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Membrane Modeling and Simulation for a Small Scale Reverse Osmosis Desalination Plant

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Abstract

Reverse osmosis (RO) has proven to be the most effective and efficient desalination method in recent years. Modelling and optimization of RO desalination plants is ongoing in order to come up with sustainable and efficient RO plants, leading to several techniques being employed in relation to mathematical models of mass and heat transfer, salt rejection and membrane solute permeability. Membrane designs and specifications are factors that affect the efficiency of the RO desalination system. Membrane design tools and software such as ROSA and IMSDesign, which are provided by the membrane manufacturing companies, help in the selection and authentication of low energy consumption and high salt rejection membranes for the design of desalination units.

Keywords— desalination; reverse osmosis; modeling; simulation

I. Introduction

Reverse osmosis (RO) is a process that occurs when pressure that is greater than the osmotic pressure is applied to a high saline solution (concentrated) through a membrane. Water is pressurized to flow from the high saline side to the diluted side, and dissolved salts are retained by the membrane. Membrane technologies such as RO use high electrical and mechanical energies. Future supplies of conventional energy sources are uncertain. Therefore, for sustainable development purposes, it is imperative to optimize and reduce energy requirements of the existing processes [1]. Of late, substantial membrane technology advancement has resulted in improvements in the quality of filtering processes and reduction of costs [2].

In the current study two membrane software tools were used and compared with each other in the prediction and selection of membranes to be used in the plant. The two software tools used were the Reverse Osmosis System Analysis (ROSA) for FILMTEC™ membranes (DOW Water and Process Solutions) and Integrated Membrane Solutions Design (IMSDesign) (Hydranautics Nitto Group Company).

IMSDesign is described as a comprehensive membrane projection program that allows users to design an RO system based on hydranautics membranes [3]. ROSA on the other hand, is membrane simulation software that uses FILMTEC™ thin film composite membranes and gives excellent performance for a wide variety of applications, including brackish water purification, low-pressure tap water use, seawater desalination, waste treatment and chemical processing [4].

II. Mathematical Modeling of a Reverse Osmosis System

There are two basic approaches in the mathematical modeling of any process. The first approach is the knowledge based approach, which involve theoretical or parametric models based on fundamental and essential knowledge (mechanisms) of the process and the second approach is the empirical or the non-parametric models, which do not involve the knowledge of the fundamental principles governing the process [5]. There are many approaches that have been used to model RO systems. Different scholars and researchers have come up with many models, some of which include the modeling of membranes [6, 7], modeling of RO plants using neural networks [8], and modeling of RO plants using different algorithms [9, 10]. Fig. 1 shows the schematic diagram of an RO plant with a pre-treatment mechanism, and Fig. 2 shows the RO desalination with ERD or pressure exchanger (PX), 1st pass and 2nd pass RO membranes.

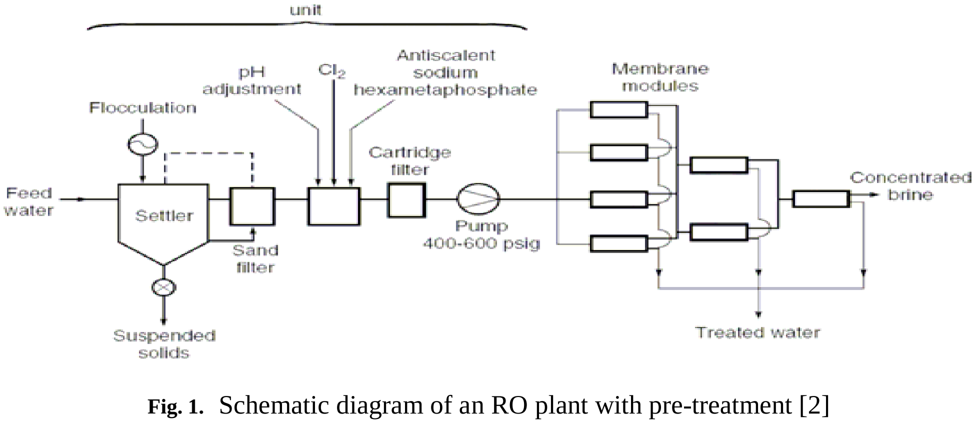


Fig. 1. Schematic diagram of an RO plant with pre-treatment [2]

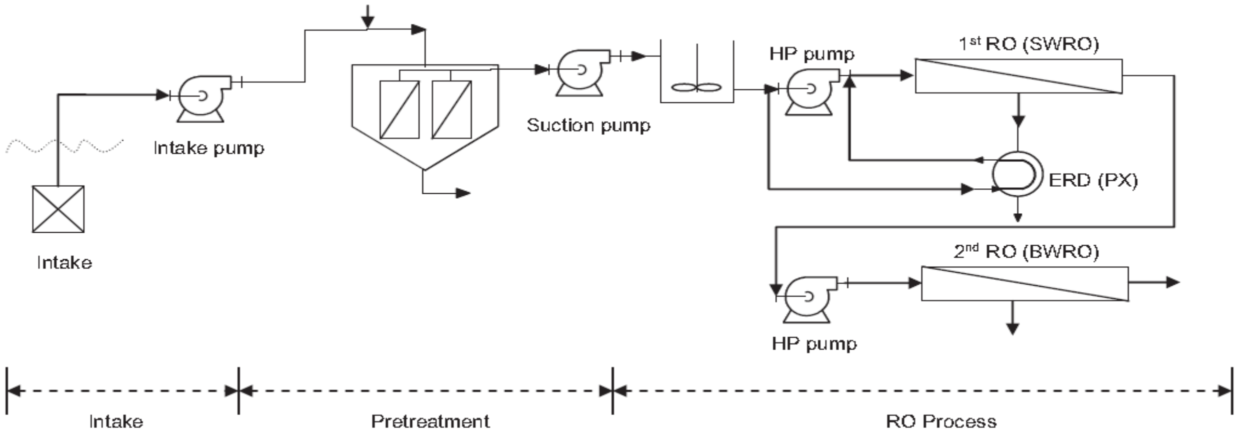


Fig. 2. RO desalination system with ERD/PX module [11]

A. *RO System Monitoring*

- Pressure and flow are measured at various points in the RO system to ensure proper function.
- Conductivity is used to monitor the removal of solute by the RO system. Conductivity describes the ability of the water to conduct electrical charge. If more dissolved solute is present, water will conduct electricity more readily.
- The conductivity of product water from the RO is monitored continuously during RO operation and often displayed as total dissolved solids or TDS.
- The percent rejection of an RO system describes the ability of the system to remove solute, thus reducing conductivity in the product water, and can be thought of as the percentage of solute that was removed from the water during reverse osmosis. The percent rejection is calculated using (1):

$$\%\ rejection = \frac{Feed\ water\ conductivity - Product\ water\ conductivity}{Feed\ water\ conductivity} * 100\% \qquad (1)$$

Modern RO systems will monitor and display the percent rejection in real time during operation. There is no absolute value that is desirable for the percent rejection. Rather, the dialysis facility should use the percent rejection to monitor the efficiency of the RO over time. Percent recovery (also known as the water conversion factor) can be used to monitor the performance of the RO system. The percent recovery can be calculated using (2), where Q is the flow rate:

$$\%recovery = \frac{Q_{permeate}}{Q_{permeate} + Q_{reject}} * 100\% \qquad (2)$$

The percent recovery does not inform water quality, but it is useful for trending the performance of the RO membrane. Membranes that become fouled over time will drop their percent recovery. Permeate flow rate can also vary due to changes in pressure and temperature. For example, a seasonal decrease in water temperature would be expected to decrease the percent recovery. The various measures of RO function—pressure, flow, conductivity, % rejection, % recovery, etc.—should be recorded in a daily treatment log for regular review and trending analysis.

Table I is a summary of the quality and typical characteristics of sea water found in different areas of South Africa [13, 14]. Table II shows the main constituents of standard seawater and their respective concentrations, and Table III shows the analysis of seawater near Cape Town, West Coast region.

TABLE I. AVERAGE FEED WATER TEMPERATURE AND TOTAL DISSOLVED SOLIDS (TDS) IN MILLIGRAMS/LITRE (MG/L) FOR DIFFERENT LOCATIONS IN SOUTH AFRICA

Location of raw water type	**Feed water TDS (mg/l)**	**Feed water temperature (^{0}C)**
West Coast	> 35 000	9 to 14
South Coast	35 000 to 35 400	16 to 21
East Coast	34 700 to 35 400	21 to 25

Where: East Coast stretches from East London up to the Mozambican boarder, South Coast stretches from East London to Cape Agulhas and the West Coast is a region that stretches from Cape Agulhas to the mouth of the Orange river [13]

TABLE II. STANDARD SEA WATER MAIN CONSTITUENTS AND THEIR RESPECTIVE CONCENTRATIONS [14]

Constituent	**Concentration (mg/l)**
Sodium Na^+	10 561
Magnesium, Mg^{2+}	1 272
Calcium, Ca^{2+}	400
Potassium, K^+	380
Chloride, Cl^-	18 980
Sulphate, SO_4^{2-}	2 649
Bicarbonate, HCO_3^{2-}	142
Bromide, Br^-	65
Other solids	34
Density (20 °C)	1.0243 s.g.

TABLE III. SEA WATER MAIN CONSTITUENTS OFF THE WEST COAST, NEAR CAPE TOWN [14]

Total Dissolved Solids (mg/litre)	35 644
Sodium (as Na mg/litre)	10 957
Magnesium (as Mg mg/litre)	1 312
Potassium (as K mg/litre)	393
Calcium (as Ca mg/litre)	406

Chloride (as Cl mg/litre)	19 677
Sulphate (as SO4 mg/litre)	2 757
Alkalinity (as CaCO3 mg/litre)	117
Fluoride (as F mg/litre)	1.1
Cyanide (as CN mg/litre)	< 0.05
Dissolved Organic Carbon (mg/litre)	< 1
Conductivity (µS/cm) @ 25 °C	51 000
pH (Lab)	8.1
Hardness (as CaCO3 mg/litre)	6 417
CATIONS (meq/litre)	614.87
ANIONS (meq/litre)	614.82
Suspended Solids (mg/litre) (No. 1 filter)	3.7
Suspended Solids (mg/litre) (0.45 µm)	1.5
Turbidity (NTU)	6.5

B. RO Model Equations

The following section is a summary of the RO model equations [15]:

Permeate flux, Jw:

$$J_w = A_w(\Delta P - \Delta\pi) \tag{3}$$

$$J_w = \frac{Q_p}{A_{mem}} \tag{4}$$

Salt rejection, R_s:

$$R_s = [1 + \frac{B_s}{A_w(\Delta\rho - \Delta\pi)}]^{-1} \tag{5}$$

Also, salt rejection, R_s, can be calculated by [14]:

$$R_s = 1 - \frac{TDS_p}{TDS_f} \tag{6}$$

Osmotic pressure, Δπ:

$$\Delta\pi = RT\sum\frac{n}{v} \tag{7}$$

Specific energy consumption, SEC:

$$EC = \frac{P_f\,Q_f\,(E_{pump})^{-1} - P_r\,Q_r\,E_{ERD}}{Q_p} \tag{8}$$

Recovery ratio, R:

$$R = \frac{Q_p}{Q_f} \tag{9}$$

Assuming no softening is done, the following calcium salts may typically limit recovery:

Calcium carbonate (calcite) at a feed pH of 7, R_{CaCO3}:

$$R_{Ca\,co_3} \approx 1 - \frac{\sqrt{Alk * C_{Ca}}}{2000} \tag{10}$$

Calcium sulphate (gypsum), R_{CaSO4}:

$$R_{Ca\,so_4} \approx 1 - \frac{\sqrt{C_{so_4} * C_{Ca}}}{2500} \tag{11}$$

Calcium fluoride, R_{CaF2}:

$$R_{Ca\,F_2} \approx 1 - \frac{[(C_F)^2 * C_{Ca}]^{0.33}}{40} \tag{12}$$

Total mass balance:

$$Q_f C_f = Q_p C_p - Q_r C_r \tag{13}$$

Transmembrane pressure difference, ΔP:

$$\Delta P = \frac{P_f + P_r}{2} - P_p \tag{14}$$

Normalised specific energy, SEC*:

$$SEC^* = \frac{SEC}{\Delta\pi} \tag{15}$$

Actual permeate hourly flow rate, Q_h, [14]:

$$Q_h = \frac{Q_d}{24 * \alpha} \tag{16}$$

Total membrane area, A_{mem}:

$$A_{mem} \approx \left(\frac{1000 * Q_h}{\emptyset_1}\right) + z\left(\frac{1000 * Q_h}{\emptyset_2}\right) \tag{17}$$

Feed pressure at a given temperature, P_f:

$$P_f \approx \frac{0.00076 * TDS_f}{1 - R} + \left(\frac{\emptyset}{\varepsilon} + 5\right) * 1.034^{25-T} \tag{18}$$

Mass transfer coefficient, k_i [11]:

$$k_i = 0.5510\left(\frac{ud_h}{v}\right)^{0.4}\left(\frac{v}{D_i}\right)^{0.17}\left(\frac{c_{b,i}}{\rho}\right)^{-0.77} \tag{19}$$

Desalination energy, E_{desal}, other additional energy, E_{other}, and the total energy required for the entire RO process, ET [1, 14]:

$$E_{desal} = \left[\frac{Q_h * P_f}{36 * R * \eta_p}\right] - s\left[\frac{Q_h(P_f - 5)(1 - R)}{36 * R * \eta_r}\right] \tag{20}$$

$$E_{other} \approx \left[\frac{Q_h * P_f}{36 * \eta}\right] \tag{21}$$

$$E_T = E_{desal} + E_{ERD} + E_{other} \tag{22}$$

The specific energy required per volume of permeate water, E_{spec}:

$$E_{spec} = \frac{E_T}{Q_h} \tag{23}$$

Maximum possible TDS of reject, TDS_r:

$$TDS_r = \frac{TDS_f}{1 - R} \tag{24}$$

The equations for the modeling of the UF unit are summarized below [16].

