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Operating experience of the Dhekelia seawater desalination plant using an innovative energy recovery system

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Abstract

Dhekelia Desalination Plant in Cyprus has been in operation for 7 years. It includes eight 5,000 m^3/d seawater reverse osmosis trains operating with Mediterranean seawater with a TDS content of 41,800 ppm, with water temperature ranging from 17°C to 32°C. The energy recovery system originally installed at the plant is the Francis turbine, which, at the time, was considered one of the most efficient and economical devices on the market. Since then, however, market forces to reduce operational costs, by cutting down energy consumption, led to the advent of new energy recovery systems. Today several systems are in operation which reduce the RO energy consumption. Apart from the versions of the Francis turbine and Pelton wheel they include the hydraulic turbocharger, work exchanger and pressure exchanger, all harnessing the pressure energy of the brine. In our effort to be competitive for the years to come we decided to convert our existing energy recovery system from Francis turbines to the pressure exchanger. This paper outlines how it was decided to go ahead with the pressure exchangers, and gives comparisons with other energy recovery methods, and describes our operating experience with the pressure exchangers.

Keywords: Operating experience; Energy recovery systems; Pressure exchangers

1. Original process description

The seawater is drawn from a 600 m long undersea pipe to a reservoir. After chemical addition and some standard coarse filtering screens, the water is pumped to the dual media filters (DMF's) for a first removal of suspended solids and colloids by 4 raw seawater pumps (4 RSWP's). The water is then collected in an underground tank and after further chemical conditioning, the pretreated water is pumped to the reverse osmosis stacks (RO's) by 8 filtered water feed pumps (FFP's) through the 1 micron cartridge filters (CF's) and the high pressure pumps (HPP's).

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Permeate water from the RO's is further remineralized with CO_2/lime/magnesium sulphate and finally disinfected before reaching the client's tank. Seawater is pumped to the RO's at an approximate pressure of 83 bar. Brine water is passed through an energy recovery device (ERD) in order to recover the available energy in the brine stream.

2. History

Energy is the largest single operating and maintenance item for a desalting plant, exceeding in most cases 50% of the total operating cost.

The guaranteed contracted energy consumption for the whole Dhekelia Desalination Plant (DDP) is 5.3 kWh/m^3 with guaranteed specific energy consumption for the HPP's of 4.42 kWh/m^3. However, values obtained from these units from the original start up of the plant reached values as high as 4.7 kWh/m^3 (only for the HPP's) with current values of approximately 5.0–5.3 kWh/m^3, i.e. total energy consumption of about 6.0–6.3 kWh/m^3.

As a result of the high energy consumption figures obtained in DDP, a feasibility study on the plant energy consumption was initiated. This study concentrated mainly on the type of energy recovery system to be installed to replace the existing energy recovery Francis turbines (ERT's).

The ERT's were selected back in 1996, when the DDP was under design, and at the time, Francis turbine was the most advance applied (tested) technology available on the market.

The expected power recovered from the Francis turbines was 341 kW, corresponding to 27% of the HPP's power requirements. However, since the plant start up these values have not been achieved.

During the feasibility study all the electrical equipment was examined in order to decrease the overall plant energy consumption to the contracted figure of 5.3 kWh/m^3.

Resulting from this study, certain modifications were carried out which are listed below. However, at this point it is important to point out that, one *main restriction* that was to be taken into consideration in the study was that the original plant design (arrangement/equipment) had to be respected as the plant is to be handed over to the client at the end of the contract period in exactly the same condition as it was tendered. In other words, the contract does not allow for major modifications of the plant.

The main modifications carried out are the following:

- Installation of frequency converters to the raw seawater pumps in order to control the speed operation of these pumps in accordance with feed flow requirements.
- Installation of frequency converters to the filtered water feed pumps in order to automatically control the pumps' speed operation according to RO feed pressure requirements.
- Modification on the operating cartridge filter replacement regime in order to ensure the lowest possible Δp across the CF's.
- Refurbishment of the high pressure units in order to increase their efficiency to the maximum values by sharpening the impellers and replacement of impeller rings.
- Replacement of the existing ERD's for a more efficient system in order to recover the maximum possible energy available in the brine stream. This modification is the topic of our presentation and details are given below.

3. Modification

The feasibility study concentrated on the impact of various ERD's. The main aspects taken into consideration in the evaluation of the new energy recovery systems were: Specific energy consumption, system efficiency, required degree of modifications in order to respect our contractual obligations (handing over the plant to the client in exactly the same conditions as it was tendered), required capital investment, ERD's supplier's experience and degree of maintenance requirements.

All types of ERD's studied, harness the pressure energy of the brine stream. Today, there are several systems in operation which reduce the RO energy consumption and include the Francis turbine, Pelton wheel, hydraulic turbocharger, the work exchanger, pressure exchanger.

