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Closed circuit desalination series no-3: high recovery low energy desalination of brackish water by a new two-mode consecutive sequential method

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ABSTRACT

A new method for continuous Brackish Water desalinated by a two-mode consecutive sequential process which incorporates closed circuit and plug flow desalination (PFD) techniques is exemplified with a commercial apparatus (named REIM-II) comprising 10 modules (8″), each of four elements (ESPA2+), with their inlets and outlets connected in parallel, and with recycled concentrate mixed with fresh pressurized feed admitted at inlet to modules. When the salinity of the recycled concentrate inside the closed circuit manifests the desired system recovery level, the apparatus switches from closed circuit to PFD by valve means until the entire brine in the closed circuit replaced by fresh feed, and thereafter, closed circuit desalination (CCD) resumed. CCD in said apparatus experienced most of the time with the same fixed flow rate of feed and permeate under variable pressure conditions; whereas, PFD takes place briefly only after the system attains its desired recovery level at a predefined pressure in order to enable replacement of brine by fresh feed without stopping desalination. Replacement of brine by fresh feed takes place with enhanced feed flow under reduced pressure with a lower momentary recovery in order to expedite the process and minimize brine energy losses. The new method is exemplified by the commercial operation of the REIM-II unit with feed of 6800 μS cm^{-1} according to conditions as followed: *CCD Mode*: 35 m^3 h^{-1} flow rate of feed and permeate (≈19 lmh); 36 m^3 h^{-1} flow rate of recycled concentrate; 1.1 bar of module pressure difference (Δp); and 17–25 bar of an effective variable pressure range. *Plug Flow Desalination Mode*: 45 m^3 h^{-1} flow rate of feed; 16 m^3 h^{-1} flow rate of permeate (≈10 lmh); 29 m^3 h^{-1} flow rate of rejected brine; 0.5 bar of module pressure difference (Δp); and 9 bar average pressure. *Overall Performance*: 30.7 m^3 h^{-1} average flow rate of permeate; 37.04 m^3 h^{-1} average flow rate of feed; 82.9% recovery; 28.83 kW power consumption; 0.94 kWh m^{-3} specific energy with 61.5% efficiency of the high pressure pump; 20 min total sequence duration with 65% of the time experienced with CCD, 20% experienced with PFD, and 15% experienced during transitions between cited modes. The commercial REIM-II unit has been operated continuously over the past 20 mo and produced some 400,000 m^3 permeates with 88–80% recovery in the respective feed salinity range 5800–8900 μS cm^{-1}.

Keywords: High salinity brackish water; Closed circuit desalination; High recovery; High flux; Low energy; Reduced fouling; Commercial unit performance

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CCD is a unique batch desalination process of enormous energy saving benefits [1–3] and the making of such a process continuous with respect to permeate production by simple mean [4,5] opened the door to its commercial application. The first paper in this series [6] describes the theoretical principles of CCD and practical aspects illustrated with SWRO-CCD trials of Mediterranean Water (4.1%) of 47.5 ± 1.5% recovery with RO energy of 1.85–2.25 kWh m^{-3} in the respective flux range 6–18 lmh using an apparatus comprising four modules (M) each of four membrane elements (E) – ME4 configuration. The second paper in this series [7] describes SWRO-CCD Mediterranean trials using the 4MEn apparatus of four different configurations (n = 1–4) which revealed the RO energy range 1.8–2.8 kWh m^{-3} in the respective flux range 8–40 lmh for recovery up to 50%. The current paper describes a new RO method for Brackish Water desalination by the integration of the CCD and the PFD techniques into a continuous two-mode consecutive sequential desalination process of high recovery and cost effectiveness.

The new technology which integrates CCD and PFD to achieve a continuous desalination process applies primarily to Brackish Water of low to medium salinity and allows high RO recovery with low energy since most of the time the system operates in a CCD mode without any loss of brine energy; whereas, PFD under reduced pressure applies only for the replacement of brine with fresh feed inside the close circuit with a minimum loss of energy. The theoretical aspects of this process were already considered elsewhere [6] and the practical aspects of this deceptively simple proprietary method are exemplified hereinafter by the commercial application of an apparatus comprising ten modules each of four membrane elements (10ME4 configuration) for the desalination of a f feed source of 6800 µS cm^{-1} with 82.9% recovery.