Normalized Temperature, TMP*:

$$TMP^* = TCF * TMP \tag{25}$$

Temperature correction factor (TCF), which is a factor that takes into consideration the effect of the temperature, T (°C) and its influence on the viscosity of water:

$$TCF = \frac{10^{\left(\frac{247.8}{25+273.16-140}\right)}}{10^{\left(\frac{247.8}{T+273.16-140}\right)}} \tag{26}$$

Different TMP values obtained at different temperatures can be compared and transported to the same reference temperature of 25 °C [17].

Efficiency of the UF process, which is defined as the net yield of the UF process:

$$Efficiency = Availability * Recovery \quad (27)$$

Availability, which is the measure of the time the UF module is producing water:

$$Availability = \frac{t_f}{t_r} \quad (28)$$

Recovery, which is the measure of the net water produced:

$$Recovery = \frac{V_f - V_{CEB} - V_{BW}}{V_f} \quad (29)$$

Hourly feed capacity of the pre-treatment plant, $Q_{h(in)}$ [14]:

$$Q_{h(in)} = \frac{Q_h}{R(1-\beta)} \quad (30)$$

C. *Theoretical Values of RO Parameters*

Specific energy consumption (SEC) is the amount of energy consumed per unit freshwater produced (kJ/kg) and recovery ratio, and r (%) is the volume of freshwater produced per unit volume of the seawater fed. Fig. 3 shows the graph of theoretical minimum energy consumed against the recovery ratio [1].

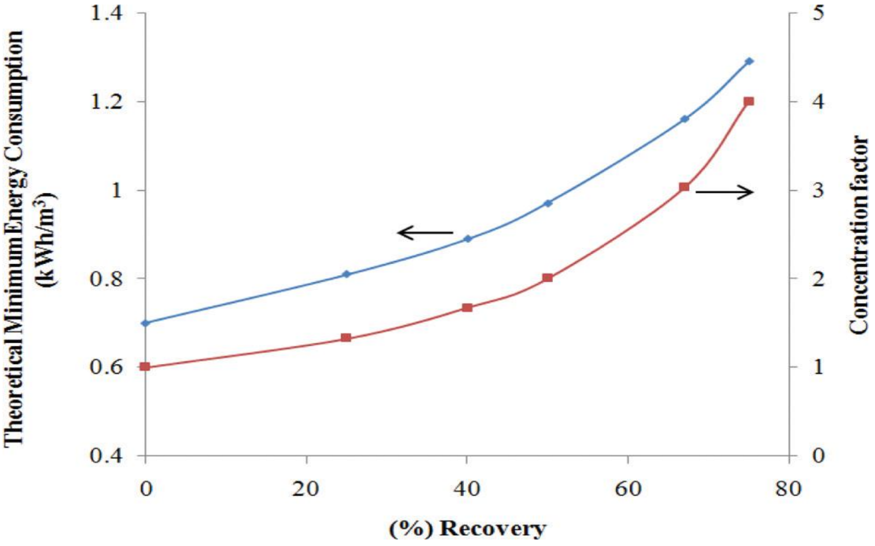
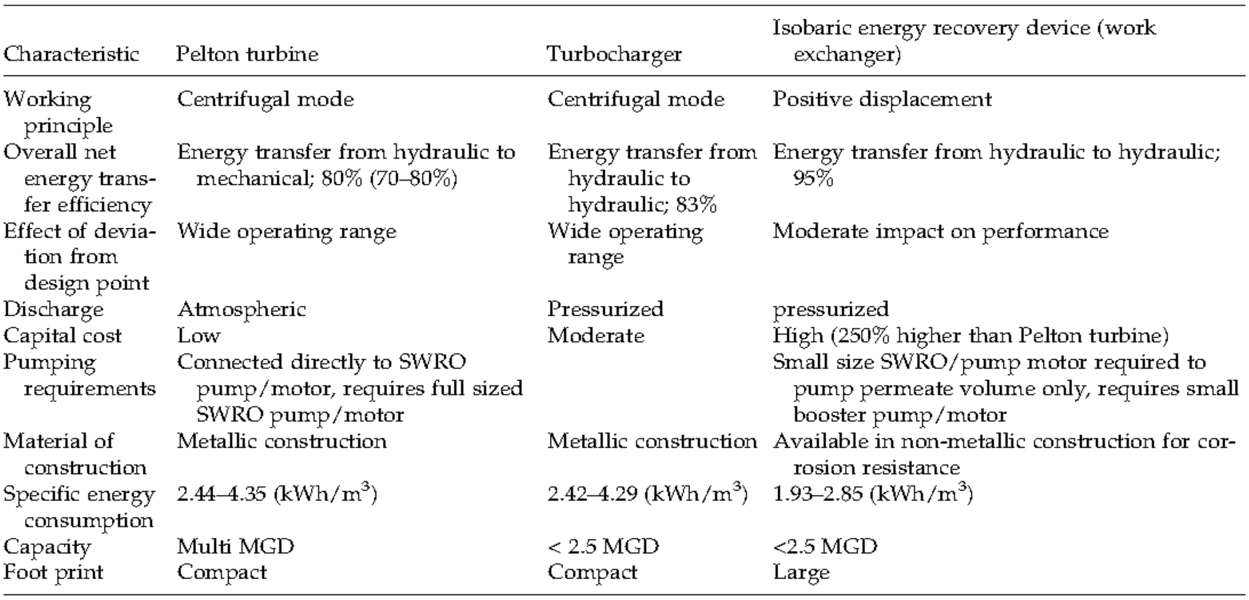


Fig. 3. Theoretical minimum energy consumed against the recovery ratio [1]

1) *Energy Recovery Devices*

There are four types of energy recovery devices (ERDs) that can be used in RO process. These are pelton turbines, hydraulic turbochargers, pressure exchangers and work exchangers. Table IV shows the characteristics of three of these ERDs [1].

TABLE IV. CHARACTERISTICS OF THREE TYPES OF ERDS [1]



Characteristic	Pelton turbine	Turbocharger	Isobaric energy recovery device (work exchanger)
Working principle	Centrifugal mode	Centrifugal mode	Positive displacement
Overall net energy transfer efficiency	Energy transfer from hydraulic to mechanical; 80% (70–80%)	Energy transfer from hydraulic to hydraulic; 83%	Energy transfer from hydraulic to hydraulic; 95%
Effect of deviation from design point	Wide operating range	Wide operating range	Moderate impact on performance
Discharge	Atmospheric	Pressurized	pressurized
Capital cost	Low	Moderate	High (250% higher than Pelton turbine)
Pumping requirements	Connected directly to SWRO pump/motor, requires full sized SWRO pump/motor		Small size SWRO/pump motor required to pump permeate volume only, requires small booster pump/motor
Material of construction	Metallic construction	Metallic construction	Available in non-metallic construction for corrosion resistance
Specific energy consumption	2.44–4.35 (kWh/m^3)	2.42–4.29 (kWh/m^3)	1.93–2.85 (kWh/m^3)
Capacity	Multi MGD	< 2.5 MGD	<2.5 MGD
Foot print	Compact	Compact	Large

III. System Modeling

A. Design Modeling

Fig. 4 shows the design methodology used for the design of the single stage SWRO desalination unit.

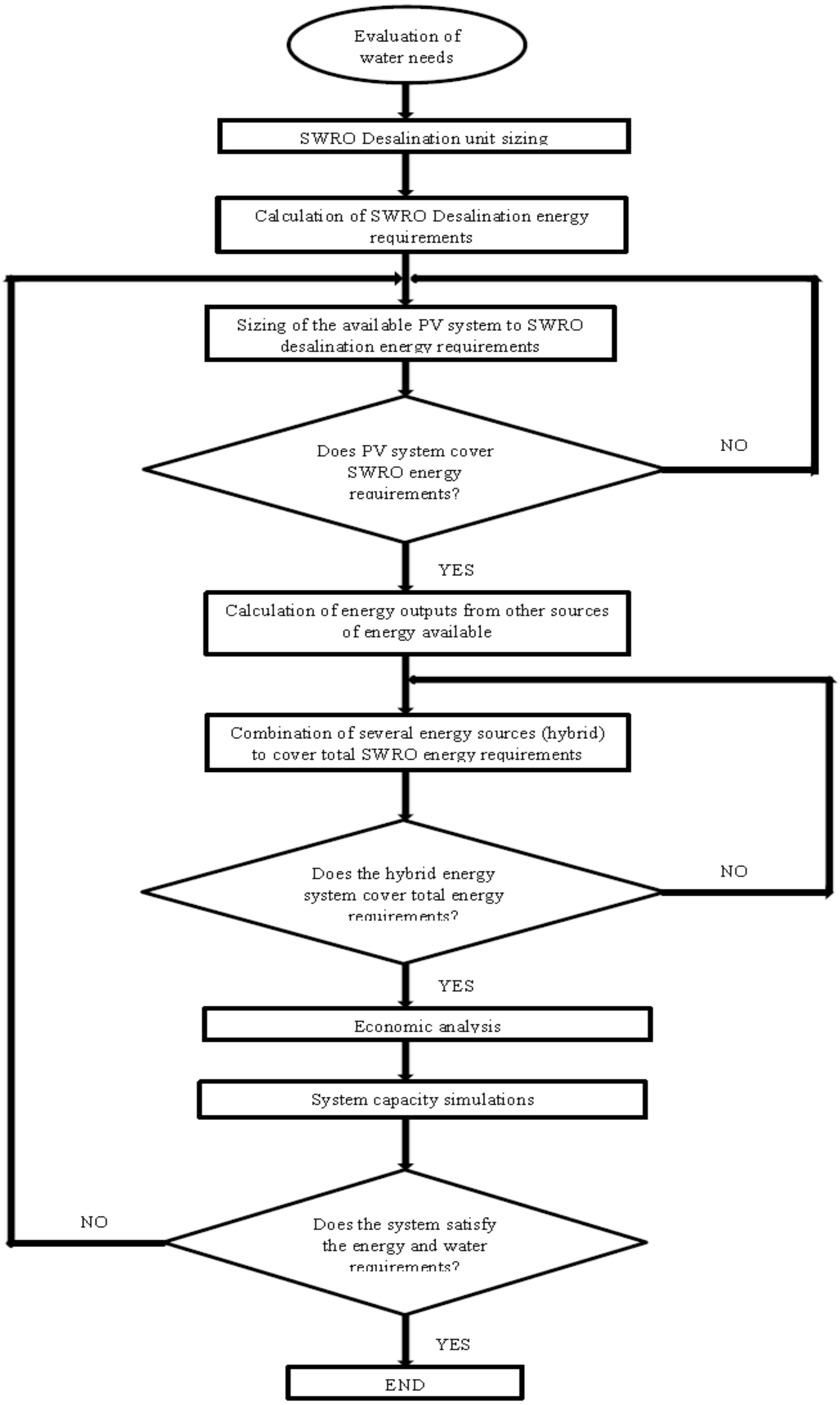


Fig. 4. Flow diagram for SWRO desalination unit

B. *Permeate Flow Rate and Actual Permeate Hourly Flow Rate (Q_h)*

The desired permeate flow rate of the plant is 10 m3/d. The actual permeate hourly flow rate, assuming 8 % idle time or 92 % availability of the plant, is 0.45 m3/h.

