U.S. DEPARTMENT OF ENERGY
ABRASION TESTING OF CRITICAL COMPONENTS OF HYDROKINETIC DEVICES
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FINAL TECHNICAL REPORT

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Project Title: Abrasion Testing of Critical Components of Hydrokinetic Devices
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EXECUTIVE SUMMARY

Ocean Renewable Power Company, LLC and its wholly-owned subsidiary ORPC Alaska, LLC (collectively ORPC) is a global leader in hydrokinetic technology and project development. ORPC develops hydrokinetic power systems and eco-conscious projects that harness the power of oceans and rivers to create clean, predictable renewable energy. ORPC's technology consists of a family of modular hydrokinetic power systems: the TidGen[®] Power System, for use at shallow to medium-depth tidal sites; the RivGen[®] Power System, for use at river and estuary sites; and the OCGen[®] Power System, presently under development, for use at deep tidal and offshore ocean current sites. These power systems convert kinetic energy in moving water into clean, renewable, grid-compatible power. The core technology component for all ORPC power systems is its patented turbine generator unit (TGU). The TGU uses proprietary advanced design cross flow (ADCF) turbines to drive an underwater permanent magnet generator mounted at the TGU's center. It is a gearless, direct-drive system that has the potential for high reliability, requires no lubricants and releases no toxins that could contaminate the surrounding water.

The objective of the Abrasion Testing of Critical Components of Hydrokinetic Devices (Project) was to test critical components of hydrokinetic devices in waters with high levels of suspended sediment – information that is widely applicable to the hydrokinetic industry. Tidal and river sites in Alaska typically have high suspended sediment concentrations. High suspended sediment also occurs in major rivers and estuaries throughout the world and throughout high latitude locations where glacial inputs introduce silt into water bodies. In assessing the vulnerability of technology components to sediment induced abrasion, one of the greatest concerns is the impact that the sediment may have on device components such as bearings and seals, failures of which could lead to both efficiency loss and catastrophic system failures.

In the TGU, fluid power is transferred from the turbines to the underwater sealed permanent magnet generator via a rotating shaft that is supported by bearings and passes through a seal, excluding water from the generator. Seal failure could lead to water intrusion and catastrophic generator failure. Bearing wear could lead to excess energy loss, and could transfer excessive load to the seals, causing their premature failure or increasing the frequency of costly maintenance operations. This Project tested various combinations of bearings and seals to determine the wear rate of these components, in order to identify which configurations best resist degradation from suspended sediment abrasion.

ORPC partnered with the University of Alaska Anchorage (UAA) to test one-fifth scale bearings and seals of various types in laboratory controlled high suspended sediment conditions. This

testing produced rigorous data on bearing wear rates and seal performance over long-term operation.

The research adds to the understanding of the area investigated by providing information on how various bearings responded to lateral loading typical of cross flow hydrokinetic turbines in both clear and high suspended sediment water conditions. Data on this type of application was either non-existent or not in the public domain. Bearing manufacturers themselves were highly interested in this data for this reason, and this data may be useable by other hydrokinetic turbine manufacturers as well.

COMPARISON OF ACTUAL ACCOMPLISHMENTS WITH GOALS AND OBJECTIVES

Objectives:

1. Assess the vulnerability of technology components to sediment-induced abrasion

Accomplishment:

In this project, four bearing types (Vesconite, CIP, Feroform T814, and PCD) and single- and double-cartridge Chesterton seals were tested in a flume with high suspended sediment concentrations (1 g/L). Each bearing type was tested in a test station that consisted of a 25.4 mm diameter steel shaft (rotated at 300 rpm), three loaded bearings on that shaft, and two single-cartridge Chesterton seals on either end of the shaft preventing water and sediment from leaking out of the flume. The polymer bearings (Vesconite, CIP, and Feroform T814) were tested on an unmodified 25.4 mm diameter steel shaft. The PCD bearings were tested on a specially designed shaft.

Two 60 hour tests – one with clear water and one with high suspended sediment water – were performed on each bearing type. The steel shaft used for the polymer bearing tests was, therefore, employed for a total of six 60-hour tests. Measurements of wear (abrasion) of the four bearing types were made following testing with both clear and high suspended sediment water. Overall, the PCD bearing suffered significantly less wear than the three polymer bearings, which had varying amounts of wear in each test; however wear was not significantly higher in the high suspended sediment tests than in clear water. The seals exhibited leakage during testing, and one was deemed to be not repairable by the manufacturer. Following the testing with high suspended sediment water, the team observed significant scoring of the shaft that had not appeared in clear water testing. The scoring was most pronounced near the location of the bearing edge. Measurements conducted with a dial indicator (from a lathe) found that, on average, the shaft diameter (nominally 25.4 mm before testing) was reduced by 0.189 mm in the areas where bearings were located. The maximum amount of abrasion observed was 0.309 mm.

