

COATING SELECTION PROCESS FOR GULF STREAM
HYDROTURBINES

by

Andrew Spicer Bak

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The College of Engineering and Computer Science
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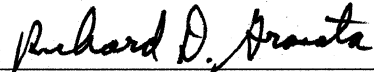
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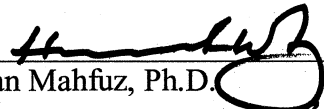
Andrew Spicer Bak

This thesis was prepared under the direction of the candidate's thesis advisor, Dr. Richard D. Granata, Department of Ocean and Mechanical Engineering, and has been approved by the members of his supervisory committee. It was submitted to the faculty of the College of Engineering and Computer Science and was accepted in partial fulfillment of the requirements for the degree of Master of Science.

SUPERVISORY COMMITTEE:



Richard D. Granata, Ph.D.
Thesis Advisor



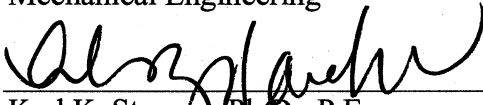
Hassan Mahfuz, Ph.D.



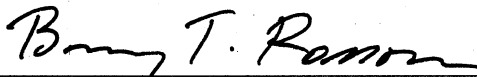
Francisco Presuel-Moreno, Ph.D.



Mohammad Ilyas, Ph.D.
Chair, Department of Ocean and
Mechanical Engineering



Karl K. Stevens, Ph.D., P.E.
Dean, College of Engineering and
Computer Science



Barry T. Rosson, Ph.D.
Dean, Graduate College

Nov. 16, 2009

Date

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ABSTRACT

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The study addresses the coating selection for a proposed placement of a hydroturbine into the Gulf Stream. The turbine will generate energy in a similar manner to a wind turbine. The effects of biofouling and corrosion in the current project are assessed. A review of different types of traditional paint coatings is given, as well as the option for a copper-nickel alloy. Testing that should be undertaken for the coating selection is described in detail. Coating considerations are offered and discussed. Design considerations and modifications are also offered.

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ABBREVIATIONS AND SYMBOLS

ASTM	ASTM International, also known as American Society for Testing and Materials
BMT HRA	British Maritime Technology hull roughness analyzer
C_F	Coefficient of friction
D_{cyl}	Cylinder diameter
EPS	Extracellular polymeric substances
F	Frequency in rpm
F_D	Force of drag
FIT	Florida Institute of Technology
gmd	Grams per square meter per day
LLC	Limited liability company
MIC	Microbial influenced corrosion
mm/y	Millimeters penetration per year
mpy	Mils penetration per year (thousands of inch corrosion penetration)
n	Rotational rate in hertz
ϕ	Reduction potential versus standard hydrogen electrode
ONR	Office of Navy Research
PDMS	Polydimethylsiloxane

PVC	polyvinyl chloride
r	Radius
Re	Reynolds number
SPC	Self polishing copolymer
TBT	Tributyltin
U_{rel}	Relative velocity across surface
V_o	Free stream velocity
V_r	Relative velocity
V_{rot}	Rotational velocity
μ	Dynamic viscosity
ρ	Density
τ	Torque
τ_{cyl}	Shear stress on cylinder
ν	Kinematic viscosity
NACE	NACE International, also known as National Association of Corrosion Engineers

1. INTRODUCTION

Florida Atlantic University is undertaking a major research project. The idea behind this project is to deposit a turbine into the Gulf Stream to collect energy. The idea works in a similar fashion to a modern wind turbine: The wind or water in this case, spins the blade and through use of a generator creates electricity which is then transported to shore through a subsea power line. Eventually the idea is to create a field of these hydroturbines to satisfy the ever growing need for energy of South Florida and beyond.

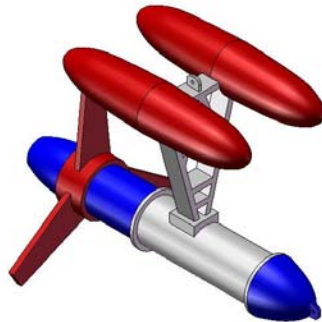


Figure 1: Computer generated model of hydroturbine.
(Photo courtesy of FAU Center for Ocean Energy Technology)

The system being designed in the project contains three different parts. The first part of the system is a buoyant pressure vessel. The pressure vessel will house the generator, which turns the rotational energy to electricity and other parts integral to the

system. It rests behind the second part of the system, the blade. The blade is made of carbon composite material supported by a steel skeleton frame. The third part of the system is the mooring. The mooring consists of cables that hold the turbine in the proper position within the Gulf Stream. If any one of these parts of the system is disabled or destroyed by biofouling or corrosion it can leave the system inoperable and therefore ineffective.

1.1 Biofouling

When an object, natural or manmade, is underwater organisms tend to collect and grow on the surface. These organisms range in size from the common mussel to even as small as microorganisms such as *Thiobacilli*, that collect as a thin film over the surface often times called 'slime.' It has been documented that these fouling organisms can live at depths of 2,000 meters and beyond [1]. Because the project is being applied in the warm tropical waters of South Florida, the fouling issue will be specifically difficult because fouling grows increasingly fast in warmer tropical water as opposed to colder water.

The fouling pressure varies drastically between areas as well as season. In the North Sea growths of 40 cm in twelve years are not uncommon. In Southern California growths can accumulate up to 25 cm per year [2]. It has greatest impact near the surface of the ocean where the current and wave action is the greatest. Fouling is seasonally dependent. Some organisms will grow in different seasons while others will not. Florida Institute of Technology (FIT) has a test site in the Indian River Lagoon, in Melbourne,

Florida [3]. Figure 2 below, shows the fouling abundance of different organisms at the exposure site throughout the year.

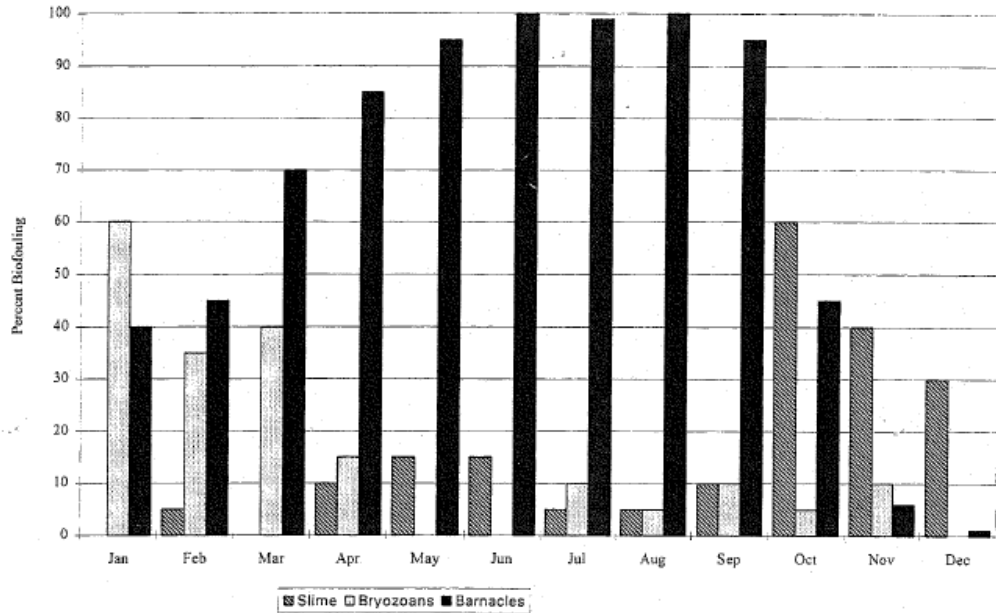


Figure 2: Typical monthly biofouling by dominant fouling types on unglazed ceramic tiles at the FIT exposure site. [3]

1.1.1 Effects of Biofouling

The most important problem of fouling growth on a substrate is the eventual corrosion, leading to deterioration of the material. Even before corrosion occurs, if left unattended, organic growth can increase the roughness of the surface, thereby increasing drag on the system. As the drag increases on the system it will put an unnecessary increase of stresses on the mooring lines, linkages, and joints and eventually could cause a catastrophic failure of the whole system.

1.1.2 Biofilm Colonization

The specific process of colonization and development of marine biofouling most often starts with the biofilm layer. The main process of the attachment of a biofilm by any organism has five parts. The first is the transport of the organism to the surface, followed by the settlement on the surface. Once the organisms have settled, they then attach themselves to the surface, followed finally by the development and growth of the organisms and film [4].

When a chemically inert substrate is placed into the ocean almost immediately it develops an organic residue which allows for microorganisms to attach to the surface to form a biofilm. These organisms, once they land, secrete what are called extracellular polymeric substances (EPS) in order to attach themselves. These substances vary depending on the organisms. It is this layer of EPS that encompasses most of the biofilm. Figure 3 below shows a good depiction of how the settlement process takes place. It protects the organisms from the environment and can also influence the flow of ions to and from the surface which can lead to a type of corrosion called microbial influenced corrosion (MIC). This biofilm can create a differential aeration concentration cell due to their ability to generate decomposition products.

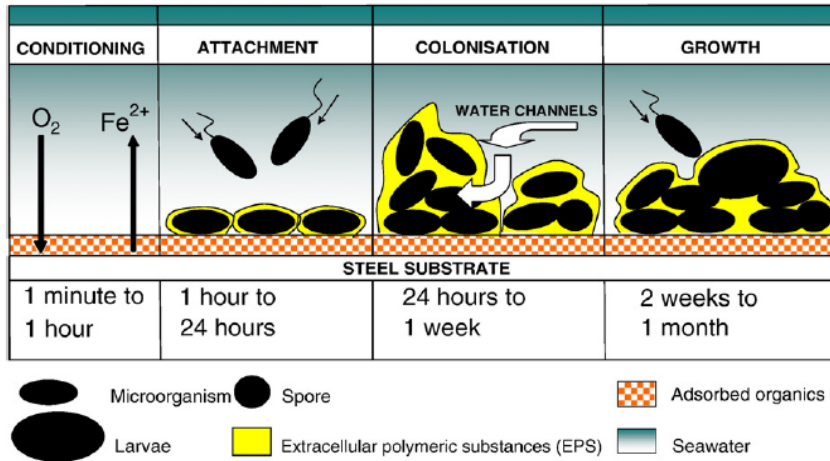


Figure 3: Fouling development process [5]

1.1.3 Boundary Layer and Shear Stress Effects

As Wood states, the settlement of these organisms is affected by the boundary layer development and shear stress imposed on the organism by the moving fluid [6]. These organisms need to fall or settle through the boundary layer. The boundary layer is the fluid layer directly over a surface. When a fluid passes over a surface a ‘no-slip boundary condition’ is encountered. This means that the fluid particles in direct contact with the surface cannot move. In the boundary layer the flow gradually increases with distance away from the surface until free stream velocity is reached. It is not clear whether these organisms are simply transported to the surface or actively pursue a satisfactory habitat.

In the discussion of the boundary layer, a flat plate will be used as an example, because it is scientifically the most straightforward. Figure 4, below, shows a depiction of the development of a boundary layer.

