Reliability and Design Life of the PX Pressure Exchanger Energy Recovery Devices

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SECTION 1: INTRODUCTION

PX® Pressure Exchanger® (PX) energy recovery devices (ERDs) manufactured by Energy Recovery, Inc. are designed and built for long-term reliability and safe performance. PX devices contain no wear parts and require no routine maintenance. With careful choice of materials, robust designs developed using advanced computational and analytical tools, precision manufacturing, and rigorous inspection and validation testing, PX devices in seawater reverse osmosis (SWRO) applications are built for several decades of operating life. The consistently high performance of over 35,000 PX devices deployed worldwide since 2002 demonstrates the reliability and durability of these devices.

This paper provides a thorough assessment of PX device design, construction, and performance characteristics as they relate to reliability and design life. Specifically, it lists and analyzes materials of construction, design standards, fatigue assessments, quality control procedures and data, customer return information, and strength and durability tests on both new and long-running PX devices. This information is used as a basis for estimating the design life of PX devices in SWRO applications where most of these devices are employed. This analysis supports the conclusion that PX devices provide a 30-year design life in reverse osmosis water applications.

Note that for PX ERDs to provide reliable, safe performance, and maximum design lives, operators are required to adhere to specified operating limits, including minimum feedwater quality, maximum and minimum flow rates and pressures, and maximum and minimum temperatures. These requirements are presented in product data sheets and in product installation, operation and maintenance manuals available by contacting Energy Recovery at desalsales@energyrecovery.com.

SECTION 2: OVERVIEW

2.1 Materials of Construction and Housing Design Standards

Seawater reverse osmosis is a challenging application because of long-term continuous operation in high-pressure, highly corrosive seawater and brine. Energy Recovery’s PX devices are constructed with advanced materials specifically selected for SWRO service, including:

- High purity (>99%) aluminum oxide ceramic (alumina)
- Super duplex stainless steel (2507)
- Super-austenitic stainless steel (AL6XN)
- Titanium
- Fiberglass
- Brine-resistant thermoplastics plastics, and
- Brine-resistant elastomer seals

This section and the next provides an assessment of the reliability and design life of the materials used to make PX components.

Energy Recovery’s PX devices have a single moving part – a ceramic rotor – that is surrounded by a close-fitting ceramic sleeve and ceramic end covers. See Figure 1 below. The ceramic material employed – aluminum oxide – is characterized by high hardness, high thermal stability, and exceptional corrosion resistance. Its abrasion-resistant nature ensures that any foreign particles are harmlessly broken up to pass through with the process fluids. In addition, it offers exceptional resistance to erosion damage.

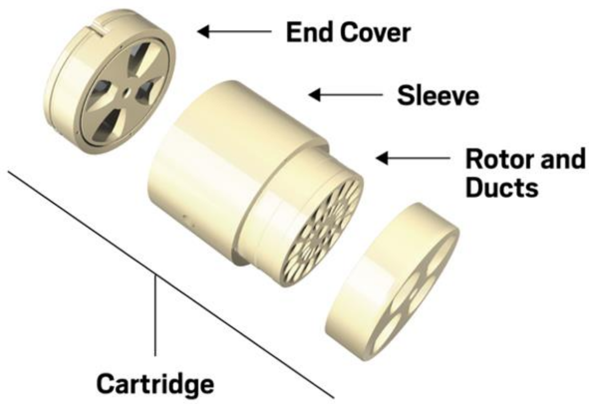


Figure 1: PX ceramic components

During rotation, the rotor is suspended radially upon hydrodynamic bearings and axially upon hydrostatic bearings that ensure contactless operation and no wear. The ceramic components in the PX maintain a high degree of dimensional stability over the rated operating temperature and pressure range, assuring the integrity of the hydro bearings. The seawater that fills the bearing gaps is constantly refreshed.

The metal alloys employed in PX assemblies are rated for brine service, with pitting resistance equivalent numbers (PRENs) of greater than 40. These metals exhibit "exceptional resistance" to strong solutions of oxidizing salts, developing a passivation layer that prevents crevice corrosion. They are, therefore, not expected to experience degradation in fatigue strength due to corrosion.

PX internals are housed in filament wound fiberglass (FRP) pressure vessels, which are standard in the desalination industry. These vessels are designed according to the ASME Boiler and Pressure Vessel code – Section X. Compliance with ASME Section X requires that the first articles of a vessel design undergo a burst test to 6 times the working pressure plus 10%. The first articles are also subject to 100,000 full pressure range cycles, corresponding to 3.5 pressure cycles per day for 30 years, which far exceeds the number of pressure cycles experienced by any PX device in SWRO applications. FRP pressure vessels operating for more than 30 years in SWRO applications exhibit no fatigue damage.

