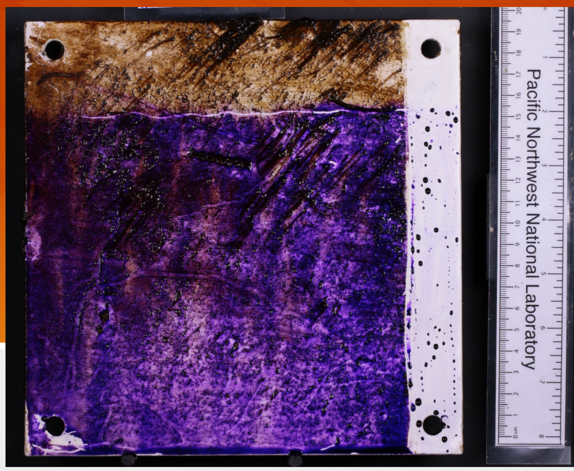
PNNL-24799



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Advanced Materials and Manufacturing Reliability

Performance Analysis of Antifouling Coatings

September 2015

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J Park
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C Larimer

U.S. DEPARTMENT OF
ENERGY

Prepared for the U.S. Department of Energy
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Performance Analysis of Antifouling Coatings;
EERE Project 65500 Report

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Pacific Northwest National Laboratory
Richland, Washington 99352

Abstract

Several experimental and commercially available coatings were tested to evaluate their antifouling performance in unfiltered, natural seawater. The coatings were applied to replicate sets of test coupons with one set exposed to near static flow conditions and the other set exposed to fast currents of ~2.5 knots. All of the coupons experienced fouling, but some fouled more heavily than others. A critical finding of the test campaign included the importance of the application technique to achieving a consistent surface and good adhesion. Some coatings may be ruled out for further study due to the fragility of the coating. Other coatings will require additional research to achieve scale-up of production and application onto larger and geometrically complex surfaces. At this time, none of the experimental coatings significantly outperformed commercially available coatings, but some of the novel coatings did achieve equal performance and may be able to improve upon those results.

Summary

Pacific Northwest National Laboratory (PNNL) conducted tests to assess the efficacy of various coatings designed to prevent biofouling. Sandia National Laboratory (SNL) and its partners provided coupons with various antifouling coatings and these coupons underwent time-series exposures under controlled laboratory tests at PNNL's Marine Sciences Laboratory in Sequim, Washington. The PNNL team assessed the coupons to evaluate the extent, timing, and type of fouling buildup that occurred. A companion report from SNL provides details about each coating, including the intended mechanism of protection and the methods of fabrication and application onto the coupon surfaces.

Acknowledgments

The authors wish to thank their collaborators at Sandia National Laboratory (Bernadette A Hernandez, Michele Denton, Michael Hibbs, and Susan Altman), North Dakota State University (Shane Stafslien), and Brigham Young University (Paul Savage) for providing the coatings samples and for technical interactions during the course of the testing.

The authors also wish to thank the Facilities and Operations staff (Jeff Breithaupt, Chris Dissing, M. Dwight Hughes, and Brett Romano) at PNNL's Marine Science Laboratory for their assistance maintaining the seawater systems.

Acronyms and Abbreviations

BYU	Brigham Young University
in.	inch(es)
lb	pound(s)
MHK	marine hydrokinetic
µm	micron(s)
m/s	meter(s) per second
mL	milliliter(s)
mm	millimeter(s)
MSL	Marine Sciences Laboratory
NDSU	North Dakota State University
NPOC	Non-Purgeable Organic Carbon
O&M	operation and maintenance
ppm	parts per million
PNNL	Pacific Northwest National Laboratory
PVC	polyvinyl chloride
SNL	Sandia National Laboratory
TOC	total organic carbon

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1.0 Introduction

Biofouling, the undesired accumulation of organic and cellular material on a surface, is a critical problem for any system operating in an aquatic environment. Marine power systems, such as those based upon tidal, wave, and wind energy, may suffer diminished performance, accelerated corrosion, and increased operations and maintenance (O&M) costs as a consequence of biofouling. The shipping industry has faced these challenges for centuries and at present, the most cost-effective strategy to mitigate the negative effects caused by biofouling is to protect vulnerable surfaces with anti-fouling coatings. There are, however, many differences in the operation, materials, and geometries of power generators in comparison to ships that may impact the selection of coatings and their performance. The Pacific Northwest National Laboratory (PNNL) was contracted by the US Department of Energy's Office of Energy Efficiency and Renewable Energy (DOE-EERE) to compare the performance of a set of commercial and experimental coatings designed to prevent biofouling on marine-exposed surfaces. This report details the test conditions, methods of analysis, results of the tests, and discusses the significance of the findings and recommendations for future development. The tests were performed at PNNL's Marine Sciences Laboratory (MSL), located on the Strait of Juan de Fuca in Washington State during 2014-2015. The coatings were provided by Sandia National Laboratory (SNL) and its collaborators; details about the design and fabrication of the coatings are provided in a separate report written by the SNL team.

2.0 Background

The DOE-EERE Wind and Water Power Technologies Office supports research in the application of maritime power systems, including tidal-driven power, wave generated power, ocean thermal energy conversion, and offshore wind turbines. Biofouling is a major concern for each of these systems: fouling may impact operability, efficiency, safety, and the stability of the platforms. Fouling also accelerates many forms of corrosion, including pitting, delamination of materials, crack and crevice corrosion, and galvanic corrosion. Therefore, it is critical to prevent fouling in order to reduce O&M costs, prevent loss of efficiency of wave or tidal energy converter systems (e.g., by the added weight or drag from fouling organisms), reduce corrosion, and to maintain safety (e.g., slick or sharp surfaces).

Fouling occurs as a four-step process beginning immediately when an object enters the water. The first phase spans the first seconds to several hours and entails coating of exposed surfaces with freely available biomolecules, such as nucleic acids, peptides, complex sugars, and lipids. During the second phase, unicellular organisms (bacteria as well as diatoms and other unicellular eukaryotes) settle onto surfaces, attach, and begin to colonize. This phase begins hours after immersion and may last days or weeks. During the third phase, the colonies of microorganisms multiply and grow to form a biofilm: a sticky, highly adhesive, and highly durable matrix of cells enveloped in an organic polymeric matrix. The sticky nature of biofilms leads allows these to capture particulates from the surrounding water and allows small multicellular organisms, such as the larval forms of animals or algal spores, to attach to the surface. During the fourth phase, the larvae and spores grow to form macrobiotic fouling, such as mollusks, tunicates, sponges, and macroalgae.