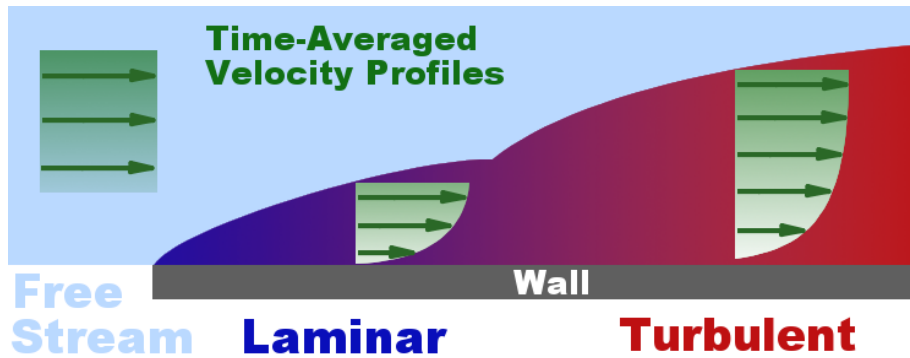


Figure 4: Boundary layer development showing transition from laminar to turbulent (original image courtesy of Symscape www.symscape.com)

As the boundary layer develops so does the shear stress. The shear stress is imposed on the surface due to the viscous forces of the fluid passing over the surface. This stress is due to the no-slip boundary condition. As both Wood [6] and Swain [7] suggest, shear stress is an important factor that helps determine the settlement of objects. There is a very thin layer, the viscous sublayer, within the boundary layer (at the surface interface) in which the viscosity dominates and damps the turbulence. When these organisms settle, these ‘bumps’ disrupt this viscous sublayer. Once these organisms have settled, they experience the standard drag and lift forces that one would expect in flow. The drag force acts in the direction of the instantaneous velocity, which can vary greatly in turbulent flow. The lift force acts in an upward direction from the substrate. Figure 5 below shows a diagram of the forces acted on a settled larva. In general the acceleration forces are small compared to the drag [8]. If the water velocity fluctuates, as it does in turbulent flow, the drag and lift can vary greatly from one instant to the next [8]. This can cause the organisms to be pushed or rolled along the surface or it can give them a

chance to settle on the surface. For an organism to settle the instantaneous resultant force, R , must be lower than the adhesion strength of the organism.

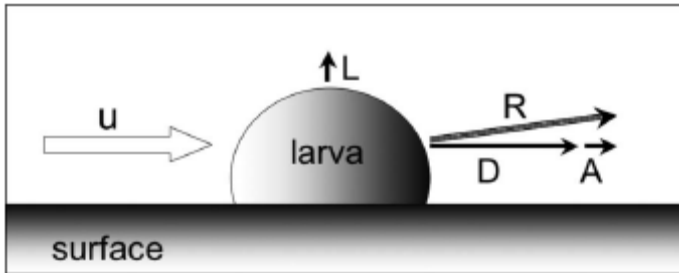


Figure 5: Forces acting on larva in flow [8] u – flow velocity; L – lift; D – drag; A – acceleration; R – resultant;

1.1.4 Organisms

There are over one hundred and sixty different types of fouling organisms of interest. Most research is concentrated on larger, macrofouling organisms. It is seen that some fouling organisms are not able to settle above a particular free stream velocity, for example barnacles are unable to settle in velocities above 2 meters/second [9]. But this is an average value, just as with height in people this varies in the species, each particular barnacle will not have the same adhesion strength. This shows, if one refers to Appendix I for relative surface velocity calculations, that the hydroturbine blade will most likely be unfouled by barnacles.

In Miami, the following organisms tend to settle in this chronological order: bacteria, diatoms, autotrophic flagellates, amoebae, heliozoans, and ciliates. Once the biofilm and microfouling has been established the following process is known as macrofouling. Propagules (any material used for plant propagation) of macroorganisms, spores of macroalgae, and larvae of invertebrates and lower chordates (ascidians) settle on hard surfaces [4].

A paper [10] was reviewed that identified the organisms versus depth on oil platforms off the coast of Louisiana. The oil platforms in this area only reached a depth of 30 meters, while this project will be working in a depth of 50 meters. This comparison will not be exactly what can be expected but will provide a general idea of the fouling organisms that may be present. Generally speaking there seemed to be a much lower biomass of fouling at the 30 meter depth compared to the shallower depths. In Table 1, looking at the 30 meter mark for P3 and P4 one can see that the scraped biomass at this level is significantly less than the shallower depths.

Total Drained Weight of 25 x 25 cm Scraped Samples (Mean [Range] for Three Replicates)

Depth (m)	Platform				Overall Mean	Overall mean (g/m ²)
	P1	P2	P3	P4		
1	597 [491-712]	336 [315-370]	653 [527-726]	528 [355-633]	529	8456
10	845 [667-1001]	602 [467-748] *608 [599-616]	535 [348-636]	967 [782-1209]	711	11382
20	-	-	684 [436-907]	600 [542-676]	642	10272
30	-	-	123 [41-171]	119 [60-218]	121	1936
Overall mean	721	515	498	554		
Overall mean (g/m ²)	11536	8245	7980	8856		

*P2-DL (Discharge Leg)

Table 1: Scraped biofouling mass vs. depth on Gulf Oil platform [10]

There were several specific species found at the lower bound of this study. The most predominant types of colonial fouling seen at this depth are as follows: two unidentified species of *Demospongiae*. This class of animal contains 90% of all the sponges. Also, another type of animal was the *Homocoelid* sp. A, which is another type of sponge. There were five types of Hydroids, all of very low percent coverage at this depth. There were four types of Bryozoans found at this depth, which are tiny colonial animals that build structures out of calcium carbonate, ‘superficially similar to coral’ [10].

There are also several types of non-colonial types of fouling, most of whom have statistically significant differences in habitat preference [10]. Some of the most prominent types of fouling of this type were of the taxa Amphipoda (*podocerus brasiliensis*, *Erichthonius brasiliensis*, *Stenothoe gallensis*, *Caprella equilibra*, *Paracaprella pusilla*). The next most populous species was Actiniaria, or sea anemones, though it appears that this species was beginning to dissipate with greater depth. Other organisms include types of Syllidae (*Autolytus spp.*, *Brania spp.*, *Syllis spp.*, *Odontosyllis enopla*, *Haplosyllis spongicola*, *Eusyllis sp.*) and Bivalvia (*Chama macerophylla*).

1.2 Corrosion

Corrosion is the destructive attack of a metal by chemical or electrochemical reaction with its environment. When two dissimilar metals are placed into an electrolyte and are connected electrically, it creates a voltage. This voltage causes positive current to flow from the positive electrode (cathode) to the negative electrode (anode). The anode dissociates into ions and flows through the electrolyte causing it to lose mass as a corrosion product (i.e. $\text{Fe}(\text{OH})_2$) which can initially passivate the surface although it often dissociates into solution and results in mass loss.

1.2.1 General corrosion

This type of corrosion includes the rusting of iron or tarnishing of silver. This is uniform attack over the entire substrate. It is usually a low level, well distributed attack with little or no localized penetration. General corrosion is the least damaging of all types of corrosion and can be measured in many different types of units most commonly,

millimeters penetration per year (mm/y) to grams per square meter per day (gmd) and even inches per year (ipy).

1.2.2 Pitting

Pitting is a localized type of attack, with the localized rate of corrosion being greater in some areas than others. Usually, pitting is a deep penetration of the metal surface with little corrosion of the surrounding area. Due to surface deposits, electrical imbalance or some other initiating mechanism, the corrosion will attack a select number of individual sites. Most commonly pitting is found where there are incomplete chemical protective films, and insulating, or barrier deposits of dirt, iron oxide, or other foreign types of materials on the surface. Depth of pitting is sometimes expressed by the pitting factor, which is the ratio of deepest metal penetration to average metal penetration as determined by the weight loss of the specimen [11]. Many metals, when exposed to high velocity liquids, will experience a specific type of pitting corrosion called impingement attack or sometimes called corrosion-erosion, often seen in copper and brass [11].

1.2.3 Dealloying

When an alloy is placed into a corrosive environment one specific metal of the alloy is depleted. When this dealloying occurs it leaves a porous residue of the other component of the alloy. The alloy will remain in the original shape, and often appears undamaged, though it has significantly reduced properties of strength and ductility [11]. This does not happen with all alloys. A common example is dezincification in brass where a porous copper structure is produced.

1.2.4 Intergranular Corrosion

This is another type of localized attack like pitting, though instead of the surface, it will attack the grain boundaries. This results in a loss of strength and ductility. The grain acts as the cathode, while the grain boundary acts as the anode. The attack is often rapid, penetrating deeply into the metal, sometimes causing catastrophic failures. This often happens in improperly heat treated 18-8 stainless steels and Duralumin-type alloys [11].

1.2.5 Cracking

If a metal cracks at a higher rate when subjected to an alternating stress while in a corrosive environment versus clean, dry air, it is often called corrosion fatigue. There is no endurance or fatigue limit when operating in a corrosive environment. If the metal is subject to a constant tensile stress and exposed to a corrosive environment, it is said to fail by stress-corrosion cracking [11].

1.2.6 Microbial Influenced Corrosion (MIC)

MIC can cause many different types of localized corrosion including pitting, dealloying, enhanced erosion corrosion, enhanced galvanic corrosion, stress corrosion cracking, and hydrogen embrittlement [11]. It can cause accelerated corrosion or even corrosion where it would otherwise be unexpected. The most common cause of MIC is sulfate-reducing bacteria, which are active only in anaerobic environments. On the other hand, organisms like *Thiobacilli* are sulfur-oxidizing bacteria, which oxidize sulfur compounds to sulfuric acid on the surface. When the acidic products of bacterial action are trapped in the biofilm-metal interface, their impact on corrosion is intensified [11].

2. PROBLEM STATEMENT

With the hydroturbine application in the marine environment the problem of biofouling is inevitable. When a structure is placed into the marine environment it is exposed to many key elements such as salt water, biological attack, and temperature fluctuations. The goal of this portion of work is to lay out the steps necessary to handle the problem of biofouling in the application of a marine hydroturbine. The most traditional way to solve the problem of biofouling is with a marine antifouling coating which must be capable of expanding and flexing with the underlying surface, resisting the influx of water, and controlling the diffusion of ions [5]. The coating selection for the hydroturbine system is in fact two or more different problems in one. The first major part is the coating of the pressure vessel. The second, being the coating of the turbine blade. Also, the mooring system needs to be coated and protected from corrosion. Each part involves different properties should be considered separately in order to properly and most efficiently coat these surfaces.

2.1 Pressure Vessel

First, the pressure vessel and housing unit, which holds the generator and other parts integral to the system, is sitting stationary in the Gulf Stream while a low current passes over the system. The current velocity ranges between 1.7 and 2.5 meters per second, a relatively low velocity as far as coating requirements are concerned. The

system is similar to many other stationary structures, like oil rigs, that require antifouling characteristics. These stationary structures have been protected for many years.

2.2 Hydroturbine Blade

Another concern is coating the blade of the system, though similar projects have been undertaken, the antifouling coating of the blades have not been studied or documented in the way ship hulls or structures have. The blade itself is a very complicated design. The blade is an open turbine design, meaning there is nothing surrounding the turbine blade. It is not screened off nor shrouded. It is composed of three blades each 3 meters in length. The hub in the center of the blade system is 0.75 meters in diameter giving an overall diameter of 6.75 meters. It rotates between 20 and 30 rotations per minute depending on the current speed which ranges from 1.7 to 2.5 meters per second.

The blade itself made from a carbon composite material with a metal structure to support. Carbon composites are very susceptible to swelling in a marine environment, and must be adequately protected. The blade will be spinning at different rotational rates and therefore will be experiencing a variation of many different flow velocities which makes the problem even more complicated. The coating system must be capable of flexing with the underlying surface, resist the ingress of water, and control the diffusion of ions [5]. Because the hydroturbine blade is fairly pliable, the coating must be able to flex with the blade to prevent cracking of the coating. When the coating cracks it can chip off leaving an ideal site for fouling growth as well as leaving the substrate open to uncontrolled corrosion.

