TP 15547E

Clean Marine Stream 1 – Emerging Technologies

On-the-go Robotic Ship Hull Cleaner for Ocean Going Vessels

Final Report

By: Offshore Designs Ltd.

Disclaimer

Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

Un sommaire français se trouve avant la table des matières.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.	2. Project No.	3. Catalogue No.	4. ISBN
TP 15547E	-	T89-21/2022E-PDF	978-0-660-46121-2

5. Title and Subtitle On-the-go Robotic Ship Hull Cleaner for Ocean Going Vessels	6. Publication Date October, 2021 7. Performing Organization Document No.
8. Author(s) V. Klaptocz, B. Rawlings	9. Transport Canada File No. --
10. Performing Organization Name and Address Offshore Designs Ltd 604 Tercel Court Mill Bay, British Columbia V0R 2P4	11. PWGSC File No. -- 12. PWGSC or Transport Canada Contract No. T8009-190192/004/XLV
13. Sponsoring Agency Name and Address Innovation Centre 330 Sparks Street Ottawa, Ontario K1A 0N5	14. Type of Publication and Period Covered Final 15. Project Officer J. O'Reilly

16. Supplementary Notes (Funding programs, titles of related publications, etc.)

17. Abstract

Offshore Designs Ltd (ODL) is developing an On the Go (OTG) ship hull cleaning robot to service large ocean-going vessels while they transit between ports. The goal is to provide ship operators a cost-effective means of maintaining a clean hull to maximize fuel savings, minimize GHG emissions and prevent spreading invasive species.

At the start of this project ODL had completed preliminary engineering design and analysis to evaluate the feasibility of operating a hull cleaning robot while a vessel is underway.

The funding from Transport Canada (TC) allowed ODL to advance from the preliminary design stage to having a detail design complete and ready for fabrication and field trials. Physical testing of key systems such as the cavitating waterjets used for cleaning and magnetic crawler used for maneuvering was completed as part of the project to inform the detail design. In addition, an environmental impact study completed by environmental consultants provided clear science-based guidelines for performing hull cleanings both in-harbour and underway for local and international vessels.

18. Key Words	19. Distribution Statement
Ship hull cleaning, biofouling, invasive species, cleaning in transit.	Digital Copy

20. Security Classification (of this publication)	21. Security Classification (of this page)	22. Declassification (date)	23. No. of Pages	24. Price
Unclassified	Unclassified	--------------	xvi, 79, apps	--

CI/IC 79-005

Rev. 96

Canada

Transports Canada / Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. No de la publication de Transports Canada TP 15547E	2. Nº de l'étude -	3. No de catalogue T89-21/2022E-PDF	3. No de catalogue du destinataire / ISBN 978-0-660-46121-2
4. Titre et sous-titre Robot nettoyeur de coque de navire nomade pour les navires océaniques			5. Date de la publication octobre 2021 6. No de document de l'organisme exécutant --
7. Auteur(s) V. Klaptocz, B. Rawlings			8. No de dossier - Transports Canada --
9. Nom et adresse de l'organisme executant Offshore Designs Ltd 604 Tercel Court Mill Bay, Colombie-Britannique V0R 2P4			10. No de dossier - TPSGC -- 11. No de contrat - TPSGC ou Transports Canada T8009-190192/004/XLV
12. Nom et adresse de l'organisme parrain Centre d'innovation 330, rue Sparks Ottawa (Ontario) K1A 0N5			13. Genre de publication et période visée Finale 14. Agent de projet J. O'Reilly
15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)			

16. Résumé

Offshore Designs Ltd. (ODL) développe actuellement un robot nettoyeur de coque de navire nomade (« On the Go ») pour entretenir les grands navires océaniques transitant entre les ports. L'objectif est de fournir aux exploitants de navires un moyen rentable de garder la coque de leurs navires propre pour maximiser les économies de carburant, réduire au minimum les émissions de gaz à effet de serre (GES) et empêcher la propagation des espèces envahissantes.

Au moment où ce projet a été lancé, ODL avait terminé l'étape préliminaire de la conception technique et de l'analyse afin d'évaluer s'il est possible d'exploiter un robot nettoyeur de coque sur les navires en déplacement.

