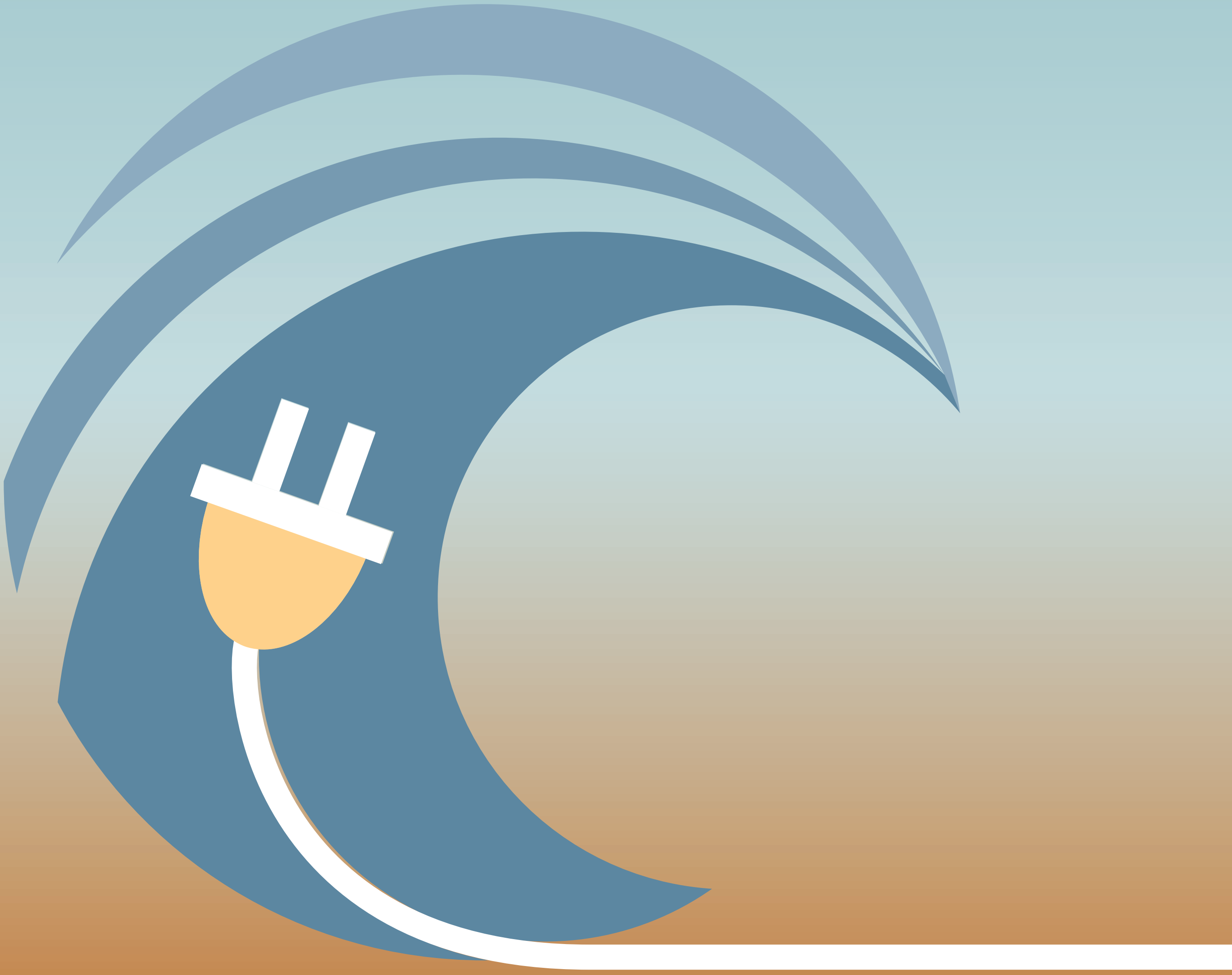
Northwest National Marine Renewable Energy Center

Report #1
April 8, 2010

Screening for Biofouling & Corrosion of Tidal Energy Device Materials

Brian Polagye and Jim Thomson



UNIVERSITY of WASHINGTON

Oregon State UNIVERSITY

NNMREC
Northwest National Marine
Renewable Energy Center

Oregon State University

Belinda Batten
Director
541-737-9492
belinda.batten@oregonstate.edu

Meleah Ashford
Program Manager
541-737-6138
meleah.ashford@oregonstate.edu

nnmrec.oregonstate.edu

University of Washington

Brian L. Polagye
Co-Director
206-543-7544
bpolagye@uw.edu

depts.washington.edu/nnmrec

Suggested Citation: Polagye, B. L. and J. Thompson. 2010. Screening for Biofouling and Corrosion of Tidal Energy Device Materials: In-situ results for Admiralty Inlet, Puget Sound, Washington. Northwest National Marine Renewable Energy Center Report no. 1. Seattle: NNMREC. 10 pp.