The coating system chosen must be easy to use and require little to no maintenance. The system is being placed at a depth of 50 meters, which is too deep for a diver to perform maintenance. This means that any and all work must be done at the surface or by a robotic sub, which is an expensive and intensive process. Therefore it is of the utmost importance for this to be properly coated to prevent both corrosion and excessive fouling.

3. COATING OPTIONS

There are many options available for today's antifouling needs. The coating options are mainly, though not limited to, antifouling paints. There is also a lot of promising research being done in the industry, namely Sharklet®, a project being funded by the Office of Navy Research (ONR) and researched by University of Florida. It models the surface after the nanoscale topography of a shark's skin to prevent the settlement on the substrate. Another project being developed by ONR is an autonomous hull cleaning robot. The robot is placed on the hull of a vessel, while in port, and roams around cleaning the vessel much in the way a Roomba® (robotic home vacuum) works.

3.1 Types of Paint

To understand better how to coat this system one must understand the different coating options available today. For many years the fouling was controlled with paints that employed the use of the biocide tributyltin (TBT). The International Maritime Organization, in 2003, imposed a world wide ban on the use of this substance because of unacceptable environmental impacts. TBT was responsible for almost shutting down ecosystems within ports where concentrations were high. TBT has also been found in other larger non-target marine animals such as otters, dolphins and squid. Right now the industry is using cuprous oxide as a replacement for the TBT based systems.

3.1.1 Contact Leaching

There are two main types of copper based coatings that are offered right now. The first type is the hard or ‘contact leaching’ coating. This type of coating dries to a hard porous film, which is packed full of biocides, some up to very high percentages of solids by volume. These biocides diffuse through the membrane when in contact with the water. It is designed to diffuse throughout the lifetime of the coating, though over time it gets progressively less effective. A depiction of this is shown in Figure 4. “Extra thick build-up is not effective, since the bio-toxins buried deep in the under layers are never in contact with the marine growth” [12]. It is often difficult to remove old coatings to recoat. This is done most often and effectively with water, sand, or grit blasting. Though, the upside to this paint is that it works well in areas of high abrasion or rubbing, making it good for high-speed vessels.

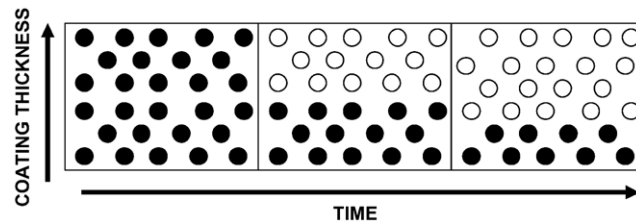


Figure 6: Contact Leaching Coating with time [13]

3.1.2 Ablative

The second type of coating is the ablative coating. Mechanically, this works by softening the surface as the seawater penetrates. The coating surface will react and deteriorate, always leaving a fresh layer of biocide at the surface. Chemically the binders are hydrating and not based on a copolymer. Initially, they perform very well and

function on a leaching mechanism where the biocidal agents leach from the coating layer. These leach at a fairly fast rate, resulting in a much shorter life expectancy. This faster leach rate leaves this type of coating more susceptible to temperature, salinity and alkalinity, therefore making it less controlled. They are also much less expensive than self polishing copolymer coatings.

3.1.3 Self Polishing Copolymer (SPC)

The third type of coating is the self polishing copolymer (SPC), which is based on the original TBT SPC systems that worked well for many years. These coatings, as the name suggests, are self polishing which means as the polymer reacts with seawater, the top layer is released as the coating polishes in a slow and controlled manner. This property is due to the resin chemistry of the acrylic that is hydrolyzed. The polishing action works in the same manner as a bar of soap, thereby constantly leaving a fresh layer of biocide at the surface and also adding to the hydrodynamic performance [13]. As the coating surface wears away, it takes with it the fouling organisms. These can also have booster biocides and tend to be the best option in areas of high fouling. Both of these coatings, the ablative and the SPC, wear away as water passes over them, this therefore means that the thickness of the coating will dictate the lifetime of the system.

3.1.4 Foul Release

The industry employs copper based coatings as a replacement for the TBT systems, which soon may become the target of environmental legislation [14]. For this reason, a lot of research has been aimed at a non-toxic substitute to control biofouling. The most promising development has been in the use of polydimethylsiloxane (PDMS) for what are

called foul release coatings. PDMS is a non-polar polymer with an extremely flexible (low T_g) backbone, which allows the polymer chain to readily adapt to the lowest surface energy configuration [15]. These coatings have an extremely low surface energy and a lower surface roughness. Instead of preventing the attachment of organisms, these coatings work by lowering the adhesion strength by an order of magnitude or more [15]. The organisms are then removed more easily by the shear action of the water passing over the surface of the coating system or by light scraping.

The main problem with these types of coatings is, because they do not prevent the attachment to the surface but rather lower the adhesion strength, there must be a flow over the coating for them to work properly. If fouling release surfaces are not hydrodynamically self-cleaned or mechanical cleaning is not utilized then they will likely provide significantly poorer performance [14]. Boats that remain in port for extended periods of time often develop extensive fouling, though they are easily removed once the vessel is underway. These types of coatings are known to handle macrofouling (e.g. barnacles, muscles) sufficiently, although slime on these coatings has been known to stay attached at surface velocities of >30 knots [15]. Even though these coatings do not protect effectively against this slime, it does not seem to offer nearly as large of a hydrodynamic penalty as the macrofouling. This slime, though, does offer more penalty than some are willing to accept [7].

3.2 Copper-Nickel Alloy

The use of copper alloys in marine environments has been employed for more than a hundred years. Specifically, copper-nickel alloys will be addressed. These metals have very good fouling resistance as well as a low corrosion rate.

3.2.1 Corrosion

The first thing to be considered about the candidate copper-nickel alloy materials is the effect of corrosion. The corrosion resistance that is observed with the alloys has to do with the inherent values of the material. The actual rates are difficult to gauge on short term exposures. Once a good surface film has formed, in clean water, the corrosion rate is expected to be around 0.02-0.002 mm/year [16]. The general corrosion rate should be compared versus the thickness of the alloy coating. Appendix II goes through the calculation for the thickness required for the design life. If the substrate corrodes quickly then the thickness of the applied metallic coating must be increased to obtain the same design life than an alloy that has a more controlled corrosion rate. The increase needed in coating thickness would have negative consequences, such as higher cost, lower strength to weight ratio, as well as lower flexure in the blade system. The lower the corrosion rate, the thinner the coating that needs to be applied, thereby maximizing the efficiency of the blade design.

The surface film is the most important aspect for protecting the alloy from corrosion. Pitting has been seen in a sulfide rich environment. It is necessary to further investigate because some of the biofilms, in the presence of sulfate-reducing bacteria, excrete these chemicals [17]. However, there is a trade off in the increase of velocity

because the increase in velocity will cause the sulfides to be washed away. Although at high velocities, the surface film can be damaged and removed causing pitting and impingement attack [16]. Often cathodic protection is the answer to the problem of pitting. This may not be an applicable solution in this case, because cathodic protection tends to reduce the biofouling resistance [18]. In addition raising temperature may also increase corrosion, though the warmer the water, the quicker the protective film is formed. Furthermore, these effects are complicated and interact with one another. Hence, it would be noteworthy to further investigate them before a conclusion can be inferred.

3.2.2 Biofouling

The second aspect that should be looked at is the biofouling resistance. It has been seen that the release of the copper must be at least $10 \mu\text{g cm}^{-2} \text{ day}^{-1}$ in order to keep the fouling to a minimum [9]. It is observed with the cupronickel alloys, that the surface film is a major reason for the protection from fouling organisms, as well as the release of copper ions. Directly on top of the material, a copper oxide film is formed which is gradually converted to a cupric hydroxychloride film [16]. This film is less adherent as well as less protective, leaving the film to be freely fouled, until it is released from the substrate and falls away exposing the copper oxide film once again. Often in the formation of a biofilm in the presence of sulfate reducing bacteria sulfides are produced in the local environment. This presence of sulfides has been shown to increase the localized corrosion or pitting of these copper nickel alloys and needs to be further investigated.

3.2.3 Application method

This alloy seems to be very promising for the application in this project. It needs to be applied to the surface in some manner. Below are some methods the material may be deposited on the surface.

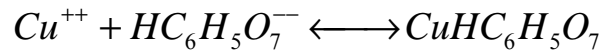
3.2.3.1 Electrodeposition Application

The alloys in question can be electrodeposited into a thin layer on the surface of the carbon composite blade. This will allow the blade to keep the desirable strength to weight ratio of the carbon composite blade, while still keeping the surface clean from fouling organisms, as well as protected from the surrounding environment. The electrodeposition process that looks the most promising is a process called NanoVate™. This process plates the substrate with an average grain size of 20 nm, which is 1000 times smaller grain size than a conventionally electroplated material. This smaller grain size allows for the increase in yield strength, ultimate tensile strength, and hardness. The process also keeps a good ductility and allows flexure, which is important when coating the blade. Unfortunately this company was unable to supply samples for testing purposes.

The most common copper-nickel alloys applied for marine use are the 90-10 and 70-30 copper-nickel alloys. Monel, a trademarked version, is an alloy with a composition of simply nickel, up to 67%, and copper as well as other minute additives such as iron. These alloys seem very promising for this particular application. However there are many things that need to be looked into further. In review of literature the use of the 90-

10 and 70-30 alloys appear more applicable and therefore, will be the primary aim for further research.

The process of electrodepositing the cupronickel alloy is complex. The difference between the standard electrode potentials of the copper and nickel are 0.592 volts [11]. Appendix III calculates the ratio of nickel to copper that is required in solution for the two metals to codeposit simultaneously. This ratio is extremely large (10^{20} nickel molecules: 1 copper molecule). For these to codeposit correctly, the copper must be complexed with a ligand. This means that the copper ions are, in effect hidden, within the solution. The chelate, a type of ligand, ties up the copper so it is not active in solution and holds it in equilibrium with the ions in solution. As the solution is deprived of copper, i.e. through electrodeposition, the copper is released from the chelate back into solution.



Over the years several different types of complexing agents have been applied to this process such as cyanide, oxalate, tartrate, citrate, pyrophosphate, glycine, and L-asparagine [19]. According to Ying et al. [19], Ghosh et al. [20], and Rode et al. [21] citrate baths appear the most suitable. Citrate is chosen because it has a low toxicity and its ability to give good quality deposits with stress-free Ni-rich alloys with very high efficiency rates. The citrate also acts as a buffering, brightening, and leveling agent. Smooth metallic deposits can be obtained, through low current densities. To get a high nickel percentage the current density must be increased, often yielding a dark, matted, and rough surface. The ideal range, according to Ying [19], to deposit the metals

together is between -1.0 Volts and -1.3 Volts versus the standard hydrogen electrode. The effect of the different overpotentials as well as copper concentrations in solution can be seen in Figure 7. The different baths from which the coating was deposited had different concentrations ranging from 5 (7a), 10 (7b), and 20 (7c) molar percent. At low overpotentials, where it is mostly copper deposited, the deposit is much more clustered. As the overpotential is increased and more nickel is deposited, the surface becomes smoother.

