Post Access Report

MRE Dynamic Seals Performance Investigation

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TEAMER

Testing & Expertise for Marine Energy

EXECUTIVE SUMMARY

This TEAMER project allowed NREL to use and augment a custom special-purpose testing system to perform accelerated-life testing of rotating seals for use in the MRE industry. The requirements of this industry are different from most applications including marine, and relevant performance information is lacking. In order to achieve low costs with extremely effective and reliable operation over long periods deployed underwater, more study of the best seals and arrangements of seals must be performed. By developing a rigorous framework for such testing, NREL can greatly improve the understanding of the relevant factors, and provide significant data to the industry. Further, this work can inform standards for this critical component of MRE systems, leading to maturation and improved acceptance of the industry in commerce.

This report briefly discusses the observations and results from accelerated lifetime testing performed by the National Renewable Energy Laboratory (NREL) on the main shaft seal for the Verdant Power fifth-generation (Gen5) underwater tidal energy converter turbine, which successfully performed at the Roosevelt Island Tidal Energy project in 2020–2021. To evaluate a 5-year service interval (SI) for this component, the main shaft seal was operated nearly continuously for 137 days at a rotational velocity of 160 rotations per minute while the test stand recorded water pressure, barrier fluid pressure, temperature, and number of cycles, representing ~ 40% of the SI. An additional separate test was conducted to measure the aging behavior of the rubber drive rings. For the SI evaluation the water pressure reservoir was held constant as 199,9 kPa (29 psi). Barrier fluid pressure remained relatively constant throughout the duration of the test but fell to as low as 69.6 kPa (10.1 psi). No barrier fluid leakage was observed throughout the test. A sudden failure occurred within the seal after the power to the test machine was interrupted for a scheduled building maintenance procedure. Upon restarting, the main shaft seal lost all ability to prevent water ingress. The exact cause is not known but is believed to be either a seal assembly issue or a change in the alignment of the seal components during or following the power outage. Following seal disassembly, one of the graphite sealing rings showed significant wear. Verdant Power, Dovetail Solutions LLC, and Garlock Sealing Technologies reviewed the seal wear for consensus evaluation of results. NREL returned the seal faces to Garlock, and a review of them indicated a misalignment of the test stand, both overall (shaft moving as a whole) and from front to back (more movement on the water side than the air side). Garlock further indicated that minor misalignment is usually absorbable by the seals; so, the noted wear leads to the conclusion of a test stand disruption. Therefore, the operation of the Gen5 seals to the point of power outage is indicative of long-term performance. Based on these results, it is recommended that follow-on testing be conducted through NREL's Testing Expertise and Access for Marine Energy Research (TEAMER) program to rectify protocol and assembly issues to further evaluate the SI of this component.

1 INTRODUCTION TO THE PROJECT

There is very little literature on seal performance for the conditions required by MRE, i.e. large-shaft, low-speed, low-pressure, with a limited temperature range, but over very long service periods between maintenance. Other relevant conditions include salt water, water sediment content and biofouling potential. Such an understanding, and proven cost-effective solutions are critical to the long service intervals required for economic power generation.

As a central part of this project, Verdant provided NREL its custom-built seal test device that it designed and built for automated life testing of its Gen5 main shaft seal arrangement. This testing machine is a flexible, general-purpose system that currently has a 6" diameter shaft rigidly held in pillow block bearings on a steel frame. The shaft is rotated by a variable speed gearmotor arrangement controlled by a PLC with a touchscreen HMI. A variety of parameters were programmed for automatic operation including stop/starts to simulate tidal operation. A variety of seals and seal arrangements were used with the system, and leakage through the seal(s) from the 14-gallon water pressure (depth) chamber was collected and measured over time. Parameter data such as shaft rpm and temperatures were acquired for documentation and further analysis.

2 ROLES AND RESPONSIBILITIES OF PROJECT PARTICIPANTS

2.1 APPLICANT RESPONSIBILITIES AND TASKS PERFORMED

Verdant team member	Responsibility
Leighton Paradis	Lead, Verdant Power Operating Engineer
Dean Corren	Seal and testing advisor, CTO
Jonathan Colby	Modeling/control, Verdant Power, Dir. of Performance

2.2 NETWORK FACILITY RESPONSIBILITIES AND TASKS PERFORMED

NREL team member	Responsibility
Robynne Murray	Project management and engineering
Scott Lambert	Technical lead and running tests

3 PROJECT OBJECTIVES

Overall Objective: The objective of this work was to perform an in-depth investigation of dynamic shaft seal performance for MRE, including the various system factors that influence it, and to perform representative accelerated-life tests on practical seals and sealing arrangements.

First, the project developed a better understanding of the seal testing process itself. For example, we determined the factors, such as seal surface speed and temperature, the number of start/stops that limit the rate of accelerated life testing, and the measurement methods. This information was used to investigate ways to optimize such tests. Second, the project studied several seals and seal arrangements to help inform validation methods and development of standards. Third, the test system was modified to include additional test variables such as shaft loading or changes to sensors to record existing parameters more accurately or additional sensors, as necessary. Lastly, both fundamental general testing information, and specific seal test results were published to help Verdant design scaled-up turbines, and assist the MHK industry as a whole.

4 Test Facility, Equipment, Software, and Technical Expertise

TEAMER support allowed NREL to operate the seal test device, enhance its operation within a more rigorous framework of long- term MRE seal modeling and requirements, test practical seals for MRE, and provided important and valuable information to the entire industry.
A budget of $150,000 allowed NREL personnel to do an analysis of the current seal testing equipment and make necessary modifications, followed by operation of the equipment and publication of the procedures and outcomes to advance the performance and cost-effectiveness of dynamic seals for the MRE industry as a whole.

5 Test or Analysis Article Description

Figure 1 shows the seal test equipment as used in 2018. Details on the testing stand and the particular Verdant seal arrangement test article in 2018 can be found in the attached report “Roosevelt Island Tidal Energy (RITE) Demonstration Project (Project No. 18785) Task 3B Deliverable – Appendix A: Gen5 KHPS Main Shaft Seal Test Technical Report.”

Figure 1Verdant Main Shaft Seal Test Stand at Garlock Functional Testing Lab

The key seal parameters and test input parameters include:
-seal/shaft speed
-start / stops, timing and duty cycle
-water pressure
-water type
-temperatures
-seal type and seal arrangement design
-barrier fluid type (if any)
-length of test

The resulting test data that was produced during the test:
-leakage rate - and estimates of usable service interval
-seal wear - estimates of lifetime based on post-test inspection

Overall seal performance information would include comparisons of:
-seals under various operating conditions

-various seal types
-various seal arrangements, including smaller or larger seals

Big picture, this information, along with seal costs will directly relate to both CAPEX and OPEX, and lead into LCOE. It allows justifiable seal type and arrangement selections and the concomitant service interval and OPEX planning. By testing this key component advancement to higher TRLs will be accelerated, and the available literature on this component will be augmented greatly.

