Double Pass Electro-Deionization

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ABSTRACT: This paper will review the lessons learned in designing, commissioning and operating a water treatment system consisting of second pass reverse osmosis system, complete with an antiscalant feed, sodium bisulfite feed system and cartridge filters as pretreatment; followed by a membrane degasifying system, primary polishing electro-deionization; followed by a second pass polishing electro-deionization system for a combined cycle co-generation power plant. This paper shall provide background on equipment selection, unit operation, water quality issues, system rework, operational problems, system profiling and validation protocol.

Special consideration will be placed on profiling the reverse osmosis system (ROS) and electro-deionization (EDI) system performance due to radical changes in feed water quality and system operation.

INTRODUCTION

DDPS is a 630 MW combined cycle power station, the largest power station of its kind in Australia. It operates at intermediate to full base load capacity and is one of Australia's most efficient base load power stations.

DDPS is powered by natural gas piped from the company coal seam gas fields in southwest Queensland and produces enough power to supply the equivalent of 400,000 homes. This power plant supplies 630 MW of the 8233 MW supply by Origin.

On 12 June 2007, DDPS committed to constructing the 630 MW gas-fired power station. Work began in August 2007 and the power station has been fully operational since 1 July 2010.

This plant is one of Australia's cleanest base load power stations in terms of carbon emissions. It has three gas turbines each with a capacity of 120 MW and a steam turbine with a capacity of 270 MW, emitting less than half of the greenhouse gas than a typical coal-fired power station.

Using air-cooled technology also allows DDPS to use less than three percent of the water used by a typical water-cooled, coal-fired power station when generating electricity.

GAS TURBINE PLANTS

Most gas turbine plants and combined cycle co-generation applications use either water injection or steam injection into the combustion zone to reduce the emission of nitrogen oxides (NO_x) in the exhaust.

For simple-cycle installations, water injection control is the most widely used means for controlling NO_x emission. For combined cycle co-generation, where waste heat from the exhaust of the gas turbine is used to produce steam, either for process or combined cycle electrical power generation, steam injection or water injection is used to control NO_x. Some gas turbines can accept massive quantities of steam injection (relative to that required for NO_x control) for both power augmentation and heat rate improvement.

Gas turbines require high purity water for injection into the harsh environment of the combustion zone. Today, turbine manufacturers have established guidelines for the water and steam purity used for injection into the gas turbine. Typical Gas Turbine Injection Water Requirement is illustrated Table 1 below:

TABLE 1 – TYPICAL GT INJECTION

Parameters	Limits	ASTM
Total Solids	5 ppm	D5907
Dissolved Solids	3 ppm	
Sodium	0.10 ppm	D2751
Silica	0.10 ppm	D589
Particle Size	10 max	F312
Conductivity	1.0 max	D5391
(micro/cm)	1.5 max	

If these water and steam requirements are not met, serious damage can occur in the gas turbine's hot section.

To meet these stringent requirements, it is necessary to provide process makeup water to the gas turbine or boiler that meets the requirement of 3 parts per million (ppm) of total dissolved solids (TDS).

Lower boiler water silica concentrations are particularly important in steam-injection applications for high-compression-ratio gas turbines (requires steam pressure above 600 pounds per square inch (psig)) since silica will become volatile at high boiler pressures and will pass through moisture separators and deposit on turbine components.

By using the latest air-cooled technology, this facility will use less than three percent of the water of a conventional water-cooled, coal-fired power station. The technology employed in the DDPS design and construction will cut annual water use to around 200 megalitres, compared to more than 8,500 megalitres for a conventional water-cooled-coal-fired power stations.

BACKGROUND

The traditional approach to producing high quality water for combined cycle plants has changed from the historic use of ion-exchanger (IXS) systems to the more advance membrane systems especially for New Greenfield Plants.