In our evaluation, we took into consideration four different systems; Calder Pressure Systems, Desalco Ltd., Energy recovery Inc. and Siemag Transplan GmbH. The latter was soon counted out in the evaluation due to the prohibitively high capital investment cost required at the time.

The overall price for the whole modification of the remaining three companies was quite similar and therefore, capital investment was not anymore a criteria on the selection.

Table 1 illustrates the grade of modifications and equipment required for each system, which was used in our comparison evaluation. It is important to note that Table 1 includes data corresponding to the refurbishment of our system and not for a new plant.

Under Table 2, a system performance comparison including the guaranteed values for the contract of Dhekelia Desalination Plant is given.

4. System selection

System selection was carried out taking into consideration the main parameters listed in section 3 above. From Tables 1 and 2 it can be seen that the guaranteed highest efficiency and the lowest

Table 1
General comparison

Item	Description	Original design	Pelton wheel	Work exchanger	Pressure exchanger
1	General				
	Number of trains	8	8	4	4
	Capacity of each train, m^3/d	5000	5000	10,000	10,000
	Recovery, %	50	50	50	50
	Operating pressure, bar	83	83	83	83
	Number of HPP's	8	8	4	4
	Number of high voltage (HV) motors	8	8	4	4
	Size of each HV motor, kW	1000	1000	bigger	bigger
	Number of booster pumps required	—	—	4	4
2	Extra equipment requirements				
	Check valves		No	Yes	No
	Specialized control valves		No	Yes	No
	Control valves with 4-20 mA signal		Yes	No	Yes
	Hydraulic power pack		No	Yes	No
	Control cabinet		No	Yes	No
	Replacement of HV motors		No	Yes	Yes
	Extra transformers HV to LV for the booster pumps		No	Yes	Yes
	Extra low voltage (LV) controls		No	Yes	Yes
3	Civil works				
	Extra brine channel required		Yes	No	No
	Important civil works modifications		Yes	No	No
	Bypass return system tank required		No	Yes	No
4	Is the main restriction regarding modifications complied with?		No	Not complete	Yes

Table 2
System performance comparison (Guaranteed values given by suppliers for the retrofitting of the Dhekelia Desalination Plant)

Description	Original design Francis	Pelton wheel	Work exchanger	Pressure exchanger
Model			DWEER 2200	ERI PX120
No. of units	8	8	2×24 inch PV/stream	20/stream
Salinity increase (recovered high pres. feed vs. membrane brine by volume), %	N/A	N/A	1.5[1]	Not given
TDS increase (Mixing flow) (recovered mixed high pres. feed Vs membrane brine by volume), %	N/A	N/A	Not given	1.73[1]
Overflush amount (low pressure seawater vs. recovered high pres. feed flow rate) — (Lead flow), %	N/A	N/A	105[1]	100[1]
Low pressure differential across the unit, bar	0	0	1.4	1.2
High pressure differential across the unit, bar	0	0	1.0	1.1
Total leakages and pressurized flows from the system, m^3/h	0	0	12.1	10.7
Performance warranty at no charge, year	1	1	2	2
Performance warranty at charge for remaining years, % of original cost/year	N/A	Not discussed	3.8	2.8
Guaranteed efficiency, %	76.5[2]	88.0	92.6	94.0
Guaranteed recovered power, kW	341[2]	398	No guarantees given	No guarantees given
Energy savings after changing ERT's to other ERD's, kWh/m^3	—	0.27	No guarantees given	No guarantees given

[1] DWEER system: Determined by chlorine titration, data indicates 1.5% salinity increase at 5% higher low pressure seawater flow.
ERI: Determined by conductivity readings, data indicates 1.73% TDS increase of the mixed flow at 0% higher low pressure seawater flow (balanced conditions)
[2] These values were never reached. Therefore, energy savings for the Pelton wheel were expected to be much higher.

degree of required modifications correspond to the pressure exchangers. Also, as explained in section 3, capital investment was not a criteria in the final selection as the price from the three candidate companies was quite similar. The company with the highest experience was Calder pressure systems with the Pelton wheel; The other two companies had, at the time, very limited experience on large RO trains (train size to be refurbished was 10,000 m^3/d). The largest trains these two companies had at the time were about 3000 m^3/d. Therefore, experience seemed to be a problem.

Dhekelia Desalination Plant had at the time a pilot plant, which is still running, with a capacity of 300 m^3/d where the PX's were being tested. The pilot plant had being at the time running for about 3 years, and the PX's did not present any problems during that time. The next step forward was to think of the PX's in terms of individual small items that they could be grouped together to form large lines, similar to the membranes train philosophy, i.e. in the event of a PX failure, sorting the problem out without jeopardizing the whole train operation.

In order to achieve this, it was necessary to find means to evaluate the performance of each individual PX and to ensure that in the event of a failure, the system could continue running until a new PX was installed.