Biofilms with a roughness of a mere 50 μm thick (1/20th mm) can increase drag on a surface by 22% (Characklis 1990). A 250 μm thick biofilm may decrease the efficiency of heat exchangers by 50% (Goodman 1987; Venkatesan and Murthy). Heavy fouling with mussels, anemones, and blades of algae or kelp is significantly more impactful. Although it is these third and fourth phases of fouling that are the most problematic for marine energy systems, strategies to prevent fouling attempt to disrupt fouling at all phases, particularly phases 2 and 3.

Antifouling coatings may employ one or more strategies to prevent or limit the extent of fouling: including the use of toxins (e.g., copper, zinc), structural features (e.g., micro and nanotextured surfaces), physical properties (e.g., hydrophobicity, ablative paints), or various chemistries (e.g., zwitterionic). Some of the materials proposed by SNL and its partners require persistent currents across the surface of the substrates to promote the release of toxins and the intentional gradual erosion of the paint – so called self-ablative surfaces – resulting in the continuous refreshing of the surface (similar to how the human body sheds skin cells). Other strategies, such as low surface energy coatings, prevent fouling organisms from rapidly establishing strong adhesive bonds and therefore also rely on currents to wash the organisms off the surface (known as a "fouling release" strategy). A challenge for these two classes of materials is how well they perform in environments where currents are intermittent and velocities are variable; extended periods of slow current speeds can result in irreversible fouling buildup.

At present, commercial coatings developers have focused their energy on developing paints for various boating and shipping scenarios. Toxic ablative paints are used for vessels that may remain stationary for extended periods, such as US Navy vessels deployed to foreign water or pleasure craft that remain at dock for days or weeks at a time. Fouling release coatings are used on ships that are most often under way, such as cruise ships, some cargo ships, and performance racing yachts that are trailered between use. The disadvantages of these coatings for offshore energy systems are that the toxic ablative paints require periodic velocity or light cleaning to refresh the surface and after a few years the paint must be reapplied. Additionally, the use of some toxins (e.g., copper) is controversial in some locations and the toxins are not 100% effective. The disadvantage of the fouling release coatings is that these have typically required surface velocities of >10 knots (5.1 m/s), more than twice the velocity of a very strong tidal current. During the course of this study, International Marine released a new coating, Intersleek 100SR, that is effective with velocities of 5 knots, approaching the effective range for some energy systems and locations.

Lowering the cost of O&M and improving reliability & performance of marine hydrokinetic (MHK) technology requires advances in coating technology. Numerous fouling-resistant coatings are now being touted for this purpose, but suitable test data and comparisons are lacking and a singular coating that exhibits broad-spectrum, long-term effectiveness has not been developed. Wave energy converter or other MHK devices will have many different components (moving, anchored, surface exposed, intermittently submerged, fully submerged) and equally complex corrosion problems that require careful selection and optimization of protection.

To address the need for a coating that works in low current settings and with little or no toxicity in the environment, SNL and its partners at North Dakota State University (NDSU) and Brigham Young University (BYU) developed novel molecular and nanoparticle antifouling coatings. These were tested initially at NDSU where the coatings were exposed to artificial seawater for less than 72 hours to downselect candidate materials for further analyses. PNNL-MSL was engaged in summer 2013 to provide scaled-tests in real seawater for extended periods of time.

Traditional testing methods for antifouling materials (e.g., ASTM International standards D3623-78a1[1] and D6990-052[2]) entail conducting exposures for periods of time and then visually assessing the buildup of fouling materials over the exposed surfaces. These methods are highly subjective: the interpretations are limited by the expertise of the evaluator at identifying all of the possible fouling organisms at all life stages, and the results are poorly quantifiable. Furthermore, the ASTM methods do not discriminate between microorganisms and therefore any effects that a coating may have on particular species or classes

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[1] Designation: D3623-78a (Reapproved 2012); Standard Test Method for Testing Antifouling Panels in Shallow Submergence.

[2] Designation: D6990-05 (Reapproved 2011); Standard Practice for Evaluating Biofouling Resistance and Physical Performance of Marine Coating Systems.

of organisms are not captured. To resolve this problem, PNNL has perfected a variety of advanced analytical methods that provide detailed characterization and objective measures of fouling buildup on surfaces. These include methods that provide highly accurate quantification of fouling (e.g., by total carbon and total organic carbon analysis), quantitative molecular-based enumeration of microscopic and macroscopic species, fouling community fingerprinting, and biomolecular characterization. The methods are highly reproducible and may be performed by individuals with limited skills and training (Bonheyo et al. 2014; Larimer et al. *submitted* a and b; Park et al. *submitted*; Jeters et al. *submitted*).

3.0 Tests

Staff at PNNL provided SNL and its partners with a standardize test format to create coupons on which the coatings would be applied. SNL had aluminum coupons cut to size with a small hole drilled into each of the four corners to allow the coupons to be held in position during the tests. The coupons were then painted (all sides) with a standard marine epoxy-based primer (Intergard 264) suitable for aluminum surfaces. The primed coupons were provided to all of the coatings developers who were instructed to coat the coupons on all sides and edges with their antifouling materials. Coupon sizes included 1 x 1 in. squares, 3 x 3 in. squares, and 8 x 8 in. squares. The thickness of the coupons was not important for these tests, but was 1/8 in. For each coating, a total of eighteen 1 x1 in., six 3 x 3 in., and twelve 8 x 8 in. were requested, adding up to 1746 in^2 total surface area per coating (not including the holes). For the coatings developers, this reflected a significant scale-up in production compared with the preliminary studies that required less than 1 in^2 of total surface area to be painted and may be considered a preliminary test of scalability for the coatings.

Figure 1. Low- and high-velocity testing environments. Top: One of the 500 gal tanks used for the low-velocity studies. Bottom left: Raceway used for the high-velocity studies. Bottom right: Frames (empty) used to hold coupons in the raceway.

Exposures were conducted using two different flow velocity regimes in tanks filled with unfiltered seawater to simulate real marine environments where dynamic currents typically range between 0 to 5 knots (0.0 ~ 2.5 m/s). A simulated low-flow velocity environment used circular 500 gal tanks (Figure 1, top photo) with rotational currents <0.5 knots. The high flow environment used a raceway tank with a flow velocity of ~2.5 knots (Figure 1, bottom photos). The low velocity tanks were located indoors and used ambient temperatures and a diurnal light cycle. The raceway was located outdoors and also used ambient conditions.

For the indoor, low-flow rate tank tests, water exchange rates were maintained at 30% volume per hour or greater. Salinity and temperature were monitored and recorded. For the outdoor, high-flow rate tests, the flow velocity was set at a single (non-varying) rate and measured at multiple locations along the length of the racks.

