MODULAR PUMPS BRING EFFICIENCIES CASE STUDY

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Abstract

Water lubricated axial piston pump technology has been growing in popularity and by unit size in the seawater reverse osmosis (SWRO) industry since 2000. A “tipping point” exists for this technology to replace the less efficient centrifugal high pressure pumps that have dominated in large scale SWRO systems for more than 30 years. The axial piston pump can be efficiently and economically linked together in parallel to provide high pressure feed to any size system, including large municipal-scale plants. The axial piston pump array requires up to 25% less power than an otherwise equivalent centrifugal (turbine) pump. In October-2014, an exemplary 1,450 m^3/day SWRO system using an array of axial piston pumps was commissioned in the Caribbean Islands. Since commissioning, specific energy consumption for the SWRO process has averaged a remarkably low 2.1 kWh/m^3 (7.8 kWh/kgal) at 58 bar (845 psi) feed pressure. This paper will provide a practical case study for this installation during its first year of operation. An analysis of the pump array and system performance over time will include flow rate, pressures, power consumption, pump efficiency, feed water quality and specific energy consumption, for example. In addition, general design guidelines, best practices and lessons learned will be presented.

I. BACKGROUND

The water lubricated axial piston pump has been growing in popularity and by unit size in the SWRO industry for more than fourteen years. The axial piston pump can be efficiently and economically linked together in parallel to provide high pressure feed to any size system, including large municipal-scale plants.

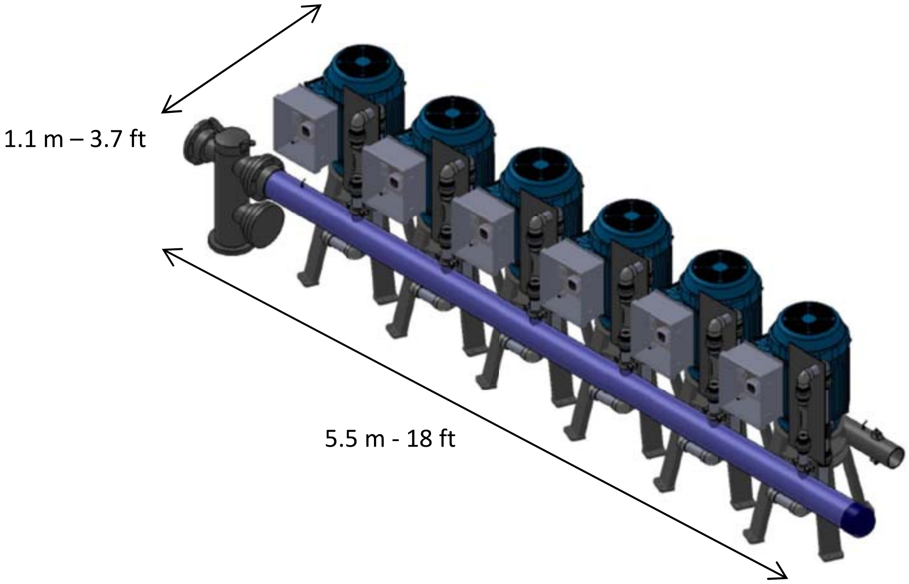

Figure 1. Six Pump Array Provides up to 257 m3/hr (1,134 gpm) at 90% Efficiency

This kind of modular application in pumping systems was pioneered by Energy Recovery, Inc. and modular Pressure Exchanger (PX) arrays are now the standard for energy recovery in SWRO. Many parallels can be drawn between the modern axial piston pump and isobaric pressure exchangers because both operate on the same revolutionary technology platform of water lubricated bearings. When ceramic is used, these bearings can provide maintenance free operation for tens of thousands of hours. Furthermore, both devices employ a positive displacement axial piston design that results in very high efficiencies and virtually pulsation free flow. The progression in size of the axial piston pump has also been similar to the PX. The initial commercial PX units in 1995 produced only 9 m3/hr (40 gpm) and were therefore only considered suitable for smaller scale systems. But as the size of the individual PX units grew and their reliability in modular arrays was proven the technology became an industry standard applicable to the largest systems in the world. Similarly the modern water lubricated axial piston pump has grown in size from its original introduction into the SWRO market in 2000 with maximum capacities of approximately 10.2 m3/hr (45 gpm) to capacities up to 78 m3/hr (343 gpm) available today. Through its progression the water lubricated axial piston pump has also proven its compatibility in modular array applications.