C. *Recovery Rate (R)*

The typical recovery rate design guideline for the desalination of seawater is about 0.4 or 40 %, assuming no softening of feed water is performed.

D. *Feed Flow rate (Q_f)*

Assuming $R = 0.4$ and $Q_p = 10\ m^3/d$, the design feed flow rate is 25 m^3/d.

E. *Feed and Permeate Total Dissolved Salts Concentrations (TDSp and TDSf)*

Total dissolved solids of feed water, TDS_f, is approximately 35 600 mg/l, the desired design total dissolved solids of permeate water; TDS_p is less than 500 mg/l.

F. *Salt Rejection*

Salt rejection, Rs, is calculated and found to be around 0.99 or 99 %.

G. *Operating Temperature (T)*

Water becomes less viscous at higher temperatures, hence the need for a generally high feed operating temperature. The proposed feed operating temperature is in the range of 25 °C to 30 °C. The design temperature for this system is 25 °C.

H. *Energy Recovery Devices (ERD) and Power Exchangers (PX)*

Research and design has shown that multi-stage systems, with modules connected to reject water with booster pumps, are able in principle to minimize electricity consumption. This system will have no energy recovery devices.

I. *Maximum Possible TDS of reject, (TDS_r)*

The calculated maximum possible TDS of reject is 59 406 mg/l.

Input parameters are shown in Table V.

IV. Computer Simulation of the RO Simulation

Computer simulations for the RO system were carried out using two different membrane design software tools to analyze the performance of the RO system and to ascertain the calculations above. ROSA and IMSDesign software tools were used. The results obtained from the two tools were compared and the software with the results that showed greatest similarities to the desired output was selected for further manipulation and optimization of the RO process. The software tools also helped in the selection of suitable membranes for the desired output.

A. *Simulation Results*

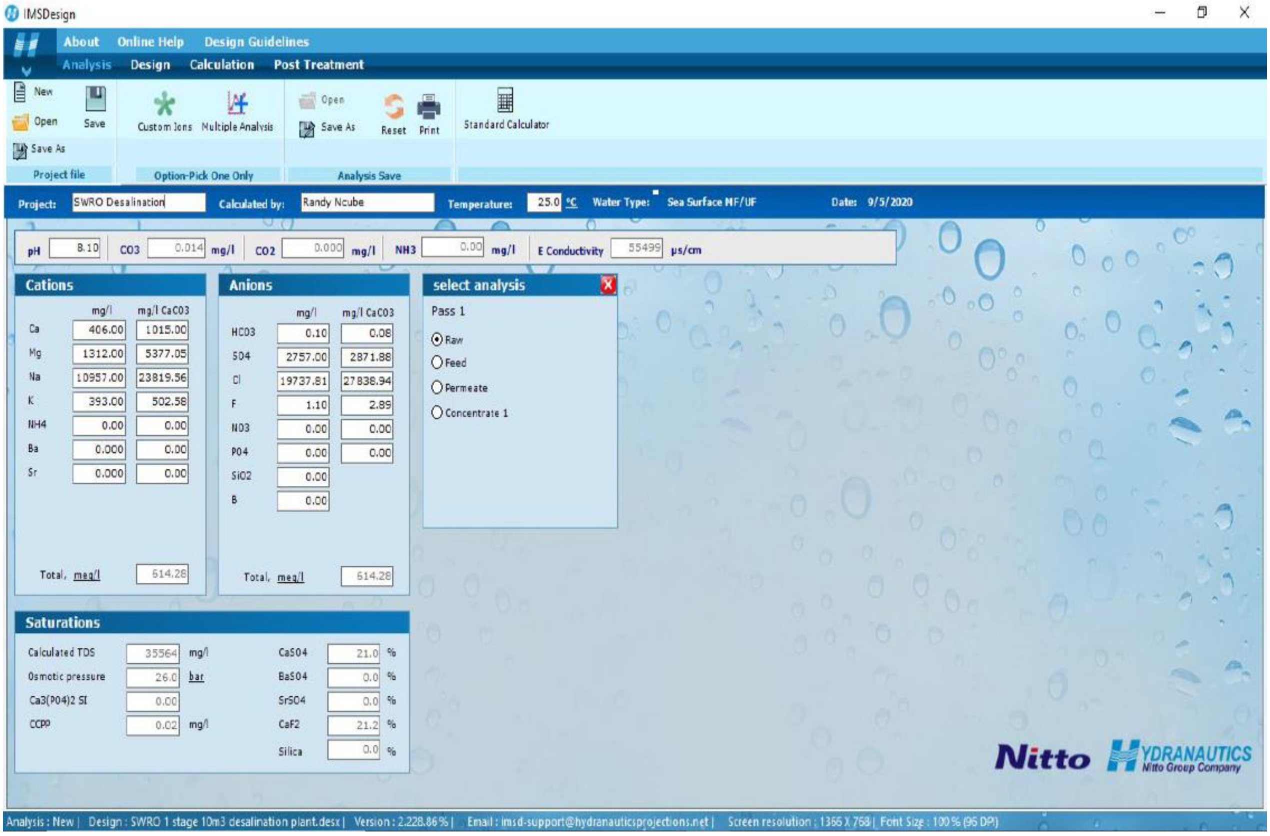
According to several simulation processes carried out for small scale SWRO desalination plants, a single stage RO system was discovered to be much more economical and energy efficient compared to a two-stage or multi-stage system. Capital costs and power requirements were slightly lower in a single stage than in a two-stage system for comparable permeate water quality. In this regard, a single stage SWRO desalination system was chosen and the above selected/assumed parameters were captured in the two simulation software tools and the following results were obtained.

B. *IMSDesign Results*

Seawater quality inputs tabulated in Table III and the selected/assumed parameters in Table V were fed into the IMSDesign software as shown in Fig. 5. A summary of the results is shown in Fig. 6 and the detailed report of the results of the simulations is shown in Appendix 1 at the end of this document.

TABLE V. SUMMARY OF THE CALCULATED, ASSUMED/SELECTED PARAMETERS TO BE SET AS INPUT PARAMETERS FOR THE PERFORMANCE ANALYSIS OF THE RO SYSTEM.

Parameter	Calculated value	Assumed/ Selected	Equation
pH (Lab)		8.1	Table 3
Permeate flow rate		10 m^3/d	-
Recovery rate		0.4	-
Actual permeate hourly flow rate	0.45 m^3/h		(16)
Salt rejection	0.99		(6)
Operating temperature		25 °C	-
Feed TDS		35 644 mg/l	Table 3
Permeate TDS		< 500 mg/l	-
Maximum possible TDS of reject	59 406 mg/l		(24)



Project: SWRO Desalination Calculated by: Randy Ncube Temperature: 25.0 °C Water Type: Sea Surface MF/UF Date: 9/5/2020

pH 8.10 CO3 0.014 mg/l CO2 0.000 mg/l NH3 0.00 mg/l E Conductivity 55499 μs/cm

Cations

	mg/l	mg/l CaCO3
Ca	406.00	1015.00
Mg	1312.00	5377.05
Na	10957.00	23819.56
K	393.00	502.58
NH4	0.00	0.00
Ba	0.000	0.00
Sr	0.000	0.00
Total, meq/l		614.28

Anions

	mg/l	mg/l CaCO3
HCO3	0.10	0.08
SO4	2757.00	2871.88
Cl	19737.81	27838.94
F	1.10	2.89
NO3	0.00	0.00
PO4	0.00	0.00
SiO2	0.00	
B	0.00	
Total, meq/l		614.28

select analysis

Pass 1

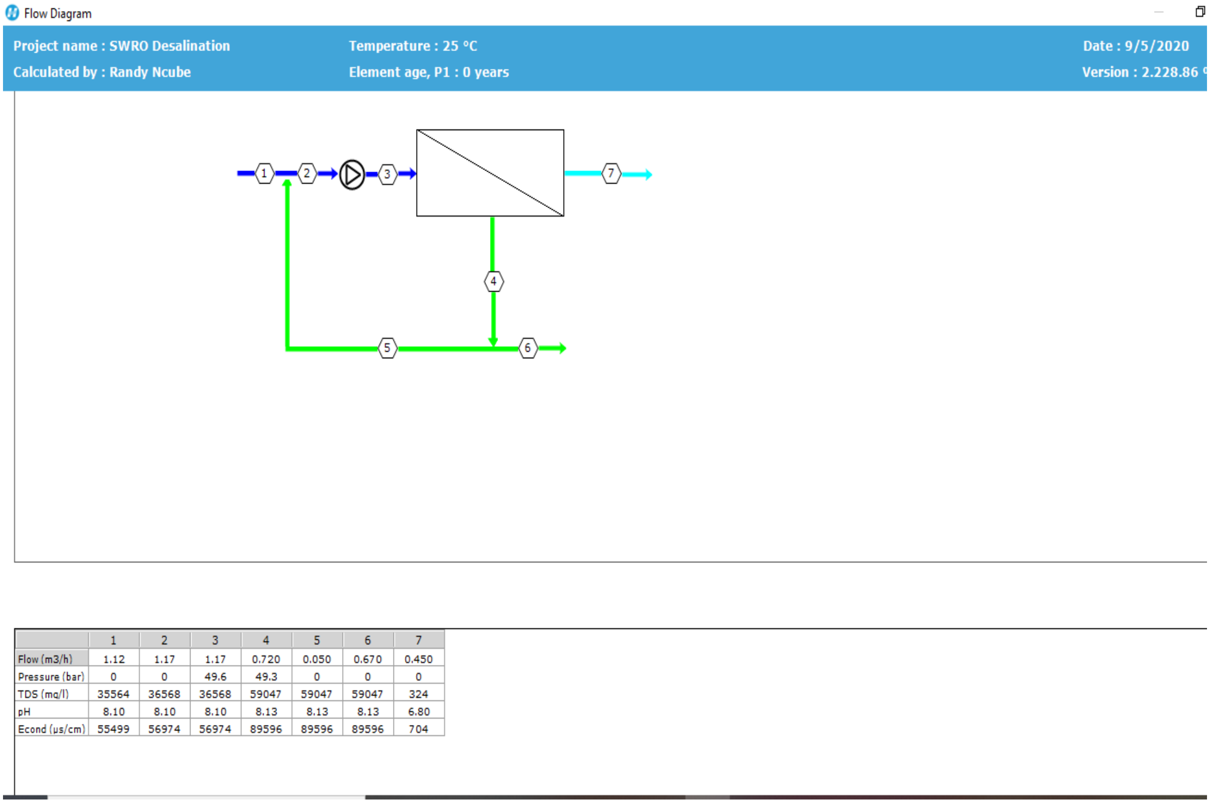
● Raw
○ Feed
○ Permeate
○ Concentrate 1

Saturations

Calculated TDS	35564	mg/l	CaSO4	21.0	%
Osmotic pressure	26.0	bar	BaSO4	0.0	%
Ca3(PO4)2 SI	0.00		SrSO4	0.0	%
CCPP	0.02	mg/l	CaF2	21.2	%
			Silica	0.0	%

Analysis : New | Design : SWRO 1 stage 10m3 desalination plant.desx | Version : 2.228.86 % | Email : imsd-support@hydranauticsprojections.net | Screen resolution : 1365 X 768 | Font Size : 100 % (96 DPI)