Grâce au financement de Transports Canada (TC), ODL a pu passer de l'étape de la conception préliminaire à l'étape de la conception détaillée complète aux fins de la fabrication et de la réalisation d'essais sur le terrain. Afin d'affiner la conception, des essais physiques des systèmes clés, comme les hydrojets à cavitation utilisés pour le nettoyage et la chenille magnétique utilisée pour les manœuvres, ont été réalisés dans le cadre du projet. De plus, une étude d'impact environnemental réalisée par des experts-conseils en environnement a permis d'établir des lignes directrices claires reposant sur des données scientifiques pour le nettoyage des coques de navires locaux et internationaux, tant à quai qu'en mer.

17. Mots clés Nettoyage de la coque, salissures biologiques, espèces envahissantes, nettoyage durant les transits.		18. Diffusion Copie numérique		
19. Classification de sécurité (de cette publication) Non classifiée	20. Classification de sécurité (de cette page) Non classifiée	21. Déclassification (date) —	22. Nombre de pages xvi, 79, ann.	23. Prix --

CI/IC 79-005

Canada

Acknowledgements

The financial contribution from Transport Canada via the Clean Marine program was instrumental in advancing our ship hull cleaning technology as well as building our understanding of the impact that hull cleaning operations can have on the environment - both in harbour and out in open ocean. We would also like to express our gratitude to the team at Transport Canada who administered this project for their feedback and guidance.

We also acknowledge the financial contribution from the NRC-IRAP youth employment program that helped partially support hiring two recent mechanical engineering graduates to assist with this project.

Finally, we acknowledge the contribution made by consultants, contractors, equipment suppliers and interns. Their deep industry knowledge and expertise enabled us to complete the detail design of our first-generation hull cleaning robot.

EXECUTIVE SUMMARY

Offshore Designs Ltd (ODL) is developing a robotic ship hull cleaner that provides ship operators a cost-effective means of pro-actively maintaining a clean hull to maximize fuel savings, minimize Greenhouse Gas (GHG) emissions and prevent spreading invasive species. ODL's hull cleaning robot has the unique ability to clean both in harbour and while the vessel is underway transiting between ports. Cleaning while underway ensures that non-native species removed from the hull cannot establish in harbour and become an invasive species.

Before the start of this project, we completed a preliminary engineering design and analysis to evaluate the feasibility of operating a hull cleaning robot while a vessel is underway at up to 15 kn. This project enabled us to advance our technology, develop a deeper understanding of the environmental impacts of cleaning both in harbour and while underway, and review the existing regulatory framework that governs in-water hull cleaning. The following work was completed as part of this project:

- Experimental test program to quantify the impact of two cavitating waterjet cleaning technologies on four different marine coatings commonly used on Canadian vessels.
- Experimental testing of underwater crawler tracks manufactured by Eddify Technologies that will be used to navigate the robot along the hull.
- Design of custom high-speed tracks by Eddyfi Technologies to meet the specific need of our application - Eddyfi's existing production tracks do not meet our speed requirements.
- Detailed engineering design of the hull cleaning robot informed by experimental test results.
- A brief assessment of cold weather operation.
- Environmental impact study by Bailey Environmental to develop safe operating guidelines for hull cleaning both in harbour and underway.
- Regulatory review of in-water hull cleaning.
- Analysis of CO_2 emission reductions.

The key outcomes of the above work are summarized as follows:

- Experimental testing of cleaning system on marine coatings demonstrated that cavitating waterjets do not cause any visual damage (under microscope) to the coating when operating in accordance with manufacturer's recommendations. Damage to the coating was clearly visible and could be measured using a dry film thickness gauge if the cavitating waterjet nozzles were run outside recommended operating conditions such as too closely to the surface.
- Analysis of water samples collected before and after operating the cleaning system showed an increase in both copper and zinc concentrations in the water post cleaning. The increase was more pronounced for the two anti-fouling type coatings containing copper and zinc versus the two foul-release type coatings that do not.
- The increased metals concentrations measured for certain tests were above British Columbia's water quality guidelines for aquatic life. It was determined that the metals concentrations in the potable tap water used for the experiments exceeded water quality guidelines for aquatic life. In addition, it was found that the brass pump and non-stainless-steel fittings that comprise the cleaning system further contributed to increasing the metals concentration. In general, it was therefore concluded that future tests need to better isolate the contribution of metals specifically from the coating vs. from the source water or equipment used.
- Eddyfi Technologies designed custom tracks capable of advancing at up to 0.4m/s which is the target advance speed of the robot. Several design options were presented to cover a range of torque

and speed requirements. It was determined that Eddyfi's standard crawler tracks will be used for an initial prototype to confirm final design requirements in the field before an investment is made to build the custom tracks.