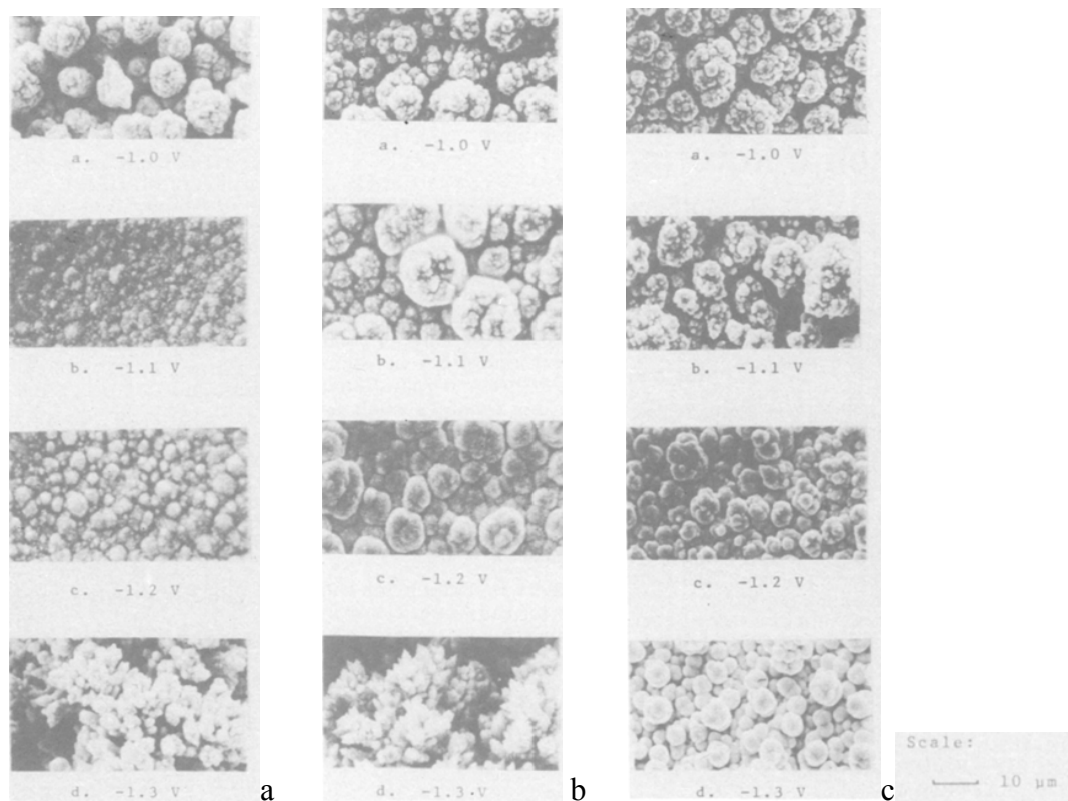


Figure 7: Scanning electron micrographs of the copper-nickel alloy plated in: a) Cu-5, b) Cu-10, and c) Cu-20 [19]

3.2.3.2 Other Application Methods

There are other methods by which the alloy can be deposited on the surface. The first method is a copper-nickel foil. This is a thin sheet of the alloy that can be pressed onto the surface, through the use of an adhesive. Flame spray is another possibility. Flame spray melts the two metals of the alloy and projects them to the surface in the form of a spray where they harden into the desired alloy. Because these metals would be molten hot, a coating would need to be placed over the carbon composite surface to better dissipate the heat. The idea of explosive bonding was also brought up. This uses an explosion to bond the two materials into one. It was a very popular method of bonding the copper to nickel before the TBT polishing paints became popular in the 1970's [9]. Because these paints seemed to be the solution to all problems of biofouling, the explosion bonding method was not thoroughly researched and soon forgotten. This application method may be difficult for the curved surfaces encountered in this application.

3.3 Coating Considerations

When choosing a coating system for this or any project there are many things to consider. The first consideration is the type of coating to be chosen. To correctly choose the type of coating one must consider the system parameters. Some of the parameters include but are not limited to temperature, depth, velocity over the surface, and even serviceability.

3.3.1 General

When assessing the quality of the coating there are many parameters that should be considered including biocide release rate, self-polishing capacity, biofouling adhesion strength, flexibility, toughness and surface roughness. It has been documented that the minimum effective leaching rate for copper is $10 \mu\text{g cm}^{-2} \text{day}^{-1}$ [2]. Obviously rates greater than this are wasteful and will deplete the effectiveness of the paint while rates lower than this will be ineffective. The self-polishing capacity of a coating system is important because if the paint is removed too quickly it will diminish the lifetime of the coating. Although, if the coating is removed too slowly it will allow for organisms to grow on the surface adding extra hydrodynamic penalty. ASTM standard D5618 [22], describes a standard for barnacle adhesion measurement. The adhesion strength is specifically important for foul release or contact leaching type coatings. This ASTM standard is not really a fair assessment of a SPC or an ablative type coating because it is often the paint sublayer that is removed rather than simply the fouling organism. Swain has developed a biofilm adhesion measurement using a water jet [3]. It is claimed that biofilms are responsible for a much larger hydrodynamic penalty than some are willing to accept [9]. The flexibility and toughness are important for longevity of the coating, if there are vibrations present or abrasion, it could cause the coating to crack, peel, or wear away leaving areas of vulnerability.

3.3.2 Surface Roughness

Surface roughness was a quality that was initially considered specifically for the marine industry for hydrodynamic purposes. It also is an important characteristic for

organism settlement; the rougher the surface the easier it is for an organism to attach. The quality of surface roughness varies with different application types and is a very important quality with fouling release type coatings, though it is relevant for other types of coatings as well. Paint application types include but are not limited to spray mist, electrochemical deposition, powder coating followed by baking or simply brush or roller. Each of these application types will leave different surface roughness qualities, the airless spray being the best and brush being the worst. Application by brush can cause added frictional resistance up to 2.5% [13].

Obviously the smoother the micro-profile of the surface, the better off the coating will be for drag as well as fouling attachment. For a fouling release coating it is of the utmost importance that the surface roughness be as low as possible. The surface roughness along with the surface energy seems to dictate the performance of the coating. The surface can be considered hydrodynamically smooth in the unfouled condition. Surface roughness is an important characteristic for a biocidal coating as well, because as it increases so too can the porosity, and there by the likelihood of biocide dissolution [13]. Despite the large amount of research done on the surface roughness and drag on coating systems, little has been done on comparing the traditional biocide based paint systems with the fouling-release type over the entire coating life cycle [14]. It has been shown though that initially a foul release type coating will have a lower surface roughness and thereby better hydrodynamic properties than a traditional biocidal coating. In a biocidal coating, the pigment particle size distribution indirectly influences the surface roughness. As the coating dries the solvent evaporates and the coating thickness

reduces, therefore forcing the cuprous oxide to influence the surface profile. Figure 8 shows a SPC coating as it evolves with time once applied.

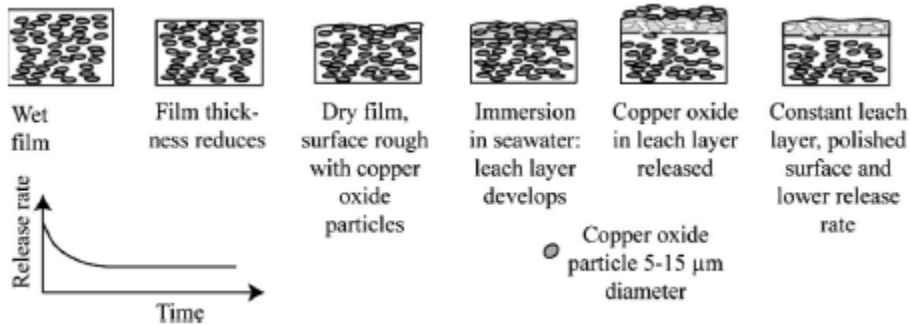


Figure 8: Diagrammatic representation of an AF coating drying after application [13]

3.3.3 Surface Roughness Measurement

There are two main ways to measure surface roughness, by stylus or optically. The stylus method doesn't quite have the resolution that optical methods have. The most common stylus used is the BMT HRA (British maritime technology hull roughness analyzer), though the resolution is lower than some of the standards for measuring surface roughness. The optical methods include laser profilometry or scanning electron microscope and can measure to a higher resolution than stylus methods. They can measure three dimensional profiles rather than indirectly by way of a mechanical stylus [13]. Figure 9 and 10 below compares the aluminum substrate surfaces coated with a fouling release coating and a SPC coating.

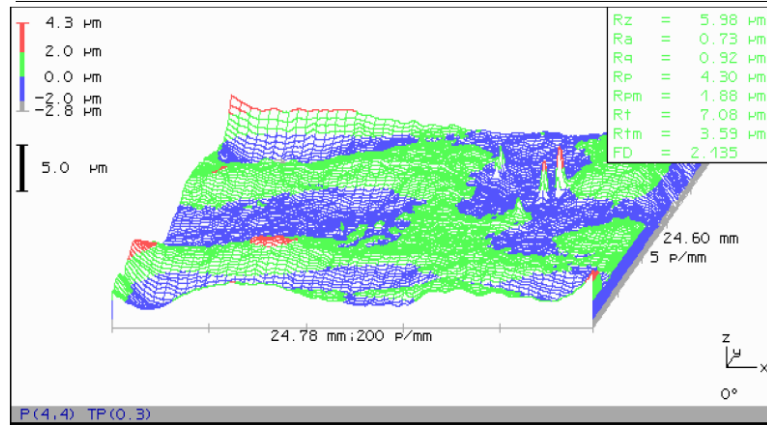


Figure 9: Laser profilegram of aluminum coated with fouling release coating [23]

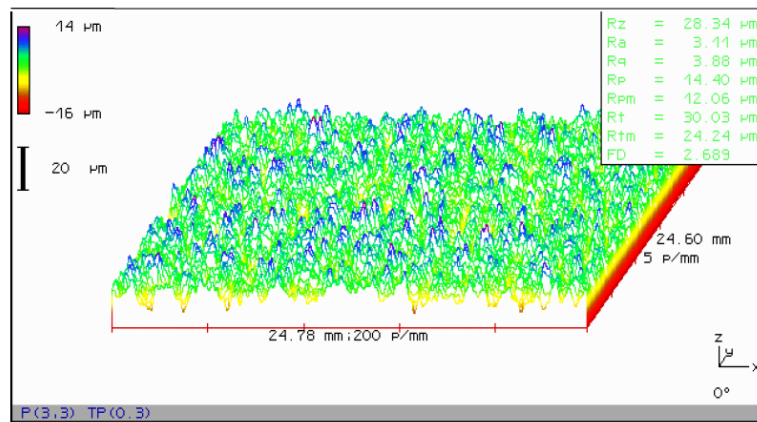


Figure 10: Laser profilegram of aluminum coated with SPC coating [23]

The viscous drag occurs in the region known as the boundary layer immediately next to the surface. When the Reynolds number is high, it is desirable to keep this boundary layer in the laminar region because it will impart less frictional drag to the surface [13]. As the fluid flows along the surface it becomes more turbulent, thereby imparting more drag, though there remains a laminar sublayer below. If the height of the surface roughness profile is small, by comparison to the laminar sublayer, then surface will behave as if it were hydrodynamically smooth [13]. This basically states that there is a specific roughness height below which, there will be no increase in drag.

The surface roughness is an important characteristic with the use of the copper-

nickel alloy. If the surface is allowed to be kept rough it gives the larvae a better chance to mechanically attach themselves to the surface. The smoother a surface is, the more difficult it will be for the organisms to attach. The surface roughness is also a good way to judge the quality of application for the electrodeposition process.

