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Post Access Report

Biofouling and Corrosion Study for a Novel Linear Guided Wave Energy Converter

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EXECUTIVE SUMMARY

The overall objective of this project was to examine the reliability and performance of antibiofouling coatings used for a wave energy converter (WEC) developed by E-Wave Technologies. The particular coatings were selected for their low toxicity and potential compatibility with aquaculture. The aim of this work was to 1) test coating solutions to prevent biofouling growth and saltwater corrosion on the static (paddle and attachment frame surface) components of the WEC that are submerged, 2) determine adhesion of the coatings to system components, and 3) assess the ease and effectiveness of biofouling cleaning to insure long term performance of the system.

An analysis of commercial coatings was performed using methods to examine the prevention of biofouling and coating adhesion properties on two key materials of the WEC, which were 316L low carbon marine grade stainless steel (SS) and Ultra High Molecular Weight Polyethylene (PE). Three marine antifouling paints were selected based on their unique properties to test how different paint styles perform on different materials. The selected paints were ePaint Ecominder self-polishing paint with Zinc Omadine for slime control, Pettit ECO HRT Copper-Free ablative antifouling with Econea biocide, and Intersleek 1100SR foul release.

Pacific Northwest National Laboratory (PNNL) prepared PE and SS substrates coated with the three paints and compared the performance against uncoated substrates when submerged in raw seawater for 3-, 6-, and 9-month (m) time periods. Results in adhesion testing indicated that Pettit and ePaint materials clearly bonded strongly to SS, but did not bond comparably well to PE. It was noted during adhesion testing that the Intersleek surfaces were especially difficult to test as the paint highly resists bonding to the epoxy adhesives used with the adherence testing platform. The wear rate of the coatings was not measured under this study; however, based on adhesion testing, coatings in the sliding regions of the E-wave device are expected to wear rapidly. Sandia National Laboratories (SNL) evaluated the adhesion of three different paints to PE and SS substrates which were exposed to a marine environment for time intervals of 0, 3, 6, and 9 months. From qualitative visual analysis of the 3 in^2 coupons when pulled from the tank, the 3 in^2 coupons generally only appeared to have biofouling consisting of filamentous algae or diatoms, which all have relatively low mass and can be easily wiped from the surface of coupons. Qualitative visual analysis indicated that ECO HRT and Unpainted were consistently worse than Intersleek and Ecominder at all time points.

Results provide insight to aid with down-selection of commercial coatings under static conditions to support reliability of the WEC and potential maintenance schedules. This investigation was conducted using small coupon samples suspended in seawater and the development of testing rigs for dynamic component level testing is needed for future work. In addition, the potential toxicity of these commercial coatings on aquaculture has not been determined by this study. One recommendation is to conduct toxicity investigations at the Environmental Toxicity Laboratory at Oak Ridge National Laboratory.

1 INTRODUCTION TO THE PROJECT

Offshore aquaculture is a growing industry with a global market value of $55 billion that requires electricity for farm operations, such as fish feeding and farm monitoring systems. Currently, the only energy solution is to use diesel generators that have fuel costs 9–24 times higher than usual, due to the remote location of farms in the open ocean. With a typical power density greater than 10 kW/m, ocean wave energy is a promising alternative to meet the electricity needs of aquaculture farms.

E-Wave Technologies (E-Wave) is partnering with Innovasea Systems Inc. to develop and commercialize an innovative ocean wave energy converter (WEC) that can be retrofitted into existing aquaculture farm infrastructure to harvest ocean wave energy and power aquaculture operations. As shown in **Figure 1**, the WEC is a system of dual inclined paddles retrofitted to the existing feed buoy platform of the Open Blue offshore fish farm in Panama. The partially submerged forward and aft paddles are excited by incident waves and oscillate along the inclined guide rails, via linear bearings.

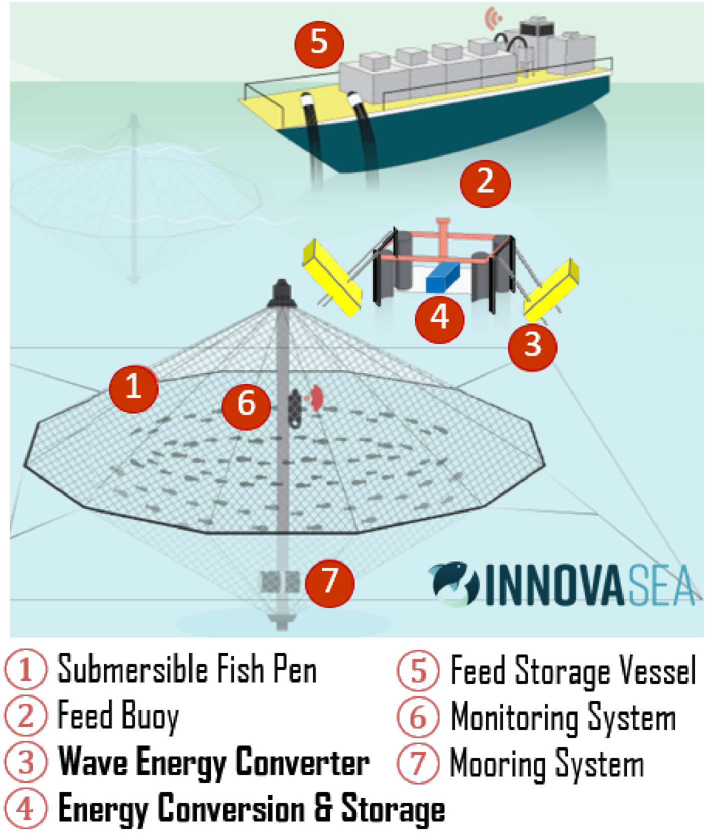

Figure 1 | WEC retrofitted into the existing feed buoy of an offshore aquaculture farm.

E-Wave's WEC has a unique design entailing a paddle that slides on linear guide rails, which is different from commonly known oscillating surge wave energy converter (OSWEC) design where the paddle rotates on a hinge. This aspect is critical to improve the power performance of E-Wave's WEC, which is at small-scale (less than 10 m) and attached to either floating or fixed structures. At the same time, use of this new guide rail and slide design in the ocean has created concerns from experts in the field with regards to biofouling and corrosion of the material components. This project generated experimental data concerning the fouling potential of the proposed materials of construction and effectiveness of antifouling coatings. The scope of the effort did not address mechanical wear of materials or components due to the sliding action of the paddle on the guide rails.

In this project, E-Wave collaborated with Sandia National Laboratories (SNL) and Pacific Northwest National Laboratory (PNNL) to examine biofouling and corrosion effects on static material components (paddle and attachment frame surface) of the WEC. SNL and PNNL will select and assess coatings that ensure long term resistance to corrosion and overall performance in the ocean. PNNL will assess biofouling accumulation on coated materials for the WEC. Final Tests include adhesion studies of the coatings to the substrates of interest.

2 ROLES AND RESPONSIBILITIES OF PROJECT PARTICIPANTS

2.1 APPLICANT RESPONSIBILITIES AND TASKS PERFORMED

E-Wave's responsibilities included: (1) provide samples of WEC components to SNL and PNNL for coating and biofouling testing, (2) provide SNL and PNNL support on coating assessment, biofouling assessment, and selection of non-toxic coatings for use near aquaculture farms, (3) collaborate with SNL and PNNL to write the post-access report, and (4) E-wave to submit the post-access report and project data to TEAMER.

2.2 NETWORK FACILITY RESPONSIBILITIES AND TASKS PERFORMED

- SNL performed coating reliability studies to determine adhesion, wear rate, and performance.
- PNNL provided to SNL and E-Wave, coated and uncoated samples exposed to raw seawater to assess the development of fouling on the samples.
- SNL and PNNL worked with E-Wave in the final selection of suitable non-toxic coatings.
- SNL and PNNL discussed results and key take-aways of the entire project and wrote the post-access report with E-Wave.

3 PROJECT OBJECTIVES

The objectives were as follows:

- Examination of three coatings identified via literature and DOE-WPTO's Advanced Materials Program for adhesion performance and toxicity under low flow conditions.
- Conduct biofouling and corrosion studies relevant to the WEC components (e.g., paddle and attachment frame).

4 TEST FACILITY, EQUIPMENT, SOFTWARE, AND TECHNICAL EXPERTISE

SNL Test Facility

The Advanced Materials Laboratory (AML) is one of seven laboratories that comprise SNL's Materials Science and Engineering Center. The Center has expertise in the development and testing of materials and coatings for marine renewable energy. Staff also collaborate with other SNL programs focused on reliability, non-destructive inspection, modeling and simulation, and systems engineering. These capabilities were employed for testing the adhesion and durability of coatings and materials of construction. In addition to the AML, the team had access to several other laboratories within the center devoted to understanding the reliability and aging of materials.

SNL Testing Conditions Needed, Proposed Test Plan: The selected coatings will be tested in three zones. Zone 1 which is above the water (splash zone), Zone 2 which is in the air and water interface, and Zone 3 which is below water. The selected coatings will be applied by SNL to steel substrates and then pre-conditioned in salt fog (Zone 1), partially in simulated seawater and air (Zone 2), and simulated seawater environmental chambers. A set of three samples per coating will be conditioned for 1, 3, 6, and 8 months. All samples will be tested against baseline dry coatings. The system will be conditioned in artificial seawater, temperature-controlled, and with no biologicals.

PNNL Test Facility

PNNL operates the Marine and Coastal Research Laboratory (MCRL) in Sequim, WA. This facility is the primary site for marine testing in DOE-WPTO's Advanced Materials Program, including controlled (tank) and open-water marine exposures to evaluate biofouling processes, composite materials, and antifouling coatings and treatments. PNNL has developed and patented several quantitative processes for evaluating fouling and staff member Dr. George Bonheyo chairs the IEC TC-114 standards committee for biofouling assessments. The MCRL provides the necessary facilities and staff expertise to support the in-water exposures and fouling assessment required to address the critical performance questions that E-Wave has.

PNNL Testing Conditions Needed, Proposed Test Plan: The seawater exposures will require tanks that are plumbed with natural, unfiltered seawater, and overhead controlled lighting to simulate the diurnal lighting cycle. These conditions allow for natural fouling growth to occur on the test articles. The panels do not require additional infrastructure (all test equipment is available).

Environmental Conditions of the Tanks: In general, conditions in Sequim Bay are identical to those where temperate zone aquaculture occurs, a notable example being salmon. Raw (unfiltered) seawater is pumped directly from Sequim Bay, which is equivalent to locations along the Pacific Northwest coastline. The tanks naturally receive larvae, cells, and spores for all fouling organisms (e.g., barnacles, mussels, tunicates, anemones, macroalgae, diatoms, bacteria) and these grow to maturity in the tanks. While the specific species of these organisms may be unique to the region, they represent the genera of fouling organisms found in all marine environments.

The tanks will receive diurnally cycled artificial illumination (multi-spectral grow lights) to enable growth of photosynthetic fouling species (the system is intended to operate in the photic zone). Temperatures in the tanks vary with season, though temperatures in the tanks can be a few degrees warmer in winter. Salinity will not be altered.

The temperature conditions in Sequim will be considerably cooler (typical range is 9 to 15 Celsius), whereas water temperatures in the proposed fish farm (located in the Caribbean coastal waters of Panama) fall between 24 and 30 Celsius. While specific fouling species would be different, the types of fouling would be the same. Temperature does affect the performance of paints, but that is controlled by the binders and polymers used and paint companies sometimes make a warm and cold-water version of the same paint. In other words, temperature has less bearing on the antifouling strategy, so we can use the data from Sequim to select paints for tropical and temperate waters. We can also use the fouling in Sequim to assess whether any fouling would impair the operation of the WEC.