- The detail design of the robot was completed that meet performance requirements. An overview of the mechanical, electrical, hydraulic, instrumentation/controls/telemetry systems is provided in the report. A 3D CAD model, specification, bill of materials, cost estimate and weight estimate are also provided.
- A high-level assessment of the hull cleaning system for operation in cold temperatures concluded that the minimum rated operating temperature for the hull cleaning system be kept at or above 0°C to ensure the water supplied to the cavitating waterjet nozzles does not freeze.
- The environmental impact study and regulatory review suggest that routine hull cleaning without capture and filtration will be permitted in Canadian and US ports provided that:
    - The cleaning method does not damage the hull coating or exceed allowable levels of pollutants, and,
    - Cleaning is limited to microfouling for non-local vessels (limits on level of fouling of local vessels will not be imposed).
- Bailey Environmental developed guidelines for ODL to ensure that in-water hull cleaning operations do not result in the spread of non-indigenous aquatic species. The guidelines provided in tabular form with the report recommend a safe distance from shore and depth for cleaning heavier fouled international vessels.
- An analysis of CO_2 emissions reduction potential showed that operating a clean vessel vs. a vessel with a 7% increase in resistance due to fouling could save ship operators $230 kCAD/year in fuel costs for a typical 200 m long bulk carrier and $2M CAD for a large 360 m container ship. In addition, operating a clean vessel would avoid annual emissions of 1,333 mT of CO_2 for a bulk carrier and over 10,000 mT of CO_2 for a large container ship. The motivation for operating a clean vessel is therefore very clear for ship owners who are interested in saving fuel costs while doing their part to reduce GHG emissions caused by Marine Transportation – an industry that accounts for approximately 3% of global GHG emissions.

All of work completed over the course of this project enabled the advancement of ODL's robotic ship hull cleaning technology from a preliminary design stage to a detail design that is ready for fabrication and field trials on a vessel.

SOMMAIRE EXÉCUTIF

ODL développe actuellement un robot nettoyeur de coque de navire afin d'offrir aux exploitants de navires un moyen rentable et proactif de garder la coque de leurs navires propre afin de maximiser les économies de carburant, de réduire au minimum les émissions de GES et d'empêcher la propagation des espèces envahissantes. Le robot nettoyeur de coque d'ODL a la capacité unique de nettoyer la coque des navires lorsque ceux-ci sont à quai et en transit entre les ports. Cette seconde option permet de s'assurer que les espèces non indigènes retirées de la coque ne se propagent pas dans les ports et ne deviennent pas une espèce envahissante.

Au moment où ce projet a été lancé, ODL avait terminé l'étape préliminaire de la conception technique et de l'analyse afin d'évaluer la possibilité d'exploiter un robot nettoyeur de coque sur un navire exploité à une vitesse maximale de 15 nœuds. Ce projet nous a permis de faire progresser notre technologie, de mieux comprendre les répercussions du nettoyage sur l'environnement à la fois à quai et en mer, et d'examiner le cadre de réglementation régissant le nettoyage des coques dans l'eau. Les travaux suivants ont été réalisés dans le cadre de ce projet :

- un programme d'essais expérimentaux visant à quantifier l'incidence de deux technologies de nettoyage à l'hydrojet à cavitation sur quatre revêtements marins différents couramment utilisés sur les navires canadiens;
- des essais expérimentaux de chenilles sous-marines fabriquées par Eddify Technologies qui seront utilisées pour guider le robot le long de la coque;
- la conception de pistes à grande vitesse personnalisées par Eddyfi Technologies pour répondre à nos besoins précis; les pistes de production existantes d'Eddyfi ne répondent pas à nos exigences de vitesse;
- la conception technique détaillée du robot nettoyeur de coque basée sur les résultats des essais expérimentaux;
- une brève évaluation du fonctionnement par temps froid;
- une étude d'impact environnemental par Bailey Environmental pour établir des lignes directrices sécuritaires pour effectuer le nettoyage des coques à la fois à quai et en mer;
- un examen réglementaire du nettoyage des coques dans l'eau;
- une analyse de la réduction des émissions de CO_2.