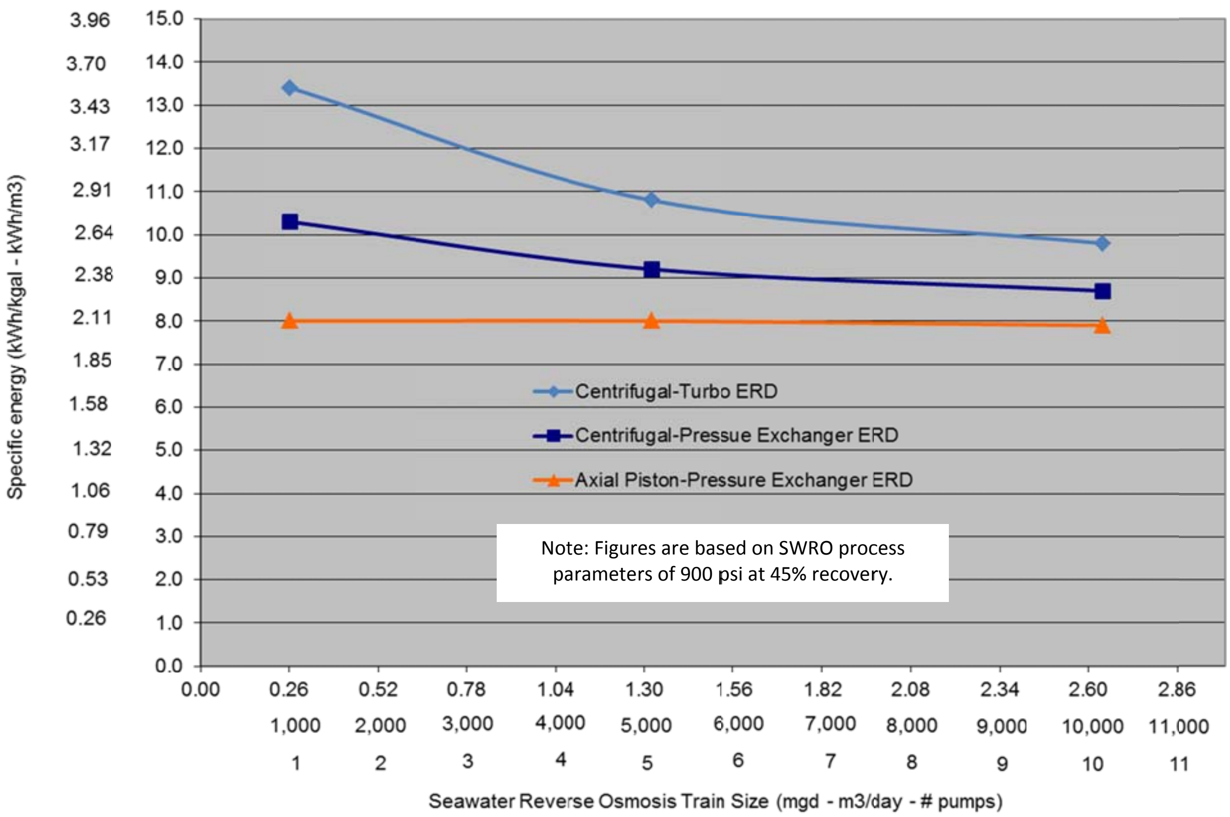

Figure 2. Specific Energy Consumption for AP and CF Pumps vs system Size

The efficiency advantage of the AP pumping system shown in Figure 3 represents the largest single gain in desalination efficiency in 30 years. It should be noted that Turbo and Pelton technologies require a 100% feed flow main high pressure pump, which when combined with the AP pump requires higher capital costs and energy consumption compared to an equivalent Axial Piston-Pressure Exchanger system ie. It is not currently practical to combine Turbos and Pelton wheels with axial piston pumps. Looking at the X-axis one can see that as the train size increases axial piston pumps are added onto a pumping array. For example, a 4,000 m3/day (1.1 MGD) train would require four AP pumps running in parallel to produce 174 m3/hr (767 gpm) at a specific energy of 2.1 kWh/m3 (8.0 kWh/kgal). In Figure three, one can see how the CF pump systems energy consumption improves as the plant size increase. This is because CF pump efficiency improves as flow rate increases. This fact diminishes the AP efficiency advantage as the CF pump size increases.

A “tipping point” exists for this technology to replace the less efficient centrifugal high pressure pumps that have dominated in large scale SWRO systems for more than 30 years. The axial piston pump array requires up to 25% less power than an otherwise equivalent centrifugal (turbine) pump. Power is the single greatest operating cost in the seawater reverse osmosis process. Pressure to convert to axial piston pumps is most intense in island regions where power costs can be as high as $0.50/kWh. In fact, in October-2014 an end-user in the Caribbean region replaced an existing centrifugal high pressure pump and turbo charger energy recovery device (ERD) line with the array of axial piston pumps and pressure exchangers shown in figure 2.

