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Innovative design of the UF and SWRO Limassol desalination plant in Cyprus

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ABSTRACT

The Water Development Department of Cyprus has awarded to a consortium of two companies: Netcom (Cyprus) and Mekorot Development Enterprise Ltd (Israel), a BOT project for the design, build operate and maintain of a 40,000 m^3/d SWRO plant. The plant will have the intake and water product delivery infrastructure already in place so as to be able to increase production to 60,000 m^3/d within a short notice from the client. The consortium, namely MN Limassol Water Co, has some tough criteria to meet such as product water: (a) TDS less than 600 ppm, (b) Boron less than 05 ppm, (c) Turbidity less than 1NTU, and (d) Alkalinity not less than 30 ppm HCO_3 as well as the tender stipulated high energy costs of 10 €/kWh. The tender specifications, high energy cost as well as the increased costs of materials and supplies due to the developed world crisis took place due to signing the contract back in 2009; and the current plant construction and operation phase has shaped the design of the plant with innovative and unique features. Furthermore, the Limassol desalination plant will be the largest SWRO—ultra filtration and reverse osmosis (RO) plant in Europe meeting the challenges of EU Desalination and Environmental standards. The above are described in this paper. The paper further describes a comprehensive model developed by Mekorot, optimizing the energy required for the first RO pass in relation to downstream second RO pass and ion exchange processes for different types/suppliers of first pass membranes. The model was tested for the whole expected operating range of seawater temperatures as well as seasonal variations. The scenarios investigated using the comprehensive model has resulted in choosing the optimum RO first pass membrane giving the lower total water cost of the produced water.

Keywords: First–second RO pass; Ion exchange; Optimization model; UF pretreatment; Resin

1. Introduction

MN Limassol Water Co. Ltd is a consortium of Mekorot Development & Enterprise Ltd—subsidiary of Mekorot Water—a company providing international advance comprehensive water solutions and Netcom Ltd, Cyprus (a company owned by Logicom Public Ltd) and Demetra Investment Public Ltd, Cyprus. MN LW Co. Ltd has been awarded by the Water Development Department of Cyprus, the Limassol Desalination Plant BOT contract for 20 years. The contract

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requires the plant to operate under the strict EU water quality, quantity, and energy standards.

Mekorot Water Company, the National Water Company of the State of Israel, is engaged in a wide range of activities in the management, operation, and treatment of all types of water resources, such as surface water, underground water, brackish water, seawater, or effluents. Mekorot is one of the world's most technologically advanced water companies and is a world leader in an efficient operation of water supply systems, management of municipal systems (24/7), wastewater and effluents reuse projects for agricultural and industrial proposes, seawater and brackish desalination projects, water treatment facilities, hydrology, and wells.

Mekorot Development & Enterprise (MDE) is the international business subsidiary of Mekorot Water. MDE leverages the 70 years of experience accumulated in Israel to carry out long-term water projects worldwide including the design, construction, operation, and maintenance (BOT, DBOT, and PPP) of various water facilities.

The Limassol desalination plant (Fig. 1, Aerial photograph) is to be commissioned in June 2012 with an initial production of 40,000 m^3/day. The plant is located at the outfall of the (dry) Kourris river, near Episkopi village within the district of Limassol. The tender required that the design and construction of the plant was such so that it takes into account expansion of the production from 40,000 to 60,000 m^3/day by installing the plants' infrastructure such as the following:

- Seawater supply pipe line.
- Brine discharge pipe line.
- The intake pit.
- The brine pit.
- Power supply connections from the national grid.
- Final product supply pipe line.
- Adequate space for future additional equipment and process units such as additional pumps, remineralization (Remi) columns, ion exchange (IX) units, ultra filtration (UF) and reverse osmosis (RO) skids etc.

The tender for the Limassol desalination plant, stipulated the build up of the total water cost and the criteria of selecting the winning bidder, according to the lowest water cost.

The produced water cost parameters were:

(A) Unit rate per cubic meter of delivered water for the recovery of the capital, based upon the capital expenditure and the recovery interest rate for 20 years.

(B) Unit rate per cubic meter of delivered water for the recovery of the operation and the maintenance cost excluding cost of electricity:

(a) Operation and maintenance mode.
(b) Stand-by mode.