PNNL’s Marine and Coastal Research Laboratory (MCRL) has the necessary tanks, pumps, and plumbing infrastructure to support this program.

5 TEST OR ANALYSIS ARTICLE DESCRIPTION

The WEC developed by E-Wave is a system of dual inclined paddles retrofitted to the existing feed buoy platform of offshore fish farms. As shown in **Figure 2**, the partially submerged forward and aft paddles are excited by incident waves and oscillate along the inclined guide rails, via a linear bearing constructed with an ultra-high molecular weight (UHMW) polyethylene sleeve. A tether is connected to the paddle at one end, and at the other to the winch of a power take off (PTO) system. During the downstroke of the paddle, the tether is pulled, and it rotates the winch wheel and drives the power generator. On the paddle’s upstroke, the generator shaft is disengaged because of a one-way clutch and the tether is rewound, making it ready for the next wave motion. Both paddles will drive a single PTO in unidirectional rotation to generate electricity. In resonance, the two paddles move up while the feed buoy moves down and vice versa. This design amplifies the relative motion between the paddle and buoy, but not the pitch motion of the whole system. As a result, the two-paddle design is more stable in operation and has much less mooring load than a single paddle design.

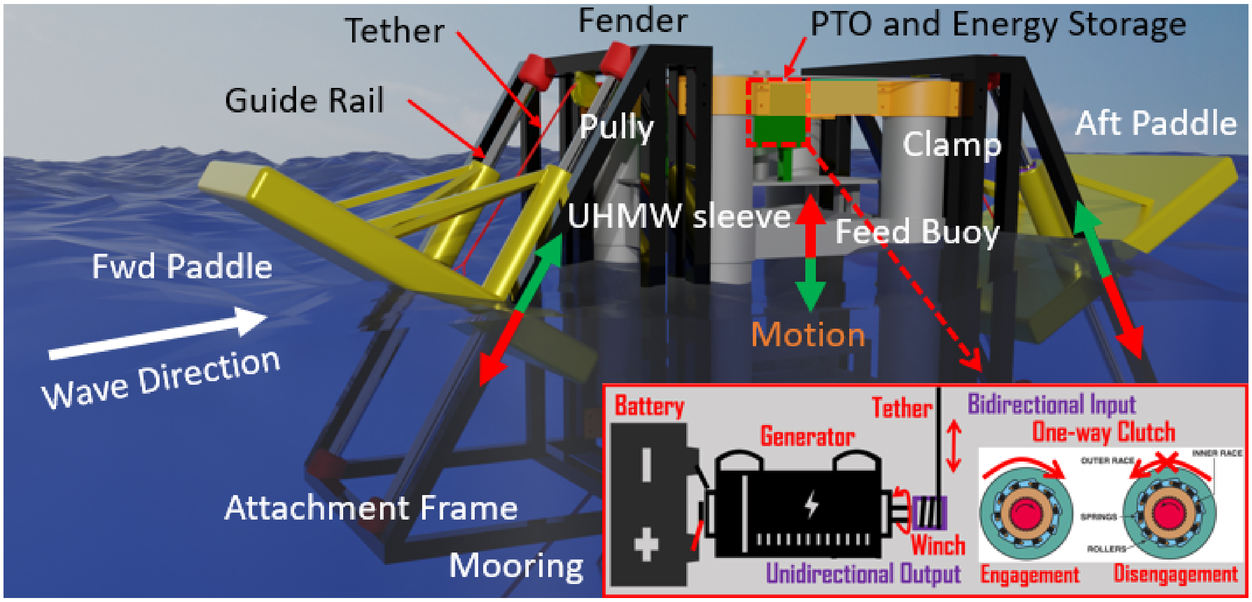

Figure 2 | WEC retrofitted into an existing buoy on an aquaculture farm. The paddle (4m wide, 5m long, 0.5m thick) oscillates along the guide rail as waves pass by, which then transfers its energy through a tether to the power takeoff system housed on the buoy.

The intent of the study was to 1) identify coating solutions to prevent biofouling growth and saltwater corrosion on the static (paddle and attachment frame surface) components of the WEC that are submerged, 2) determine adhesion of the coatings to system components, and 3) assess the ease and effectiveness of biofouling cleaning to insure long term performance of the system.

The test articles were 3 inch square, and 8 inch square panels of 316L SS (**Figure 3**) and ultra-high molecular weight (UHMW) polyethylene (PE) (**Figure 4**), linear guide rails (316 SS rotary shafts, 3/8” diameter, and 12” long, as shown in **Figure 5**), UHMW sleeve bearings (bore 3/8”, 2” long, as shown in **Figure 6**), ceramic radical ball bearings (bore 3/8”, O.D. 7/8”, and width 0.218”, as shown in **Figure 7**), and 316 SS radical ball bearings (bore 3/8”, O.D. 7/8”, and width 0.218”, as shown in **Figure 8**). Note that an off-the-shelf linear ball bearing with either 316 SS or ceramic material could not be found. Therefore, radical ball bearings with 316 SS and ceramic materials were proposed for dynamic biofouling tests, considering that the radical ball bearing has similar ball-shaft contact as linear ball bearing.

Figure 3 | 316 stainless steel sheet. (www.mcmaster.com)

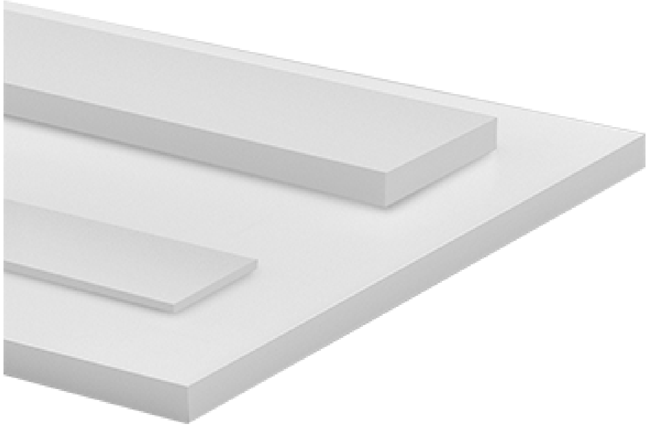

Figure 4 | UHMW polyethylene sheet. (www.mcmaster.com)

Figure 5 | 316 stainless steel rotary shaft. (www.thomsonlinear.com)

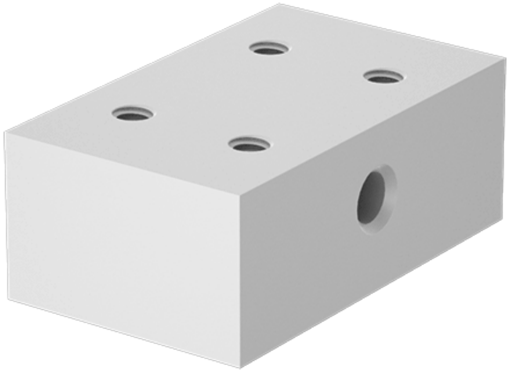

Figure 6 | Sleeve bearing made from a single piece of UHMW plastic. (www.mcmaster.com)

Figure 7 | Ceramic radical ball bearing. (www.smbbearings.com)

Figure 8 | 316 stainless steel radical ball bearing. (www.kmsbearings.com)

6 WORK PLAN

Coating assessment by SNL:

SNL assessed the capability of the selected coatings to adhere to the surfaces on E-Wave's WEC in a meaningful way to ensure long-term performance. The key parameter of these tests was a qualitative analysis of the damage incurred onto the coatings from water, motion, and friction between parts. In addition, the literature review of coatings helped to derive an evaluation of whether the coating is safe near marine life and aquaculture pens. This will have direct impact on the TRL of the WEC, as it will determine whether the system can be functional in an ocean environment, and it also determines the compatibility of the system with their target beachhead market, aquaculture.

Fouling assessment by PNNL:

PNNL staff applied the selected anti-fouling coatings and at the conclusion of each exposure period (3, 6, 9 months) assessed fouling accumulation. Fouling was determined using a staining technique followed by photographic analysis to evaluate fouling intensity on the surface. Materials were also weighed before and after submersion to facilitate weight change analysis resulting from fouling organisms aggregating on the materials. The inclusion of Intersleek 1100SR antifouling coating provided a reference standard coating to enable comparison with other studies involving a wider range of coatings.

Task Descriptions

Task 1: Coatings Reliability Studies

Discussion: SNL performed coatings reliability studies to determine adhesion, wear rate, and performance within three zone locations. Zone 1 is above the water (splash zone), Zone 2 is in the air and water interface, and Zone 3 is below water. This will include:

- Napkin Ring Testing for coating adhesion strength; 1 month per sample

Using a method developed by SNL's Nuclear Weapons reliability program, the coating was applied to a flat substrate, and torque applied to the surface via a metal component to check how well the coating adhered to the surface. This was done for a dry and wet sample to check for effects such as water uptake or chemical changes, which affect adherence.

- Tribological testing using ceramic or UHMW Polyethylene to identify potential wear rate; 3 weeks per sample.

The experimental setup accommodated flat substrates on which the coating was applied and then a tip (typically a ball bearing) was rastered across it, which was comprised of the relevant SS or UHMW PE. A scanning white light interferometer was used to scan the wear scar to find an approximation of the material removed.

- Microscopy and Optical Imaging Analysis to observe qualitative changes; 2 weeks per sample

Using a microscope, the surface of the coating before and after these tests was examined to give qualitative data on any changes to the coating. Additionally, profilometry was performed to take topographical data of the coating surface.

- Weight Measurement to identify swelling or water uptake; 2 weeks per sample

The samples were weighed while dry and wetted to check if the coating uptakes any water, which would cause swelling and potential sloughing.

- Spectroscopy to observe any chemical changes in surface chemistry; 3 weeks per sample

A spectrometer was used to check the surface chemistry of the coating while dry and wetted to see if any chemical reactions have occurred during saltwater exposure.

The adhesion testing, optical microscopy and spectroscopy were done after each of the different exposure intervals. The tribological wearing test, however, was done on one dry (unconditioned) and one conditioned sample.

Coatings were ranked based on the results from the wear testing (metrics: relative wear rate) and adhesion testing (metrics: force required to remove coating) and qualitative recommendations were given based on these results along with any other observations such as peeling or blistering.

Deliverable: SNL, with support from PNNL and E-WAVE, reported each coating's ability to adhere to the surfaces on E-WAVE's WEC in a meaningful way, which will ensure long-term performance. The key parameter of these tests was a qualitative analysis of the damage incurred onto the coatings from water, motion, and friction between parts.

Task 2: Biofouling Assessment

Discussion: PNNL prepared samples with the selected anti-fouling coatings and then exposed samples in seawater tanks to assess the development of fouling on the samples. Samples include panels (sizes specified by PNNL) of materials of construction provided by E-WAVE and coated with each of 3 different paints (noted above) by SNL. The samples entailed triplicate samples of each paint applied onto 3-inch square, and 8-inch square panels of 316 SS and ultra-high molecular weight (UHMW) polyethylene. It was anticipated that the exposures will be of short duration (<6 months) due to the short duration of the program and the need to fabricate samples and conduct post-exposure analyses. During the exposures, PNNL conducted monthly examinations and collected photos of the samples to document fouling buildup. Following the exposure period, PNNL assessed the buildup of fouling and the ease with which fouling material could be removed. Per recommendation from the proposal review, a second, replicate set of samples was set up for long-term exposure (up to 1 year); these samples are to be analyzed if a second phase TEAMER proposal and effort is funded. If a second round of funding is not supported, the samples may be discarded.