While the goal of testing was to assess the vulnerability of bearings and seals to sediment-induced abrasion, the finding of significant shaft wear was an additional concern, which was not originally anticipated.

2. Determine the impact that sediment may have on bearings and seals

Accomplishment:

Sixty-hour flume tests with high suspended sediment water were conducted following sixty-hour tests with clear water on four bearing types (Vesconite, CIP, Feroform T814, and PCD) with both single- and double-cartridge Chesterton seals. Measurements of wear on individual bearings were made for all four bearing types.

The various bearing types exhibited differing wear amounts that were measureable in both clear water and high suspended sediment water tests, allowing the different bearing types to be compared with one another for suitability for this application. Seal failures were also observed during testing in both single and double cartridge seals, highlighting the importance of the relationship between bearing wear and its impact on seal performance. The high suspended sediment water did not however show significantly higher wear on the bearings than the clear water.

3. Determine the wear rate of bearings and seals

Accomplishment:

Measurements of wear on individual bearings were made for all four bearing types with both clear and sedimented water and plotted to compare the rate of degradation of bearings. Damage to seals during testing was also noted.

4. Identify which configurations best resist degradation from suspended sediment abrasion

Accomplishment:

The PCD bearings were observed to resist abrasion better than the three polymer bearing types in both the clear and sedimented water tests. The PCD bearing also had a lower Coefficient of Friction making it a more efficient bearing choice as well. The three polymer bearings showed varying wear rates with the Feroform T814 and CIP bearings outperforming the Vesconite bearings in terms of wear.

SUMMARY OF PROJECT ACTIVITIES

Original Hypotheses

The presence of sediments in water will affect the performance of bearing-seal assembly. An experimental setup needs to be designed and fabricated to collect data on bearings-seal assembly performance under operating conditions similar to field conditions. Quantify bearing wear with time and identify effects of bearing wear on seals performance.

Approaches Used

Flume Design:

A customized flume was initially designed using Pro-Engineer part and assembly module. Finite element study was performed in ABAQUS to validate the design. Specifications were established for instrumentation. Figure 1 shows the final design of the flume with three test stations.

Figure 1. The final flume design (return pipe assembly and chiller are not shown)

An example of finite element analysis in one of the bearing supports is shown in Figures 1-2. The boundary conditions were defined by fixing the base. A bearing pressure of 850 lb/in² was applied on the projected bearing area of 1.1 inches x 1.07 inches. The initial design included steel supports. However, due to a higher projected machining cost, the support material was replaced by 6061-T6 grade Aluminum, which has yield strength of 40 ksi. In Figure 2, the stress contours show that the maximum stress value is 3.7 ksi in the 1 in. square cross-sectional column, which is well below the yield strength of the material. By taking into account the stress concentration factors due to geometric imperfections, vibrations, and partial impact loading, the design team decided to keep the dimensions of the support column as (1x1) inches in order to have a (minimum) factor of safety of 3 to 4. The displacement contours (Figure 3) showed maximum relative nodal displacement on the bushing sides and helped in selecting the clamping bolt locations.

Figure 2: Stress distribution on bearing support under 1000 lbf load.

Figure 3. Displacement contours on bearing support under 1000 lbf load.

Fabrication and Assembly:

The flume was assembled at UAA design studio facility. Parts were built using different manufacturing methods such as machining, welding, sheet metal working, etc. Figures 4 a – e show the fabrication and assembly process of first station.

