CLOSED CIRCUIT REVERSE OSMOSIS, THE NEW STANDARD FOR INDUSTRIAL DESALINATION

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I. INTRODUCTION

Reverse osmosis (RO) is the primary technology utilized in the desalination of industrial water and wastewater. Although the technology is very effective at removing salts, it has many limitations and pain points associated with its operation. These include low recovery rates, fouling and scaling of membranes, high CIP frequencies, short membrane life, difficulty in managing variations in feed water quality, compromised permeate quality, high operating costs, and the list goes on. The key to solving all of these issues, ultimately came down to thinking outside of the box and reinventing the basic filtration process starting from scratch.

In traditional multi-stage RO systems, recovery, flux and crossflow are coupled, so managing efficiency and performance is a balancing act. The systems are either reliable, but inefficient or the systems are efficient, but unreliable. There are ways to optimize this balancing act using hybrid-staging, concentrate recycle or inter-stage booster pumps, however this all comes at the sacrifice of operational flexibility. While the industry has made significant advancements to individual aspects of the RO process, none of these advancements have been due to optimization of the fundamental design.

Closed Circuit Reverse Osmosis (CCRO) represents one of the most fundamental breakthroughs in reverse osmosis since its commercialization in the 1960's. The simple solution combines the benefits of dead-end filtration with the strengths of crossflow filtration. Using standard components configured in an elegant single-stage design, recovery, flux and crossflow are uncoupled with standard triggers to purge concentrate based on volumetric recovery, pressure and/or conductivity. This flexibility provides a level of efficiency and reliability that can only be achieved with the CCRO process.

In Section 2, we'll explain how CCRO works from a basic level before we go into six case studies. In Section 3, we'll review how a beverage company reduced their water footprint and costs, while meeting corporate sustainability goals. In Section 4, we'll review how a paper mill in the Sonoran Desert was able to double production, extend CIP frequency and reduce energy and chemical costs with a single decision. In Section 5, we'll review how a Fortune 50 company in the Midwest was able to adapt to a variable feed water to meet stringent ingredient water specifications. In Section 6, we'll visit Southern California to learn how a power company upgraded all their peaking power plants to increase reliability and reduce operational costs by over $1 million at each plant. In Section 7, we'll visit a pharmaceutical facility to see how they were able to overcome the problems associated with a complex wastewater stream. In Section

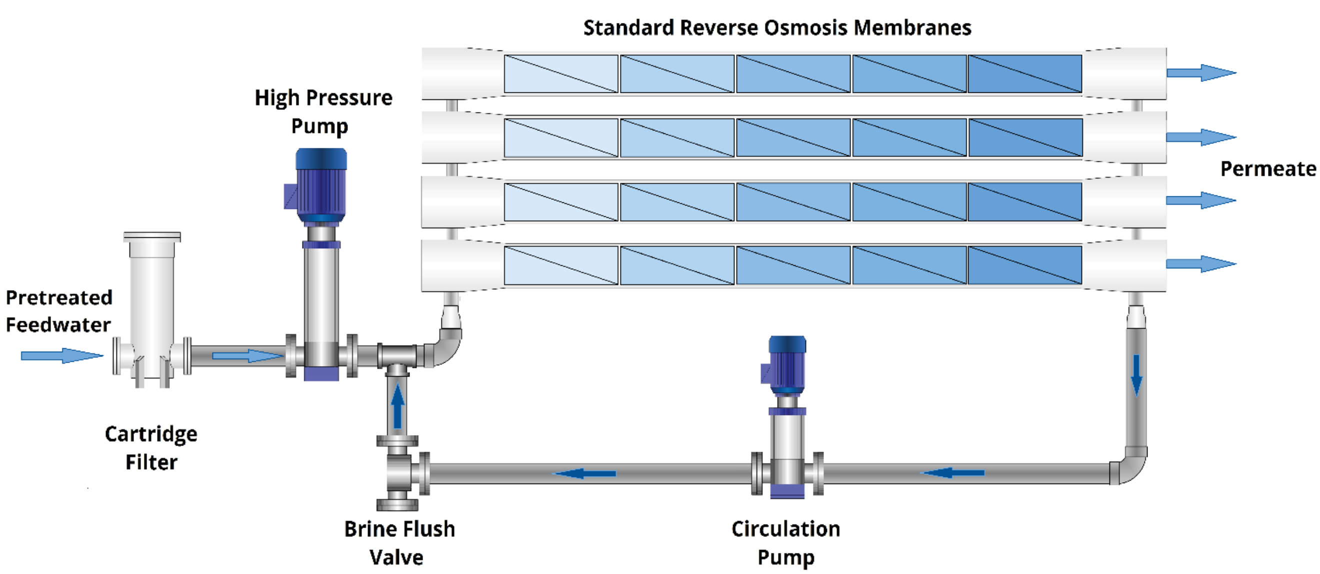
8, we'll see how municipalities in California are working hand in hand with industry to solve their water problems. In Section 9, we'll summarize the results and discuss where we go from here.