The principle components of the 10ME4 unit, displayed in Fig. 1, comprise of a feed pressurizing pump (*HP*), a circulation pump (*CP*), 10 module (*M*, rating of 450 psi) each with four membrane elements (*E* = ESPA2+), two actuated (compressed air) two-way valves labeled 1–2 (3″, SS316L, rating 450 psi), a two-way manual valve labeled 3, and various unspecified monitoring and control means. The continuously monitored data included flow and electric conductivity of feed, permeate and recycled concentrate; pressure at inlet and outlet of modules; pH of feed and permeate; and the energy consumption of the entire unit. Most of the time the unit operates in the CCD mode under fixed flow and variable pressure conditions with constant flow rates of relevant pumps (HP and CP) controlled by means of *vfd* through the appropriate flow meters. The unit under review, named *REIM-II*, was commissioned 20 mo ago and the data presented hereinafter refers to the original membrane elements operated since inception without any extensive pretreatment (no UF or Media Filtration) with the only safe guard being a micronic filter of 1.0 µ at inlet to the unit. The front and rear views of the *REIM-II* unit are displayed in Fig. 2.

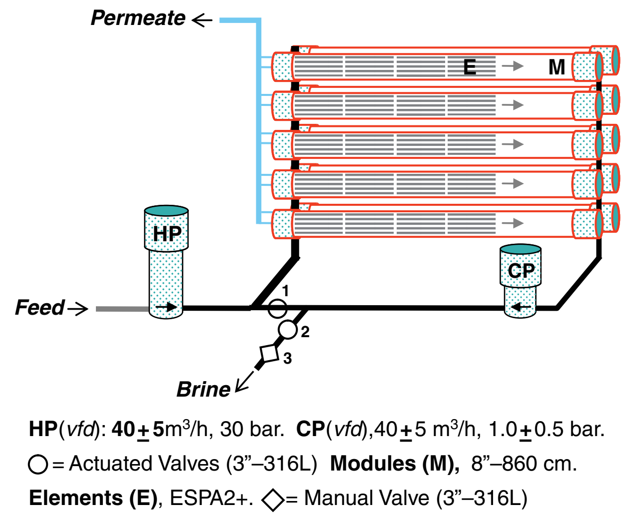

Fig. 1. The schematic design of the 10ME4 *REIM-II* unit.

The Set Points (SP) of operations of the 10ME4 *REIM-II* unit were as followed: 35 and 45 m^3 h^{-1} of HP during the respective CCD and PFD modes; 36 m^3 h^{-1} fixed flow of CP during CCD and this pump is stopped during the PFD intervals; maximum pressure of operation of 25 bar during CCD at which pressure brine replacement by fresh feed is initiated through the closure of valve 1 and the simultaneous opening of valve-2; 2000 l of monitored rejected brine volume (intrinsic volume of closed circuit); and thereafter resumption CCD through the

Fig. 2. Rear (left) and front (right) views of *REIM-II* 10ME4 unit.

simultaneous opening of valve-1 and closure of valve-2. The pressure drop during the mode of brine replacement by fresh feed is determined by the fixed partial opening of the manual valve-3, with increased partial opening of valve concomitant with lower pressure of PFD operation (a larger pressure drop) and vice versa. The exemplified data of the *REIM-II* unit operation disclosed next covers of a 45 min interval (18:00–18:45) on February 21st, 2011 with feed of 6800 ± 100 μS cm^{-1} at temperature of 22°C, average (CCD + PFD) flow rates of 37.04 and of 30.7 m^3 h^{-1} for feed and permeate, respectively, which manifest recovery of 82.9%, and overall monitored energy consumption of 0.94 kWh m^{-3} with ≈61.5% efficiency of HP and ≈50% efficiency of CP.