Fig. 5. Input parameters on the IMSDesign software



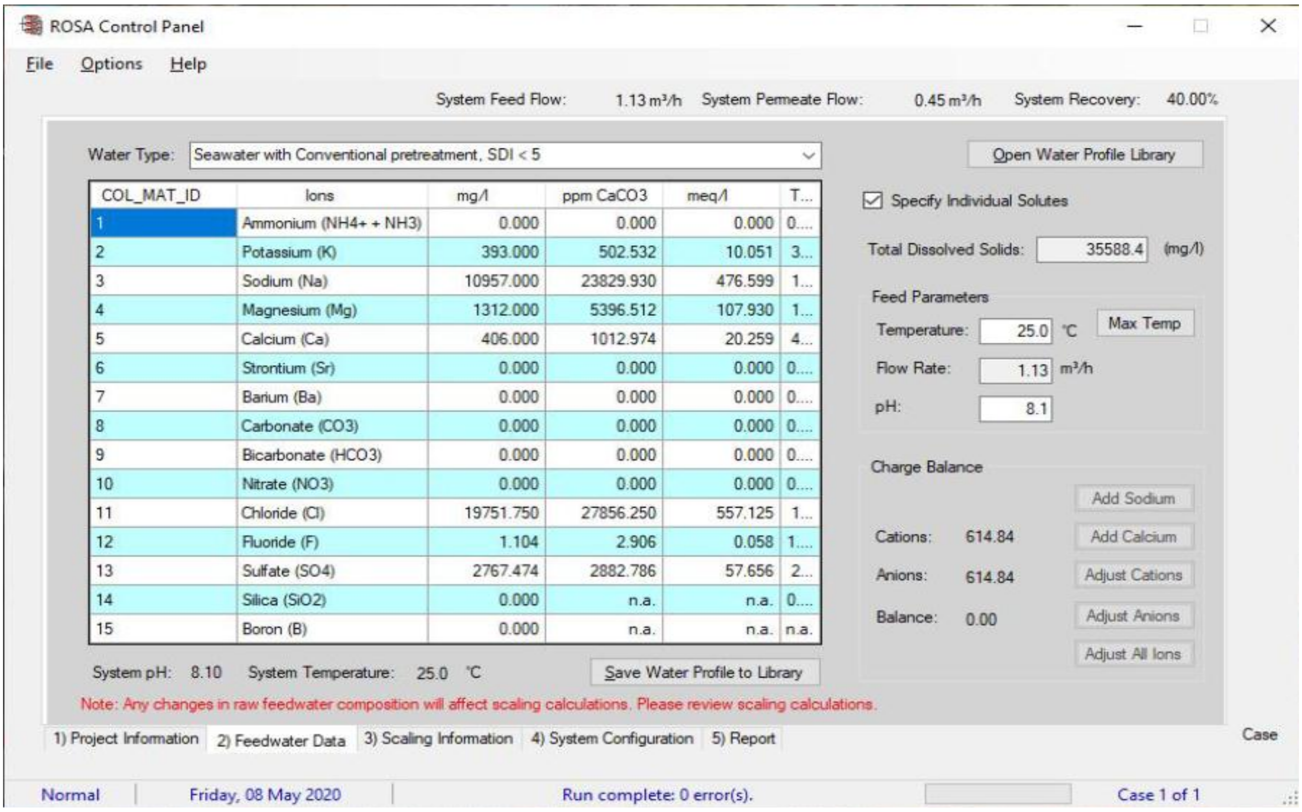
Project name : SWRO Desalination
Calculated by : Randy Ncube
Temperature : 25 °C
Element age, P1 : 0 years
Date : 9/5/2020
Version : 2.228.86

	1	2	3	4	5	6	7
Flow (m3/h)	1.12	1.17	1.17	0.720	0.050	0.670	0.450
Pressure (bar)	0	0	49.6	49.3	0	0	0
TDS (mg/l)	35564	36568	36568	59047	59047	59047	324
pH	8.10	8.10	8.10	8.13	8.13	8.13	6.80
Econd (μs/cm)	55499	56974	56974	89596	89596	89596	704

Fig. 6. A systems configuration obtained after running the IMSDesign program

C. ROSA Results

Seawater quality inputs tabulated in Table III and the selected/assumed parameters in Table V were fed into the ROSA software as shown in Fig. 7. A summary of the results is shown in Fig. 8 and the detailed report of the results of the simulations is shown in Appendix 2 at the end of this document.



System Feed Flow: 1.13 m³/h System Permeate Flow: 0.45 m³/h System Recovery: 40.00%

Water Type: Seawater with Conventional pretreatment, SDI < 5

COL_MAT_ID	Ions	mg/l	ppm CaCO3	meq/l	T...
1	Ammonium (NH4+ + NH3)	0.000	0.000	0.000	0....
2	Potassium (K)	393.000	502.532	10.051	3...
3	Sodium (Na)	10957.000	23829.930	476.599	1...
4	Magnesium (Mg)	1312.000	5396.512	107.930	1...
5	Calcium (Ca)	406.000	1012.974	20.259	4...
6	Strontium (Sr)	0.000	0.000	0.000	0....
7	Barium (Ba)	0.000	0.000	0.000	0....
8	Carbonate (CO3)	0.000	0.000	0.000	0....
9	Bicarbonate (HCO3)	0.000	0.000	0.000	0....
10	Nitrate (NO3)	0.000	0.000	0.000	0....
11	Chloride (Cl)	19751.750	27856.250	557.125	1...
12	Fluoride (F)	1.104	2.906	0.058	1...
13	Sulfate (SO4)	2767.474	2882.786	57.656	2...
14	Silica (SiO2)	0.000	n.a.	n.a.	0....
15	Boron (B)	0.000	n.a.	n.a.	n.a.

☑ Specify Individual Solutes

Total Dissolved Solids: 35588.4 (mg/l)

Feed Parameters

Temperature: 25.0 °C

Flow Rate: 1.13 m³/h

pH: 8.1

Charge Balance

Cations: 614.84

Anions: 614.84

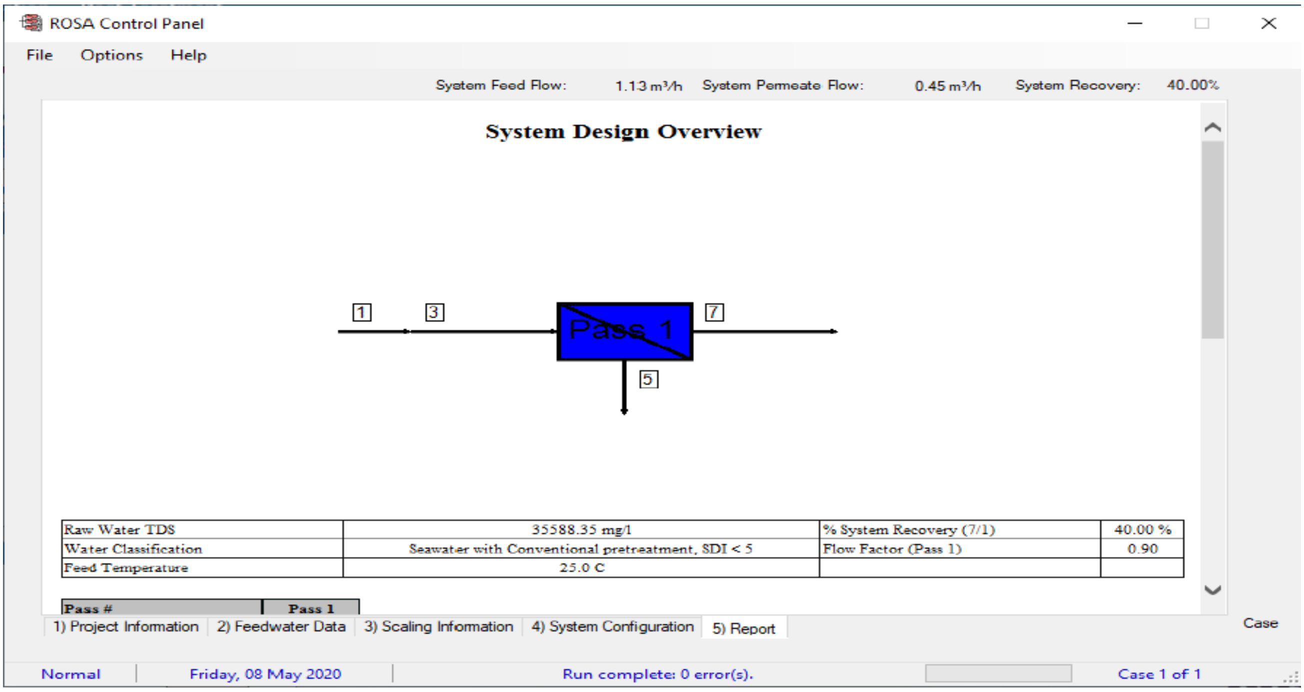
Balance: 0.00

System pH: 8.10 System Temperature: 25.0 °C

Note: Any changes in raw feedwater composition will affect scaling calculations. Please review scaling calculations.

Normal | Friday, 08 May 2020 | Run complete: 0 error(s). | Case 1 of 1

Fig. 7. Input parameters on the ROSA software



System Feed Flow: 1.13 m³/h System Permeate Flow: 0.45 m³/h System Recovery: 40.00%

System Design Overview

Raw Water TDS	35588.35 mg/l	% System Recovery (7/1)	40.00 %
Water Classification	Seawater with Conventional pretreatment, SDI < 5	Flow Factor (Pass 1)	0.90
Feed Temperature	25.0 C		

Pass #	Pass 1

Normal | Friday, 08 May 2020 | Run complete: 0 error(s). | Case 1 of 1

Fig. 8. A system design overview and summary of the ROSA program

V. Results Analysis

The following section is meant to analyze the results from the two membrane software tools to select the most feasible system for further analysis and optimization of the system.

A. Results Comparison

Table VI shows the results from the two software tools obtained after running the programs with the same inputs.

TABLE VI. RESULTS OF THE IMSDESIGN AND ROSA SOFTWARE

	IMSDesign	**ROSA**
Permeate TDS (mg/l)	324.5	633.3
Average flux rate (lmh)	15.1	14.42
Feed pressure (bars)	49.6	47.44
Average specific energy (kW/h)	5.12	3.66
Membrane type	SWC5-LD-4040	SW30-2540
Total number of elements	4	12

TABLE VII. COMPARISON OF MEMBRANE CHARACTERISTICS

	SWC5-LD-4040	**SW30-2540**
Manufacturer	Hydranautics SWC membranes	Dow Filmtec
Material	Composite polyamide	Polyamide thin-film composite
Nominal Production (m^3/d)	6.62	2.6
Salt Rejection (%)	99.7	99.4
Size (m * m)	0.1 * 1	
Active Area (m^2)	2	2.6
Max. Applied Pressure (bars)	82.7	69
pH	2 to 11	2 to 11
Max. Operating Temp. (°C)	45	45
Price/membrane (USD)	269	244
Total Number of membrane elements	4	12
Total membrane costs (USD)	1076	2928
Advantages	-High productivity and salt rejection rates, optimized flow, low fouling and low energy consumption; -Optimum salt rejection and permeate flows at low operating pressures; -High energy efficiency at low costs, low treatment cost while offering extreme durability and consistent performance.	-High flux reduces energy use or pressure required; -Good salt rejection results in good quality water.

B. Selected Design Setup

Although both the IMSDesign and ROSA desalination design tools showed certain individual advantages, there are two factors that led to the selection of the design setup to be used for optimization. These factors include the permeate TDS and the capital (setup) costs (particularly the cost of membranes). The desired output for the permeate TDS in this design was < 500 mg/l according to WHO standards for potable water for human consumption [2]. From the number of membranes elements required to set up the plant, the setup costs could be calculated and determined. From the above factors, the simulation conducted using the IMSDesign suited the design for this project.

VI. Conclusion

A clear analytical mathematical model and membrane simulations using ROSA and IMSDesign software tools was used for the performance predictions of the type of membrane module and consequently for the performance of the RO plant. The IMSDesign setup showed that the setup cost was lower than that of the ROSA software whereas the specific energy of the ROSA setup was lower than that of IMSDesign setup. The IMSDesign setup also showed that the required design output of less than 500 mg/l permeate TDS could be obtained. A pilot plant will be built based on the selected RO setup and will be used in the optimization of the complete system through experimentation so as to reduce specific energy, thereby reducing the running costs. Experiments on the effect of temperature and pressure variation on energy consumption of the pilot plant will be carried out and the optimum conditions will be employed. Optimization and simulation of the RO plant control system using Matlab Simulink will be performed so as to improve energy consumption without compromising the permeate water quality.