Figure 4. Fabrication of first station

(b) Machined bearing mounts

(c) Side bearings installed on the first station

(d) All three bearings mounted on the first station

(e) First station is filled with clean water and bearings are ready to test

Figure 4. Fabrication and assembly of first station

The entire system consisted of two test stations, inlet and outlet diffusers, water reservoir, paddle flow meter, (custom built) cross-flow heat exchanger, and instrumentation and control panel as shown in Figure 3. Each test station was comprised of three bearings and split support mounts, resistance temperature detectors (RTDs), a shaft, two seals, motor, load cell, hydraulic actuator, and linear variable differential transducer (LVDT). Each test station housed three bearings, which were aligned in a single row and positioned in such a way as to imitate the arrangement of bearings deployed in the field. Figure 4 shows the portion of the cross-section of the station containing bearing, bearing mounts, and seals. In order to reduce any unnecessary wear due to deflection of the shaft, the two outer bearings were kept as close as possible to the center load-carrying bearing. The center bearing was mounted in such a way that horizontal motion was constrained with limited vertical motion. The two outside bearings were mounted in fixed positions and acted as supports when the center bearing was loaded. This arrangement constrained any deflection transferred to the seals. Each of the bearing mounts was equipped with an RTD to measure the temperature of the bearings during the flume operation. A force of

2250 N was applied on the middle bearing mount by using a linear hydraulic mechanical actuator. A one horsepower Marathon Electric washdown motor was used to turn the shaft at 300 rpm. The shaft speed and applied load developed a Pressure-Velocity (PV) value (in the contact area) comparable to that expected in the field. Water was circulated through the flume at a rate of 1136 liters per minute and maintained at a temperature of 7.22 degrees Celsius using the heat exchanger. In order to prevent water from leaking from test stations, mechanical seals with single contact surface and double contact surfaces were installed. These seals emulated the seals in a hydrokinetic device that exclude water from a submerged generator. Station 1 was used to test polymer bearings and Station 2 was used to test special Polycrystalline Diamond Coated bearings.

Figure 5. The fabricated flume

Figure 6. The cross-sectional view of a single station

Tests:

Four types of bearings were tested; Polycrystalline diamond, CIP Marine, Feroform T814, and Vesconite Hilube, as shown in Figure 7.

Figure 7. The four candidate bearings tested in this study are shown left to right – Vesconite, CIP Marine, Feroform T814, and Polycrystalline diamond radial bearing

A list of relevant mechanical and thermal properties of candidate bearings is presented in Table 1.

Table 1. *Mechanical and thermal properties of candidate bearings*

	Vesconite	CIP	Feroform T814	PCD
Bearing type	Fluted Bushing	Fluted Bushing	Fluted Bushing	Bushing/Diamond inserts ring
Bearing material	Specialized thermoplastic made from internally lubricated polymers	Proprietary blend of textile, lubrication and resin mixture specifically formulated for the Marine industry	composite material made from woven fiber bonded with resin with PTFE as a friction modifier	Diamond grit fused together under high pressure, high temperature in the presence of a catalytic metal
Density (g/cm ³)	1.3	1.3	1.3	not available
Hardness	Shore D, 84	Rockwell, 100	Brinell, 25	Knoop, 49
Compressive strength (MPa)	92	103	68.9	7,000
Modulus of Elasticity (MPa)	Tagent, 3400, compression, 2290	Tensile, 3240, flexure, 1793	not available	Young's, 841,000
Operating temperature (°C)	-40 to 65	-40 to 93	100	not available
Co-efficient of thermal expansion (°C ⁻¹)	6x10 ⁻⁵	7.2 x10 ⁻⁵ normal to laminate direction, 3.6x10 ⁻⁵ parallel to laminate	70 x 10 ⁻⁶	not available
Co-efficient of friction	Dry, vesconite on steel, 0.09 to 0.1	not available	Dry, 0.04-0.08, wet, 0.06 to 0.09	Wet, PCD on PCD, 0.05 to 0.08
Reasons for selection	Each bearing type was selected based on <ul style="list-style-type: none"> • recommendations by bearing experts • manufacturer's recommendation that the bearing was designed to operate under the test conditions of present study. • Interest or experience from Hydrokinetic device developer in using bearing type 			

Two types of seals, single cartridge seal and double cartridge seal, were tested in the present study and shown in Figure 8.

Figure 8. The candidate seals tested in this study. The left seal is single cartridge mechanical seal and the right seal is double cartridge seal.

Each bearing type was tested for 60 hours in clean water and then an identical but new bearing was used for the same duration in the sedimented water (1 g/L sediment concentration). This duration was long enough to allow measureable wear on bearings. A test protocol was developed and implemented to maintain consistency in performing the tests.