Partial funding for this material was provided by U.S. Department of Energy and the Oregon Wave Energy Trust (OWET).

OWET is funded in part with Oregon State Lottery Funds administered by the Oregon Business Development Department. It is one of six Oregon Innovation Council initiatives supporting job creation and long-term economic growth.

U.S. DEPARTMENT OF ENERGY

OregonWaveEnergy TRUST

Screening for Biofouling and Corrosion of Tidal Energy Device Materials: *In-situ* results for Admiralty Inlet, Puget Sound, Washington

Northwest National Marine Renewable Energy Center Technical Memorandum

University of Washington, Seattle, WA, United States

Authors

Dr. Brian Polagye, Department of Mechanical Engineering

Dr. Jim Thomson, Applied Physics Laboratory/Civil and Environmental Engineering

Date

April 8, 2010

Abstract

From April 2009 to February 2010, coupons of materials which could be used in the rotor, drive train, or foundation of tidal energy devices were deployed *in-situ* on the seabed at a prospective tidal energy site to screen for biofouling and corrosion. Materials include glass and carbon fiber composites, stainless steel, aluminum, structural steel, and common steel. Several potential rotary bearing materials were also screened. Coatings, including high copper anti-fouling, low copper anti-fouling, and inert foul-release are also evaluated for their ability to control biological fouling. For smooth surfaces, there is limited biological fouling at this particular site, which is below the photic zone. Stainless steel shows excellent corrosion resistance, while common and structural steels experience major surface oxidation after three months of exposure to the marine environment – even with sacrificial anodes. More quantitative work is required to evaluate corrosion rates and the potential strength degradation of glass and carbon fiber composites over long-term exposure to the marine environment.

Table of Contents

1 Introduction

From April 2009 to February 2010, material coupons which might be used in the rotor, drive train, or foundation of tidal energy devices were deployed *in-situ* on the seabed in Admiralty Inlet, Puget Sound, Washington. This location has been selected by Snohomish Public Utility District for the deployment on an OpenHydro tidal turbine. Coupons were deployed for between three and ten months. Deployment depths vary from 55 to 75m and tidal currents close to the seabed approach 3 m/s on strong spring tides. The purpose of this testing is to screen materials for biofouling and corrosion and develop an indication of how tidal energy devices deployed at this location might be affected. Because device developers envision operational deployments on the order of several years and it has been demonstrated that biofouling may significant degrade rotor performance (Orme et al. 2001), an understanding of biofouling and corrosion is necessary.

The test matrices consist of uncoated and coated coupons, nominally 2.5 inches wide, 2.25 inches long, and 0.125 inches thick. For expediency, coupons are attached to a fiberglass plate using a marine grade adhesive (3M 5200). Each plate is secured to the leg of an instrumentation tripod, as shown in Figure 1.1. The primary purpose of this tripod is to characterize the physical and biological environments at tidal energy sites.

Figure 1.1 – Material samples attached to instrumentation tripod

The test materials and their potential application in a tidal energy device include:

- Carbon fiber and glass fiber composite: rotor, hub, or duct/shroud
- Aluminum (6061): rotor
- Stainless steel (314 and 316): hub or shroud
- Steel (1018 and 539): support structure
- High density polyethylene (HDPE): bearings
- Fiber reinforced phenolic resin (Feroform T14 from Tenmat): bearings
- Low friction liner on stainless backing (Feroglide 700 from Tenmat): bearings

Additionally, three potential marine coatings are evaluated:

- Trinidad (high copper antifouling) from Pettit Paint
- Vivid (low copper antifouling) from Pettit Paint

- Intersleek (inert foul release) from International Paint

Trinidad and Vivid were supplied as wet product and applied to coupons prior to deployment per manufacturer specification. Intersleek was supplied as a pre-coated rubber mat, which was cut in-house to the standard sample size.