II. CLOSED CIRCUIT REVERSE OSMOSIS

Closed Circuit Reverse Osmosis™ (CCRO) is branded by Desalitech as ReFlex™ RO featuring Closed-Circuit Desalination™ (CCD) technology [1,2,3,4]. The process is illustrated in **Figure 1**. The system operates in two modes: closed circuit at 100% recovery and in plug flow or flushing mode at 15-50% recovery. A high-pressure pump (HPP) feeds a closed loop comprised of a single-stage of membrane elements and a circulation pump (CP). Multiple pressure vessels are operated in parallel with short membrane arrays. Permeate is produced at a rate equal to the flow rate of the HPP. Brine is recirculated without depressurization. When a desired recovery percentage is reached, brine is purged from the system, displaced by feed water from the high-pressure pump in a single plug-flow (PF) sweep. Brine displacement is executed without stopping the high-pressure pump or the production of permeate. The process then returns to closed-circuit (CC) operation, during which there is no brine reject stream.

As an example, when operating at 90% overall recovery, the system may be in CC mode for 20 minutes and PF mode for 1.5 minutes. At 95% recovery, the system may be in CC mode for 40 minutes and PF mode for 1.5 minutes. In addition to volumetric recovery, the brine flush valve can also be triggered to purge concentrate from the system based on pressure or permeate/concentrate conductivity. Custom triggers can also be incorporated, including permeate silica concentration, permeate nitrate concentration, permeate sodium concentration, etc. Operating with multiple set-points provides the system the flexibility to automatically adapt to changing feed water conditions, while always maximizing recovery relative to the desired permeate quality targets.

Figure 1. Illustration of Closed Circuit Reverse Osmosis (CCRO) System



The overall recovery rate in the CCRO process is a function of the time between brine flushes. Therefore, it is not necessary to use multiple stages of six to eight element long membrane arrays to achieve high recovery as is required in traditional RO processes. A high-recovery CCRO process can be constructed with just one membrane element, for example. In practice however, CCRO membrane arrays consist of vessels of four or five elements per vessel. These quantities optimally balance performance and costs [5,6].

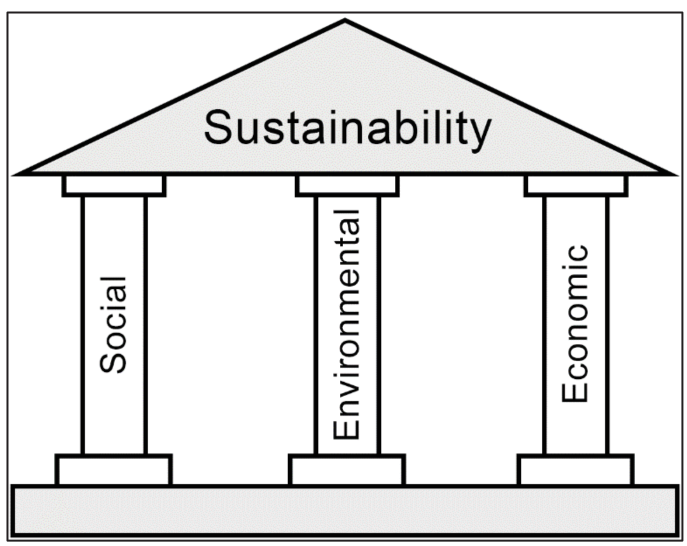
Good resistance to fouling and scaling and high recovery operation are important in most brackish water desalination, industrial water purification and water reuse applications. CCRO systems provide new or enhanced means for addressing these challenges. Independently controlled crossflow supplied by a circulation pump efficiently washes the membranes resulting in lower Beta values (concentration polarization) and reduces the effects of scaling and fouling [7,8,9]. As the salinity throughout the CCRO process cycles from the feed water salinity to that of the most concentrated brine, biofilm formation and scale precipitation can be disrupted and even reversed. Notably, the cycle time of the CCRO process is much shorter than the induction time for precipitation of most sparingly soluble salts. This contrasts sharply from the steady-state conditions in traditional RO systems, which maintain nearly constant concentrations throughout their membrane arrays for months or even years. Also, because recovery can be easily manipulated, CCRO processes can be tuned to maximize recovery if the concentration of scaling salts or other feed water properties change.

