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# Antifouling Technologies

*A Primer*

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**Defence Research and Development Canada**

**Reference Document**

DRDC-RDDC-2021-D047

March 2021

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## IMPORTANT INFORMATIVE STATEMENTS

# Abstract

A brief survey of the literature was performed several years ago (in 2015). The primary purpose was to gain familiarity with the state-of-the-art in the area of antifouling technologies to enable assessment of the potential utility for the Royal Canadian Navy (RCN). The end goal was to determine whether any of the new technologies were suitable for Naval vessels. The Reference Document (RD) provides a brief overview of commercially available hull coatings as well as various approaches to mitigate biofouling. Cursory conclusions, recommendations, and future considerations are provided; however, it is important to note that this effort was suspended, due to the closure of the Dockyard Laboratory Pacific. Hence, the document has morphed into a brief primer for antifouling technologies, with some useful references, in order to pass along corporate knowledge. It is hoped that this document will assist anyone who wishes to continue and complete this effort.

# Résumé

Il y a plusieurs années (en 2015), on a effectué un bref survol de la littérature. L'objectif principal était de se familiariser avec l'état des connaissances dans le domaine des technologies antisalissures afin de pouvoir évaluer leur utilité éventuelle pour la Marine royale canadienne. L'objectif final consistait à déterminer si certaines des nouvelles technologies convenaient aux navires de la Marine. Le présent document de référence fournit un bref aperçu des revêtements de coque offerts sur le marché et des diverses approches proposées pour diminuer les encrassements biologiques. Des conclusions sommaires, des recommandations et des réflexions pour l'avenir y figurent. Il est toutefois important de noter que ces efforts ont été suspendus en raison de la fermeture du Laboratoire du chantier naval (Pacifique). Dès lors, le document est devenu un petit guide d'introduction aux technologies antisalissures contenant quelques références utiles et servant à transmettre le savoir organisationnel. On espère que celui-ci aidera tous ceux qui souhaitent poursuivre et mener à terme ces efforts.

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# 1 Introduction

Biofouling refers to marine organisms that settle on surfaces immersed in seawater, and includes a wide range species that can be categorized into three general groups: microorganisms (e.g., bacteria, fungi, diatoms, and microalgae), *soft* fouling (e.g., sponges, bryozoans, and macroalgae), and shell or *hard* fouling (e.g., barnacles, mussels, tube worms) [1]. The accumulation of biofouling on the underwater hull and appendages of ships increases hydrodynamic drag [2] thereby negatively impacting fuel economy and increasing greenhouse gas emissions. Biofouling is particularly problematic for vessels that remain alongside for extended periods of time, such as Navy ships.

The increase in drag due to biofouling depends on the extent and type of fouling. A fouling rating scale has been defined by the United States (US) Navy and is based on the most frequently encountered fouling patterns [3]. The rating is dependent on the nature of the fouling, soft (primarily slime and grass) or hard (primarily barnacles and tube worms), and its diameter or height. The effect on drag has been investigated by Schultz (notably [2][4] and references therein) in both lab-scale experiments and full-scale ship power studies. Estimates based on lab-scale drag studies agree well with full-scale ship studies. The impact of drag is substantial; a power trial demonstrated that a ship covered in heavy slime required 9% more power than when the hull was clean to travel at 16 knots. More severe fouling requires increased power to maintain speed. With severe hard fouling, the power penalty is estimated to be approximately 86% at cruising speed [4].

In addition to increased drag, biofouling accumulation impacts survivability due to the need for more frequent replenishment at sea as well as increased acoustic signature noise, thus affecting signature. Furthermore, the presence of biofouling increases the risk of the transport of invasive, or non-indigenous, species. A fouled hull can limit where ships can operate, therefore negatively impacting operability.