Individual PX's performance was easy to monitor by measuring the unit's conductivity, (either low pressure out or high pressure out). Furthermore, continuous system operation could be ensured by installing extra standby units (2 for the PX120 and 1 for the PX220).

Finally, the only major issue left, was the flow distribution across the system manifold so as to obtain similar flow conditions for each PX. This could be achieved by a good manifold distribution system. However, in our case at Dhekelia Desalination Plant this was not possible due to space limitations.

Again, distribution philosophy was not unknown to us since it was related to the membranes configuration. Consequently the contract was awarded to Energy Recovery Inc.

It should be pointed out at this stage, that the original contract signed and guarantees were based on the PX120 model, 20 per train.

However, new developments on the PX's led to the advent of a larger rotor, the PX220 and as a result, Dhekelia Desalination Plant has one train fitted with PX120s and in the remaining trains PX220s have been implemented, 10 per train.

Data included in this paper correspond to guaranteed figures, as per contract, for the PX120 and actual performance for the PX220.

Please also refer to the system diagrams for comparison purposes, which are self explanatory and note that data given in the diagrams may not be in line with data given under Table 2 guaranteed figures. The reason being that this data was being included as per supplier's quotes, at the time, for projected performance and guaranteed performance.

5. System performance

The first two lines were refurbished with the PX120 during 2001, with a start up and commissioning date of December 2001. The next two lines with the new generation PX220 were commissioned in February 2003 and similarly two more lines in January 2004 and we expect to complete the last two lines before the end of 2004. The reason for the big gap between the first modification and the next was the various unexpected problems encountered in the first installation; not only with the PX's 120 themselves but also with the auxiliary equipment.

This was coined as the 'learning period' for all involved parties including the contractor, the main supplier and sub-suppliers. During this period however, CDPL gave the opportunity to all involved parties to remedy the problems without applying any penalties arising from the guarantees.

The main problems encountered with the PX120s were related to the quality of the materials. It now seems that the materials used were not suitable for the operating pressure of Dhekelia Desalination Plant of 83 bar and therefore, the PX's were replaced with higher grade materials such as rigid GRP end plates instead of PVC or polyethylene, SMO254 central rod instead of 316LSS, SMO254 adaptors and nipples instead of PVC. Similarly, the booster pumps supplied by Indar, Spain needed a lot of modifications in order to withstand the hard working conditions.The problems mainly concentrated on bearings, lubrication system and mechanical seals. Thankfully the supplier of these pumps always responded to the contractor's suggestions and requests.

Part of the learning process included also modifications on the system operation and controls so as to have a safe operated system with all required alarms and trip controls.

Once line one with PX120s was restarted, following all required modifications/upgrading a prudent period of about 10 months was allowed in order to follow up the system performance before putting into operation the second line.

The second line was fitted with an upgraded PX model 220 and again was allowed to run for a while before going on to the next unit. Today, all three units are operating at satisfactory conditions with minimum maintenance.

One of the drawbacks with the Dhekelia Desalination Plant retrofitting is the limited space available, making access to equipment cumbersome. However, this should not apply to a new installation or a refurbishment where the contractor can use any desired space.

6. Operating conditions

We have included in Figs. 1–4 the projected train process for each of the ERD's studied in the feasibility study, as per suppliers' quotes.

Fig. 5 shows the actual train operating conditions during last winter 2004. Fig. 5 should be compared with Fig. 2 as well as with data given for the PX120 in Table 2. The main parameters to be considered are shown in Table 3.

Figs. 7–9 show the system performance at different lead flow conditions for the PX120 and Figs. 10–12 for the PX220. From these figures it is clear that the higher the lead flow, the lower the salinity increase.

Also, energy consumption is lower for higher lead flows. However, it should be noted that at some point the energy consumption reaches a minimum value, (trough) whereby increasing further the low pressure flow is not justified as energy consumption tends to rise again after this trough point.

As regards to the lubrication flow shown in Figs. 9 and 12 it is very stable at different lead flow conditions. Changes in lead flow do not drastically affect the lubrication flow.