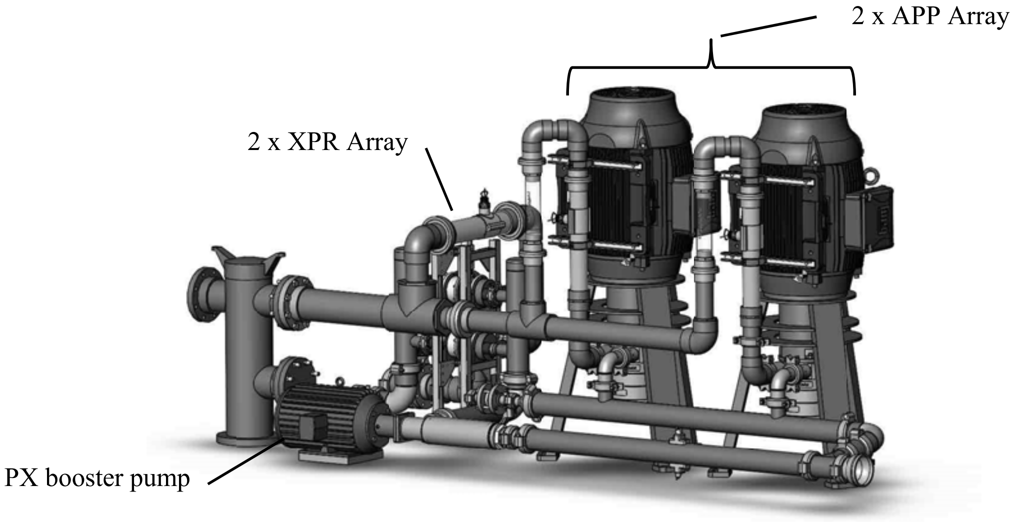

Figure 3. OPC-2000 Axial Piston Pump and ERD Pressure Center

Since commissioning, specific energy consumption for the SWRO process has averaged a remarkably low 2.1 kWh/m^3 (7.8 kWh/kgal) at 58 bar (845 psi) feed pressure. An analysis of the pump array and system performance over time includes flow rates, pressures, power consumption, pump efficiency, feed water quality and specific energy consumption. In addition, general design guidelines, best practices and lessons learned are presented.

I. ISOBARIC SYSTEM DESIGN

The axial piston pump array can be practically applied within an isobaric energy recovery design. Figure four provides a simple flow diagram for an isobaric system design, which includes the main high pressure pump (APP array), PX booster pump and pressure exchanger array. Similar to the RO membrane and pressure exchanger arrays, axial piston pumps are applied in parallel to achieve the total main high pressure pump flow.

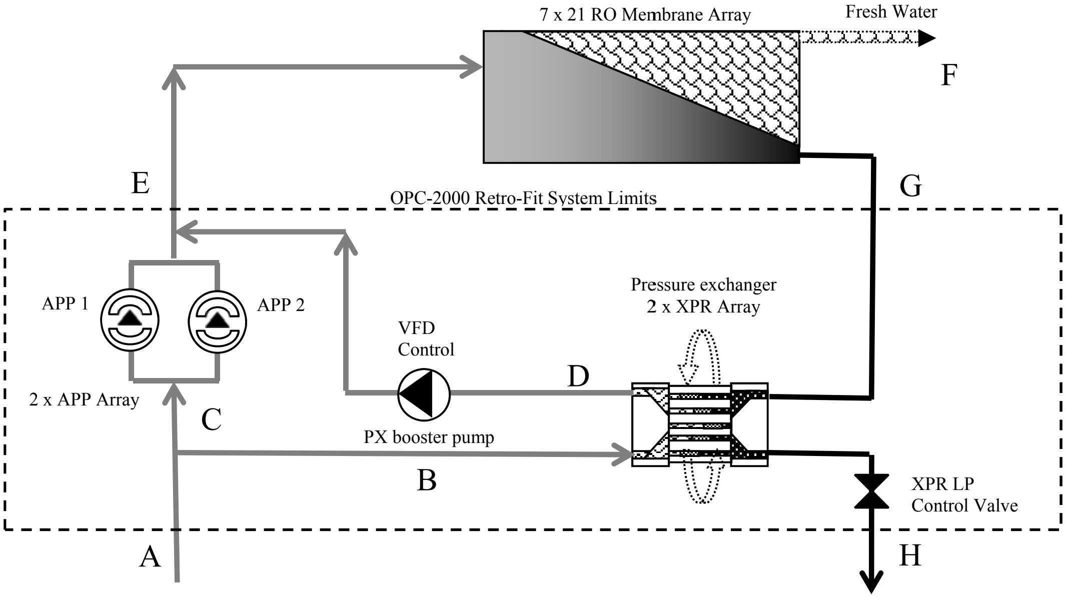

Figure 4. Simple Isobaric System Design

Table 1. Average System Performance

Stream	Description	Flow Rate m^3/hr - gpm	Pressure bar – psi	Conductivity uS
A	Seawater supply	134 - 589*	2.6 - 38	53.2
B	XPR LP Inlet/ Seawater	73 - 321	2.6 - 38	53.2
C	Main HP Pump outlet (APP array)	60 - 264*	59 - 849	53.2
D	XPR HP Outlet/ Seawater	72 - 323	56 - 816	nd
E	RO Feed Stream	133 - 585*	59 -849	53.8
F	RO Product Water	61 - 267	0	346
G	XPR HP Inlet/ Reject	72 - 319*	57 -829	nd
H	XPR LP Outlet/ Reject	73 – 323*	1.4 – 20	87.4
APP1	Axial piston pump 1	30 – 134	n/a	53.2
APP 2	Axial piston pump 2	30 – 133	n/a	53.2

*Sum of metered flows.

Table one provides the actual average system performance overtime, while table 2 provides overall equipment specifications and range of operating conditions for the OPC system.

