Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1035496

57 (2016) 9166–9179
April

Taylor & Francis
Taylor & Francis Group

CCD Series No-15: simple design batch SWRO-CCD units of high recovery and low energy without ERD for wide range flux operation of high cost-effectiveness

Avi Efraty

Desalitech Ltd, P.O. Box 132, Har Adar 90836, Israel, email: avi@desalitech.com

Received 3 December 2013; Accepted 3 March 2015

ABSTRACT

Closed-circuit desalination (CCD) is a batch process of low energy without need for an energy recovery device (ERD), high recovery irrespective of the number of elements per module, and wide range flux independent of cross-flow and/or recovery, which can be made continuous by the engagement of a side conduit for brine replacement with fresh feed. Batch units for seawater desalination (SWRO-CCD) of the general NMEn (n = 1–3) design, where N stands for the number of modules and n for the number of elements per module, are low-cost systems since avoid the need for ERD and the valves means for the making such a process continuous. Such SWRO-CCD batch units, which pose for recharge between desalination steps, can supply 10 → 1,200 m^3/d low-cost seawater permeates sufficient for communities of 100 → 12,000 resident on the basis of 100 L/d/person and for much larger communities if supplied permeates used primarily for drinking and cooking applications. Batch SWRO-CCD units are ideal for small seashore communities with access to shallow beach wells in light of their low-energy consumption and great operational flexibility such as of low flux energy saving mode during night time of low demand with increased production as function of demand at higher flux and greater energy expense during daytime. The wide range flux performance capability of the referred batch units make them ideal for integration with renewable energy sources through solar panels and/or small wind turbines. The energy consumption and permeates quality (parenthesis) as function of flux for the referred units with ME3 (E = SWC6-MAX) modules' designs for ocean seawater (35,000 ppm) operation of 50% recovery using pressurizing means of 85% efficiency are as follows: 1.79 kWh/m^3 (595 ppm) at 13 Lmh; 1.97 kWh/m^3 (388 ppm) at 20 Lmh; 2.12 kWh/m^3 (309 ppm) at 25 Lmh; and 2.25 kWh/m^3 (259 ppm) at 30 Lmh. The experimentally confirmed cited energy figures, even at high flux, manifest high-energy conversion efficiency unattainable by conventional SWRO techniques.

Keywords: CCD; SWRO; Batch SWRO desalination; Seawater desalination; High recovery; Low energy; High flux

1. Introduction

The increasing dependence on SWRO desalination [1] for potable water supplies in various parts of the world requires the development of new cost-effective technologies of low-energy consumption and high recovery for small- and large-scale applications.

Modern SWRO elements (e.g. SWC6-MAX and alike) enable high flux operation as evident from their test conditions data (e.g. 51 Lmh for SWC6-MAX [2]). However, in eight element modules used by conventional SWRO techniques under operational conditions of constant applied pressure, the average flux is only around 13 Lmh due to declined flux and the need to maintain concentrate/permeate flow ratio per element above 5.0. Distributions of pressure, flow, flux, recovery, concentrations, and power inside a typical conventional ME8 (E = SWC6-MAX) module during desalination of 32,000 ppm NaCl with 50% recovery according to an IMS design program [3] are illustrated in Table 1. The power and specific energy data in the table are based on the cited flow and pressure parameters assuming pressurizing pump efficiency of 85% and on the efficiency of the energy recovery device (ERD). Specific energy illustrations of the conventional SWRO process under review with different EDR efficiencies are displayed in Fig. 1. The data in Table 1 and curves displayed in Fig. 1 of the relations between the number of elements and recovery (A), flux (B), and specific energy for different EDR efficiencies (C) leave no doubt that almost 80% of the desalination in the ME8 module is carried out by the front 3 elements, with added ~8.9% by fourth element and only 11.1% by elements 5–8 combined. In simple terms, a technology which could utilize effectively modules of 1–4 elements, instead of 8, and reach 50% recovery with high average flux could save elements and provide better quality permeates and the newly reported [4–6] closed-circuit desalination (CCD) is one of such technologies which proceeds with near absolute energy conversion efficiency without need of ERD, and its wide range flux applications are explored and compared with conventional SWRO in the current study.

2. Design of single module SWRO-CCD ME*n* (*n* = 1–3) batch units for wide flux range operation

Recent reports describe the design and performance characteristics of compact SWRO-CCD ME*n* (*n* = 2–4) units [7] and a single element SWRO-CCD ME unit [8] for low-energy continuous desalination of seawater including theoretical background and model simulations.

The design of single module SWRO-CCD ME*n* (*n* = 1–3) units for batch desalination of high flux requires special attention to the duration of the CCD sequence expressed by Eq. (1); wherein, T_{CCD} is sequence duration (min); R, sequence recovery (%); V, intrinsic free volume of the closed circuit (L); Q_f, pressurized feed flow (L/min); Q_p, permeate flow (L/min); J, average flux (Lmh); n, number of elements per module; and S, for membrane surface area per element (m^2). CCD under fixed flow and variable pressure conditions proceeds with identical CCD cycles each of the same time duration $T_{CCD\text{-}CYCLE}$ (min/cycle) expressed by Eq. (2); wherein, Q_{CP} is the flow rate (L/min) of recycled concentrate. Therefore, sequence duration of a known number of cycles (δ) is expressed by Eq. (3). It should be reminded that two different recovery terms are encountered in CCD processes, the so-called sequence recovery (R) and module recovery (MR) which are expressed by Eqs. (4) and (5), respectively, wherein ΣV_p is the total produced volume (L) of permeate during the sequence. The flow rates Q_p and Q_{CP} are independent of each other; however, under operation with fixed MR, these flow terms are interrelated according to Eq. (6).

$$\begin{aligned} T_{CCD} &= R \times V/[Q_f \times (100 - R)] \\ &= R \times V/[Q_p \times (100 - R)] \\ &= R \times V/[(J \times n \times S/1000) \times (100 - R)] \end{aligned} \quad (1)$$

$$T_{CCD\text{-}CYCLE} = V/Q_{CP} \quad (2)$$

$$T_{CCD} = \delta \times V/Q_{CP} \quad (3)$$

$$\begin{aligned} R &= \textstyle\sum V_p/(\sum V_p + V) \times 100 \\ &= 100 \times Q_p \times T_{CCD}/(V + T_{CCD} \times Q_p) \\ &= 100 \times Q_f \times T_{CCD}/(V + T_{CCD} \times Q_f) \end{aligned} \quad (4)$$

$$\mathrm{MR} = 100 \times Q_p/(Q_{CP} + Q_p) \quad (5)$$

$$Q_{CP} = Q_p \times (100 - \mathrm{MR})/\mathrm{MR} \quad (6)$$

The aforementioned considerations imply the need for large intrinsic volume (V) in order to carry out batch CCD of high flux and reach the desired recovery for seawater desalination (50–60%) with a reasonable long batch sequence duration such as of ~10 min at flux of 40 Lmh that of the front element in a conventional ME8 (E = SWC6-MAX) module according to the IMS design data furnished in Table 1. A single-element module design which meets the specified flux and sequence duration conditions should consist of an intrinsic closed-circuit volume of ~175 L and such a design is revealed for the SWRO-CCD ME*n* (*n* = 1) batch unit displayed in Fig. 2. The design in Fig. 2 comprises a single-element 8´´ module connected in line to an empty 16´´ pressure vessel (PV) of 175-L total intrinsic closed-circuit volume, one circulation pump with *vfd* (CP), one positive displacement pump of high pressure with *vfd*

Table 1
Pressure, flow, flux, recovery, concentration, power and energy distributions inside ME8 (E = SWC6-MAX) module during desalination of 32,000 ppm NaCl with 50% recovery at 25˚C using a pressurizing pump efficiency of 85% and assuming energy recovery efficiency of 75%

		Flow rates			Flux		Recovery		Concentrations			Power & Energy				
			Permeate							Permeate				Net RO		
Elem No	Pres Bar	Feed m^3/h	m^3/h	$\Sigma m^3/h$	Elem Lmh	av Lmh	Elem (%)	CUM Σ%	Feed ppm	ppm	Σppm	Gross KW	ERD KW	KW	kWh/m^3	Conc/Perm ratio
1	52.5	8.600	1.636	1.636	40.1	40.1	19.0	19.0	32,000	122	122	14.75	7.62	7.14	4.363	4.3
2	52.2	6.964	1.081	2.717	26.5	33.3	15.5	31.6	39,518	147	132		6.40	8.36	3.076	5.4
3	52.0	5.883	0.698	3.415	17.1	27.9	11.9	39.7	46,781	176	141		5.62	9.14	2.676	7.4
4	51.8	5.185	0.388	3.803	9.5	23.3	7.5	44.2	53,076	210	148		5.18	9.58	2.519	12.4
5	51.7	4.797	0.228	4.031	5.6	19.8	4.8	46.9	57,364	248	154		4.92	9.83	2.440	20.0
6	51.6	4.569	0.135	4.166	3.3	17.0	2.9	48.4	60,233	288	158		4.77	9.99	2.398	32.9
7	51.4	4.434	0.078	4.243	1.9	14.9	1.7	49.3	62,061	330	161		4.67	10.09	2.378	56.2
8	51.3	4.357	0.045	4.288	1.1	13.1	1.0	49.9	63,166	373	163		4.61	10.15	2.366	96.1

Abbreviations: Elem, element; Pres, pressure; Σ, cumulative; av, average; ERD, energy recovery device; SE, specific energy calculated from gross power less energy recovered from brine with 75% efficiency.