The two-mode sequence performance of the *REIM-II* unit is evident from Fig. 3 with respect to pressure variations. The data in Fig. 3 reveals an overall sequence duration of 20 min with 13 min of CCD and a gradual pressure rise (16–25 bar), 4 min of PFD at a steady low pressure (8–9 bar), and 3 min of transitions from CCD–PFD and vice versa (1.5 min per transition). The high sequence pressure of 25 bar in Fig. 3 which dictates the system recovery (82.9%) is a selected SP whereby recovery is controlled. The two-mode consecutive sequential operation of the *REIM-II* unit is evident in all the data presented hereinafter as exemplified in Fig. 4 with an average feed flow of 35 and 45 m^3 h^{-1} during the respective CCD and PFD modes which manifest the selected SP of operation. The purpose of the enhance feed flow during the PFD mode is to shorten the duration of brine replacement by fresh feed, and this could be achieved also by means of a second pump for feed flow supplement during the PFD modes of the process. The permeate flow on time scale during the exemplified *REIM-II* operation, displayed in Fig. 5, reveals the expected pattern of a two-mode process with ≈35 m^3 h^{-1} during CCD and ≈16 m^3 h^{-1} during PFD, with mean permeate production of ≈30.7 m^3 h^{-1}. The permeate production on time scale as function of applied pressure displayed in Fig. 6, reveals fixed flow under variable pressure conditions (≈35 m^3 h^{-1}; 16–25 bar) during CCD and fixed flow and pressure (≈16 m^3 h^{-1}; ≈9 bar) during PFD.

The lower operational pressure during the PFD mode of the process, whereby brine is released to the outside, implies much lower energy loss compared with a conventional process without energy recovery means. The combination of high recovery (>80%) with small brine energy loss makes such a process highly energy efficient.

The flow rate difference between feed and permeate displayed in Fig. 7 of the exemplified operation reveals near zero value during the CCD mode as expected since essentially all the pressurized feed is converted

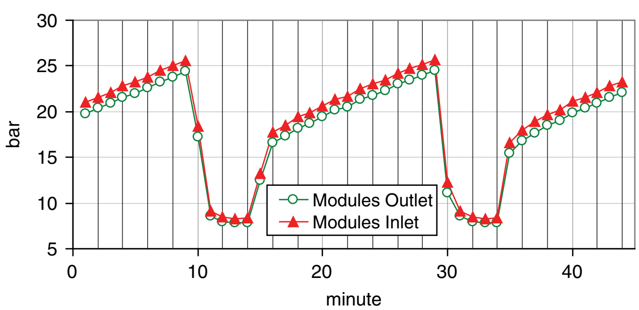

Fig. 3. Sequential pressure variations on time.

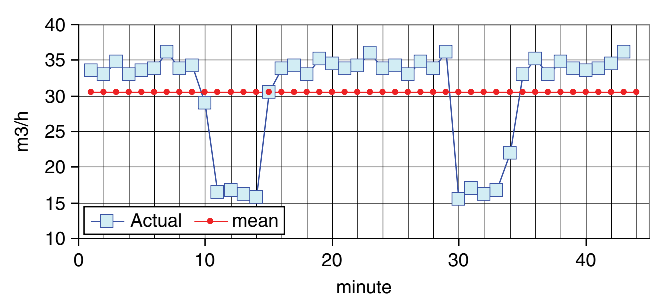

Fig. 5. Permeate flow on time.

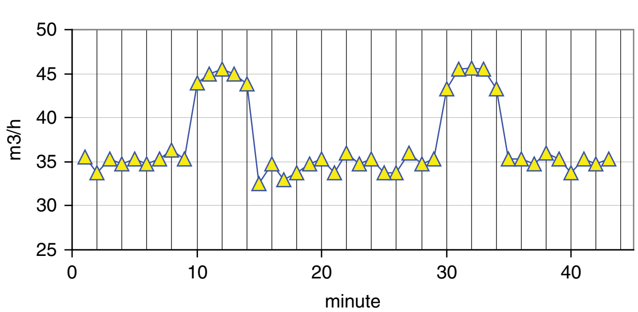

Fig. 4. Feed flow on time.

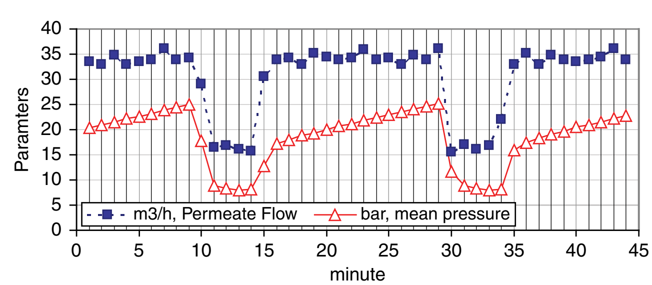

Fig. 6. Pressure variations and permeate flow on time.