Deliverable: PNNL, with support from E-WAVE and SNL, reported fouling accumulation and any noted evidence of corrosion on all samples to assess whether fouling and corrosion may negatively impact the performance of the selected materials.

Task 3: Selection of Coatings Suitable for Use Near Aquaculture Pens

Discussion: SNL and PNNL worked with E-WAVE in the final selection of non-toxic coatings suitable for use near aquaculture pens, on the identified materials of construction, and under the relevant operating and environmental conditions, for example, lower velocity (relative to ships), shallow water depth (photic zone), dynamic components, and static components. Literature review of coatings was used to evaluate whether the coating is safe near marine life and aquaculture pens. This will have direct impact on the technology readiness level of the WEC, as it will determine whether the system can be functional in an ocean environment, and it also determines the compatibility of the system with the target beachhead market, aquaculture.

Deliverable: Summary report on coatings selection and results.

Task 4: TEAMER Post-Access Report

Discussion: SNL and PNNL discussed results and key take-aways of the entire project, Tasks 1–3, with E-Wave. SNL and PNNL advised on future steps E-WAVE can take to further develop their device.

Deliverable: SNL and PNNL collaborated with E-WAVE to write the post-access report. E-WAVE will submit the post-access report and project data to TEAMER for distribution, per the award regulations.

6.1 EXPERIMENTAL SETUP, DATA ACQUISITION SYSTEM, AND INSTRUMENTATION

Two Experimental Setups were used to support **Task 1. Coatings Reliability (Napkin Ring, Figure 16)** and **Task 2. Biofouling Assessment (Biofouling Tank, Figure 9)** and are shown below. This includes exposure of coated coupons to unfiltered seawater plumbed into the biofouling tanks at PNNL and the Napkin Ring Test at SNL. No instrumentation was required to be applied to the samples during exposure to unfiltered seawater at PNNL. Tank samples were monitored visually and weighed. Water conditions within the Tanks were monitored for temperature and other parameters. The All-data acquisition was provided through established methodologies used to understand biofouling processes. Error bars and statistical analysis was conducted. The tank monitoring and change in sample weight methods are included among biofouling measurement methods that PNNL is working to standardize with the IEC.

6.2 NUMERICAL MODEL DESCRIPTION

- **N/A**

6.3 TEST AND ANALYSIS MATRIX AND SCHEDULE

The proposed performance period was 12 months. A no cost time extension (NCTE) was requested after the project performance period after March 2023 to support the long-term biofouling studies.

Table 1 Tasks and Division of Responsibilities.

Task No.	Subtask No.	Task Title	Duration (Estimated Starting & Ending Project Month)	Responsible Parties
1		**Coatings Reliability Studies**	1-4	SNL/PNNL/E-Wave
	1.1	Napkin Ring Testing for coating adhesion strength	1 month preparation time per sample before testing	Samples from PNNL to SNL
	1.2	Tribological testing using ceramic or UHMW Polyethylene to identify potential wear rate	3 weeks per sample	SNL
	1.3	Microscopy and Optical Imaging Analysis to observe qualitative changes	2 weeks per sample	SNL/PNNL
	1.4	Weight Measurement to identify swelling or water uptake	2 - 4 weeks per sample	PNNL
	1.5	Spectroscopy to observe any chemical changes in surface chemistry	1 month preparation time per sample before testing	PNNL
2		**Biofouling Assessment**	4-8	SNL/PNNL/E-Wave
	2.1	Biofouling assessment on WEC components without sliding contact (steel WEC structure surface)	4 months (9 months if NCTE is granted)	PNNL
3		Selection of Coatings Suitable for Use Near Aquaculture Pens	8-11	SNL/PNNL/E-Wave
4		TEAMER Post-Access Report	11-12	SNL/PNNL/E-Wave

6.4 SAFETY

The work at SNL followed the safety document Advanced Materials Laboratory Routine Operations (NEPA ID: NM19-0304). The done at PNNL followed PNNL’s documented (e.g., LabAssist) safety and environmental compliance procedures for biofouling testing of materials and coatings as well as safe electrical and mechanical device operations near seawater.

6.5 CONTINGENCY PLANS

Redundant or backup test systems and spare components were available in case of mechanical component failures during the testing.

6.6 DATA MANAGEMENT, PROCESSING, AND ANALYSIS

6.6.1 Data Management

- The data acquired was be stored on both local disk and the cloud. The form of the data can be in any format that the data acquisition system outputs. All data can be shared to the MHKDR in its acquired format. The acquired data and their formats are listed in the following table. Data will also be uploaded to Teamer repository.

Table 2 Acquired data and tests formats.

Task No.	Subtask No.	Task Title	Data description and format
1		**Coatings Reliability Studies**	
	1.1	Napkin Ring Testing for coating adhesion strength	Photographs, force measurements (tabulated & graphed)
	1.2	Tribological testing using ceramic or UHMW Polyethylene to identify potential wear rate	Photographs, microscopic image capture, weight measurements (tabulated & graphed)
	1.3	Microscopy & Optical Imaging Analysis to observe qualitative changes	Photographs, microscopic image capture
	1.4	Weight Measurement to identify swelling or water uptake	Weight measurements (tabulated & graphed)
	1.5	Spectroscopy to observe any chemical changes in surface chemistry	Processed spectroscopic data
2		**Biofouling Assessment**	
	2.1	Biofouling assessment on WEC components without sliding contact (steel WEC structure surface)	photographs, weight measurements (tabulated & graphed); processed image data (tabulated & graphed)

6.6.2 Data Processing

SNL and PNNL were responsible for data processing. The data was analyzed as acquired and compared with previously acquired data to observe changes and identify system failures or errors. The imperfection of the test conditions, which may lead to some fluctuation on the data, was deemed acceptable. Once it was determined as noise, a numerical filter could be added when processing the data to eliminate the influence from these uncertainties. PNNL used a published process and software tool for converting digital images of fouled surfaces treated with a stain to quantify fouling accumulation. SNL used a published method developed to understand adhesion and quantifies strength base on torque needed to remove coating. Error bars were used on results. Optical micrographs were used to capture finals resulting behaviors.

6.6.3 Data Analysis

- SNL and PNNL analyzed the data with the support of E-Wave.
- Biofouling accumulation was calculated as a change in weight and organic matter over time.
- Corrosion and wear were evaluated as a loss of substrate weight, by visual analysis and photo documentation of surfaces before and after exposure, and by direct measurement of any change in size, dimensions, or the emergence of features such as pitting.
- Adhesion was measured through analysis of torque forces required to remove coating (Napkin Ring).
- Tribology was removed from the test matrix due to budget.

7 PROJECT OUTCOMES

7.1 RESULTS

The next two sections below describe the results for both tasks of this program. To support the storyline, results from the biofouling assessment will be presented first as PNNL prepared samples for biofouling, tested these, and then sent the exposed samples to SNL for coating adhesion analysis.

Task 2. Biofouling Assessment

Task 2.1 Biofouling assessment on WEC components without sliding contact.

Marine biofouling is an ongoing problem for marine energy harvesting devices. Therefore, continuing research is necessary to develop and test both materials and antifouling coatings used to reduce fouling and associated operations and maintenance costs. To evaluate materials and antifouling coatings proposed for use in a marine energy device being developed by E-Wave, PNNL prepared substrates coated with three commercial antifouling paints and compared the performance against uncoated substrates when submerged in raw seawater for 3-, 6-, and 9-month (m) time periods. Two different size coupons, 3 in^2 and 8 in^2, were prepared from PE and low carbon marine grade 316L SS. Coupons were fabricated such that holes were drilled in each corner of the coupon to facilitate hanging the materials in a daisy chain fashion using zip ties to string the coupons together through the holes (**Figure 9**). SS coupons were sandblasted to uniform roughness, and PE was sanded by hand using 60 grit sanding blocks. It was noted that PE was difficult to sand to roughness despite repeated applications of the sanding technique and using a course grit sandpaper. Prior to coating, all 3 in^2 coupons were numbered and the weight of each coupon was recorded. Triplicate sets of both 3 in^2 and 8 in^2 coupons were established for coating with each antifouling paint for all time points.

Three marine antifouling paints were selected based on their unique properties to test how different paint styles perform on different materials. The selected paints were ePaint Ecominder- a self-polishing paint with Zinc Omadine for slime control, Pettit ECO HRT Copper-Free – an ablative antifouling paint with Econea biocide, and Intersleek 1100SR - a foul release paint. Unpainted controls of SS and PE were also used as negative controls. For clarity, these are referred to herein as Ecominder, ECO HRT, Intersleek, and Unpainted. Coupons were coated on one side first, according to manufacturer's guidelines, by applying the necessary primers, tie coats, and topcoats to the required thickness or number of coats and allowed to cure. Then the coupon was turned to the second side and the process was repeated. All edges and the inside of the drilled holes were also coated. After painting, coupons were allowed to continue curing at room temperature for 1 week before 3 in^2 coupons were weighed again. Coupons were strung together in groups of 6 for 3 in^2 coupons, and groups of 3 for 8 in^2 coupons. Zip ties were used to attach coupons to one another, and they were then packed carefully for transport to the PNNL Sequim Marine and Coastal Research Laboratory.

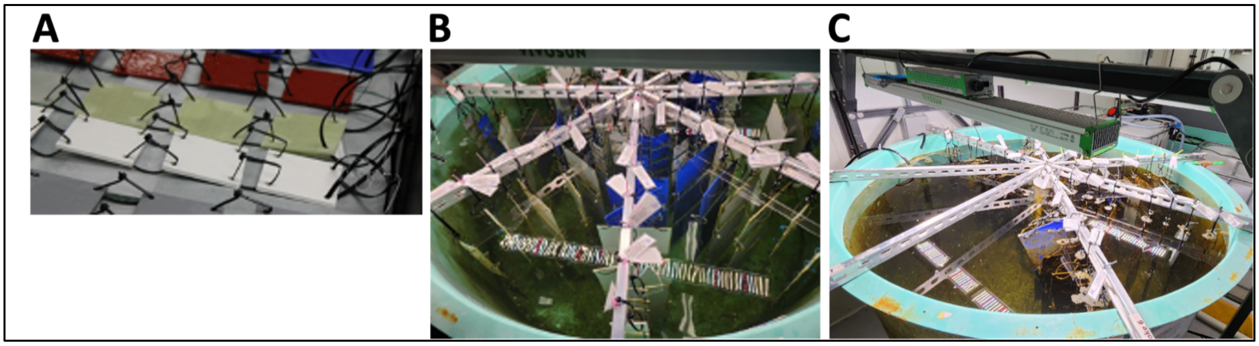

Figure 9 | Coupons prepared and suspended in biofouling tanks. A. Depiction of the daisy chain hanging style where 3 in^2 coupons are shown zip-tied to each other. **B**. E-Wave biofouling tank 1 month after all coupon samples were submerged. **C.** E-Wave biofouling tank photo taken after 6 months (note that 3- and 6-month time point coupons had been pulled for processing).