Studies have shown that recovery rates that produce high degrees of super-saturation of sparingly-soluble salts can be achieved in batch RO processes without the use of scale inhibitors [10]. Specifically, recovery rates of over 90% have been achieved and maintained from water sources with high concentrations of silica and calcium sulfate. Furthermore, scale depositions can be dissolved by batch cycling, making sustained run times at high recovery rates possible even with source waters with high levels of sparingly soluble salts. These results are directly applicable to CCRO processes in which intrinsic system volumes are typically much smaller.

III. CASE STUDY 1: SECURING A GLOBAL BUSINESS FOR THE LONG TERM

As the primary ingredient in beverages is water, beverage industry leaders are making a major push to reduce their water footprint through aggressive sustainability goals. One of the easiest ways to meet these goals is by increasing water-use efficiency within the production facilities. As an example, Coca-Cola, the world's largest beverage company has managed to reduce their water-use efficiency by 27% from 2004 to 2016, reducing their water-use ratio from 2.70 to 1.96 [11]. This means that it requires 1.96 liters of water to make 1.00 liter of sellable product. As impressive as these results are, the industry leader is not stopping there with even more aggressive goals for the future.

Figure 2. The Pillars of Corporate Sustainability



It should come as no surprise that Coca-Cola has already installed over a half-dozen CCRO systems with more systems currently under construction. These systems around the globe operate at recovery rates ranging from 91-97% depending on the quality of their feed water source and the specific bottling line. This is a massive improvement as compared to the 75-

80% recovery rates that they were accustomed to with traditional multi-stage RO systems, saving them millions of gallons of water every year.

The driving operational metric for Coca-Cola is ensuring that all QA/QC specifications are met in terms of the product water, while maximizing water recovery rates and system utilization rate. While this seems like a simple request, the majority of the plants see slight or drastic variations in feed water conductivity and/or temperature. These values will both change the achievable recovery, particularly when bottling a sodium free product with strict permeate quality requirements. In the past, the traditional multi-stage RO systems would be designed and operated based on a single point in time, which was the worst-case condition over the course of the year. However, there were many months that the feed water conductivity or temperature would drop, allowing for higher achievable recovery rates. The opportunity to increase efficiency during these times was dismissed though, as adjustment to the steady-state systems was a manual process, requiring mechanical modifications and coming at the sacrifice of membrane performance. In the CCRO units, the trigger to purge concentrate is based on a recovery set-point (limited by scaling potential at a defined temperature) and/or a permeate conductivity set-point (TDS). This allows for automatic adjustment so regardless of feed water conductivity or temperature, the unit will maximize the recovery relative to the conditions of the feed in real-time while simultaneously ensuring permeate quality. This data-driven process has been a simple solution for Coca-Cola in reducing water-use ratios without any operator engagement.

When it comes to corporate sustainability, the foundation is based on three pillars as seen in **Figure 2**; social, environmental and economic or more commonly referred to as people, planet and profits. In addition to conserving our planet's most precious resource so future generations will continue to have access to fresh water, the financial savings and increased bottom line has made the switch to CCRO a no brainer. Muhtar Kent, Chairman of the Board and Former CEO of Coca-Cola said it best, "If you aren't responsibly managing water in your business, you won't be in business 20 years from now. [12]"

IV. CASE STUDY 2: PRODUCING PAPER PRODUCTS IN THE SONORAN DESERT

The groundwater in the Sonoran Desert is not known for it's quality. If anything, it's known for its high salinity and high concentrations of silica. Not only are the salts a problem, but many of the wells draw water with high concentrations of iron and manganese. In the instance of this particular paper mill, the well water not only had metals, but also high levels of biological activity due to the geothermal conditions (105^{o}F).

Over the years, the paper mill had accepted that purification of the groundwater source was never going to be an easy task. A significant budget was allocated every year for membrane cleanings (a supervised event) and system maintenance. Ultimately, the performance of the water treatment equipment became the limiting factor in the overall plant production.

To secure access to freshwater for the paper making process, the mill drilled, cased and developed two (2) groundwater wells and utilized a treatment train consisting of pressure filtration with greensand media for pretreatment of iron and manganese prior to entering a multi-stage traditional RO system. The traditional RO system struggled to perform with the challenging feed water, requiring three (3) biocides a week and bi-weekly high and low pH cleanings (CIPs). The CIPs were triggered based on a reduction in normalized permeate flow and/or a reduction in differential pressure across the membrane array. Membrane autopsies confirmed the culprit was organic fouling and silica scaling due to the difficult groundwater.