6 Work Plan

6.1 Test and Analysis Matrix and Schedule

Four successive stages of this project are outlined below:

1) Equipment readiness, preparation, and test matrix development

The first phase (approximately 1.5 months) of the project was dedicated to setting up the equipment, preparing the required Safe Work Permits and instrumenting and setting up the data acquisition system. This phase will include:

- Receive and check out equipment
- Have NREL ESH and ESO inspect and approve equipment for operation (electrical safety check out and safe work permit if required)
    - Make any necessary modifications required for unattended operation. This includes setting sensors with interlocks such as temperature.
- Perform attended testing initially to validate safety protocols and gain experience with equipment. The goal is to go to unattended testing where we check it twice per day to log hours, however, an initial attended period is necessary.
- Develop and verify functionality of safety interlock chain
- Selection of other seal types and procurement of additional equipment/test articles

Due to the unique nature of the test equipment, test conditions, and device being tested that test method development will be an important consideration. For these reasons NREL spent some time refining the test methods and developing a test matrix. From their prior experience, Verdant has identified the important test parameters in the following table, NREL will use this as a starting point for development of a test matrix.

The Gen5 KHPS main shaft seal test parameters are listed in Table 3.1.

Table 3.1. Gen5 KHPS Main Shaft Seal Test Parameters

Parameter	Testing Target	Actual Test
Test Article	Gen5 KHPS Main Shaft Seal Assembly	
Seal Materials (Vendor: Garlock)	Carbon/bronze for both face pairs	
Test Period	60 days (3.3% of SI)	69 days (3.8% of SI)
Main Shaft Speed (Test Stand Range: 40-180 rpm)	160 rpm (4x normal)	
Start/Stop Cycles (24/day, 6x normal of 4/day)	1,440 (19.7% of SI)	1,663 (22.8% of SI)
Cycle Timing	ON (running): 59 min. OFF (stopped): 1.0 min.	ON: 59.5 min. OFF: 0.5min.
Effective Duty Cycle (Normal: ~75%)	98.3%	99.2%
Revolutions (5-yr SI → 78.8M)	13M (16.5% of SI)	15.8M (20.1% of SI)
Water	East River (RITE) seawater with suspended sediment	
Water Pressure (External seawater vessel)	20 psi (Equivalent to 40' depth) (Internal gearbox unpressurized – worst case delta-P)	
Barrier Fluid (BF)	Mobil SYNTURION 6 100% fill inter-seal and reservoir volume	
BF Pressure	Atmospheric to start, then pressurized by seawater pressure through seal; Gearbox side at atmospheric (worst case)	

2) Reproduction of Verdant seal test results

The second phase (approximately 1.5 to 3 months) of the project was dedicated to normal operation of the equipment as outlined in the attached Test Report provided by Verdant. NREL gained an understanding of the requirements and limitations of the test setup, and worked to identify ways in which the process can be improved. The test rig was run, and data collected using the same configuration as Verdant did to enable NREL to verify repeatability of the test methods. Additionally, several anomalies in the first round of testing were noted by Verdant, NREL will attempt to reproduce these unexpected observations, identify a root cause for each, and implement corrective action. These observations include the following:

1. The collection and measurement of the fluid that leaked past the seal was difficult due to the very small amounts of fluid and long duration of the collection time.
2. The river water tank was found to contain rust at the conclusion of the testing performed by Verdant and it was noted that the source should be found and replaced with a corrosion resistant component.
3. Some incidental fitting leaks occurred which did not affect the operation of the test, but should be remedied. These included the upper barrier fluid (BF) piping, and the inner leakage container drain fitting.

4. For further testing, a non-contact system to pre- and post- measurement of the carbon face height that can measure extremely small changes should be identified and used. A mechanical micrometer is not suitable.

3) Modification of test equipment or methodology

The third phase (approximately 1 month) of the project was used to make any modifications to the test equipment that could offer improvements in the accuracy of the testing or shorter durations required for lifetime testing of MRE seals . Potential areas NREL considered are listed below, however, others were investigated that are not identified here.

- Instrumentation such as sensors and measurement equipment
- Types of seals – new or different seal types to try
- Pressure variation during operation – consider looking at depth of site vs seal performance – machine health vs installation location
- Rotational speed variation – Answer questions such as - can we conduct seal validation faster, what is the influence of speed on the test results? What are the limits? Would it change the failure mode?
- Measure water content in the barrier fluid (if any) oil and potentially in lubrication gear oil

4) Operating of seal testing using improved methods

Phase 4 (approximately 1 to 2 months) focused on testing the modifications made to the equipment and testing methods in Phase 3. NREL prepared a final report that describes the testing and test methodology and published it as a Technical Report here https://www.nrel.gov/docs/fy24osti/89380.pdf.

6.2 Safety

The NREL engineering team worked closely with the NREL Safety group to ensure safe operation of the equipment. A Safe Work Permit was required to undertake this work.

6.3 Contingency Plans

Not applicable.

6.4 Data Management, Processing, and Analysis

6.4.1 Data Management

The data generated during tested was stored locally on a machine being used to record the data, and backed up using OneDrive (up to 1TB available). The final dataset containing results was uploaded to a Box folder for sharing.

6.4.2 Data Processing and Analysis

Data was analyzed and processed throughout Phase 2-4 of this project and was summarized in a final technical report.

7 Project Outcomes

7.1 Results

This document will briefly discuss the observations and results from accelerated lifetime testing of the main shaft seal for the Verdant Power fifth generation underwater power generation turbine. The results of this project have been published as a technical report here: https://www.nrel.gov/docs/fy24osti/89380.pdf. This technical report has more detail than provided in this post access summary.

Task 1 and 2 Results Summary:

During testing at NREL the main shaft seal was operated nearly continuously for over 231 days at a rotational velocity of 80 rpm. The volume of water leakage was recorded periodically. After reaching 50% of the expected 5-year service interval the testing machine was shut down and disassembled to inspect each component. After inspection the components were found to be in good conditions with no visible cracks or chips. A significant amount of graphite dust had worn away from the wear rings and formed a thick mixture with the BF. This mixture heavily coated all surface in the seal. In total approximately 26% of the wear surface had been removed from the wear rings. Despite the loss of material, the wear rings did not lose any mass indicating they adsorbed 2 g of water, BF, graphite dust, or a combination of these. The rubber drive rings appear to have lost about 6 g when compared to new drive rings, however the cause of this difference is uncertain. The bronze face rings did not show any signs of wear other than polishing the contact area. These results suggest the seal was not approaching end of life at the time of shutdown.