The remarkable advancement and market penetration of membrane technologies being used as both pre and post treatment water treatment systems have grown steadily. With the introduction of thin-film composite (TFC) type membranes, current ROS operate successfully at 85% recovery at less than 150 psig, and the RO elements may last longer than 5 years with infrequent cleaning.

The use of RO systems in place of the traditional two beds (IX) has had a major impact in the decline of chemical usage at many operating facilities. The current generation of the RO membranes works very well as a pretreatment roughing process for total dissolved solids (TDS), particulates, and total organic carbon (TOC) reduction. Many applications require further deionization, which was frequently done by mixed bed ion-exchangers (MB-IXS), although they required chemicals and produce large volumes of waste water that requires neutralization.

The recent re-introduction of electro-deionization (EDI) technology that has the ability to produce high purity water without chemicals has again revolutionized the industry where EDI now replaces MBS-IXS for co-generation, power and semiconductor application requiring high purity water.

This facility is in a remote desert area and the system required high purity water without regeneration waste. It was designed for the water treatment system to have a guaranteed minimum recovery of 78% feed water, calculated by the ratio of EDI product flow to the ROS feed water flow times 100. To obtain this system recovery rate a ROS system, followed by a polishing EDI, followed by a second EDI was employed. This type of design requires chemical minimization, waste water reduction and high purity water.

WATER QUALITY

Feed water for this power plant system is well water supplied. Well water is usually high in mineral content, low in biological and organic content. This well water source is provided high in iron. The well water is treated by others with a 75% recovery Reverse Osmosis System and ancillary treatment equipment, resultant in the following feed water quality.

The Designed Feed Water Analysis is presented in Table 2. The low concentration of hardness and silica makes it ideal for an ROS/EDI combination. The high carbon dioxide resulting from Bicarbonate and pH adjustment can be easily handled with a Membrane Degasifier System (MDS).

TABLE 2 – DESIGN WATER QUALITY

Cations	$CaCO_3$	Anions	$CaCO_3$
Ca	<0.001	HCO_3	138
Mg	<0.002	SO_4	0.002
Na	183.0	Cl	45
K	0.0	NO_3	0.0
Total	183	Total	183
		SiO_2	13
pH	7-9	Adjusted	196
		Fe	<0.005

The effluent design parameters listed in Table 3 below can be easily obtained with conventional ROS/EDI technology with the exception of the cation conductivity. A polishing system is required downstream of the EDI is required to obtained the cation conductivity of <0.1 µS/cm. This site selected a polishing EDI to accommodate this goal.

TABLE 3 – EFFLUENT WATER QUALITY

Parameters	Concentration
Specific Conductivity	<0.1 µS/cm
Cation Conductivity	<0.1 µS/cm
Total Silica	<10 µg/l as SiO_2
Total Organic Carbon	<100 µg/l

The cation conductivity can be calculated by several difference methods. Our method of calculation is summarized as follows:

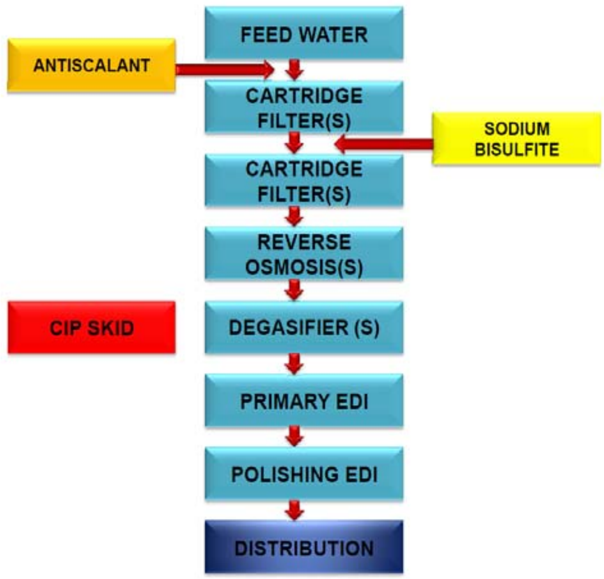
TABLE 4 – CATION CONDUCTIVITY

Parameter	Limits	µS/cm
HCO_3	0.005	0.030
Cl	0.004	0.046
Total		0.076

SYSTEM DESIGN

The Make-up Water Treatment System (MWTS) illustrated in Table 1 consists of two-(2) 100% trains indentified as A & B rated at 50 gpm of permeate each. The system consists of one-(1) Antiscalant Feed System (AFS), one-(1) Sodium Bisulfite System (SBS) four-(4) Cartridge Filters, two-(2) Reverse Osmosis Systems (ROS), two-(2) Membrane Decarbonator Systems (MDS), two-(2) Electro-deionization (EDI), one-(1) Clean-In-Place (CIP) System and one-(1) Waste Neutralization System (WNS). Other ancillary equipment was provided as required to make this system a complete and workable system.

FIGURE 1–WATER TREATMENT SYSTEM



The Antiscalant Feed System (AFS) is designed to prevent scaling of the ROS caused by calcium carbonate and calcium salts from the water supply at the design flow rates. The AFS consists of three-(3) simplex metering pumps complete with automatic speed control based on system feedback and the integrated rate controls on the face of the metering pump. The pump will operate when the ROS feed pump is in operation.

The AFS is designed for an antiscalant feed rate of 0.30 GPH of a 10% solution based on 4 ppm of chlorine in the raw water.

A Sodium Bisulfite System (SBS) is used to de-chlorinate the ROS feed water. De-chlorination is essential for protection of the RO membranes. The SBS consists of three-(3) simplex metering pumps complete with automatic speed control based on system feedback and the integrated rate controls on the face of the metering pump. The pump will operate when the ROS feed pump is in operation.

The ROS is designed for a sodium bisulfite feed rate of 0.50 GPH of a 10% sodium bisulfite solution based on 2 ppm of chlorine in the raw water. A control loop will automatically adjust the feed rate for the actual chlorine content.

Cartridge filters are provided, designed at 3 gpm per 10" equivalent. Five-(5) & One-(1) nominal micron polypropylene elements with double O-rings to assure proper fit was provided. These filter systems are the ROS pre-treatment filtration equipment designed to remove turbidity, particulates and reduce the feed water Silt Density Index (SDI) below 3. This type of elements allows for depth filtration, and will provide adequate filtration to the ROS system.

Various types of computer modeling software are utilized to create and verify ROS designs, including process modeling. For this application, high quality TFC membranes were selected. The ROS system design is a 1 x 1 x 3 x 1 array at 85% recovery. The feed water design flow is 60 gpm, producing 50 gpm permeate and resulting in 10 gpm reject and 6 gpm recycle from the EDI systems at the design temperature of 85^{0}F.

The ROS array of this design is a bit unusual since the system design uses both 8” and 4” RO elements as illustrated in Table 5.

TABLE 5 – ROS SYSTEM ARRAY				
Array	1	1	3	1
# of RO Elements	6	6	18	8
# of RO Elements/Tube	6	6	6	6
Size of RO Elements	8”	8”	4”	4”

From experience, we know that manufacturer’s computer modeling programs are slightly conservative with regards to actual operating experience; therefore, we take the output from the model at “face-value” and use them in our designs. The complete output from the ROS simulation program is illustrated in Figure 2 and Table 6.