Although the original purpose of this RD (which was started several years) was to capture the state-of-the-art in antifouling technologies, and to comment on viability for Naval vessels, progress was suspended after the announcement of the closure of the Dockyard Lab Pacific. The intent of publishing as a Reference Document (RD) is to inform the Defence Science and Naval communities—to transition corporate knowledge, and to guide potential future work at the Dockyard Lab Atlantic. The reader may note that the "current" literature is not so current anymore, hence the information presented may no longer be considered state-of-the-art. As the information may still be useful, the author has endeavoured to finalize the RD based on information already gathered. Additional information can be found in several excellent reviews [1][5]–[8]. If current research is of interest, it may be worthwhile performing a current literature search of the following prominent authors: E.G. Haslbeck, E.R. Holm, M.P. Schultz, G.W. Swain, K.A. Zargiel, K.Z. Hunsucker and E.A. Ralston.

## 1.1 Current Hull Coatings

Current hull coatings may be categorized as either biocidal (also commonly known as antifouling coatings), foul release, or a hybrid (of the two). This section provides a brief background on these types of coatings commercially available in 2015. More up to date information may be acquired directly from the websites of the biggest marine coatings producers:

- Akzo-Nobel (International Marine Coatings) [9],

- Hempel [10],
- Sigma (PPG Coatings) [11], and
- Jotun [12].

### 1.1.1 Biocidal Antifouling Coatings

For many years, and up until approximately 2005, most ships typically utilized hull coatings containing a tin-based biocide to mitigate biofouling growth. Tributyl tin (TBT)-based antifouling coatings performed extremely well, due to the efficacy of the biocide in conjunction with the uniform, controllable release rate furnished by the self-polishing characteristics[1] of the matrix [1]. However, TBT is quite persistent in the environment, and found to negatively impact non-target organisms, such as oysters [1][5]. As a result, the International Maritime Organization introduced a ban on its usage, for most ships, in 2003. Since then, copper-based antifouling coatings have served as the primary replacement, although they have been found to be less effective than their tin-based predecessors. The lower efficacy is attributed to the non-uniform release rate, despite continued efforts to tailor the coating matrix. There have also been numerous attempts to improve the efficacy of copper-based antifouling coatings through the use of booster biocides in conjunction with the copper-based biocides.

Antifouling coatings that utilize alternative biocides have been developed but have been found to be less effective and, in some cases, also harmful to the environment [1]. It is anticipated that this will be an area of continuing development.

### 1.1.2 Foul Release Coatings

Foul release (FR) coatings are non-biocidal, low surface energy coatings which function by ensuring that biofouling organisms are only weakly adhered, thus relatively easily removed. The adhesion strength is sufficiently weak that the biofouling can often be removed through ship movement or gentle cleaning; it should be noted, however, that adhesion strength increases with biofouling maturity. For example, juvenile barnacles are significantly easier to remove than mature barnacles.

Foul release coatings have been in development for many years, and the most recent generation of FR coatings are designed to facilitate fouling removal at lower speeds (lower shear stress) than previous generations. FR coatings work very well for vessels that sail frequently, and thus do not require cleaning. For Naval vessels, however, which tend to sit alongside for extended periods of time, periodic cleaning is required in order to mitigate biofouling. It might seem cost-effective to allow biofouling to develop and mature, and clean only before sailing, however, FR coatings are relatively soft, thus susceptible to damage. Damage can be caused by cleaning, if the cleaning process does not strictly follow manufacturer’s recommendations. Furthermore, it has been reported (anecdotally) that shells of mature barnacles can grow into the soft FR coatings, leaving significant damage when removed. Thus, it is important that biofouling be removed sufficiently frequently, through sailing (preferred method) or gentle cleaning, to minimize coating damage. Although FR coatings are soft, compared to other types of coatings, there are some that are more

[1] Self-polishing coatings usually refer to coatings that reveal a fresh surface, reducing the thickness of the leached layer (layer depleted in biocide), via reaction with water, i.e., hydrolysis, in contrast to those that rely on ablation via friction with water. Thus self-polishing coatings can be effective (to a degree) when the ship is alongside, and do not require ship movement to ablate the leached layer.

mechanically robust, and are preferable to those that are exceptionally soft. A range of coatings were evaluated by the Dockyard Laboratory Pacific over several biofouling seasons [13].