Sets of coupons were deployed in April 2009, August 2009, and November 2009, as described in Table 1.1. Not all possible positions were occupied during each deployment.

Table 1.1 – Material sample test matrix by deployment

Deployment	Recovery	Plate	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6
Apr 2009	Aug 2009[1]	1	Carbon fiber	Glass fiber	Vivid on carbon fiber	Trinidad on glass fiber	Intersleek on rubber mat	
		2	Aluminum (6061)	Stainless steel (314)				
Apr 2009	Feb 2010[2]	1	Carbon fiber	Glass fiber	Vivid on carbon fiber	Trinidad on glass fiber	Intersleek on rubber mat	
		2	Aluminum (6061)	Stainless steel (314)				
Aug 2009	Nov 2009	1	Carbon fiber	Glass fiber	Vivid on carbon fiber	Trinidad on carbon fiber	Intersleek on rubber mat	HDPE
		2	Aluminum (6061)	Stainless steel (314)	Stainless steel (316)	Steel (1018)	Steel (1018) w/ Zn anode	
Nov 2009	Feb 2010	1	Carbon fiber	Glass fiber	Vivid on glass fiber	Trinidad on carbon fiber	Intersleek on rubber mat	HDPE
		2	Steel (539)	Steel (539) w/ Zn anode		Stainless steel (316)	Feroform T14	Feroglide 700

The following sections of this report describe the performance of materials and coatings. Section 2 describes material performance, Section 3 describes coating performance, and Section 4 concludes with a brief summary of preliminary findings and recommendations for future work.

2 Material Performance

2.1 Glass Fiber Composite

This composite test material is glass fiber in an epoxy matrix. Degradation of material properties due to long-term water permeation is possible and will be addressed through future studies, but the present effort focuses on surface fouling. In general, glass fiber composite performed well, with limited surface fouling after 10 months of deployment. A barnacle adhered to the edge of one material coupon (Apr 2009 – Aug

---

[1] Coupons recovered to surface and exposed to air in May 2009

[2] Coupons recovered to surface and exposed to air in May 2009, Aug 2009, and Nov 2009

2009, Figure 2.1), part of a general trend that biological fouling is more common on edges/in crevices, than on smooth surfaces.

Table 2.1 – Performance of glass fiber composite

Deployment	Recovery	Duration	Changes
Aug 2009	Nov 2009	3 months	Minimal fouling on surface.
Nov 2009	Feb 2010	3 months	Minimal fouling on surface.
Apr 2009	Aug 2009	4 months	Minimal fouling on surface. One barnacle on edge.
Apr 2009	Feb 2010	10 months	Minimal fouling on surface. Surface color has darkened.

Figure 2.1 – Barnacle attached to edge of glass fiber composite sample

2.2 Carbon Fiber Composite

This composite test material is carbon fiber in an epoxy matrix. As with glass fiber composite, the carbon fiber composite developed minimal surface fouling after up to 10 months of deployment.

Table 2.2 – Performance of carbon fiber composite

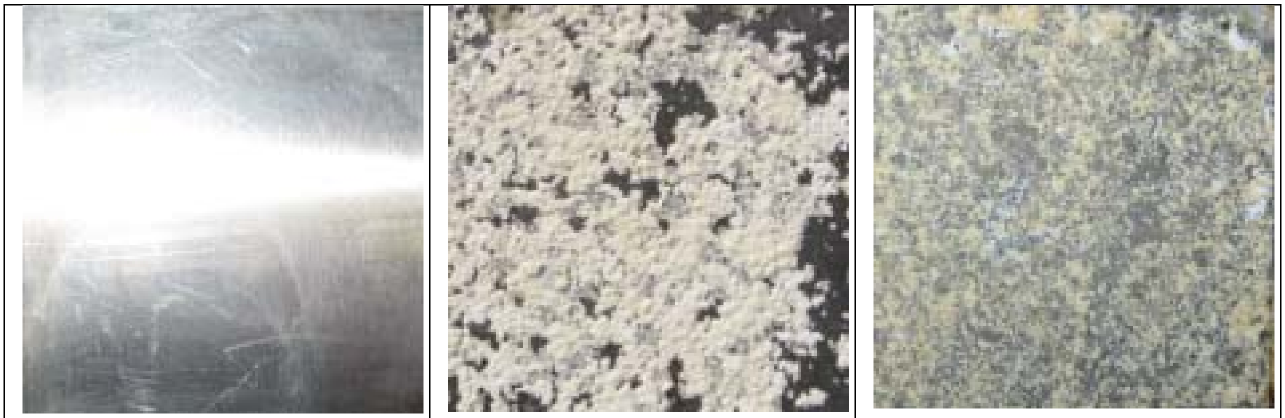
Deployment	Recovery	Duration	Changes
Aug 2009	Nov 2009	3 months	Minimal fouling on surface.
Nov 2009	Feb 2010	3 months	Minimal fouling on surface.
Apr 2009	Aug 2009	4 months	Minimal fouling on surface.
Apr 2009	Feb 2010	10 months	Minimal fouling on surface.