3.4 Comments on Paint

When the traditional coatings were being considered, the most promising candidate seemed to be the fouling release type coating for many reasons. The first reason is that it is a longer term solution and does not seem as though it would lose effectiveness, the way the others would. Long term studies of foul release coatings have not been encountered. These paints are expected to last 5 years in good shape and possibly up to 15 years, though without guarantee. The idea of a 'green' or environmentally responsible option is also appealing. But the fact remains that until this type of coating is further developed to work at a lower velocity, it will remain inapplicable to this project. The other coating options seem mediocre at best. The ablatives and SPC type coatings have questionable performance in the velocity field as encountered by the hydroturbine blade. They could wear away quickly or just not be effective. In discussions with one company, it was recommended using a hard coating type because the velocity wouldn't affect the performance. Appendix IV lists the major antifouling paint companies and comments about them along with their applicable coatings. These types of coatings are still options, though the copper-nickel electrodeposited alloy seems to be the most promising option. As long as it can be fabricated, it could possibly solve all of the issues faced in this design. It could have the

longest design life well beyond that of traditional coatings while also keeping the lightweight design of the system.

4. PROPOSED TEST APPARATUS – ROTATING CYLINDER METHOD

The experiment was designed in order to gauge biofouling as a function of velocity for the hydroturbine project. The system can test multiple specimens simultaneously. It involves rotating coated cylinders in an exposure tank. The cylinders rotate at different velocities in order to simulate service conditions. Appendix V lists the important considerations for testing and coatings planned to be tested. Test methods are described in Appendices VI – X.

4.1 ASTM D4939-89: Rotating Drum

There are a few dynamic test systems in use today, but none as used and well accepted as the rotating drum standard. It has been a workhorse for the industry for many years [24]. ASTM standard D4939-89: Standard Test Method for Subjecting Marine Antifouling Coating to Biofouling and Fluid Shear Forces in Natural Seawater [25] describes this test method. The scope for this standard is listed in Appendix X. In this standard, curved test panels are placed on a drum at least 18 inches in diameter. The drum is then rotated at a specific revolution rate to simulate a relative velocity and shear stress across the surface. The hydrodynamics of a rotating cylinder are well documented [26]. Because the shear stress decreases from the leading edge of a flat plate (and a ship) an average value should be selected to test sample specimens [25]. This drum can hold

only hold a limited number of specimens making it difficult to test multiple samples at multiple velocities. Figure 11 below shows a diagram of the apparatus.

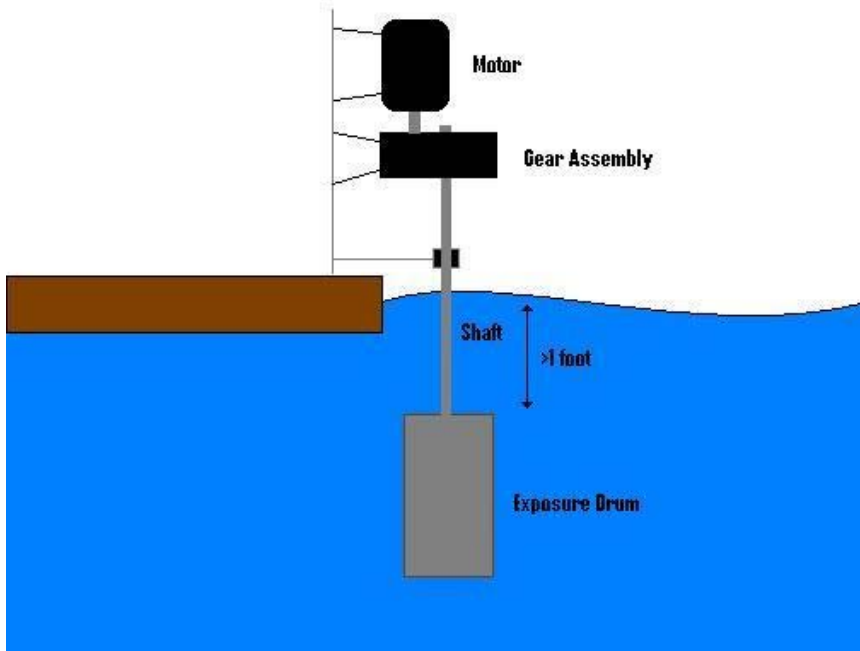


Figure 11: ASTM Rotating drum standard

There are many standards that are applicable for the testing of marine paints. A few of the most prominent standards are described in the Appendices VI –X and are listed in Table 2 below.

ASTM #	Standard Name	Appendix Number
G52-00	Standard Practice for Exposing and Evaluating Metals and Alloys in Surface Seawater	VI
D3623 - 72a	Standard Test Method for Testing Antifouling Panels in Shallow Submergence	VII
D5618 - 94	Standard Test Method for Measurement of Barnacle Adhesion Strength in Shear	VII
D6990-05	Standard Practice for Evaluating Biofouling Resistance and Physical Performance of Marine Coating Systems	IX
D4939	Standard Test Method for Subjecting Marine Antifouling Coating to Biofouling and Fluid Shear Forces in Natural Seawater	X

Table 2: Applicable ASTM Standards and Summaries Listed

4.2 Design Explanation

The rotating cylinder method is designed to test biofouling as a function of velocity. The system utilizes a rotating cylinder for specimen testing and is based on the rotating drum standard. The rotating cylinder method is capable of evaluating electrodeposited coatings as well as paint coatings, as long as applied directly to the cylinder surface.

4.3 Cylinder Assembly

The rotating cylinder method uses a 3 inch diameter aluminum cylinder for coated specimens to conserve space. The specimen will be 12 inches long with $\frac{1}{4}$ inch bevels at the top and bottom to facilitate the coating application. Each cylinder will test one coating. At each end of the specimen, there is a screw hole tapped into the specimen cylinder. These screw holes are occupied with bolts or threaded handles during the application process for ease of handling by the coating applicators. Once the specimens are coated the bolts are replaced with longer threaded rods. These rods are used to connect the drive system via attached pulley. Figure 12 shows an exploded view of the cylinder assembly.

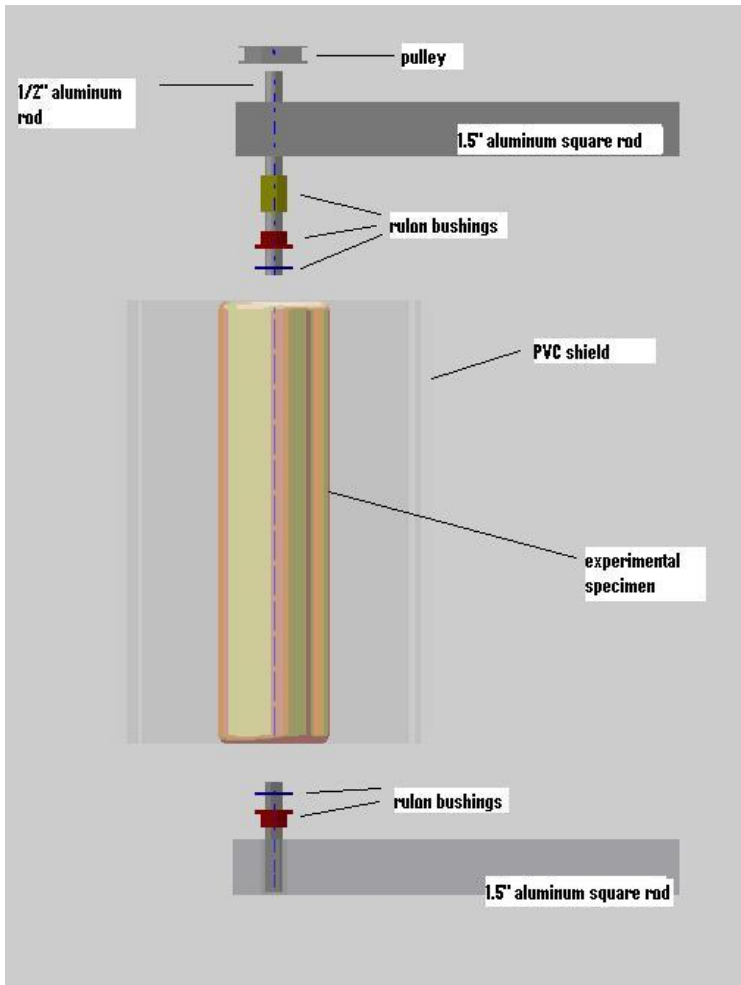


Figure 12: Exploded view of test cylinder assembly

4.4 Design Speed Considerations

The test design speeds for the current design are: a) 11.0 meters per second, the maximum velocity for the hydroturbine application; b) 4.6 meters per second, a minimum for the fouling release coating functionality; and c) 1.8 meters per second, the minimum velocity for the hydroturbine application. Speed b is used to test the functionality of the foul release coatings which only work above a certain velocity. Appendix XI provides the detailed velocity calculations for the designed system.

Speed Set	Designed Speed (m/s)	Design Rotation (rpm)	Actual Rotation (rpm)	Actual Speed (m/s)	Shear Stress (Pa)
High	10.9	2723	2760	11.01	164
Medium	4.6	1128	1112	4.43	34.9
Low	1.8	423	447	1.78	7.14

Table 3: Important Design Values

The designed system currently accommodates 16 specimens at the high and low velocities and 2 specimens at the middle velocity. The high and middle velocity is driven by a 5 horsepower electric motor. The lower velocity set is driven by a separate ½ horsepower electric motor, because it is more practical than gearing down the higher rotational rate. The ½ horsepower motor is directly connected to the drive pulley of the low speed set while the 5 horsepower motor is geared down and split to drive the middle and high speed sets. The two motors are supported by a platform.

4.5 Exposure Tank and Control

In one scenario, a 3 feet deep pool is filled with seawater from the SeaTech intake system and piped to the pool. This water must contain the larvae of the fouling organisms. It is presumed that with the warm water and closed container the tank should fill with fouling organisms fairly quickly and provide heavy fouling pressure. The water must be refreshed on a regular basis to keep the water from becoming stale and killing the organisms rather than promoting their growth. In another scenario, the system can be placed in a natural exposure environment. Figure 13 shows a general picture of what the entire system set up will look like. The three different colors of the pulleys are to designate the different velocity loops. The yellow and blue boxes are the 5 horsepower and ½ horsepower motors respectively. An iron control cylinder specimen for each

speed, as well as an iron flat plate specimen placed in the pool, should be included as control standards. If the flat plate is not fouled, then the experiment cannot be considered valid.