PX devices are also comprised of non-metallic and non-ceramic wetted components, including O-ring seals made of ethylene propylene diene monomer (EPDM), dowels and washers made of glass-reinforced polymer (GRP), and seal plates and thrust rings made of thick poly-vinyl chloride (PVC). All these materials are rated "excellent" for their compatibility with seawater and brine and are commonly used in SWRO applications.

SECTION 3: TEST METHODS AND ASSESSMENT OF RELIABILITY

3.1 Quality Control Procedures and Data

Quality control at Energy Recovery entails rigorous, 100% inspection of components upon receipt and subassemblies and full assemblies after construction. Finished products are tested to maximum rated service pressures. Special attention is paid to ceramic quality. Rotor/stator gaps (radial and axial), roundness, parallelism, and perpendicularity are measured on every ceramic cartridge with a precision of fractions of a micron. Out-of-specification parts, if any, are either further machined to achieve compliance or discarded. All parts are subjected to dye-penetrant testing, a procedure that flags any flaw larger than 75 microns.

To evaluate the integrity of finished products, every PX device and pump manufactured by Energy Recovery is subjected to wet testing. Minimum and maximum rated flow rates are applied at the maximum rated service pressure, which is 82 bar or 1,200 psi for SWRO units.

PX devices are tested for efficiency, which is a measure of how well the PX recovers and delivers energy in an RO system. Therefore, if PX efficiency is 96%, this means that it recycles 96% of the available energy while the remaining 4% is lost. PX efficiency in SWRO applications can be as high as 98%. The relatively small efficiency losses in the PX are attributed to 1) flow reduction due to water compression, 2) pressure reduction due to inertial and viscous resistance, and 3) volume loss due to lubrication of the hydrodynamic bearing.

Efficiency testing is conducted concurrently with integrity testing on the wet test system. Pressure sensors and flow meters in the PX inlet and outlet streams and a flow meter in the lubrication pump inlet in the test system provide the necessary data for calculating PX efficiency. Efficiency measured in field tests shows an excellent correlation with efficiency measured in Energy Recovery’s wet test system.

When the brine and seawater streams contact each other inside a PX, contact between the fluids is direct, with no intervening barrier or piston. As a result, there is a small degree of mixing between the streams such that the high-pressure seawater stream produced by the device has a slightly increased salinity compared to the seawater source. To evaluate mixing performance, the wet test system is modified so that there is a salinity difference between low-pressure inlet and high-pressure inlet. The salinities in the PX inlet and outlet streams are measured and used to calculate volumetric mixing. Extensive testing has shown that when a PX device meets efficiency performance requirements, it meets mixing requirements as well. Therefore, mixing testing is conducted in product development but not in production. As with efficiency, field tests have shown an excellent correlation between mixing measured in the wet test system and in the field.

Energy Recovery’s manufacturing and testing operations are managed under a comprehensive Quality Management System (QMS). Energy Recovery’s QMS has been registered to ISO 9001 since 2014 and is currently registered to the most recent ISO 9001:2015 standard. This is a globally recognized standard used to help ensure consistent products and services that meet customer, regulatory, and statutory requirements while continually improving manufacturing and testing processes. Under the QMS, no devices are released for shipment without meeting all testing and performance standards.

3.2 Fatigue Life of PX Components

Each component of the PX is chosen for its high strength and durability, compatibility with highly corrosive brines, and dimensional stability over the maximum operating pressure and temperature ranges that these products are subjected to in the field. Importantly, all components that undergo fatigue loads are evaluated for cycles to failure at the maximum fatigue loading condition during design qualification. Ceramic components are evaluated for fatigue fracture resistance, ensuring that the manufacturing process does not produce a flaw that can exceed the critical flaw size. All other components are designed to endure stress levels well above structural endurance limits, ensuring unlimited fatigue life.

If a component is going to fail under constant stress, it is likely to occur early in its design life or after the component has suffered wear, erosion, or corrosion over a long period of operation. Therefore, factory testing of new assemblies to maximum service pressure, retests of older assemblies to maximum service pressure, and inspection of older assemblies for signs of wear, erosion, or corrosion are means to assess the longevity of PX devices.

For assessing the fatigue life of components subject to cycling stress, a fatigue life analysis is conducted. The PX rotor was selected for this evaluation because it is the component that undergoes maximum pressure cycling. It is, therefore, the component in the PX assembly that experiences the highest degree of cycling stress. Under steady-state operation, the duct walls of a pressure exchanger rotor are stressed with a constant amplitude and constant frequency of load variation. Amplitude and frequency are proportional to the difference between maximum and minimum pressure (DP) and the product of the rotation rate in revolutions per minute (RPM) multiplied by the number of pressure cycles per rotation (# cycles), respectively.

$$Amplitude \propto DP$$
$$Frequency \propto RPM \times \#\, cycles$$

The PX Q300 experiences a maximum DP of 1,200 psi (82 bar), rotates at a maximum of 500 RPM, and operates with 2 cycles per rotation. Therefore, the stress frequency for 30 years of operation is computed as:

$$\#\, of\ stress\ cycles\ in\ 30\ years = 1.6 \times 10^{10}$$

Fatigue data is commonly presented as a plot of maximum stress versus number of fatigue cycles on a semi-log scale. Reference fatigue data for sintered alumina at room temperature is shown in Figure 2.