Table 2. OPC-2000 Equipment Specifications

Parameter	Unit	Min	Max	Design
Seawater temperature range (A)	Fº-Cº	33-0.5	110-43	80-27
LP/HP filtered seawater inlet/outlet flow rate (B,D)	gpm-m3/hr	424-99	600-136	585-133
HP/LP reject water inlet/outlet flow rate (G,H)	gpm-m3/hr	200-45	360-82	318-72
RO permeate flow (F)	gpm-m3/hr	253-58	270-61	267-61 (fixed)
RO recovery rate	%	42	63	46
Water quality requirements	SDI	n/a	< 5	3
Filtration requirements (nominal)	Micron	n/a	5	5
LP filtered supply pressure (A)	psi-bar	25-1.7	60-13.6	40-2.7
HP RO feed pressure (E)	psi-bar	700-48.3	1000-69.0	795-54.8
LP reject outlet pressure (H)	psi-bar	20-1.4	40-2.7	20-1.4
pH range (short term at upper and lower limits)	pH	1	12	8
Voltage	VAC/Phase	n/a	n/a	480/3
Electric service	kW	165	165	165

HP = High Pressure, LP = Low Pressure

II. WATER QUALITY AND PREFILTRATION REQUIREMENTS

It is important to note that on average 1/3 of the lifecycle energy savings can be offset by axial piston pump spare parts replacement expenses[1]. The primary reasons for replacement include wearing of the sliding/bearing surfaces which decreases the overall efficiency and reliability of axial piston pumps. Replacing worn parts recovers the efficiency to "like-new" condition, but the added expense acts like drag on the efficiency advantage. Water quality can play a major role in the maintenance intervals between parts replacement, because small particulates in the RO feed water (lubricating fluid) can accelerate the wear on sliding surfaces. This is particularly true in the case of the plastic-stainless bearings that come standard in the Danfoss axial piston pumps.

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[1] Axial Piston Pumps Bring Efficiencies; MacHarg, Sessions; AMTA-2015 Annual Conference

Danfoss recommends using 10 µ absolute filters with a Beta value > 5000, which roughly translate to a high quality 1-2 micron nominal filter. By contrast the industry standard for SWRO membranes is 5 micron nominal filtration with a water quality of less than 5 silt density index (SDI). There is a conflict where the typical filtration required for full-scale SWRO membranes is insufficient for the APP manufacturer's water lubricated bearing systems. On the other hand, one manufacture offers ceramic replacement parts and claims extended service intervals and resistance to particulates over the plastic-stainless steel parts.

In any event, water quality with respect to pre-filtration and particulates must be carefully considered when using axial piston pumps. Counter measures to insure sufficient water quality may include more robust pre-filtration designs ie. lower micron filter flux rates, additional stages of filtration or advanced filtration, and water quality monitoring equipment to warn of lapses or upsets in the SWRO feed water quality.

In this case, the feed water supply comes from wells that have produced excellent quality water for many years. Water quality directly from the well has an average SDI of less than 3. The pre-filtration system consists of single stage, 5 micron, 40 inch long cartridge filtration sized at 1 gpm per 10 inch equivalent. Although the water quality is excellent, this case has shown us how pre-filtration and monitoring are critical items when operating APPs.

III. SYSTEM PERFORMANCE OVER TIME

The following analysis of the pump array and system performance over time includes flow rates, pressures, power consumption, feed water quality and specific energy consumption.

3.2 Major System Flows

Major system flows include the low pressure (B-H) and high pressure (G-D) flows through the XPR units, the axial piston pump array flow (C) and permeate flow (F). There was a loss in the data connection between 560 hours and 1,600 hours noted by the blue vertical line in Figure 5. Furthermore, a permeate flow meter was added to the system after the 560 hour mark.

The low pressure XPR flow (B-H) is controlled using a diaphragm valve at the low pressure outlet of the XPR unit. The pressure at the low pressure inlet is held constant via a pressure feedback loop controlling the speed of the well pumps. Variations in cartridge filter differential pressure are compensated for via the feedback control i.e. pressure is held constant down stream of micron filters. Once the control valve is set, a constant flow rate will be maintained by maintaining constant feed pressure to the inlet of the system/XPR array.

The high pressure XPR flow rate (G-D) is controlled via a variable frequency drive (VFD) on the PX booster pump. There is no feedback control for the PX booster pump. Changes in membrane differential pressure are compensated for by manual adjustments to the PX booster VFD speed. Inexplicable variations in the PX booster pump flow were observed at 212, 259, 306 hours. These were related to internal parts failing, and the pump eventually failed completely at around 550 hours. The PX booster flows remained stable after repairs were made to the pump.

APP array flow is the sum of APP1 and APP2 flows. The APPs run at a fixed 1250 RPM avoiding the 3% efficiency loss associated with VFD control. The smooth transition between 560 and 1600 hours indicates very little change occurred on the APP array flow rate during the blackout period. No maintenance has been performed on the APPs.