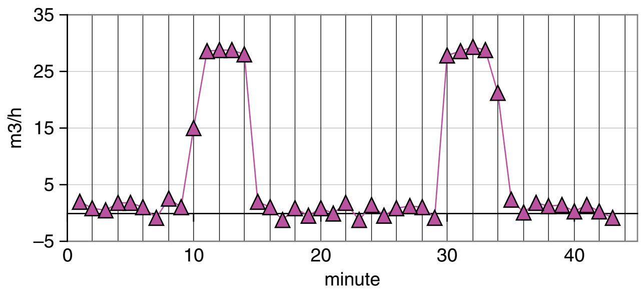

Fig. 7. Feed-permeate flow difference on time.

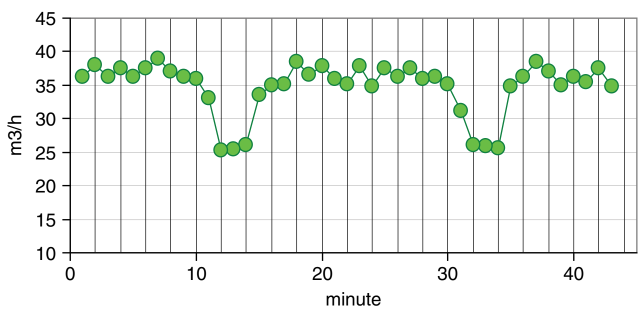

Fig. 8. Concentrate flow variations on time.

into permeate. During the PFD mode of operation with enhanced feed flow (45 instead of 35 m^3 h^{-1}) the entire concentrate (≈26 m^3 h^{-1}, Fig. 8) is being rejected instead of recycled, the flow difference between feed (≈45 m^3 h^{-1}) and permeate (≈16 m^3 h^{-1}) become 29 m^3 h^{-1} exactly as is displayed in Fig. 7. Enhanced feed flow and/or reduced permeate recovery with lower pressure of brine rejection during the PFD mode serve to shorten the time interval of this mode in absolute and relative terms.

Electric conductivity variations on time scale of all the system constituents displayed in Fig. 9 in mS cm^{-1} (milli-Siemens cm^{-1}), reveal a large sequential change in concentrate conductivity (range: 15–35 mS cm^{-1}) with lower range value manifesting the concentrate derived by ≈38% Module Recovery (MR) of the incoming feed of 6800 mS cm^{-1} during the PFD mode of operation. The large sequential salinity variations of recycled concentrate over a relatively short time intervals (20 min) combined with the use of short modules (four elements each) without low flow tail elements of conventional techniques, fast cross flow and the frequent replacement of the entire brine in the system by fresh feed, serve to minimizes bacteria growth and scale formation, remove particulate matter from membrane surfaces and avoid the accumulation

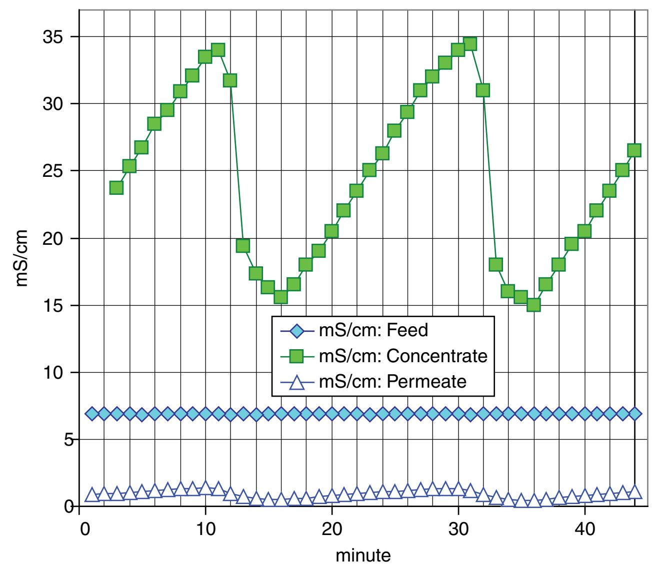

Fig. 9. Conductivity variations on time.

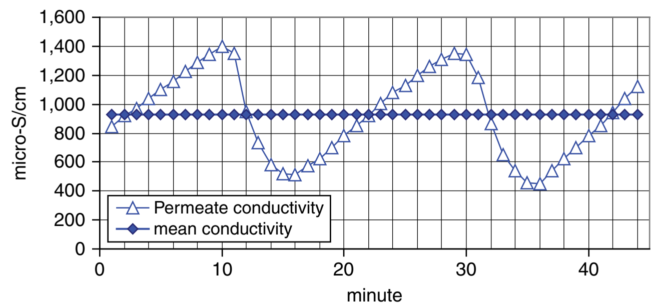

Fig. 10. Permeate conductivity on time.

of contaminants inside the closed system. The aforementioned imply a system of low fouling factors (bio and particulate matter) accumulation with lesser needs for CIP.