FIGURE 2–ROS OVERVIEW

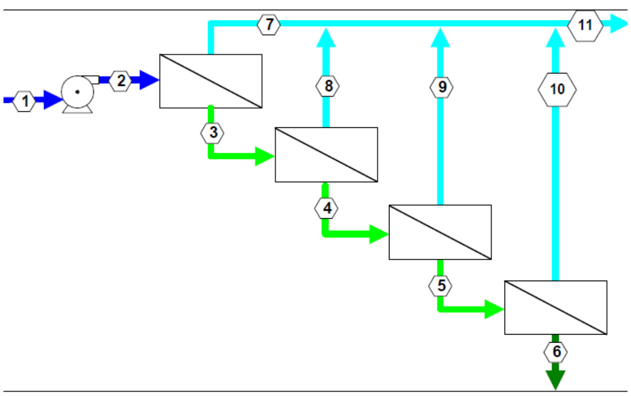
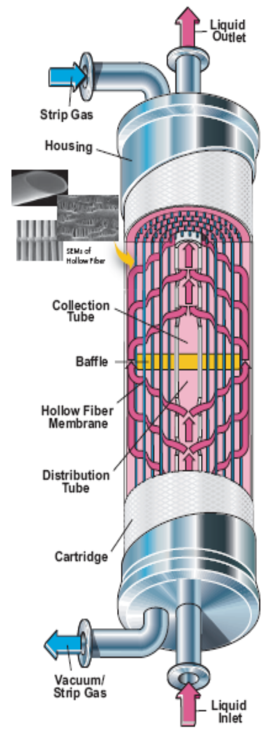


TABLE 6 – ROS PROJECTION					
		1	2	6	11
Flow	gpm	60	66	10	56
Press	psig	60	250	60	60
TDS	ppm	336	336	2244	3.4

The purpose of the Membrane Contactors is to remove transfer gas, primarily carbon dioxide, from the feed stream prior to it’s entering the electro-deionization modules. The Membrane Contactors contain thousands of micro-porous polypropylene hollow fibers knitted into an array that is wound around a distribution tube.

Because the hollow fiber membrane is hydrophobic, the aqueous stream will not penetrate the pores. The gas/liquid interface is immobilized at the pore by applying a higher pressure to the aqueous stream relative to the gas stream.



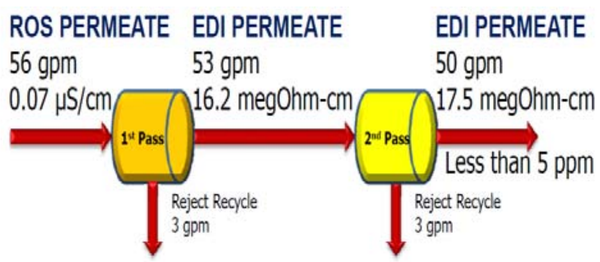
The Membrane Contactors utilize membranes that have thinner walls with a larger inside diameter, which allows for greater carbon dioxide removal. In the Membrane Contactors for gas stripping applications such as de-carbonation, a vacuum, stripping gas or combination of those is applied to the lumen side (inside) of the hollow fiber. The liquid stream is introduced to the outside of the fiber.

The first stage of demineralization is the ROS followed by a second stage polishing step using electro-deionization (EDI), the EDI module was utilized to enhance water quality to the standards required for this application as presented in Table 3, less cation conductivity.

At the heart of this system is advancement on conventional ion exchange technology in which the ion exchange resins are continuously removed ions with an imposed DC voltage resulting making the process chemical free. The complete output from the EDI simulation program is illustrated in Figure 3.

A review of this model verifies that the EDI system design has the proper design flow rates, which leads to a reduction in chemical cleaning and longer membrane life.

FIGURE 3 – EDI SYSTEM



The 1st pass EDI system will produce a permeate flow of 53 gpm. The system requires a feed rate of 56 gpm combined with a 5% reject flow of 3 gpm. The 1st pass EDI permeate will feed a 2nd pass EDI system to meet the stringent requirement of the cation conductivity.

The 2nd pass EDI system will produce a permeate flow of 50 gpm. The system requires a feed rate of 53 gpm combined with a 5% reject flow of 3 gpm.