In 2014, the paper mill decided it was going to double its capacity by installing a second paper making machine. The expansion not only required more paper making equipment, but also required a 100% increase in the capacity of purified water. To minimize water footprint, the paper mill upgraded its traditional multi-stage RO system to two (2) CCRO systems. Not only did the CCRO systems double the required permeate capacity, but the units did so while reducing the volume of concentrate wastewater produced, extending the CIP frequency and significantly reducing the energy and chemical consumption. The results are presented in **Table 1.**

Table 1. Multi-Stage RO vs CCRO, Long Term Performance

		Multi-Stage	Closed Circuit	CCRO Value	
Reverse Osmosis Design	# of Trains	1 x 100%	2 x 100%		
	# of Stages	2	1		
	Array (per train)	3:1 (28 Membranes)	10 (40 Membranes)		
	Process	Steady-State	Dynamic		
	Recovery	73%	88%		
	Utilization Rate	90%	63%		
	Permeate Flux (gfd)	15.4	15.5		
System Performance	Daily Process Water (gallons)	155,520	311,040	200%	Increase in Permeate Production
	Daily Wastewater (gallons)	57,521	42,414	26%	Reduction in Wastewater Generated
	Specific Power Consumption (kWh/kgal)	1.75	1.67	5%	Reduction in Energy Required
	Antiscalant Consumption (ppm)	8	3	63%	Reduction in Antiscalant Consumption
	Biocide Frequency	3X / Week	1X / Week	300%	Extension in Biocide Frequency
	CIP Frequency	24X / Year	4X / Year	600%	Extention in CIP Frequency
Membrane Performance	Lead Element Flux (gfd, avg)	20.5	18.0	12%	Reduction in Lead Element Flux
	Flux Distribution (gfd, avg)	(6.5 - 20.5)	(13.9 - 18.0)		
	Max Beta Value	1.14	1.09	4%	Reduction in Max Beta Value
	Beta Range	1.03 - 1.14	1.04 - 1.09		

Organic and inorganic fouling in a traditional, steady-state RO process typically occurs on the lead elements where individual membrane element fluxes are the highest and microorganisms have a stable environment, giving them the ability to flourish. Scaling occurs on the tail elements where membrane elements are continuously exposed to the highest salinity and individual membrane element fluxes are at their lowest. When it comes to fouling and scaling, higher crossflow velocities always help to reduce concentration polarization (Beta values), however in a steady-state process where recovery, flux and crossflow are coupled, this is difficult to achieve unless operators are willing to sacrifice performance elsewhere in the system.

In the semi-batch CCRO process recovery is achieved in time, versus in space as with traditional RO, so shorter membrane arrays can be utilized to reduce lead element flux. Salinity cycling and continuous purging disrupts organic fouling, and crossflow is independently controlled with a circulation pump providing ultimate membrane performance. Antiscalant consumption is also reduced due to reduced concentration polarization and slower induction times associated with silica scale formation.

Although energy is not typically a driving operational metric for brackish water or wastewater RO systems, it's still a cost that needs to be included in the total cost of ownership of an RO asset. In CCRO systems, the initial pressure required to desalinate the source water is a function of the composition, temperature, flux and number of membranes in series. In the case of the paper mill, the traditional 2-stage RO had fourteen (14) membranes in series where the CCRO system has four (4) in its single-stage design. This means the initial pressure of the CCRO is much lower than that of the traditional RO, however as the system concentrates up salts, the required osmotic pressure rises. Ultimately, the system reaches the same pressure as the traditional RO, but all the time spent below the continuous pressure of the traditional RO reduced energy consumption by 5%, even when operating at a higher recovery.

V. CASE STUDY 3: ENSURING THE SAFETY OF CONSUMERS' CHILDREN

On November 29th, 1944, a team of doctors at John Hopkins Hospital performed the first successful surgery to cure Tetralogy of Fallot, more commonly known as "blue baby syndrome" [13]. The congenital heart disease in infants can be caused by methemoglobinemia or a reduced oxygen carrying capacity of hemoglobin, the iron-containing protein that transports oxygen throughout the body. It's generally accepted within the medical community that high concentrations of nitrates in drinking water can be a co-factor for this disease [14]. In an effort to reduce the quantity of infant-related surgeries, the World Health Organization (WHO) and Environmental Protection Agency (EPA) have set regulatory limits to the concentrations of nitrates in potable (drinking) water. While the majority of potable water sources fall below these nitrate limits, regions with shallow wells or surface water can be significantly effected when located in agricultural regions where fertilizers are used to increase the yields and quality of harvests.