The intent of the exemplified *REIM-II* unit was to supply quality water for irrigation with electric conductivity under 1300 µS cm^{-1} and the data displayed in Fig. 10 reveals permeate conductivity variations in the range of 450–1400 µS cm^{-1} with an average of ≈950 µS cm^{-1}, in full compliance with the original intent. It should be pointed this system was operated occasionally with up to 88% recovery by the selection of a maximum applied pressure SP of 27 bar, instead of 25 bar in the exemplified data. During the CCD mode of operation of the exemplified *REIM-II* unit, the average flux was determined solely by the SP selection of the HP flow rate; whereas, both

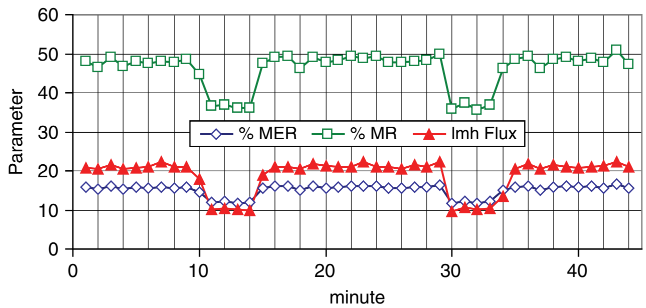

Fig. 11. MR, MER and flux variations on time.

MR and head element recovery (or MER, Maximum Element Recovery) were determined by the former SP combined with the flow rate SP selection for CP. Likewise, the same performance parameters during the PFD mode of operation were determined by the selection of enhanced flow rate SP for HP and the selected pressure of brine release through the fixed setting of the adjustable manual valve 3 of the unit under review in Fig. 1. In simple terms, change of average flux achieved through the SP selection of flow rate for HP; whereas, changes of MR and MER at a selected flux induced through SP selection of flow rate for CP during CCD mode or through pressure control in the PFD mode. Contrary to conventional techniques, the selected operational parameters of flux, MR and MER in the exemplified new technology are unrelated to system recovery which depends on SP selection of maximum operational pressure during the CCD mode of operation (Fig. 11).

The monitored energy of 28.8 kW per 30.7 m^3 h^{-1} average production rate of permeate manifests a specific energy of 0.938 kWh m^{-3} for the exemplified *REIM-II* unit. The breakdown of energy consumption by the exemplified *REIM-II* unit in Table 1 accounts for all sections and sub-sections of the two-mode consecutive sequential process. The sections and sub-sections in Table 1 were characterized from the data in Fig. 3 and account for the principle modes of CCD and PFD as well as for the transitions of CCD > PFD and PDF > CCD which link between the principle modes. The origin of data in Table 1 is as followed: mean pressure derived from the relevant sections in Fig. 3 less pump inlet pressure of 2.0 bar; %-hour derived from the duration of the entire sequence and the relevant sections and sub-sections in Fig. 3; mean feed flow derived from Fig. 4; and the efficiency (*Effic.*) terms are estimates on the basis of flow, pressure and power consumption characteristics of the pumps. The specific energy of the CCD section in Fig. 3, wherein flow rates of feed and permeate are the same, is 0.87 kWh m^{-3}, or about 92% of the overall consumption. The RO specific energy 0.68 kWh m^{-3} should be attainable by the *REIM-II* unit under the specified trial conditions (feed of 6800 µS cm^{-1} and 83% recovery) if the HP and CP pumps are made to operate with the respective efficiencies of 80% and 60%. The high recovery and low energy prospects of the new technology manifest its enormous benefits and advantages over existing techniques.