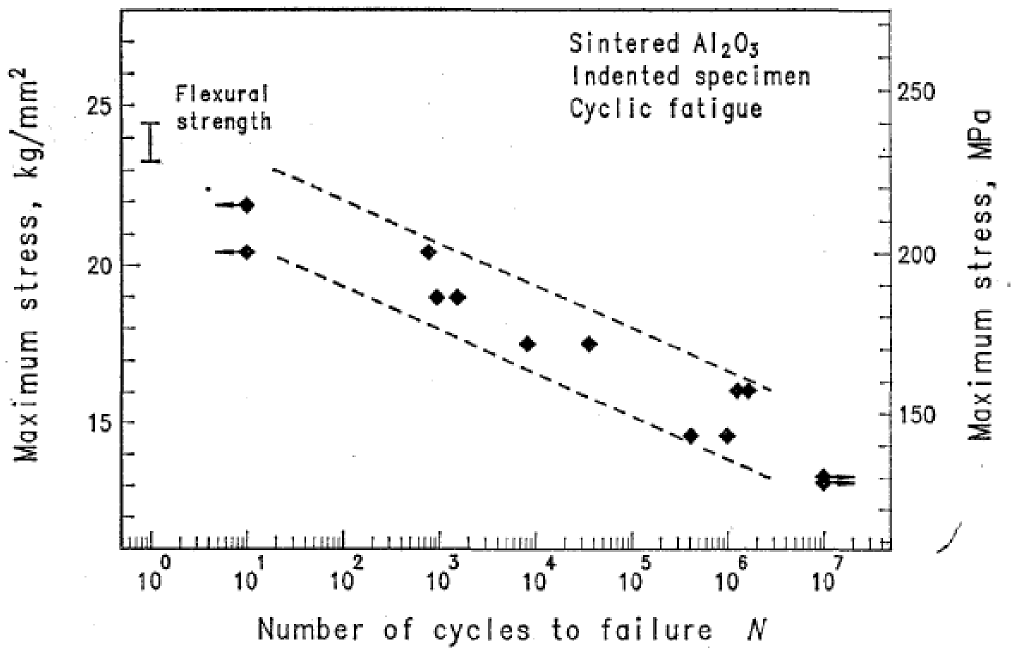


Figure 2: Cyclic fatigue life of Alumina at room temperature (Kawakubo et. al.*)

**Cyclic fatigue behavior of ceramics at room temperature, T. Kawakubo and A. Goto, 1987, Journal of The Society of Materials Science, Japan.*

Extrapolating the reference data to $1.6 \text{ x } 10^{10}$ cycles, we can estimate that the maximum stress the rotor can be subjected to for a 30-year life is about 90 MPa or 13,000 psi.

Figure 3 shows the max principal stress contours in a rotor duct subjected to a 1,200 psi (82 bar) pressure differential across its walls. This conservative plain strain analysis at the maximum operating stress at the weakest place in the part indicates that the maximum stress will not exceed 11,100 psi (765 bar).

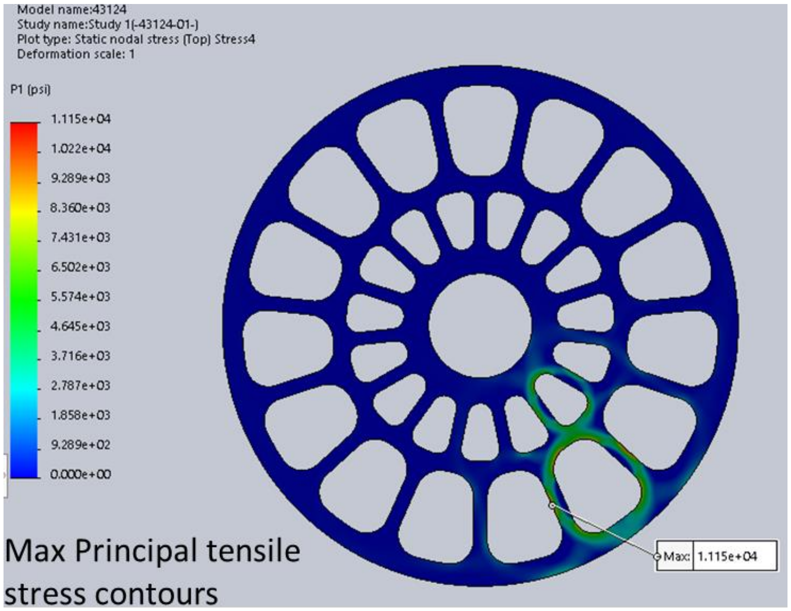


Figure 3: Stresses in the duct wall of a PX rotor subjected to 1,200 psi (82 bar) pressure differential.