The performance of FR coatings is dependent on several factors, such as age and physical condition of the coating, as well as the nature of the coating. Studies have shown that the formulation of the coating matrix can affect the adhesion strength of different fouling organisms, thus it is important to test coating performance against a broad range of organisms, and to choose products most suitable to the expected environment [14].

### 1.1.3 Hybrid Coatings

Hybrid coatings have been developed in which a biocide is incorporated into the foul release matrix. Such coatings offer superior antifouling performance and are commercially available (e.g., Hempel Hempaguard X7), however, cannot currently be used in Canada unless the biocide has been approved for use by Health Canada. As of the initial writing of this document, no hybrid coatings had been approved.

## 1.2 Biofouling Growth

In order to understand how biofouling can be mitigated, knowledge of its initiation and development is critical. The nature and extent of fouling depends on many factors including temperature, nutrient levels, light, salinity, flow rates, and pH [5][6]. These factors vary as a function of geographic location, time of year, as well as depth. The effects of depth can be seen in the variation in biofouling growth on the same ship. For example, weed growth is higher near the surface owing to the higher level of light, whereas at greater depths, where there is less light, barnacles tend to dominate.

Typically, the first step in biofouling is the development of a conditioning film, comprised of large organic molecules, such as proteins, polysaccharides, and/or glycoproteins. This film forms within one minute of immersion; subsequent biofilm formation begins with the accumulation of bacteria followed by the development of slime (microfouling). Macrofouling, comprised of soft foulers (algae, sponges, grasses, etc.) and hard foulers (barnacles, tubeworms, etc.) generally develops at some point after the biofilm formation, however, the biofilm is not necessarily a requirement for micro- or macro-fouling development [5][6]. For example, some algae and barnacle cyprids can settle on pristine surfaces, and higher fouling organisms have been found to exploit substrate niche areas [5].

In addition to the environmental conditions (temperature, light, etc.), the nature of the surface is also very important. Surface energy, wettability, charge, and topography also affect biofouling adhesion [6]. Larvae settlement locations are determined by different cues in the environment: chemical cues (inorganic and organic compounds, including stimulatory peptides and odors) and physical cues (surface energy, vibration, light) [15]. Another consideration is that biofilm community structure (adhesion, abundance, diversity, and composition) has been found to be affected by dynamic conditions [16].

Another factor in biofouling growth is the effect of previous growth. Studies have shown that the original fouling community can impact future fouling even when the original community has been removed from the surface [17]. In addition, niche areas have been found to provide an excellent environment for growth (e.g., small gaps), and reduce the efficacy of removal mechanisms [18].

# 2 Approaches to Mitigating Biofouling

There are three main strategies designed to mitigate biofouling[2] [6]:

- Prevent settlement of higher fouling organisms
- Decrease adhesion strength of biofouling
- Degrade or kill higher fouling organisms

Each of these strategies targets a different stage in the biofouling process. Preventing settlement targets the initiation of biofouling, whereas decreasing adhesion strength or killing the organisms target post-settlement stages. There are technologies that utilize more than one approach, such as hybrid foul release coatings, which reduce adhesion and kill the organism. This section provides an overview of various approaches and briefly discusses recent publications in the context of the strategy described above.

## 2.1 Prevent Settlement of Higher Fouling Organisms (Fouling Prevention)

Coatings designed to prevent biofouling settlement, also known as fouling-resistant coatings, function by inhibiting the development of the conditioning film or bacterial biofilm [1][6]. By preventing the growth of these films, higher fouling development is generally precluded.