Coupons were submerged in a designated indoor biofouling tank plumbed to provide continuously flowing raw (unfiltered) seawater from Sequim Bay, WA (**Figure 9B** and **9C**). Tanks and coupons were monitored weekly to evaluate accumulation of fouling material and to prevent coupons from floating to the surface. Tungsten weights were tied to the PE coupons to keep these fully submerged, and occasionally during the fouling process additional weight had to be added. For each time point, a set of 3 in^2 samples was removed and sacrificed to record the wet and dry weights (**Figure 10**). The 3 in^2 coupons were subjected to weight change analysis by blowing off loose water with a Dyson Airblade hand dryer and then recording the wet weight. After recording the wet weight, coupons were dried overnight at 50 °C and weighed again to determine the dry weight of added biomass. The percent weight gain of each coupon was then determined by the following **Equation 1**, where W_f is the dry weight final, and W_i is the dry weight initial.

Equation 1. $$\% \Delta \boldsymbol{Weight} = \frac{\boldsymbol{W_f - W_i}}{\boldsymbol{W_i}} * \mathbf{100}$$

For all time points, the 8 in^2 samples were removed and sacrificed for staining and subsequent digital analysis (more details below). For all time points and coupon sizes, qualitative visual analysis was performed in addition to the quantitative methods described.

Weight change analysis of 3-inch coupons

From qualitative visual analysis of the 3 in^2 coupons (**Figure 10**) when pulled from the tank, the 3 in^2 coupons generally only appeared to have biofouling consisting of filamentous algae or diatoms, which all have relatively low mass and can be easily wiped from the surface of coupons. The 3-month coupons appeared to accumulate more biofouling material than the 6-month coupons (**Figure 10,** 3 m and 6 m rows), with the exception of the Ecominder coupons which appeared to have similar degrees of fouling throughout. This trend was also noted when comparing to the 9-month coupons (**Figure 10,** 9 m row), where the 9 m painted coupons appeared similar to the 6 m painted coupons, with minor increases in fouling materials. However, the 9 m Unpainted coupons (in contrast to the 9 m coated coupons) appeared significantly more fouled than at earlier time points. These temporal differences in fouling were most likely due to seasonal changes in ocean flora, which causes different algal or diatom blooms over time. As the ocean flora blooms, it may increase its mass enough that it detaches from especially low surface energy surfaces. Periodic die-offs may also cause ocean flora to detach from the surface after having generated a noticeable biofilm. Therefore, any accumulation that happened at 3 months may die off or be different at 6 months, which is evidenced by the appearance of less fouling material on the 6-month coupons, especially the control unpainted coupons. These temporal fluctuations in fouling affected the different test materials differently, leading to inconsistent antifouling behavior and making it difficult to conclude any strong findings from visual analysis of the 3 in^2 coupons.

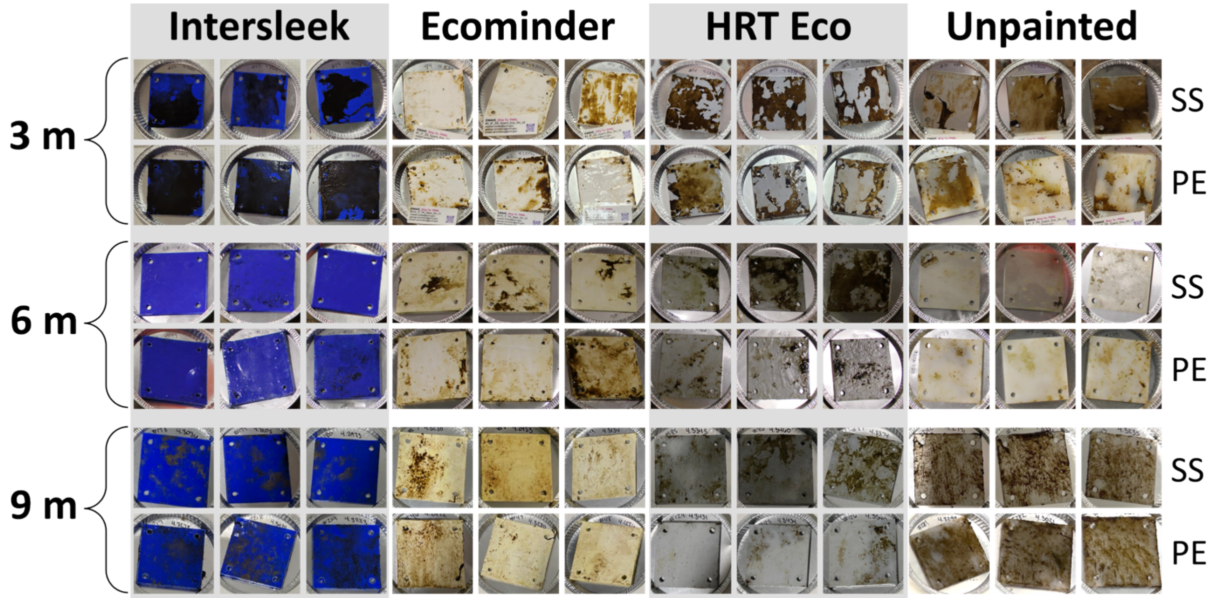

Figure 10 | Photographs of 3 in^2 coupons after drying overnight. All time points (3, 6, and 9 month) of coupons are depicted and indicated by the designation on the left. For each time point, the top row is SS and the bottom row is PE (marked on the right). The paint type is marked above and shading (gray and white) between the paints is provided for clarity. Coupons are depicted sitting in individual aluminum weigh boats used to contain biofouling.

When evaluating the weight change data of the same 3 in^2 coupons over the fouling periods, the pattern that emerged told a different story, where mostly a decrease in weight was observed, except on Unpainted coupons and Intersleek coupons (**Figure 11**). This is encouraging, in that low amounts of fouling materials accumulated on the coupons over 9-months. Out of all time points, it is interesting to note that all coupons (except Unpainted) lost mass at the 6 m time point, where it was visually determined that biofouling accumulation was lowest (**Figure 10**). Because of this trend, we concluded that the mass loss had two likely causes: 1) an actual loss of paint materials during the submersion and subsequent drying process, and/or 2) weighing method/instrument errors. Each potential cause was investigated.

More than one mode of action could have caused paint loss during the experimental process. It should be noted that two out of the three paints investigated (Ecominder and ECO HRT) are ablative style paints, meaning they are designed to wear away over time and release biocides to deter attachment of organisms. The remaining paint, Intersleek, is a foul-release paint, which is not designed to wear away over time. If designed paint loss was occurring in the ablative style paints, the paint loss may be expected to occur at a consistent rate over time, as opposed to the varying loss seen in **Figure 11**. However, exposure of the paint to the water shear forces may have been modulated by the presence of (variable levels of) biofouling, which could cause variability in the loss rate of the ablative paint mass. Time and funding constraints prevented experimental verification of ablative erosion as a cause of the mass loss, but the higher weight loss of the two ablative paints compared to the one foul release paint and Unpainted coupons supports the hypothesis that ablative erosion is a cause of the weight loss.

Another potential cause of coupon weight loss was the vaporization and release of paint compounds during the oven drying process. To determine how much mass was lost solely due to drying the coupons after removal from the tanks, we painted 5 additional coupons of both SS and PE, allowed the paint to thoroughly cure, weighed them, and then oven dried the coupons for 24 hrs. at 50 °C and then re-weighed (**Figure 12**). All painted coupons lost weight as a result of this process, which enabled determination of a correction factor for each paint on its designated material. To determine the correction factor, the coupon net weight change for each group (**Figure 12B**) was averaged to obtain a negative value which was then added back into data to correct for loss in paint (**Figure 11B**). Overall, the change in data was very minimal with the maximum value of paint loss seen being ~140 mg. The patterns of the data remained the same, but the corrected data indicated a small weight increase on the Intersleek coupons, which aligns with the hypothesis that Intersleek (like the Unpainted coupons) was not losing any mass to ablative erosion and thus should not have truly lost any mass during the experiment.

Note: Ecominder on PE loses the most mass during baking, which was likely because this paint and material combination has the most paint applied (**Figure 12D**), followed closely by ECO HRT SS and Intersleek SS. Each paint and material combination has specific manufacturer recommendations that were closely followed during painting, which includes more or fewer coats of paint for each system and substrate combination. Ecominder requires multiple additional coats of paint for PE substrates, so it has the most volatile organic solvents that likely are released during the drying process.

After applying the paint vaporization correction factor, we conclude that any remaining paint loss was primarily due to a combination of the aforementioned designed ablative erosion. A secondary cause of paint loss may have been the loss of paint during rigging of coupons, which occasionally dislodges minor amounts of paint from inside the holes in the coupons.

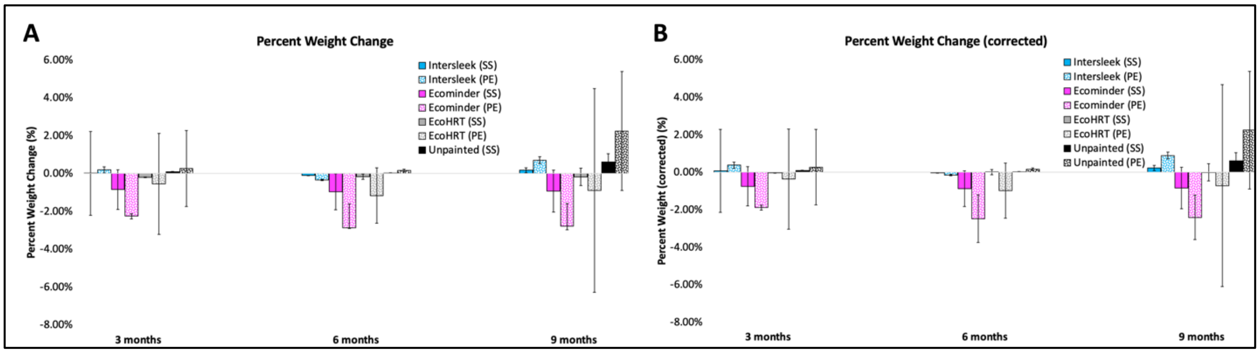

Figure 11 | Percent weight change data of 3 in^2 SS and PE coupons for all timepoints. **A.** Average percent weight change for SS and PE coupons relative to their weights prior to submersion. Error bars indicate the standard deviation of the mean of three independent replicates. **B.** Percent weight change data after correction for mass lost during drying process.

The potential for instrumentation and/or method errors during the weighing process was also investigated. When considering the issue of mass loss from the initial mass weighing compared to the final dry mass weighing, the consistent recording of mass loss at 6 months was potentially problematic and indicative of instrumentation issues such as a faulty balance. To address this issue, coupons were weighed on a single balance at the Richland campus, and then transported to the Sequim campus where the coupons were weighed on two balances, heated overnight at 50 °C and then weighed immediately, allowed to cool, and weighed again. We noted a range in the deviation between the initial weights and final weights of ± 5 mg which explained many of the negative weight change data recorded at 6 months, except for the Ecominder paint on PE substrates.

In conclusion, the negative weight changes were unexpected because the accumulation of fouling was expected to generate positive weight changes. However, after careful analysis of the potential causes, it appears that the negative weight change was a genuine phenomenon that was likely caused by a combination of ablative erosion, evaporation of volatile compounds, and minor flake loss during the rigging process. A correction factor was enacted to correct for the evaporation of volatile compounds, and the loss of paint flakes during the rigging process was concluded, upon reflection, to be minor. After the volatile compound correction factor was put in place, the largest cause of paint loss appears to be ablative erosion. In light of this, weight change is a difficult measure of fouling resistance from which to draw conclusions regarding comparative antifouling efficacy. Some paints are designed to ablatively erode, the rate of which may differ from paint to paint. However, the negative weight changes measured in this study indicate that the paints are performing as designed to prevent the formation and accumulation of massive, thick biofilms on the surface.