2.3 Aluminum (6061)

As expected, aircraft grade aluminum does not perform well in the marine environment. More than 90% of the exposed surfaces on all aluminum coupons oxidized during each 3-4 month deployment, as shown in Figure 2.1. After 10 months deployment in the marine environment, the surface is almost entirely oxidized and embrittled to the point that one corner of the coupon broke away during routine handling.

Table 2.3 – Performance of aluminum (6061)

Deployment	Recovery	Duration	Changes
Aug 2009	Nov 2009	3 months	>90% surface and edge corrosion.
Apr 2009	Aug 2009	4 months	>90% surface and edge corrosion.
Apr 2009	Feb 2010	10 months	>95% surface and edge corrosion. Coupon edges embrittled.



(a) Deployment: Apr 2009 | **(b) Recovery: Aug 2009** | **(c) Recovery: Feb 2010**

Figure 2.2 – Aluminum (6061) coupon corrosion (Apr 2009 - Aug 2009 deployment)

2.4 Stainless Steel (314/316)

Both 314 and 316 grade stainless steel general show minimal corrosion or biofouling after prolonged exposure to the marine environment. One sample developed superficial corrosion along the contact surface between the stainless steel and fiberglass panel and a barnacle attached to one edge, as shown in Figure 2.2.

Table 2.4 – Performance of stainless steel (314)

Deployment	**Recovery**	**Duration**	**Changes**
Aug 2009	Nov 2009	3 months	Minor fouling on surface with origin in edge/crevice fouling.
Apr 2009	Aug 2009	4 months	Minimal fouling on surface.
Apr 2009	Feb 2010	10 months	Minimal fouling on surface.

Table 2.5 – Performance of stainless steel (316)

Deployment	**Recovery**	**Duration**	**Changes**
Aug 2009	Nov 2009	3 months	Minimal fouling on surface. One barnacle on edge.
Nov 2009	Feb 2010	3 months	Superficial corrosion on one edge, concentrated at fiberglass/steel interface.

(a) Edge corrosion (Nov 2009-Feb 2010) | **(b) Barnacle growth (Aug 2009-Nov 2009)**

Figure 2.3 – Stainless steel (316) edge corrosion and biofouling

Other 316 grade hardware used to secure instrumentation to the measurement tripod developed more severe corrosion during some deployments. In most cases this appears to be caused by depriving the stainless steel of oxygen (e.g., occluding the surface). During the April-May, 2009 deployment, approximately half of the stainless fasteners corroded to the near the point of mechanical failure, with the common cause being the use of nylock nuts (stainless nuts with a nylon insert in lieu of a lock washer). Interestingly, corrosion was often more pronounced on the head of the bolt than the end with the nylock nut. On subsequent deployments, nylock nuts were replaced by stainless steel nuts and lock washers and no further widespread corrosion has been observed. In another instance, seine twine (tarred nylon cord) was looped around a 316 grade U-shaped bracket. After three months in the water, the bracket had been oxidized to the point of failure, as shown in Figure 2.4.