7. Conclusions

A lot of process adjustments and system modifications have been carried out at Dhekelia Desalination Plant. All these modifications have

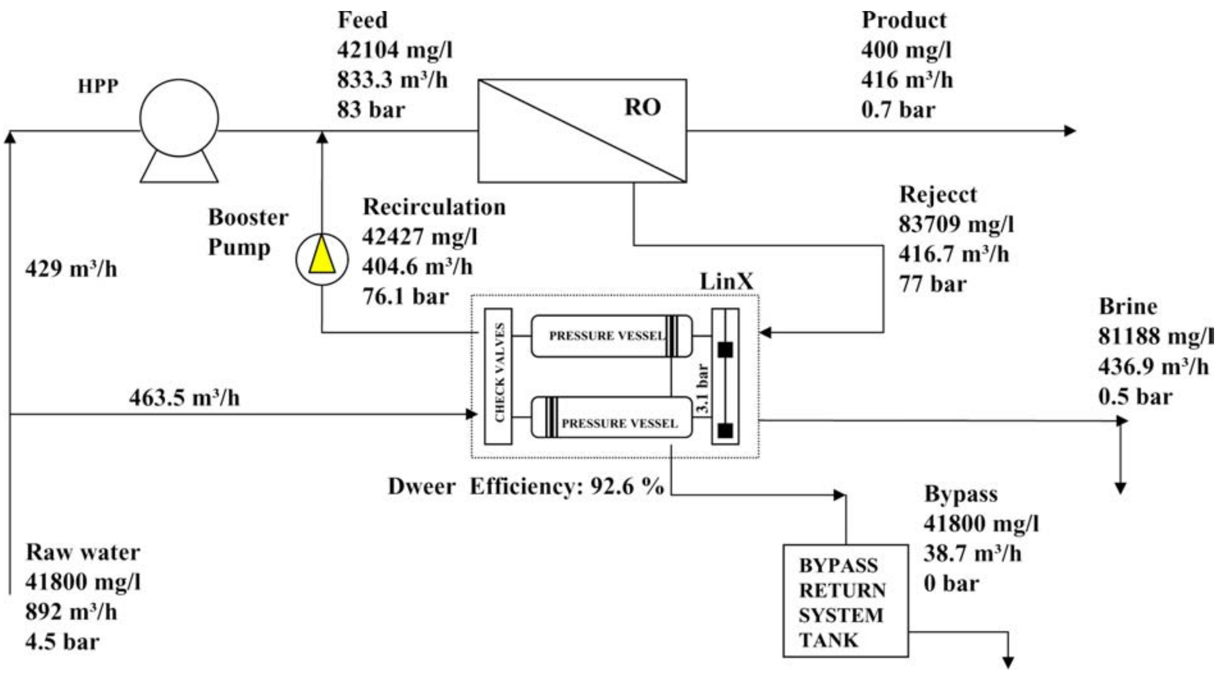

Fig. 1. Projected train process flow using DWEER 2200.

Table 3
Comparison for the PX's

Description	Guaranteed value (based on PX120)	Projected value (based on PX120)	Actual value (based on PX220)
TDS increase in mixing flow, %	1.73	1.73	Unknown[4]
Overflush [1] (lead flow), %	100	100	100
Low pressure Δp, bar	1.2	1.2[2]	1.2
High pressure Δp, bar	1.1	1.0[2]	0.9
Efficiency, %	94	96.2[2]	95.3
Salinity increase, % (PX HP out)	Not given	3.5	2.8
Total leakage, m^3/h	10.7	5.6 [3]	10.0

(1) 100 means 0% lead flow ie, balanced conditions (LP in flow to PX = HP out flow from PX)
(2) Manifold losses were not considered in the projected values
(3) Data included as per documentation submitted by ERI to CDPL. However, ERI admitted that 5.6 m^3/h projected was a typing error and the actual value was 0.56 m^3/h/rotor, instead.
(4) TDS increase makes reference to the volumetric mixing from the pressure exchanger HP out (through the booster pump) and the system HPP flow discharge. In Dhekelia Desalination Plant there are in actual fact two separate streams; one is supplied by the trains main HPP at raw water TDS conditions and the second stream is supplied by the booster pump at increased raw water salinity conditions. Therefore, it is not possible to measure the guaranteed value for TDS increase.