The conditioning film is comprised of large organic molecules (proteins/glycoproteins, carbohydrates, nucleic acids), and typically is the first step in the development of biofouling. Primary colonization describes the stage immediately after conditioning film development, in which bacteria settle and grow, forming the bacterial biofilm [5]. There are several strategies to prevent the development of the conditioning and/or bacterial film (each of which is discussed in more detail in the following sub-sections):

- Hydrophilic surfaces
- Antibacterial agents
- Micro- and nanotopography

### 2.1.1 Hydrophilic Surfaces

Extremely hydrophilic coatings prevent conditioning film development by holding water so tightly to the surface that the energy penalty of displacing the water molecules with the large organic molecules is prohibitively large. Examples of hydrophilic polymers include hydrogels (highly cross-linked hydrophilic polymers), poly(ethylene glycol), zwitterionic polymers (polymers containing associated ions), and polysaccharides. A commercially available foul release coating, Hempasil X3, has a hydrogel outer layer that mitigates biofouling [19]. The hydrophilicity of the surface circumvents organic molecule adsorption,

[2] Biofouling removal methods are not addressed in this RD.

thereby inhibiting the development of the conditioning film. Biofouling of hydrogel-based foul release coatings have been noted to exhibit a delay in the onset of biofilm formation [13].

### 2.1.2 Antibacterial Agents

Another strategy is to create an antimicrobial surface through the incorporation of species that inhibit microbial growth. Such species include antibiotics, quaternary ammonium salts [20], silver [21], and chlorhexidine. Other additives, such as surfactants and antioxidants have also been found to inhibit biofilm formation, thereby interfering with biofouling growth [22]. It is proposed that surfactants disturb interactions between colonizing organisms and the surface, decreasing bacterial adhesion, and facilitating removal via water flow [23].

A coating comprised of a biodegradable polyester matrix and containing three active ingredients (chlorhexidine [antibacterial agent], $ZnO_2$ [creates $H_2O_2$, a disinfectant], and Tween 85 [non-ionic surfactant, a detergent]) was subjected to immersion studies in sea water (Atlantic Ocean). The coating successfully exhibited antifouling activity; after six months of immersion, some slime (40% coverage) and algae (15% coverage) was observed [23].

Promising results were also observed with a hybrid coating comprised of a low surface energy matrix containing silver-loaded mesoporous silica [21]. The block copolymer matrix containing fluorine and silicone in conjunction with the nanoscale morphology imparted by the silver-loaded silica resulted in superhydrophobic characteristics (contact angle approximately 151°). The antibacterial effect of the silver nanoparticles was demonstrated with a bacterium and two algae species.

Antibacterial activity has been successfully incorporated into a self-polishing coating based on a copolymer comprised of polyurethane and glycol-modified silane. Tethered quaternary ammonium salt (QAS) biocides functioned as the active agent. Studies performed at the US Naval Research Lab showed that varying the alkyl length of the tether impacted efficacy; longer chains allowed the segregation and ultimate migration of QAS functionality to the surface, improving antimicrobial activity [20].

### 2.1.3 Micro- or Nanotopography

Micro- or nanotextured surfaces have also been found to exhibit antibacterial properties, although the configuration of the topography (distance between micro-topographical structures) impacts species differently, and may require tailoring to target specific biofoulers. The inability of a spore to be supported entirely on a single topographical feature will preclude its settlement [24]. For example, Sharklet AF™ [25], a synthetic surface designed to mimic shark skin, exhibits bacterial resistance. It has features that are smaller than *Ulva* zoospores, which can't settle in between or on individual features; a depth of 40 microns was found to be effective to mitigate settlement of *B. Improvises* cyprid larvae (barnacle), whereas a depth of 4 microns was more effective for *Ulva* spore settlement [1].