In order to replicate sediment conditions that might be encountered in an actual river or tidal deployment in Alaska, natural sediment conditions were examined. There is a wide range of sedimentary conditions in Alaska waters in which hydrokinetic devices could potentially be deployed. In Cook Inlet (by Fire Island), analysis of suspended sediments by UAA (and others) found grain sizes ranging from fine silt (10 microns) to fine sand (100 microns). Suspended sediment concentrations up to 600 mg/L were measured. Similarly, in the Kashunuk River on the Yukon Kuskokwim Delta, analysis of samples indicate suspended sediments ranging from fine silt to fine sand (100 microns) and concentrations up to 800 mg/L. A USGS study of suspended sediments in the Yukon River found concentrations up to 1.1 g/L, with most common mineral in the silt and sand size range being quartz (USGS 2006, http://pubs.usgs.gov/of/2006/1258/pdf/OFR_20061258.pdf). The USGS 2006 study also found concentrations up to 1.6 g/L in the Tanana River at Nenana. Given these considerations, the sediment sizes, mineralogy, and concentration tested in the flume were chosen to be representative of the sediments typically seen in Alaska waters where hydrokinetic devices might be deployed.

Table 2. *Sediment size and quantity introduced into flume*

Sediment type	Grain size	Quantity
Yukon bed sample	d ₅₀ = 0.2 mm (range 0.18mm-0.25mm)	90 g
Industrial sample 1	d = 0.010 mm	40 g
Industrial sample 2	d = 0.028 mm	50 g
Combined samples	d ₅₀ = 0.07mm	180 g

The main purpose of utilizing flowing water in the flume was to keep this sediment suspended and create turbulence that would be present in a natural setting and would provide a mechanism for sediment intrusion into bearing parts. When designing the system, the flow rate (300 gpm, 0.019 m³/s) and velocity (0.53 m/s) were chosen to ensure particles would remain suspended in the test section of the flume. Assuming a flume bottom/wall roughness of 0.2 mm, the bottom/wall shear stress and friction velocity (u_*) are about 0.8 Pa and 0.028 m/s, respectively. Sediment transport calculations indicate that the finer particles ($d < 0.05$ mm, with fall velocity $w < 0.008$ m/s) would have a u_*/w ratio of 13.8 and would be distributed nearly uniformly throughout the flume cross-section. The larger particles ($d \sim 0.2$ mm, $w \sim 0.026$ m/s) would have a u_*/w ratio of about 1.1 and would not be expected to be uniformly distributed in the flume cross-section, assuming that it was uniform in the flow direction. Calculations indicate that between 40-50% of the sediments would be transported in the suspension (the remainder would be transported along the bottom as bed load). Further, concentrations of suspended 0.2 mm particles would be much higher near the bottom than they would be at the elevation of the bearings under testing. However, the reality of the flume geometry, with an expansion section upstream of the test section and with several bearing mounts in the flow path, would suggest that the actual turbulence was much higher than that suggested by a uniform flow model. Hence, it is expected that the courser 0.2 mm diameter particles would be suspended at the elevation of the bearings in significant numbers.

Data collection, analysis and results:

During each test, bearing contact surface temperature, vibrations, and wear rates were recorded. Seals were monitored visually for any obvious water leak. At the end of 60 hours test for each bearing, power consumption of the motor drive assembly was recorded while loading the center bearings from no load to full load at ramping load rate. Following collection of power data, bearings were dismounted and total wear was measured using internal contact gauges and micrometers.

Clean Water:

Figures 9 and 10 display the total wear on the inner diameter of each bearing tested in the load-bearing (vertical) and water flow (horizontal) directions, respectively, after 60 hours of testing in fresh clean water. The center bearings which were exposed to the highest pressure-velocity (74.17 MPa. m/min) experienced the highest amount of wear as compared to drive and far side

bearings with roughly half the pressure-velocity values of the center bearing. The PCD bearings experienced the least amount of wear among the candidate bearings followed by Ferroform T814, CIP Marine, and Vesconite, respectively. The far side Vesconite bearing experienced slightly more wear in the load-bearing direction than the drive side and center bearings in the load direction. In the flow direction, far side Vesconite bearing showed less wear as compared to Ferroform T814 and CIP Marine bearings. These deviations may be attributed to misalignment of the shaft during the Vesconite bearing test. The drive side PCD bearing showed a negative value of wear in the flow direction. The reason of this anomaly is probably due to the deposition of wear particles on PCD inserts or some metrological error or uncertainty in wear data. No noticeable wear on the shaft surfaces was observed at the end of clean water tests.

Wear in load direction

Figure 9. Total wear of bearings in loading direction

Wear in flow direction

Figure 10. Total wear of bearings in flow direction

Table 3 lists the wear data collected for candidate bearings tested in the present study.