(HP), three one-wary check valves (CV), one two-way actuated valve (AV), and an air release valve (ARV). The unit under review is operated under fixed flow and variable pressure conditions dictated by the selected flow rates set points of HP and CP which according to Eq. (5) determine the MR of operation. The operation is initiated by the start of the HP and CP pumps and at a maximum selected applied pressure which manifest the desired recovery (*R*), the pumps are stopped, pressure released by the opening of AV and thereafter, fresh feed of set point defined volume is admitted for brine replacement with fresh feed at near atmospheric pressure and when this step is completed according to the water meter set point, the CCD operation is resumed and a new batch desalination sequence initiated. The system is designed to execute CCD for 10 min at average flux of 40 Lmh, reach recovery of ~60% and thereafter, perform brine replacement by fresh at near atmospheric pressure for ~2 min before the resumption of a new CCD sequence. Batch desalination of said unit at 40 Lmh and the cited time periods implies that CCD is experienced 83.3% of the time and brine replacement by fresh feed without desalination during the remaining time (16.7%).

The designs of the SWRO-CCD ME*n* (*n* = 1–3) batch units are distinguished from each other by the number of elements and length of PV with 140 cm for ME*n* (*n* = 1), 240 cm for ME*n* (*n* = 2), and 340 cm for ME*n* (*n* = 3). Acceptable MR of maximum 16.5% for ME*n* (*n* = 1); 31.4% for ME*n* (*n* = 2); and 39.5% for ME*n* (*n* = 3) are suggested by the relevant IMS design data in Table 1.

3. Single-module SWRO-CCD ME*n* (*n* = 1–3) batch units performance of wide range flux operation

The batch performance characteristics of the single-module units ME*n* (*n* = 1–3) under review are evaluated by means of model simulations using feed of 32,000 ppm NaCl, equivalent to average ocean water of 35,000 ppm, using SWC6-MAX membranes or alike. The simulation database presented hereinafter is of the type already discussed elsewhere [7,8] for continuous SWRO-CCD processes with minor alterations related to the expanded closed-circuit volume by means of 16´´ PV and the recharge time interval of the closed circuit during which period both HP and CP pumps are inactive and desalination stopped. The simulated data presented hereinafter is for CCD sequences of 10 cycles each performed under fixed flow and variable pressure conditions with module inlet feed flow kept below 17 m^3/h and

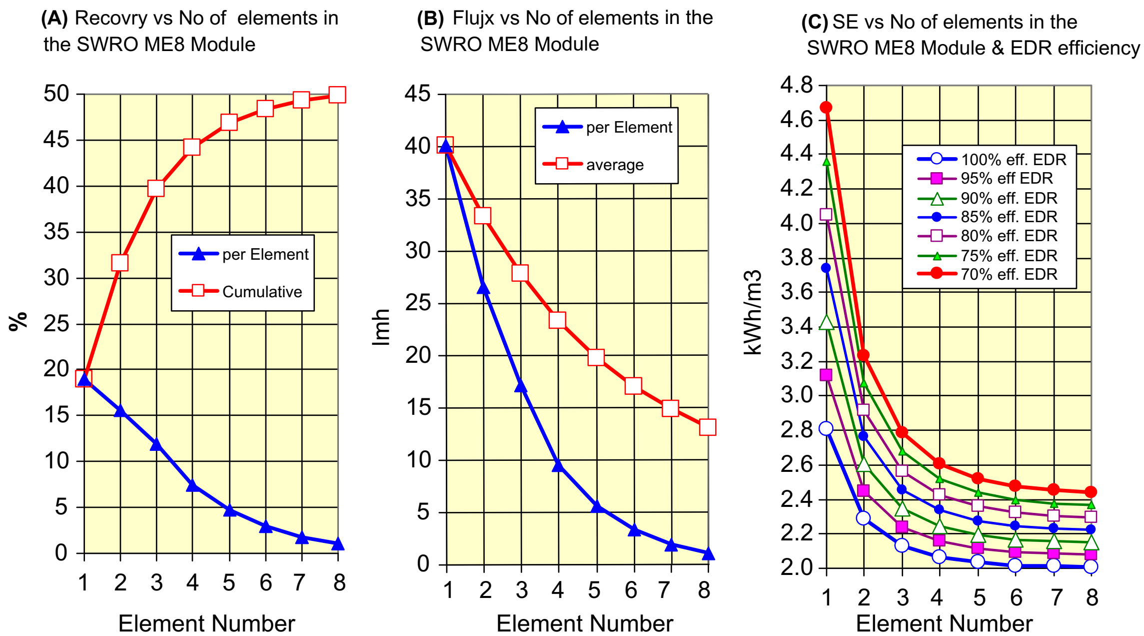

Fig. 1. Recovery (A), flux (B), and specific energy (C) variations as function of number of elements per conventional ME*n* (n = 1–8; E = SWC6-MAX) module according to Table 1.

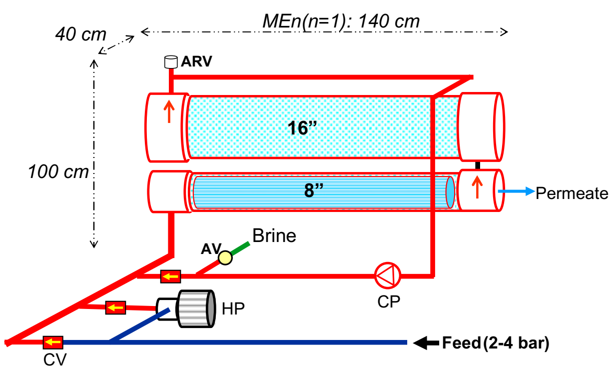

Fig. 2. SWRO-CCD ME batch unit design comprising a single element 8´´ module connected in line to an empty 16´´ PV of 175 L total closed circuit volume, one circulation pump with *vfd* (CP), one positive displacement pump for high pressure with vfd (HP), three one-wary CV, one AV, and an ARV—red lines stands for pressurized sections and blue for none pressurized lines.

concentrate/permeate flow ratio per element retained above 5.0. The simulation database for ME (40 Lmh—MR = 16.5%); ME2 (33.3 Lmh—MR = 31.4%); and ME3 (27.9 Lmh—MR = 39.5%) displayed in Tables 2–4, respectively are exemplified with the cited flux with MR values (in parenthesis) below the average of the front elements in the conventional ME8 module design specified in Table 1.

3.1. SWRO-CCD ME (E = SWC6-MAX) batch unit performance with 3.2% NaCl

The data displayed in Table 2 is of a simulated SWRO-CCD batch sequence performance of 10 CCD cycles by the ME (E = SWC6-MAX) unit (Fig. 1) with 3.2% NaCl at MR = 16.5% and 25°C under fixed flow of variable pressure conditions (Q_{HP} = 1.63 m^3/h, 40 Lmh average flux and Q_{CP} = 8.26 m^3/h), module inlet flow of 9.89 m^3/h (<17 m^3/h limit), and concentrate/permeate flow ratio of 5.1. Change of flux in the database (Table 2) over the range of 10 → 40 Lmh leads to the sequential time variations vs. CCD cycles and recovery displayed in Fig. 2.1(A); pressure variations vs. CCD cycles and recovery in Fig. 2.1(B); specific energy variations vs. recovery in Fig. 2.2(A); permeate TDS variations vs. recovery in Fig. 2.2(B); daily permeates production vs. recovery in Fig. 2.3(A); and community size supply needs vs. recovery in Fig. 2.3(B).