Results are promising considering the water volume leaked through the seal during testing. In total less than 400 ml of water leaked through the seal, and of that only 125 ml leaked through the back of the seal into, i.e. the main body of the hydroturbine. Water leakage and wear data is given in tables 1 and 2 below. Figure 1 displays the leakage rate as a function of predicted service interval.

Table 1: Mass of new and used seal components. The new component mass is measured from a different seal than the one tested.

	New	Ring 1	Ring 2
Wear Rings	203.5 g	204.5 g	205.0 g
Face Rings	349.75 g	350.0 g	344.5 g
Drive Rings	87.0 g	80.5 g	81.0 g

Table 2: Water leakage collected in the lower BF reservoir throughout testing.

Num Cycles	Height [in]	Num Days	ΔDays	ΔCycles	Up Time [hr]	Num Rev [Mil]	%SI	Leakage Vol [ml]	ΔLeak Vol [ml]	Leak Rate [ml/hr]
3132	1.125	130.5	130.5	3132	3,105.9	30.71	39.0	130.3	130.3	0.041
4062	1.5	169.25	38.75	930	4,028.2	35.14	44.6	173.8	43.4	0.047
4417	1.625	184.04	14.79	355	4,380.2	36.82	46.8	188.3	14.5	0.041

4753	1.75	198.04	14	336	4,713.4	38.42	48.8	202.7	14.5	0.043
4898	1.8125	204.08	6.04	145	4,857.2	39.11	49.7	209.9	7.2	0.050
5205	1.875	216.88	12.79	307	5,161.6	40.58	51.5	217.2	7.2	0.024
5547	1.9375	231.13	14.25	342	5,500.7	42.20	53.6	224.4	7.2	0.021

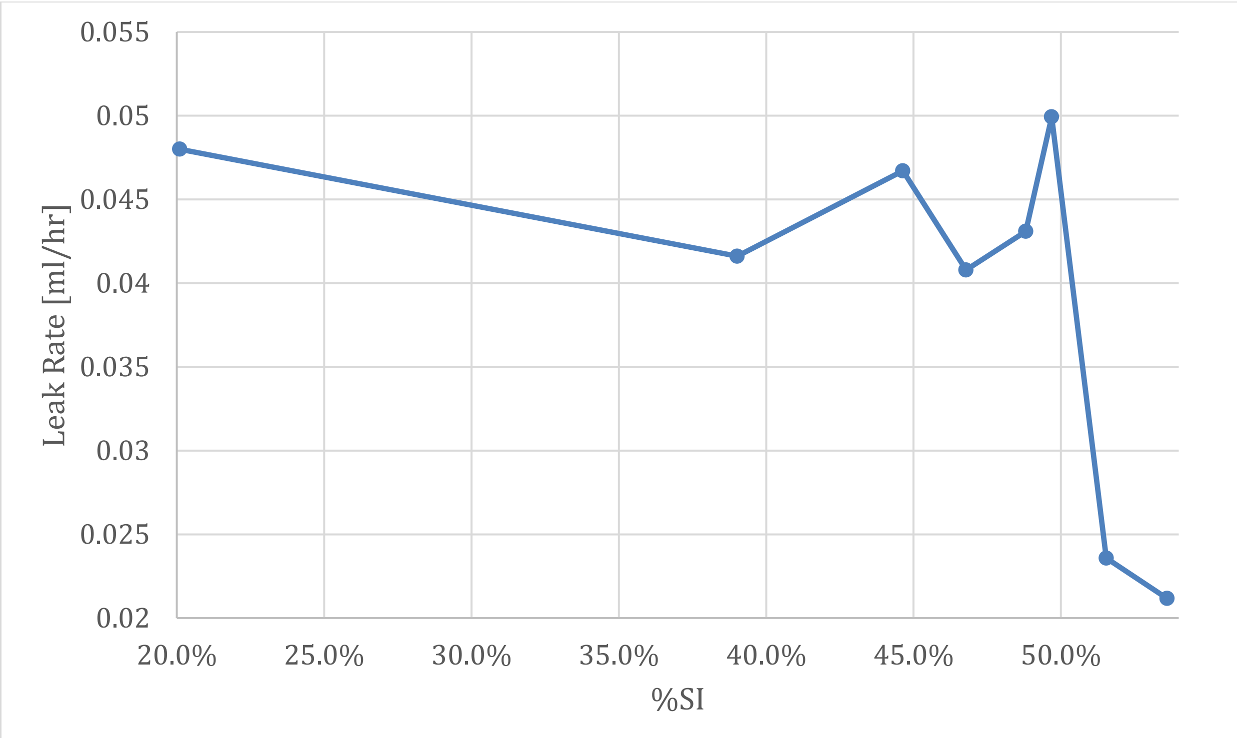


Figure 2: Water leakage rate vs percent of total service interval.

Water leakage was relatively consistent throughout testing and with previous testing conducted by Garlock and Verdant Power. It did not appear to have a deleterious effect on internal seal components. Increased leakage through the back of the seal was observed toward the end of testing, however the rate of this increase is uncertain at this time. Over a 5-year service interval water leakage will need to be addressed; possibly by filtering and discharging overboard. Given the similarities between this data and previous work these results were seen to satisfy task 1 and 2 objectives.

Task 3 Results Summary:

Several modifications were made to the test stand to facilitate future testing and generate more detailed information on the behavior of the seal during operation. These modifications focused mostly on installing new sensors, some of which required minor changes to the stand. The test stand and modifications are detailed below. A diagram and photograph of the seal test stand are provided in Figure 3 in which all the primary components are visible including:

The main shaft seal (MSS) which is filled with the barrier fluid (BF) from the upper (UR) and lower (LR) reservoirs, necessary for lubrication and to separate the water from the rest of the components, The pressurized water tank which simulates the aquatic operating environment, and various sensors and valves necessary for operation and data collection.

This test stand closely follows ISO 6194 [1] intended for accelerated lifetime testing of lip-type seals incorporating elastomeric sealing elements. Some deviations have been taken from the standard, particularly the BFUR volume has been increased and a sampling valve has been added below the seal. These modifications were made to facilitate the periodic collection of BF to monitor particulate size and generation rate.