FACTORY ACCEPTANCE TEST

The system was run and provided with a complete Factory Acceptance Test (FAT) at the manufacturing shop prior to shipment. A 5,000 gallon storage tank was filled with demineralized city water at a feed rate of 56 gpm to produce an EDI permeate of 47 gpm. Permeate and reject waters were recirculated to allow continuous running of the system.

All other instruments were calibrated at the factory. Several of the EDI power supplies were found to overheat and required replacement before shipment. Minor problems found during the FAT were identified and corrected at the factory prior to shipment.

SYSTEM OPERATING PROBLEMS

The Water Treatment System (WTS) plant has experienced several adverse conditions related to water quality since startup as illustrated in Table 7.

TABLE 7 – EXCEEDED WATER QUALITY

Parameters	Sp-W	SWB	%	SWA
pH	8.3	7.3	----	7.4
Turbidity	<0.01	1.7	1600	0.5
Chloride	25	38	52	38
Iron	<0.005	2.2	4300	<0.05

Sp-W = Specified Warranty
SWB = Service Water before Cartridge Filters
% = Percent of parameters that exceeded Warranty
SWA = Service Water after Cartridge Filters

Most important, the raw water has higher than expected concentrations of iron, and ROS pressure limits have been exceeded.

Other operating problems have resulted from these parameters, as illustrated:

- iron fouling of all membranes
- o-rings failing on the ROS 4th array
- flow & pressure imbalance
- chemical fouling of the membranes
- water quality changes

After several months of operation, the system was fouling cartridges filters, RO elements and finally the EDI membranes. All data indicated that the iron is not present in the dissolved form and confirmed that filtration through the cartridge filters is acceptable provided the membranes are not run to a point of failure. However, more research has to be obtained to better define the source and forms of the iron.

The WTS first experienced operational failure in August 2009. Failure of the permeate port O-rings at the north end of the 4th stage of both ROS-A/B trains account for many of the pressure surge problems as illustrated in Table 8.

This failure causes the ROS permeate conductivity to increase which prevents the ROS from starting up, particularly if the associated EDI is slightly degraded.

TABLE 8–4th TRAIN ROS PRESS SPIKES

Parameters	Reject Pres	DP Press
1-Service	239	
1-Shutdown	70	169
1-Permeate	0	239*
2-Service	256	
2-Shutdown	65	196
2-Permeate	0	256*

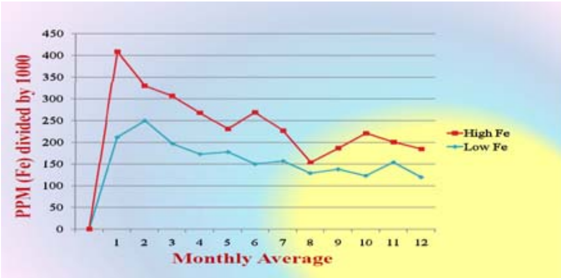
1 - ROS Clean Membranes
2 - ROS Foul Membranes
**- Equals 1 Second of Time*

A redesigned permeate port with a tighter tolerance and a larger O-ring was provided, this seems to have resolved this problem.

The 3rd & 4th stages containing 4" elements are the most susceptible to reduction in flow and higher pressure due to fouling compared to the 1st & 2nd stage containing 8" elements. Under these conditions the feed flow and pressure are increased to compensate causing spiking and possible failure of the 4th train. Membranes' fouling consists of both chemical scaling and biological films.

Graph 1, illustrated the higher iron feeding this water treatment system. Iron fouling of the membranes has a major impact on the flow & pressure imbalance of the system.

GRAPH 1 – IRON CONCENTRATION



From data collected, the most significant pressure spikes occur during the system shut down. The service water has water quality changes that contributed to the system operation problems encountered. The rate of fouling and frequency of CIPs is affected by variations in the service water chemistry. The main influencing factors are iron & ammonia from the blow down return, calcium chloride, sodium hydroxide and chlorine from the RWTP make up and particulates stirred up when the fire pumps run.