3.2. SWRO-CCD ME2 (E = SWC6-MAX) batch unit performance with 3.2% NaCl

The data displayed in Table 3 is a simulated SWRO-CCD batch sequence performance of 10 CCD

Table 2
SWRO-CCD batch sequence simulation of time, pressure, flow, power, specific energy, permeate TDS and daily production for the ME (E = SWC6-MAX) unit with 3.2% NaCl at 40 Lmh under fixed flow and variable pressure conditions

SWC6-MAX Test Conditions

40.8	m2/Element
50	m3/day
32,000	ppm NaCl
54	bar Applied Pressure
10	% Recovery
25	Centigrade
99.60	% Salt Rejection
28.4	bar NDP
51.06	l/m2/h Flux
1.798	l/m2/h/bar -A
0.160	l/m2/h - B

π(bar)-C(%)

32000	ppm NaCl Feed
25.60	bar Osmotic Pressure
8.00	π(bar)/C(%)

UNIT Design

1	Modules
1	Elements/Module
120	cm long PV
20	cm diameter PV
15	liter element volume
5	% lines volume
23.8	liter per module

CCD Extension(16")

120	cm long PV
40	cm diameter PV
150.7	liter volume
175	liter TOTAL per module
175	liter TOTAL per design

CCD per Module		per Design
3.20	% Initial feed	3.20
40.0	lmh Flux	40.00
1.63	m3/h Permeate (=Q_{HP})	1.63
16.5	% Module Recovery	16.50
8.26	m3/h Q_{CP}	8.26
0.34	bar Δp	0.34
1.27	min/cycle CCD	1.27
0.165	av-Element Recovery	0.17
1.059	av-pf - CCD*	1.06
5.1	Ratio Concen/Perm	5.06
10	m3/h Flow Set-Point	10
1.00	minute valve time	1.00
1.05	minute Recharge time	1.05
2.05	minute recharge total	2.05
100	liter average consumption per person	

Pumps Efficiecy

0.85	HP *eff*.
0.60	CP *eff*.

ME1 Module Data				CCD Sequence Cycles							CCD Sequence Combned Data					Permeate			Net Daily Prodcution	
		Inlet	Outlet	Time	Applied-p_{appl}		HP		CP		Permeate - m3		Energy		REC	Cycle		average		
Mode	Cyle	%	%	min	bar	mean	kW	kWh/m3	kW	kWh/m3	m3/cycle	Σm3	kW	kWh/m3	%	ppm	μS/cm	ppm	m3	Residence
CCD	1	3.20	3.83	1.27	50.5	50.5	2.696	1.652	0.130	0.080	0.034	0.034	2.826	1.732	16.5	149	299	149	15.0	150
CCD	2	3.73	4.46	2.54	55.2	52.9	2.943	1.728	0.130	0.080	0.034	0.069	3.073	1.883	28.3	174	348	162	21.7	217
CCD	3	4.26	5.10	3.80	59.8	55.2	3.191	1.804	0.130	0.080	0.034	0.103	3.321	2.035	37.2	199	397	174	25.5	255
CCD	4	4.78	5.73	5.07	64.5	57.5	3.438	1.879	0.130	0.080	0.034	0.138	3.568	2.187	44.1	223	446	186	27.9	279
CCD	5	5.31	6.36	6.34	69.1	59.8	3.686	1.955	0.130	0.080	0.034	0.172	3.816	2.338	49.7	248	496	199	29.6	296
CCD	6	5.84	6.99	7.61	73.8	62.2	3.934	2.031	0.130	0.080	0.034	0.207	4.064	2.490	54.2	272	545	211	30.9	309
CCD	7	6.37	7.63	8.88	78.4	64.5	4.181	2.107	0.130	0.080	0.034	0.241	4.311	2.642	58.0	297	594	223	31.8	318
CCD	8	6.90	8.26	10.14	83.0	66.8	4.429	2.183	0.130	0.080	0.034	0.276	4.559	2.793	61.3	322	643	235	32.6	326
CCD	9	7.42	8.89	11.41	87.7	69.1	4.676	2.259	0.130	0.080	0.034	0.310	4.806	2.945	64.0	346	693	248	33.2	332
CCD	10	7.95	9.52	12.68	92.3	71.4	4.924	2.334	0.130	0.080	0.034	0.345	5.054	3.097	66.4	371	742	260	33.7	337

Table 3
SWRO-CCD batch sequence simulation of time, pressure, flow, power, specific energy, permeate TDS and daily production for the ME2 (E = SWC6-MAX) unit with 3.2% NaCl at 33.3 Lmh under fixed flow and variable pressure conditions

SWC6 MAX -Test Conditions

40.8	m2/Element
50	m3/day
32,000	ppm NaCl
54	bar Applied Pressure
10	% Recovery
25	Centig.
99.60	% Salt Rejection
28.4	bar NDP
51.06	l/m2/h Flux
1.798	l/m2/h/bar -A
0.16	l/m2/h - B

π(bar)-C(%)

32000	ppm NaCl Feed
25.60	bar Osmotic Pressure
8.00	π(bar)/C(%)

UNIT Design

1	Modules
2	Elements/Module
220	cm long PV
20	cm diameter PV
15	liter element volume
5	% lines volume
41.0	liter per module

CCD Extension (16")

220	cm long PV
40	cm diameter PV
276.3	liter Conduit
317	liter TOTAL per module
317	liter TOTAL per design

CCD per Module		per Design
3.20	% Initial feed	3.20
33.3	lmh Flux	33.30
2.72	m3/h Permeate (=Q_{HP})	2.72
31.4	% Module Recovery	31.40
5.94	m3/h Qcp	5.94
0.47	bar Δp	0.47
3.21	min/cycle CCD	3.21
0.172	av-Element Recovery	0.17
1.061	av-pf - CCD*	1.06
		0.00
20	m3/h Flow Set-Point	20
1.00	minute Valve time	1.00
0.95	minute Recharge Time	0.95
1.95	minute recharge total	1.95
100	liter average consumption per person	

Pumps Efficiency

0.85	HP *eff*.
0.60	CP *eff*.

ME2 Module Data				CCD Sequence Cycles							CCD Sequence Combned Data					Permeate			Net Daily Prodcuiton	
		Inlet	Outlet	Time	Applied-p_{appl}		HP		CP		Permeate - m3		Energy		REC	Cycle		average		
Mode	Cyle	%	%	min	bar	mean	kW	kWh/m3	kW	kWh/m3	m3/cycle	Σm3	kW	kWh/m3	%	ppm	μS/cm	ppm	m3	Residence
CCD	1	3.20	4.66	3.2	50.2	50.2	4.459	1.641	0.129	0.047	0.145	0.145	4.588	1.688	31.4	201	402	201	40.5	405
CCD	2	4.20	6.13	6.4	60.1	55.2	5.336	1.802	0.129	0.047	0.145	0.291	5.465	2.011	47.8	264	528	233	50.0	500
CCD	3	5.21	7.59	9.6	70.0	60.1	6.213	1.964	0.129	0.047	0.145	0.436	6.342	2.334	57.9	327	654	264	54.2	542
CCD	4	6.21	9.06	12.8	79.8	65.0	7.091	2.125	0.129	0.047	0.145	0.581	7.219	2.657	64.7	390	781	296	56.6	566
CCD	5	7.22	10.52	16.0	89.7	70.0	7.968	2.287	0.129	0.047	0.145	0.726	8.097	2.980	69.6	453	907	327	58.1	581
CCD	6	8.22	11.99	19.2	99.6	74.9	8.845	2.448	0.129	0.047	0.145	0.872	8.974	3.303	73.3	516	1033	359	59.2	592
CCD	7	9.23	13.45	22.5	109.5	79.8	9.722	2.609	0.129	0.047	0.145	1.017	9.851	3.625	76.2	580	1159	390	60.0	600
CCD	8	10.23	14.92	25.7	119.4	84.8	10.599	2.771	0.129	0.047	0.145	1.162	10.728	3.948	78.5	643	1285	422	60.6	606
CCD	9	11.24	16.38	28.9	129.2	89.7	11.476	2.932	0.129	0.047	0.145	1.307	11.605	4.271	80.5	706	1412	453	61.1	611
CCD	10	12.24	17.85	32.1	139.1	94.7	12.354	3.094	0.129	0.047	0.145	1.453	12.483	4.594	82.1	769	1538	485	61.5	615

Table 4
SWRO-CCD batch sequence simulation of time, pressure, flow, power, specific energy, permeate TDS and daily production for the ME3 (E = SWC6-MAX) unit with 3.2% NaCl at 27.9 Lmh under fixed flow and variable pressure conditions

SWC6 MAX Test Conditions	
40.8	m2/Element
50	m3/day
32,000	ppm NaCl
54	bar Applied Pressure
10	% Recovery
25	Centig.
99.60	% Salt Rejection
28.4	bar NDP
51.06	l/m2/h Flux
1.798	l/m2/h/bar -A
0.16	l/m2/h - B

π(bar)-C(%)	
32000	ppm NaCl Feed
25.60	bar Osmotic Pressure
8.00	π(bar)/C(%)

UNIT Design	
1	Modules
3	Elements/Module
320	cm long PV
20	cm diameter PV
15	liter element volume
5	% lines volume
58.3	liter per module

CCD Extension (16")	
320	cm long PV
40	cm diameter PV
401.9	liter Conduit
460	liter TOTAL per module
460	liter TOTAL per design

CCD per Module		per Design
3.20	% Initial feed	3.20
27.9	lmh Flux	27.90
3.41	m3/h Permeate (=Q_{HP})	3.41
39.5	% Module Recovery	39.50
5.23	m3/h Q_{CP}	5.23
0.65	bar Δp	0.65
5.28	min/cycle CCD	5.28
0.154	av-Element Recovery	0.15
1.055	av-pf - CCD	1.05
30	m3/h Flow Set-Point	30
1.00	minute Valve time	1.00
0.92	minute Recharge Time	0.92
1.92	minute recharge total	1.92
100	liter average consumption per person	

Pumps Efficiecy	
0.85	HP *eff*.
0.60	CP *eff*.