There are several mechanical means by which surface texturing can be introduced to metallic substrates (laser structuring, rolling, and micro-drilling), however these techniques are not well-suited to large scale application [26]. Efforts are underway, however, to develop techniques that are suitable for large areas. A coating with a riblet microstructure (raised parallel lines), known to reduce drag, has been prepared using a robotic device. The coating application and embossing is performed in a single step, exploiting the benefits of a dual-cure lacquer and a UV curing process [26]. This application technique appears to be suitable for scaling up to large area applications, although the side of a ship would be extremely challenging. Introducing more complex (hierarchical) topographical features having different length scales, in order to target a variety of biofoulers, would render this technique more promising.

Microtexturing can also be accomplished via the chemistry of the matrix (coating) through judicious selection of matrix elements (i.e., certain block copolymers) and preparation conditions, for example through layer-by-layer spray coating of oppositely charged poly(acrylic acid) and polyethyleneimine (PEI) [6]. By varying the pH of the PEI solution, the texture size can be controlled, which affects the settlement of zoospores of *Ulva*. Apparently the capillary forces within the nanostructure bind water quite strongly, and the spore adhesive cannot displace the water.

## 2.2 Decrease Adhesion Strength of Biofouling

There are several approaches to reduce the adhesion strength of biofouling organisms to submerged structures.

- Low surface energy surfaces
- Amphiphilic surfaces
- Hydrolyzable/peelable surfaces

### 2.2.1 Low Surface Energy Surfaces

As discussed in Section 1.1.2, low surface energy coatings (i.e., foul release coatings) do not prevent settlement, but facilitate removal of fouling organisms through reduced adhesion strength. Newer foul release coatings are more mechanically robust addressing the fragility demonstrated by the earlier generations of foul release coatings. One of the ways in which robustness is improved is by exploiting the self-stratification (segregation of blocks) exhibited by siloxane-polyurethane block copolymers. The siloxane blocks migrate to the surface of the coating, imparting the desirable low surface energy characteristics, while the polyurethane blocks form the bulk of the coating, imparting durability [27]. An attempt to exploit the increased durability and impart hydrophilicity to the surface was carried out by tethering carboxylic acid groups onto the siloxane blocks [27]; comparison with commercial off-the-shelf FR coatings revealed that performance was species dependent. Unfortunately, barnacle cement was found to adhere quite strongly to the acidic groups.

Recently, the addition of a small quantity (< 0.1%) of well-dispersed carbon nanotubes has been observed to enhance the foul release performance without modifying the bulk properties [6]. There are anecdotal reports that the inclusion of graphene into coatings results in a reduction of biofouling, however, rigorous scientific investigation is not known to the author [28].[3]

### 2.2.2 Amphiphilic Surfaces

Different organisms have different adhesion profiles, for example the green algae *Ulva* adheres weakly to hydrophobic surfaces, whereas *Navicula* (diatoms, another type of marine algae) adheres strongly to hydrophobic surfaces, including silicone elastomers [27]. Bryozoans prefer settling on low energy (10–30 mN/m) surfaces, whereas barnacles prefer to settle on high energy (30–35 mN/m) surfaces, and hydroids exhibit no preference [5]. Given the variation in affinity for different types of surfaces

[3] A Google search revealed one publication, which suggests benefits to inclusion of graphene, however, the study compared graphene in silicone rubber to polystyrene, and suggested that observed benefits were due to the elastomeric nature, which could be attributed to the matrix alone.

(e.g., hydrophobic or hydrophilic), also known as adhesion profile, amphiphilic surfaces are expected to exploit the effect of both hydrophobic and hydrophilic attributes.

In a recent paper, a series of coatings were prepared in which the siloxane (hydrophobic) was modified with pendant carboxylate groups to provide hydrophilic functionality to the hydrophobic siloxane at the surface of the siloxane-polyurethane system. The coatings did exhibit enhanced hydrophilicity and improved performance with respect to microalgae removal, however, it was noted that barnacle adhesion was quite strong [27].