(C) Unit rate per cubic meter of delivered water to cover the cost of energy based upon selling cost by the Cyprus electricity authorities at 0.10 €/kWh.

The criteria of selecting the winning bidder were:

- Total unit rate of desalinated water, production mode = A + B(a) + C.
- Total unit rate of desalinated water, stand-by mode = A + B(b).

MN
Limassol Water Co Ltd

Fig. 1. Aerial photograph of Limassol desalination plant.

2. Design details and submitted total water cost

The tender price of MN consortium (MN Limassol Water Co. Ltd) was 0.8725 €/m^3, a figure which includes all plant stages (Fig. 2) including pumping the product water to 170 m elevation.

The tender stipulated the required water quality with main parameters: TDS less than 600 ppm, Boron less than 0.50 ppm, turbidity less than 1.0 NTU, and alkalinity more than 30 ppm. Also a conspicuous value in the tender was the very high energy cost stipulated for the calculation of energy cost component.

Two points became quite obvious:

- The unit power cost of 0.10 €/kWh is very high. Taking into account that in addition to the desalination energy, an energy for the transportation of the water to the Ypsonas reservoir (8.5 km from the plant at a level of 170 m above seawater level) shall be required. One can understand that the energy cost component was crucial to win the tender.
- The demand for less than 0.5 ppm Boron in the product water is very severe, but the demand to supply TDS less than 600 ppm is far from severe.

3. Innovative design process stages and process optimization

The plant has seven main process stages as shown in Fig. 2.

3.1. Stages 1 and 2: intake

Seawater is gravity fed via a 1 km pipe into the intake pit where it undergoes initial filtration via rotary screens; all screenings greater than 2 mm^2 are removed and the filtered water is then pumped to Stage 2. The intake pit consists of the brine pit/pipe outfall some 1.2 km into the sea. Special purpose diffuser system has been design for the efficient dispersion of the brine into the sea currents.

3.2. Stage 3: prefiltration and UF

Seawater is filtered through self-cleaning basket type filters which remove particulates above 300 microns in size and then filtered through "Ultra-Filtration" modules containing hollow fiber membranes that remove particulate and microbial contaminants greater than 0.3 µm in size. Permeate from the UF is stored in a tank that then is supplied the next stage. As the UF membranes become fouled they will require cleaning. Specific-designed backwashing cycles are in place to deal with short-, medium-, and long-terms cleaning requirements of the UF membranes. Optimization of these backwashing *g* cycles will be performed during the initial stages of the plant operation.

The pretreatment is based upon six UF modules, the units are supplied by Dow Chemicals. This UF pretreatment process stage incorporated several substantial advantages in comparison to the traditional