Coupons in the low-flow tanks were mounted as follows: Triplets of identical 1 x 1 in. coupons were tied to each other using loose, non-tightening loops of 40 lb fishing line to form a short chain. A single length of braided fishing line (40 lb test) was tied using non-tightening loop knots (to avoid damage to the coating) to two holes on one side of the 3 x 3 in. and 8 x 8 in. coupons and to one of the 1 x 1 in. in coupons in a triplet, creating a large loop. This large loop was used to hang the coupons from hooks mounted to spokes (the white bars in Figure 1, top photo). A jig was used to ensure that all coupons had a loop that would position the coupons at the same depth. The coupons were held such that the plane of the coupon was vertical (perpendicular to the surface of the water) and parallel relative to the direction of the rotational flow.

Coupons in the raceway were held within polyvinyl chloride (PVC) mounting racks as follows. Triplets of 1 x 1 in. coupons were prepared as for the tanks. Four small non-tightening loops of 40 lb braided fishing line tied to each of the four holes on the 3 x 3 in. and 8 x 8 in. coupons and to opposite ends of the 1 x 1 in. coupon chains. These loops were used as attachment points for bungee cords that held the coupons within the PVC racks and allowed rapid insertion and removal of the coupons from the frames (Figure 2). The bungee cords provided even tension to hold the coupons within the current. Coupons were mounted such that the plane of the coupon was vertical (perpendicular to the surface of the water) and parallel relative to the direction of flow. Baffles mounted on each rack in front of the first set of coupons (facing the current) were used to ensure that even first coupons experienced turbulence due to the presence of a preceding object.

Coupons were submerged in the tanks and recovered after 30 days (short-term), 60 days (mid-term), and 90 days (long-term). For each antifouling coating, PNNL used a total of three 1 x 1 in. coupons, one 3 x 3 in. coupons, and two 8 x 8 in. coupons per time period for the raceway and an identical number of coupons for the low-flow tanks. The 1 x 1 in. coupons were used for non-purgeable organic carbon analysis (NPOC) measurements. The 3 x 3 in. coupons were used to assess changes in weight during the exposure period. The 8 x 8 in. coupons were used for visual analysis, staining, and for limited molecular characterization.

Figure 2. 8 x 8 in. coupons mounted within a PVC frame.

In addition to the experimental coatings, a primer control (Intergard 264 primer, no outer coating), SN1 paint from ePaint Inc., and Intersleek 900 series paint from International Marine Inc. were used as reference standards.

4.0 Methods of Analysis

4.1 Non-Purgeable Organic Carbon Analysis

Chains of three 1 x 1 in. coupons were cut to separate the coupons and remove the fishing line. Each 1 x 1 in. coupon was transferred to a sterile 50 mL polypropylene centrifuge tube and then 30 mL of 3%

hydrogen peroxide was added. Each tube containing a coupon was incubated in a 55°C water bath for an hour. The tube was vortexed vigorously and then attached to a Vial Tweeter sonication unit and oriented such that one face of the coupon faced the Vial Tweeter horn. Following a 1-minute insonification (100 % amplitude, 0.75 cycle), the tube was rotated 180° so the other side of coupon faced the horn for a second 1-minute insonification. The resulting suspension was transferred to a 40 mL certified clean NPOC test vial and analyzed for NPOC using a Shimadzu TOC-L. The Shimadzu device creates a dilution series for each sample, assays three subsamples from each dilution, and calculates the total organic content from the composite results. Additional details are outlined in a forthcoming publication (Jeters et al. *submitted*).

4.2 Image Analysis

Each 8 x 8 in. coupon was digitally photographed and assessed to determine percent coverage by biofilm and macrobiota species. Briefly: one edge of one side of the coupon was wiped clean (approximately ½ inch wide) and the coupon was then stained with mixture of three different dyes. Erythrosine B is a generalist red dye for biomass, Rhodamine detects nucleic acids and Coomassie Brilliant Blue is used to detect proteins. The coupon was photographed and analyzed using a program written at PNNL that separates images into multiple color channels and then measures fouling growth intensity by measuring color saturation in each pixel, subtracting the background intensity from the clean surface, and then integrating the values from the area examined (Larimer et al. *submitted*).

4.3 Wet and Dry Weight

Each 3 x 3 in. coupon was weighed prior to exposure and the data was recorded. After being exposed to seawater, coupons were removed and passed through a Dyson Airblade hand dryer unit to remove unincorporated 'bulk' water and then weighed. Wet coupon weights were recorded and initial coupon weight was subtracted to establish wet biomass weight. The coupons were then dried in an oven to remove all of the water and reweighed. The wet mass provides a measure of the contribution of soft tissued organisms such as anemones, tunicates, algae, and bacteria that are >70% water. These organisms are under-represented relative to hard shelled organisms (e.g., barnacles, mussels) when standard dry mass measurements are used. The use of the Airblade provides reproducible wet weight results.

5.0 Results

5.1 Samples

Table 1 lists all of the samples that were provided for testing and a brief description of the materials (if available). A more complete description of each coating, including the intending mechanism of protection and the methods of fabrication and application onto coupon surfaces is provided in the companion report from Sandia National Laboratory.

5.2 Issues

The intent of the study was to ensure that all of the coupons were exposed to seawater during an overlapping period of time to ensure that any changes in the seawater due to seasonal variation were experienced by all coupons within an exposure set (i.e., short, medium, and long-term exposures). Due to the number of coupons and the amount of time necessary to perform the analysis on each, start times were staggered and the intent was to have all coupons within an exposure group start within a two week window. However, all of the test coupons were not delivered at the same time; one coupon set arrived on time and based upon communication with the coatings developers, the exposures were started on the belief that the remaining coupons would arrive days later. Due to various complications that the developers faced, the remaining coupons did not arrive on time and all other exposures were started months later. We do not believe that this had a significant impact on the results as performances were consistent.

A second issue is that the coupons were prepared inconsistently with respect to the quality of how the coating was applied. Surface textures varied greatly within sets of a single coating. Some paints had bubbles within the coating, others had particulates (e.g., dust), and some were already delaminating when delivered. These issues may be a symptom of the early stage development of the coatings and that further development is needed in the scale-up of both production and application methods. Photos were taken of all coupons prior to exposure so that any unique results following exposure could be correlated back to the original surface properties. In some instances, the coating completely delaminated and therefore no results are presented: that coating would be considered to have failed completely. The variability in surface quality probably contributed to the standard deviation found with some of the measurements. As none of the coupons performed particularly well, individual differences in surface quality were not used in the interpretations.

Table 1. List of coupons provided for testing in this study.