Figure 3. Two (2) R30 CCRO Systems

A Fortune 50 midwest based food and beverage company was in the process of expanding one of their production plants when they encountered this exact problem. The corn processing facility was located in a region with significant agricultural activity and used surface water as makeup water to the plant. Over the course of the year, they would encounter high (20 mg/L) and low (5 mg/L) levels of nitrate (as NO_3) with a feed water temperature ranging from 15-25˚C. Normally this wouldn't be an issue, however, one week out of each month, the plant produces ingredient water used in baby food products, requiring a nitrate limit not to exceed 2 mg/L for the downstream processes.

In order to manage the variable nitrate concentrations, the company installed two (2) CCRO systems to purify this variable feed source, see **Figure 3**. The systems utilized a custom trigger connected to an online nitrate analyzer to automatically adapt to the seasonal changes in feed water nitrate concentrations and temperature (temperature effects salt passage in RO systems). The CCRO systems typically operate at 90% recovery, however when the custom nitrate algorithm is activated, the unit will automatically adapt to the changing feed water conditions to ensure the nitrate levels in the permeate never exceed the QA/QC specifications for the ingredient water. The systems achieve this by automatically adjusting recovery, dropping down to 82% when the water is the warmest and at the highest concentration of nitrate and maintaining 90% recovery when the water is the coolest and the concentration of nitrate is at its lowest.

This is all done with no operator engagement, aside from pushing a button on the Human Machine Interface (HMI).

This flexibility has provided the plant with a simple and reliable solution to what was initially a very difficult challenge that could not be achieved with a traditional, multi-stage RO system.

VI. CASE STUDY 4: POWERING LOS ANGELES AT A FRACTION OF THE COST

Figure 4. Containerized R3 CCRO System

Southern California Edison (SCE) depends on ultrapure water for emission control and cooling in five (5) of its peaking power plants. In most of these applications, this water comes from municipal sources, and must be made ultrapure before use to prevent damage to the turbines in use to generate power. Until recently, SCE had been relying solely on rented, mobile demineralization trailers to purify water for use in these peaking power plants. However, these systems were costly, consumed a lot of water in SCE's supply chain and presented a singular point of failure in the plant.

Any potential replacement needed to be extremely reliable, with exemplary water recovery rates. "If the demineralized water is not available, we cannot run the turbines which can impact grid reliability," explains Kishore Billapati, with SCE Generation Plant Engineering. Given that many of these peaking power plants are not manned on a daily basis, it was vital that any alternative to the mobile demineralizers be largely autonomous and reliable.

SCE identified five gas-fired peaking plants that were looking for reliable and cheaper ways to manage their water needs. Stanton, Norwalk, Ontario, and Rancho Cucamonga in the Los Angeles Basin, with the fifth in Ventura County, at Oxnard, on the Pacific coast. The company needed an alternative to mobile demineralizers that would allow them to simultaneously reduce their operational expenses and improve operational reliability without sacrificing water quality.

A reverse osmosis (RO) system made the most sense to replace the temporary, expensive demineralization trailers; but traditional RO systems have limited water recovery rates. This can be overcome, in part, by setting up multi-stage RO systems, but the tradeoff is an increase in operational complexity. Multi-stage RO systems are also more difficult to maintain with each subsequent stage and require significant downtime for cleaning and maintenance. The end result is that a traditional RO system with more than two or three stages will suffer from reduced reliability.

SCE adopted CCRO along with mixed-bed polishers to address all of their concerns at the five peaking power plants. SCE estimates a savings of 44 million gallons of water per year through the CCRO systems. The systems operate at 91% recovery in a simple and flexible single-stage design, producing a guaranteed water purity of <10 μS/cm. When compared to a traditional multi-stage reverse osmosis system, the CCRO systems provide an additional 18% savings in feed water consumption and a 64% savings in brine disposal costs.