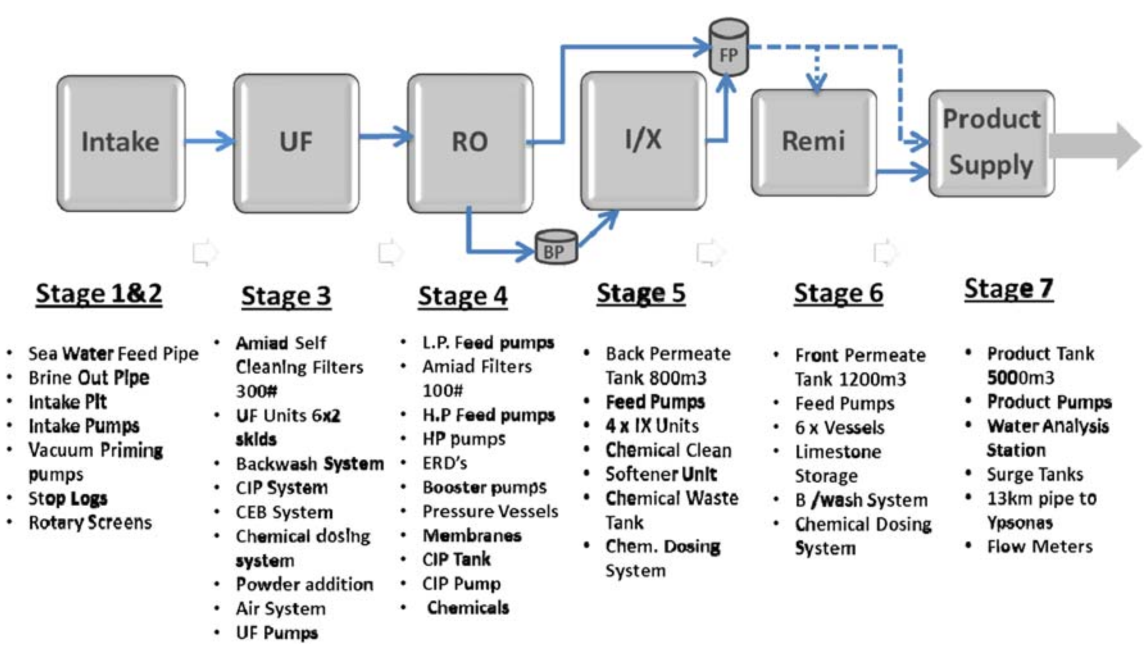

Fig. 2. Limassol desalination plant—general process overview.

dual media filtration deign: the construction period is rather shorter i.e. about four month, whereas with the conventional multimedia filters it was estimated to take at least nine month (taking into account the curing of the very large concrete works). Also the UF pretreatment can handle high turbidity seawater derived from rough/stormy sea conditions. Seawater fed to the UF with turbidity of 100 NTU poses no problem to the UF, and subsequently the shutdown time is reduced substantially.

3.3. Stage 4: RO

UF permeate is fed through a series of increasing pressure pump systems at high pressure, via low- and high-pressure feed pumps followed by the high-pressure pumps before entering into the RO stage. Low pressure UF permeate water is fed into the energy recovery systems of the RO stage before boosting their pressure to the RO feedwater pressure, before entering the RO skids. Permeate from the RO modules is separated into two parts based on Boron levels. "Front Permeate" which is fed to the front permeate tank and "Back Permeate" is sent to the back permeate tank and then onto the IX system for Boron removal.

3.4. Stage 5: IX

Back permeate is fed through columns which contain IX resin beads. These resins are designed specifically to remove Boron; as the permeate passes up through the column, the charged ions on the resin beads remove the Boron ions. The IX system contains a water softening stage which prevents scaling of the columns and as the resin beads become "loaded" they require a regeneration stage, explained later. All permeate from the IX system is fed to the front permeate tank which feeds both the final product tank and the remineralization columns.

For the removal of the Boron from the desalinated water, an ion exchanging resin process stage was used rather than the conventional second RO pass. The ion exchanging resin is manufactured by Rohm and Haas, affiliated of Dow Chemicals. The advantages of ion exchanging resin in comparison to the conventional "second pass" are: lower energy consumption as the pressure drop over the resin bed is about 0.5 Bar, compared to pressure of about 12 Bar in the conventional "second pass"; the recovery of the resin is about 100% compared to 90–95% in the "second pass" design; the guaranteed replacement rate is 10 years compared to 5–7 years in the "second pass" design; and the danger of the precipitation of Calcite and Brurite in the second pass does not exist in the IX unit.

3.5. Stage 6: Remi

A proportion of the front permeate is fed through the Remi columns, these contain locally produced Limestone gravel which is used to return hardness and increase the alkalinity of the permeate; this makes the water palatable and less corrosive. The remineralized water pH is adjusted before is then fed to the product supply tank.

3.6. Stage 7: product supply

Permeate directly from the front permeate tank is fed into the bottom i.e. 5,000 m^3. Permeate from the Remi filters is fed into the top of the product tank. From the product tank, the product water is pumped into the final product pipeline that supplies the Cleint's 5,000 m^3 reservoir at 170 m elevation.

4. Membrane selection model

In addition to the above, a comprehensive model was developed in order to find the best-performing membranes from well-known manufacturers and the type among the commercially available membranes (approved by the tender) which shall provide the lowest total water desalination cost.

This was done in accordance with the prevailing economical parameters of the tender namely: electricity cost, cost of the utilized chemicals, capital expenditure of the various components, discount interest rate, cost for the replacement of the first pass and second pass membranes (if needed) and subsequent cost for the replacement of the IX resin in order to maintain the low boron levels (<0.5 ppm), and other cost parameters.