Similar high-cycle fatigue analyses were conducted on the rest of the ceramic parts, supporting the conclusion that all the cartridge parts have a high-cycle fatigue life of more than 30 years. A summary of the analysis results is shown in Table 1.

Ceramic Part	End Cover Feedwater	End Cover Concentrate	Rotor	Sleeve
Material	Alumina	Alumina	Alumina	Alumina
Allowable Stress for 30-Year Life (psi)	13800	13800	13800	13800
Peak Stress @ 82 bar (psi)	4500	4500	10497	1488

Table 1: Allowable stress for 30 years life vs peak stress at rated condition for ceramic parts

For non-ceramic components in the PX assembly, if the stress level is below the endurance limit, the material can withstand an infinite number of loading cycles without failing. All parts except for the rotor are subjected to constant load during operation, cycling only during startup and shutdown, unaffected by the pressure exchange cycles in the rotor. A summary of the key parts in the PX, their peak stress at 1,200 psi (82 bar) operation, and their endurance limits are shown in Table 2. All these components have endurance limits that far exceed the peak stresses they are exposed to in their lives. Therefore, under normal operation, these materials are designed and fabricated for infinite fatigue life.

PX Metal Part	Bearing Plate	Lock Ring	Interconnect	Low-Pressure Port	Tension Rod
Material	6061-T651 Aluminum	316 Stainless Steel	Titanium	2507 Super Duplex	AL6XN or Super Duplex
Endurance Limit (psi)	13,778	13,600	58,000*	80,000	80,000
Peak Stress (psi)	1,000	3,406	10,300	257	29,473

Table 2: Peak stress and endurance limit of PX metal parts*

** Can vary with alloy grade and heat treatment*

3.3 Fatigue Fracture of PX Ceramics

Alumina ceramic can exhibit fatigue crack growth through a process of micro-cracking and coalescence around preexisting flaws. An estimate of critical crack size can be approximated in terms of the fatigue threshold stress intensity factor, ΔK_{Th}, in units of $MPa\sqrt{m}$. Fatigue threshold stress intensity factor depends on the specimen geometry, the size and location of the crack or notch, and the magnitude and distribution of loads on the material. It can be calculated as:

$$\Delta K_{Th} = \Delta\sigma\sqrt{\pi a_c}Y$$

where: $\Delta\sigma$ is the maximum applied stress,
a is the crack length, and
Y depends on geometry relative to the crack length.

Fatigue crack growth can begin when applied fatigue threshold stress intensity factor exceeds fracture toughness. For high-purity alumina, fracture toughness is approximately 4 $MPa\sqrt{m}$. The geometry factor Y can vary from 1.0 for a central crack oriented perpendicular to the loading direction, 1.2 for an edge crack oriented perpendicular to the loading direction, or less than 1.0 for a crack inclined to the loading direction. For this analysis, Y=1.2 represents the worst case. Under an applied stress of 11,100 psi (765 bar), which is the maximum stress expected in the PX ceramic assembly, the critical crack size can be estimated to be about 800 microns, leading to fatigue fracture is negligible. Therefore, under normal operation, these materials are designed and fabricated for infinite fatigue fracture life.

3.4 Customer Return Information

Energy Recovery tracks details of field service work and customer returns to assess customer satisfaction and inform engineering and manufacturing of potential design or fabrication issues. The PX Q300 was introduced to the market in 2011. With over 25,000 of these devices deployed in the field, it is the company's largest-selling device and constitutes the vast majority of PX models sold to date. A total of 164 PX Q300 units have required service by Energy Recovery in the field and/or have been returned to the manufacturing facility due to performance problems. This represents less than a 0.7% overall return rate. Careful analyses of these devices indicated no incidences of materials or manufacturing defects. Rather, all returned devices had suffered some sort of contamination, most typically hard debris in the water fed to the device. Therefore, the PX Q300 has enjoyed a 0% return rate for design or fabrication issues in 14 years of production and operation.

SECTION 4: DURABILITY ASSESSMENT SAMPLING

4.1 Factory Performance Testing

After receipt and an external visual inspection, the field units were factory-tested to measure their performance and assess any changes. Both the field units started readily, indicating that the long-term operation had no detrimental impact on startup reliability. Factory acceptance tests (FATs) were redone on both the units on the wet test system to compare current performance with that recorded at the time of manufacturing. In addition, testing was done in the research and development lab to measure additional performance parameters like mixing.

Figures 4 and 5 compare PX performance from the decade-old FATs with retest performance. Since the test temperature is no longer controlled on the wet test system and to discount any variability due to test temperature, performance tests were also done in the research and development lab at a controlled temperature. In the research and development lab, the test temperature was kept at the same value as the original FAT, and additional performance data, including mixing performance, was collected.