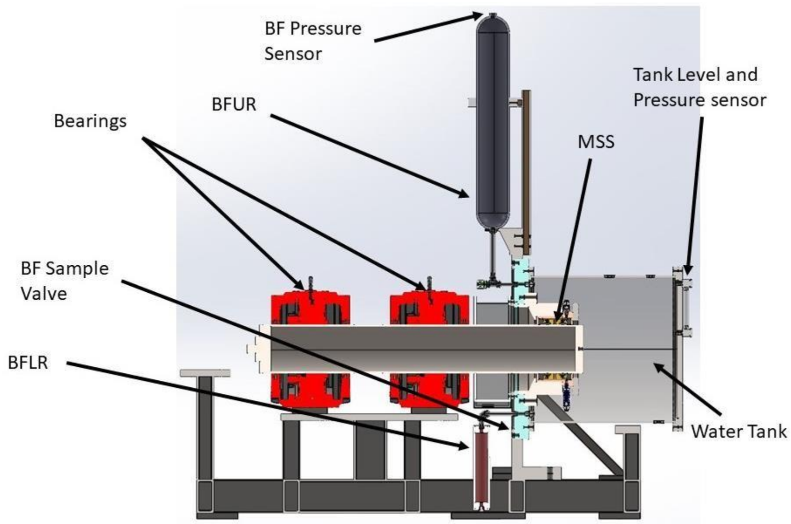


Figure 3: Cross sectional diagram of the accelerated lifetime MSS test stand with major components labeled. Note the electric motor, gear box, and oil hoses are not shown.

The electric motor and gear box is designed to rotate the main shaft at 160 rpm with a duty cycle of 59.5 minutes on and 0.5 minutes off repeating 24 times per day. This rotational velocity is four times the expected operational rotational velocity, 40 rpm, and the duty cycle is six times the expected operational cycle, four times per day. Under these operating conditions the seal will complete its desired service interval of 5 years of 78.8 million revolutions, 24 times faster than operational counterparts. The bearings are SAF534 pillow block bearings [2] (SKF, Gothenburg, Sweden) which support all rotational and translational forces except for axial rotation and thrust loading.

A detailed view of the MSS is provided in Figure 3 showing all primary components. The water tank was pressurized to approximately 199.95 kPa (29 psi) to simulate the 20.45 m (67.1 ft). This is greater than the expected operating conditions, however it is deemed acceptable because this exceeds expected loading and would accelerate any leakage that may occur during testing. BF was supplied to the MSS through the barrier fluid upper reservoir (BFUR) while the lower reservoir (BFLR) provides a space for leaked water to collect and oil samples to be taken. Hoses connect the reservoirs to the housing.

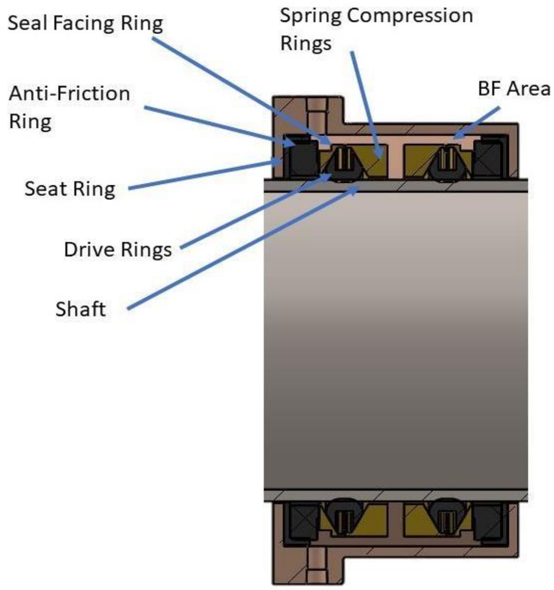


Figure 4: Cross section of the MSS and housing showing primary components. The seal is symmetric between the spring compression rings. In-situ four springs press these rings apart. The interior space is filled with BF with liquid tight seals at the drive ring/shaft interface and the anti-friction ring/seal facing ring interface. The front, on the left, is upstream and faces the water tank. The back of the seal, on the right, is downstream and faces the atmosphere.

The water tank was filled with 56.8 L (15 gallons) of fresh water. While the Gen5 KHPS is expected to operate in brackish water, fresh water was chosen because this minimized the risk of damaging nearby equipment, facilities, and surrounding laboratory environment in the event of significant seal leakage. It is recognized this will affect the applicability of these results, however given this KHPS is intended to operate in combined salt and freshwater environments this compromise was accepted.

The MSS is a Syntron RP style mechanical shaft seal produced by Garlock [3] (Garlock Sealing Technologies, Palmyra, NY, USA). The rotating components, shown in dark grey, interface with the shaft using the nitrile butadiene rubber (NBR) drive rings. These are compressed by bronze seal face rings and are kept in compression by four tension springs evenly spaced radially around the seal. The rotating components press against front and rear graphite anti-friction rings. This entire assembly is held inside a brass housing. The seal face and anti-friction rings are constructed from bronze and graphite respectively. The rubber driving rings are molded from nitrile butadiene rubber. The entire housing is filled with Synturion 6 BF [4] (ExxonMobil, Irving, TX, USA). BF fills the seal as well as the BFUR and BFLR.

The main sealing surfaces are at the anti-friction ring/seal face ring interface, and the shaft/drive ring interface. If water leaks past the front anti-friction ring interface without leaking through the rear anti-friction ring water mixes with the BF and pressurizes the housing. This water may remain in suspension or fall into the BFLR. The volume of this water can be measured either in the graduated lower reservoir or as a concentration in the oil samples. Leaking through the front and rear anti-friction rings would be observed at the back of the housing and collected into a lower drip pan but does not pressurize the housing. Leaking between the shaft and drive rings will have similar outcomes.

Instrumentation

Pressure

The water tank and BF pressures are monitored individually throughout the experiment by Omega PX309-050A10V pressure transducers (Omega Engineering, Norwalk, CT, USA). The pressure range for these sensors is between 0 and 344.7 kPa (0 psi to 50 psi), an accuracy of ±0.25%, and an operating temperature range of -40°C to 85°C (-40°F to 185°F). These sensors are connected to an etherCAT network via a NI9144 DAS chassis to a computer which records the pressure of each fluid every 5 minutes throughout the experiment.

Temperature

Temperature in the BF is recorded by a 3-wire Pt100 resistance temperature detector (RTD) throughout the experiment (McMaster-Carr number 6568T47, Robbinsville, NJ, USA). The RTD passes through the BF hoses and into the housing so the temperature of the seal can be directly measured. The temperature range for this RTD is from -20°C to 176°C (-4°F to 350°F) with an accuracy of ±0.12% which is acceptable for this application where the temperature is expected to remain below 100°C (212°F). The RTD was connected to a DAQ module and recorded at the same interval as pressure.