Fixed RPM results in a fixed permeate flow/RO flux rate. The permeate flow rate equals the APP array flow rate minus the XPR lubrication flow. The lubrication flow averaged -0.8 m3/hr (-3.5 gpm) indicating an approximate 2% error between the APP array and/or permeate flows. Per the manufacturer's specifications, lubrication flow was expected to be approximately 1.6 gpm. An increase in XPR lubrication flow will affect the difference between the APP array flow and the permeate flow and would result in a loss in permeate flow. From the graph, one can see that the XPR lubrication flow remained constant (no change in the difference) after the 1,600 hour mark. This is indicative of ceramic pressure exchanger technology, which generally does not wear and/or change performance over time. The APP array flow is trending downward resulting in an equal loss in permeate flow. This issue will be discussed further in the following section.

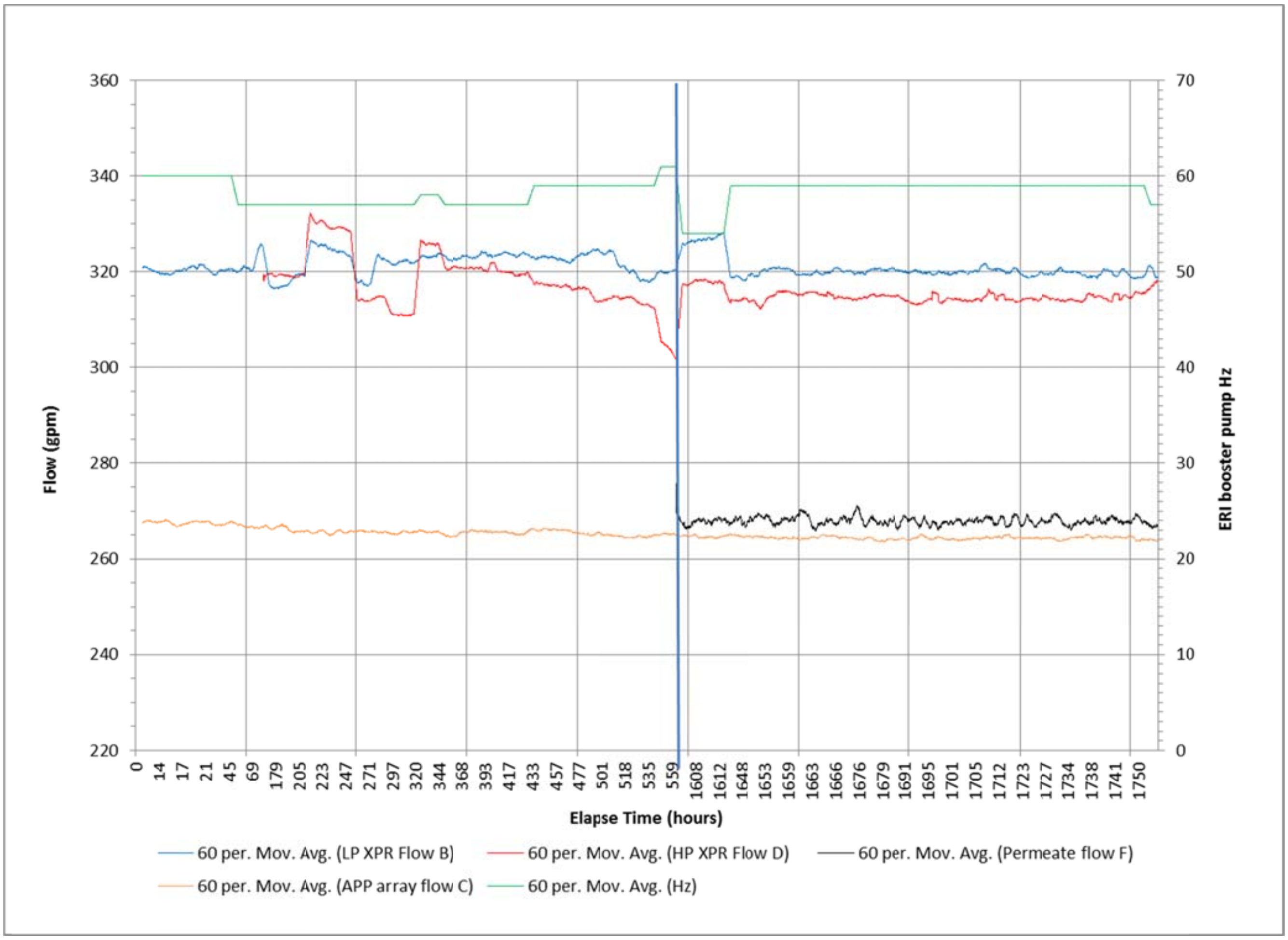

Figure 5. Major system flows over time

3.3 Axial Piston Pump Flows and Water Quality

Spikes in turbidity were observed at 21, 223, 368, 1663, and 1721 hours. The increases in turbidity were linked to recurring failures of the cartridge filter elements except between 1660-1690 hours where it was determined that a loose wire in the meter was the cause. No change in membrane differential pressure was observed as a result of the filter failures. Although, turbidity cannot provide an indication of particle size or hardness it can be a helpful indicator for when a failure or upset in the filtration system may be occurring. There was an approximate 1% loss in flow over the initial 1600 hours. This initial loss in flow is unusual, because APP flows generally increase by a few percent during the first few thousand hours of operation when excellent water quality is consistently maintained. It is likely that upsets in filtration were the cause of the initial loss in flow. The data high lights the importance of water quality in maintaining APP flows and efficiency. It also supports the need for and potential benefits of ceramic bearing materials, which promise to be resistant to upsets in pre-filtration and water quality. It is also worth pointing out that this was not an open intake. On the contrary, the wells consistently produce water quality with SDIs below three.