		Coupons Received		
Sample ID	Description	8x8	3x3	1x1
Primer Control	Intergard 264 primer only	12	20	38
SN1	ePaint SN1	10	6	18
Intersleek	Intersleek 900	12	6	18
NDSU 1	no information	12	6	18
NDSU2	no information	12	6	18
NDSU 3	no information	12	6	18
NDSU 4	no information	12	6	18
NDSU 5	no information	12	6	18
BYU 1	IS731 base coat; IS970 top coat containing 1.0% CSA-120	12	6	18
BYU 2	IS731 base coat; IS970 top coat containing 2.5% CSA-120	12	6	18
SNL-MLBD1	no information	12	6	18
SNL-MLBD2 (aka: BAHS3)	Intersleek 970 + $NH3^{+}$	12	6	18
SNL-MH1	zwitterionic brush polymer	12	6	18
SNL-MH2	polydopamine + Ag nanoparticles	12	6	18
SNL-BAHS1	Ag Nanoparticles + Int 900 system	12	6	18
SNL-BAHS2	Ag Nanoparticles + Epoxy (Epon 8021)	4	2	6
SNL-EPON	Epoxy Blank (Epon 8021)	4	2	6

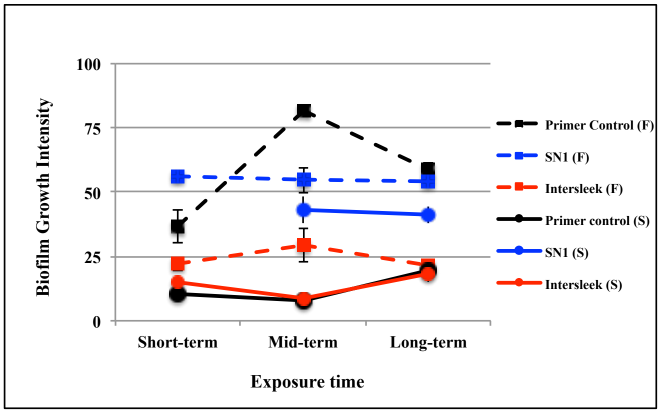
5.3 Data

Water from the tanks was tested routinely for toxicity (MicroTox Assay) and no toxicity was detected. This indicates that the coupons were not emitting toxins into the water at a rate that exceeded the exchange of fresh water into the tank (i.e., no toxin accumulation or cross-coupon effects). Additionally, each tank maintained a healthy and diverse population of microorganisms and macrobiota, including crabs, shrimp, sea cucumbers, mussels, clams, sea anemones, tunicates, sea urchins, and algae.

5.3.1 Biofilm Growth Intensity

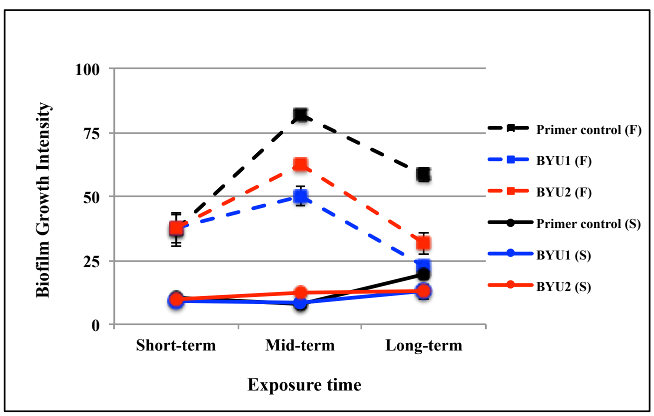
The graphs below show the average of measurements taken from two 8 x 8 in. coupons and standard deviation values are shown as error bars. Three reference standards: Intergard 264 primer control, commercial ePaint SN1, and commercial Intersleek 900 were compared. The table to the right of each graph provides the numerical values for each datapoint on the graph. Missing values occur if a coupon was not provided or if the coating delaminated to such an extent that no measurement could be made.

- (F): Flume, dashed line, (S): Static tank, solid line

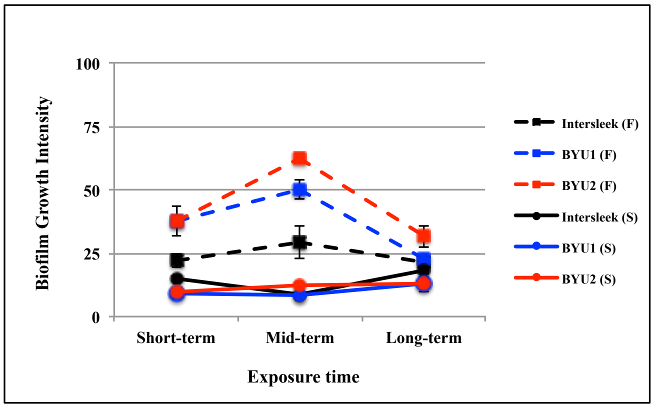


	Short-term	Mid-term	Long-term
Primer control (F)	36.72	81.67	58.50
SN1 (F)	56.28	54.73	53.88
Intersleek (F)	21.86	29.43	21.40
Primer control (S)	10.10	7.88	19.71
SN1 (S)		43.14	41.25
Intersleek (S)	15.18	8.74	18.33

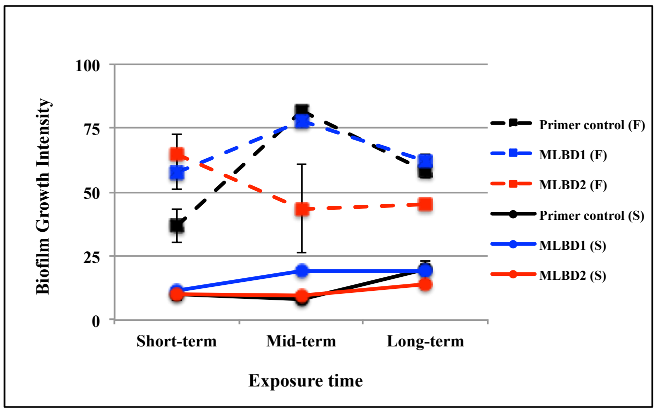
The Primer control and Intersleek showed the highest and the lowest biofilm growth intensities, respectively, and these were used as reference standards to evaluate other coatings.



