up on the membrane surfaces during operation until thy cause loss in water output, loss of salt reject, or both. Element should be cleaned whenever the normalized water output rate drops by 10% or differential pressure ΔP increase by 15% from the reference conditions. Cleaning is most important to keep highly performance of membrane. In this plant, according to operational conditions it is preferable to apply cleaning for the membrane each three months interval using two types of solutions:

(a) Acidic solution (citric acid with pH 2.5-3, and 1% concentration)

(b) Basic solution (sodium tripolyphosphate, trisodium phosphate and EDTA ethylene diamine tetraacertic acid -with pH 10.5-11, and 1% concentration). Figures 6 and 7 show the performance of membrane particularly TDS and permeate with running time in tested period starting with cleaning No.9 and they continue to the end of the year with cleaning No 13. It is noted that at the time of cleaning, there is sudden change in TDS and Q_p. The permeability coefficient B given by equation (4) measures the salt passage through membrane and it is highly influenced by frequency of cleaning.

CONCLUSION

While it is too early to recommend a final solution to the membrane problem from its performance, the following conclusions are obtained:

1) Plant performance is generally evaluated with the corrected performance, considering feed pressure, TDS (conductivity), temperature, flow rates and water recovery, corrected to the design condition or manufacture's standard conditions
2) RO performance naturally deteriorates with time and part of RO modules installed is subjected to replacement in order to maintain the plant performance. To determine the replacement ratio; ask the RO manufacturer and calculating the ratio by the user if the future deterioration curve of each RO membrane is known.
3) From the experience of this plant, in case of more than 150 sampling points, it is preferable to design the monitoring system to be fully automatic.
4) It should be emphasized for that frequent cleaning is not required for properly designed and properly operated RO system, but because of membrane's combination of pH stability and temperature resistance, cleaning can be accomplished very effectively.
5) Silt density index (SDI) of feed water (seawater) is between the range of 5-7 but for the feed water to the membrane is between 2.9-3.5.
6) The carbonate is much suitable to lower the pH value to the operating condition of membrane than antiscalent of Sodium hexameta phosphate.

Nomenclature

A	Water permeability coefficient (kg/m^2hr bar)
a	Membrane surface area (m^2)
B	Salt permeability coefficient (m^2/hr)
C_f	Feed water concentration or feed salinity (kg/m^3)- ppm
Cp	Product water concentration or product salinity (kg/m^3)- ppm
c	Concentration of salt in product (kg/m^3)
c_s	Concentration of salt in membrane (kg/m^3)
GW	Water mean concentration in membrane (kg/m^3)
D_s	Diffusivity of salt in membrane (m /hr)
D_w	Diffusivity of water in membrane (m^2/hr)
F_s	Salt flux (Kg/m^2.hr)
F_w	Pure water flux (Kg/m^2.hr)
QP	Flow rate of product (permeate) (m^3/hr)
Qf	Flow rate of feed water (m^3/hr)
R	Gas constant (m^3 bar/mole K)

S.R.F. Salt Reduction factor (C_f/ C_p)
T Temperature (K)
V Partial molar volume of water
ΔP Hydro-static pressure difference across the membrane (deference between feed pressure and permeate pressure (bar)
$\Delta \pi$ Osmotic pressure difference across the membrane (deference between feed pressure and permeate pressure (bar)
ρ Density of permeate (kg/m^3)
%R Rejection percent (1 - 1/S.R.F.)
%Y Recovery percentage

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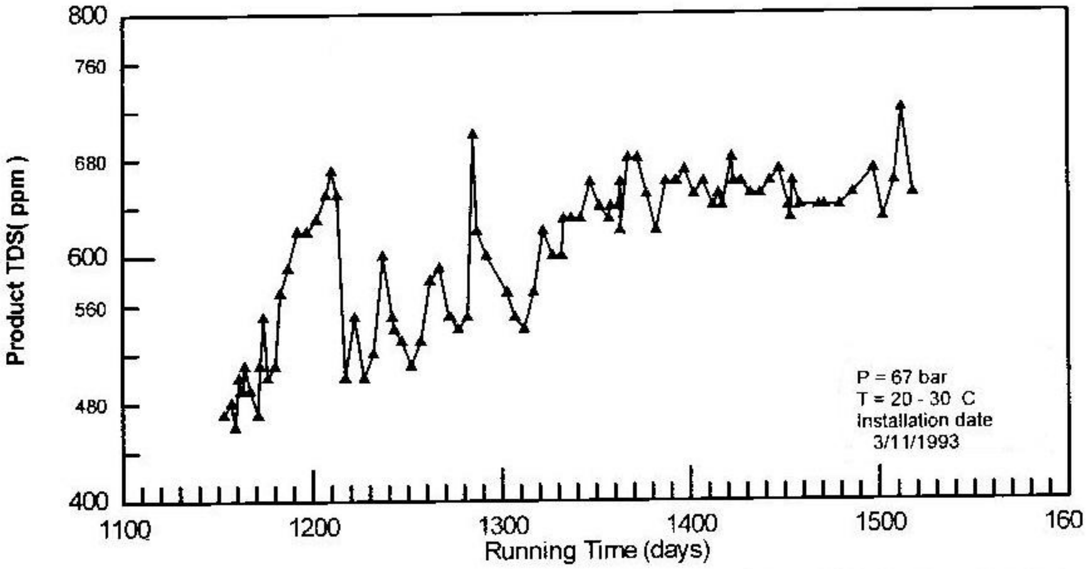