It should be stressed that the evaluation of each and every commercial membrane was based upon the comparative parameters such as the energy consumption, where as other parameters common to all the membranes such as intake and seawater supply, the pretreatment, the transmittal of the final product, etc. were not taken into account.

The simplified procedure was as follows:

- The model was run for all the potentially preferred RO membranes per chosen supplier, for seawater temperature range of 16–30˚C.
- Based upon the availability of each seawater temperature (percent of the yearly time namely

Table 1
Model for the determination of overall specific energy for the RO stage (example at 16°C; the model was tested for each degree increase up to 30°C)

R =	46%		$P_{min\ (bar)}$=	55.800
Prod.flow=	60,500	m3/day	$P_{max(bar)}$=	57.900
Brine flow=	71,022	m3/day		
Inlet flow=	131,522	m3/day		

Data: 60,500 m3/day; lapse of 3.6 years
Membrane : X. Production at 10,084 per skid x 6 skids (m3/day)

RO Stage Specifc Energy Calculation at 16° C

ITEM	FLOW RATE	INLET PRESS	DISCH. PRESS	DIFF. PRESS	PIPING PRESS LOSS	EQUIP PRESS LOSS	ELEV. PRESS LOSS	PUMP EFF	MOTOR EFF	VFD EFF	OVERAL EFF	PUMP POWER CONS.	NO. OF OPER UNITS	STAND BY UNITS	total pumps power consum	SPECIFIC CONS. ALL OthER UNITS
	M3/H	BARG	BARG	BAR	BAR	BAR	BAR	% / 100	% / 100	% / 100	% / 100	KW			KW	KWh/m^3
LP FEED PUMPS	2740.0	0.000	2.120	2.120	0.125	0.000	0.000	0.810	0.960	0.975	0.758	212.83	2	1	425.656	**0.169**
LP RO FEED PUMPS	1260.4	2.000	5.100	3.100	0.000	0.000	0.000	0.790	0.959	0.975	0.739	146.93	2	2	293.868	**0.117**
HP RO FEED PUMPS	1260.4	5.100	57.900	52.800	0.125	0.000	0.500	0.850	0.966	1.000	0.821	2,251.38	2	1	4502.767	**1.786**
PX ERD BOOSTER PUMP	493.2	55.775	57.775	2.000	0.125	0.500	0.500	0.875	0.930	0.975	0.793	34.54	6	0	207.211	**0.082**
															OVERALL RO SPECIFIC POWER CONSUMPTION	**2.154**

365 days per year), find the average energy consumption per the investigated RO membrane (example shown in Table 1).

- Each investigated first pass RO membrane is possessing properties which define the split between the front permeate and the back permeate as required to conform with the demands in the contract with the water authorities. The TDS and the boron concentration of these streams are known; the capital expenditure and operating expenditure were defined of the second pass (if required) and that of the ion exchanging resin.
- The capital expenditure is defined according to the "worst case" namely the maximum size units required to remove maximum Boron and maximum TDS. The maximum shall be generally at the highest seawater temperature.
- The operating expenditure includes the energy consumption of the second pass (if needed) and the ion exchanging columns, their chemicals consumption (example shown in Table 2), and rate of replacement of membranes and resins.

As a result of the model application, one can find the most economical membrane pertaining and subjected to the economical parameters of the project.

In this particular project, second pass for the reduction of the TDS was not required as a result of the high value of 600 ppm in the final product as stipulated in the tender.

5. The design parameters selected

The result of the above membrane selection model and design optimizations was as follows:

- Six UF Pretreatment skids using DOW UF membranes.
- Five SWRO Skids, with 120 pressure vessels, each vessel containing eight RO membrane (for 40,000 m^3/d).
- The pressure is supplied according to a power pressure principle, namely: low-pressure feed pumps followed by high-pressure feed pumps and then high-pressure pumps batteries feeding the RO skids at 60 bar.
- The energy recovery is individual per skid, and supplied by ERI which are fed by the LP Feed pumps.
- The economical membrane pertaining to the prevailing economical date was a combinations of