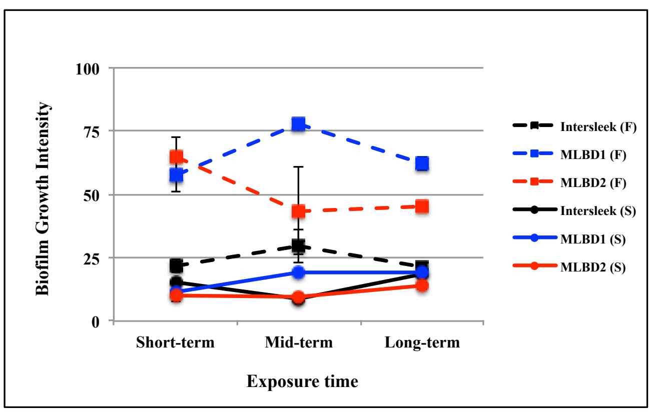
	Short-term	Mid-term	Long-term
Primer control (F)	36.72	81.67	58.50
BYU1 (F)	37.44	50.09	22.80
BYU2 (F)	37.60	62.40	31.72
Primer control (S)	10.10	7.88	19.71
BYU1 (S)	9.13	8.33	13.16
BYU2 (S)	9.63	12.42	12.75



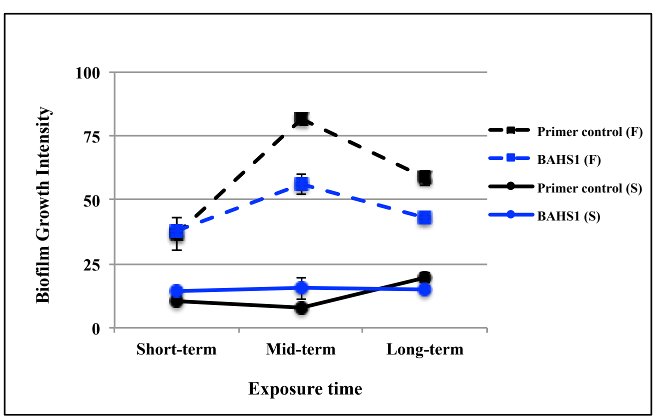
	Short-term	Mid-term	Long-term
Intersleek (F)	21.86	29.43	21.40
BYU1 (F)	37.44	50.09	22.80
BYU2 (F)	37.60	62.40	31.72
Intersleek (S)	15.18	8.74	18.33
BYU1 (S)	9.13	8.33	13.16
BYU2 (S)	9.63	12.42	12.75



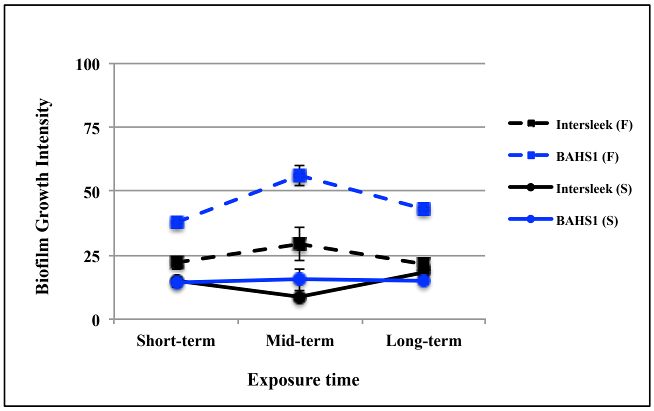
	Short-term	Mid-term	Long-term
Primer control (F)	36.72	81.67	58.50
MLBD1	57.68	77.86	62.16
MLBD2	64.76	43.35	45.40
Primer control (S)	10.10	7.88	19.71
MLBD1	11.51	19.20	18.92
MLBD2	10.14	9.59	14.11



	Short-term	Mid-term	Long-term
Intersleek (F)	21.86	29.43	21.40
MLBD1	57.68	77.86	62.16
MLBD2	64.76	43.35	45.40
Intersleek (S)	15.18	8.74	18.33
MLBD1	11.51	19.20	18.92
MLBD2	10.14	9.59	14.11



	Short-term	Mid-term	Long-term
Primer control (F)	36.72	81.67	58.50
BAHS1 (F)	37.92	56.25	42.83
Primer control (S)	10.10	7.88	19.71
BAHS1 (S)	14.09	15.42	15.13



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Intersleek (F)	21.86	29.43	21.40
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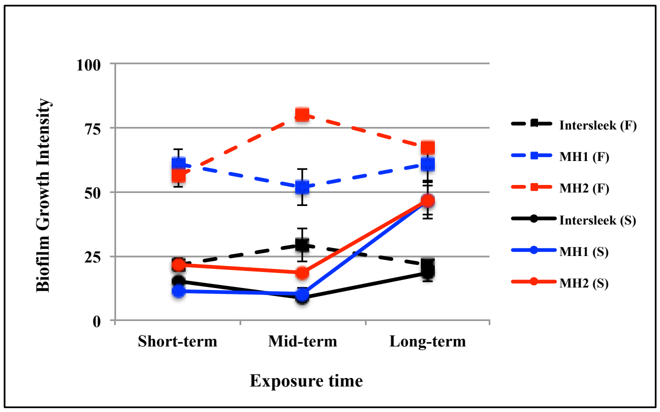
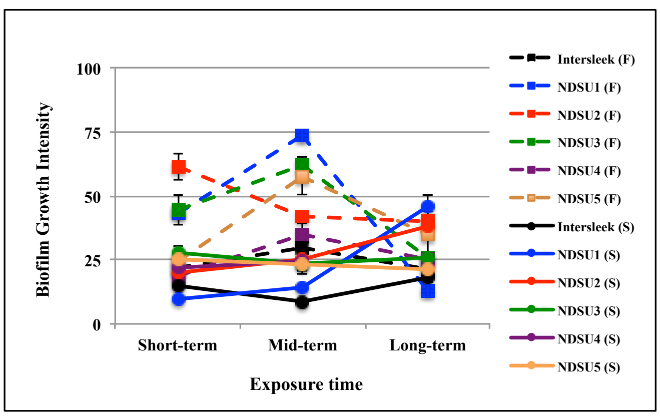


	Short-term	Mid-term	Long-term
Intersleek (F)	21.86	29.43	21.40
MH1 (F)	60.72	51.91	60.62
MH2 (F)	56.21	80.34	67.63
Intersleek (S)	15.18	8.74	18.33
MH1 (S)	11.53	10.32	47.02
MH2 (S)	21.91	18.57	46.84

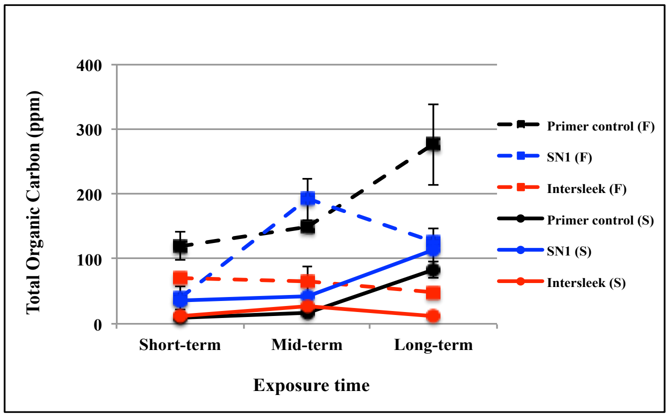


	Short-term	Mid-term	Long-term
Intersleek (F)	21.86	29.43	21.40
NDSU1 (F)	43.40	73.67	13.09
NDSU2 (F)	61.60	41.74	39.77
NDSU3 (F)	44.31	62.36	25.84
NDSU4 (F)	18.80	35.21	24.91
NDSU5 (F)	24.48	57.84	34.74
Intersleek (S)	15.18	8.74	18.33
NDSU1 (S)	9.56	14.34	45.77
NDSU2 (S)	19.79	25.45	38.11
NDSU3 (S)	27.78	23.58	25.83
NDSU4 (S)	21.97	24.47	
NDSU5 (S)	24.93	23.47	21.33