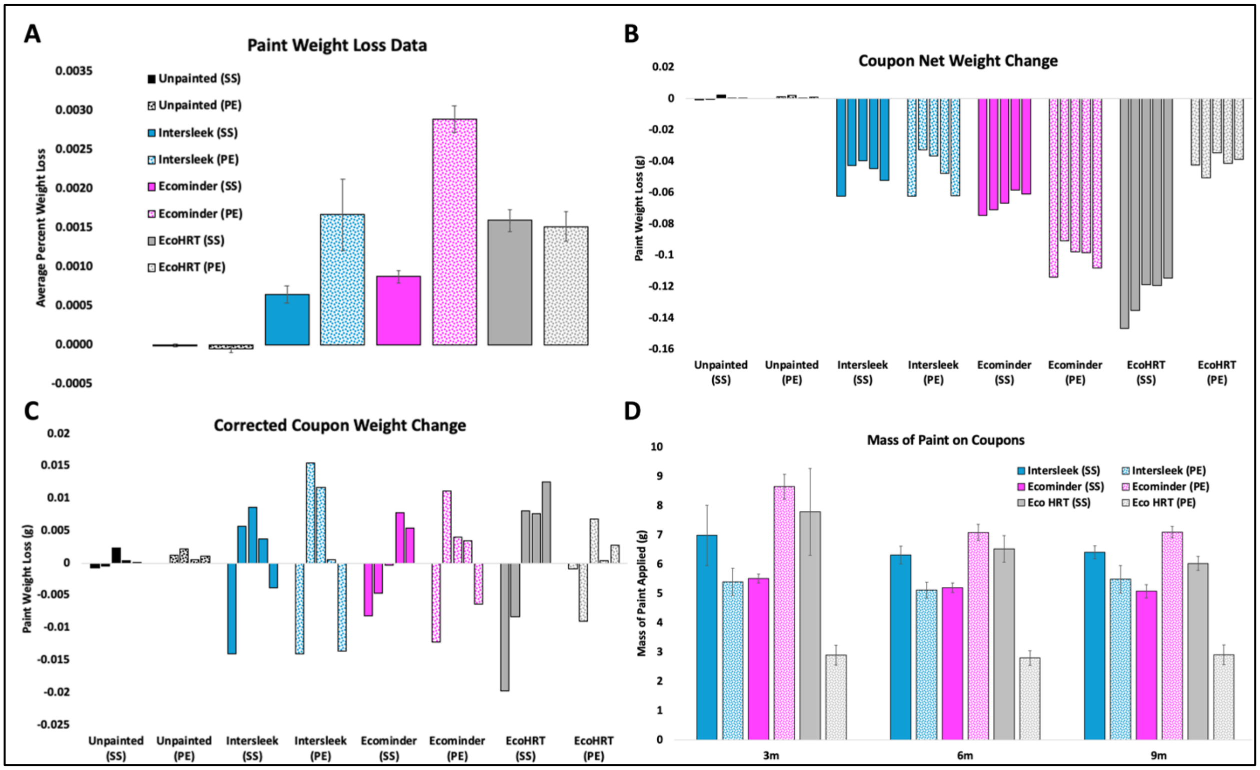

Figure 12 | Determination of paint mass loss and impact on coupon weights. A. Bar plot indicating how much mass is lost when painted coupons of SS and PE are baked at 50 °C overnight and then weighed again. Each bar represents n = 5, with error bars depicting the standard deviation of the mean. B. Shows the coupon net weight change for each individual replicate in a group. C. Correction factor of paint mass lost was applied to determine the effect on coupon weight change to gain a corrected weight change. D. Average mass of paint applied to submerged coupons for each time point and combination of paint and material type. Error bars indicate the standard deviation of the mean of three replicates.

<u>Staining and photograph digital analysis</u>

As with the 3 in^2 coupons, the 8 in^2 coupons were analyzed in two ways: visual qualitative analysis to gauge overall trends, and quantitative analysis using an established process. For the 8 in^2 coupons, the quantitative analysis was a published PNNL biofouling staining process accompanied by a digital image analysis algorithm [1].

Qualitative visual analysis (**Figure 13**) indicates that ECO HRT and Unpainted were consistently worse than Intersleek and Ecominder at all time points. For coated coupons, the fouling appears to have remained constant or decreased slightly from 3 months to 9 months. Decreases in fouling would be caused by the biofilm falling off the substrate, which can occur when ablative paints (Ecominder and ECO HRT) are eroded away (by design) or when the fouling layer becomes heavy enough to slide off a vertically oriented, low-surface energy foul release surface (Intersleek). For Unpainted coupons, the fouling appears to decrease from 3 m to 6 m and then increase from 6 m to 9 m. Since the unpainted coupons are not designed to perform like ablative or foul release paints, this fluctuation in fouling is best explained by biological fluctuations in the biofouling communities forming on the surface, which can undergo seasonal changes that result in die-offs followed by reestablishment of new biofouling communities.

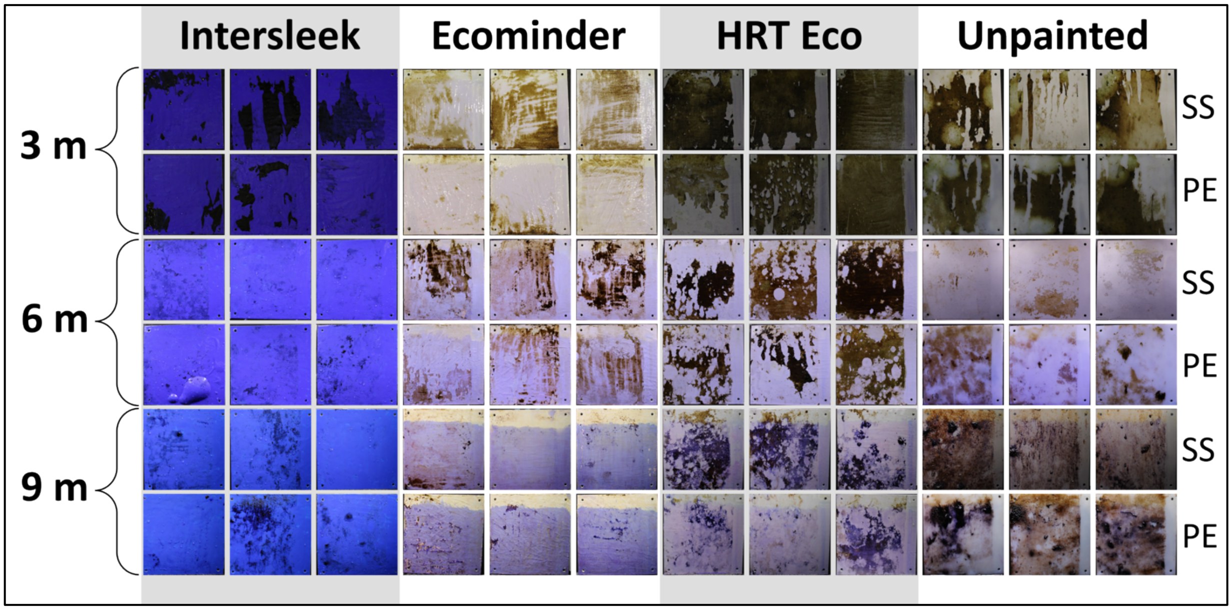

Figure 13 | Determination of biofilm growth intensity. All time points (3, 6, and 9 month) of coupons are depicted and indicated by the designation on the left. For each time point, the top row is SS and the bottom row is PE (marked on the right). The paint type is marked above and shading (gray and white) between the paints is provided for clarity. Coupons images are depicted after staining and rinsing.

The quantitative PNNL biofouling analysis process was performed as follows using multiple steps: (1) 8 in^2 coupons were removed from tanks individually and photographed, (2) coupons were stained to visualize fouling and photographed, (3) excess stain was rinsed away followed by photographing. Prior to staining the coupons, a 1-inch strip of the coupon was wiped clean to provide a negative control surface against which the algorithm compares the rest of the coupon. This 1-inch strip also serves as a qualitative cleanability assessment, with Intersleek being the easiest to clean, followed respectively by ECO HRT, Ecominder, and then Unpainted coupons. Coupons at all tested time points were easily cleaned, suggesting low volume and weak adherence of soft fouling. The stain is a mixture of erythrosine B, Rhodamine, and Coomassie Brilliant Blue, in 1x phosphate buffered saline, which results in a deep purple color that stains a wide range of biofilm constituent types. The stained films appear darker when the biofilm is thicker, allowing the overall mass of the biofilm to be quantified through image analysis.

The photographs were subsequently analyzed using a MATLAB routine that quantifies the level of fouling based on the area and intensity of the stained regions. The Biofilm Growth Intensity (BGI) MATLAB routine compares the darkness of the fouled region of the coupon to the darkness of a cleaned region of the coupon, resulting in a normalized BGI index that quantifies the biofilm mass on the coupon. The BGI algorithm was written in MATLAB and is operated within a standalone user interface using MATLAB Runtime. More information about the biofilm stain and the BGI algorithm can be found in [1].

The BGI algorithm requires that one area of the image be selected as the region of interest for the biofilm quantification and another area (the area that was wiped clean prior to staining) be selected as a control region (**Figure 14**). The regions for biofilm and control were selected manually on each coupon, and these regions were kept consistent from coupon to coupon. The edges and corner mounting holes of the coupons were avoided.

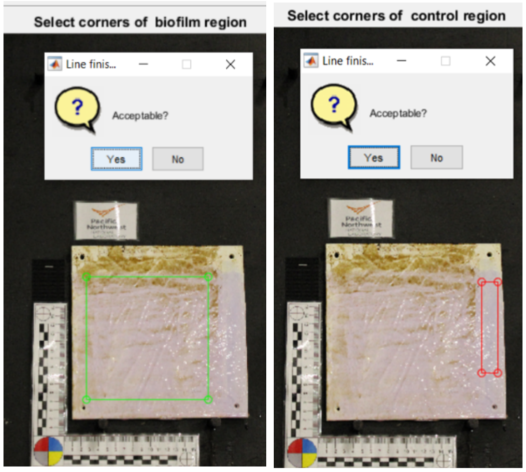

Figure 14 | Example of the selection of the biofilm and control areas of an 8 in^2 coupon within the BGI user interface. Left: The stained region of the coupon was selected as the biofilm region being quantified. Care was taken to avoid the edges and the holes in the coupon. Right: The wiped, then stained, portion of the image was selected as the control region.

After the user selected the ROIs, the BGI algorithm calculated the amount of biofouling by comparing the pixel intensity histogram of the biofilm area with the pixel intensity histogram of the control area (accompanied by additional data transformation discussed further in [1]). This calculation resulted in a BGI intensity (percentage) for each coupon, which was then averaged for the three coupons of each type and plotted in **Figure 15.** Higher BGI values indicate more fouling, and vice versa.