Les principaux résultats des travaux susmentionnés sont récapitulés ci-dessous :

- Les essais expérimentaux du système de nettoyage sur les revêtements marins ont démontré que les hydrojets à cavitation ne causent aucun dommage visuel (au microscope) au revêtement lorsqu'ils sont utilisés conformément aux recommandations du fabricant. Des dommages étaient visibles sur le revêtement et ont pu être mesurés à l'aide d'une jauge d'épaisseur de feuil sec lorsque les buses des hydrojets à cavitation étaient utilisées de manière non conforme aux conditions d'exploitation recommandées, trop près de la surface par exemple.
- L'analyse des échantillons d'eau prélevés avant et après l'utilisation du système de nettoyage a révélé une augmentation des concentrations de cuivre et de zinc dans l'eau après le nettoyage. Cette augmentation était plus prononcée pour les deux peintures de type antisalissure contenant du cuivre et du zinc par rapport aux deux peintures antiadhésives qui n'en contiennent pas.
- Les concentrations accrues de métaux mesurées dans le cadre de certains essais étaient supérieures aux recommandations de la Colombie-Britannique sur la qualité de l'eau pour la protection de la vie aquatique. Il a été déterminé que les concentrations de métaux dans l'eau potable du robinet utilisée pour les expériences étaient supérieures aux recommandations sur la qualité de l'eau pour la protection de la vie aquatique. De plus, il a été conclu que la pompe en laiton et les raccords qui composent le système de nettoyage, qui ne sont pas en acier inoxydable, contribuaient davantage à augmenter la concentration de métaux. En général, il a été conclu que les futurs essais doivent mieux

distinguer la contamination par les métaux provenant précisément du revêtement par rapport à l'eau de source ou à l'équipement utilisé.

- Eddyfi Technologies a conçu des pistes personnalisées capables d'assurer une progression jusqu'à 0,4 m/s, ce qui est la vitesse de progression cible du robot. Plusieurs options de conception ont été présentées pour couvrir un éventail d'exigences relatives au couple et à la vitesse. Il a été déterminé que les chenilles standard d'Eddyfi seront utilisées pour un prototype initial afin de confirmer les exigences de conception définitives sur le terrain avant qu'un investissement ne soit fait pour construire les chenilles personnalisées.
- La conception détaillée du robot a été achevée pour répondre aux exigences de rendement. Un aperçu des systèmes mécaniques, électriques, hydrauliques, d'instrumentation/de contrôle/de télémétrie est fourni dans le rapport. Un modèle CAO 3D, des caractéristiques techniques, une nomenclature des matériaux, une estimation des coûts et une estimation du poids sont également fournis.
- Une évaluation de haut niveau de l'utilisation du système de nettoyage des coques par temps froid a permis de conclure que la température de fonctionnement nominale minimale du système de nettoyage des coques doit être maintenue à 0 °C ou plus afin que l'eau projetée par les buses des hydrojets à cavitation ne gèle pas.
- L'étude d'impact environnemental et l'examen réglementaire suggèrent que le nettoyage de routine des coques sans captage ni filtration sera autorisé dans les ports canadiens et américains, à condition que :
  - la méthode de nettoyage n'endommage pas le revêtement des coques et soit conforme au niveau de polluants admissibles;
  - le nettoyage se limite aux microsalissures pour les navires non locaux (aucune limite concernant le niveau d'encrassement des navires locaux ne sera imposée).
- Bailey Environmental a élaboré des lignes directrices pour ODL afin de garantir que les opérations de nettoyage des coques dans l'eau n'entraînent pas la propagation d'espèces aquatiques non indigènes. Selon les lignes directrices fournies sous forme de tableau avec le rapport, il est recommandé d'établir une distance de sécurité par rapport au rivage et une certaine profondeur pour le nettoyage des navires internationaux les plus encrassés.
- Une analyse du potentiel de réduction des émissions de CO_2 a révélé que l'exploitation d'un navire propre par rapport à un navire présentant une augmentation de la résistance de 7 % due à l'encrassement pouvait permettre aux exploitants de réduire leurs coûts en carburant (230 000 dollars canadiens par année pour les vraquiers typiques de 200 m de long et deux millions de dollars canadiens par année pour les gros porte-conteneurs de 360 m). De plus, l'exploitation d'un navire propre permettrait d'éviter des émissions annuelles de 1 333 Tm de CO_2 pour un vraquier et de plus de 10 000 Tm de CO_2 pour un gros porte-conteneurs. Les raisons d'exploiter un navire propre sont donc très claires pour les armateurs qui souhaitent économiser des coûts de carburant tout en faisant leur part pour réduire les émissions de GES causées par le transport maritime – un secteur qui représente environ 3 % des émissions mondiales de GES.