Figure 3. Variation of TDS of Product along Running Time (1/1/1997 - 1/1/1998)

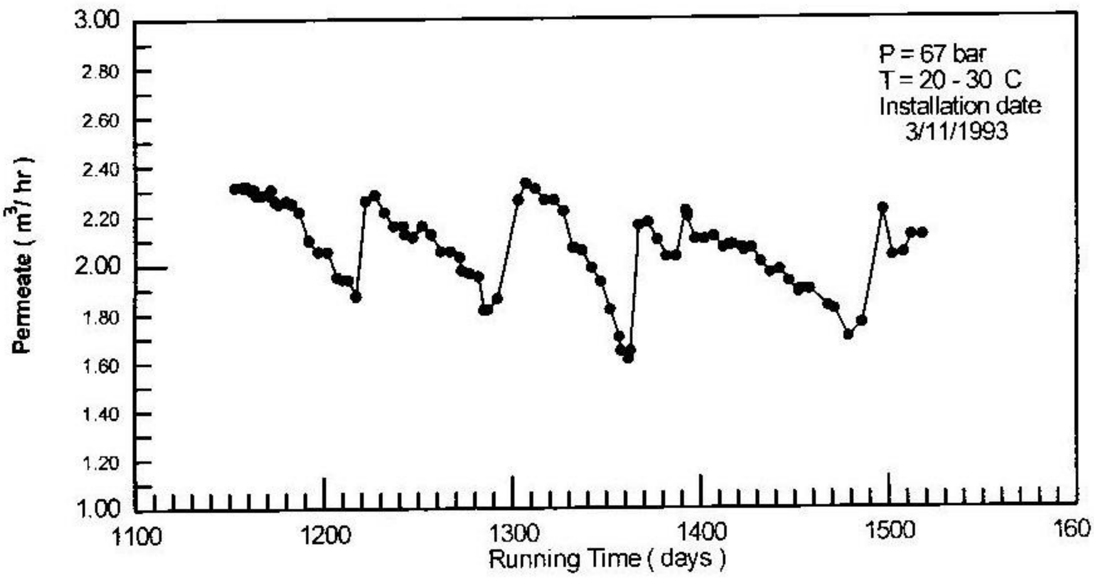

Figure 4. Product Flow Rate vs Running Time for one Prressure Vessel of Membrane (1/1/1997 - 1/1/1998)

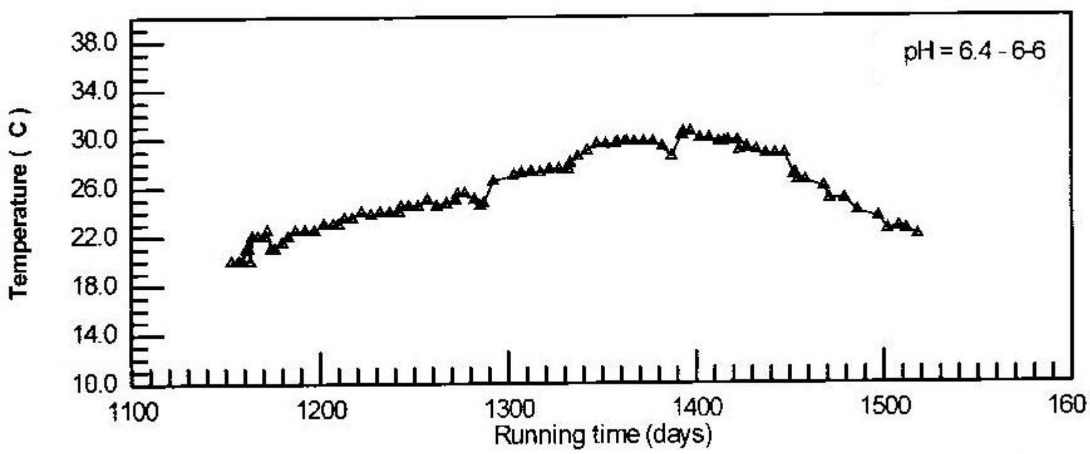

Figure 5. Feed Water Temperature vs Running Time (1/1/1997 - 1/1/1998)