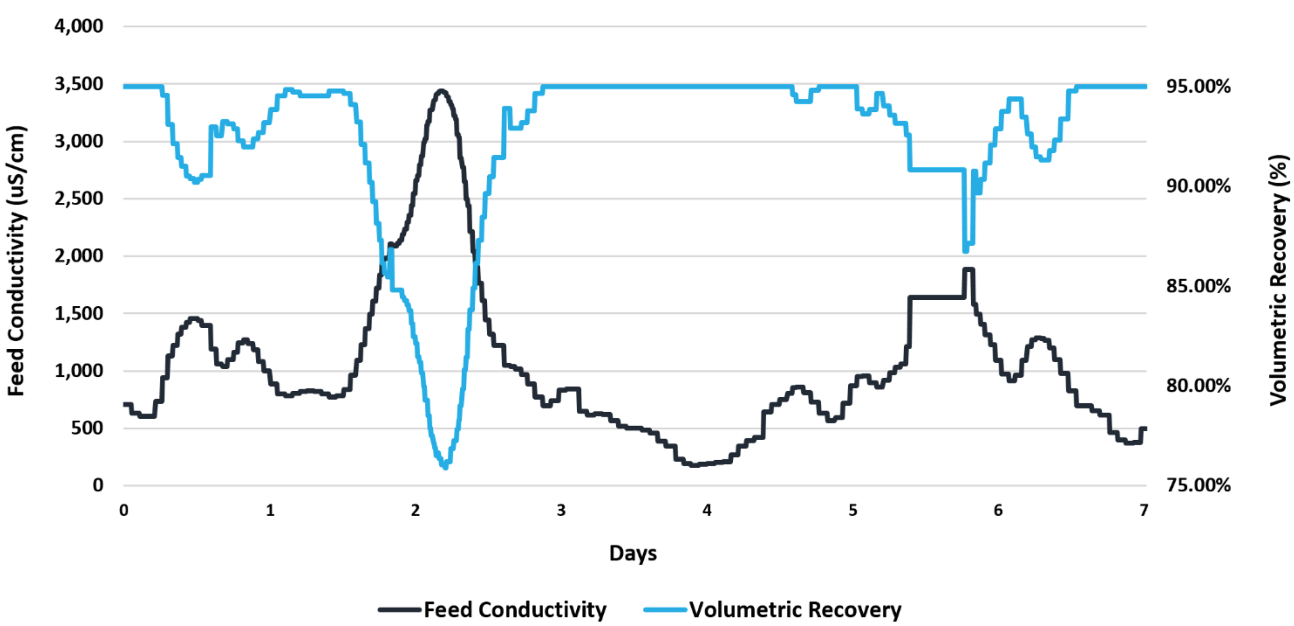
In addition, SCE will greatly improve reliability due to the high quality CCRO permeate and by operating the mixed-bed polishers in series. This novel approach has enabled SCE to reduce its annual water operating costs by 85%, from about $1.5 million to $0.225 million per plant. The CCRO systems have been successfully commissioned at all five plants, see **Figure 4**. For adopting new technology in the pursuit of sustainability, this project earned SCE the prestigious 2017 Power Magazine Water Award, which is given to innovative leaders in the power industry [15].

VII. CASE STUDY 5: REUSING PHARMACEUTICAL WASTEWATER IN CALIFORNIA

In pharmaceutical manufacturing, water is critical not only for the highly regulated ultrapure process water, but for boilers and cooling towers. To mitigate risk associated with water-scarcity, the industry has taken a proactive approach to minimizing water footprint with a significant focus on the reuse of high strength organic effluent. However, the reuse of these complex wastewater streams present significant challenges, from the high TSS, BOD and COD levels to the daily variations in salinity and its associated water composition.

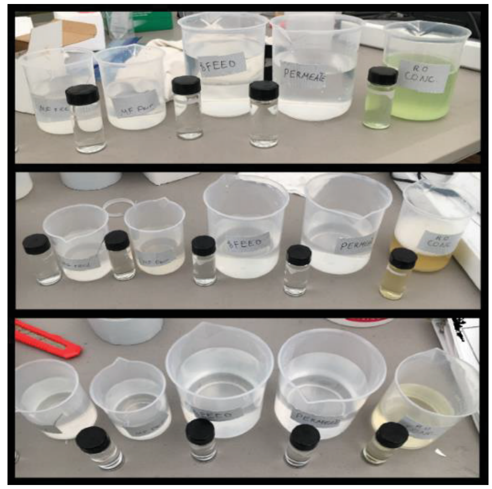
A pharmaceutical facility in drought-stricken California was urgently trying to find a way to reuse their wastewater, however encountered a significant challenge due to the variability in the wastewater characteristics. The salinity of the wastewater fluctuated daily, with conductivity values ranging from below 100 µS/cm to over 2,000 µS/cm and COD levels as high as 2,000 mg/L. Under the guidance of their trusted environmental engineering firm, Carollo Engineers, the company contacted Desalitech to pilot a treatment train consisting of microfiltration (MF) followed by CCRO. The MF would remove any suspended solids and the CCRO would remove the salts, so the water could be reused for boiler and cooling tower makeup in addition to irrigation water.