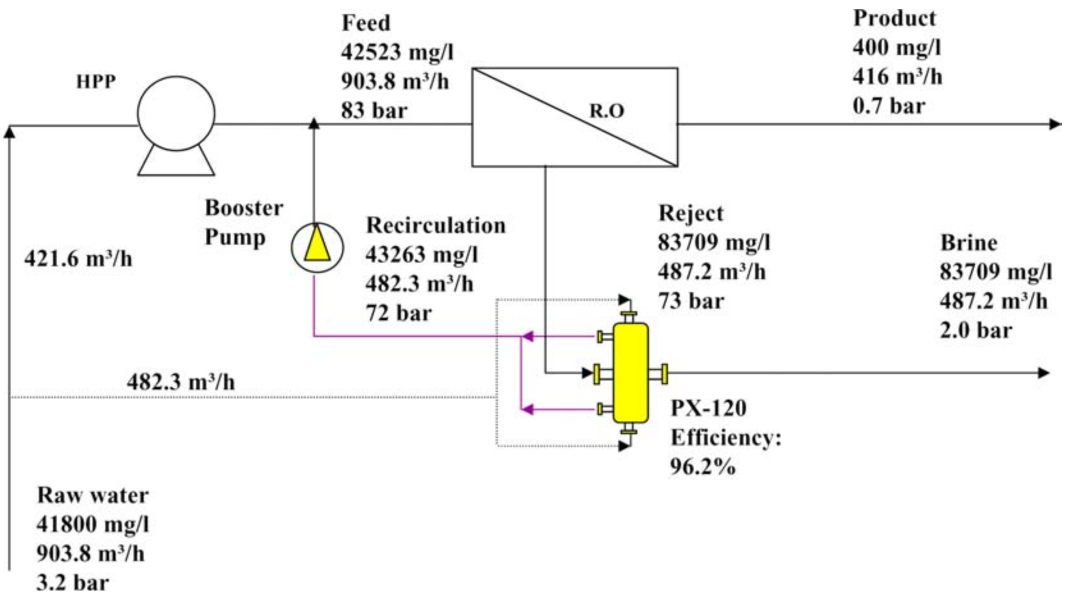

Fig. 2. Projected train process flow using ERI PX 120.

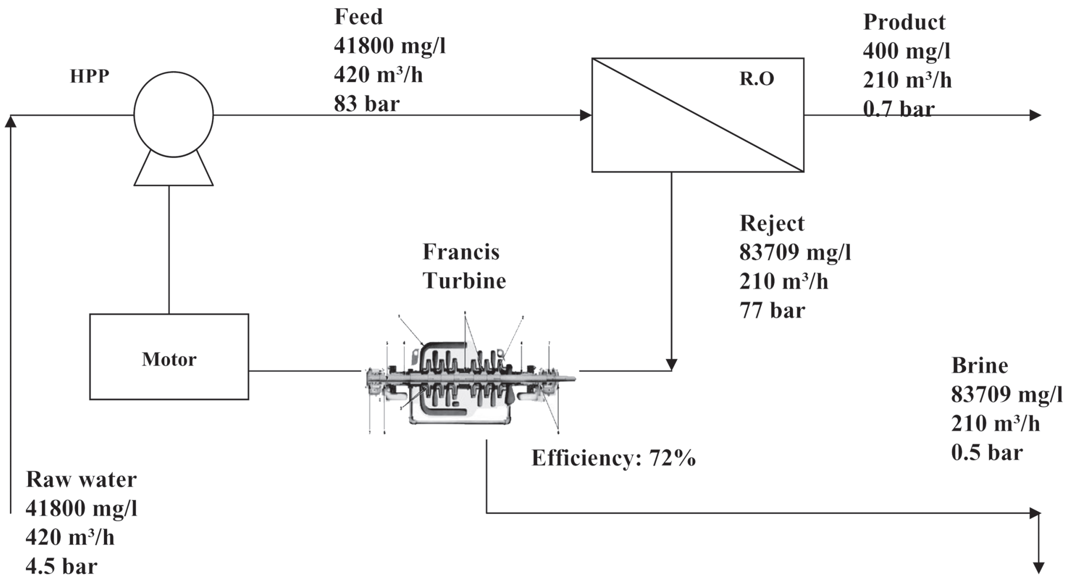

Fig. 3. Projected train process flow using Francis turbine.

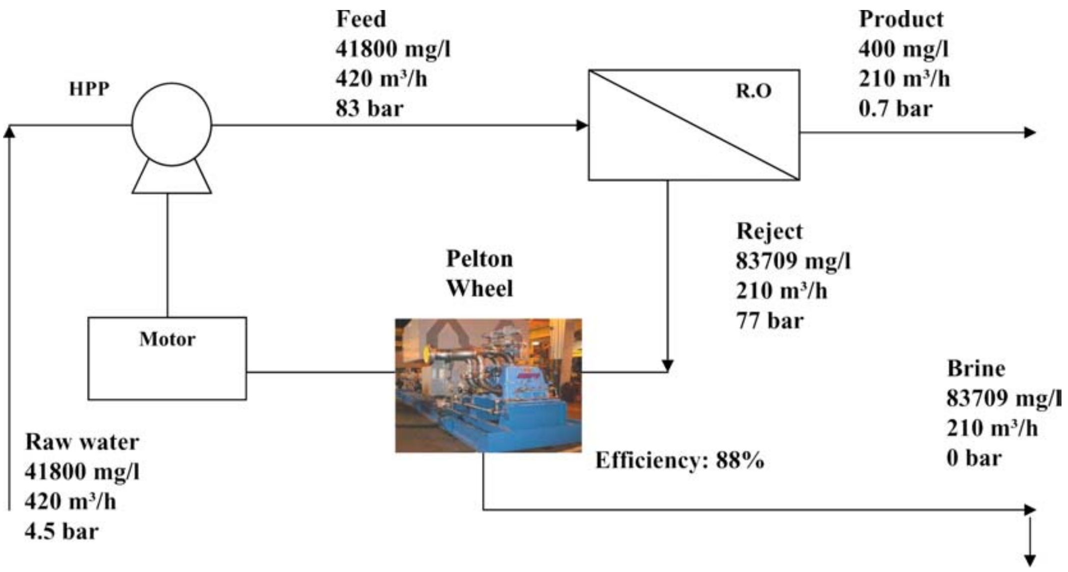

Fig. 4. Projected train process flow using Pelton wheel.