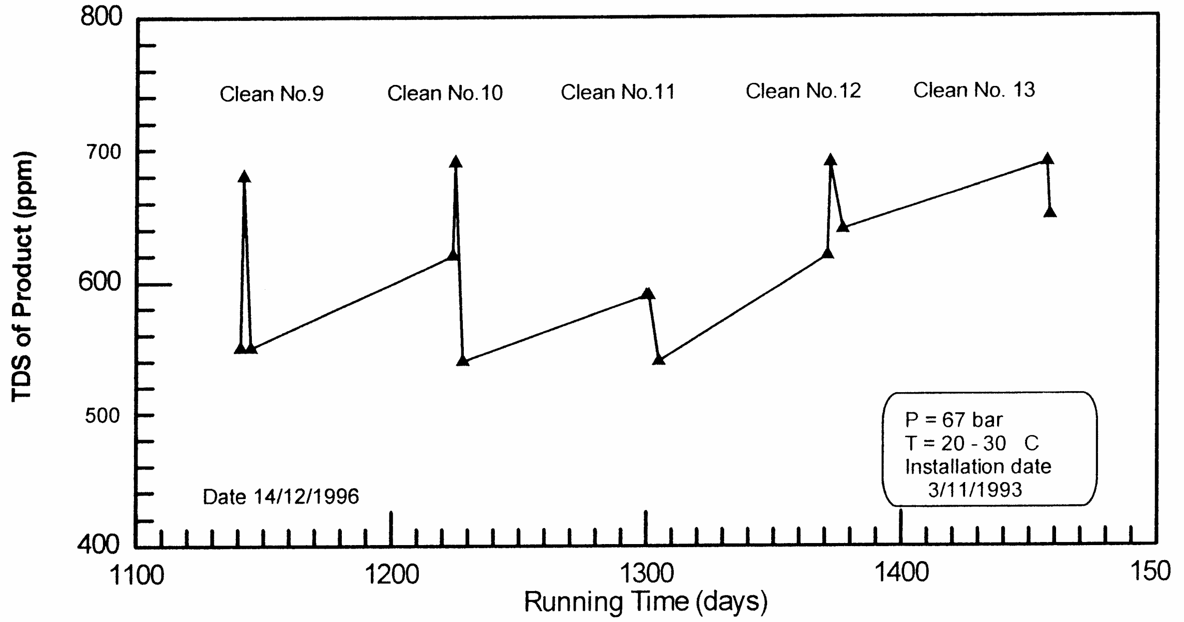

Figure 6. Variation of TDS of Product with Operating Time during Cleanings (year 1997)

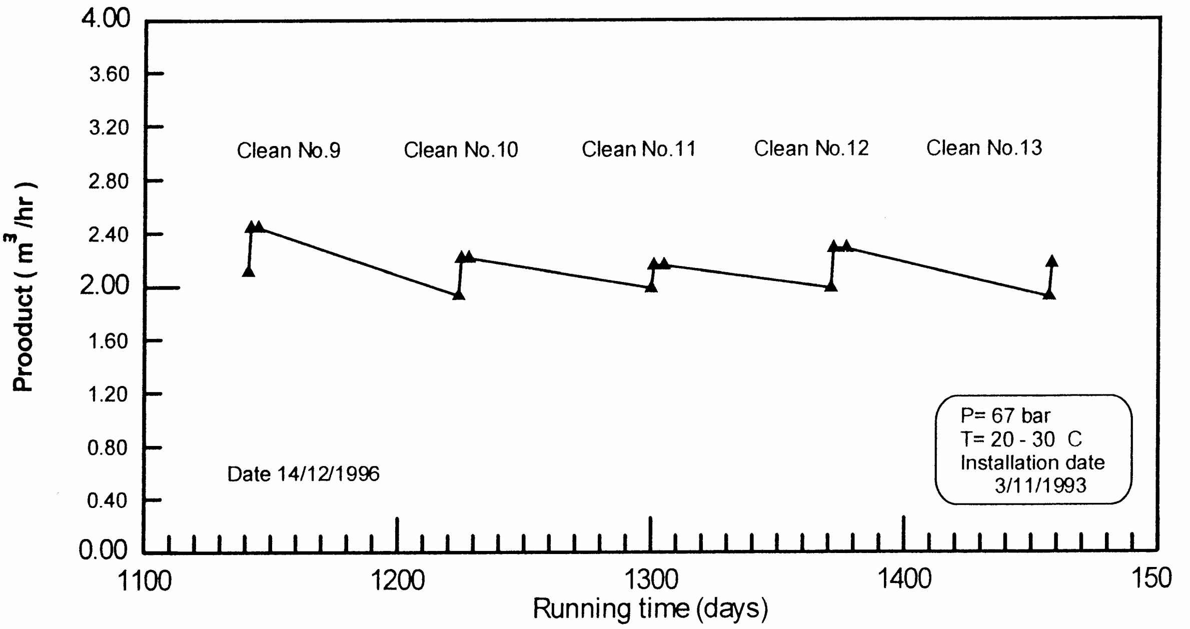

Figure 7. Product Flow Rate with Running Time for one Pressure Vessel of Membrane