Lower Reservoir Leakage

The lower reservoir is a cylinder with an ID of 38.1 mm (1.5 inches) and an axial scale is water leakage volume. Water collected during oil sampling is also measured with a graduated cylinder. The BF is initially at atmospheric pressure. The volume of water collected in the BFLR was recorded every five days.

Motor Current

The electric motor controller, which regulates the main shaft's rotational velocity, also monitors the current draw during operation. Any power spikes or dips larger than 1 amp are recorded along with a time stamp. Due to the limitations of the controller this was the smallest possible interval. Initially the motor current was highly variable and was recorded automatically by the system, however after a period of time the current stabilized at which point the current was recorded manually every five days along with leakage and rubber hardness, discussed below.

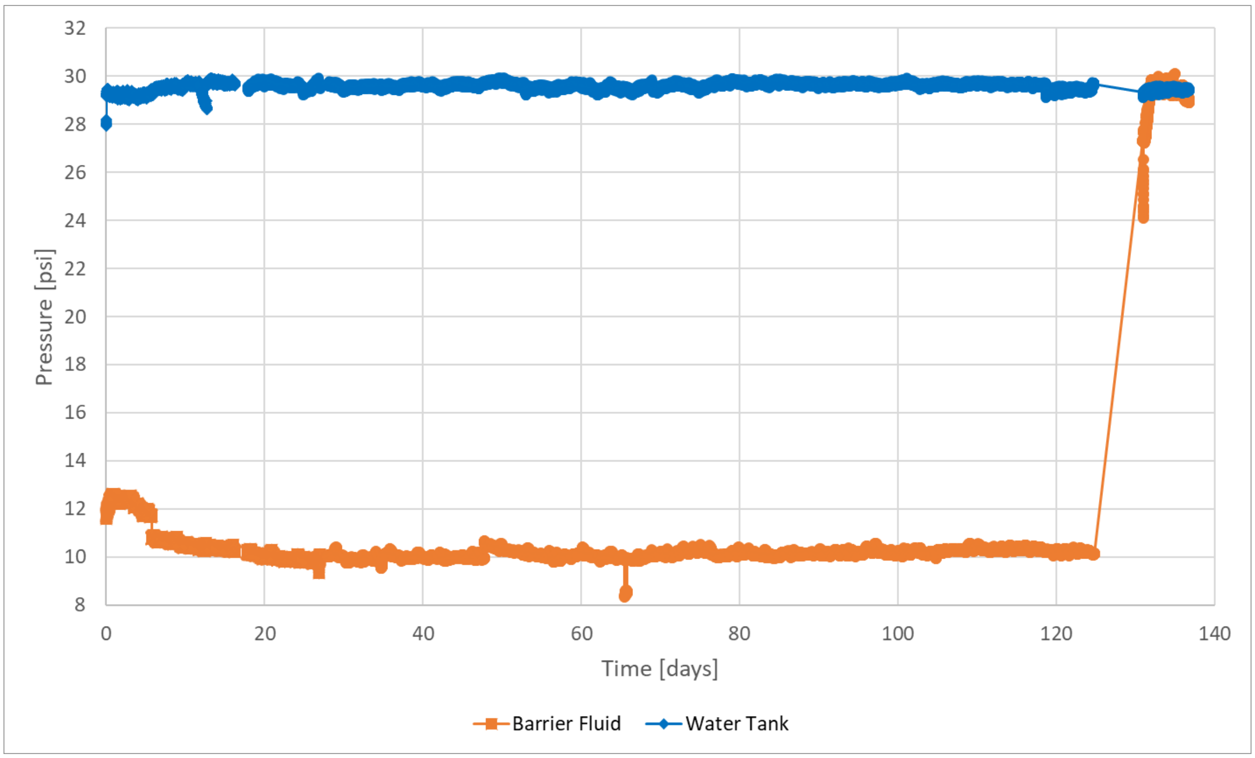
Task 4 Results Summary:

Main Shaft Seal Wear

The main shaft seal was tested continuously for 130 days while recording the water tank pressure, BF pressure, and seal temperature. These results are shown in Figure 5 below. The test stand operated in cycles of 59.5 minutes on at 160 rpm and 0.5 minutes off. During this time, it recorded a total of 3,312 cycles and 31.5 M revolutions. In terms of revolutions this is approximately 40% of the expected 78.8 M revolution during the 5-year SI. These cycles occurred over a total on time of 137 days.

The water tank was maintained at a constant pressure of 29 psi with a regulator. The BF began at 11.4 psi which is atmospheric pressure in the facility in which this testing was conducted. The initial drop in BF pressure after 5 days was due to the oil sampling discussed in section 2.1. After taking this first oil sample the BF pressure decreased to 10.2 ± 0.3 psi and remained there for more than 100 days. An attempt was made to collect another oil sample around day fifty, however this was unsuccessful. Air was heard drawing into the valve and only a few milliliters of oil were collected. This sample did not show any measurable water volume. For the remainder of testing the system was left to operate while pressure and temperature were monitored continuously. During this time pressure remained stable and no leakage was observed in the BFLR or through the back of the seal indicating the seal was successful in preventing water ingress.

The test system was shut down due to a planned power outage for maintenance of the test facility and remained down for five days. Upon restarting the system, it was seen that pressure had equalized across the main shaft seal and significant water leakage was observed in the BFLR. After an oil sample was taken it became clear the seal could no longer prevent water leakage at the front anti-friction ring/seal facing ring interface. This change in behavior could not be accounted for so the testing was stopped.