A newer body of work includes the preparation and evaluation of ABA[4] triblock copolymers, in which the A blocks were zwitterionic[5] poly(sulfobetaine methacrylate) and the B blocks were low surface energy polydimethylsiloxane (PDMS) [29]. The amphiphilic triblock copolymers were then incorporated into a polyurethane system which would provide mechanical robustness. Good foul release performance was demonstrated with one bacterium and a diatomic species, while another bacterium and sporelings of a green macroalga showed an affinity for the zwitterions-containing coatings.

### 2.2.3 Hydrolyzable/Peelable Surfaces

Hydrolyzable surfaces react with water (i.e., they undergo hydrolysis), causing degradation of the outermost matrix layer, resulting in self-polishing. This mechanism is not new, and has been exploited by biocidal coatings to reduce the leached layer (revealing a fresh biocidal surface), however it is mentioned here in the context of non-biocidal coatings. Such coatings mitigate biofouling through the continuous loss of the outermost layer. Some hydrogel coatings (discussed in Section 2.1.1) are sometimes considered to be hydrolyzable coatings, in that they achieve their hydrogel nature via initial reaction with water, however, they are not intended to function as a traditional self-polishing coating, and are not intended to continuously reveal a fresh surface.

A recent report [30] of terpolymer resins comprised of methyl methacrylate (MMA), acrylic acid, and triisopropylsilyl or tributylsilyl methacrylate (hydrolysable content), and cross-linked with a polyfunctionalaxiridine (XAMA 7), demonstrates that these resins readily undergo hydrolysis, resulting initially in the development of a hydrogel layer. Control of the self-peeling, or self-polishing rate was achieved through varying the ratios of the three monomers utilized in the synthesis. The antifouling performance was achieved through the hydrophilic nature of the surface (protein resistance), and continual surface replenishment.

## 2.3 Degrade or Kill Fouling Organisms

In order to degrade or kill organisms, an active ingredient (biocide) of some sort must be incorporated into the coating matrix. For such coatings there are two important aspects—the release rate of the biocide, and its efficacy. TBT coatings were so successful, as antifouling coatings, because the TBT was very effective and was released at a controlled and uniform rate. Control over the release rate was achievable as the biocide was an integral part of the matrix (i.e., chemically). The release rate needs to be high

[4] A triblock copolymer in which the repeat unit is composed of two of the same blocks (A) on each side of a different block (B).
[5] Zwitterions are neutral molecules with both a positive and a negative electrical charge (in different locations of a neutral (overall) molecule). Zwitterionic materials bind water very tightly via electrostatically induced hydration.

enough that the active ingredient concentration is adequate for antifouling performance, yet not so high that threshold concentrations, as dictated by Health Canada, are exceeded.

### 2.3.1 Control of Release Rate

The release rate can be controlled via the matrix (ablation or hydrolysis, as discussed in Section 2.2.3) or through biocide configuration (encapsulation or tethering). Several decades of research into microencapsulation is summarized in a recent paper [31], which provides excellent background information on encapsulation. There are several benefits of encapsulation, such as providing control over release rate, reducing biocide degradation in the coating, and mitigating premature release. In addition, it is noted that several biocides are required to address a broad range of fouling, and encapsulation ensures compatibility of the mixture of biocides.

Chemically binding, or tethering, biocides to the matrix helps to address issues surrounding non-uniform release rate (assuming matrix behaviour can be controlled).

### 2.3.2 Newer Biocides

Significant effort has gone into developing “environmentally friendly” or “green” biocides, defined as having minimal toxicity to humans and vertebrates, minimal effect on environment, rapid degradation to benign species, and no bioaccumulation [32].

A wide range of potentially environmentally benign biocides have been evaluated with respect to persistence, bioaccumulation, and toxicity, using prediction programs. The analyses identified some small synthetic and natural products as potential candidates for green biocides [32].