Figure 5. CCRO Performance



The CCRO pilot was setup to operate using all three (3) standard set-points; volumetric recovery, internal conductivity and pressure. The volumetric recovery set-point was set at 95%, the internal conductivity set-point was set to 14,800 µS/cm and the pressure set-point was set to 300 psi. Regardless of the continuously changing composition of the wastewater, the unit would adapt in real-time to maximize recovery relative to the continually changing wastewater composition. As you can see from **Figure 5**, the CCRO automatically adapts over the course of a week to drastically changing feed water conditions. To show just how much this wastewater varied, you can see the color of the CCRO concentrate change over the course of the week in the far right beaker in **Figure 6**. The pilot ran for over six (6) months with no antiscalant and a single clean in place (CIP), which was completed only to set a baseline.

Figure 6. CCRO Performance



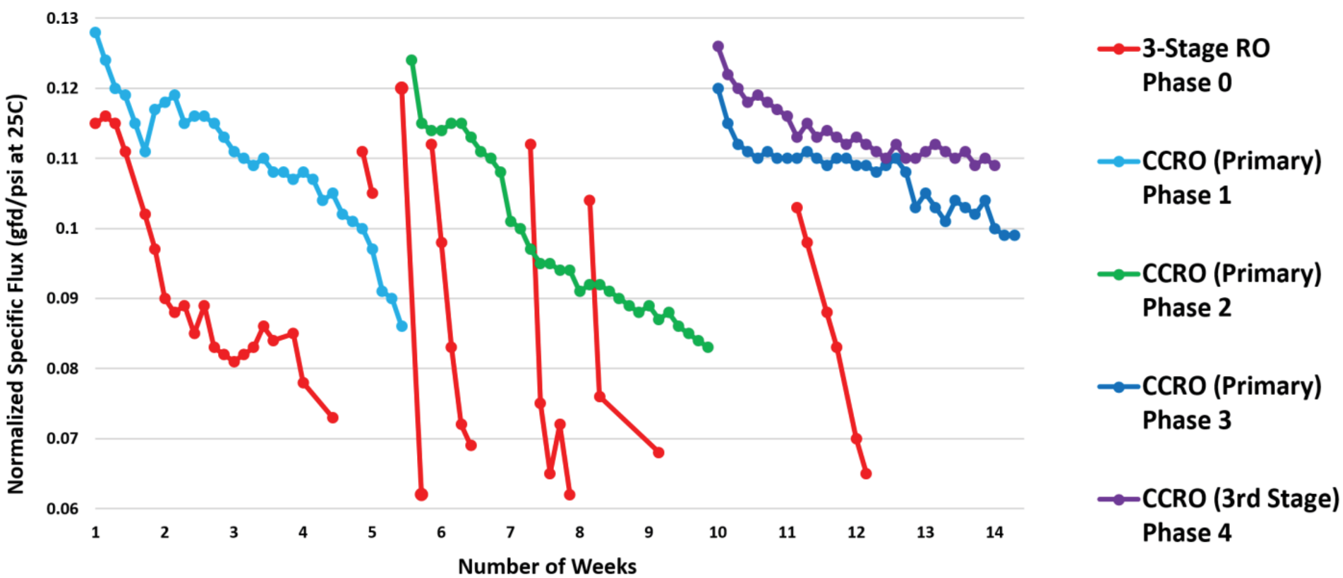
The pilot was a success and the full-scale system is currently under final design. The full-scale system will be implemented in two phases using a 3x50% configuration to provide complete redundancy in the event one of the units is cleaning or requires maintenance. This represents the first application of CCRO to a wastewater stream in the pharmaceutical industry.

VIII. CASE STUDY 6: MUNICIPAL WASTEWATER FOR INDUSTRIAL REUSE

A common theme in the water industry is reusing municipal effluent for industrial applications, including boilers, cooling towers and process streams. The primary treatment equipment required is microfiltration (MF) or ultrafiltration (UF) to remove suspended solids and reverse osmosis (RO) to remove dissolved solids. Ultimately the limiting factor on the overall plant efficiency becomes the performance of the RO, as the MF or UF must all be designed around the full-flow. Increasing recovery rates beyond 85% on municipal effluent in Southern California has proved challenging due to the high concentrations of organic matter and silica scaling characteristics of the feed.

In 2014, the Sanitation Districts of Los Angeles County completed a seven-month pilot study to evaluate the performance of a traditional 3-stage RO versus a CCRO using the same feed water, pretreatment, membranes, antiscalant chemistry, etc. The goal of the project was to maximize the recovery rate while maintaining a minimum CIP frequency of one (1) month. A CIP greater than one (1) month was considered a success, a CIP frequency less than one (1) month was considered a failure. The pilot was broken down into multiple phases, with the Phase 0 (3-stage RO) to be operated in parallel with Phases 1, 2, 3, 4 (CCRO). The performance for these phases is shown in **Figure 7** [16].