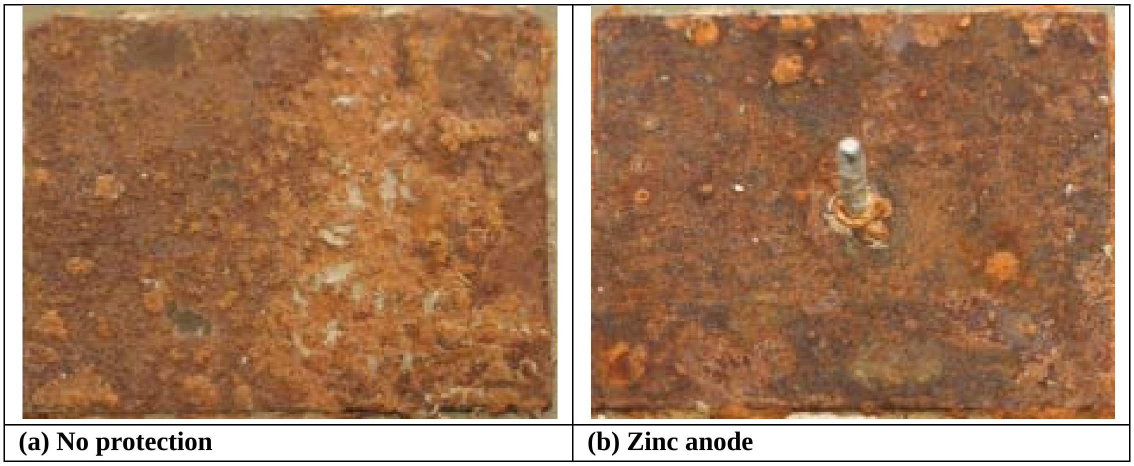
Figure 2.4 – Stainless steel (316) hardware corrosion due to oxygen deprivation by seine twine

2.5 Common Steel (1018)

Common steel is included in a single deployment matrix (Aug-Nov 2009). In addition to bare steel, protection by a zinc anode screwed into the center of the coupon is tested. The surfaces of both coupons were almost entirely oxidized upon retrieval. Anodic protection reduced, but did not eliminate, oxidation of the common steel. The surface corrosion was similar in character (e.g., oxidation blisters), but not as pronounced and the zinc anode showed significant reduction upon retrieval.

Table 2.6 – Performance of common steel (1018)

Deployment	Recovery	Duration	Protection	Changes
Aug 2009	Nov 2009	3 months	No protection	Heavy surface oxidation (100% coverage). Bioaccumulation within oxidation blisters.
Aug 2009	Nov 2009	3 months	Zinc anode	100% surface oxidation, but not as pronounced as unprotected surface.



(a) No protection | **(b) Zinc anode**

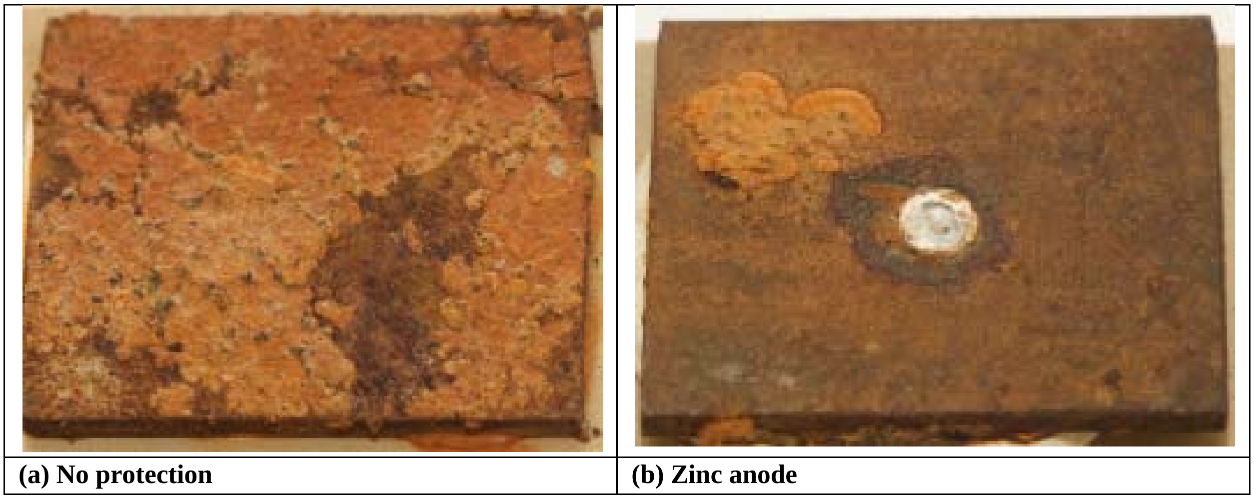
Figure 2.5 – Common steel (1018) coupon corrosion (Aug - Nov 2009 deployment)

2.6 Structural Steel (539)

Structural steel is included in a single deployment matrix (Nov 2009-Feb 2010). As with common steel, in addition to a bare surface, protection by a zinc anode screwed into the center of the coupon was also tested. The protection significantly reduced, but did not entirely eliminate, oxidation of the structural steel. The anode was missing upon tripod retrieval and presumed to have been dislodging during retrieval operations.