Dosing the service water to achieve the correct LSI for evaporator cooler operation tends to cause higher conductivities and faster fouling rates in the ROS. The ROS performance is better running at these lower LSI valves.

There are pretreatment cartridge filters prior to the ROS. They consist of a series of two filters, originally the lead filter had 5 micron elements and the second filter 1 micron. Concern over high iron levels in the ROS during commissioning resulted in the filters being changed to 1 micron for the lead and 1 micron absolute for the secondary. These generally require changing after 4-5 days of normal operation. During plant restarts when there are sustained periods of high make up water, the filters require changing more frequently.

The requirement to continue using service water for ROS makeup needs to be reviewed. The design of the onsite water treatment system has evolved since construction with the addition of a permanent RWTP, the construction of the new pipeline and the WSAC installation. Feeding the DWTP with RWTP permeates rather than service water could potentially reduce operating costs by reducing the frequency of CIPs.

EDI SYSTEMS

This system is unique whereas it uses a primary EDI for a 1st pass and a 2nd pass EDI as a polisher. To date, several EDI units have been replaced and the performance of replacement unit on EDI-B train has also become degraded.

There are three-(3) possible causes for the degradation in performance of the primary units:

- o Chemical damage to the resins
- o Mechanical damage due to pressure/flow spikes
- o Incorrect set up of the reject flows and pressures

The autopsy carried out on the original B train unit identified mechanical damage due to pressure/flow surges as the most likely cause of failure. These mechanical surges were believed to be related to the iron fouling of the membranes and resin.

Review of the operating trends indicates that flow rates up to 75% above design occur during the EDI prestart flushing cycle particularly if one train is already in service. This is because the piping configuration allows both ROS units to feed the flush.

The flow rates through the ROS and EDI units are set by manually adjusting the inlet, reject and permeate flows. The flows can become significantly elevated if all throttle valves are opened fully. There is potential for poor adjustment of these valves to cause damage to equipment. At present it was not possible to set up the EDI reject outlet pressures to the OEM recommendations.

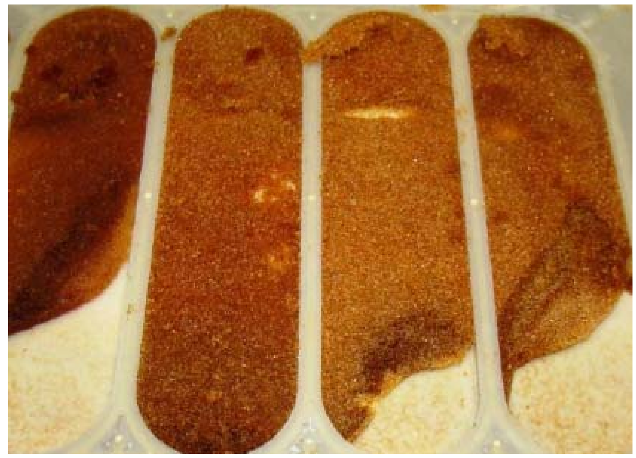
EDI AUTOPSY REPORT

It was determined the primary cause of high electrical resistance was due to high pressure fluctuations (water hammer). This was based on the collapse of the concentrate support resin.

The slumping of resin illustrated in Figure 4 in most of the concentration cells indicated two-(2) possibilities:

- o Pressure imbalance/spikes during operation
- o Module was under filled when built

FIGURE 4 – RESIN SLUMPING



Normally, the resin in all chambers is consistent and completely filled. This allows consistent path for electrical current to flow across the EDI module as highlighted in the resin filled concentrate chamber patent. With this module, it is clear the degradation of resin structure increased the electrical resistance.

In reviewing the as-built test data, pressure drops were within the normal range indicating that the modules were not under filled. It appears more likely that this module operated with some pressure imbalances or hydraulic shock that resulted in slumping in the concentrate. This condition would cause an increase in the module resistivity and thus affect water quality.