ME2 MODULE DATA				CCD Sequence Cycles							CCD Sequence Combned Data					PERMEATE			Net Daily Prodcuiton	
		Inlet	Outlet	Time	Applied-p_{appl}		HP		CP		Permeate - m3		Energy		REC	Cycle		average		
Mode	Cyle	%	%	min	bar	mean	kW	kWh/m3	kW	kWh/m3	m3/cycle	Σm3	kW	kWh/m3	%	ppm	μS/cm	ppm	m3	Residence
CCD	1	3.20	5.29	5.3	49.8	49.8	5.557	1.627	0.156	0.046	0.300	0.300	5.714	1.673	39.5	257	515	257	60.1	601
CCD	2	4.46	7.38	10.6	63.2	56.5	7.054	1.847	0.156	0.046	0.300	0.601	7.211	2.112	56.6	359	718	308	69.3	693
CCD	3	5.73	9.47	15.8	76.6	63.2	8.551	2.066	0.156	0.046	0.300	0.901	8.708	2.550	66.2	461	921	359	73.1	731
CCD	4	6.99	11.56	21.1	90.0	69.9	10.048	2.285	0.156	0.046	0.300	1.202	10.205	2.988	72.3	562	1125	410	75.1	751
CCD	5	8.26	13.65	26.4	103.4	76.6	11.545	2.504	0.156	0.046	0.300	1.502	11.701	3.427	76.6	664	1328	461	76.4	764
CCD	6	9.52	15.74	31.7	116.9	83.3	13.042	2.723	0.156	0.046	0.300	1.803	13.198	3.865	79.7	766	1531	511	77.3	773
CCD	7	10.78	17.82	37.0	130.3	90.0	14.539	2.942	0.156	0.046	0.300	2.103	14.695	4.303	82.0	867	1735	562	77.9	779
CCD	8	12.05	19.91	42.2	143.7	96.7	16.036	3.162	0.156	0.046	0.300	2.404	16.192	4.742	83.9	969	1938	613	78.4	784
CCD	9	13.31	22.00	47.5	157.1	103.4	17.533	3.381	0.156	0.046	0.300	2.704	17.689	5.180	85.5	1071	2141	664	78.8	788
CCD	10	14.58	24.09	52.8	170.5	110.2	19.029	3.600	0.156	0.046	0.300	3.004	19.186	5.618	86.7	1172	2344	715	79.1	791

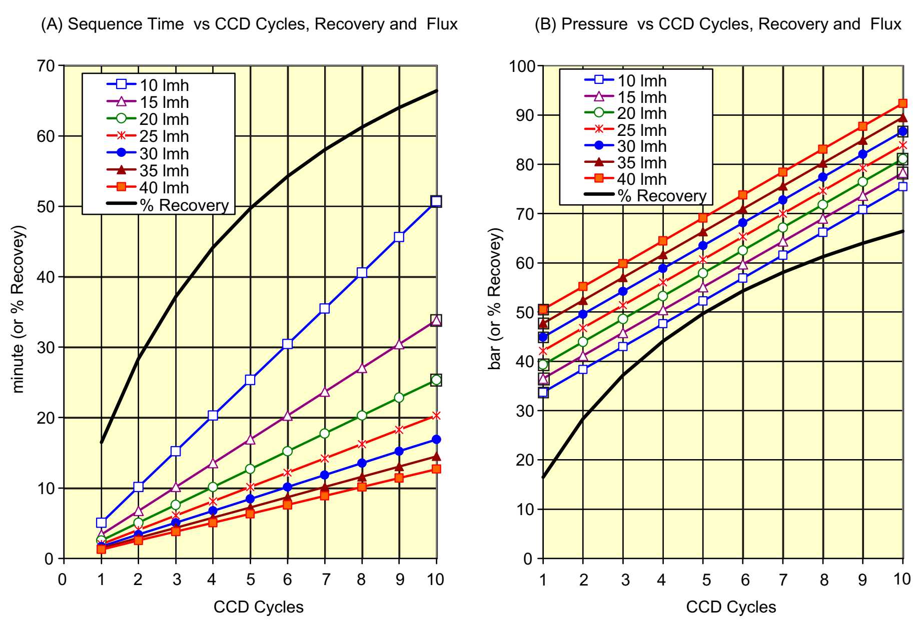

Fig. 2.1. Sequential variations of time (A) and pressure (B) as function CCD cycles, recovery, and flux for the SWRO-CCD ME (E = SWC6-MAX) unit according to the database in Table 2 for the flux range 10–40 Lmh.

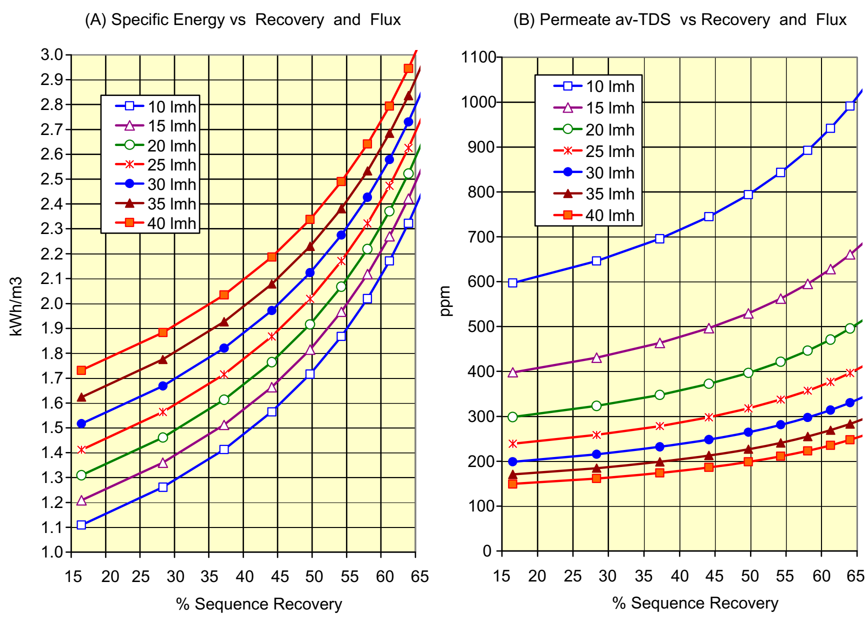

Fig. 2.2. Sequential variations of specific energy (A) and TDS of permeates (B) as function of recovery and flux for the SWRO-CCD ME (E = SWC6-MAX) unit according to the database in Table 2 for the flux range 10–40 Lmh.