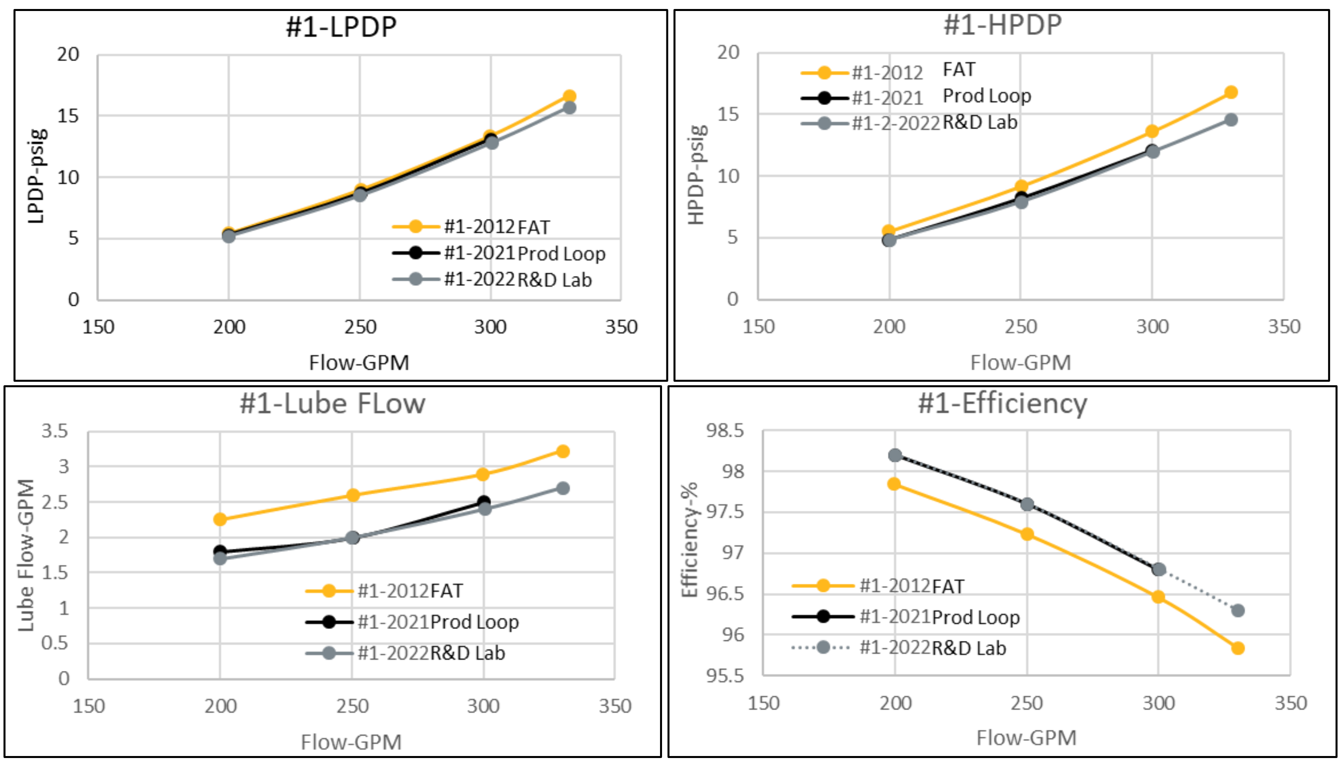


Figure 4: Performance Data for Unit # 1. Original factory acceptance test (FAT), current wet test system and research and development lab testing.

