Lifetime Durability of Ceramic PX™ Energy Recovery Devices

Energy Recovery Inc

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A White Paper on Long Life Materials for Desalination Applications

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Executive Summary

➔ Overview

In order to ensure the long-term and trouble-free lifetime of the seawater reverse osmosis (SWRO) process and its enabling technology, it is essential to utilize the most advanced and reliable materials of construction. One of the more advanced and unique materials currently in use in SWRO desalination applications is high purity (>99%) aluminum oxide (alumina) ceramics. Due to its hardness, self-lubricating properties, high compressive strength and chemical resistance, alumina ceramics create an ideal fluid bearing for the rigors of seawater applications, which perform in conditions that combine corrosive and potentially two-phase (solid/fluid) environments.

High purity alumina ceramics developed and manufactured by Energy Recovery Inc (ERI™) are particularly unique because of the innovative design of the company's PX™ devices and the intense conditions of SWRO plants in which they operate. When in use, the ceramic-based devices are supported by a seawater fluid bearing while rotating and being pressure-cycled millions of times per year. The durability of ceramics in high pressure, corrosive seawater environments is fundamental to the success of these devices and is quantified and categorized throughout this paper. The enhancement of ERI material science and technological improvements has shown to improve the overall durability of the product and significantly reduce sound levels to below 81 decibels.

Technical data shows that at peak rates, ERI ceramics inside the PX device wear at less than 3 microns per year (.003 inches over 25 years). **The findings identify wear and prove that ERI alumina ceramics can last longer than 25 years in a seawater desalination reverse osmosis plant.**

More than 9,700 PX units have been installed world-wide. Some units have been in operation for as long as 12 years. With zero failure as a result of PX technology designed ceramics, research indicates that PX devices will continue operating well into the future.

How Long Can Materials Withstand a Beating?

While every SWRO plant has to manage against the corrosion of engineering materials, plants operating in warm climates are a “worst case” environment for this issue. The corrosion of pipes and/or plant structural materials occurring in these hot and demanding conditions can lead to unplanned component failures, unnecessary downtime and costly repairs.

In fact, unplanned downtime can cost you up to $15 million US dollars over the average life of a 120,000 cubic meters per day plant for 25 years.

The combination of seawater, wind, sand, high humidity, warm water and processing chemicals create a challenge that most engineering materials cannot withstand. As a result, we see the expanding use of duplex (2205), super duplex (2507) and super austenitic stainless (AL6XN) steels in plant construction. These alloys actually protect themselves by growing a protective scale of corrosion byproducts. This protection keeps away crevice corrosion and prevents pitting that could lead to high pressure leaks or piping failures. However, as with all metals, there is always a risk that this layer is damaged and will be unable to repair itself, which can lead to locally weakening the surface corrosion resistance of the steel. In SWRO applications, plant operating conditions are not ideal and debris can enter process streams.

Other materials, such as soft polymers like polyethylene terephthalate (PET), acetal and UHMW, perform well in seawater, but are relatively soft and become dimensionally unstable unless consistently stored at the proper temperature. Because of low surface hardness, sand and debris are easily caught in sliding polymeric components such as the pistons or poppet valves found in piston-type work exchanger energy recovery devices. Captured debris can scratch through passivation layers on advanced stainless steels, causing galling and negatively and unpredictably affecting corrosion resistance.

The best materials for SWRO applications deliver certain advantages including:

- Corrosion-resistance.
- Dimensional stability.

- ➔ Debris-tolerance.

Alumina Traits	Benefits
Corrosion resistance	No chemical reaction with seawater
Dimensional Stability	98% the density of sapphire, temperature and pressure resistant
Debris-tolerance	Pulverizes debris, able to withstand up to 20 microns

TABLE 1. Alumina Traits and Benefits

➔ A natural affinity to water

Unlike alloys and soft polymers, alumina ceramics are stable and do not chemically react with seawater. Aluminum oxide is only exceeded by titanium oxide in its thermodynamic stability, thus making it one of the most corrosion-resistant engineering materials presently available. It is also electrically insulating and therefore cannot influence galvanic corrosion in metallic piping systems. Alumina is naturally hygroscopic in a pH range from 3 to 11 and therefore has a natural affinity for water.