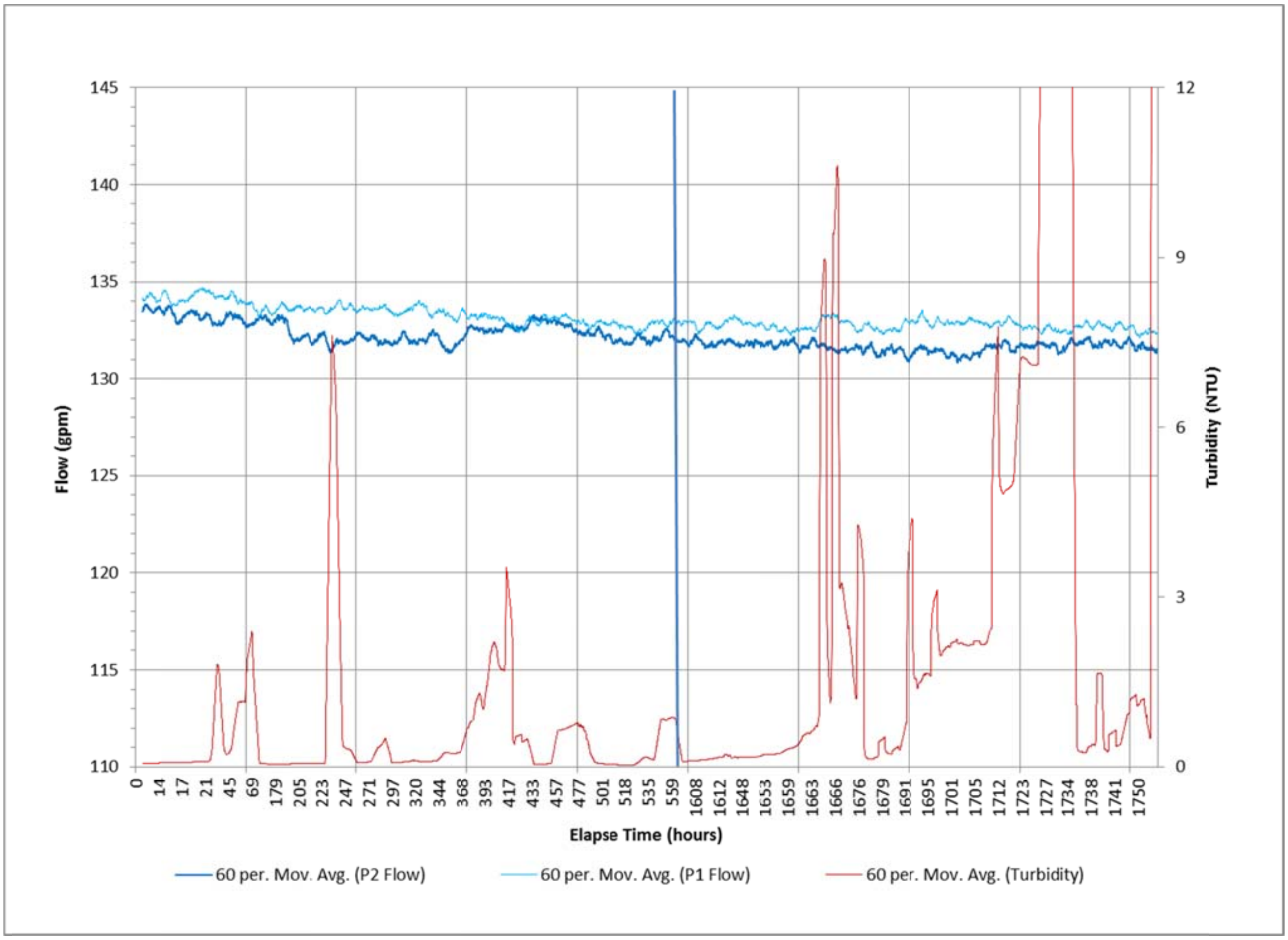

Figure 6. APP1 and APP2 Flows and turbidity over time.

3.4 Power and RO Feed Pressure

APP power trended downward 2-3% during the first few hours of operation, which is typical. After this initial break-in the power has remained constant and/or tracked proportionally with RO feed pressure.

PX booster pump power was high and somewhat erratic during the first 560 hours of operation. This was determined to be related the subsequent failure that occurred at 560 hurs.