Table 2.7 – Performance of common steel (1018)

Deployment	Recovery	Duration	Protection	Changes
Nov 2009	Feb 2010	3 months	No protection	Heavy surface oxidation (85% coverage).
Nov 2009	Feb 2010	3 months	Zinc anode	Corrosion on 15% of surface and egdes.



(a) No protection | **(b) Zinc anode**

Figure 2.6 – Structural steel (539) coupon corrosion (Nov 2009 - Feb 2010 deployment)

2.7 Bearing Materials

Three types of potential bearing materials were exposure tested as a proxy for operational biological fouling. High density polyethylene (HDPE) experienced minimal surface and edge fouling. No fouling was visible on either Feroform T14 or Feroglide 700 material samples.

Table 2.8 – Performance of bearing materials

Deployment	Recovery	Duration	Material	Changes
Aug 2009	Nov 2009	3 months	HDPE	Minimal fouling on surface and edges.
Nov 2009	Feb 2010	3 months	HDPE	Minimal fouling on edges.
Nov 2009	Feb 2010	3 months	Feroform T14	No visible fouling on surface or edges.
Nov 2009	Feb 2010	3 months	Feroglide 700	No visible fouling on surface or edges.

3 Coatings

3.1 Trinidad

Trinidad is a high copper content anti-fouling paint proprietary to Pettit Paint. The manufacturer supplied a sample quantity of Trinidad for application to various surfaces. The paint is applied to glass and carbon fiber composite coupons, following manufacturer recommendations to roughen the surface with 80 grit sandpaper and clean with a solvent prior to paint application. Coupons coated with Trinidad developed minimal fouling on the surfaces or edges, regardless of deployment length.

Table 3.1 – Performance of Trinidad (Pettit Paint) coating

Deployment	Recovery	Duration	Substrate	Changes
Aug 2009	Nov 2009	3 months	Carbon fiber	Minimal fouling on surface and edges.
Nov 2009	Feb 2010	3 months	Carbon fiber	Minimal fouling on surface and edges.
Apr 2009	Aug 2009	4 months	Glass fiber	Minimal fouling on surface and edges.
Apr 2009	Feb 2010	10 months	Glass fiber	Minimal fouling on surface and edges.

3.2 Vivid

Vivid is a low copper content anti-fouling paint proprietary to Pettit Paint. The manufacturer supplied a sample quantity of Vivid for application to various surfaces. The paint is applied to glass and carbon fiber composite coupons, following manufacturer recommendations to roughen the surface with 80 grit sandpaper and clean with a solvent prior to paint application. Coupons coated with Vivid developed minimal fouling on the surfaces or edges, regardless of deployment length.

Table 3.2 – Performance of Vivid (Pettit Paint) coating

Deployment	Recovery	Duration	Substrate	Changes
Aug 2009	Nov 2009	3 months	Carbon fiber	Minimal fouling on surface and edges.
Nov 2009	Feb 2010	3 months	Glass fiber	Minimal fouling on surface and edges.
Apr 2009	Aug 2009	4 months	Carbon fiber	Minimal fouling on surface and edges.
Apr 2009	Feb 2010	10 months	Carbon fiber	Minimal fouling on surface and edges.

3.3 Intersleek

Intersleek is an inert, foul-release coating proprietary to International Paint. The manufacturer supplied two pre-coated rubber mats, each consisting of Intersleek 970 over a coat of Intersleek 737, though in different colors. The Intersleek coated surfaces and edges exhibited minimal fouling, with the exception of the blue painted mat (Figure 2.3), which was mildly fouled upon recovery.

Table 3.3 – Performance of Intersleek (International Paint) coating

Deployment	Recovery	Duration	Color	Changes
Aug 2009	Nov 2009	3 months	Red	Minimal fouling on surface and edges.
Nov 2009	Feb 2010	3 months	Blue	Minor fouling on ~15% of surface.
Apr 2009	Aug 2009	4 months	Red	Minimal fouling on surface and edges.
Apr 2009	Feb 2010	10 months	Red	Minimal fouling on surface and edges.