Table 3. *Wear data of bearings in loading and flow direction in clean water. All dimensions are in millimeters.*

		Initial ID avg.	Final (Load)	Final (Flow)	Change (Load)	Change (Flow)
Vesconite	Drive	25.21	25.71	25.40	0.50	0.19
	Center	25.15	26.65	25.46	1.50	0.31
	Far	25.29	26.05	25.37	0.76	0.08
CIP Composite	Drive	25.53	25.87	25.69	0.34	0.16
	Center	25.51	26.08	25.70	0.57	0.19
	Far	25.53	25.93	25.68	0.40	0.15
Feroform T814	Drive	25.65	25.86	25.78	0.21	0.13
	Center	25.62	25.99	25.78	0.37	0.16
	Far	25.66	25.92	25.80	0.26	0.14
PCD	Drive	25.38	25.38	25.37	0.00	-0.01
	Center	25.36	25.36	25.36	0.00	0.00
	Far	25.35	25.36	25.36	0.01	0.01

Figure 11 shows the wear of the center bearing of each type with time in clean water. Due to the absence of the LVDT sensor in the Vesconite bearing test, the data for Vesconite bearing is unavailable for clean water. The curve for PCD bearing remains more or less constant reflecting no wear at all. The Ferroform T814 bearing shows lower rate of wear as compared to CIP bearing. For the first eight to thirteen hours of testing, the high wear rate for both Ferroform T814 and CIP is evident in Figure 11, which is probably due to the settling of bearing surfaces on the shaft contact contour. The wear curves are approximated by bilinear equations. The wear rate for

[Pages 18-29 have been removed.]

Pump malfunction:

During the clean water test for the Vesconite bearings, the pump stopped working. The authorized pump dealer was contacted to diagnose the problem. It was found that the pump impeller was locked. This problem was repeated while performing the Ferroform clean water test and the team learned that if the pump sits inactive for more than a week, impeller lock occurs. Therefore, a preventive plan was implemented where flume operators would run the entire system at least once a week.

Load cell creep:

During the tests, load cell readings will creep. This problem was investigated and it was discovered that load cells are prone to creep with time. A plan was implemented to check and adjust load cell every two to three hours.

Vibration data analysis:

Anticipated vibrations in the shaft-bearing assembly were not measurable due to the experimental setup. The fixed unidirectional load applied to the center bearing did not allow for excess lateral movement. Additionally, any vibration due to the bearing-shaft interface was within the noise floor of the accelerometer measurements. The largest vibrational components in the measurements were directly in-line with the frequencies of the main circulation pump and the chiller pump. These vibrations traveled through the cement floor and were coupled into the steel structure supporting the flume. Frequency domain analysis of the vibrations showed a direct correlation to the pump and chiller. There was no discernable vibrational component at the frequency, or any harmonically related components, of the shaft drive motor. Because vibrations of the shaft-bearing assembly were not measureable, collection of vibration data was terminated.

Departure from Planned Methodology

- Initially 9 test stations were proposed, however, a decision was made to design (and fabricate) a single station first and add additional stations later. This approach allowed the project team to identify problems in early stages of (station) design and the fabrication phase.
- It was originally proposed that the apparatus, once built, would be operated in auto mode without any direct supervision. However, due to load cell and seal adjustments on regular time intervals and issues with main pump, the flume had to be monitored during its operation. For this purpose, an undergraduate mechanical engineering student was hired.
- After carefully analyzing the number of bearings to be tested, installing two different types of seals on a single station, and performing tests in series (instead of in parallel), the total number of needed stations to complete testing were reduced to two stations.
- In the proposed methodology, seals were to be tested to their failure, however, with bearing wear data, a relationship was established that would project seal failure using seal tolerances in relation to bearing wear. This critical piece of information voided the need for long term testing for seals.

- An unplanned aspect of data collection and analysis was that the power data was also utilized to establish the COF for each bearing type, an additional analytical piece of work and accomplishment not originally proposed in the project scope.
- The Project team decided not to introduce saline water in order to preserve the test apparatus from corrosion to allow it to have a longer operational lifetime for future tests.
- The duration of long term testing was reduced as data in 60 hour tests proved adequate in collecting comparative data of bearing wear for the prospective bearings investigated under this project and project timelines and budgets precluded further testing.