The BGI results (**Figure 15**) are in partial agreement with the qualitative visual analysis, with Intersleek and Ecominder clearly outperforming ECO HRT and unpainted coupons at the 3 m time point. However, at the 6 m time point, Ecominder was slightly outperformed by Unpainted coupons. At the 9 m time point, the BGI process indicated that the materials performed approximately equally. The 9 m time point BGI results are in stark contrast to qualitative visual analysis, which indicates that Intersleek and Ecominder strongly outperformed ECO HRT and Unpainted coupons at that time point.

The 8 in^2 fouling experiment with quantitative and qualitative image analysis suggests that Intersleek and Ecominder are the best performing paints on short time scales (<6 months), and the performance of all three paints, including ECO HRT, may be similar at longer time points (9+ months). However, further qualitative visual analysis suggests that the ECO HRT and Unpainted coupons are, in fact, quite heavily fouled at the 9 m time point, further solidifying Intersleek and Ecominder as the better performing antifouling paints. This ranking of Intersleek and Ecominder as the top performing antifouling paints in this study is supported by the results of the 3 in^2 fouling experiment as well.

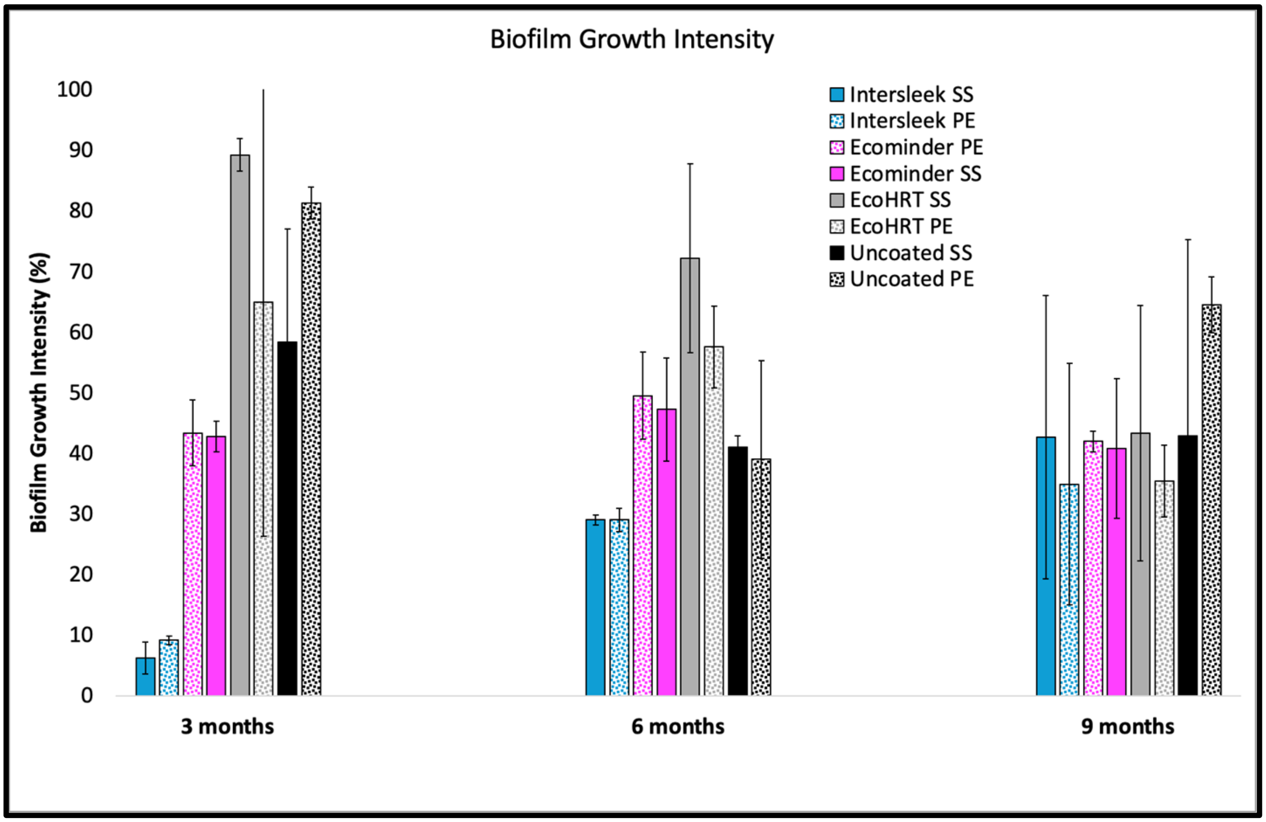

Figure 15 | Graph of biofilm growth intensity. Each bar plot represents n = 3 replicates of the BGI calculated for all time points and coatings. Error bars are the standard deviation of the mean for three replicates.

Task 1. Coatings Reliability Study

The adhesion evaluation results for three different paints applied onto PE and SS substrates tested above for resistance to biofouling are presented here. Details about the specific paints and the various application methods are shared above. These samples were prepared at PNNL and then exposed to a marine environment for time intervals of 0, 3, 6, and 9 months as described above. After samples were measured for their adhesion after exposure to understand reliability and potential wear. For brevity, the sample types will be referred to by the labeling on the bags in which they were delivered to SNL. The study was conducted after PNNL had finished exposure testing for full durations for complete comparison.

Important findings include:

- The ECO HRT and Ecominder paints clearly bonded more strongly to SS than to polyethylene.
- None of the paints adhered very well to polyethylene.
- The Intersleek surfaces were difficult to bond to, so the test results are inconclusive, although the paint was easily chipped off some of the 6-month samples on polyethylene while wiping them clean.

Test Procedures for Adhesion Testing:

In this study, three different antifouling coatings were applied to SS and PE substrates. The coatings were applied at PNNL and details about the application process are mentioned above. The names for the three paints, based on the labeling on the sample bags are:

1. Pettit ECO HRT Copper-Free (hereafter referred to as ECO HRT)
2. ePaint Ecominder (hereafter referred to as Ecominder)
3. Intersleek 1100SR (hereafter referred to as Intersleek)

The painted coupons (either PE or SS) were then exposed to a marine environment for 0-, 3-, 6-, and 9-month increments. The “0 month” samples provided baseline coating adhesion data to compare with the 3-, 6-, and 9-month exposure intervals. The goal of this “aging” study was to see if the exposure affected the adhesion of the paint coatings to various substrates over time. In addition to the painted coupons, coupons with no paint were also included in the test, presumably to determine if the marine exposure would cause any degradation of the substrate that might influence the adhesion of coatings.

Based on previous experience testing similar samples, it was determined that a napkin ring test was the best option for comparing the adhesive strengths of these paint samples. The napkin ring test is a shear adhesion measurement developed by SNL for evaluating adhesion of thin coatings. Samples are prepared by using an adhesive to bond a metal ring onto the surface of the coating and then measuring the torque required to turn the ring (example photos in **Figure 16**).

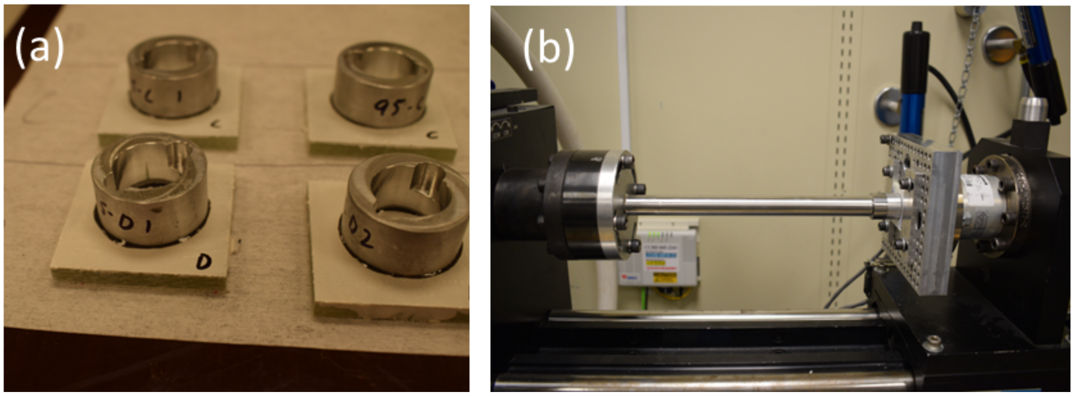

Figure 16. | Napkin Ring Test Setup for Coatings Adhesion Strength. (a) Example of a sample with a napkin ring bonded onto a white paint on a plastic substrate. (b) Sample mounted in torque instrument prior to testing.

The bonded sides of the aluminum napkin rings were abraded by blasting with garnet at 80 psi to improve adhesion. The rings were then cleaned with acetone and IPA. The roughened surface of each ring was then brushed with a solution of [3-(2-aminoethylamino)propyl] trimethoxysilane (0.5 wt. % in water) to serve as a coupling agent. The rings were then dried at 230 ^{o}F for 0.5 hours. After cooling to room temperature, EA9394 epoxy was brushed onto the rings, and they were pressed against the painted surfaces and given a 90^{0} turn. A 59 g mass was placed on each ring to apply slight pressure as the adhesive was curing. Samples were cured at 150 °F for 1 hour.

The adhesion test was conducted by measuring the force required to twist the plugs using a Instron 55MT Torsion load frame operating at a rate of 5^{o}/min. The maximum torque value for each sample was recorded. After the samples were tested to failure, they were inspected to determine where the adhesive failure occurred.

Testing of the ECO HRT and Ecominder samples proceeded as intended but the Intersleek samples were not testable because the epoxy used to bond the napkin rings did not adhere very well to the Intersleek paint. From the product literature, it is evident that Intersleek is based on a fluoropolymer. An etchant, TetraEtch, was used to activate the surface of the Intersleek samples. Two coats of TetraEtch were brushed onto the Intersleek samples and allowed to dry for roughly one minute before being cleaned off with water and isopropyl alcohol. This etching method gave a modest improvement in epoxy adhesion, and it was used for all the Intersleek samples.

Figures 17–21 show the test data plotted beside representative photos of each sample type. Each bar in these figures represents the average of six test results on three coupons with the error bars indicating +/-1 standard deviation. Each photo shows one of the three coupons, with two napkin rings per coupon.