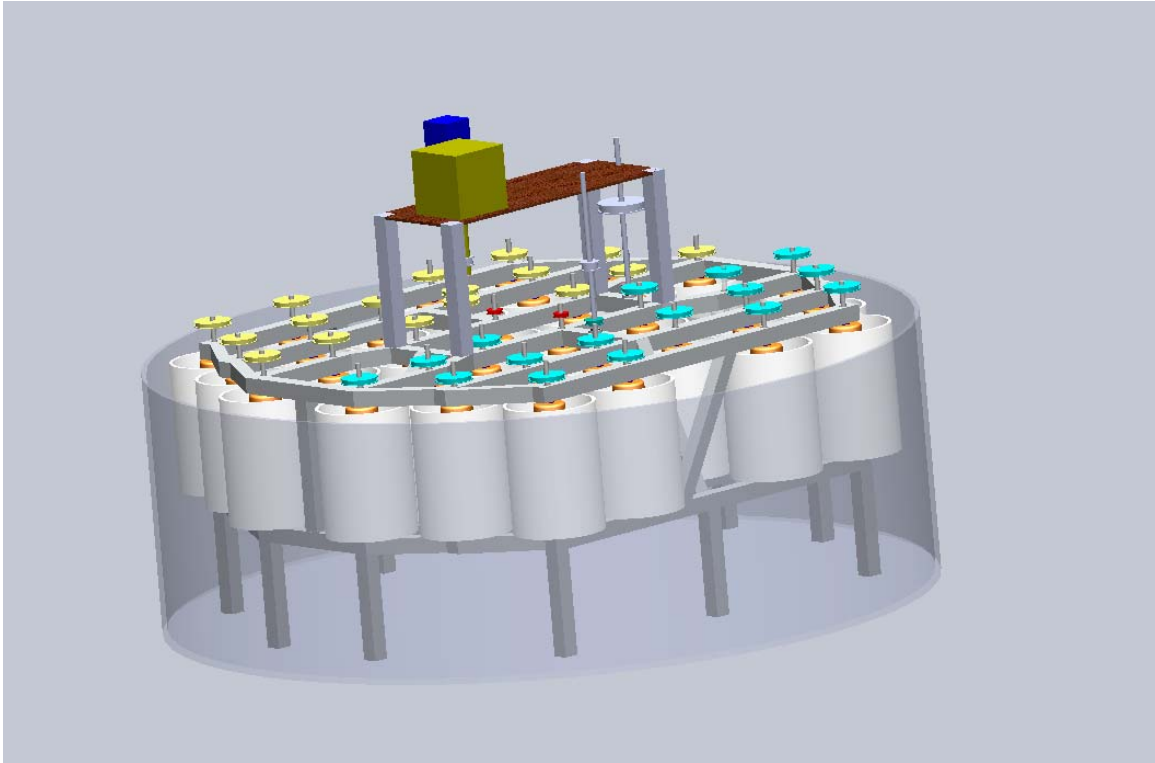


Figure 13: Proposed experiment - general system set up

4.6 Miscellaneous design

The test cylinder is shrouded by 8 inch diameter schedule 40 PVC sections. This PVC shield acts to keep each specimen's hydrodynamics from affecting the next. This shield will inevitably become fouled during the testing process. To keep the fouling to a minimum, these shields can be scraped on a regular basis and/or replaced, for a minimum system cost, when the fouling reaches an unacceptable level. With the current design multiple specimens can be tested in close proximity without interfering with the hydrodynamics of the adjacent specimen.

The Rulon® bushings are used as bearings; they are a polymeric substance that provides lubrication without any balls or rollers involved. Because they are made from a polymer instead of a metal, they will not corrode. The skeleton structure needs to support all surfaces of the Rulon® bushing to keep the wear uniform. For this reason, solid 1-½ inch aluminum square members were selected. The pulleys themselves are made from aluminum, to avoid a galvanic cell that will cause corrosion. The belt system design was done with the help of some software (DesignIQ™ and Design Flex Pro) and expertise provided by the Gates Corporation and is a fairly complicated procedure. The small diameter of the specimen increases the rotational velocity needed to achieve the desired relative velocities. Consideration can be given to increase this diameter if space allows. This would allow for a decrease in motor size, but would require a redesign of the belt system.

4.7 Comments on Design

This type of experiment is useful because it can test different types of coatings simultaneously in different flow velocities. If the test system is set up with incrementally increasing speeds, the test specimens can be examined to show threshold speeds above which specific species can not settle. The use of larger radius cylinders is an option. With a smaller radius of curvature the adhesion strength of organisms decreases from their adhesion strength on flat plates. The surfaces of the hydroturbine system are mostly curved though they do have larger radii of curvature which would lead to higher adhesion strength of the organisms. To make a proper assessment of the radius of curvatures a test should be set up to compare organism adhesion to the radius of curvature established in

the system. The test system is developed for hydroturbine studies, which will experience multiple velocity profiles across the blades and pressure vessel. It will provide data for a proper coating selection dependent on the speeds anticipated in actual service.

5. DISCUSSION

Throughout the course of this research, many discussions were held with companies, industry professionals, and researchers. The companies guard their test data closely. They consider it proprietary information. Even if it was possible to obtain this data from the companies, they all do testing in different geographic areas and do not use the same test methods. These areas that the companies use all have different fouling ‘signatures’ (e.g. pressure, seasonal variances, etc.) Each of these organisms’ settlement depends on depth, light, seasons, and even orientation. So to compare this data, if obtained from different sources, would be futile. The fouling on one panel might vary from year to year in the same conditions. There is no objective answer. This makes it very difficult to compare different companies’ products. The only way to do this would be through the use of an experiment to expose multiple coatings to the service conditions.

In speaking with the leading companies in the industry it is believed that the foul release type is the best answer. When these companies were questioned about the inner 1/3 portion of the blade that rests below the threshold velocity, most simply state that fouling will remain minimal. These coatings are expected to last for five to ten years in excellent to good condition and have a possibility of lasting up to fifteen years at a maximum.

The most promising coating, overall, seems to be the copper-nickel alloy. The alloy has a proven track record in the marine environment and long lifetime. The first copper-nickel hull, named the Asperida, was built in 1967 and has been in operation for over 30 years [27]. To date the hull still remains unfouled.

If it was possible to redesign the hydroturbine to minimize for antifouling concerns the following would be recommended. Considering the power curve for a turbine blade as one moves from the rotational axis out the radius of the blade the estimated power drawn ramps up until around the first 1/3 of the blade and flattens out near the second 1/3 of the blade, after which it tapers off. Most of the power is drawn from the 1/3 to the 2/3 portion of the blade, which for our case is above the threshold value for foul release coatings (~8 knots). If there was a way to eliminate the inner third portion of the blade, this would be beneficial, because with this inner third portion fouled it offers a hydrodynamic penalty with out providing that much power. One thought to accomplish this idea of eliminating the inner portion is to simply extract the portion, and replacing it with structural skeleton members attaching to the outer portion. This would allow for water to pass through, creating less surface area exposed at the lower velocity while still allowing for the significant energy-providing portion of the blade, the outer portion, to still operate as designed, without the added penalty from the fouled inner portion.

6. CONCLUSION

This type of research is important to pursue. Hydroturbines offer a promising solution to energy needs. When dealing with underwater components, biofouling can lead to a significant increase in drag. This is especially detrimental for rotating components because it can lead to a loss of efficiency that could render the project nonfeasible. This thesis addressed the problems associated with biofouling, and a variety of solutions to this issue:

- Researched the settlement process
 - Boundary layer and shear stress effects
- Researched the types of paint systems available
 - Contact Leaching
 - Ablative
 - Self Polishing Copolymer
 - Fouling Release
 - Threshold at 7-8 knots
- Researched and found the characteristics important to antifouling coatings
 - Surface roughness
 - Water temperature
- Researched the idea of a copper-nickel alloy

- Found the importance of the oxide film layer
- Determined the electrochemical process needed to electroplate the alloy
- Researched applicable standards
 - Rotating drum standard
 - Static exposure standard
 - Visual evaluation standard
- Designed a dynamic exposure system

The idea of an electroplated copper-nickel alloy coating is a very attractive option for the application in the hydroturbine project. The superior protection from biofouling and corrosion would offer a best fit long term solution that traditional paint coatings just cannot offer. The alloy has a proven track record in the marine environment. With electroplating all surfaces would be covered sufficiently, while keeping the thickness to a manageable level. Even the best paint coatings cannot be counted upon to last more than 5-10 years of guaranteed service. To further complete the problem of biofouling in the application of a marine hydroturbine the following is suggested:

- Expose a panel at service depth and evaluate species
- Perfect the electrodeposition process for CuNi alloy
- A comparative experiment must be undertaken.

APPENDIX I: SURFACE VELOCITY CALCULATION

In considering whether the system would be able to use a foul release type coating for the blade structure one must calculate the relative surface velocity, because fouling release paints only work above a certain surface velocity. According to Smyth [28], Pence [29], and Yebra [30] the surface velocity must be at least 8 knots for the most contemporary coatings to be considered in the fouling release regime. With the help of Asseff [31], the designer of the carbon composite blade structure, the following surface velocity calculations were created.

The relative surface velocity V_r :

$$V_r = \sqrt{V_o^2 + V_{rot}^2}$$

The free stream velocity V_o is simply the velocity of the current which ranges from 1.7 m/s to 2.5 m/s. The rotational velocity is calculated as follows: $V_{rot} = 2\pi * r * n$ where r is the radius at which the velocity is to be calculated and n is the rotations per second (must be in hertz). The blade will be rotating at 20 rpm when the current is at the 1.7 m/s value and at 30 rpm when the current is at the upper bound, 2.5 m/s value. This gives us values for n of 20/60 or 1/3 and 30/60 or 1/2.

Using these values for V_{rot} we get:

$$V_r = \sqrt{V_o^2 + (2 * \pi * r * n)^2}$$

The nub of the blade is 0.75 meter in diameter, yielding a value of 0.75/2 meter for r at the beginning of the blade structure. To calculate the lower bound value we will use this value for r . Calculating the lowest possible value for V_r , which is at the base of the blade and the lowest free stream current velocity (1.7 m/s).

$$V_r = \sqrt{\left(1.7 \frac{m}{s}\right)^2 + \left(2 * \pi * \frac{.75 m}{2} * \frac{20 rpm}{60 s}\right)^2} \cong 1.87 \frac{m}{s} \cong 3.64 \text{ knots}$$

To calculate the lower bound for the high current, simply exchange the values for n and V_o .

$$V_r = \sqrt{\left(2.5 \frac{m}{s}\right)^2 + \left(2 * \pi * \frac{.75 m}{2} * \frac{30 rpm}{60 s}\right)^2} \cong 2.76 \frac{m}{s} \cong 5.37 \text{ knots}$$

To calculate the highest possible value for the relative velocity we use the above equation and extend r to the tip of the blade.

$$V_r = \sqrt{\left(2.5 \frac{m}{s}\right)^2 + \left(2 * \pi * \left[\frac{.75 m}{2} + 3m\right] * \frac{30 rpm}{60 s}\right)^2} \cong 10.89 \frac{m}{s} \cong 21.2 \text{ knots}$$

To solve for the critical point where on the blade the system enters into the foul release regime, 8 knots or 4.1 m/s, the above equation was solved for an r value (at 2.5 m/s current):

$$r = \frac{\sqrt{V_r^2 - V_o^2}}{2 * \pi * n} = \frac{\sqrt{\left(4.1155 \frac{m}{s}\right)^2 - \left(2.5 \frac{m}{s}\right)^2}}{2 * \pi * \frac{30 rpm}{60 s}} \cong 1.04 m$$

This is approximately 1 meter from the direct center which is only 0.665 m from the edge of the hub. When this is calculated using the low current it is approximately 1.8 m from the center of the blade, which is 1.4 m away from the edge of the hub.

APPENDIX II: DESIGN LIFE CALCULATION

Corrosion rates given by International Nickel Company (INCO) in an experiment at Wrightsville beach North Carolina circa 1970 with five year exposure time [32]:

CuNi 90-10: 0.1 mpy

CuNi 70-30: 0.1 mpy

Given design life 30 years this equates to a 3 mm to corrode.

Corrosion rates determined at the LaQue Center for Corrosion Technology over fourteen years shows corrosion rate decreasing over the first 5-6 years stabilizing at 1.3 $\mu\text{m}/\text{yr}$, though the rate seems higher in flowing water (0.6m/s) [33].