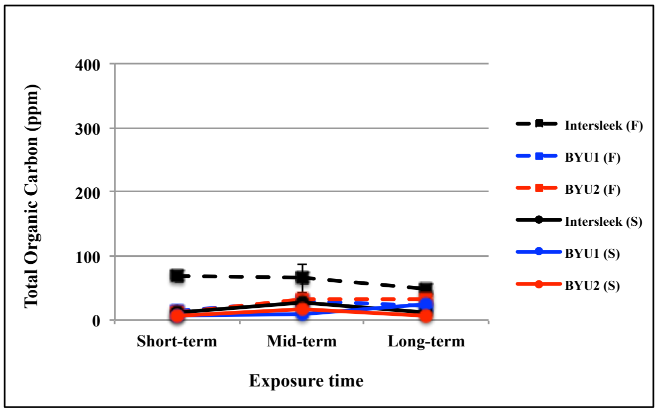
5.3.2 Total Organic Carbon

Each data point on the graphs represents the average of three 1 x 1 in. coupons and the standard deviation values are shown as error bars. The table to the right of each graph also provides the numerical average value for each triplet of coupons. Three reference standards: Intergard 264 primer control, ePaint SN1, and International Marine Intersleek 900 were compared and are used as reference standards in every graph. The test coupons are organized into sets based upon the provider. Specific information about the coatings will be available in a report from Sandia National Laboratory.

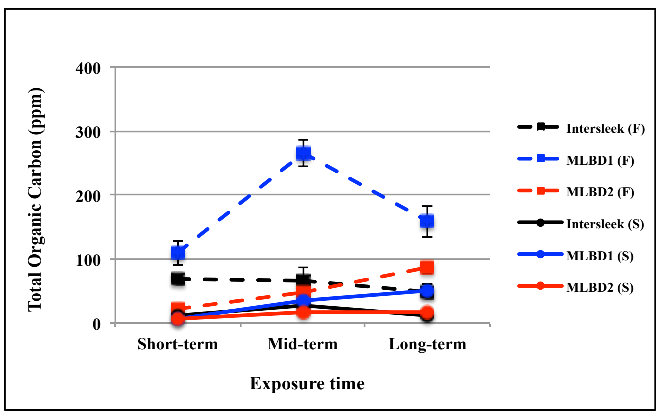
- (F): Flume, dotted line, (S): Static tank, solid line



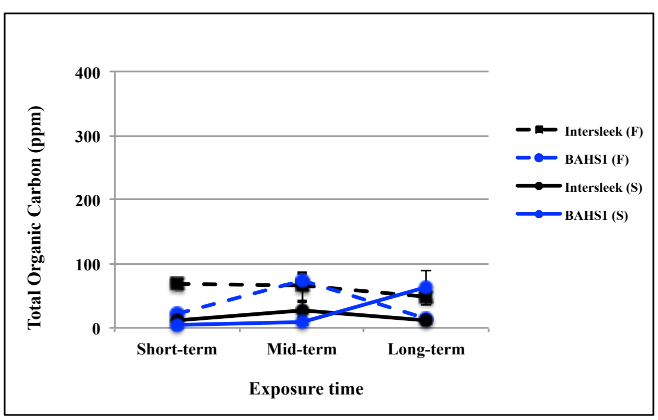
	Short-term	Mid-term	Long-term
Primer control (F)	119.48	149.78	275.71
SN1 (F)	39.75	191.58	125.70
Intersleek (F)	69.34	65.23	48.64
Primer control (S)	8.35	16.51	83.28
SN1 (S)	35.92	43.30	114.20
Intersleek (S)	12.81	28.08	11.73



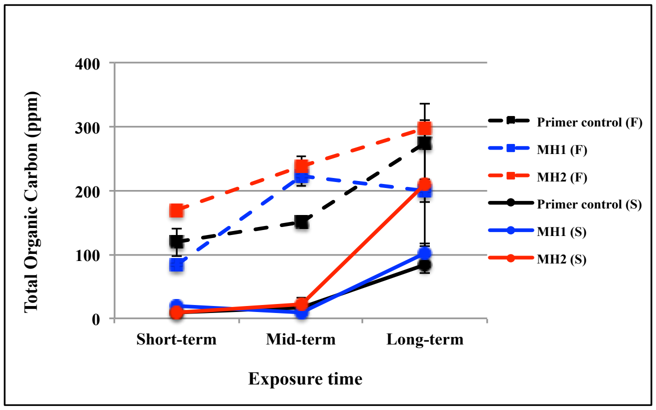
	Short-term	Mid-term	Long-term
Intersleek (F)	69.34	65.23	48.64
BYU1 (F)	13.90	29.32	22.80
BYU2 (F)	11.88	32.30	31.72
Intersleek (S)	12.81	28.08	11.73
BYU1 (S)	6.93	9.92	25.82
BYU2 (S)	6.45	17.56	7.52



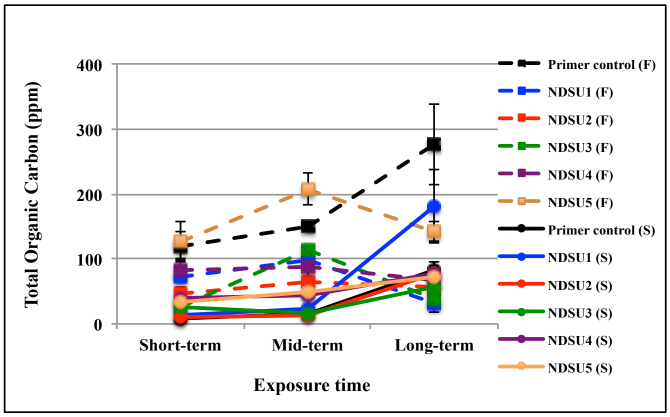
	Short-term	Mid-term	Long-term
Intersleek (F)	69.34	65.23	48.64
MLBD1 (F)	109.81	264.88	158.48
MLBD2 (F)	21.92	47.92	86.02
Intersleek (S)	12.81	28.08	11.73
MLBD1 (S)	5.78	34.61	50.57
MLBD2 (S)	5.54	16.64	15.76