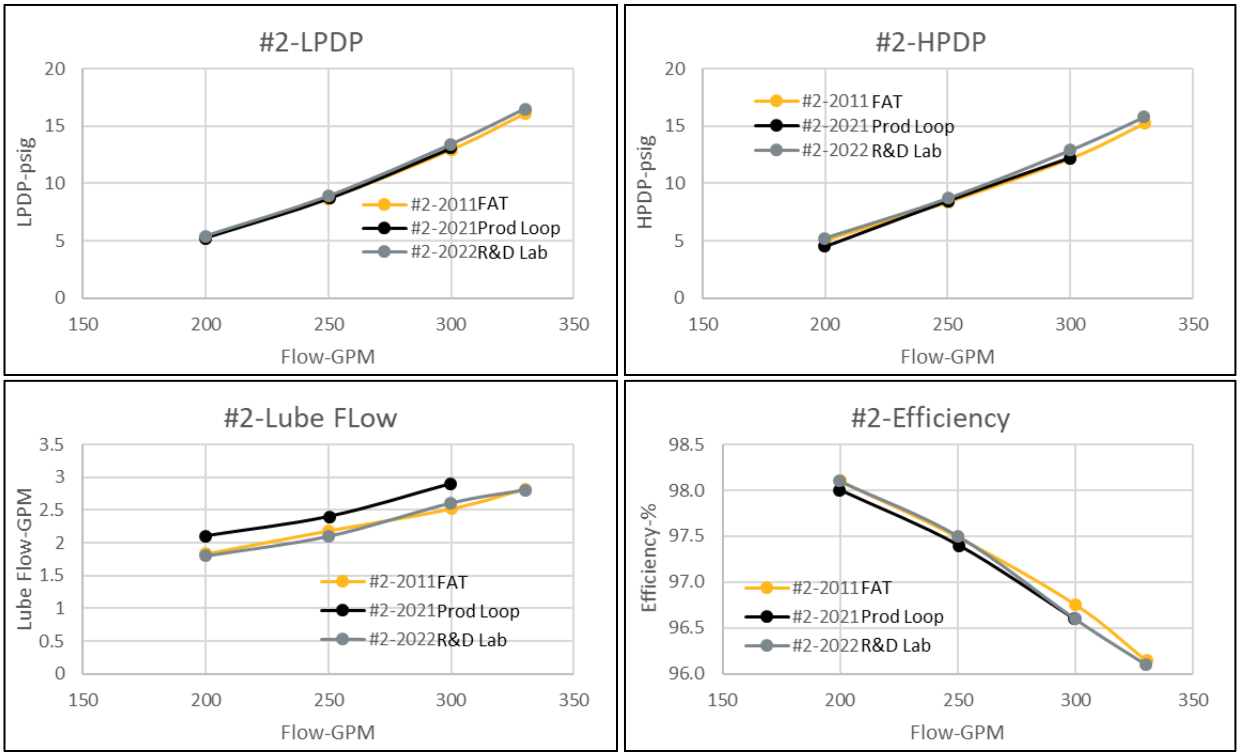


Figure 5: Performance data for Unit # 2. Original factory acceptance test (FAT), current wet test system and research and development lab testing.

Both the units showed no degradation in performance – the DP, or pressure drop, on the high-pressure side of the PX (HPDP) and the DP on the low-pressure side of the PX (LPDP) remained the same after 10 years of field operation. Lubrication (lube) flow reduced after long-term operation in the field, resulting in a slight increase in PX efficiency. This is possible due to the small changes in some key proprietary dimensions within the ceramic assembly, resulting in reduced effective end clearance. Mixing and rotor speed had not been assessed in the original FAT. However, the retest values fell well within the specifications for PX Q300 units.

4.2 Disassembly and Visual Inspection

The field units were disassembled, and all components were inspected. Key observations from the visual inspection were as follows:

- None of the components in the assemblies exhibited corrosion, erosion, or wear damage.
- Ceramic cartridge parts had no damage, such as chipping, wear, or abrasion, observable to the naked eye.
- Lapped surfaces of the end covers and rotor were clean and appeared polished.
- No signs of cavitation or erosion were observed on end covers, rotor, or any other parts of the PX unit.
- Radial bearings on both rotors looked clean with no signs of damage.
- No hard deposits, such as precipitated salt scale, were present.

4.3 Measurement of Contact Surface Quality

Rotor/stator gaps (radial and axial), roundness, parallelism, perpendicularity, and wear were measured on the ceramic components of both field units. Key observations were as follows:

- Unit #1 brine end cover had 1 to 2 microns of measured wear.
- Unit #2 feedwater end cover had 1 to 2 microns of measured wear.
- All the rotor/stator interfaces appeared smooth and polished, and no signs of cavitation damage were observed.
- Radial and end clearances were well within established tolerance limits, indicating no appreciable wear.

Although end cover wear could nominally result in increased lubrication flow, performance testing demonstrated that lubrication flow had not increased in either field unit after over 10 years of operation. Indeed, slight decreases in lubrication flow were measured, suggesting a reduction in effective end clearance. As a result, efficiency slightly improved in both units.

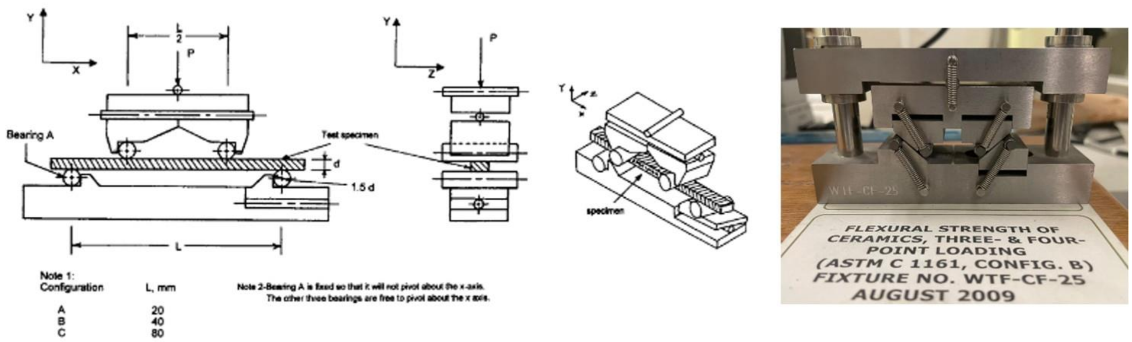
Careful inspection of other PX devices retrieved after field operation in SWRO applications has shown similar negligible wear rates between the rotor and stator. Surface roughness reduces with wear, and micro-scratches from fabrication disappear, resulting in smoother contact surfaces. Localized contact stresses are reduced as surface roughness and micro-scratches disappear, resulting in a continually declining wear rate.