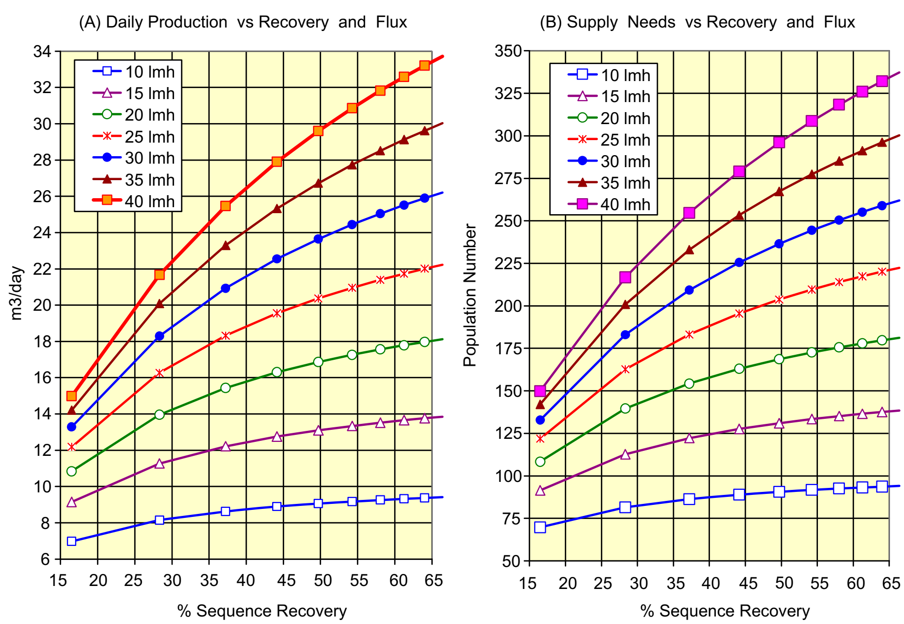

Fig. 2.3. Sequential variations of daily permeates production (A) and community size supply needs (B) as function of recovery and flux for the SWRO-CCD ME (E = SWC6-MAX) unit according to the database in Table 2 for the flux range 10–40 Lmh.

cycles by the ME2 (E = SWC6-MAX) unit with 3.2% NaCl at MR = 31.4% and 25°C under fixed flow of variable pressure conditions ($Q_{HP} = 2.72$ m^3/h, 33.3 Lmh average flux and $Q_{CP} = 5.94$ m^3/h), module inlet flow of 8.66 m^3/h (<17 m^3/h limit), and concentrate/permeate flow ratio per element over 5.0.

Change of flux in the database (Table 3) over the range of 10 → 35 Lmh leads to the sequential time

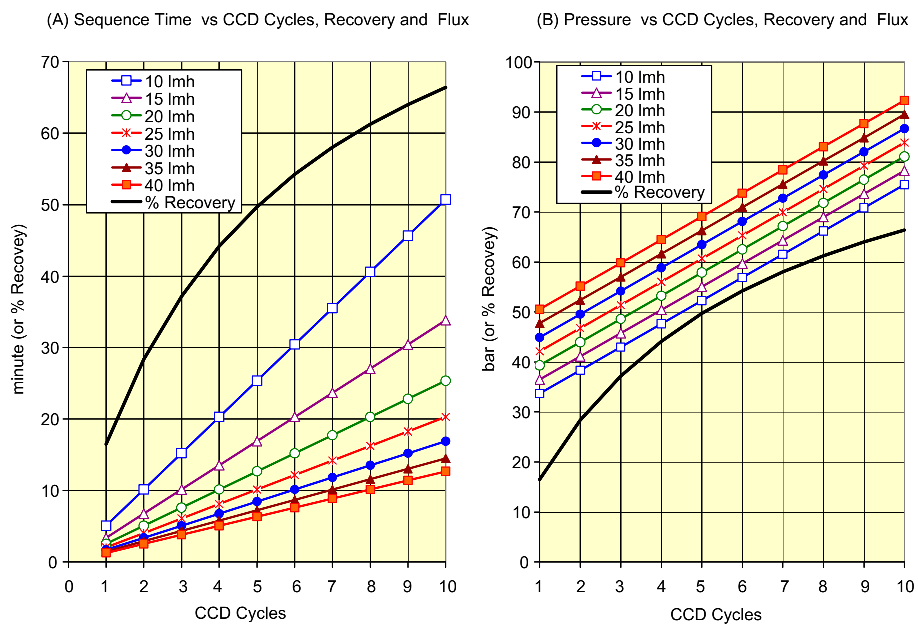

Fig. 3.1. Sequential variations of time (A) and pressure (B) as function CCD cycles, recovery, and flux for the SWRO-CCD ME2 (E = SWC6-MAX) unit according to the database in Table 3 for the flux range 10–40 Lmh.

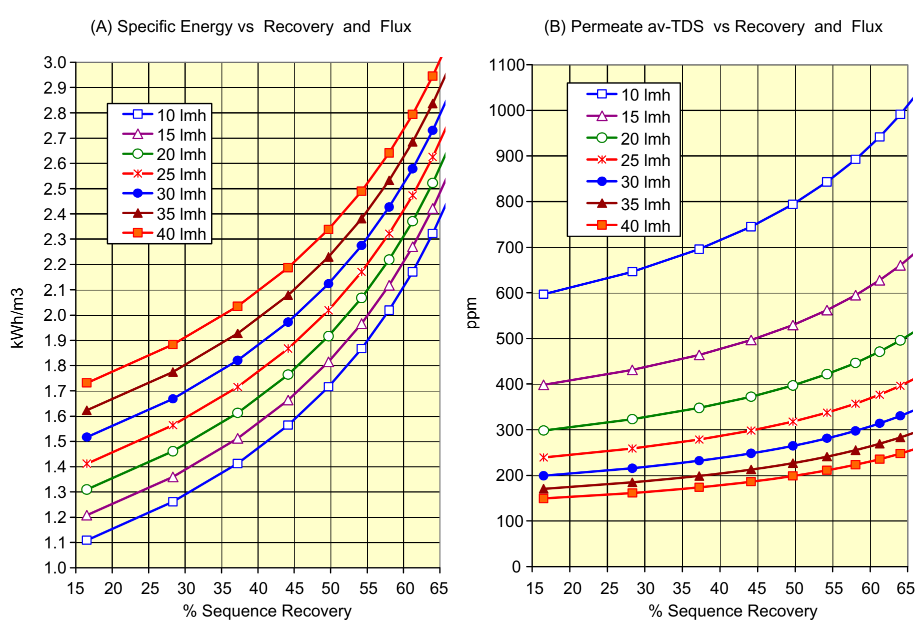

Fig. 3.2. Sequential variations of specific energy (A) and TDS of permeates (B) as function of recovery and flux for the SWRO-CCD ME2 (E = SWC6-MAX) unit according to the database in Table 3 for the flux range 10–40 Lmh.

variations vs. CCD cycles and recovery displayed in Fig. 3.1(A); pressure variations vs. CCD cycles and recovery in Fig. 3.1(B); specific energy variations vs. recovery in Fig. 3.2(A); permeate TDS variations vs. recovery in Fig. 3.2(B); daily permeates production vs. recovery in Fig. 3.3(A); and community size supply needs vs. recovery in Fig. 3.3(B).

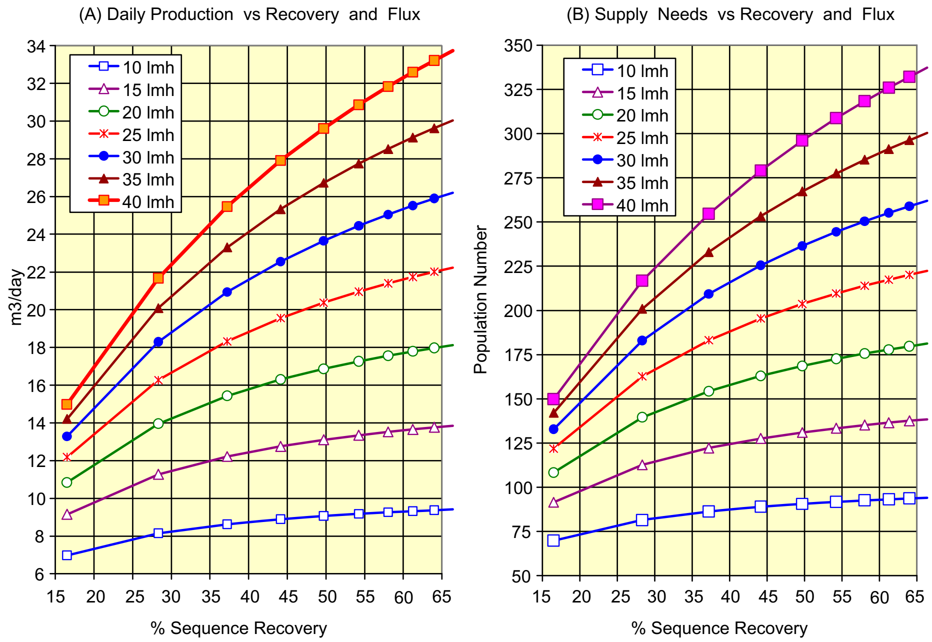

Fig. 3.3. Sequential variations of daily permeates production (A) and community size supply needs (B) as function of recovery and flux for the SWRO-CCD ME2 (E = SWC6-MAX) unit according to the database in Table 3 for the flux range 10–40 Lmh.