	Short-term	Mid-term	Long-term
Intersleek (F)	69.34	65.23	48.64
BAHS1 (F)	21.56	74.98	14.63
Intersleek (S)	12.81	28.08	11.73
BAHS1 (S)	4.57	9.56	63.04



	Short-term	Mid-term	Long-term
Primer control (F)	119.48	149.78	275.71
MH1 (F)	83.34	223.98	200.14
MH2 (F)	169.98	239.11	296.81
Primer control (S)	8.35	16.51	83.28
MH1 (S)	18.65	8.48	102.33
MH2 (S)	8.95	23.10	209.21

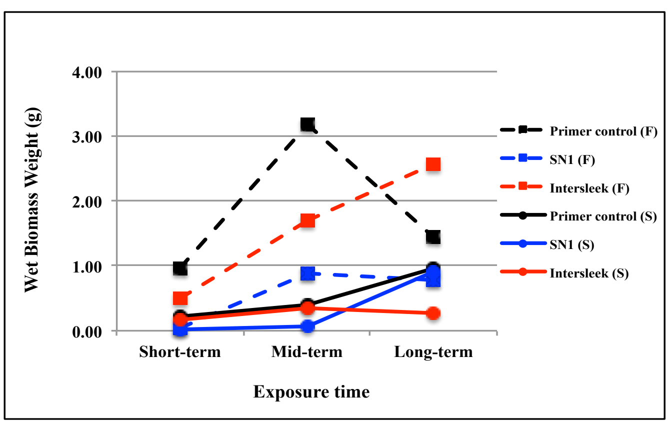


	Short-term	Mid-term	Long-term
Primer control (F)	119.48	149.78	275.71
NDSU1 (F)	71.93	98.46	32.19
NDSU2 (F)	46.46	65.71	56.01
NDSU3 (F)	24.75	112.78	38.45
NDSU4 (F)	82.71	86.74	66.64
NDSU5 (F)	126.64	207.25	142.07
Primer control (S)	8.35	16.51	83.28
NDSU1 (S)	13.62	23.95	181.05
NDSU2 (S)	10.37	12.22	78.73
NDSU3 (S)	25.80	16.44	56.57
NDSU4 (S)	39.90	43.79	77.17
NDSU5 (S)	33.15	48.51	71.32

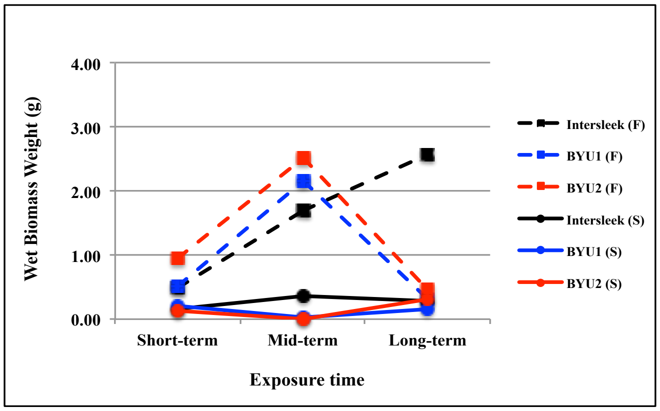
5.3.3 Wet Biomass Weight

The graphs below show the wet biomass weight accumulated on the 3 x 3 in. coupons. Three reference standards: Intergard 264 primer control, ePaint SN1, and International Marine Intersleek 900 are used as reference standards for comparisons in each graph. The table to the right of each graph provides the numerical values for the weights. Missing values occur if a coupon was not provided or if the coating delaminated to such an extent that no measurement could be made.

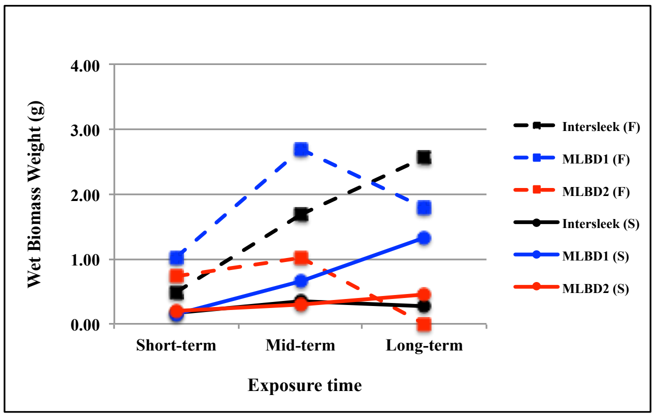
- (F): Flume, dotted line, (S): Static tank, solid line



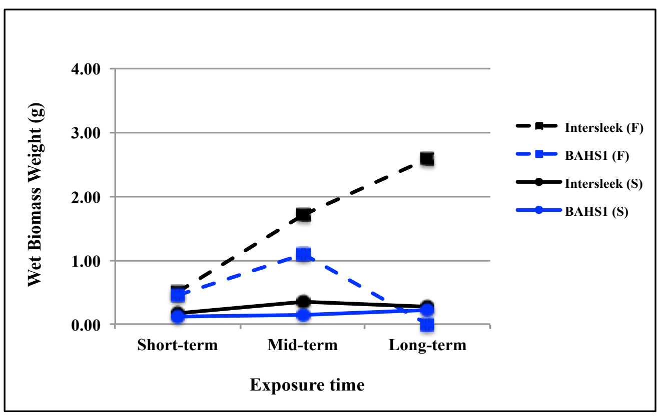
	Short-term	Mid-term	Long-term
Primer control (F)	0.97	3.19	1.45
SN1 (F)	0.03	0.88	0.78
Intersleek (F)	0.49	1.70	2.57
Primer control (S)	0.22	0.40	0.97
SN1 (S)	0.02	0.08	0.90
Intersleek (S)	0.16	0.36	0.28



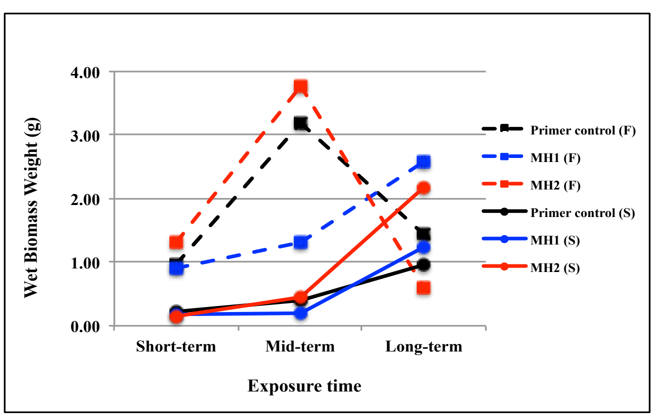
	Short-term	Mid-term	Long-term
Intersleek (F)	0.49	1.70	2.57
BYU1 (F)	0.51	2.17	0.32
BYU2 (F)	0.95	2.52	0.46
Intersleek (S)	0.16	0.36	0.28
BYU1 (S)	0.22	0.02	0.16
BYU2 (S)	0.13	0.00	0.30