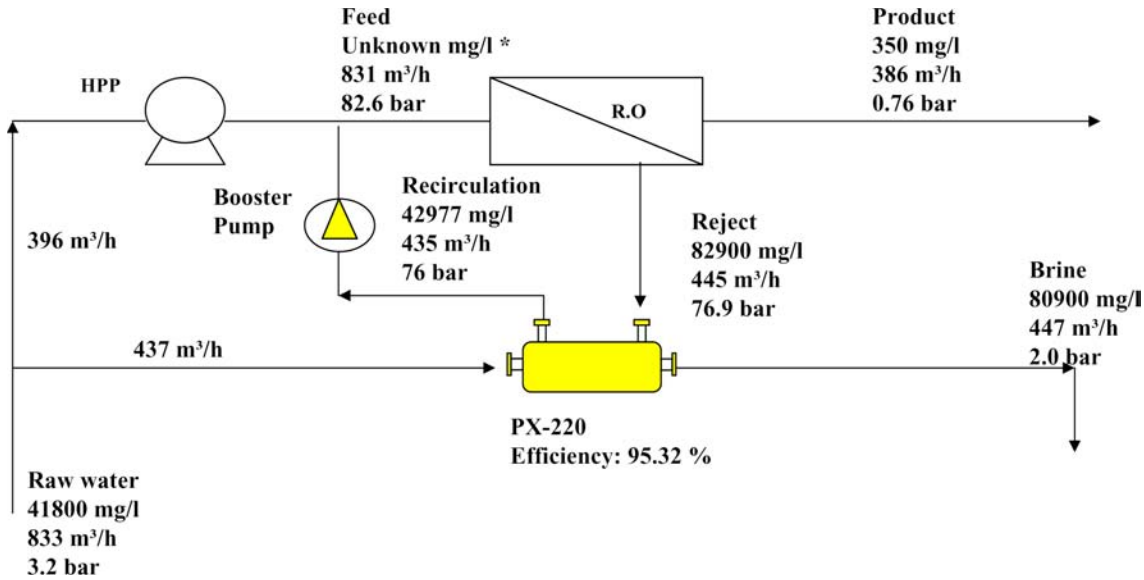

Fig. 5. Actual train process flow during winter ERI PX 220. Sketch used for representation purposes only. Actual design consists of 2 RO's. One RO is supplied by the HPP at 41,800 mg/L and second by the booster pump at 42,977 mg/L.