Table 2
Example of model calculations for assessing operational costs of RO pass 1, 2, and IX unit

Operational costs	SEA WATER TEMPERATURE																Total Cost by time fraction
	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
	3.66%	5.38%	12.44%	7.53%	6.88%	6.02%	11.61%	13.55%	11.40%	10.97%	5.20%	2.40%	2.10%	0.86%	0.00%	0.00%	[Euro / day]
Energy cons. Pass 1, [Euro / day]	19,546	19,395	19,386	19,348	19,305	19,272	19,198	19,235	19,165	19,161	19,161	19,231	19,226	19,189	19,189	19,258	19,265
Pass 2																	
(1) Energy cons.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(2) NaOH 100%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(3) Antiscalant 100%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
(4) Waste in the brine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Pass 2 oper. cost, [€ / day]	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	0.0
IX																	
(1) Energy cons.	100.1	114.0	139.5	179.9	201.7	224.6	247.9	279.9	296.0	313.9	333.2	352.7	367.9	383.7	391.3	394.8	239.8
(2) NaOH 100%	140.4	174.2	218.6	262.6	302.3	343.3	381.5	402.1	404.8	411.9	409.3	407.3	401.8	396.5	389.8	380.9	335.9
(3) H2SO4 100%	101.3	125.7	157.9	189.7	218.5	248.3	276.0	291.0	292.9	298.1	296.2	294.8	290.8	287.0	282.0	275.6	243.0
(4) Rinse Water	27.7	35.0	44.8	54.8	64.0	73.6	82.7	87.6	88.4	90.1	89.6	89.1	87.8	86.5	84.9	82.8	72.2
Total IX Oper., [Euro / day]	**369.4**	**448.8**	**560.9**	**686.9**	**786.5**	**889.8**	**988.0**	**1,060.6**	**1,082.0**	**1,114.0**	**1,128.3**	**1,144.0**	**1,148.2**	**1,153.8**	**1,148.0**	**1,134.1**	891.0
Total daily Oper. Costs, [Euro / day]	19,916	19,843	19,947	20,035	20,092	20,162	20,186	20,296	20,247	20,275	20,289	20,375	20,375	20,343	20,337	20,392	**20,155**

SWC5 MAX Hydranautics, 60,000 m3/day, 3.6 years	
Operational costs, Ec / m3 product	
Pass 1 - Energy consumption	**32.108**
Pass 2 -	**0.0000**
(1) Energy consumption	**0.0000**
(2) NaOH 100%	**0.0000**
(3) Antiscalant 100%	**0.0000**
(4) Waste in the brine	**0.0000**
IX -	**1.485**
(1) Energy consumption	**0.3997**
(2) NaOH 100%	**0.5599**
(3) H2SO4 100%	**0.4050**
(4) Rinse Water	**0.1204**
Total operational costs, Euro ce	**33.592**

Data:		
Permeate flow	60500	m3/day
Product flow	60000	m3/day
Energy cost.	15	Ec/KWh
Energy factor Pass 2	1.50	
Availability	90%	

DOW membranes: SW30X HR and SW30 HRLE-440i.

- The front permeate is about 80% of the total permeate during the winter month. The balance permeate is feed to the ion exchanging columns. During the summer month, the front permeate is reduced to 60% and the balance 40% flow as feed to the ion exchanging resin.
- The UF recovery is 97% and that of the SWRO 45%.
- Second pass is not required. The rejection of the first pass membranes is adequate for the supply of TDS as required in the tender (Remi is taken into account).

6. Conclusion

The tough competition and tender requirements and in particular the low boron requirements of 0.5 ppm. of the Limassol desalination plant have imposed innovative and optimized process design in order to drive the total water cost down to winning levels. This was achieved with the use of a detail and comprehensive model developed to evaluate options and combinations of RO membranes and IX resins stage together with the UF membrane treatment.

The Design and Engineering of the SWRO Limassol Plant by MN consortium has successfully combined innovative UF per treatment with advanced boron removal process of IX and together with an optimized pumping and energy recovery systems has resulted in the final Limassol Desalination plant design has almost completed its construction on time and is commissioned in June 2012. The plant is expected to meet all the contractual requirements of water quality, quantity, and specific energy consumption.