One recent study investigated the performance of various types of biocidal moieties (e.g., QAS, phosphonium salts, sulfonium salts, chlorophenyl derivatives) bound to a polyisoprene matrix. Zone of inhibition experiments evaluated the performance with respect to hindering bacterial growth (against five strains), as well as the ability to release biocidal moieties were examined. It was found that materials prepared with cationic photocrosslinkers were inactive against adhesion of microalgal spores and fungal growth, whereas the presence of QAS groups resulted in increased antifouling activity [33].

In an attempt to mimic the antifouling performance of TBT-based coatings, various block and random copolymers of a silyl ester (*tert*-butyldimethylsilyl methacrylate) and MMA were prepared. Coatings comprised of the formulated binders, in addition to other coatings additives, notably ZnO, were evaluated with and without commercial biocides (Sea Nine 211, zinc pyrithione, and Preventol A4S). The coatings were subjected to erosion performance and antifouling efficiency (lab bioassays and fouling field tests in two locations), and the results were compared to a TBT-based reference coating (M150) and a commercially available biocidal coating containing Sea Nine 211. The erosion performance indicated that control of the erosion rate is achievable with the diblock copolymer, vice the random block copolymer. In addition, an erosion rate comparable to a TBT-based coating (M150) was found to be possible through formula optimization. An important point made was that the lab bioassay results were not reasonable indicators of performance in the field testing. Hence it is critical to evaluate coatings under true in-service conditions to determine the best candidates [34].

# 3 Conclusions and Recommendations

The RCN currently applies a copper-based biocidal coating on most of its surface ships. A non-biocidal foul release (FR) coating is currently applied to one frigate (HMCS TORONTO) and the Victoria class submarines. Although the FR coating is considered to be environmentally friendly, it is not without issues. Extended periods alongside result in significant fouling that must be cleaned. Such cleaning has been found to damage the coating.

Although the cost of FR coatings may appear prohibitively high (relative to the copper-based biocidal coating), a recent cost benefit analysis demonstrates that they are actually cost effective, even with required coating repair [35].

## 3.1 Future Considerations

In the short-term, selection of a better FR coating (more mechanically robust and superior biofouling mitigation through delayed biofouling onset) will reduce required maintenance (cleaning and repair), decrease overall lifespan cost, therefore improving both affordability and operability. The use of current commercially available hybrid (biocidal foul release) coatings will be the most suitable for the RCN, particularly if a durable product is selected. Application of such a hybrid coating will be feasible once the product is approved for use in Canada. Selection of a durable hybrid will significantly reduce repair and maintenance costs.

The use of biocidal coatings may still be required in niche, or low-flow areas, where foul release products tend to be ineffective. Concentration and coating thickness should be optimized for conditions and planned maintenance. However, it is possible that hybrid foul release coatings (particularly those having a hydrogel nature) may provide adequate performance in these areas, with occasional cleaning required.

In the longer term, coatings exhibiting antimicrobial activity, thus mitigating biofilm formation, may prove to be more environmentally friendly and as effective as biocidal coatings that target more advanced biofouling. Once the technology is feasible for large vessels, both from a scaling and cost perspective, micro-textured coatings may prove to be a viable option.

Regardless of what route is taken in the future, it is highly recommended that lab-scale immersion testing (in the location where ships are expected to be alongside the most) be done first to facilitate down-selection of the most promising products, followed by a patch trial on an actual vessel—to assess performance under true in-service conditions. Consideration for hydrodynamics should be done to ensure that patches are subjected to appropriate and uniform conditions.