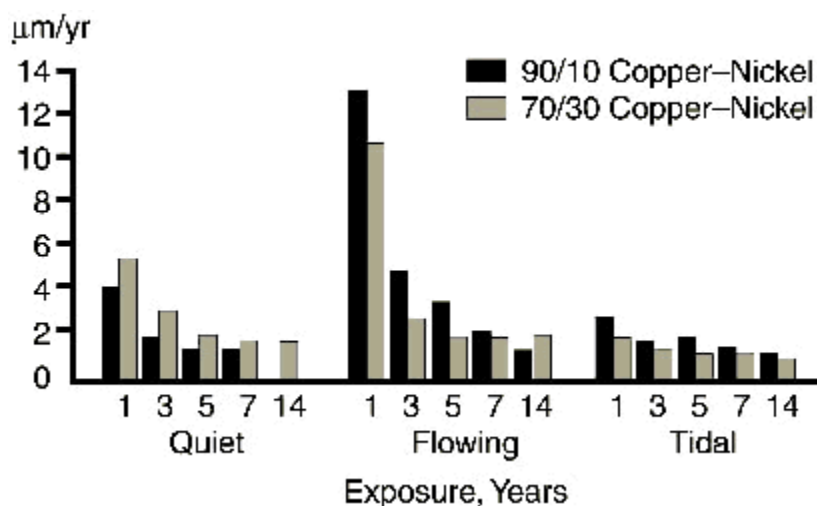


Figure 14: The change in corrosion rate with time for 90-10 and 70-30 copper-nickel in quiet, flowing (0.6m/s) and tidal seawater. [33]

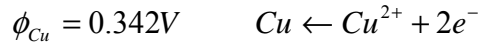
Powell et al. claim that it is commonly considered that 90-10 has a higher biofouling resistance than the 70-30 alloy, due to the higher copper content, though it is not always “bourne out of practice.” [20].

Because the blade surface will be placed in 50 meters of water and the fouling pressure decreases with depth, the fouling is expected to be relatively low. It is expected, by the researcher, that 70-30 have a lower general corrosion rate than the 90-10 due to the higher concentration of nickel. In the interest of keeping the coating as thin as possible for design life, it is believed that the 70-30 is the most promising candidate. Though, 90-

10 offers better fouling protection and is less expensive this may end up being the best candidate.

APPENDIX III: COPPER-NICKEL DEPOSITION RATIO

Reduction Potentials



Because Copper citrate has a valence of two Cu^{2+} reduction potential will be used [11]. Using the Nernst Equation at equilibrium to solve for the ratio of Copper to Nickel required to deposit evenly. This employs the following overall chemical reaction:

By setting the following Nernst equation to zero, at this potential the system is in equilibrium. There is both oxidation as well as reduction of both elements equally causing no overall imbalance or repercussive result. The system is in chemical harmony and does not care to change it self. With an applied current these should theoretically deposit evenly.

$$0 = E_{Cu} - E_{Ni} - \frac{RT}{nF} \ln \frac{[Cu][Ni^{2+}]}{[Cu^{2+}][Ni]}$$

Here R is the gas constant, T is the absolute temperature, n is the number of electrons transferred and F is Faraday's constant. The terms in brackets refer to the concentrations in solution. Because Cu and Ni are elements in their standard state, the values in brackets become unity. By moving the third term to both sides, converting the natural log to log base ten, and replacing with the values known:

$$\frac{0.0592V}{2} \log \frac{[Ni^{2+}]}{[Cu^{2+}]} = 0.342V + 0.250V$$

Solving for the concentration ratio:

$$10^{20} = \frac{[Ni^{2+}]}{[Cu^{2+}]}$$

It is because this ratio is so large that makes the electrodeposition of these materials so difficult. Because this ratio is so large, the best way to approach this ratio is through the use of a chelating agent. The chelating agent ties up the copper in solution so it is not

longer active in solution. It holds the copper in equilibrium freeing it back into solution when it is needed. This keeps the ratio of nickel to copper at a much more useful level.

APPENDIX IV: COATING SUPPLIERS

Many companies supply antifouling coatings. The biggest companies are International Paint LLC., Chugoku Marine Paints, Hempel, and Jotun.

International is a child company of AzkoNobel and is based out of Amsterdam. Chugoku is based out of Japan. Hempel is based out of Denmark and Jotun is based out of Norway. Sherwin-Williams is a company based here in the United States. All of these companies have been contacted about potential coatings for our project. Most companies have suggested the use of the foul release type coating for the blade.

There has been much contact with a few of these companies in hopes of acquiring some of their own test data. Most consider their tests proprietary information and are not open with it. This situation is why the testing is recommended. There is no way to objectively compare these companies without the use of a direct comparison test. These companies mostly recommend their fouling release coating and when questioned about the inner portion of the blade that remains below the threshold velocity, they stated that the fouling would remain minimal.

Paint Companies	SPC	Foul Release
Chugoku	Sea GrandPrix	BioClean*
International	Intersmooth	Intersleek 900
Jotun	SeaQuantum	SeaLion
Hempel	Globic NCT	Hempesil X3
Sherwin Williams	---	Sher-Release

* not usually applicable to ships due to softness of coating

Table 4: Companies of Interest and Applicable Coatings

APPENDIX V: TESTING CONSIDERATIONS AND SPECIFIC COATINGS

Important Considerations for Testing

Consideration	Evaluated	Reason
Velocity	1	SPC & Ablative wear away as a function of free stream velocity seen to cause effects with copper-nickel alloy some species cannot settle above certain velocity
Depth	2	with depth changes coverage (light, temperature, and salinity) too expensive to test at depth, try to replicate
Light	2	on surface fouling tends to grow in the shade over direct sun
Temperature	N/A	not considered because top 100m are similar (22-30 deg C)
Salinity	N/A	not believed to affect growth
Oxygen Content	3	does not seem to affect growth, only corrosion (destruction of protective oxide layer); could possibly be monitored
Proximity to shore	3	different species near shore versus open ocean
Larva	1	Samples need to be exposed to unfiltered water

KEY: 1 = Imperative to experiment 2= Should be accounted for 3 = would like to consider if possible

Table 5: Considerations When Developing Test Method

COATING SELECTION TEST				
Candidate	Product	Type	Company	Comment
1	Iron	Control	-----	Used as a control
2	Intersleek 970	Foul Release	International	recommended by navy
3	SeaLion	Foul Release	Jotun	
4	Hempesil X3	Foul Release	Hempel	
5	Intersmooth	SPC	International	
6	SeaQuantum	SPC	Jotun	"works well in high fouling"
7	Global NCT	SPC	Hempel	
8	CuNi 70-30	Flame Spray	FlameSpray USA	often times rough surface
9	CuNi 90-10	Flame Spray	FlameSpray USA	
10	CuNi 70-30	Foil	Orbel	don't know if composition can be designed
11	CuNi 90-10	Foil	Orbel	
12	CuNi 70-30	Electrodeposit	-----	Must be made in house but custom
13	CuNi 90-10	Electrodeposit	-----	
14	Copper	Pure	-----	Used as a control

Table 6: Samples to be Tested

APPENDIX VI: ASTM G52-00(2006) STANDARD PRACTICE FOR EXPOSING AND EVALUATING METALS AND ALLOYS IN SURFACE SEAWATER [34]

Significance and Use

The procedures described herein are recommended for evaluating the corrosion or marine fouling behavior, or both, of materials exposed to quiescent or local tidal flow conditions, or both.

4.1.1 This practice is not intended to cover the influence of high seawater velocity or the behavior of materials in seawater which has been transported from its source.

4.1.2 Some aspects of this practice may be applicable to testing in tanks and troughs which are continuously provided with fresh surface seawater. Additionally, some aspects may also be applicable to deep ocean testing.

Note 1—Guide G 78 provides guidance for conducting crevice corrosion tests under controlled seawater test conditions. While the duration of testing may be dictated by the test objectives, exposures of more than six months or one year are commonly used to minimize the effects of environmental variables associated with seasonal changes or geographic location, or both.

The procedures described are applicable for the exposure of simple test panels, welded test panels, or those configured to assess the effects of crevices, or both, such as those described in Guide G 78. In addition, they are useful for testing of actual components and fabricated assemblies. It is prudent to include control materials with known resistance to seawater corrosion or fouling, or both, as described in Test Method D 3623.

Note 2—Materials which have been included in ASTM Worldwide Seawater ASTM G52 -00(2006) Standard Practice for Exposing and Evaluating Metals and Alloys in Surface Corrosivity Studies include UNS K01501 (carbon steel), UNS C70600 (90/10 CuNi) and UNS A95086 (5086-H116 Al).

Note 3—In the case of evaluations of aluminum alloys, care should be exercised in the location of specimens near copper or high copper-containing alloys. In some instances, it is not sufficient to simply electrically isolate specimens to prevent bi-metallic (galvanic) corrosion; copper ions from nearby corroding copper or copper-base alloys can deposit on aluminum and accelerate its corrosion.

1. Scope

1.1 This practice covers conditions for the exposure of metals, alloys, and other materials in natural surface seawater such as those typically found in bays, harbors, channels, and so forth, as contrasted with deep ocean testing. This practice covers full immersion, tidal zone and related splash, and spray zone exposures.

1.2 This practice sets forth general procedures that should be followed in conducting seawater exposure tests so that meaningful comparisons may be made from one location to another.

1.3 This practice identifies recommended procedures for evaluating the effects of natural surface seawater on the materials exposed.

1.4 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only. This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

D3623 Test Method for Testing Antifouling Panels in Shallow Submergence
G1 Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens
G15 Terminology Relating to Corrosion and Corrosion Testing
G30 Practice for Making and Using U-Bend Stress-Corrosion Test Specimens
G38 Practice for Making and Using C-Ring Stress-Corrosion Test Specimens
G39 Practice for Preparation and Use of Bent-Beam Stress-Corrosion Test Specimens
G46 Guide for Examination and Evaluation of Pitting Corrosion
G58 Practice for Preparation of Stress-Corrosion Test Specimens for Weldments
G78 Guide for Crevice Corrosion Testing of Iron-Base and Nickel-Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments

APPENDIX VII: ASTM D3623-78a(2004) STANDARD TEST METHOD FOR TESTING ANTIFOULING PANELS IN SHALLOW SUBMERGENCE [35]

Significance and Use

This method is designed as a screening test in evaluating antifouling coating systems. Results of the standard system in a specific marine environment are included to assist in interpreting results (see Annex A2).

Antifouling systems providing positive comparisons with the standard system should be considered acceptable for use in protecting underwater marine structures.

The degree and type of fouling will vary depending on the environment. Hence, differences in geographic location of test sites, in time of year when panels are exposed, and in weather conditions from 1 year to the next can affect results. Therefore, a fouling census on a nontoxic surface is taken. For the exposure to be valid the nontoxic surface should show heavy fouling, and the standard system should show significantly less fouling than the nontoxic surface (see Annex A3 and Annex A4).

1. Scope

1.1 This test method covers a procedure for testing antifouling compositions in shallow marine environments and a standard antifouling panel of known performance to serve as a control in antifouling studies. Subcommittee D01.45 has a revised rating procedure now being evaluated by round robin.

1.2 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.3 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the application of regulatory limitations prior to use.

2. Referenced Documents

A569/A569M Specification for Steel, Carbon (0.15 Maximum Percent), Hot-Rolled, Sheet and Strip, Commercial Steel

D2200 Pictorial Surface Preparation Standards for Painting Steel Surfaces

MIL-P-15328D Primer Pretreatment (Formula 117 for Metals)

MIL-P-15929C Primer Coating, Shipboard, Vinyl-Red Lead (Formula 119-For Hot Spray)

MIL-P-15931B Paint, Antifouling, Vinyl, Red (Formula 121/63)
MIL-S-22698A Steel Plate, Carbon, Structural

APPENDIX VIII: ASTM D5618 -94(2005) STANDARD TEST METHOD FOR MEASUREMENT OF BARNACLE ADHESION STRENGTH IN SHEAR [22]

Significance and Use

This test method is designed as a screening test in the evaluation of coating systems and other materials designed to resist biofouling attachment. The degree and type of barnacle fouling will vary according to the geographic location of test sites and the time of year when tests are implemented. Surfaces with known barnacle adhesive shear strength should be exposed to provide comparative data.