This affinity to water is one of the reasons why alumina creates such a long lasting fluid bearing. High purity alumina is interestingly also found in the medical industry for orthopedic hip implants. The cushion of water above the ERI™ PX™ ceramics is continually flushed of debris, dramatically reducing the chance for cohesive wear from foreign particles. Scratches from entrained debris are possible, but short lived, since they are pulverized by the much harder ceramics surfaces of the PX unit fluid bearings.

The PX device ceramics are strong, more than 98% the density of sapphire, and have surface hardness within 90% of the commercial orthopedic alumina ceramics trusted by doctors to be used in patients. In summary, alumina ceramics are able to withstand the long life durability required in desalination environments. In applications containing warm seawater and debris, metallic based components are chemically inferior to alumina ceramics since they are partially sacrificial and reliant on their own corrosion byproducts for self-protection.

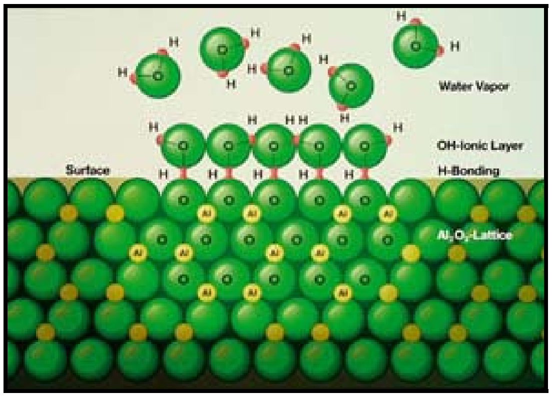

FIGURE 1. The strong hydrogen bonds that form between ceramic surfaces and seawater give ceramic materials wetting properties that are superior to those of metal and plastics.

Long Life, Little Wear

PX™ alumina ceramics formulated and manufactured by Energy Recovery Inc offer desalination plant owners and operators an exceptional value for their investment. PX device ceramics are tolerant to many types of environmental wear, and are able to operate at high efficiency even after long operations and extended periods of use.

Based on vast experimental data and observations gathered from more than 9,700 devices deployed throughout the company's many years of service, ERI has observed only three modes of physical wear in the PX unit application. These ceramic wear modes are contact erosion, cohesive (particulate) wear, and localized fluid wear. Wear from each of the modes is subtle and therefore careful analysis is required to quantify exact rates.

Alternatively, hydraulic performance may also be used to extrapolate the possible end of life for the unit. Contact erosion wear results in local smoothing of the PX surfaces, while cohesive wear is caused by large debris (>20 microns) and results in localized scratches on the device. Fluid wear results in localized surface roughness changes and can occur in devices that are operated outside of their hydraulic design envelope, however it is very rare and does not appear to measurably affect the performance of the device. The PX unit design is tolerant to most types of wear, thus allowing it to operate at high efficiency even after occasional abuse.

Technical Specifications

➔ Long term performance and high efficiency from Perth seawater desalination plant analysis

All PX™ devices are fully tested before shipment. Hydraulic performance data is comprised of eight different measured parameters that are used in the calculation of the device's overall hydraulic efficiency. For example, to quantify the effects of ceramic wear on PX device performance, four PX-220 units were retrieved from the Perth Seawater Desalination Plant in Kwinana, Australia, and performance tested after four years of actual SWRO process exposure. All four units exhibited average efficiencies *equal to or greater than 96%* at 220 [gpm] on a production test stand.

Overall, test results showed that all four units tested within 0.5% of the original values measured prior to shipment in 2005. Additionally, all four units investigated met original product efficiency requirements. The ceramics did not exhibit any measurable degradation during performance testing.

Overall, the long term efficiency of the PX-220 devices in operation for more than four years performed at over 96% - well within the original design parameters.

➔ Physical wear analysis of PX™ device ceramics

ERI™ engineering regularly evaluates used components for physical wear. To complement this data, ERI developed materials testing capabilities. To date, quantifying the measure of wear of ERI ceramics using this test generates results that are undetectable; even when operated at almost 10 times the designed thrust load applied to the PX unit. ERI has been unable to quantify wear rates on ERI ceramics using this test since wear channels generated are within the limits of ERI test metrology; even when operated at almost 10 times the designed thrust load applied to the PX unit.