Tous les travaux réalisés dans le cadre de ce projet ont permis de faire progresser la technologie robotique de nettoyage de coque de navire d'ODL, et de passer de l'étape de conception préliminaire à l'étape de conception détaillée en vue de la fabrication et de la réalisation d'essais réels sur un navire.

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1 INTRODUCTION

Offshore Designs Ltd (ODL) is developing an On the Go (OTG) ship hull cleaning robot to service large ocean-going vessels while they transit between ports. The goal is to provide ship operators a cost-effective means of maintaining a clean hull to maximize fuel savings, minimize Greenhouse Gas (GHG) emissions and avoid spreading invasive species from port to port. The motivation for developing the capability to clean in transit is to avoid the need for using a capture and filtration system to contain invasive species. Cleaning underway in deep water ensures that non-native organisms removed during the cleaning process cannot establish in coastal waters.

Before the start of this project, we (ODL) completed the preliminary engineering design of the OTG hull cleaning robot. This preliminary design work confirmed via calculations and simulations that it was possible to maneuver the hull cleaning robot along the sides and bottom of the hull while the vessel was underway at up to 15 knots (highest speed simulated). An overview of the technology as envisaged at the onset of this project is shown in Figure 1-1.

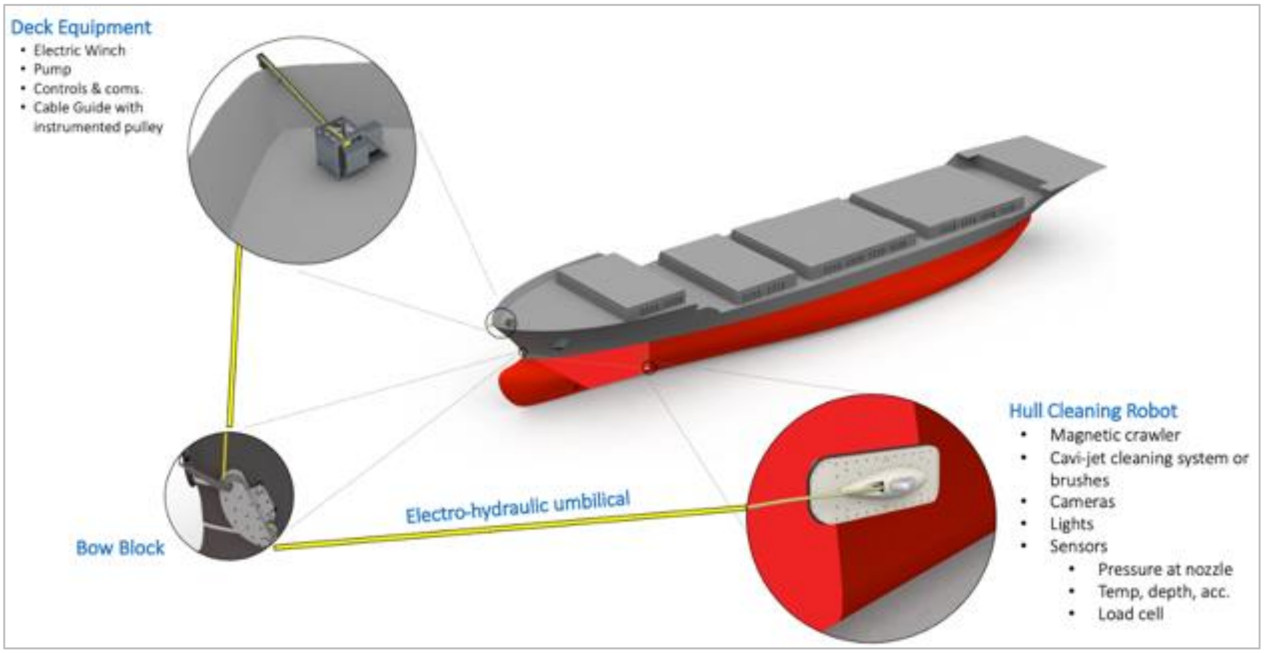


Figure 1-1: Overview of ODL On-The-Go hull cleaning system (preliminary design stage)