Figure 7. 3-Stage RO versus CCRO at 93% Recovery



The traditional 3-stage RO immediately lost flux over the first two (2) weeks before slowly trending downwards. The first CIP was somewhat effective in recovering the membranes, however after the first CIP, the system was only able to run for 4-6 days before another CIP would be required. After six (6) CIP's, the final three using specialty chemicals, the traditional 3-stage RO was considered a failure and the membranes to be non-recoverable. The CCRO on the other hand, was able to exceed the targeted CIP frequency at all tested flux rates with the lowest flux trending towards a 2-3 month CIP interval, as seen in **Table 2** [16]. The membranes were fully recoverable with standard cleaning chemicals. In addition, the flexibility of the process was demonstrated by operating as a concentrate recovery CCRO on a traditional 2-stage RO, where the same successful results were repeated.

Table 2. Testing Conditions & Results

Phase	Configuration	Process Conditions	Feed Source	Overall Recovery (%)	Flux (gfd)	Crossflow Velocity (ft/sec)	Flux Decline (%)	Projected CIP Interval	Result
0	Multi-Stage	Steady-State	MF Effluent	93	8.6	No Control	**Immediate**	N/A	**Failure**
1	CCRO	Dynamic	MF Effluent	93	13.1	0.32	**32.8**	> 1 Month	**Success**
2	CCRO	Dynamic	MF Effluent	93	10.9	0.32	**33.7**	> 1 Month	**Success**
3	CCRO	Dynamic	MF Effluent	93	9.2	0.33	**18**	2-3 Months	**Success**
4	CCRO	Dynamic	2-Stage RO Concentrate	93	8.9	0.33	**14.3**	2-3 Months	**Success**

Since the successful pilot study at the Sanitation Districts, other municipalities in the region have followed suit. The City of Los Angeles used CCRO to achieve a sustained recovery of 93% [17], Padre Dam Municipal Water District sustained 96% recovery [18], Orange County Water District sustained 92% recovery [19] and is optimizing to go higher and Eastern Municipal Water District has purchased a demonstration unit in favor of GE's expensive AquaSel technology for concentrate recovery [20]. It's not only the municipalities that are adopting this approach, San Jose State University just installed a CCRO system to treat tertiary treated wastewater from the San Jose/Santa Clara Water Pollution Control Plant for makeup to their boiler system. The solution will guarantee the university a minimum recovery rate of

93%, with a permeate conductivity less than 30 µS/cm. Whether it's a municipality treating their wastewater for indirect potable reuse or an industrial customer treating the wastewater, CCRO has proven to be the most efficient and reliable solution.

IX. CONCLUSIONS

If we go back to the original pain points of reverse osmosis; with CCRO, achieving high recovery is no longer a hydraulic limitation, fouling and scaling is mitigated, CIP frequency is extended, membrane life is extended, managing variations in water quality is automatic using adaptive controls, permeate quality is a set-point, chemical and energy costs are reduced and the systems operate using data-driven, autonomous software. The microelectronics industry struggles from many of the same pain points summarized in the case studies in this paper, both on the upstream and downstream sides of the plant. In addition, many large manufacturing facilities are located in drought-stressed regions where water security is a real threat to the business. As the market for semiconductor-based devices and flat panel displays grows globally, the required efficiency, flexibility and overall reliability of treatment systems is increasing.

Reverse osmosis will continue to be the primary technology used for the desalination of industrial water and wastewater, however the operational platform will be based on CCRO. The inefficiencies and limitations of traditional multi-stage designs will become a thing of the past as from every perspective, CCRO is a superior process. With over 100 new installations in the past five years on six continents and in over a dozen different industries, it's clear the industrial sector has spoken.

However, this is not the end of the road for the advancement of reverse osmosis. If anything, this is just the beginning as CCRO has opened the door to the potential for all sorts of future innovations. These include the potential for more sophisticated active/adaptive control strategies, enhanced fluid mixing using complex spacer geometries [21], modeling techniques for quantifying induction times for sparingly soluble salts [21], new antiscalant chemistries and the list goes on. The beauty in all of this is that the flexibility of the CCRO process will allow for the integration of any of these advancements that occur in the future using today's standard products. Welcome to 21st century reverse osmosis, where a fundamental change has disrupted a 50-year-old technology.

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