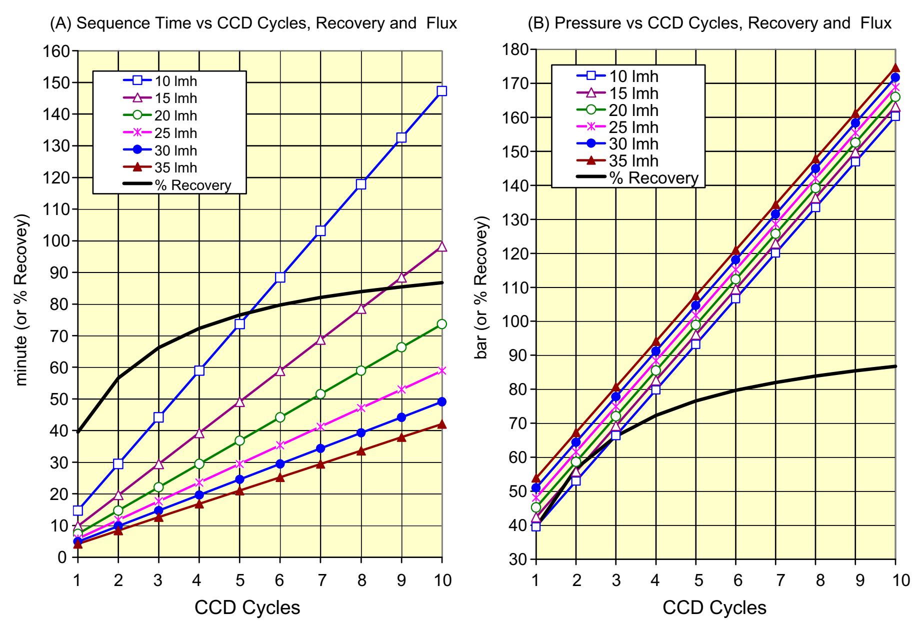

Fig. 4.1. Sequential variations of time (A) and pressure (B) as function CCD cycles, recovery, and flux for the SWRO-CCD ME2 (E = SWC6-MAX) unit according to the database in Table 4 for the flux range 10–35 Lmh.

3.3. SWRO-CCD ME3 (E = SWC6-MAX) batch unit performance with 3.2% NaCl

The data displayed in Table 4 is of a simulated SWRO-CCD batch sequence performance of 10 CCD cycles of the ME3 (E = SWC6-MAX) unit with 3.2% NaCl at MR = 27.9% and 25°C under fixed flow and variable pressure conditions (Q_{HP} = 3.41 m^3/h, 27.9 Lmh average flux and Q_{CP} = 5.23 m^3/h), module

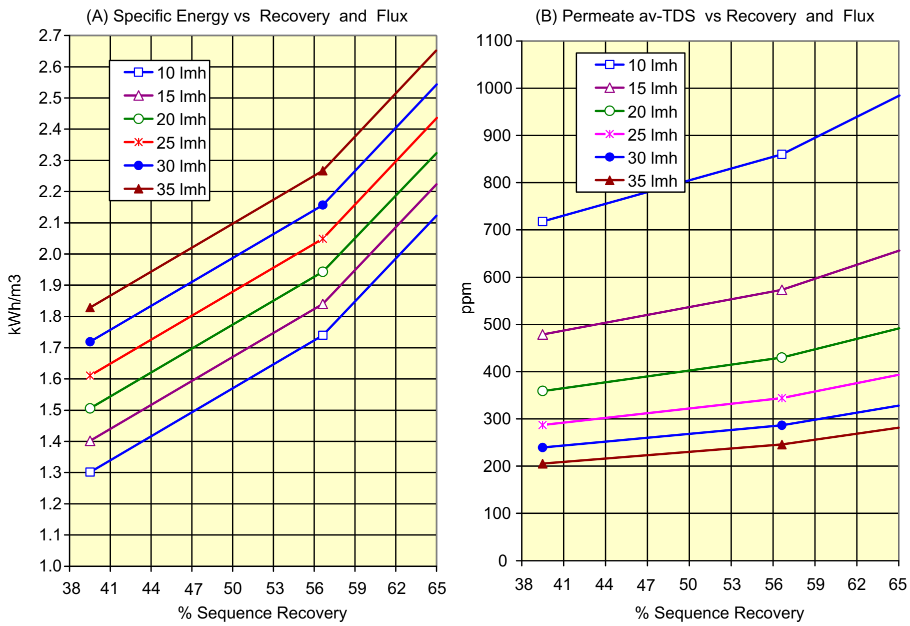

Fig. 4.2. Sequential variations of specific energy (A) and TDS of permeates (B) as function of recovery and flux for the SWRO-CCD ME3 (E = SWC6-MAX) unit according to the database in Table 4 for the flux range 10–35 Lmh.

inlet flow of 8.68 m^3/h (<17 m^3/h limit), and concentrate/permeate flow ratio per element >5.0.

Change of flux in the database (Table 4) over the range of 10 → 35 Lmh leads to the sequential time variations vs. CCD cycles and recovery displayed in Fig. 4.1(A); pressure variations vs. CCD cycles and recovery in Fig. 4.1(B); specific energy variations vs. recovery in Fig. 4.2(A); permeates TDS variations vs. recovery in Fig. 4.2(B); daily permeates production vs. recovery in Fig. 4.3(A); and community size supply needs vs. recovery in Fig. 4.3(B).

4. Discussion

Continuous SWRO-CCD and batch SWRO-CCD are based on the same sequential process which in case of the former is made continuous with respect to permeate production by the engagement/disengagement of a side conduit with valve means of the same intrinsic volume of the closed circuit. Accordingly, the batch units circumvent the need of a side conduit, extra valve means, and extensive control board requirements at the expense of lower permeate production which is a function of the sequence duration determined by the operational flux. The reduced daily production rates of permeates by batch compared with continuous units on the recovery scale are illustrated for ME3 (E = SWC6-MAX) in Fig. 5 at flux of 15 Lmh (A), 20 Lmh (B), and 25 Lmh (C). The curves in Fig. 5 for daily production vs. recovery at the 50% level reveal batch/continuous percent of ~80% for 15 Lmh (A), ~75% for 20 Lmh (B), and ~70% (C) for 25 Lmh or declined daily batch production in reference to continuous production with increased flux manifesting a greater fraction of time experienced by the batch unit during recharge without desalination. In simple terms, greater daily production of the batch process is conditioned with a smaller recharge/CCD time fraction. Batch recharge time (T_R, min) without desalination is expressed by V/Q_R; wherein V(L) stands for the closed circuit intrinsic volume and Q_R (L/min) for the flow rate of feed during recharge. Likewise, sequence duration (T_{CCD}) is expressed by Eq. (1) as a function of V, R, and Q_f or flux (J). Accordingly, the ratio T_R/T_{CCD} is expressed by Eq. (7) with higher flux (J) and/or lower R contributing to a larger T_R/T_{CCD} ratio of lower daily batch permeate production compared with a continuous CCD process.

$$T_R/T_{CCD} = (Q_f/Q_R)(100 - R)/R = (Q_p/Q_R)(100 - R)/R = (J \times n \times S/Q_R)(100 - R)/R \quad (7)$$

The energy consumption and permeates quality of the MEn (n = 1–3) units are essentially a function of the average flux and recovery irrespective of a specific design and batch or continuous modes of operation. Seawater desalination of 50% recovery with the batch units under review at flux of 13, 20, 25, and 30 Lmh

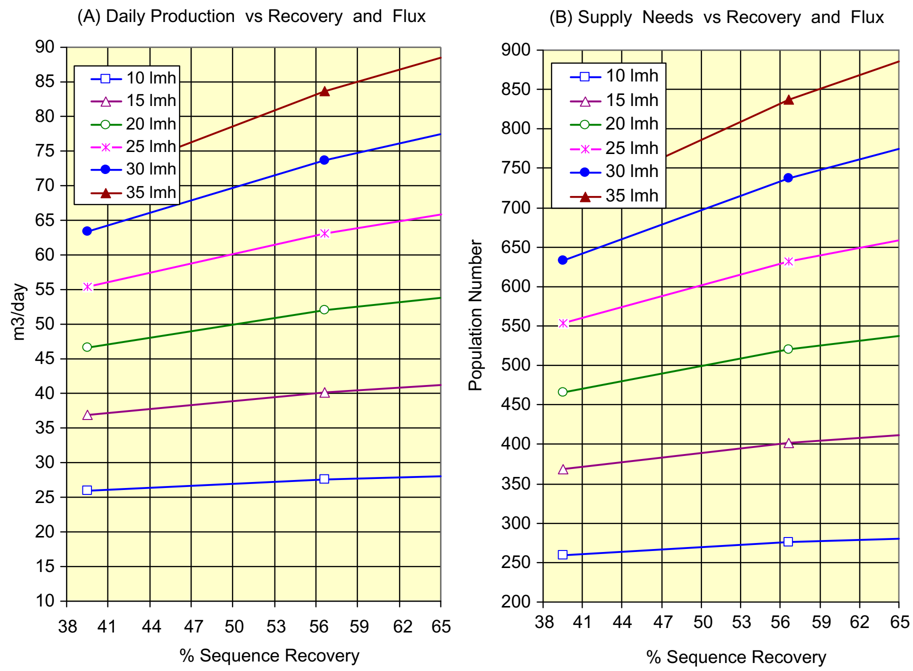

Fig. 4.3. Sequential variations of daily permeates production (A) and community size supply needs (B) as function of recovery and flux for the SWRO-CCD ME3 (E = SWC6-MAX) unit according to the database in Table 4 for the flux range 10–35 Lmh.