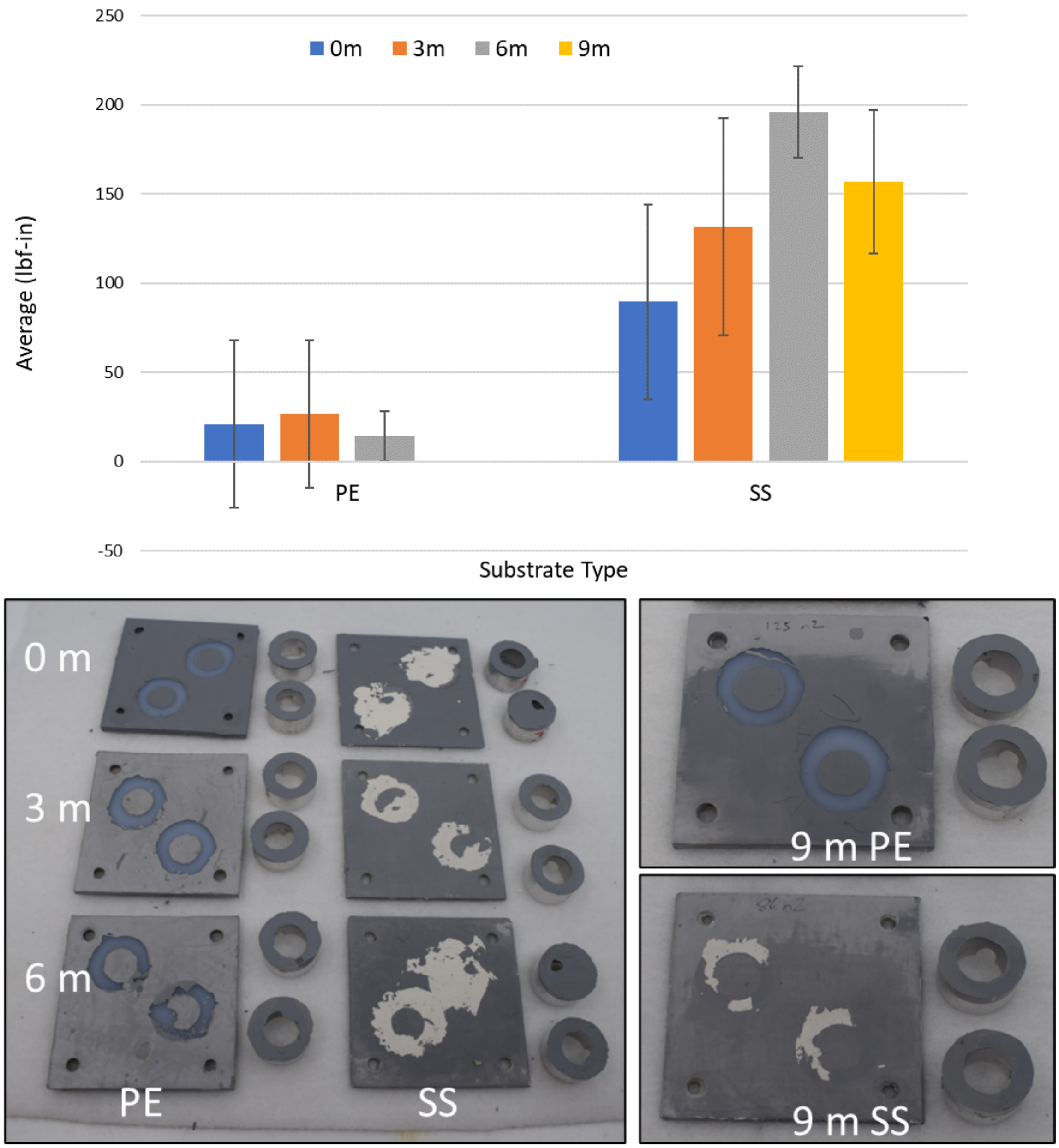

Figure 17| Results of (top) Torque test results for ECO HRT coating on PE and SS substrates and (bottom) ECO HRT post-test photos.

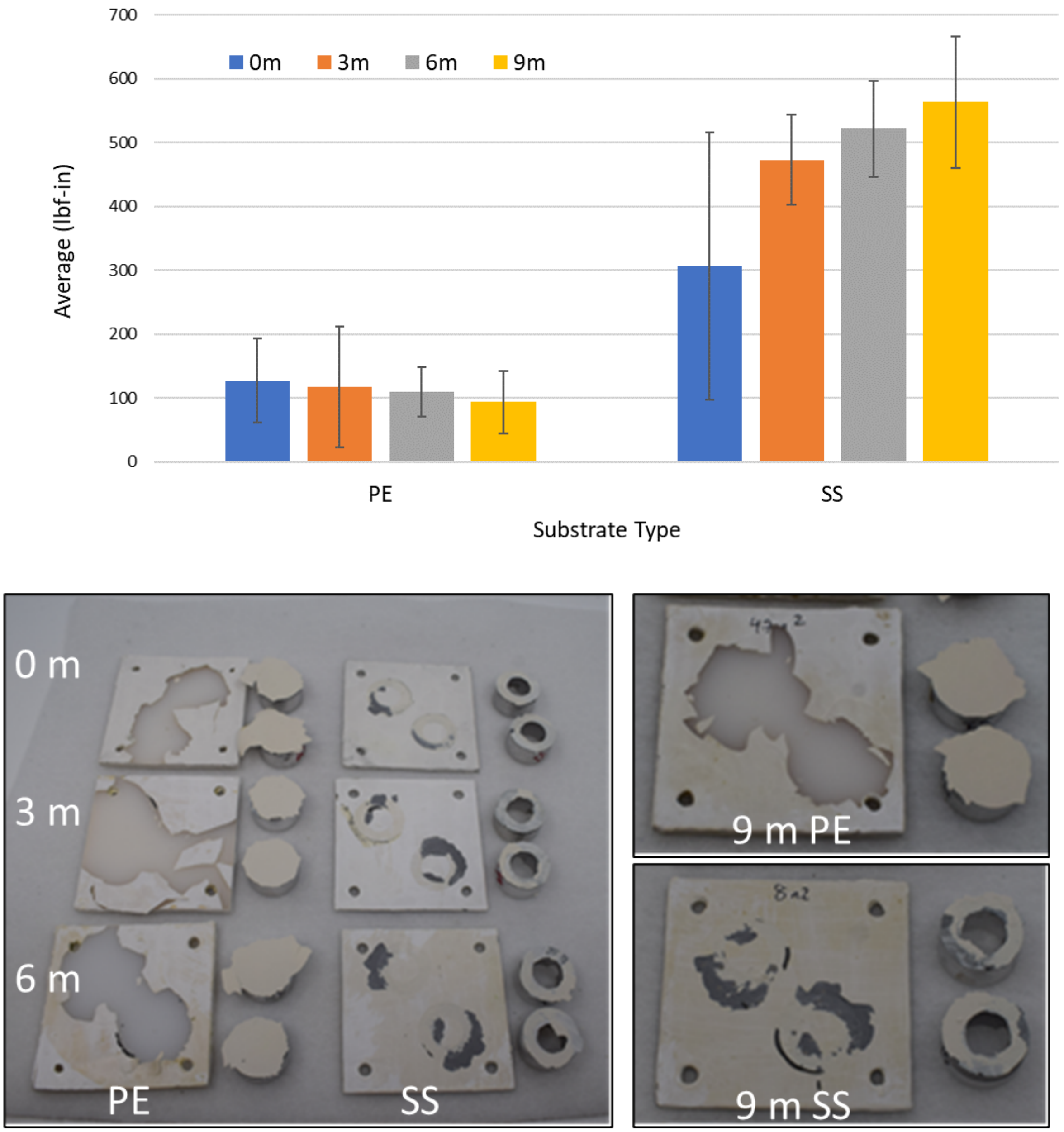

Figure 18. | (top) Torque test results for Ecominder coating on PE and SS substrates and (bottom) Ecominder post-test photos.

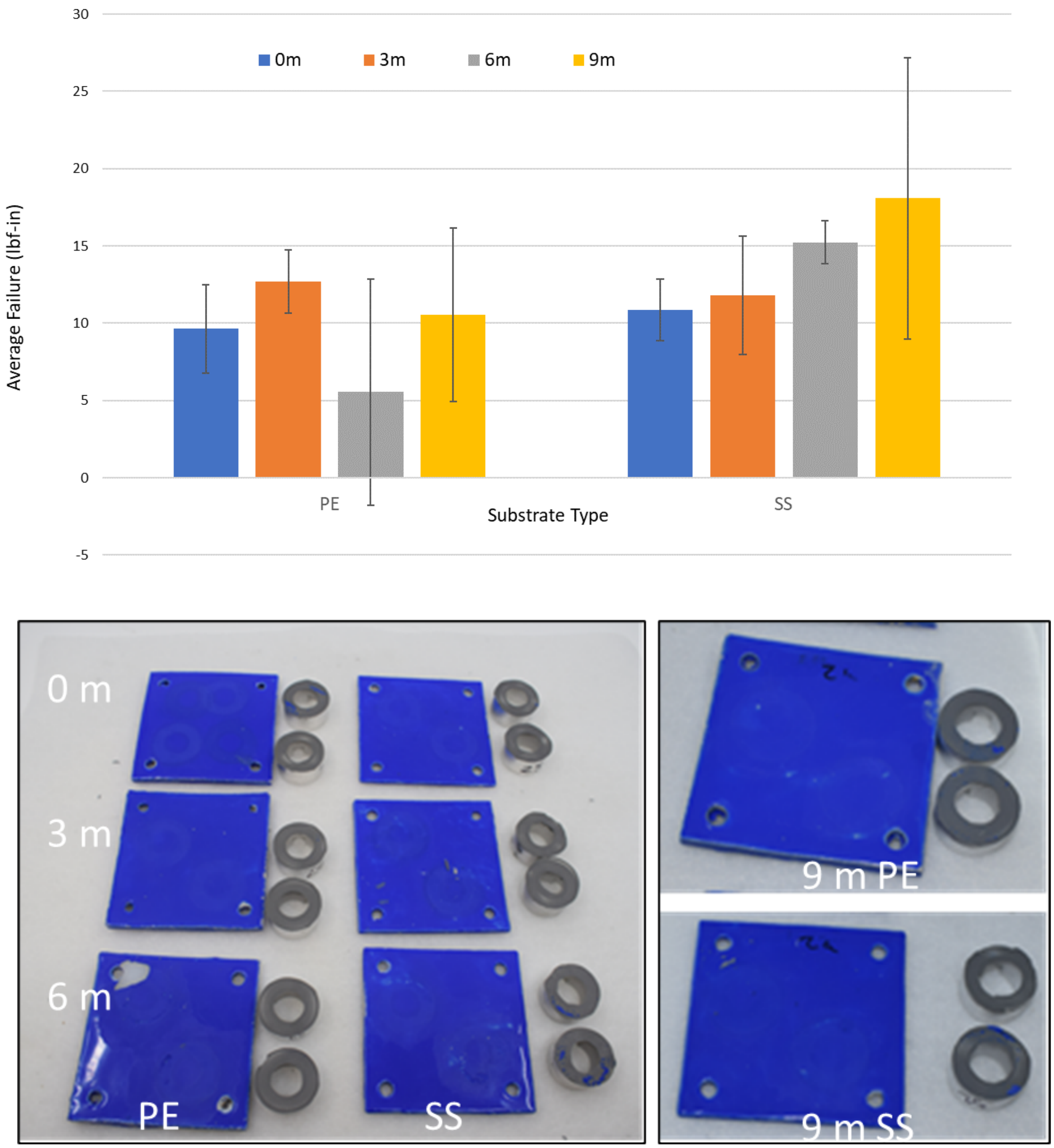

Figure 19| Results of (top) Torque test results for Intersleek coating and (bottom) Intersleek post-test photos.