Studies suggest that friction couples made from ERI's ceramic materials, including our internally formulated ERI 998, wear at peak rates less than three microns per year (.003 inches over 25 years). This result is comparable to studies of biomedical alumina ceramics, such as "Biolox Forte" from Ceramtec, which indicates average wear rates of alumina ceramic couples in water can be as low as one micron per year[1]. Since laboratory testing based wear rates are very low, ERI has determined that data gathered from deployed PX™ device ceramics is far more valuable.

FIGURE 2. ERI Submersible “Pin on disk” Ceramic wear testing apparatus

Many techniques were utilized to physically measure and quantify wear patterns on recovered PX™ units operating for more than four years. Physical wear was so slight in many cases that pencil marks, written by original production personnel during the grinding phase, were still visible on the rotors when disassembled. Characterization of wear was a difficult task since dimensional changes in the PX device are barely detectable using production inspection gauges and the naked eye. Photos of “as-ground” and used ceramic surfaces can be seen for comparison in Figure 3.

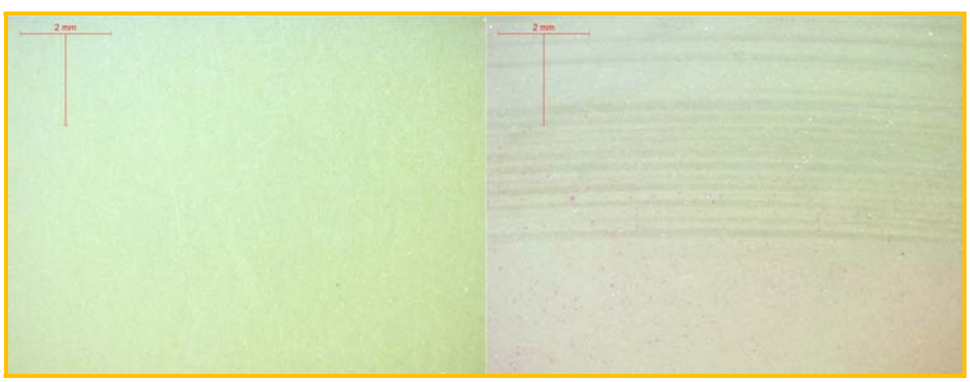

FIGURE 3. “As-ground” ceramic surface in comparison localized scratches from large (>>20 micron) entrained debris on used PX ceramic surface

To fully evaluate wear on alumina that has been in operation for more than four years, ERI™ conducted research to understand contact stress. Wear detected on the PX device ceramic components, operating for more than four years, appears to be typical for an alumina fluid bearing. Alumina ceramics wear via plastic deformation and micro-fracture were driven by localized contact stresses. Since the PX™ device uses fluid bearings and large contact surfaces, overall macroscopic stresses that generate wear on PX unit ceramic surfaces can only be attributed to gravity when seawater is not flowing.

As an engineering material, high purity alumina does not wear at low applied loads since the material has to overcome hydrostatic and threshold contact forces to trigger physical wear. Alumina wears at higher contact loads and becomes smoother by dulling micro scratches from fabrication related grinding. Localized contact stresses are reduced as surface micro scratches disappear, therefore resulting in a continually declining wear rate at constant applied load. Foreign particles, such as sand, can momentarily generate stresses that can cause highly localized wear such as surface scratches. However, since these particles are softer than alumina they crumble and are washed away as they leave witness marks on the surface.

➔ High strength and hardness fine grained alumina, such as ERI998, perform better in regards to wear and debris resistance in comparison to lower purity commercial ceramics.

➔ In general, the smoothing "break in" type behavior is natural and self-limiting for fine grained and high purity alumina ceramics.

➔ Based on hydraulic testing data, this wear does not measurably affect performance of the device after more than four years in operation.

Determination of ceramic component wear based on comparing dimensional changes to "as new" measurements is microscopic to quantify even after more than four years of service. Measured dimensional changes from macroscopic wear were within the magnitude of metrology limits and experimental error. Wear patterns qualitatively suggest that the rotor is becoming rounder and smoother over time. As stated, this wear does not measurably affect the performance of the device.

The sleeve looked less affected by physical wear than other PX™ device ceramics. Rotor to end cover clearances also appear to increase slightly as the adjacent material surfaces in the PX device polishes and planarize each other, with peak material wear rates being far less than four microns per year; which corresponds with data published on alumina hip implants[2]. Dimensional clearance changes near occasional divots or scuffs were not measurable by the coordinate measuring machine (CMM), and results indicate that overall surface wear rates are relatively uniform and inert. It is likely that starting and stopping the device causes most of this wear and the occasional scuff marks characterized in the next section. In addition, during plant start-up, debris was observed in many of the PX™ units' system and therefore may be the source of these scuffs.