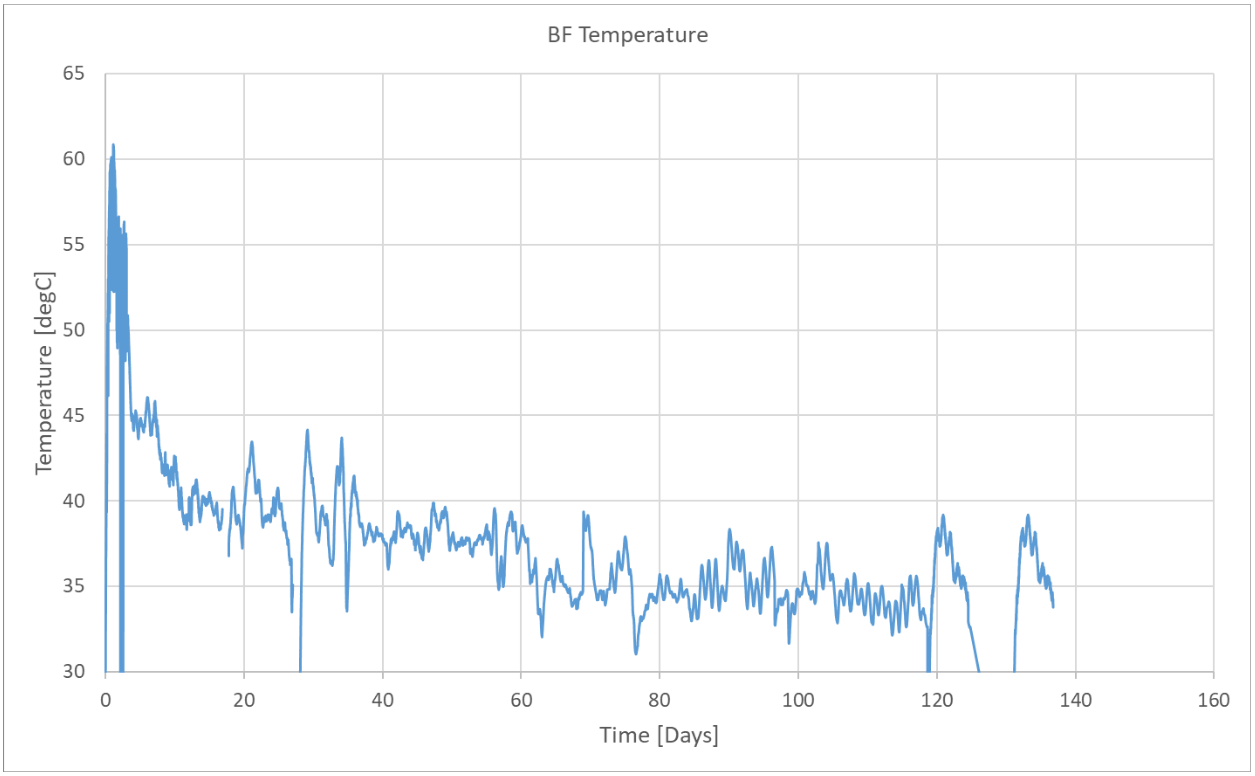


Figure 5: (Top) Water tank and BF pressure during operation. (Bottom) Temperature of the BF during operation. The BF temperature sensor is placed inside the housing to best measure the operating temperature of the seal.

Figure 5 (top) shows the BF pressure increases marginally during the first few days of testing. During this time the BF temperature varied from a peak of 61°C to a low of 30°C. While the average temperature range for most of the testing was 35°C to 40°C. The highest temperatures were recorded during the first 10 days. This period also corresponds to the largest motor current draw, shown in Figure 6 and when the most water leakage was recorded in the initial oil sample, 26 ml. It is likely this initial period corresponds to a brief wear in time where asperities between the anti-friction rings and seal facing rings are eroded away and smooth sealing surfaces form. After this period temperature stabilized and was significantly influenced by diurnal rhythms within the testing facility. Additionally motor current draw reduced and stabilized.

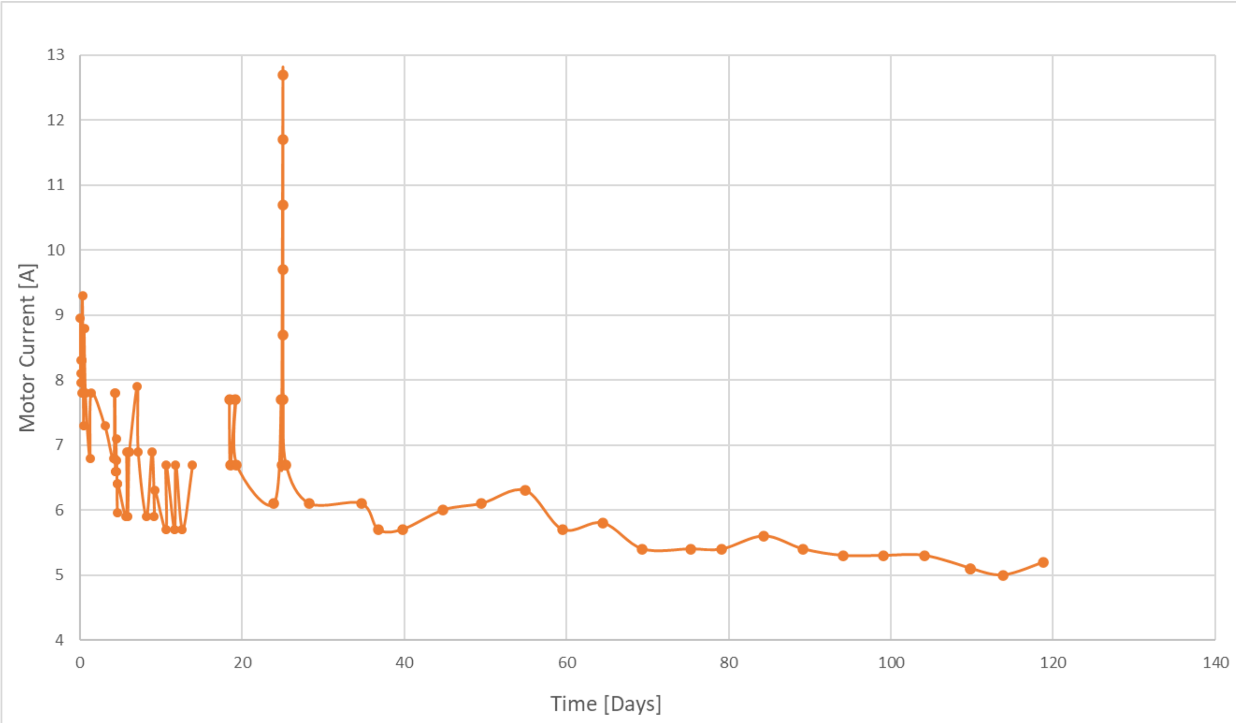


Figure 6: Motor current draw of test stand during operation. This measured the current required to maintain a constant 160 rpm.

The gap in the data at 18 days and the spike in at 25 days were due to a circuit braker failure and reactivation. The motor current draw was relatively large and chaotic initially during the theorized wear in period before settling into a more stable, slowly decreasing trend for most of the testing. This is consistent with a brief wear in period while the asperities are worn away between the mating surfaces. It also suggests the combination of BF and carbon particulate form an effective lubricating medium that produces a more favorable interface conditions during operation.