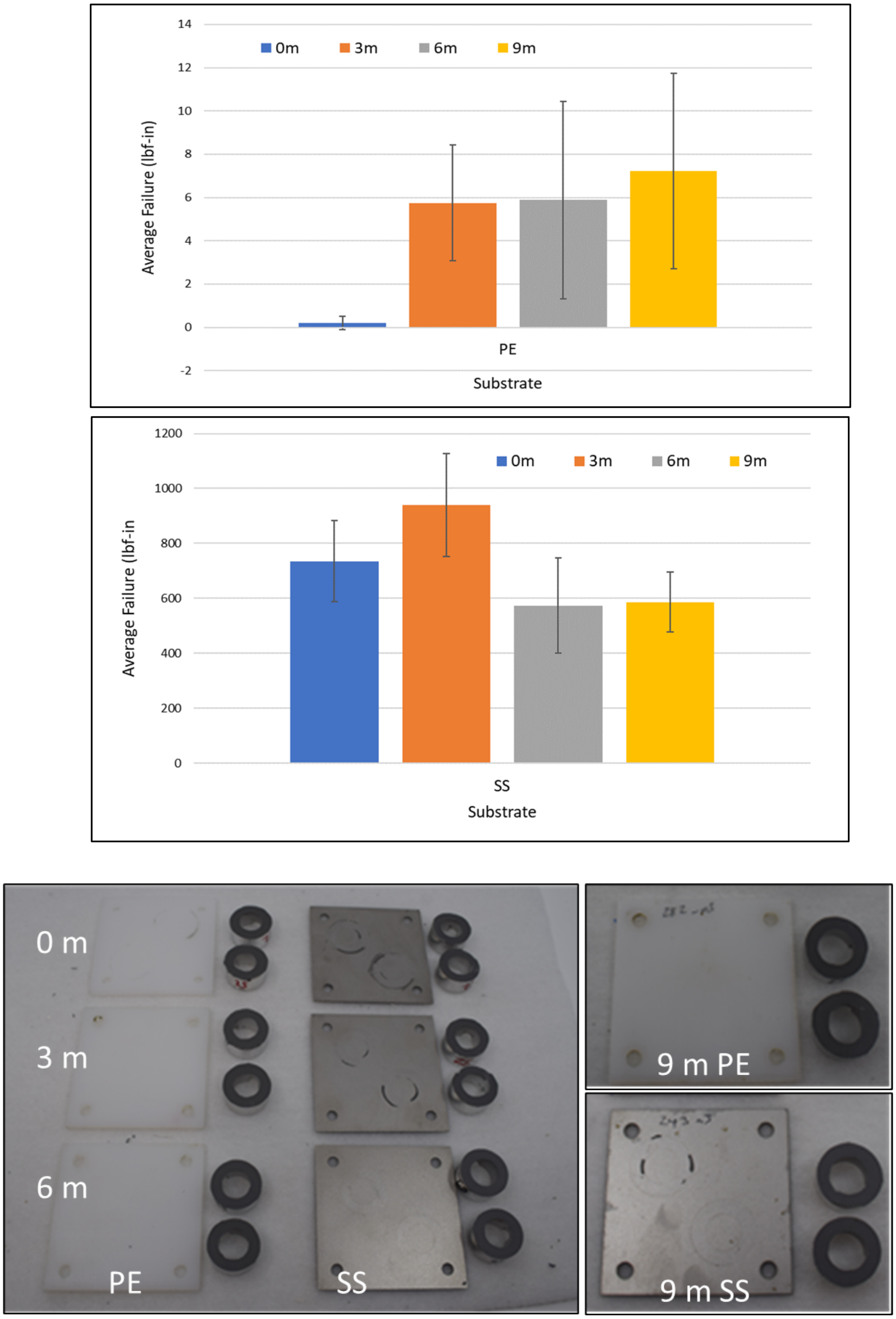

Figure 20| Results of (top) Torque test results for uncoated polyethylene, (middle) torque test results for uncoated SS, and (bottom) uncoated post-test photos.

The ECO HRT paint did not adhere well to polyethylene, with the paint breaking off most of the coupons before they could be tested. In those cases, a torque value of zero was assigned. ECO HRT adhesion to SS was weak, but testable. **Figure 17** shows an increase in the average adhesion strength to SS as the samples were aged although the error bars are quite large.

The Ecominder coating only showed a few pretest failures on polyethylene (**Figure 18**) but the average was fairly low (around 100 lbf·in). When the samples were tested, large chunks of the paint were removed from the coupons. The average adhesion value did not change much with increasing marine exposures. The Ecominder did adhere rather well to SS with only one pretest failure and average torque values between 300 and 500 lbf·in.

The Intersleek paint torque values in **Figure 19** are quite low (between 5 and 20 lbf·in) but in almost every case, the epoxy debonded from the paint. These test results can be interpreted as minimum torque adhesion values for Intersleek but there is no way of knowing how much higher the actual values are. The Intersleek paint appears to be designed with a low surface energy to deter the adhesion of biofilms and microorganisms. This low surface energy also prevents the adhesion of the napkin ring test epoxy. It is worth noting that the Intersleek paint broke off in large chunks on three of the 6-month polyethylene coupons during handling and/or testing **(Figure 21).**

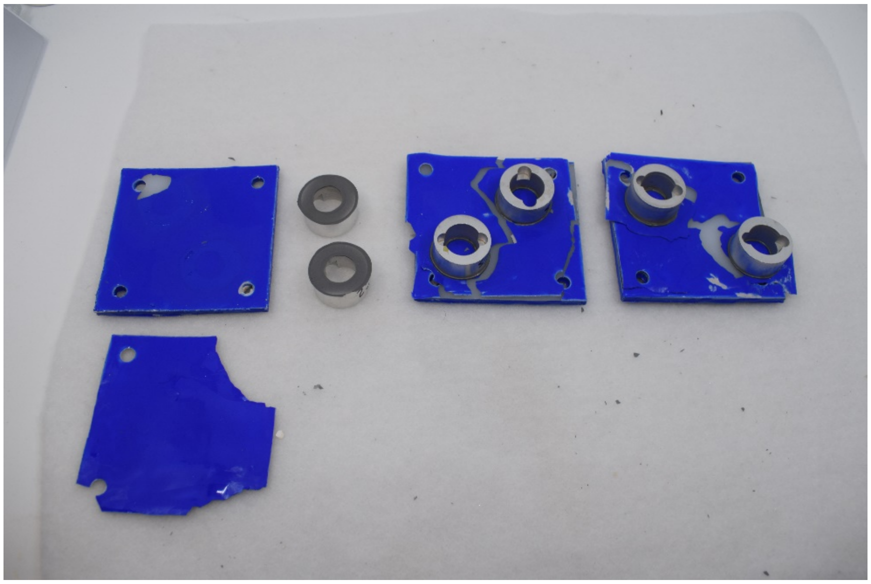

Figure 21| "Chipping" of Intersleek paint from polyethylene coupons.

Figure 20 shows test results for uncoated coupons, for baseline purposes. The napkin ring epoxy did not adhere very well to polyethylene although there was a small improvement after marine exposure, possibly due to a roughening of the coupon surface. In contrast, the epoxy adhered quite well to SS with no discernable trend correlating to marine exposure.

7.2 LESSON LEARNED AND TEST PLAN DEVIATION

Due to budgetary constraints, linear guide rails, UHMW PE sleeve bearings, ceramic radical ball bearings, and 316 SS radical ball bearings were not tested in biofouling or corrosion studies. Tribology studies on these materials were also not conducted. This situation was communicated to the TEAMER network directors once the team realized this was not a possibility. Because the project was already at the maximum allowable budget, it was determined that it would not be feasible to acquire additional funds necessary to execute this aspect of the test. The teams decided the static testing was an ideal starting point and that information gained from these tests might better inform a future dynamic test by having clearer insights into viable coatings. This would likely permit a scenario for testing more replicates of a given treatment, leading to increase statistical robustness of a study design. In addition to this deviation, the teams learned that mass data gained from gravimetric tests was largely inconclusive due to low or negative mass gain. The effects of erosion on ablative paints must be studied so a correction factor can be applied to all the ablative paints' mass data.

8 CONCLUSIONS AND RECOMMENDATIONS

BIOFOULILNG:

An envisioned use of the E-Wave system is to provide power for offshore aquaculture. Consequently, a key metric in the selection of an antifouling system is that it must not be toxic or cause other harm to finfish. PNNL staff selected three marine anti-fouling coatings based on their unique properties (i.e., polymer chemistry, toxin-free or fish-safe biocide, surface energy) to test how different paint styles perform on different WEC materials. Since each paint is designed to operate in specific conditions, evaluating different paint types and their compatibility with WEC materials is critical for establishing maintenance and cleaning schedules. The coated and uncoated samples were pulled from seawater tanks at the end of each exposure period (3, 6, and 9 months) to assess for fouling accumulation. Overall results indicated that in BGI analysis, the Intersleek and Ecominder paints outperformed ECO HRT and Unpainted coupons, especially at shorter time scales of 3-6 months. When evaluating weight change of coupons over time as an indicator of biofilm growth, it was necessary to develop a vaporization correction factor for paints, as volatile solvents from the paint compounds were lost during the drying process, resulting in the appearance of a net weight loss instead of the expected weight gain. After applying the correction factor, it was noted that paints were performing as designed with minimal fouling buildup on the surfaces. Taken together with qualitative data from ease of cleanability, lack of fouling buildup on the surface, as well as compatibility with aquaculture, the Intersleek paint is the likely frontrunner, followed by Ecominder. All paints appeared to perform similarly well to prevent fouling within the 9-month study, but both Ecominder and ECO HRT contain toxins or biocides to prevent fouling growth. The manufacturers state that the biocides act at the paint surface and should have no effect on surrounding marine life, but specific compatibility with aquaculture has not been thoroughly tested. If applied to WEC components, it is likely that Intersleek would be compatible and that a 9-month cleaning schedule should be sufficient.

Adhesion testing:

None of the paints adhered well to PE. To improve adhesion to a plastic such as this, some type of surface treatment would probably be necessary (a primer, surface abrasion, plasma activation, etc.). ePaint adhered to SS better than ECO HRT. It is possible that Intersleek had better adhesion than ePaint but the test method used here was inconclusive. There were no strong trends indicating a reduction in paint adhesion due to marine exposure. In a few cases, the adhesion appeared to increase after marine exposure, possibly due to extended curing, but the large error bars make these trends uncertain.

Recommendations:

Results provide insight for potential down selection of commercial coatings under static conditions to support reliability of the WEC and potential maintenance schedules. This investigation was conducted on samples at the coupon level and the development of testing rigs for dynamic component level testing is needed for future work. In addition, the toxicity impact of these commercial coatings for aquaculture has not been determined by this study. One recommendation is to conduct toxicity investigations at the Environmental Toxicity Laboratory at Oak Ridge National Laboratory.

Benefits to the Department of Energy:

Analysis of key materials evaluated for marine energy provides methodology and potential standards development that can be applied to IEC TC-114 standards committee for biofouling assessments that are currently being determined. Results impact DOE- Water Power Technologies Office's Program on Advanced Materials and current strategic objectives to overcome engineering barriers that impact development and testing of wave energy devices, lowering cost of energy, and accelerating manufacture of marine energy technology. Capabilities established here will be applied to future studies and can be applied to other energy programs.

Economic impact:

The results of this project will be directly applied to the advancement of E-Wave's wave energy converter (WEC) technology. Biofouling, if left untreated, can significantly degrade WEC performance by reducing power output and increasing structural weight, thereby impacting system efficiency and reliability. This project evaluates the effectiveness of various antifouling coatings and identifies the most suitable solution, providing critical data to support coating selection and inform long-term maintenance schedules. The findings will not only accelerate E-Wave's path toward commercial deployment but also offer transferable insights for the broader marine energy sector using similar materials. By enhancing durability and reducing maintenance frequency, this work contributes to lower lifecycle costs and improved system performance. The WEC is intended to power aquaculture farms, reducing reliance on diesel generators, lowering operational energy costs, and enabling more sustainable, precision-driven aquaculture operations. The project is expected to support job creation in engineering, manufacturing, and operations, drive revenue growth through renewable energy deployment, and deliver environmental and public health benefits by reducing emissions and fuel handling risks.

9 REFERENCES

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