High pressure readings were also inaccurate and erratic during the first 560 hour period due to a failing pressure transducer. Gauge readings indicated an average 850 psi during the first 560 hours of operation. An anomalous spike in pressure between 517-527 was verified by the spike in APP power. This pressure increase may have been caused by an increase in permeate back pressure.

After the 1600 hour mark and installation of the permeate flow meter, specific energy has averaged 2.1 kWh/m3 (7.9 kWh/kgal) at 58 bar (845 psi) and 46% RO recovery. Variations in PX booster pump power/flow have had the greatest impact to the overall energy consumption and steady state of operation.

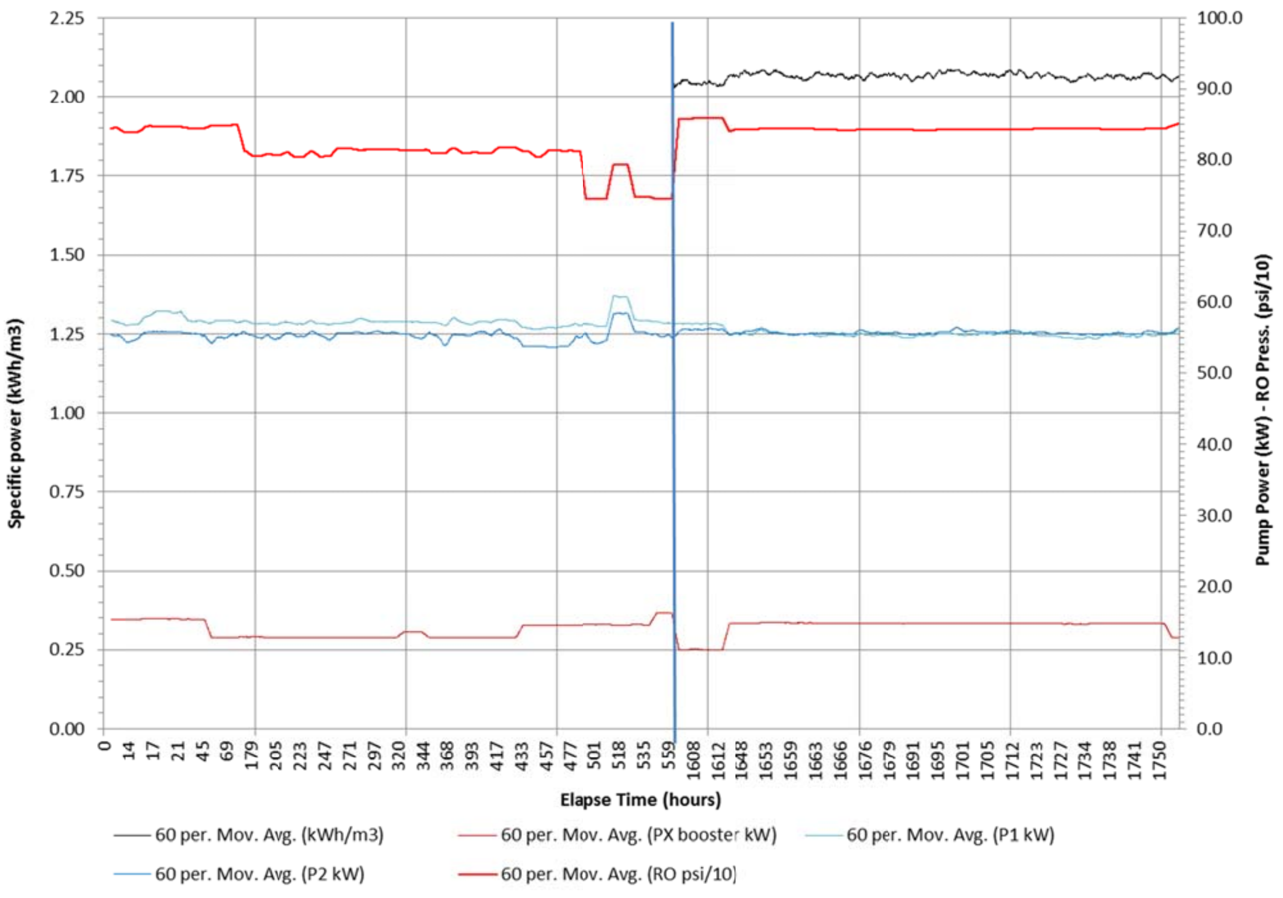

Figure 7. Power and RO Feed Pressure Over Time

Notes: Actual APP power readings were adjusted upwards by 9.9 and 10.1 for APP1 and APP2 respectively to correct for error in the APP soft start kW meters.

3.5 Axial piston pump net efficiency

APP Net efficiency = Flow x Pressure / 1714 / motor efficiency / motor kW / 0.746 kW/HP

Motor efficiency is assumed to be 95%. Flow, pressure and motor kW are measured readings.

During the first 560 hours the arratic changes in efficiency were related to the pressure transducer failure mentioned above. A new pressure transducer was in place for data after 1600 hours, where APP 1 efficiency averaged 93% while APP2 efficiency averaged 91%.