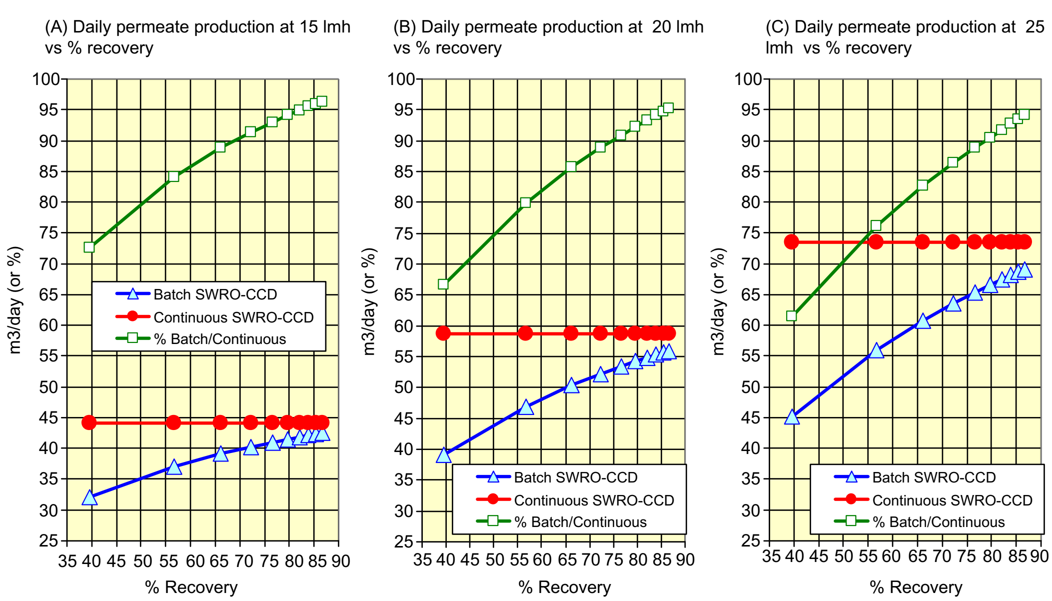

Fig. 5. Daily permeate production of continuous and batch ME3 (E = SWC6-MAX) units at flux of 15, 20, and 25 Lmh on the recovery scale according to the database in Table 4 with the cited flux.

proceeds according to the data in Tables 2–4 with average specific energy and permeate TDS (in parentheses) of 1.79 (595), 1.97 (388), 2.12 (309), and 2.25 kWh/m^3 (259 ppm), respectively, irrespective of the number of elements per module and assuming 85% efficiency of the pressurizing pump (HP), 60%

efficiency of the CP, and the use of membrane elements such as SWC6-MAX or alike. The low-energy projection of 1.79 kWh/m^3 at 13 Lmh for the ME*n* (*n* = 1–3) SWRO-CCD batch units is well below that of 2.366 kWh/m^3 displayed in Table 1 for a conventional ME8 (E = SWC6-MAX) module at the same average flux (13 Lmh) with HP of the same efficiency (85%) which is operated with ERD of 75% efficiency. The projected specific energy of 2.366 kWh/m^3 in Table 1 for 50% recovery of ocean water with ERD of 75% is well below the reported [9] specific energy of 2.46 kWh/m^3 for the large and modern conventional SWRO plant in Perth Australia with PX ERD. Moreover, a comprehensive performance report [10] of the large advanced Palmachim SWRO desalination plant in Israel with its ERT-PX HYBRID ERD system makes clear reference to energy conversion efficiency "just over 76% at the best efficiency point" and less below the referred point, a figure consistent with the 75% ERD efficiency according to data in Table 1. The low specific energy projections for the batch units under review are consistent with the reported trials' results of the SWRO-CCD 4 ME*n* (*n* = 1–4) units [4–6] with Mediterranean water and their extrapolation to ocean seawater [11].

The SWRO-CCD batch desalination technology considered hereinabove in the reference to the single module units ME*n* (*n* = 1–3) may be extended to include any desired number (*N*) of the specified modules with their inlets and outlets connected in parallel of the general design expressed by *N*ME*n* (*n* = 1–3). The performance characteristics of such multiple module designs in reference to specific energy, average TDS of permeates, and sequence duration are exactly the same as revealed for the single-module units of the same number of elements per module in Table 2–4 provided that flow rates and intrinsic closed-circuit volumes are *N*-fold larger. The expanded batch units approach is illustrated by the design of the SWRO-CCD 12ME3 unit displayed in Fig. 6 comprising 12 modules (8´´) each of 3 elements connected in line to an array of five parallel empty PV (16´´), one circulation pump with *vfd* (CP), one positive displacement high-pressure pump with *vfd* (HP), three one-wary CV, and one AV. The upper spread design in Fig. 6 is intended for clarity to show the connection of the 12ME3 array with the free volume contributed by the 5 parallel 16´´ PV vessels; whereas the schematic design at the bottom is that of the compact system with emphasis of its dimensions if placed in a 40 ft container. The intrinsic free volume of the 12 ME3 design of 5,139 L is somewhat smaller than the 12-fold volume of the ME3 design revealed in Table 4 (12 × 460 = 5,520 L) and this implies a 7% faster

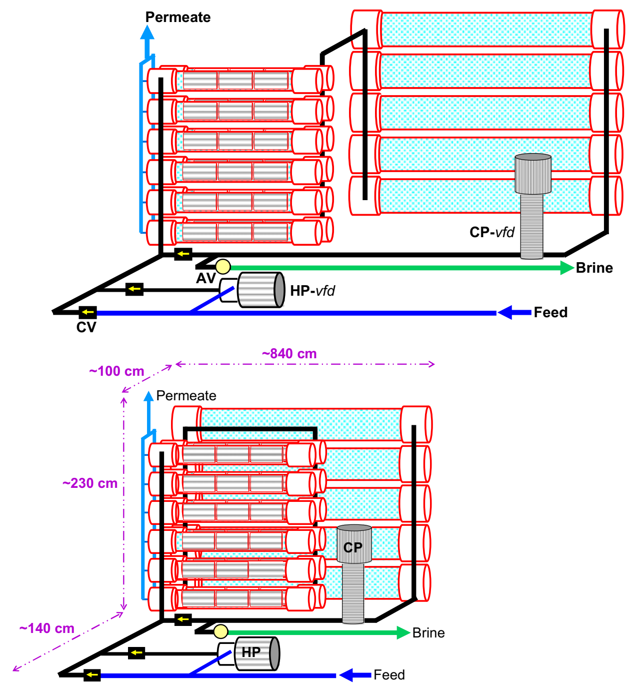

Fig. 6. Spread (top) and compact (bottom) designs of SWRO-CCD 12ME3 batch unit comprising 12 modules (8´´) each of 3 elements, connected in line to an array of five parallel empty PV(16´´) of 5.1 m^3 total intrinsic closed circuit volume, one circulation pump with vfd (CP), one positive displacement high-pressure pump with vfd (HP), three one-wary CV, and one AV; wherein red stands for pressurized PVs, blue and green for none pressurized lines of feed and brine, respectively, and black for pressurized manifold lines.

sequence duration of the large units if flow rates per module remain the same. The module performance characteristics of ME3 and 12ME3 with the same feed and elements are essentially analogous to those displayed in Table 4 and Figs. 14.1–4.3 with small differences due to the smaller intrinsic volume per module of the latter design. The projected performance characteristics of the SWRO-CCD 12ME3 batch unit with feed of 32,000 ppm NaCl, equivalent to average ocean seawater of 35,000 ppm, and flux of 10, 13, 15, 20, and 25 Lmh at 25°C are displayed in Table 5. Noteworthy in Table 5 are the flexible operational conditions of the batch unit under review over a wide flux range for providing desalinated water supplies to coastal communities of 3,122 → 6,661 residence on the basis of an average specific consumption of 100 L/d/person as function of flux. The operational flexibility enables low flux operation with energy saving during night time for storage and higher flux operation according to demand during day time.