This same condition could occur from improper adjustment control valves used to balance the pressure between compartments, or by pressure transients (water hammer) illustrated in the system. Such pressure transients could be created by opening and closing the downstream valves, for instance when a system changes from service to recycle.

Pressure spikes can also be caused by abrupt starting or stopping the ROS. The system operation should be reviewed for possible causes of water hammer (such as rapid opening and/or closing of valves) and of product/reject pressure imbalance.

FIGURE 5–RESIN / MEMBRANE FOULING

Figure 5 illustrates fouling that was also observed on the resin and membranes. Chemical testing was inconclusive, but iron is suspected. The fouling is considered a secondary cause of the electrical resistance.

Staining and discoloration of the ion-exchange membranes and resin is typically the result of some type or degree of fouling. Samples of resin were sent for evaluation.

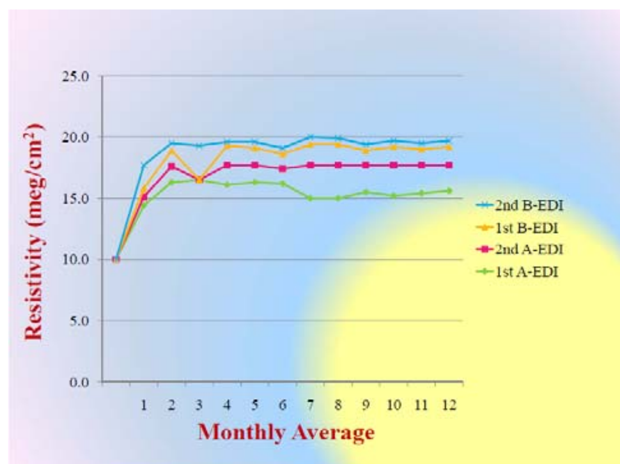
Results were inconclusive but showed some slight improvement in properties as a result of chemical cleanup.

Therefore fouling is considered to be a secondary cause of the high resistance and poor performance.

SYSTEM PERFORMANCE

Despite changes in feed water quality and higher iron content, the system has produced water quality as specified. The guaranteed results presented in Table 2 have been met throughout the system operation to date. Graph 2 illustrated data collected on both the pre & post treatment EDI. The post or polishing EDI produces the guaranteed water quality even when the ROS and primary EDI was producing poor water quality due to the site operation problems.

GRAPH 2–PRE & POST EDI RESISTIVITY



Data provided in Graph 2 above reflects the specific conductivity of the system performance by way of real time in line instrumentations. Cation conductivity is performed by grab sample and no current data was avialable. The system silica is below the 10 µg/l as SiO_2, total organic carbon is below the 100 µg/l required.

The 2nd pass polishing EDI system has shown no sign of deterioration and has performed superior to a polishing mixed bed IX for this application.

CONCLUSIONS

In selecting the best overall system for a facility, one must consider specific site conditions and requirements. They should include the designed condition and cost associated with permits, engineering, equipment design, building, installation, operation, operating cost, environmental, and site personnel preference. No two facilities are identical enough to draw a straight recommendation without evaluating all the above factors.

For this site the lessons learned are as follows:

- Obtaining a good water analysis that covers all the key parameters to properly design, fabricate and operate the water treatment system is essential. Most system operating problems occur from data not collected or evaluated correctly.

- Allow for flexibility in the design to account for seasonal feed water and operation changes.

- Analyze or predict feed water after recycled or reclaimed water is added to the feed.

- Always think outside the box, many times the solutions are there, it just requires someone to recognize them.

- If the system is experiencing operating problems, be a water treatment detective and simply follow the data and the solution will be there.

- Membrane technology has advanced, including reverse osmosis membranes, degas membranes, EDI membranes and now polishing EDI membranes.

- Consider the use of a double pass EDI system, employing EDI as the final polisher. EDI is now time proven and has provided equal to or better results than the traditional mixed bed system.