Following dimensional evaluation, rupture strength and physical property analysis was conducted on recovered PX-220 ceramics. Table 2 provides a summary of the specific gravity and hardness Vickers data from the harvested ceramics as well as data from ceramics currently being produced in-house. This destructive testing revealed that the material strength, hardness, grain size, and physical properties were unchanged and remain within ERI engineering specifications.

Tests indicate that there is no anticipation of physical property degradation of alumina ceramics in the PX unit over the lifetime of the device.

Recent developments in ERI material science efforts indicate that the new formulation has further improved performance. The data in Table 2 and Figure 4 depicts specific improvements made to ERI ceramics. The newly formulated ERI998 Gen 2 is being launched with a new and improved PX device called the PX-Q300.

Material	Specific Gravity (g/cc)	Claimed Specific Gravity (g/cc)	Hardness (GPa)	Claimed Hardness (GPa)	Purity (%)
ERI998 Gen 1 (2005)	3.925	> 3.91	15.4	>14.9	99.8
ERI998 Gen 2 (2011)	3.932	> 3.91	17.5	>16.0	99.8

TABLE 2. Data from Lab Testing of Ceramic Components

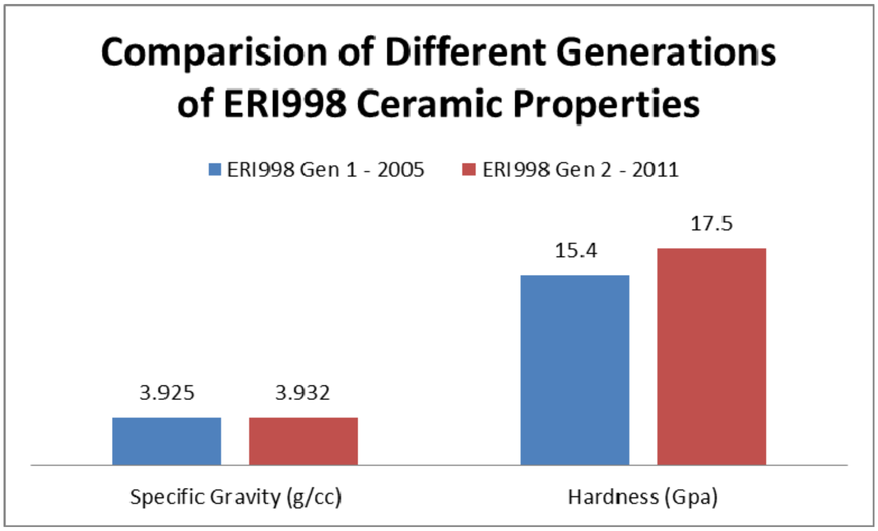

FIGURE 4. The current generation ERI998 ceramic has improved considerably over previous generations and is now produced at the San Leandro facility in California.

Summary

Overall, dimensional wear analysis data from evaluating used PX™ units, in combination with laboratory and materials tests, predicts an ***overall lifetime exceeding 25 years for the PX ceramics*** when operated within specifications using seawater. Hydraulic performance data from evaluating recovered PX220s reveal no quantifiable hydraulic performance changes within the first four years of operation, supporting claims that minimal observed wear does not affect hydraulic performance. Based on the general behavior of full ceramic wear coupled with full fluid film lubrication, ERI does not foresee hydraulic performance degradation over the lifetime of the device[3].

ERI PX Device Ceramic Materials are Designed for a Lifetime.

The economics of using PX energy recovery devices from an operations and capital costs benefit analysis prove that the ERI technology is the optimal solution with a significant advantage over competitive piston-type work exchanger devices that contain suboptimal materials and require unplanned maintenance.

More than 9,700 PX units have been installed world-wide. Some units have been in operation for as long as 12 years. With zero failure as a result of PX technology designed ceramics, research indicates that PX devices will continue operating well into the future.

➔ Contact Us

Name: Timothy Dyer, Chief Technology Officer

Address: 1717 Doolittle Drive

San Leandro, California

94577

USA

Email: tdyer@energyrecovery.com

Website: www.energyrecovery.com

Tel: +1 (510) 483 – 7370

More Information

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