Nomenclature

A_{mem} Total membrane area, m^2

A_W - Permeability coefficient, m/s.Pa

B_s - Solute transport parameter, m/s

E - Specific energy consumption, kWh/m^3

E_{ERD} Turbine energy, kWh

E_{pump} Pump energy consumption, kWh

E_{spec} The specific energy required per volume of permeate water, kWh/m^3

J_W - Permeate flux, m/s

ΔP - Pressure difference across the membrane, Pa

P_f - Feed water pressure, Pa

P_p - Permeate pressure, Pa

P_r - Rejected pressure, Pa

Q_f - Feed flow rate, m3/d

Q_h - Permeate hourly flow rate, m3/h

Q_p - Permeate flow rate, m3/d

$Q_{p,\,el}$ Permeate flow rate per membrane element, m3/s

$Q_{\_\,p}$ Mass flow rate of permeate in one element, kg/s

Q_r - Rejected flow rate, m^3/d

Q_{bypass} -Amount of water mixes with the permeate to achieve the required salinity, m^3

R - Gas constant, J/mol-k

R_s - Salt rejection, %

s - The selection parameter, s = 1 if an energy recovery unit is installed, and s = 0 if no recovery unit is installed

T - Temperature, °C

V_w - Water molar volume, m^3

$\dot{W}$ - Work, kW

E_T - Total energy requirement, kW

E_{in} - Energy required to draw the feed water from the source, kW

E_{pt} - Energy required for pre-treatment and post treatment (micro filtration and pumping), kW

E_{hp} - Energy required by high pressure pump, kW

E_{other} Energy required by other accessories (chemical dosing, filter backwashing/cleaning and pumping the product water), kW

t_f - Filtration time, h

t_t - Total time, h

V_f - Volume of filtrate, m^3

V_{CEB} Volume of chemically enhanced backwash, m^3

V_{BW} Volume of backwash, m^3

z - Selection factor, one for a double pass system, or zero for a single-pass system

$\Delta\pi$ - Osmotic pressure, Pa

α - Availability

ϕ - Average flux ($l/h.m^2$)

ε - Membrane type and its flux per driving pressure

β - Fraction feed water lost at the pre-treatment plant (typically between 3 % and 15 %, depending on the process)

η_p - Pump efficiency (typically around 0.75)

η_r - Efficiency of the energy recovery unit (if installed)

Acknowledgment

I would like to thank God for the gift of knowledge that he has bestowed in us. I would also like to pay my special regards to my supervisor and mentor, Prof. Freddie L. Inambao for his unwavering support. I would like to acknowledge Makhosi K. Mahlangu (M. Eng. Manufacturing Systems and Operations Management) for his assistance throughout the research. I wish to show my deepest gratitude to Dr. Richard Steele for his assistance in the editing of this document. To my wife and life partner, Nothando F. Ncube, thank you for your support and patience.

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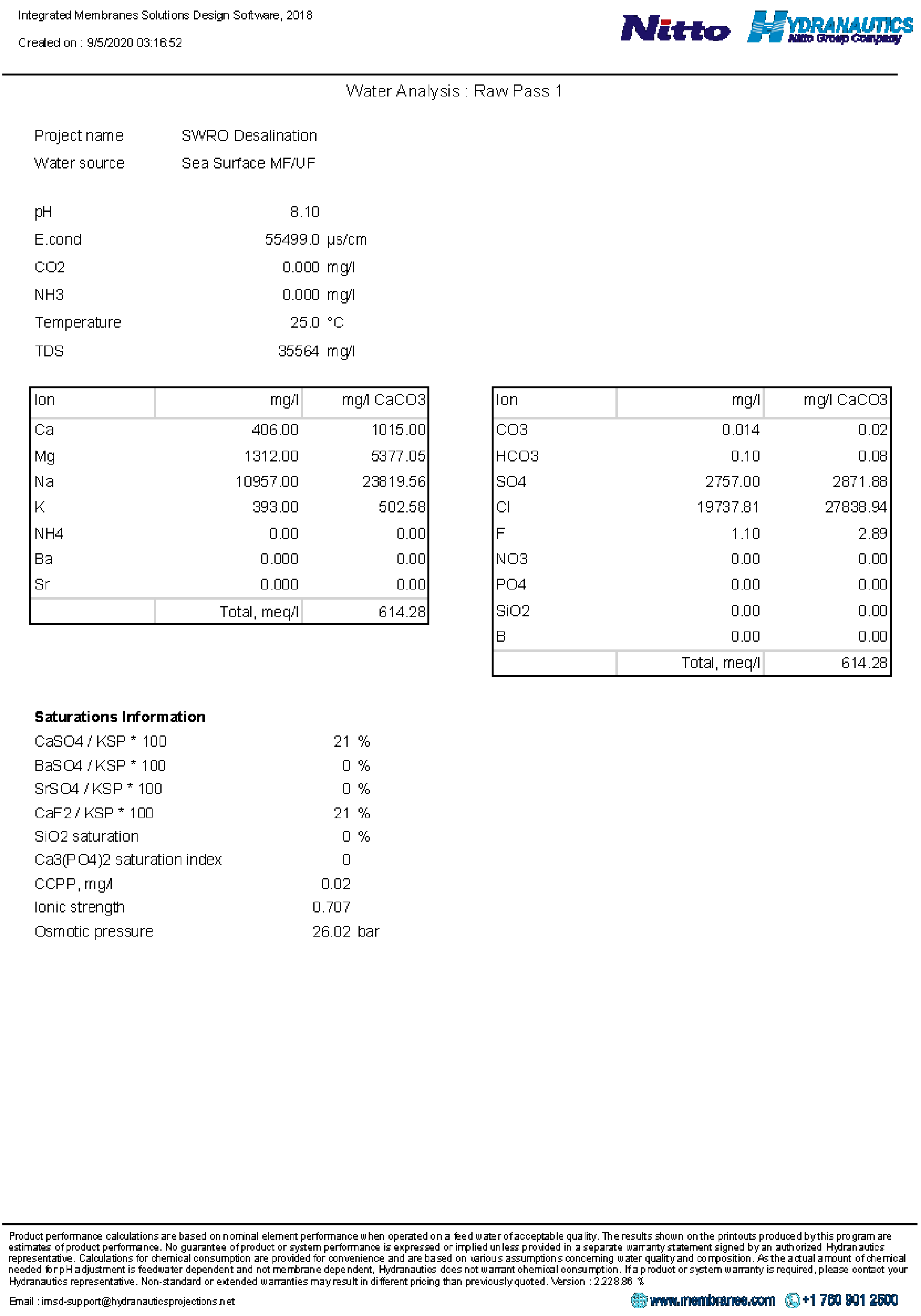
APPENDIX 1 – IMSDesign Results



Integrated Membranes Solutions Design Software, 2018

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Water Analysis : Raw Pass 1

Project name	SWRO Desalination
Water source	Sea Surface MF/UF

pH	8.10
E.cond	55499.0 µs/cm
CO2	0.000 mg/l
NH3	0.000 mg/l
Temperature	25.0 °C
TDS	35564 mg/l

Ion	mg/l	mg/l CaCO3
Ca	406.00	1015.00
Mg	1312.00	5377.05
Na	10957.00	23819.56
K	393.00	502.58
NH4	0.00	0.00
Ba	0.000	0.00
Sr	0.000	0.00
	Total, meq/l	614.28

Ion	mg/l	mg/l CaCO3
CO3	0.014	0.02
HCO3	0.10	0.08
SO4	2757.00	2871.88
Cl	19737.81	27838.94
F	1.10	2.89
NO3	0.00	0.00
PO4	0.00	0.00
SiO2	0.00	0.00
B	0.00	0.00
	Total, meq/l	614.28

Saturations Information

CaSO4 / KSP * 100	21 %
BaSO4 / KSP * 100	0 %
SrSO4 / KSP * 100	0 %
CaF2 / KSP * 100	21 %
SiO2 saturation	0 %
Ca3(PO4)2 saturation index	0
CCPP, mg/l	0.02
Ionic strength	0.707
Osmotic pressure	26.02 bar

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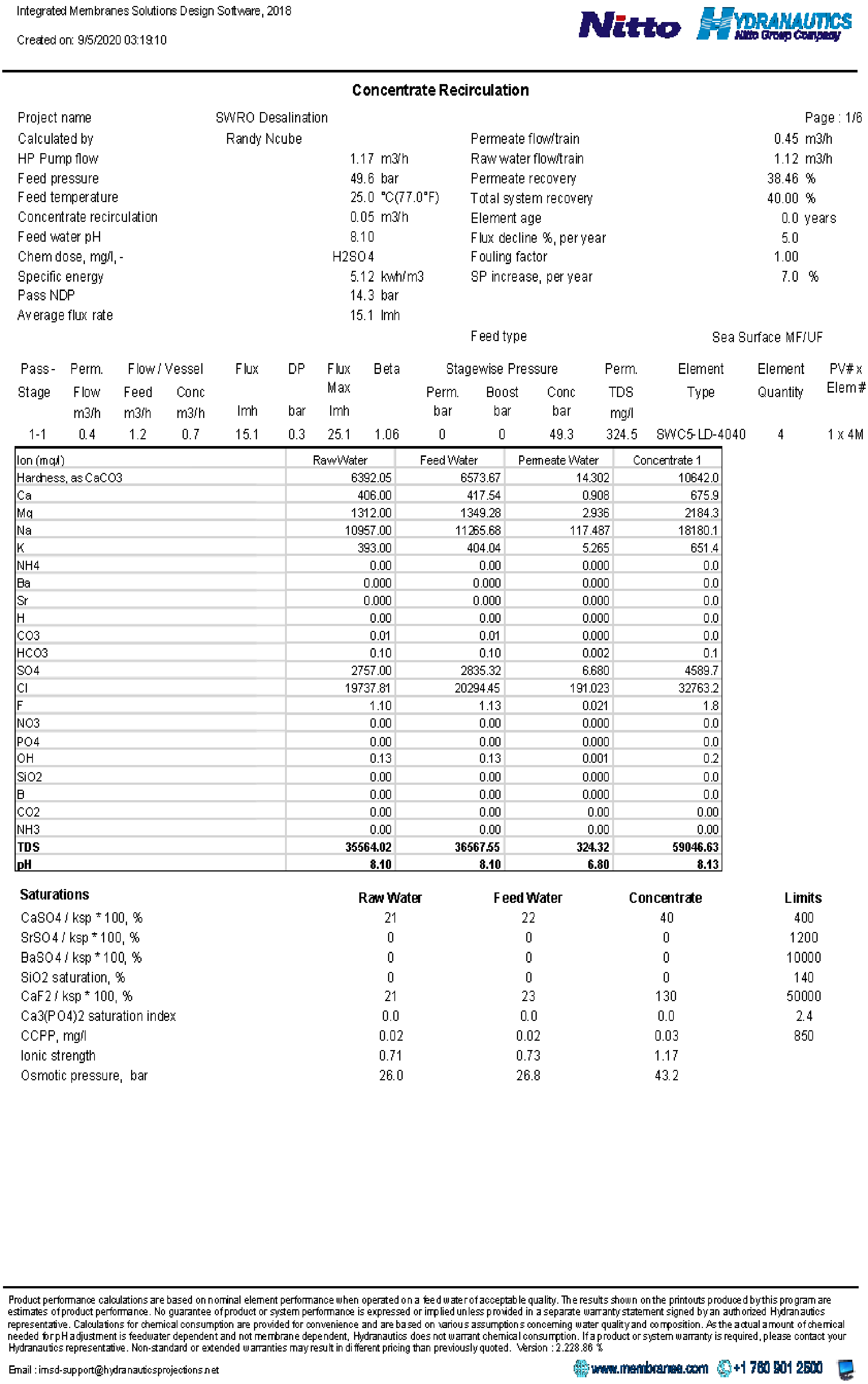

Integrated Membranes Solutions Design Software, 2018

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Concentrate Recirculation

Project name	SWRO Desalination			Page : 1/6
Calculated by	Randy Ncube		Permeate flow/train	0.45 m3/h
HP Pump flow		1.17 m3/h	Raw water flow/train	1.12 m3/h
Feed pressure		49.6 bar	Permeate recovery	38.46 %
Feed temperature		25.0 °C(77.0°F)	Total system recovery	40.00 %
Concentrate recirculation		0.05 m3/h	Element age	0.0 years
Feed water pH		8.10	Flux decline %, per year	5.0
Chem dose, mg/l, -		H2SO4	Fouling factor	1.00
Specific energy		5.12 kwh/m3	SP increase, per year	7.0 %
Pass NDP		14.3 bar		
Average flux rate		15.1 lmh		
			Feed type	Sea Surface MF/UF

Pass - Stage	Perm. Flow m3/h	Flow / Vessel Feed m3/h	Flow / Vessel Conc m3/h	Flux lmh	DP bar	Flux Max lmh	Beta	Stagewise Pressure Perm. bar	Stagewise Pressure Boost bar	Stagewise Pressure Conc bar	Perm. TDS mg/l	Element Type	Element Quantity	PV# x Elem#
1-1	0.4	1.2	0.7	15.1	0.3	25.1	1.06	0	0	49.3	324.5	SWC5-LD-4040	4	1 x 4M