Conclusion

Having observed bearing wear and seal damage in field tests of ORPC technology and with the pending deployment of ORPC technology in Alaskan waters with high suspended sediment concentrations where this wear might be accelerated, it was essential that the company understand this issue before moving forward into these environments. The lack of publicly available data on how different bearing types and materials would react to this new environment further underscored the importance of collecting laboratory data on this issue. ORPC in partnership with UAA successfully built and operated laboratory equipment to collect the first publically available data on suspended sediment and its effect on four different bearing types.

The results of the data collected from these tests confirmed some previously conceived hypothesis and also revealed unexpected information that will be essential to decision making on component selection for ORPC technology and may be useful to other hydrokinetic device manufacturers and other industries.

Of the four bearing types tested, the team expected the PCD bearing to wear the least due to the hardness of the diamond coating on its surfaces. However, we did not know how this would compare to the different polymer bearings and how they would compare to one another. Having had experience with the Vesconite bearings in the field we expected them to have a higher wear rate than some other bearings. We were, however, surprised to see how much less the PCD bearings wore than any of the polymer bearings. The observation that with polymer bearings some wear appeared to be transferred to the shaft when sediment was introduced had been previously postulated due to experience of shaft scoring in field deployments of ORPC technology, but was definitely established in this testing. The team was also surprised to see that the PCD showed lowest coefficient of friction compared to the polymer bearings. This information is all useful as ORPC moves forward in designing bearing systems.

Interestingly to the team, bearing wear in sedimented water was essentially equivalent to the wear of each bearing in clear water. The team hypothesizes that with the polymer bearings in clear water the contact was solely between the shaft and the bearing surface, however in sedimented water there was contact between sediment that was impinged on the bearing surface and the shaft. This was evidenced by the aforementioned wear that was observed on the shaft during testing. This minimized sediment induced wear on the bearing and transferred it to the shaft. For the PCD bearing a hypothesis on similar wear between wear in clear and sediment

water is that the harness of the diamond surface may exceed the hardness of the particles minimizing the wear the particles induced on the diamond coated surfaces.

Future testing will help to further clarify the results seen in this initial testing and provide longer term data on those bearings such as the PCD where initial test durations may not have been sufficiently long to characterize bearing wear trends. For the polymer bearings future tests would ideally include a dedicated shaft for each polymer bearing type because increasing shaft wear on each subsequent test increased clearances and may have biased test results. If we had not seen this increase in shaft clearance for each bearing type results may have been different. It would also be recommended to consider a hardened shaft surface to reduce shaft wear and see how that effects bearing wear in sedimented water. Longer term tests of the PCD bearing may help to establish bearing wear rates and could show a difference between wear in clear and sedimented water. Other bearing types now under consideration for ORPC technology will also benefit from testing in this apparatus to allow comparison with the bearing types investigated here. Similarly other seal types may warrant testing and validation for cross flow turbine applications.

PRODUCTS

a. Publications

Ali, M., Ravens, T., Petersen, T., Hoffman, J., & Bromaghin, A. (2014). "Wear Characterization of Critical Sliding Components of Hydrokinetic Devices in Sedimented Water", Marine Energy Technology Symposium, April 15-18, 2014, Washington, D.C. Manuscript under preparation.

Ali, M., Ravens, T., Petersen, T., Hoffman, J., & Bromaghin, A. (2014). Comparative study of tribological behaviors of critical hydrokinetic device components in clean and sedimented water, 2014. Manuscript under preparation and will be submitted to the International Journal of Renewable Energy.

Ali, M., Ravens, T., Petersen, T. (2012). "Abrasion Testing of Critical Components of Hydrokinetic Devices", Presentation at Marine and Hydrokinetic Instrumentation, Measurement & Computer Modeling Workshop, July 9-12, 2012, Broomfield, CO.

Bromaghin, A., Ali, M., Ravens, T., Petersen, T., & Hoffman, J. (2013). "Abrasion Analysis of Critical Components of Hydrokinetic Devices: An Empirical Study", Marine Energy Technology Symposium, April 10-11, 2013, Washington, D.C.

Bromaghin, A., Ali, M., Ravens, T., Petersen, T., & Hoffman, J. (2014). Experimental Study of Abrasion Characteristics for Critical Sliding Components for use in Hydrokinetic Devices, 2013. International Journal of Renewable Energy.

Accepted.

b. Web site or other Internet sites that reflect the results of this project;

<http://www.uaa.alaska.edu/schoolofengineering/research/renewable-energy.cfm>

COMPUTER MODELING

Not applicable.