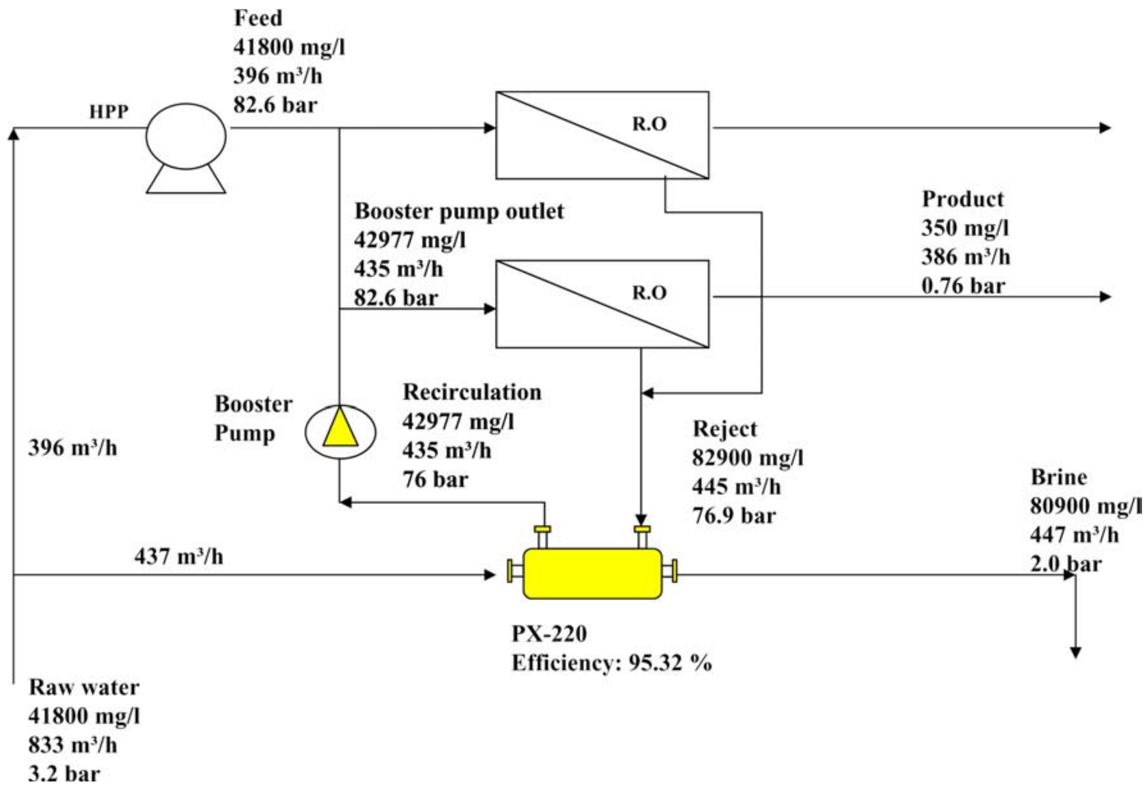

Fig. 6. Actual train process flow during winter ERI PX 220.

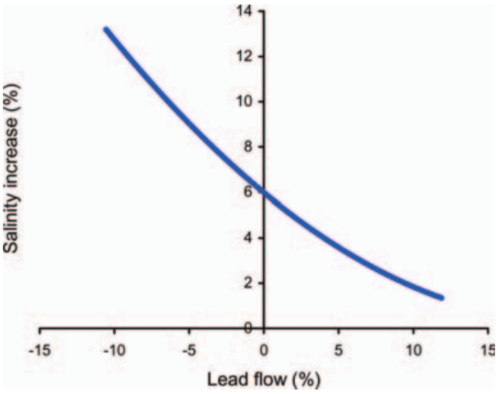

Fig. 7. Salinity increase vs. lead flow PX 120.

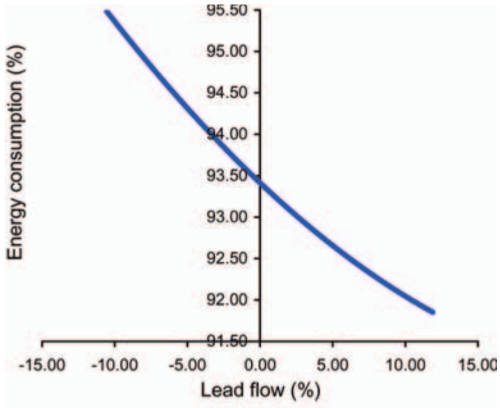

Fig. 8. Energy consumption vs. lead flow PX 120.

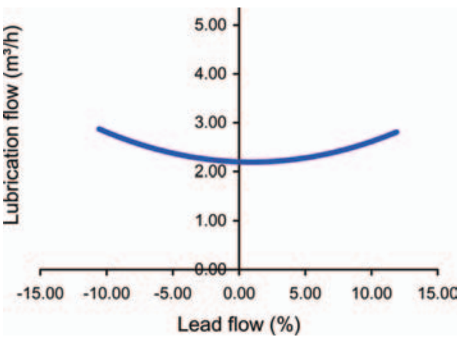

Fig. 9. Lubrication flow vs. lead flow PX 120.

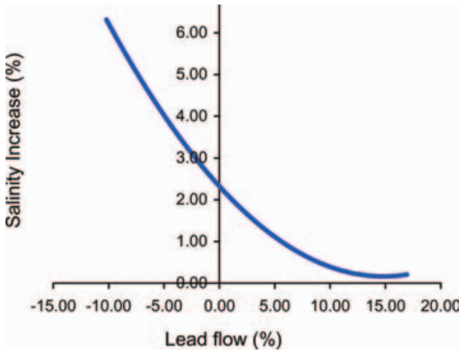

Fig. 10. Salinity increase vs. lead flow PX 220.

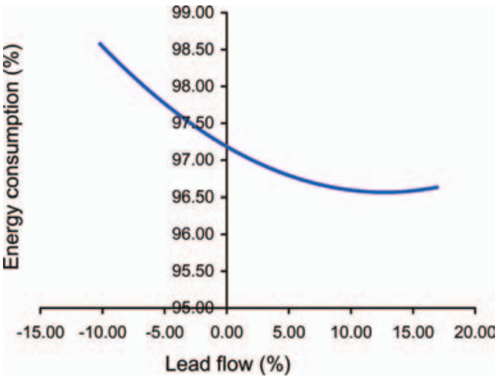

Fig. 11. Energy consumption vs. lead flow PX 220.