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# List of Symbols/Abbreviations/Acronyms/Initialisms

| | |
|---|---|
| DRDC | Defence Research and Development Canada |
| FR | foul release |
| MMA | methyl methacrylate |
| PDMS | polydimethylsiloxane |
| PEI | polyethyleneimine |
| QAS | quaternary ammonium salt |
| RCN | Royal Canadian Navy |
| RD | Reference Document |
| TBT | tributyl tin |
| US | United States |
| VCS | Victoria class submarine |

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| | |
|---|---|
| 1. ORIGINATOR (Name and address of the organization preparing the document. A DRDC Centre sponsoring a contractor's report, or tasking agency, is entered in Section 8.)<br><br>DRDC – Centre for Operational Research and Analysis<br>Defence Research and Development Canada<br>Carling Campus, 60 Moodie Drive, Building 7S.2<br>Ottawa, Ontario K1A 0K2<br>Canada | 2a. SECURITY MARKING (Overall security marking of the document including special supplemental markings if applicable.)<br><br>CAN UNCLASSIFIED<br><br>2b. CONTROLLED GOODS<br><br>NON-CONTROLLED GOODS<br>DMC A |

3. TITLE (The document title and sub-title as indicated on the title page.)

Antifouling Technologies: A Primer

4. AUTHORS (Last name, followed by initials – ranks, titles, etc., not to be used)

Huber, T.A.

| 5. DATE OF PUBLICATION (Month and year of publication of document.) | 6a. NO. OF PAGES (Total pages, including Annexes, excluding DCD, covering and verso pages.) | 6b. NO. OF REFS (Total references cited.) |
|---|---|---|
| March 2021 | 17 | 35 |

7. DOCUMENT CATEGORY (e.g., Scientific Report, Contract Report, Scientific Letter.)

Reference Document

8. SPONSORING CENTRE (The name and address of the department project office or laboratory sponsoring the research and development.)

DRDC – Centre for Operational Research and Analysis
Defence Research and Development Canada
Carling Campus, 60 Moodie Drive, Building 7S.2
Ottawa, Ontario K1A 0K2
Canada

| 9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.) | 9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.) |
|---|---|
| 01ef | |

| 10a. DRDC PUBLICATION NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) | 10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.) |
|---|---|
| DRDC-RDDC-2021-D047 | |

11a. FUTURE DISTRIBUTION WITHIN CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

Public release

11b. FUTURE DISTRIBUTION OUTSIDE CANADA (Approval for further dissemination of the document. Security classification must also be considered.)

12. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Use semi-colon as a delimiter.)

coating; antifouling

13. ABSTRACT (When available in the document, the French version of the abstract must be included here.)

A brief survey of the literature was performed several years ago (in 2015). The primary purpose was to gain familiarity with the state-of-the-art in the area of antifouling technologies to enable assessment of the potential utility for the Royal Canadian Navy (RCN). The end goal was to determine whether any of the new technologies were suitable for Naval vessels. The Reference Document (RD) provides a brief overview of commercially available hull coatings as well as various approaches to mitigate biofouling. Cursory conclusions, recommendations, and future considerations are provided; however, it is important to note that this effort was suspended, due to the closure of the Dockyard Laboratory Pacific. Hence, the document has morphed into a brief primer for antifouling technologies, with some useful references, in order to pass along corporate knowledge. It is hoped that this document will assist anyone who wishes to continue and complete this effort.

Il y a plusieurs années (en 2015), on a effectué un bref survol de la littérature. L'objectif principal était de se familiariser avec l'état des connaissances dans le domaine des technologies antisalissures afin de pouvoir évaluer leur utilité éventuelle pour la Marine royale canadienne. L'objectif final consistait à déterminer si certaines des nouvelles technologies convenaient aux navires de la Marine. Le présent document de référence fournit un bref aperçu des revêtements de coque offerts sur le marché et des diverses approches proposées pour diminuer les encrassements biologiques. Des conclusions sommaires, des recommandations et des réflexions pour l'avenir y figurent. Il est toutefois important de noter que ces efforts ont été suspendus en raison de la fermeture du Laboratoire du chantier naval (Pacifique). Dès lors, le document est devenu un petit guide d'introduction aux technologies antisalissures contenant quelques références utiles et servant à transmettre le savoir organisationnel. On espère que celui-ci aidera tous ceux qui souhaitent poursuivre et mener à terme ces efforts.