At the end of testing, 125 days, an unexplainable step change in BF pressure was recorded. Because of this it was decided that any future results would not be meaningful, so testing was stopped for the final data collection. When draining the water and BF tanks approximately 1.1 liters water was found in the BF an equal amount of BF in the water tank. Only minimal fluid leakage was recorded through the back of the seal into the atmosphere. The collected fluids can be seen in Figure 5. Considering the seal maintains a pressure gradient between the water tank and the atmosphere, it was believed a small pressure gradient would always exist across the seal. This was clearly not the case after the test ending malfunction given the observed fluid exchange.

Figure 7: Images showing the fluid removed from the water tank. The BF floats on top of the water and is stained black from suspended graphite particles worn away from the anti-friction rings.

Disassembly and Wear

The main shaft seal was disassembled at the conclusion of testing to inspect the components and measure the amount of material removed from the wearing surfaces. The mass of material removed from each ring is given in Table 1 below. The front, water facing, side of the seal suffered more wear than the back side. Additionally, the carbon anti-friction rings suffered more wear than any of the other components as expected. The carbon rings have lower abrasion resistance than the bronze seal facing rings, so they wear fastest. As anticipated, the rubber drive rings did not experience any wear because they should not slip against the shaft or the spring compression ring.

Table 1: Mass lost from each component which may experience wear during operation.

Component		Original Mass [g]	Final Mass [g]	Mass Loss [g]
Graphite Anti-Friction Ring	Front	204.5	202.0	2.5
	Rear	205.0	204.5	0.5
NBR Drive Ring	Front	80.0	79.5	0.5
	Rear	80.0	79.5	0.5
Bronze Seal Facing Ring	Front	350.0	349.0	1.0
	Rear	349.5	349.0	0.5

In addition to experiencing asymmetric wear between the front and back ant-friction rings, the individual rings were also worn radially asymmetric. The carbon ring wore on a lip at the interface between the anti-friction ring and the bronze seal facing ring. The original and final height of this ring are given in Table 2. The front ring experienced more wear than the rear ring. The height difference between the highest and lowest point was 0.6 mm. This creates a plane angled 0.2 degrees relative to the back of the ring which does not experience any wear. The rear antifriction ring had significantly less wear with a maximum height difference of 0.21 mm. After testing the wear surface of the front ring was almost completely worn away at the lowest point.

Table 2: Change in height of the wearing surface on the graphite anti-friction ring.

Component		Original Height [mm]	Minimum Height [mm]	Maximum Height [mm]
Graphite Anti-Friction Ring	Front	1.167	0.27	0.87
	Rear	1.167	0.88	1.11

Failure

The system showed no signs of failure prior to the shut down at 125 days which is slightly unusual for shaft seals of this type. Typically, some leakage is expected during operation and can be an effective method for monitoring the seal's health [5], [6]. The current setup's lack of leakage could be a result of testing conditions [7]. This system was exposed to potable water with minimal contamination from any particulate debris. There were also no external loads applied to the main shaft such as pitch or yaw moments which could be expected in deployed hydrotubrine systems. Finally, the test procedure had this seal operating on a 99.2% duty cycle 160 rpm as opposed to a more realistic 75% duty cycle at 40 rpm. It is possible that more realistic test conditions would cause more leakage during testing. Mimicking tidal conditions, as was done in the 2015 test to including dissolved minerals or suspended particles in the water tank might results in more leakage.

The axial asymmetric wear observed on the graphite anti-friction rings is a concern. It is not entirely clear why the front ring experienced wear so much more drastically than the rear ring. The compression ring should apply equal force on the front and rear ring, so compressive forces should be equalized front to rear.

Considering only the front graphite ring, the circumferentially asymmetric wear is more difficult to understand. The most likely explanation is an assembly error or disruption to the test stand setup machine during the power outage. The MSS was assembled according to instructions provided by the manufacturer and functioned continuously for 137 days suggesting the seal was assembled correctly, however, the wear pattern suggests non-uniform loading from the compression rings. The compression rings use a series of springs and alignment pins to create constant outward pressure in the wear surfaces and increase sealing potential. If these springs or pins were cocked in the housing this, in combination with the more hazardous environment at the front of the seal housing, could create the necessary conditions for the observed wear pattern. Aside from the observed results there is little evidence to support this theory, so further evaluation of the seal components is warranted.

These results suggest the MSS may not have completed the entire SI before failure. The front graphite ring was worn through 77% of the interfacial lip on one side suggesting failure was likely to occur before completing the SI, however this is difficult to determine because the wear rate is uncertain. Based on the wear in period seen in Figures 5 and 6, wear rate is not constant, but without more information it is not possible to determine its actual value. The objective of BF sampling was to determine the graphite particle generation rate, however this was unsuccessful as BF pressure prevented sampling.

NBR Accelerated Aging

The data from the accelerated rubber aging tests is shown in Figure 8: Shore A hardness of the NBR drive rings during accelerated aging testing. The rings were allowed to cool to room temperature before measurements were taken. below. The rubber drive rings began with a hardness of approximately 65 Shore A. The recorded hardness increased asymptotically up to 90 Shore A in 70 days. This is consistent with previously reported results [5]. Significant hardness variation was observed during testing and is largely attributed to variations in temperature. Hardness testing required handling, so they were allowed to cool from 90°C to room temperature. However, the ambient temperature varied significantly from 16°C to 23°C.

After wear testing completed the drive ring hardness for the in-situ rings was measured as 76.8 and 77.4 for the front and rear rings respectively. The wear testing was conducted for approximately 130 days at between 35°C and 40°C depending on ambient temperature and heat generated from friction. This suggests the seal hardness is highly dependent on ambient temperature. Considering the wear testing simulated 40% of the expected SI, the drive rings are unlikely to reach full hardness before the SI completes.