The funding from Transport Canada (TC) allowed our company to advance from the preliminary design stage to having a detailed design complete and ready for fabrication and field trials. The project also allowed us to gain a deeper understanding of the potential environmental impacts and current regulatory framework. The following work was completed over the course of this project:

- **Experimental Testing of cavitating waterjet cleaning system:** Testing two cavitating waterjet technologies on four different marine coatings to ensure coating is not damaged during cleaning process (see Section 2.0).
- **Design of hull cleaning robot prototype:** Detailed engineering design of the Gen 1 hull cleaning robot including experimental testing of components to inform custom design of high-speed tracks by Eddyfi Technologies (see Section 3.0).
- **Environmental assessment of cleaning while underway and in harbour**: 3rd party desktop study by Bailey Environmental Consultants to develop best practice hull cleaning guidelines based on origin and level of growth on hull (see Section 4.0).

- **Regulatory review**: Review of existing national and international regulations and guidelines pertaining ship hull cleaning (see Section 5.0).
- **Analysis of CO2 emissions reduction potential** Desktop study to quantify extra fuel and CO_2 emissions created by operating with a fouled hull (see Section 6.0).

2 EXPERIMENTAL TESTING OF HULL CLEANING SYSTEM

In general, hull cleaning is either done using scrapers, brushes, waterjets or cavitating waterjets. Based on our research to date, cavitating waterjets are deemed to be highly effective at cleaning while causing less damage to the hull coating compared to waterjets or abrasive brushes [1]. For this reason, only cavitating waterjet systems are being tested over the course of this project. It is possible the other technologies are also effective but comparing performance of all available technologies is outside the scope of this project.

2.1 DESIGN OF EXPERIMENT

The goal of the test program was to gain operational experience using cavitating waterjets, and provide meaningful results for Transport Canada, other regulatory bodies, and internal use. It was also important to ensure that based on the results of the experiments we could demonstrate to the coatings suppliers that our cleaning system can be safely used without causing damage to the hull coating.

We worked closely with two major coatings suppliers: Hempel and International Paints. The two companies helped us select the specific coatings to test based on market demand and availability in Canada. They also provided instructions on how to prepare the samples for testing. We also discussed our test procedure with both companies to review our approach and benefit from lessons learned from their past in-house experiments.

The following sections provide details on the test procedure and experimental plan, selection of equipment, and selection of coatings. The impact of the cavijets on the painted panels was quantified using the following techniques:

- Paint thickness gauge to measure change in paint thickness pre and post cleaning.
- Visual observation by:
  - Eye
  - Microscope
- Water samples pre and post cleaning analysed for:
  - Metal particles
  - Dissolved metal particles
  - Total Suspended Solids

Sections 2.1.1 through 2.1.6 explain the design of the experiment, coatings selection, sample preparation, and equipment specification.

2.1.1 System Diagram

A system diagram of the experimental setup is shown in Figure 2-1. The system was designed so that it was possible to vary both the pressure and flow rate providing us with the flexibility to test different nozzles.

As shown in Figure 2-1:

- Water is supplied to the pressure washer unit comprising a gasoline motor running a high-pressure pump.
- A pressure gauge directly downstream of the pump is used to measure the available pressure prior to any system losses.
- The flow downstream of the pressure gauge can be split between the main circuit (top line in diagram) and bypass circuit (bottom line in diagram).
- The main flow circuit includes a flow meter to measure flow rate going to the nozzles
- The bypass circuit allows for diversion of flow to reduced flow rate as required.
- A second pressure gauge is installed directly upstream of the nozzle so that all hydraulic losses are accounted for.