4.4 Material Characterization and Strength Testing

Following dimensional evaluation, rupture strength and physical property analyses were conducted on the ceramic components of the field units.

Rotor burst tests were conducted on both units to verify the strength of the duct walls in resisting applied pressures and stresses. Burst pressures were measured to be 2,850 psi (196 bar) and 3,200 psi (220 bar) for Unit #1 and Unit #2 respectively. With a maximum allowable working pressure of 1,200 psi (82 bar), these burst pressures correspond to 2.4 X and 2.7 X working pressure, respectively. Both of the units exceeded the pass criterion of 2.0 X, which is consistent with the strength of new units, revealing no deterioration in the ability of rotor ducts to withstand fluid pressure.

Flexural strength is a good indicator of the strength of a brittle material. If ceramic parts are damaged during operation, it is very likely that their flexural strength would reduce, reflecting a decrease in the component’s ability to handle static and fatigue loads. Samples were cut from end covers and rotors and were tested for their flexural strength using a standard 4-point bend test based on the ASTM C1161 test standard (Figure 6).



(a) *(b)*

Figure 6: (a) ASTM C1161-B flexural strength setup (b) Test fixture

Figure 7 shows the flexural strength of 4-point bend coupons drawn from end covers and rotors of both field units. In addition, the flexural strength measured is compared to strength data from new PX units. The comparison shows that there was no significant change in flexural strength after many years of pressure cycling, indicating no additional defects or growth of old defects and, hence, no damage progression. Also, comparing the strength of coupons from different parts of the cartridge shows that no part of the cartridge has experienced a strength reduction.

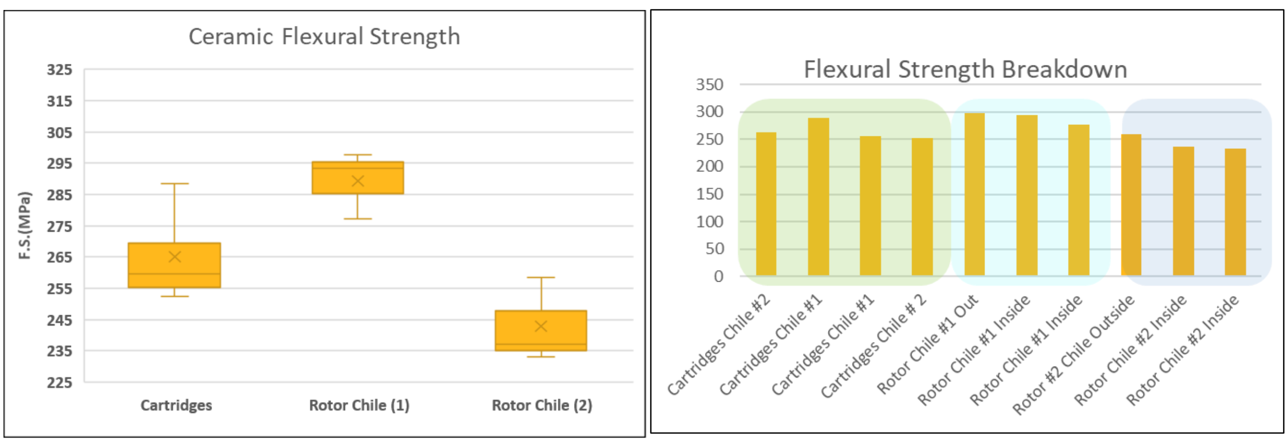


Figure 7: Flexural strength of coupons cut from different ceramic parts*

**Note: "Cartridges" refers to end covers.*

Figure 8 presents Vickers hardness measurement data of coupons from ceramic parts of the field units. The measured hardness values ranged from 15.5 GPa to 17.0 GPa, falling well within Energy Recovery's specified limits of 14.7 to 17.7 GPa. This is another indicator that there is no damage or deterioration in the strength of the material after more than 10 years of operation.