Ion (mg/l)	Raw Water	Feed Water	Permeate Water	Concentrate 1
Hardness, as CaCO3	6392.05	6573.67	14.302	10642.0
Ca	406.00	417.54	0.908	675.9
Mg	1312.00	1349.28	2.936	2184.3
Na	10957.00	11265.68	117.487	18180.1
K	393.00	404.04	5.265	651.4
NH4	0.00	0.00	0.000	0.0
Ba	0.000	0.000	0.000	0.0
Sr	0.000	0.000	0.000	0.0
H	0.00	0.00	0.000	0.0
CO3	0.01	0.01	0.000	0.0
HCO3	0.10	0.10	0.002	0.1
SO4	2757.00	2835.32	6.680	4589.7
Cl	19737.81	20294.45	191.023	32763.2
F	1.10	1.13	0.021	1.8
NO3	0.00	0.00	0.000	0.0
PO4	0.00	0.00	0.000	0.0
OH	0.13	0.13	0.001	0.2
SiO2	0.00	0.00	0.000	0.0
B	0.00	0.00	0.000	0.0
CO2	0.00	0.00	0.00	0.00
NH3	0.00	0.00	0.00	0.00
TDS	**35564.02**	**36567.55**	**324.32**	**59046.63**
pH	**8.10**	**8.10**	**6.80**	**8.13**

Saturations	**Raw Water**	**Feed Water**	**Concentrate**	**Limits**
CaSO4 / ksp * 100, %	21	22	40	400
SrSO4 / ksp * 100, %	0	0	0	1200
BaSO4 / ksp * 100, %	0	0	0	10000
SiO2 saturation, %	0	0	0	140
CaF2 / ksp * 100, %	21	23	130	50000
Ca3(PO4)2 saturation index	0.0	0.0	0.0	2.4
CCPP, mg/l	0.02	0.02	0.03	850
Ionic strength	0.71	0.73	1.17	
Osmotic pressure, bar	26.0	26.8	43.2	

Product performance calculations are based on nominal element performance when operated on a feed water of acceptable quality. The results shown on the printouts produced by this program are estimates of product performance. No guarantee of product or system performance is expressed or implied unless provided in a separate warranty statement signed by an authorized Hydranautics representative. Calculations for chemical consumption are provided for convenience and are based on various assumptions concerning water quality and composition. As the actual amount of chemical needed for pH adjustment is feedwater dependent and not membrane dependent, Hydranautics does not warrant chemical consumption. If a product or system warranty is required, please contact your Hydranautics representative. Non-standard or extended warranties may result in different pricing than previously quoted. Version : 2.228.86 %

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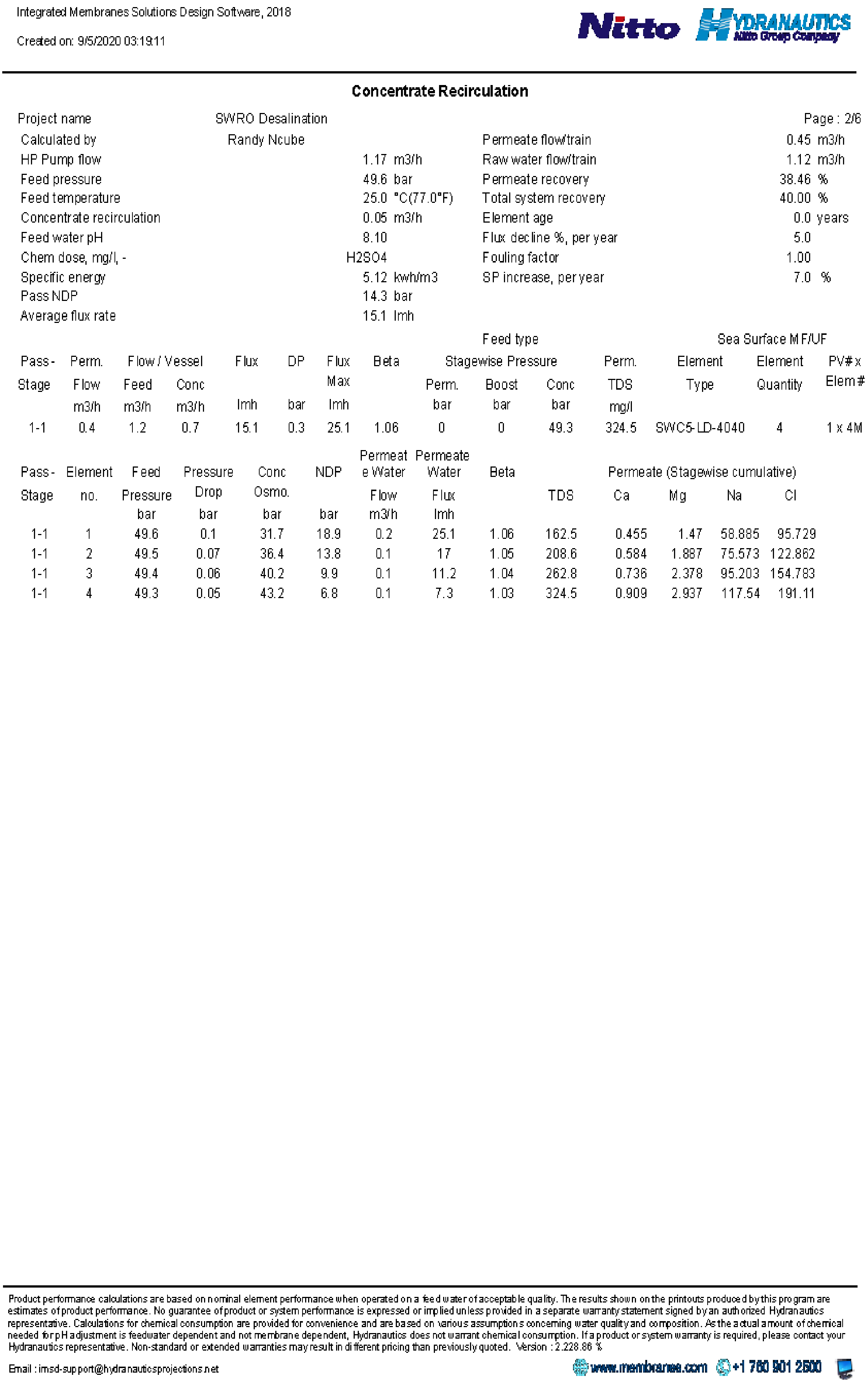

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Concentrate Recirculation

Project name	SWRO Desalination			Page : 2/6
Calculated by	Randy Ncube		Permeate flow/train	0.45 m3/h
HP Pump flow		1.17 m3/h	Raw water flow/train	1.12 m3/h
Feed pressure		49.6 bar	Permeate recovery	38.46 %
Feed temperature		25.0 °C(77.0°F)	Total system recovery	40.00 %
Concentrate recirculation		0.05 m3/h	Element age	0.0 years
Feed water pH		8.10	Flux decline %, per year	5.0
Chem dose, mg/l, -		H2SO4	Fouling factor	1.00
Specific energy		5.12 kwh/m3	SP increase, per year	7.0 %
Pass NDP		14.3 bar		
Average flux rate		15.1 lmh		
			Feed type	Sea Surface MF/UF

Pass-Stage	Perm. Flow m3/h	Flow / Vessel Feed m3/h	Flow / Vessel Conc m3/h	Flux lmh	DP bar	Flux Max lmh	Beta	Stagewise Pressure Perm. bar	Stagewise Pressure Boost bar	Stagewise Pressure Conc bar	Perm. TDS mg/l	Element Type	Element Quantity	PV# x Elem#
1-1	0.4	1.2	0.7	15.1	0.3	25.1	1.06	0	0	49.3	324.5	SWC5-LD-4040	4	1 x 4M

Pass-Stage	Element no.	Feed Pressure bar	Pressure Drop bar	Conc Osmo. bar	NDP bar	Permeate Water Flow m3/h	Permeate Water Flux lmh	Beta	Permeate (Stagewise cumulative) TDS	Ca	Mg	Na	Cl
1-1	1	49.6	0.1	31.7	18.9	0.2	25.1	1.06	162.5	0.455	1.47	58.885	95.729
1-1	2	49.5	0.07	36.4	13.8	0.1	17	1.05	208.6	0.584	1.887	75.573	122.862
1-1	3	49.4	0.06	40.2	9.9	0.1	11.2	1.04	262.8	0.736	2.378	95.203	154.783
1-1	4	49.3	0.05	43.2	6.8	0.1	7.3	1.03	324.5	0.909	2.937	117.54	191.11

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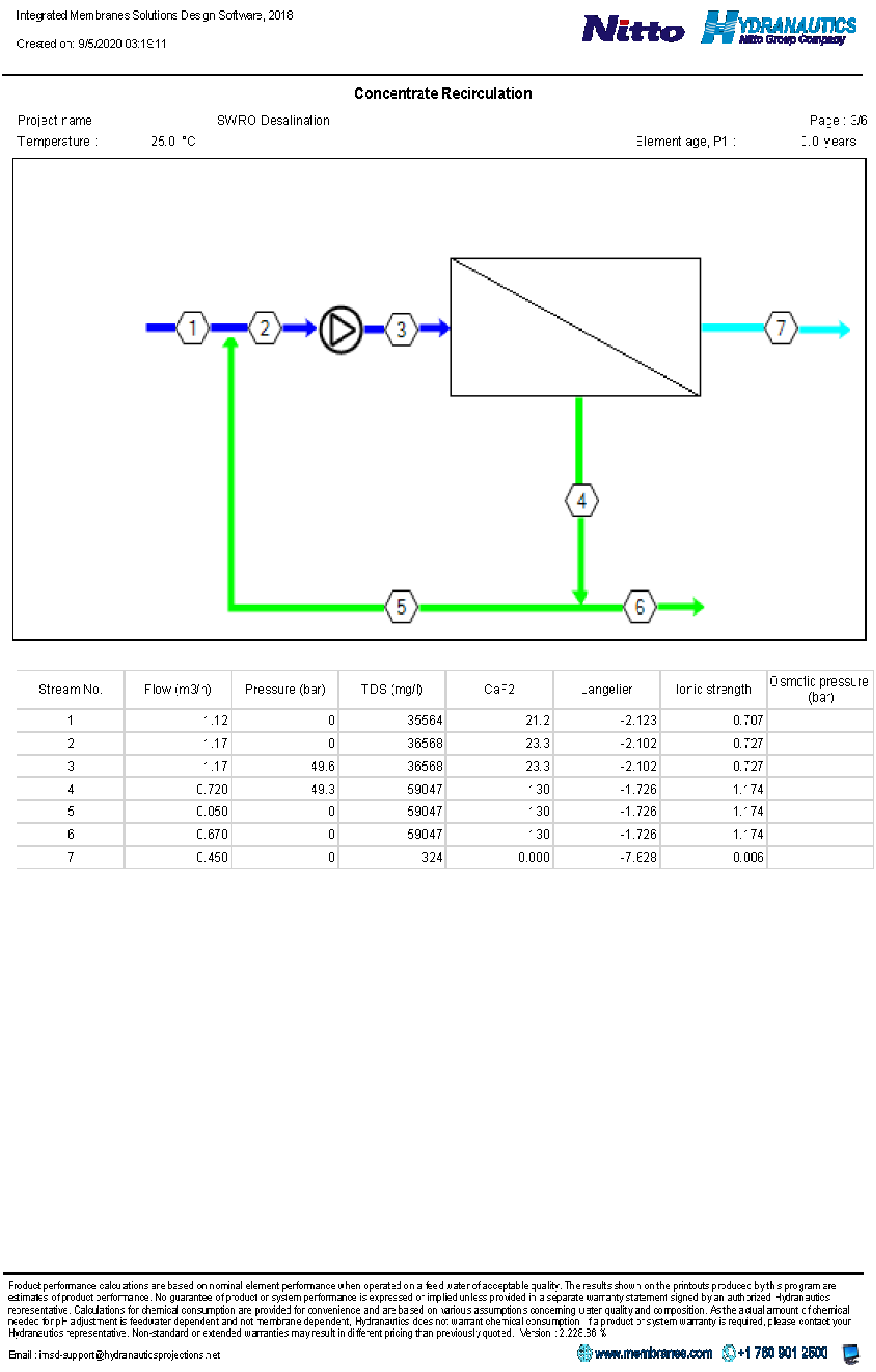