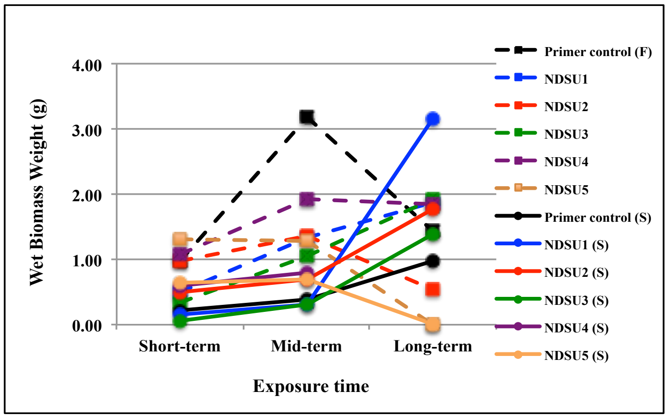
	Short-term	Mid-term	Long-term
Intersleek (F)	0.49	1.70	2.57
MLBD1 (F)	1.03	2.69	1.78
MLBD2 (F)	0.74	1.03	0.00
Intersleek (S)	0.16	0.36	0.28
MLBD1 (S)	0.15	0.66	1.32
MLBD2 (S)	0.20	0.29	0.46



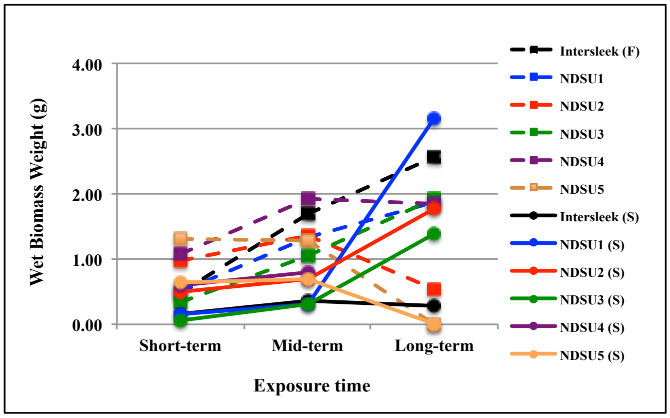
	Short-term	Mid-term	Long-term
Intersleek (F)	0.49	1.70	2.57
BAHS1 (F)	0.45	1.09	0.00
Intersleek (S)	0.16	0.36	0.28
BAHS1 (S)	0.11	0.14	0.23



	Short-term	Mid-term	Long-term
Primer control (F)	0.97	3.19	1.45
MH1 (F)	0.90	1.30	2.58
MH2 (F)	1.30	3.76	0.61
Primer control (S)	0.22	0.40	0.97
MH1 (S)	0.18	0.20	1.23
MH2 (S)	0.15	0.44	2.18



	Short-term	Mid-term	Long-term
Primer control (F)	0.97	3.19	1.45
NDSU1 (F)	0.50	1.35	1.88
NDSU2 (F)	0.98	1.37	0.53
NDSU3 (F)	0.34	1.06	1.93
NDSU4 (F)	1.07	1.92	1.84
NDSU5 (F)	1.31	1.30	0.00
Primer control (S)	0.22	0.40	0.97
NDSU1 (S)	0.15	0.30	3.17
NDSU2 (S)	0.50	0.69	1.78
NDSU3 (S)	0.06	0.32	1.39
NDSU4 (S)	0.60	0.80	
NDSU5 (S)	0.65	0.69	0.01



	Short-term	Mid-term	Long-term
Intersleek (F)	0.49	1.70	2.57
NDSU1 (F)	0.50	1.35	1.88
NDSU2 (F)	0.98	1.37	0.53
NDSU3 (F)	0.34	1.06	1.93
NDSU4 (F)	1.07	1.92	1.84
NDSU5 (F)	1.31	1.30	0.00
Intersleek (S)	0.16	0.36	0.28
NDSU1 (S)	0.15	0.30	3.17
NDSU2 (S)	0.50	0.69	1.78
NDSU3 (S)	0.06	0.32	1.39
NDSU4 (S)	0.60	0.80	
NDSU5 (S)	0.65	0.69	0.01

Interpretation

The amount of biomass accumulation on the surface of coupons was assessed by three different methods of analysis. Primer control and a couple of commercially available paints, ePaint SN-1 and International Marine Intersleek 900 (SN1 and Intersleek, respectively, in this report), were used as reference controls for making comparisons with the various coatings. SN1 is a commercial paint that has a catalytic surface; it requires light to activate the catalyst, which produces peroxide as an antifouling mechanism. Intersleek 900 is a hydrophobic fouling release coating that requires high velocity (>10 knots) to stay clean. Both SN1 and Intersleek showed lower biomass accumulation compared to Primer only control. Intersleek performed better than SN1based upon both visual and TOC analyses. Therefore, values obtained from various test coatings were compared to ones from Primer control and Intersleek. Also, the coupons that were mounted and exposed to seawater in the outdoor flume resulted in higher biomass accumulation than the coupons in indoor static tanks. The outdoor raceway consistently shows faster rates of fouling, perhaps due to the natural sunlight or the higher rate of water exchange allowing more organisms in.

Most of the test coatings showed improved inhibition of biofouling compared to the Primer control, especially in the raceway. However, Intersleek was still shown to be the most effective antifouling coating.

In some instances, the amount of fouling dropped from the mid to long-term exposures. This is not uncommon, particularly with foul release coatings: as biomass accumulates, it creates greater weight and resistance in the current until much of it ultimately falls off. Like the Intersleek coating, the BYU1 and

BYU2 coatings did not acquire any fouling other than algae (i.e., no large macrobiota) during the time period of these tests. The "slime" layer was also easily removed, indicating that cleaning would be easy.

6.0 Recommendations

Our data showed that the commercial antifouling paint Intersleek 900 inhibited biomass accumulation on the surface better than other test coatings. BYU1 and BYU2 showed the lowest biomass accumulation compared to other coatings, but the antifouling performance of this coating will need to be enhanced to outcompete Intersleek. Also, the consistency of the coating material and quality of application has to be improved. A few of the coupons, especially NDSU4, were too delaminated to be tested.

These results may be used to rule out some of the coatings due to their fragility (e.g., NDSU4) or poor performance. Others could be used for longer exposures in future studies. Further studies may consider whether the coatings provide protection against corrosion or water absorption into the underlying materials.

7.0 References

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