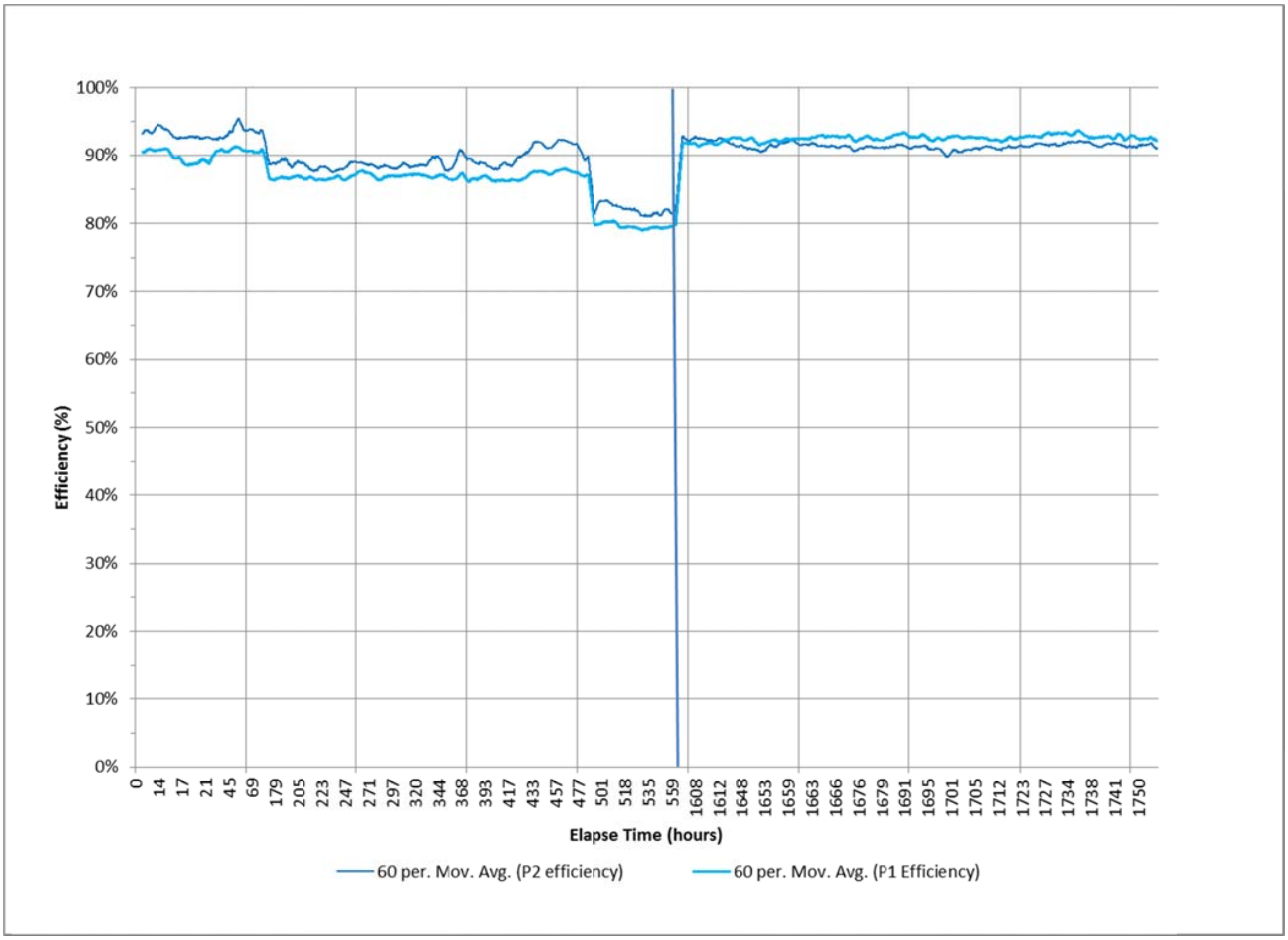

Figure 8. APP Net Pump Efficiency Over Time

IV. LESSONS LEARNED

1. Out to 1600 hours of operation the APPs have operated above 90% efficiency and therefore have delivered on their promised energy savings. There has been no maintenance performed on the pumps and their overall operation has been smooth and trouble free.

2. Water quality remains a critical issue. Upsets in pre-filtration have affected the performance of the pumps resulting in some loss in flow during an initial period of 1600 hours where we might expect to see some gain in flow.

3. There is an apparent correlation between turbidity and flow loss. Looking at Figure 6, there was some correlation between turbidity events and accelerated flow loss during the first 560 hours of operation. There was also some loss in flow during events between 1712-1875 hours. Although turbidity cannot specifically determine the size and nature of particulates it provides a relatively inexpensive, continuous monitoring of water clarity and therefore filtration performance and any events affecting the water clarity. Understanding that hard particulates (eg, sand, grit, shells) can accelerate pump wear, maintaining a low turbidity can ensure maximum pump life.

V. CONCLUSION

The case study demonstrates the axial piston pump array can provide a large energy savings over a range of centrifugal pumps.