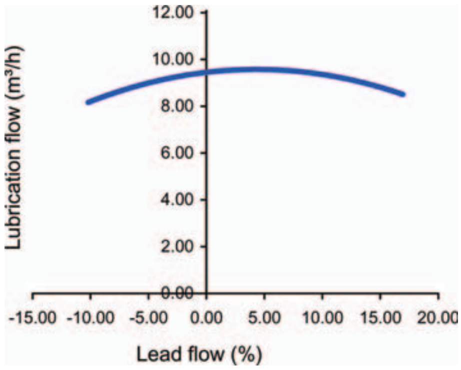

Fig. 12. Lubrication flow vs. lead flow PX 220.

$$\text{Salinity increase (\%)} = \frac{\text{Conductivity at PX HP}_{\text{out}} - \text{Conductivity at PX LP}_{\text{in}}}{\text{Conductivity at PX LP}_{\text{in}}}$$

Lubrication flow (m^3/h) = HPP feed flow – permeate flow

$$\text{Lead flow (\%)} = \left(\frac{\text{LP flow in}}{\text{HP flow out}} - 1\right) \times 100$$

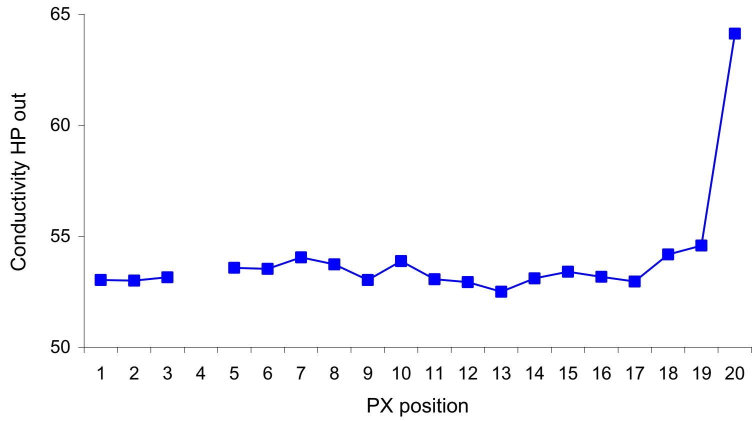

Fig. 13. Conductivity from each PX according to position of line 1.

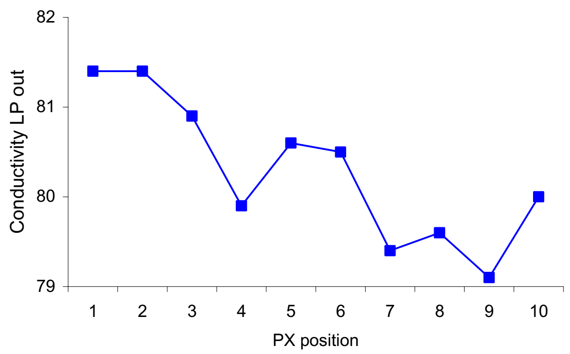

Fig. 14. Conductivity from each PX according to position of line 2.

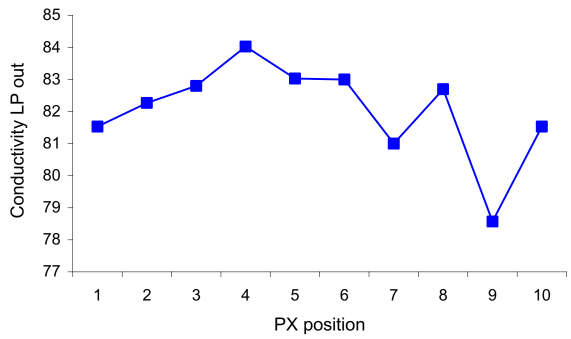

Fig. 15. Conductivity from each PX according to position of line 3.

been implemented only after thorough and detailed data evaluation and pilot tests.

Three years of pilot testing for the ERD and data accumulated was assessed and evaluated before proceeding with the full-scale system implementation. Despite this, the system presented problems at the original start up stage, and a lot of further modifications were required to bring its operation to today's conditions.

Today, the new ERD is operating satisfactorily with minimum maintenance, enabling the contractor of the Dhekelia Desalination Plant to meet the contracted energy recovery values.

An efficiency of over 94% is presently being achieved with the new ERD. However for the whole RO system, efficiency is still very low taking into consideration the RO recovery ratio of 50%.

The figures suggest that perhaps maximum efficiencies have been reached in the ERD's. However the time has come for the RO industry and membrane manufacturers in particular to concentrate and study ways on how to increase the efficiency of the RO modules, which presently are the main source of inefficiency. Development of membranes with lower operating pressures, increased recovery or/and changes in membrane configuration must be a step in the right direction.

A lot of tests and pilot studies are being carried out at Dhekelia Desalination Plant in conjunction with the company Osmo Sistemi S.r.l., which executed the refurbishment of the ERD.

Other studies carried out presently include an ultrafiltration pilot plant and a boron research project in conjunction with the University of Cyprus.

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