1. Scope

1.1 This test method covers the measurement of barnacle adhesion in shear to surfaces exposed in the marine environment. It is used to establish the ability of a surface to reduce biofouling adhesion. Surfaces with known barnacle adhesion strengths are included to serve as controls.

1.2 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.3 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

D3623 Test Method for Testing Antifouling Panels in Shallow Submergence
MIL-P-24441/1 Primer, Epoxy (Formula 150, Formula Sheet 24441/1)

APPENDIX IX: ASTM D6990-05 STANDARD PRACTICE FOR EVALUATING BIOFOULING RESTISTANCE AND PHYSICAL PERFORMANCE OF MARINE COATING SYSTEMS [36]

Significance and Use

This practice is designed to provide guidance to a panel inspector for quantitative and consistent evaluation of coating performance from test panels coated with marine antifouling coating systems. The practice assesses performance of coating systems based on both antifouling and physical properties.

The user is cautioned that the results are representative for the specific region and time of year in which the specimens are immersed. It shall be noted that interpretation of results will depend on the geographical location where the test is conducted, whether the coated specimens are exposed either totally or partially immersed, under static or dynamic conditions, and position and orientation.

Simultaneous testing of a proven standard antifouling coating system (known to minimize fouling accumulation, for example, containing biocide or active agent (s) to prevent fouling settlement/growth) in the specific marine environment shall be included as a reference to assist in interpretation of results. In addition, a negative control (inert surface susceptible to heavy fouling) shall be included on a regular basis. For the exposure to be valid, the surface of the negative control should show heavy fouling relative to the standard system(s).

Marine coating systems that produce positive results relevant to the standard system(s) show potential for use in protecting underwater marine structures.

The format can be utilized independent of exposure protocol and coating type, and provides the end user with a consistent practice and format for reporting of performance rating.

1. Scope

1.1 This method establishes a practice for evaluating degree of biofouling settlement on and physical performance of marine coating systems when panels coated with such coating systems are subjected to immersion conditions in a marine environment. Guidance for preparation or exposure and handling of test specimens can be found in related ASTM standards as noted below (see Section).

1.2 This practice and related exposure methodologies are designed as tools for the relative assessment of coating performance, and in no way are to be used as an absolute indicator of long-term performance under all conditions and in all environments. There can be high variability among and within exposure sites with respect to water quality and population or species of fouling organisms, and coating performance may vary with these and other properties.

1.3 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only. This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. A specific hazard statement is given in Section.

2. Referenced Documents

D3623 Test Method for Testing Antifouling Panels in Shallow Submergence

D4938 Test Method for Erosion Testing of Antifouling Paints Using High Velocity Water

D4939 Test Method for Subjecting Marine Antifouling Coatings to Biofouling and Fluid Shear Forces in Natural Seawater

D5479 Practice for Testing Biofouling Resistance of Marine Coatings Partially Immersed

D5618 Test Method for Measurement of Barnacle Adhesion Strength in Shear

G141 Guide for Addressing Variability in Exposure Testing of Nonmetallic

APPENDIX X: ASTM D4939 STANDARD TEST METHOD FOR SUBJECTING
MARINE ANTIFOULING COATING TO BIOFOULING AND FLUID SHEAR
FORCES IN NATURAL SEAWATER [25]

Significance and Use

This practice is designed to provide guidance to a panel inspector for quantitative and consistent evaluation of coating performance from test panels coated with marine antifouling coating systems. The practice assesses performance of coating systems based on both antifouling and physical properties.

The user is cautioned that the results are representative for the specific region and time of year in which the specimens are immersed. It shall be noted that interpretation of results will depend on the geographical location where the test is conducted, whether the coated specimens are exposed either totally or partially immersed, under static or dynamic conditions, and position and orientation.

Simultaneous testing of a proven standard antifouling coating system (known to minimize fouling accumulation, for example, containing biocide or active agent(s) to prevent fouling settlement/growth) in the specific marine environment shall be included as a reference to assist in interpretation of results. In addition, a negative control (inert surface susceptible to heavy fouling) shall be included on a regular basis. For the exposure to be valid, the surface of the negative control should show heavy fouling relative to the standard system(s).

Marine coating systems that produce positive results relevant to the standard system(s) show potential for use in protecting underwater marine structures.

The format can be utilized independent of exposure protocol and coating type, and provides the end user with a consistent practice and format for reporting of performance rating.

1. Scope

1.1 This method establishes a practice for evaluating degree of biofouling settlement on and physical performance of marine coating systems when panels coated with such coating systems are subjected to immersion conditions in a marine environment. Guidance for preparation or exposure and handling of test specimens can be found in related ASTM standards as noted below (see Section).

1.2 This practice and related exposure methodologies are designed as tools for the relative assessment of coating performance, and in no way are to be used as an absolute indicator of long-term performance under all conditions and in all environments. There can be high variability among and within exposure sites with respect to water quality and

population or species of fouling organisms, and coating performance may vary with these and other properties.

1.3 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. A specific hazard statement is given in Section .

2. Referenced Documents

ASTM Standards

D3623 Test Method for Testing Antifouling Panels in Shallow Submergence

D4938 Test Method for Erosion Testing of Antifouling Paints Using High Velocity Water

D4939 Test Method for Subjecting Marine Antifouling Coatings to Biofouling and Fluid Shear Forces in Natural Seawater

D5479 Practice for Testing Biofouling Resistance of Marine Coatings Partially Immersed

D5618 Test Method for Measurement of Barnacle Adhesion Strength in Shear

G141 Guide for Addressing Variability in Exposure Testing of Nonmetallic Materials

APPENDIX XI: TEST SYSTEM DESIGN CALCULATION

The test design speeds for the current design are: a) 11.0 meters per second, the maximum velocity for the hydroturbine application (denoted by the subscript H); b) 4.6 meters per second, a minimum for the fouling release coating functionality (denoted by the subscript M); and c) 1.8 meters per second, the minimum velocity for the hydroturbine application (denoted by the subscript L). Knowing these speeds allows for determination of rotational rate by Equation (A.V.1) below. Where F is the frequency in rotations per minute, U_{rel} is the relative velocity across the surface and D_{cyl} is the diameter of the cylinder.

Taking the values of $U_H = 11.0$ m/s, $U_M = 4.6$ m/s, and $U_L = 1.8$ m/s.

$$F = \frac{60U_{rel}}{\pi D_{cyl}} \quad (\text{A.V.1})$$

Where $D_{cyl} = 3 \text{ in} = 0.0762$ m.

Table 2 below shows the rotational rates and speeds of both the design and actual after the entire design process. The discrepancy comes about after the design of the pulley systems. It wasn't possible to get the rotational rates exact with the pulleys available.

Speed	Designed Speed	Design Rotation	Actual Rotation	Actual Speed
High	10.9 m/s	2723 rpm	2760 rpm	11.01 m/s
Medium	4.6 m/s	1128 rpm	1112 rpm	4.43 m/s
Low	1.8 m/s	423 rpm	447 rpm	1.78 m/s

Table 7: Important Speeds

The equation for the Reynolds number is listed below in Equation (A.V.2) [37]. It's a ratio of the viscous forces to the inertial forces. Here again ρ is the density of the liquid, which is seawater in this case. V is the free stream velocity, D_{cyl} , and μ is the dynamic viscosity of the fluid. The kinematic viscosity is denoted by ν , and is simply the density divided by dynamic viscosity. Where $\nu = 0.98 \times 10^{-6}$ m²/s.

$$Re = \frac{\rho \cdot V \cdot D_{cyl}}{\mu} = \frac{V \cdot D_{cyl}}{\nu} \quad (\text{A.V.2})$$

This yields Reynolds numbers of: $Re_H = 8.56 \times 10^5$, $Re_M = 3.44 \times 10^5$, $Re_L = 1.38 \times 10^5$.

The Reynolds number is then used to come up with a coefficient of friction for each cylinder. The coefficient of friction is below as Equation (A.V.3) [38].

$$C_F = \frac{0.075}{(\text{Log}_{10} Re - 2)^2} \quad (\text{A.V.3})$$

This equation yields: $C_{FH} = 4.8 \times 10^{-3}$; $C_{FM} = 6.0 \times 10^{-3}$; $C_{FL} = 7.6 \times 10^{-3}$.

This coefficient is used to calculate the force of drag that each cylinder encounters. The force of drag equation is listed as Equation (A.V.4) below. Where A is the surface area of the cylinder ($\pi Dh = 0.0730 \text{ m}^2$).

$$F_D = \frac{1}{2} \rho \cdot v^2 \cdot A \cdot C_f \quad (\text{A.V.4})$$

This yields: $F_{DH} = 21.8 \text{ N} = 4.9 \text{ lbs}$; $F_{DM} = 4.43 \text{ N} = 1.0 \text{ lbs}$; $F_{DL} = 0.90 \text{ N} = 0.2 \text{ lbs}$.

To calculate the torque required to turn one cylinder Equation (A.V.5) is used. Here the change from metric to English units for ease of grasping the power needed. Here τ here is torque.

$$\tau = \frac{D_{cyl}}{2} \times F_D \quad (\text{A.V.5})$$

This yields: $\tau_{H1} = 3.675 \text{ inch-pounds}$; $\tau_{M1} = 0.75 \text{ inch-pounds}$; $\tau_{L1} = 0.15 \text{ inch-pounds}$.

Here the subscript 1 denotes a single cylinder. To get the total torque for the entire loop, each one of these must be multiplied by the number of specimens within the loop. Here the subscript T denotes total torque for the loop.

$$\begin{aligned} \tau_{HT} &= 16 \times \tau_{H1} = 58.8 \text{ in-lb} = 4.9 \text{ ft-lb}; & \tau_{MT} &= 2 \times \tau_{M1} = 1.5 \text{ in-lb} = 0.125 \text{ ft-lb}; \\ \tau_{LT} &= 16 \times \tau_{L1} = 2.40 \text{ in-lb} = 0.2 \text{ ft-lb}. \end{aligned}$$

The power required for each loop is calculated by equation (A.V.6) below.

$$P = \omega \cdot \tau = \frac{2 \cdot \pi \cdot \tau_T \cdot rpm}{33000} \quad (\text{A.V.6})$$

The second version yields power in horsepower with τ_T in ft-lb:

$$P_H = 2.57 \text{ hp}; \quad P_M = 0.0265 \text{ hp}; \quad P_L = 0.0170 \text{ hp}.$$

Summing these up gives a total power required to drive the system: 2.61 hp.

The power of the motor must be significant enough to drive the system with the regular friction as well as the added friction of the fouled members so a 5 hp motor which is a similar price to a 3 hp motor was chosen.

The wall shear stress (τ) values on the cylinder surface are calculated in equation (A.V.7) [32].

$$\tau_{cyl} = 0.0791 \cdot \rho \cdot \text{Re}^{-0.3} \cdot U_{cyl}^2 \quad (\text{A.V.7})$$

This yields: $\tau_{cylH} = 164 \text{ Pa} = 23.8 \times 10^{-3} \text{ psi}$; $\tau_{cylM} = 34.9 \text{ Pa} = 5.06 \times 10^{-3} \text{ psi}$;
 $\tau_{cylL} = 7.41 \text{ Pa} = 1.07 \times 10^{-3}$;

These are the values of shear stress that can be expected with each speed. The shear forces are an important value because this is what the settling organisms have to resist in order to settle.

APPENDIX XII: FIGURE PERMISSIONS

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