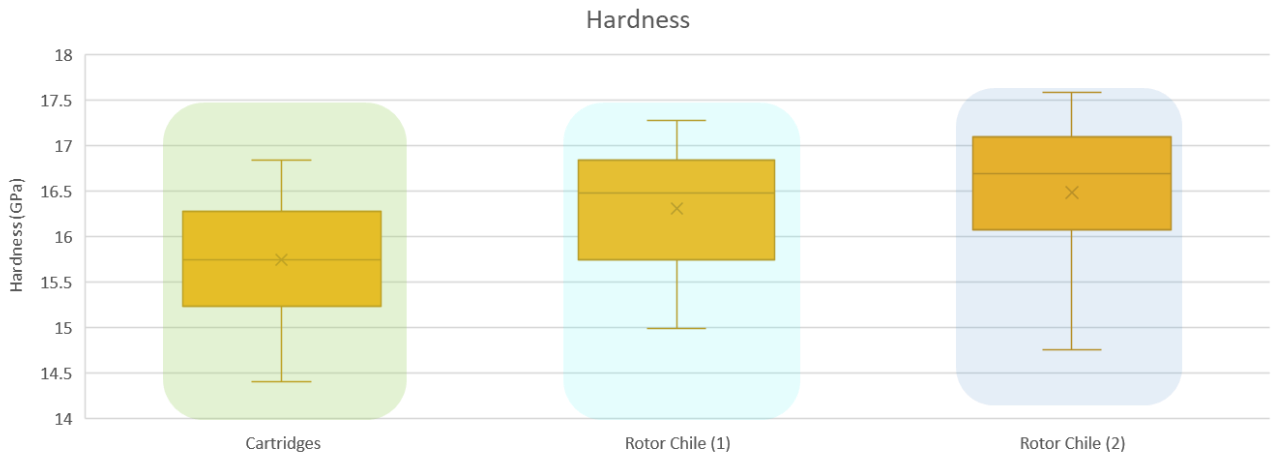


Figure 8: Vickers hardness data on ceramic coupons drawn from the field units*

**Note: "Cartridges" refers to end covers.*

Ceramic coupons from field units were etched, polished, and examined under a microscope for any signs of micro defects. A microscopic image of an end cover sample from Unit #1 is shown in Figure 9, and a summary of the grain sizes measured on all coupons is shown in Table 3. No signs of micro defects were detected. The grain size measurements were well within the limits observed in new samples, indicating no change over time or as a result of operation.

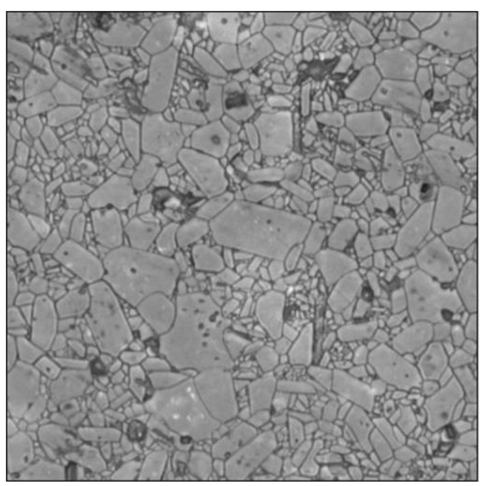


Figure 9: Grain structure in a ceramic sample from end cover of field Unit #1

	Grain Sample	Cell Profiler	Grains Sample	Manual
1 – Cartridges Chile	4827	2.88	400	4.77
2 – Rotor #1 Chile	3915	2.75	300	4.78
3 – Rotor #2 Chile	2987	2.97	300	5.16

Table 3: Grain size (in microns) measurements using a cell profiler (automated) and a manual method from coupons of ceramic parts from the field units. Grain sample indicates the number of grains used to determine the average grain size.

SECTION 6: CONCLUSION

This paper provided an assessment of Energy Recovery's PX device design, construction, and testing features as it applies to PXs in seawater reverse osmosis applications. It listed and analyzed materials of construction, design standards, quality control procedures and data, customer return information, strength and durability tests, and fatigue assessments. The fatigue life analyses demonstrated that PX components can be operated through full-pressure cycles for 30 years* without material fatigue. In addition, fatigue fracture analyses and vendor data from all procured parts show that all the components will last for at least 30 years when operated as per specifications. No PX unit has been returned by a customer for design or manufacturing defects. Two PX Q300 devices that had operated continuously for over a decade in the field were tested, disassembled, and analyzed. This analysis showed that the units and their components remained in their original condition, with no signs of life-limiting wear or damage. Wet testing showed no degradation of performance. Burst strength and material properties assessments indicated no degradation or weakening of the components.

With well over 25,000 PX Q300 units deployed worldwide with zero history of failures for material fatigue or degradation, we conclude that Energy Recovery's PX pressure exchangers provide a 30-year design life.*

**Disclaimer: Assuming proper operation of PX designed for pressures of 1,200 psi (82 bar) or less in seawater reverse osmosis applications.*