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Concentrate Recirculation

Project name	SWRO Desalination		Page : 3/6
Temperature :	25.0 °C	Element age, P1 :	0.0 years

Stream No.	Flow (m3/h)	Pressure (bar)	TDS (mg/l)	CaF2	Langelier	Ionic strength	Osmotic pressure (bar)
1	1.12	0	35564	21.2	-2.123	0.707	
2	1.17	0	36568	23.3	-2.102	0.727	
3	1.17	49.6	36568	23.3	-2.102	0.727	
4	0.720	49.3	59047	130	-1.726	1.174	
5	0.050	0	59047	130	-1.726	1.174	
6	0.670	0	59047	130	-1.726	1.174	
7	0.450	0	324	0.000	-7.628	0.006	

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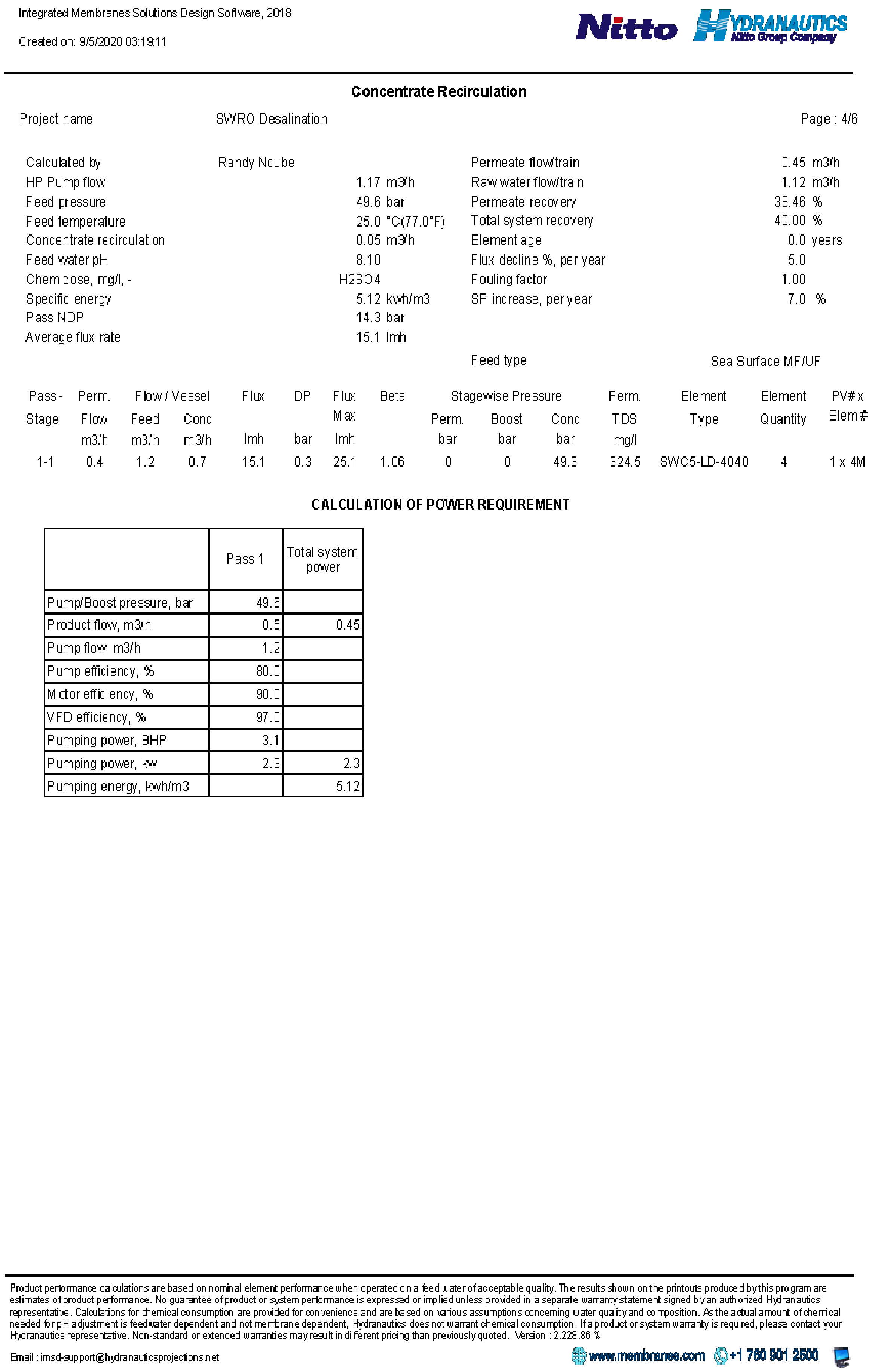

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Concentrate Recirculation

Project name	SWRO Desalination	Page : 4/6

Calculated by	Randy Ncube		Permeate flow/train	0.45 m3/h
HP Pump flow		1.17 m3/h	Raw water flow/train	1.12 m3/h
Feed pressure		49.6 bar	Permeate recovery	38.46 %
Feed temperature		25.0 °C(77.0°F)	Total system recovery	40.00 %
Concentrate recirculation		0.05 m3/h	Element age	0.0 years
Feed water pH		8.10	Flux decline %, per year	5.0
Chem dose, mg/l, -		H2SO4	Fouling factor	1.00
Specific energy		5.12 kwh/m3	SP increase, per year	7.0 %
Pass NDP		14.3 bar		
Average flux rate		15.1 lmh		
			Feed type	Sea Surface MF/UF

Pass -	Perm.	Flow / Vessel		Flux	DP	Flux	Beta	Stagewise Pressure			Perm.	Element	Element	PV# x
Stage	Flow	Feed	Conc			Max		Perm.	Boost	Conc	TDS	Type	Quantity	Elem #
	m3/h	m3/h	m3/h	lmh	bar	lmh		bar	bar	bar	mg/l			
1-1	0.4	1.2	0.7	15.1	0.3	25.1	1.06	0	0	49.3	324.5	SWC5-LD-4040	4	1 x 4M

CALCULATION OF POWER REQUIREMENT

	Pass 1	Total system power
Pump/Boost pressure, bar	49.6	
Product flow, m3/h	0.5	0.45
Pump flow, m3/h	1.2	
Pump efficiency, %	80.0	
Motor efficiency, %	90.0	
VFD efficiency, %	97.0	
Pumping power, BHP	3.1	
Pumping power, kw	2.3	2.3
Pumping energy, kwh/m3		5.12

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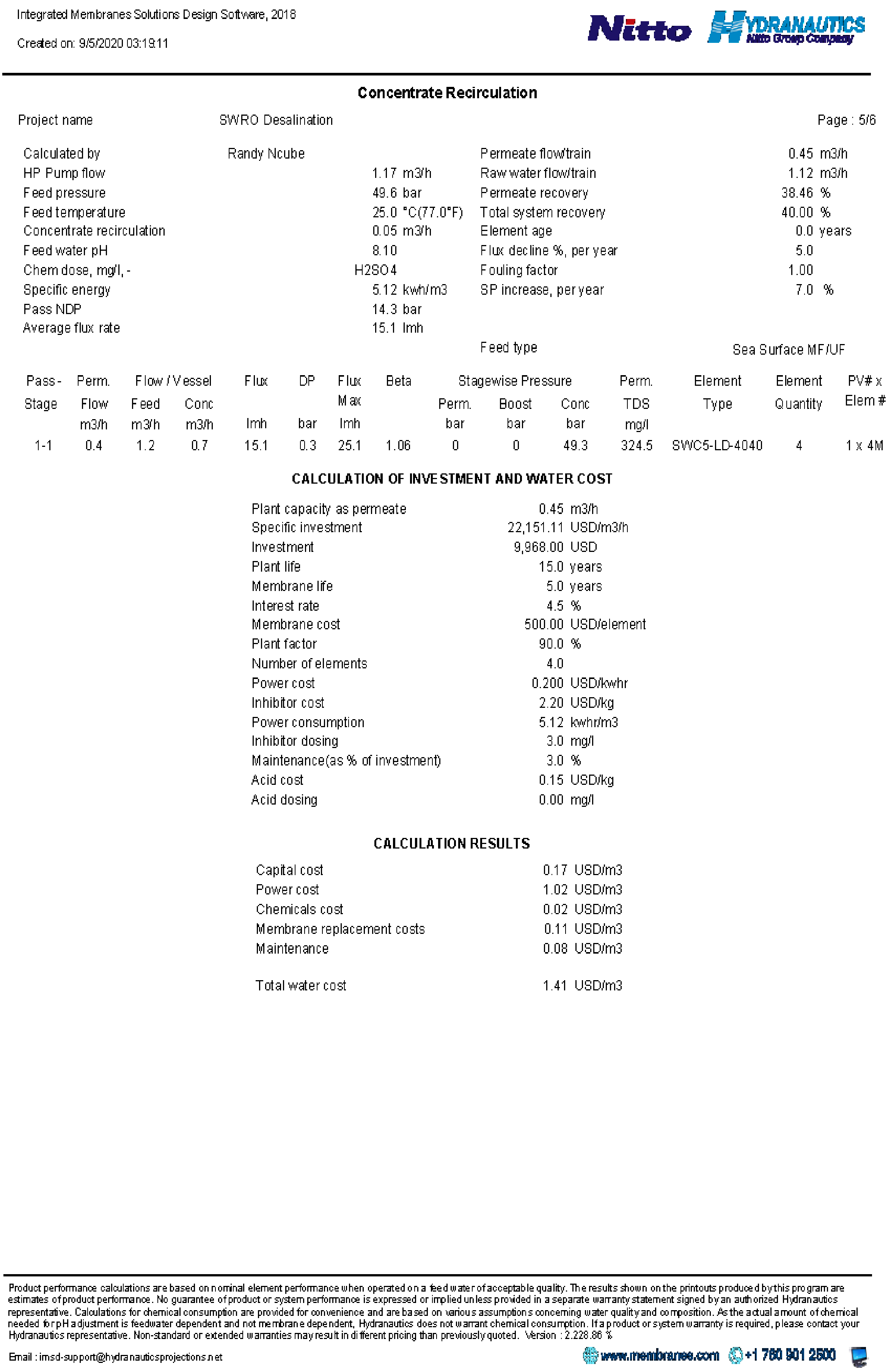

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Concentrate Recirculation

Project name SWRO Desalination Page : 5/6

Calculated by	Randy Ncube	Permeate flow/train	0.45 m3/h
HP Pump flow	1.17 m3/h	Raw water flow/train	1.12 m3/h
Feed pressure	49.6 bar	Permeate recovery	38.46 %
Feed temperature	25.0 °C(77.0°F)	Total system recovery	40.00 %
Concentrate recirculation	0.05 m3/h	Element age	0.0 years
Feed water pH	8.10	Flux decline %, per year	5.0
Chem dose, mg/l, -	H2SO4	Fouling factor	1.00
Specific energy	5.12 kwh/m3	SP increase, per year	7.0 %
Pass NDP	14.3 bar		
Average flux rate	15.1 lmh		
		Feed type	Sea Surface MF/UF

Pass - Stage	Perm. Flow m3/h	Flow / Vessel Feed m3/h	Flow / Vessel Conc m3/h	Flux lmh	DP bar	Flux Max lmh	Beta	Stagewise Pressure Perm. bar	Stagewise Pressure Boost bar	Stagewise Pressure Conc bar	Perm. TDS mg/l	Element Type	Element Quantity	PV# x Elem #
1-1	0.4	1.2	0.7	15.1	0.3	25.1	1.06	0	0	49.3	324.5	SWC5-LD-4040	4	1 x 4M

CALCULATION OF INVESTMENT AND WATER COST

Plant capacity as permeate	0.45 m3/h
Specific investment	22,151.11 USD/m3/h
Investment	9,968.00 USD
Plant life	15.0 years
Membrane life	5.0 years
Interest rate	4.5 %
Membrane cost	500.00 USD/element
Plant factor	90.0 %
Number of elements	4.0
Power cost	0.200 USD/kwhr
Inhibitor cost	2.20 USD/kg
Power consumption	5.12 kwhr/m3
Inhibitor dosing	3.0 mg/l
Maintenance(as % of investment)	3.0 %
Acid cost	0.15 USD/kg
Acid dosing	0.00 mg/l