Table1
Energy consumption of 10ME4 REIM-II Unit with feed conductivity of 6800 micro-S/cm and system recovery of 83%

Configuration		Feed m^3/h	Mean bar	Effic. %	Power kW	Hour %	Energy kWh
Pump	Step						
HP[1]	CCD	35.0	19.20	61.5	30.35	65.0	19.73
HP[1]	CCD > PFD	40.0	15.00	61.5	27.10	7.5	2.03
HP[1]	PFD > CCD	40.0	11.00	61.5	19.87	7.5	1.49
HP[1]	PFD	45.0	7.00	61.5	14.23	20.0	2.85
CP[2]	CCD	36.0	1.10	50.0	2.20	65.0	1.43
Air Compressor[3]					2.00	15	0.30
Miscellaneous[4]					1.00	100	1.00
m^3/h permeate flow rate					30.7		28.83
Total specific energy						0.93901	kWh

[1]Accounts for feed inlet pressure of 2.0 bar.
[2]Pressure difference of CP during the CCD mode was 1.1 bar.
[3]The compressor operated 15% of the time with 2.0 kW power.
[4]Anti-Scalant pump, Control board, Lights, with AC unit off.

Conclusions

The new BWRO-CCD-PFD proprietary technology operates most of the time on the basis of the hydrostatic principles of CCD and part of the time on the basis of the hydrodynamic principles of PFD [5]. This new technology of simple design and high cost effectiveness was characterized by extensive pilot trials and applied commercially for the past 20 mo on a 24 h basis with availability of 98% by remote control operational means [8]. The benefits of the new method exemplified by the *REIM-II* unit are as followed:

- A technology of exceptional simple design made of common parts and components of high cost effectiveness for a short investment return period.
- A technology of modular design for any desired production scale.
- A technology for very high recovery without the mandatory staging requirement of conventional techniques.
- A technology of low energy consumption with CCD of same flow rates of feed and permeate experienced most of the time without any energy loss due to disposed brine.
- A technology of high versatility suitable for fixed or variable salinity feed sources and for maximum recovery made possible the constituents of the source.
- A technology with simple control of flux, MR, head element recovery and cross flow for any desired system recovery made possible by the salinity and the constituents of the source.
- A technology of low fouling (bio and particulate matter) due to use of short modules (3–4 elements each) which eliminate tail elements effects of conventional techniques; large salinity variations of recycled concentrate, fast cross flow over membranes surfaces, and frequent replacement of the entire brine in the system with fresh feed.
- A technology of high automation and remote control with minimum needs for on location presence as already demonstrated by the *REIM-II* unit over the past 20 mo.
- A technology of infinite selections of operational parameters to suit the exact requirements of each specific Brackish Water Source.

The new BWRO-CCD-PFD proprietary technology applies for diverse applications, on small to large scale basis, some of which are listed below [5]:

- Upgrade of existing water supply lines at the source origin or elsewhere along the line, intended for improved quality of supplies for domestic and/or industrial applications. This approach may involve partial source desalination with high recovery and blend of permeate with the rest of the source according to the desired quality of the supply.
- Decontamination of ground and/or under ground water sources by partial or complete desalination of the source with high recovery and low energy. Exemplified already by the application of new technology with 90% desalination recovery in the presence of PC-510 (4.0 mg l^{-1}) Anti-Scale Agent for nitrates removal from a domestic water source of 555 ppm TDS; 87 ppm NO_3; 37 ppm Silica and 420 ppm hardness ($CaCO_3$) [8].
- Desalination of Brackish Water sources in the salinity range up to 6000 ppm with high recovery and low energy. Exemplified already with the data presented hereinabove with respect to the *REIM-II* unit operation.
- Desalination of clear domestic effluents to so-called "Newater" permeates, which may be used to supplement potable water supplies or mixed with the source to improve the quality of water supplied for irrigation [8].
- Desalting of excess salinity of water received from cooling towers, softening of water supplies to a desired level, quality water supplies for specific applications, treatment of industrial effluent, and other related application.

References

[1] R.I. Bratt, "Method and Apparatus for fluid treatment by Reverse Osmosis", US Patent No 4,814,086.

[2] L. Szucs, K. Jozzsef and A. Szucs, "Method and apparatus for treating fluids containing foreign materials by membrane filter equipment", US Patent No 4,983,301.

[3] A. Efraty, "Variable Pressure Closed Circuit Desalination", PCT International Publication No WO O3/013704 A2 20.02.2003.

[4] A. Efraty, "Apparatus for continuous closed circuit desalination under variable pressure with a single container", US Patent No 7,628,921 and related patents issued worldwide.

[5] A. Efraty, "Continuous closed-circuit desalination apparatus without containers", US Patent No 7,695,614 and related patents issued worldwide.

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

[7] A. Efraty, R.N. Barak and 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, accepted for publication Desalin. Water Treat., in press (2012).

[8] Desalitech Ltd, unpublished results.