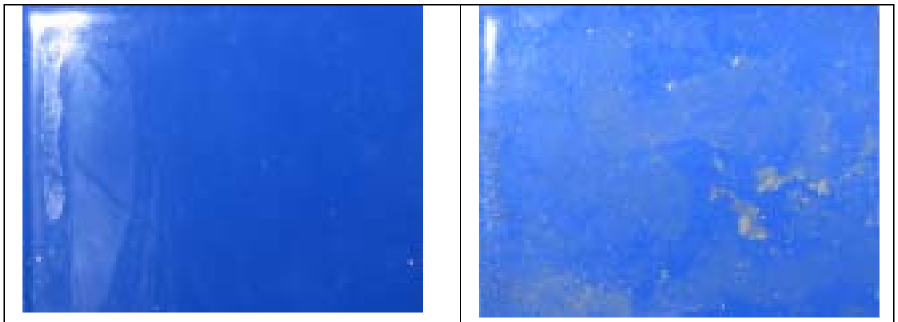

(a) Deployment **(b) Recovery**

Figure 3.1 – Intersleek coupon fouling (Nov 2009 - Feb 2010 deployment)

4 Discussion

While this series of *in-situ* tests are highly qualitative and site specific, a number of preliminary observations are made with respect to biological fouling.

1. Smooth surfaces are not prone to fouling on the time scales investigated by this study (up to 10 months).
2. Rough surfaces, edges, and crevices are prone to fouling. As previously mentioned, in two cases barnacles were able to establish themselves on the edges of composite and metallic coupons. A starfish also colonized one crevice, as shown in Figure 4.1.
3. Biological fouling is cumulative (e.g., once a surface is roughened by some degree of fouling or corrosion, it is more susceptible). If edges and crevices are fouled, fouling of adjacent smooth surfaces is observed. This emphasizes the need to minimize crevice spaces on tidal energy devices to minimize the risk of cumulative fouling.
4. Biological fouling is seasonal. In particular, the crevices between all coupons and the substrate plates were heavily fouled with sediment and krill after the April-August and August-November, 2009 deployments (Figure 4.2), coinciding with annual period maximum of biological productivity.

These observations are likely to change for deployments in different climates, geographic locales, or depth. For example, kelp and algae accumulations have been reported on uncoated surfaces in the photic zone during device tests (e.g., Clean Current deployment at Race Rocks, British Columbia, 65 km to the northwest).

Figure 4.1 – Starfish colonization of a crevice space

Figure 4.2 – Fouling and sediment deposition along edges and in crevices

A few preliminary observations may be made with respect to the corrosion/degradation of particular materials in tidal energy devices:

1. Stainless steel, glass fiber composite, and carbon fiber composite did not visually degrade over the test duration. Further studies are required to determine the time scales over which intrusion of moisture into the composite matrix degrades the strength and stiffness of composites.

2. Aircraft grade aluminum is a poor choice for the marine environment. In all tests, approximately 90% of the surface oxidized after three months of exposure to salt water.
3. Steel (both common and structural) corrodes rapidly in the marine environment. While corrosion is reduced by anodic protection, it is not eliminated. The use of marine coatings to reduce corrosion should be investigated.

Future efforts in this area by the Northwest National Marine Renewable Energy Center and its partners will focus on more quantitative assessments of material degradation. For example, an effort will begin in May 2010 to evaluate the degradation of composites in the marine environment.

5 Acknowledgements

This study would not have been possible without the efforts of a number of individuals. The authors would like to thank Alex DeKlerk for helping to fabricate/source material samples, Joe Talbert for deployment engineering, Anderson Ogg for taking on the tedious task of machining structural steel to the standard coupon thickness, Bill Kuykendall for supplying the composite coupons, Jeff Ambrose of International Paint for supplying samples of the Intersleek coating, and Tim Fagan of Pettit Paint for supplying cans for Vivid and Trinidad anti-fouling paint. The field work leveraged to perform this study is jointly funded by the US Department of Energy and Snohomish Public Utility District. Heather Dillon generously contributed her time to produce the high resolution macro photography in this report. Dr. Mark Tuttle provided valuable guidance on which materials to include in this study.

6 References

Orme, J., Masters, I., and Griffiths, R. Investigation of the effect of biofouling on marine current turbines. Proc. MAREC 2001 (Institute of Marine Engineers), 91-99. 2001.