Table 5
Projected flexible performance characteristics of the SWRO-CCD 12ME3 batch unit with feed of 32,000 ppm NaCl, equivalent to average ocean seawater of 35,000 ppm, and flux of 10, 13, 15, 20 and 25 Lmh at 25˚C

Flux (Lmh)	SEQ (min)	Energy (kWh/m^3)	Permeates			Residence No
			TDS	m^3/h	m^3/d	
10	21.0	1.690	772	13	312	3,122
13	16.1	1.769	594	16	392	3,923
15	14.0	1.825	515	18	443	4,429
20	10.5	1.971	386	23	560	5,602
25	8.4	2.128	309	28	666	6,661

The superb operational performance characteristics of the SWRO-CCD batch desalination units of the general design NME*n* (*n* = 1–3) are evident from the data in Tables 2–5 and Figs. 2–5 as compared to the IMS data for a conventional ME8 unit design in Table 1 and Fig. 1. Some brief comments may be warranted concerning the installation costs of the batch desalination units under review in order to ascertain aspects related to their cost-effectiveness. The cost estimates of the cited components and others for the ME3 (E = SWC6-MAX) batch unit describe in Table 4 under maximum operational flux of 25 Lmh and MR = 25% with pressurized feed flow of 3.06 m^3/h (HP) and recycling cross-flow of 9.18 m^3/h are as follows: 2,250 $ per 3 SWC6-MAX elements; 800 $ per single PV (8´´—320 cm); 3,400 $ per single PV (16´´—320 cm); 4,200 $ per HP of 3.2 m^3/h (Danfoss or alike); 4,500 $ per CP of 10 m^3/h (Grundfos or alike); 7,500 per manifold (1.5´´) and other metal parts (e.g. skid); 10,000 $ per control board and monitoring means; 5,000 $ per unlisted components and parts; and 7,530 $ per labor costs (20% of 37,650 $ total). The installation costs of the unit under consideration before integrator profits are 45,180 $ which manifests a specific installation cost of 747 $/$m^3$/d if unit operates at 50% recovery with flux of 25 Lmh, 1,553 $/$m^3$/d if unit operates at 50% recovery with flux of 15 Lmh, and average of 1,150 $/$m^3$/d if unit operates under variable flux conditions. The specific installation cost projections for the SWRO-CCD ME*n* (*n* = 3) batch unit also implies higher specific costs for such units with *n* = 1–2 and lower specific costs for the respective multi-module NME*n* (*n* = 1–3) batch units configurations. In this context, the specific installation cost of the 12ME3 batch unit of the design displayed in Fig. 6 with the performance revealed in Table 5 is expected to represent 20% discount over that of ME3 which translates to a total installation cost of 433,728 $ and specific installation cost of 598 $/$m^3$/d if unit operates at 50% recovery with flux of 25 Lmh, 1,242 $/$m^3$/d if unit operates at 50% recovery with flux of 15 Lmh, and average of 920 $/$m^3$/d if unit operates under variable flux conditions.

The SWRO-CCD batch units under review are intended for desalinated water supply directly to the final customers; therefore, making them independent of a municipal infrastructure of a much higher supply costs in most instances. Moreover, the design of the compact batch units can be tailored to meet the supply needs of small or large private customers at the level of homes, estates, and farms as well as sizeable vacation resorts in islands and along shore lines. The translation of power availability to flux in the SWRO-CCD batch units under review is a unique feature of considerable consequences which implies the ability of such units to operate with electricity (e.g. local grid or diesel-engine generated), solar energy (e.g. solar panels), and/or wind power (e.g. small or medium size inexpensive wind turbines). Since the desalination of seawater is an energy-intensive process and cost of electric energy in many remote locations is generally high, or even very high, a desalination technology of low-energy consumption and low installation cost which enables flexible integration with several different power sources (grid, solar, and wind) provides maximum cost-effectiveness and therefore, the application of SWRO-CCD NME*n* batch units with capacity up to 1,200 m^3/d (50 m^3/h) of the types considered hereinabove should become the method of choice for seawater desalination anywhere worldwide.

5. Summary

CCD is a batch process of low energy without EDR, high recovery irrespective of the number of elements per module, wide flux range characteristics, and recovery independent of flux which can be made continuous by the engagement of a side conduit for brine removal. Low lost batch SWRO-CCD units of the general design NMEn (n = 1–3); wherein N stands for the number of modules and n for the number of elements per module can supply 10–1,200 m^3/d of low-cost desalinated water for communities of 100–12,000 residence on the basis of 100 L/d/person and many more if used primarily for drinking and cooking applications. Compact single-module units of the MEn (n = 1–3) design could desalinate ocean water (35,000 ppm) with 50% recovery in the flux range 10–40 Lmh and produce 10–70 m^3/d with specific production rate and energy consumption determined by the operational flux and the same also applies to larger units of more modules such as 12ME3 which under the same operational conditions will deliver 392–719 m^3/d as a function of flux. The energy consumption and permeates quality of such units is essentially a function of their operational flux, rather than a specific design with estimates at 50% recovery and flux of 13, 20, 25, and 30 Lmh being 1.79 (595), 1.97 (388), 2.12 (309), and 2.25 kWh/m^3 (259 ppm), respectively, assuming the use pressurizing pumps of 85% efficiency, circulation pumps of 60% efficiency, and membrane elements such as SWC6-MAX and alike (average TDS of permeate indicated in parentheses).

The specific installation costs of the NMEn (n = 1–3) units are exceptionally low in light of their simple designs without need of ERD and wide operational flux range of greater average production per element compared with conventional techniques. Low installation costs combined with low-energy consumption and recovery independent of flux imply cost-effective desalination. The wide operational flux flexibility of the SWRO-CCD batch units implies flexible permeates production as function of demand with an option for low flux low-energy desalination during periods when demand is low and electricity costs are cheaper. The desalination recovery of the batch units under review is independent of flux and this means the ability to reach high recovery even at low flux and thereby, make efficient use of the feed source, save on pressurized feed energy requirements, and pretreatment costs. Moreover, the wide range flux performance capability of new batch units make them ideal for integration with renewable energy sources through solar panels and/or small wind turbines for extraordinarily low desalination costs of seawater with free, clean, and renewable natural energy sources.

Acknowledgments

Funds to *Desalitech Ltd* by Liberation Capital LLC (USA) and by Aquagro Fund L.P. (Israel) and are gratefully acknowledged.

References

[1] M. Elimelech, W.A. Phillip, The future of seawater desalination: Energy, technology, and the environment, Science 333 (2011) 712–717.

[2] Specifications of the SWC6-MAX membrane element by hydranautics. Available from: <http://www.memranes.com/docs/8inch/SWC6MAX.pdf>.

[3] Dow Liquid Separation, FILMTEC™ Reverse Osmosis Membranes, Technical Manual, 2011. Available from: <http://msdssearch.dow.com>.

[4] A. Efraty, R.N. Barak, Z. Gal, Closed circuit desalination—A new low energy high recovery technology without energy recovery, Desalin. Water Treat. 31 (2011) 95–101.

[5] A. Efraty, R.N. Barak, Z. Gal, Closed circuit desalination series no-2: New affordable technology for sea water desalination of low energy and high flux using short modules without need of energy recovery, Desalin. Water Treat. 42 (2012) 189–196.

[6] A. Efraty, Closed circuit desalination series no-6: Conventional RO compared with the conceptually different new closed circuit desalination technology, Desalin. Water Treat. 41 (2012) 279–295.

[7] A. Efraty, CCD series no-11: Single module compact SWRO-CCD units of low energy and high recovery for seawater desalination including with solar panels and wind turbines, Desalin. Water Treat. (in press). Available from: <http://dx.doi.10108/19443994.2013.86203>.

[8] A. Efraty, CCD series no-13: Illustrating low energy SWRO-CCD of 60% recovery and BWRO-CCD of 92% recovery with a single element module without ER means—A theoretical extreme case study, Desalin. Water Treat. (submitted). Available from: <http://dx.doi.10.1080/19443994.2015.1035495>.

[9] M.A. Sanz, R.L. Stover, Low energy consumption in the Perth seawater desalination plant, October, IDA World Congress-Maspalomas, Gran Canaria—Spain, 2007, pp. 21–26, MP07.

[10] A. Hermoni, Actual energy consumption and water cost for the SWRO systems at Palmachim—Case history, IDA conference, November 2–3, CA, USA, 2010.

[11] R.L. Stover, N. Efraty, Record low energy consumption with closed circuit desalination, IDA World Congress—Perth Convention and Exhibition Center (PCEC), Perth, Western Australia, September 4–9, 2011 - REF: IDAWC/PER11-375.