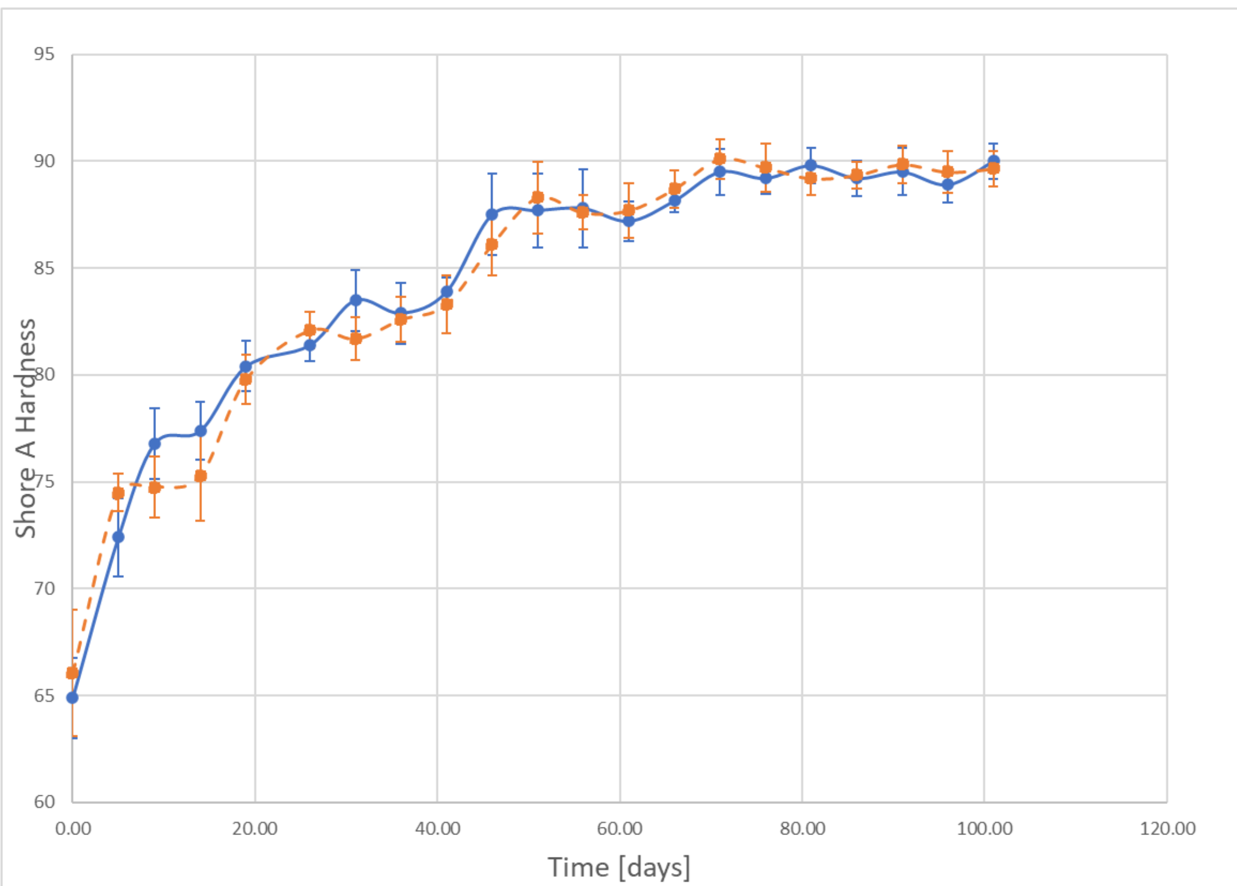


Figure 8: Shore A hardness of the NBR drive rings during accelerated aging testing. The rings were allowed to cool to room temperature before measurements were taken.

7.2 Lesson Learned and Test Plan Deviation

In this study the MSS test rig provided by Verdant Power was modified to include pressure measurements of the water tank and BF, and BF sampling. Additionally, the motor current, and water leakage volume could be monitored periodically during testing. This testing apparatus met the requirements for shaft seal testing outlined in ISO 6194. The objective for accelerated lifetime testing was to determine the MSS ability to function continuously for the 5-year SI and what factors could be used for health monitoring of the seal. An accelerated aging test was also conducted on additional rubber drive rings to measure the change in rubber hardness over time.

Wear

Initially, the MSS showed a brief wear-in period where temperatures, pressure, and motor current demands were highly variable. Based on the volume of material missing from each ring, the most significant wear occurred on the graphite anti-friction rings at the interface with the bronze seal rings. It was during this period that the largest graphite particles were produced and the rubber drive rings experienced the most significant change in hardness. This phenomenon was not seen in the 2015 testing. After this wear in period the seal behavior became much more predictable with lower temperatures, constant pressure, and stable motor current demands. This continued for the majority of testing. The seal completed 31.5M revolutions, or 40% of the 78.8 M revolutions expected in the SI prior to the NREL lab power failure and likely disruption of the test stand.

The seal showed significant asymmetric wear between the front and rear wearing surfaces as well as circumferentially around each ring. The exact cause of this asymmetry is not known, however possible causes is an assembly issue. Regardless, this is likely to reduce the effective lifetime of the seal. Documentation should be created to detail the proper assembly of the seal and, if possible, ways to inspect the assembly during operation to ensure consistent performance.

Leakage

An interesting result is the total lack of water leakage during this steady state interval. BF pressure remained approximately 1 psi below atmospheric and water leakage could not be seen in the BFLR. It is also possible the potable water used in the water tank did not provide an appropriately hazardous environment artificially reducing wear and leakage rates. Based on the expected deployments of these hydroturbines further research is recommended in sea water, brackish water, and water with suspended solids such as sand.

The MSS was able to maintain a 20 psi pressure differential between the water tank and atmosphere which was an unexpected result that did significantly impact the project's ability to determine wear rate based on particle generation measured from BF samples. A pressure relief valve could have alleviated this issue but was not included because BF pressure was used to monitor seal health, i.e., water leakage into the BF would change the BF pressure, so a valve would have negatively impacted the leakage monitoring objective.

The significant leakage and ultimate failure of the system is not entirely clear; however, it is likely due to an external perturbance of the system. Either, caused by the power outage or some other disturbance, such as an accidental collision between the test stand and another piece of equipment. Therefore, the seal failure cannot be taken as conclusive evidence of this seal's inability to meet performance requirements.

Additionally, the current test ended after the system was stopped for facility maintenance and suffered a catastrophic malfunction at that time. Again, this is unusual for this type of seal, and it is surmised that assembly or movement/ disturbance of the test stand during the outage was responsible

8 Conclusions and Recommendations

This project employed a long duty cycle of 99.2%, however the much shorter duty cycle seen in-situ may also contribute to higher leakage rates. This should be explored further in future studies. Prior to the outage, the results indicate that the seal successfully completed 40% the desired 5-year service interval. A follow-up TEAMER should be explored to reinitiate the accelerated testing by:

- Improving the setup protocol and conditions
- Involving Verdant /Garlock in assembly at setup
- The wear pattern on the front graphite ring shows a 77% reduction in volume during testing.

9 References

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10 Acknowledgements

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11 APPENDIX

See additional content at https://www.nrel.gov/docs/fy24osti/89380.pdf.