CALCULATION RESULTS

Capital cost	0.17 USD/m3
Power cost	1.02 USD/m3
Chemicals cost	0.02 USD/m3
Membrane replacement costs	0.11 USD/m3
Maintenance	0.08 USD/m3
Total water cost	1.41 USD/m3

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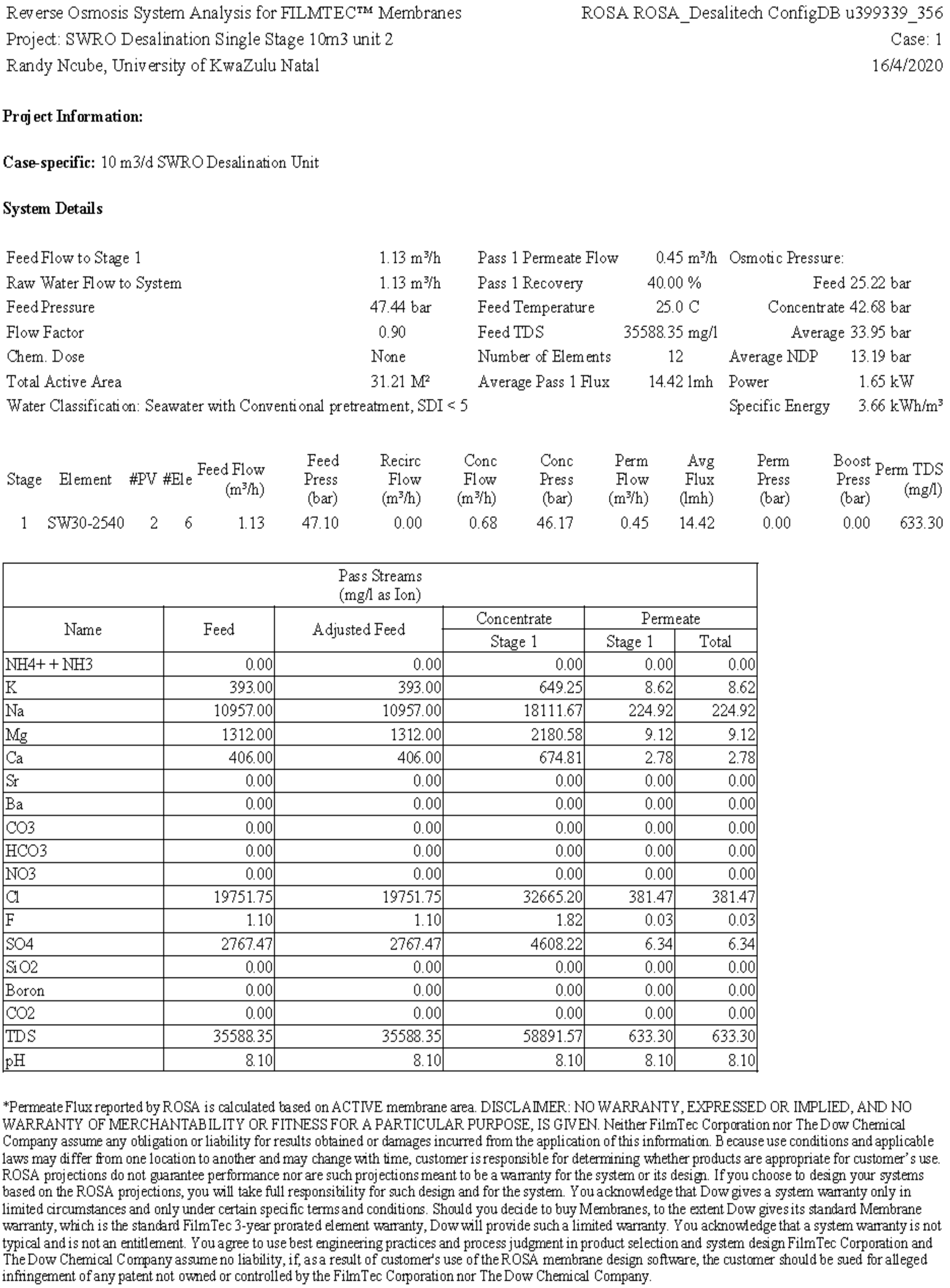
APPENDIX 2 – ROSA Results



Reverse Osmosis System Analysis for FILMTEC™ Membranes	ROSA ROSA_Desalitech ConfigDB u399339_356
Project: SWRO Desalination Single Stage 10m3 unit 2	Case: 1
Randy Ncube, University of KwaZulu Natal	16/4/2020

Project Information:

Case-specific: 10 m3/d SWRO Desalination Unit

System Details

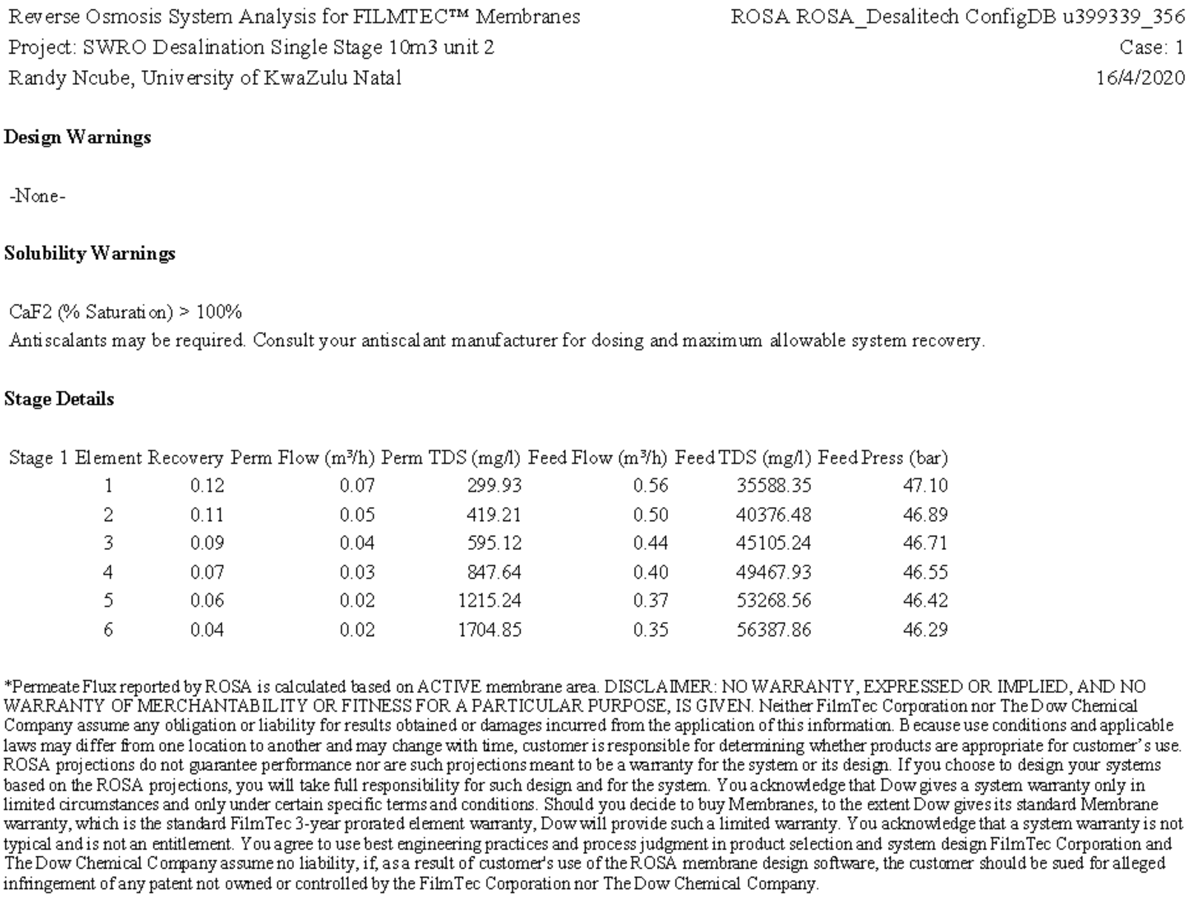
Feed Flow to Stage 1	1.13 m^3/h	Pass 1 Permeate Flow	0.45 m^3/h	Osmotic Pressure:	
Raw Water Flow to System	1.13 m^3/h	Pass 1 Recovery	40.00 %	Feed	25.22 bar
Feed Pressure	47.44 bar	Feed Temperature	25.0 C	Concentrate	42.68 bar
Flow Factor	0.90	Feed TDS	35588.35 mg/l	Average	33.95 bar
Chem. Dose	None	Number of Elements	12	Average NDP	13.19 bar
Total Active Area	31.21 M^2	Average Pass 1 Flux	14.42 lmh	Power	1.65 kW
Water Classification: Seawater with Conventional pretreatment, SDI < 5				Specific Energy	3.66 kWh/m^3

Stage	Element	#PV	#Ele	Feed Flow (m^3/h)	Feed Press (bar)	Recirc Flow (m^3/h)	Conc Flow (m^3/h)	Conc Press (bar)	Perm Flow (m^3/h)	Avg Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/l)
1	SW30-2540	2	6	1.13	47.10	0.00	0.68	46.17	0.45	14.42	0.00	0.00	633.30

Pass Streams
(mg/l as Ion)

Name	Feed	Adjusted Feed	Concentrate	Permeate	
			Stage 1	Stage 1	Total
NH4+ + NH3	0.00	0.00	0.00	0.00	0.00
K	393.00	393.00	649.25	8.62	8.62
Na	10957.00	10957.00	18111.67	224.92	224.92
Mg	1312.00	1312.00	2180.58	9.12	9.12
Ca	406.00	406.00	674.81	2.78	2.78
Sr	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00
CO3	0.00	0.00	0.00	0.00	0.00
HCO3	0.00	0.00	0.00	0.00	0.00
NO3	0.00	0.00	0.00	0.00	0.00
Cl	19751.75	19751.75	32665.20	381.47	381.47
F	1.10	1.10	1.82	0.03	0.03
SO4	2767.47	2767.47	4608.22	6.34	6.34
SiO2	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00
TDS	35588.35	35588.35	58891.57	633.30	633.30
pH	8.10	8.10	8.10	8.10	8.10

*Permeate Flux reported by ROSA is calculated based on ACTIVE membrane area. DISCLAIMER: NO WARRANTY, EXPRESSED OR IMPLIED, AND NO WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, IS GIVEN. Neither FilmTec Corporation nor The Dow Chemical Company assume any obligation or liability for results obtained or damages incurred from the application of this information. Because use conditions and applicable laws may differ from one location to another and may change with time, customer is responsible for determining whether products are appropriate for customer's use. ROSA projections do not guarantee performance nor are such projections meant to be a warranty for the system or its design. If you choose to design your systems based on the ROSA projections, you will take full responsibility for such design and for the system. You acknowledge that Dow gives a system warranty only in limited circumstances and only under certain specific terms and conditions. Should you decide to buy Membranes, to the extent Dow gives its standard Membrane warranty, which is the standard FilmTec 3-year prorated element warranty, Dow will provide such a limited warranty. You acknowledge that a system warranty is not typical and is not an entitlement. You agree to use best engineering practices and process judgment in product selection and system design FilmTec Corporation and The Dow Chemical Company assume no liability, if, as a result of customer's use of the ROSA membrane design software, the customer should be sued for alleged infringement of any patent not owned or controlled by the FilmTec Corporation nor The Dow Chemical Company.



Reverse Osmosis System Analysis for FILMTEC™ Membranes — ROSA ROSA_Desalitech ConfigDB u399339_356
Project: SWRO Desalination Single Stage 10m3 unit 2 — Case: 1
Randy Ncube, University of KwaZulu Natal — 16/4/2020

Design Warnings

-None-

Solubility Warnings

CaF2 (% Saturation) > 100%
Antiscalants may be required. Consult your antiscalant manufacturer for dosing and maximum allowable system recovery.

Stage Details

Stage 1 Element	Recovery	Perm Flow (m³/h)	Perm TDS (mg/l)	Feed Flow (m³/h)	Feed TDS (mg/l)	Feed Press (bar)
1	0.12	0.07	299.93	0.56	35588.35	47.10
2	0.11	0.05	419.21	0.50	40376.48	46.89
3	0.09	0.04	595.12	0.44	45105.24	46.71
4	0.07	0.03	847.64	0.40	49467.93	46.55
5	0.06	0.02	1215.24	0.37	53268.56	46.42
6	0.04	0.02	1704.85	0.35	56387.86	46.29

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