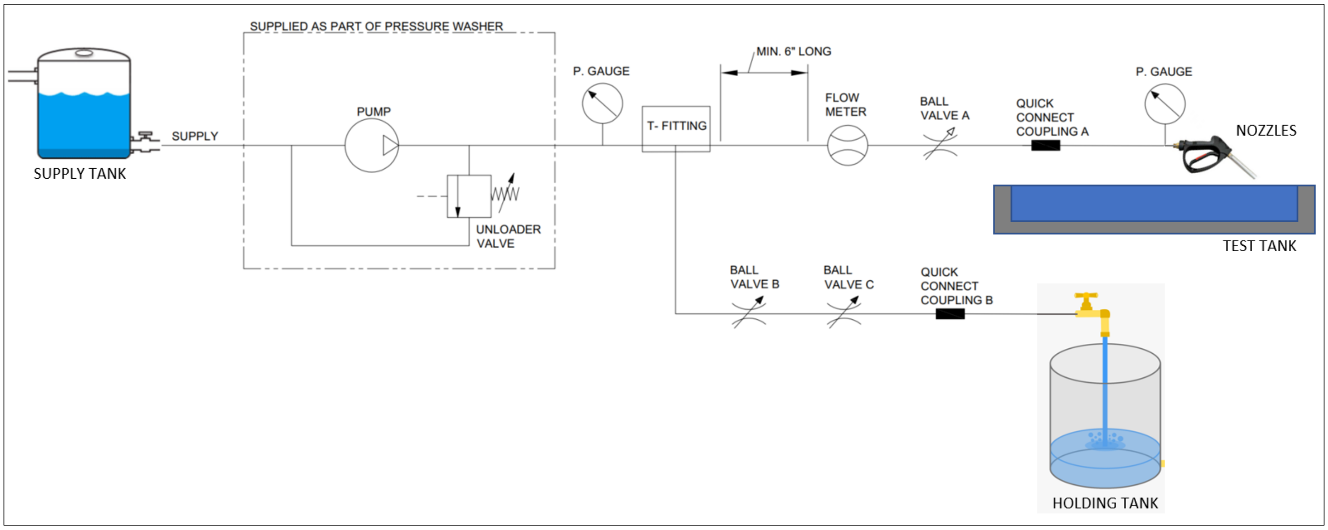


Figure 2-1: Experimental Setup

A custom aluminum tank was designed to carry out the tests in a controlled environment. The internal dimensions of the tank are 72 1/4" long x 24 1/8" wide x 24" deep as shown in Figure 2-2. The tank walls are made from 1/8" thick 5000 series aluminum suitable for marine use. Stiffeners are welded to the sides of the tank for structural support, to serve as mounting points for components, and to facilitate handling. A false floor was built into the tank to securely mount the pained steel panels.

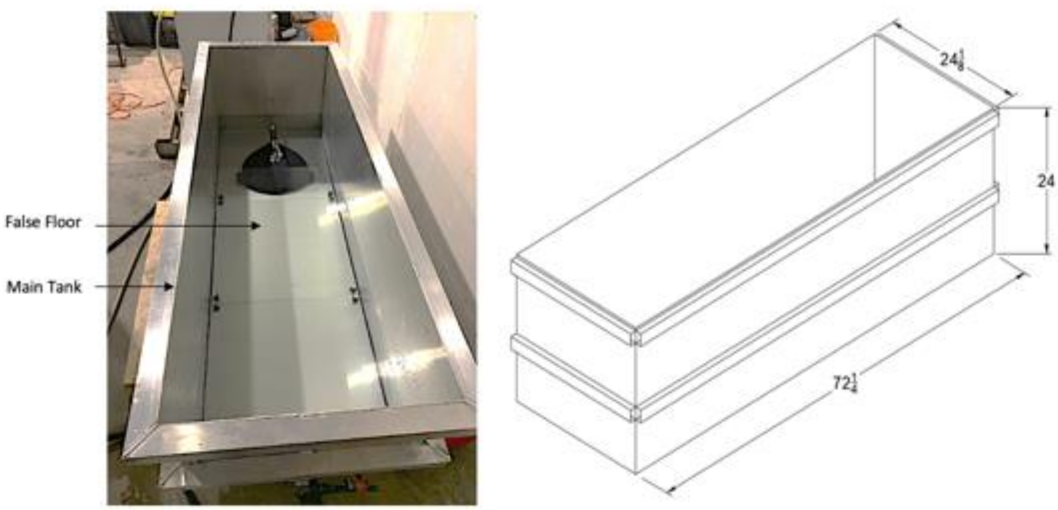


Figure 2-2: Main tank with false floor for mounting painted panels

The tank was made three times the length of the coated panel (see Figure 2-3) to:

1. Start the equipment and tune the nozzle pressure and flow rate in a "staging area"
2. Run the nozzles over the coated panel at the required speed of advance
3. Come to a stop in the "landing area" where the flow to the cavijets is turned off.

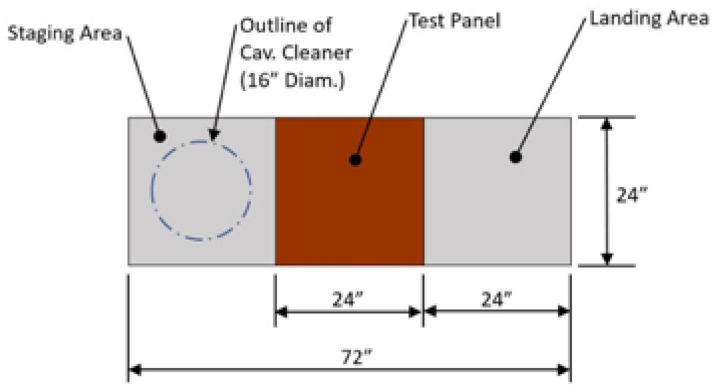


Figure 2-3: Diagram of test bed

Finally, mounts were made to secure the single nozzles at a set distance from the panel (0.875" and 1.25") over a range of angles (90 deg – perpendicular to plate, 45 deg and 22 deg). The 22-degree angle was selected for testing because this is the angle fixed for the rotating cavitating waterjet nozzles purchased. A total of 12 tests can be run on a single panel.

The components used for mounting the single nozzles is shown in Figure 2-4.

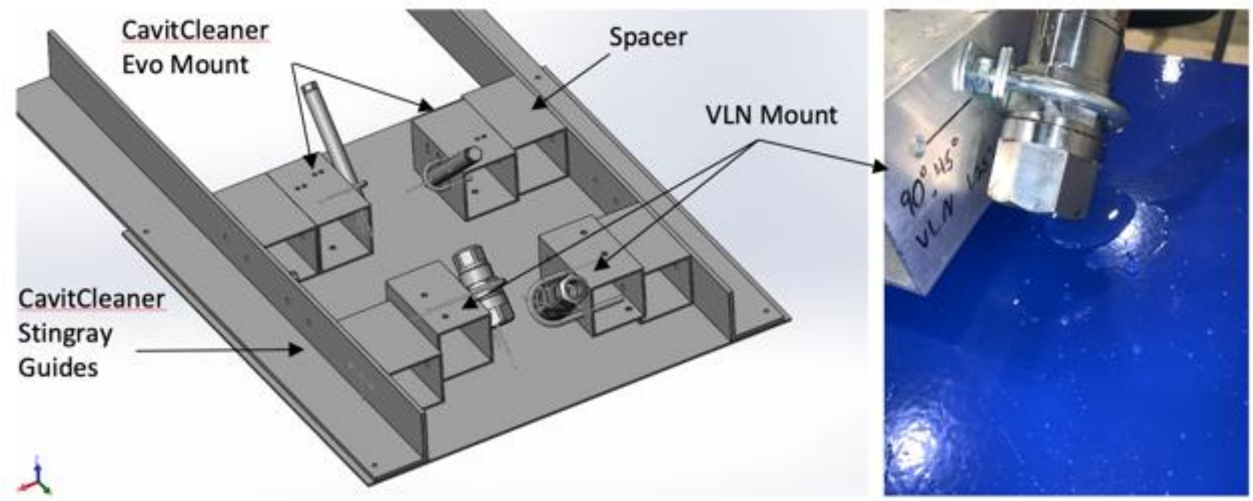


Figure 2-4: Mounting blocks for single nozzle tests at varying offsets and angles (left). VLN nozzle mounted at 45 deg (right)

2.1.2 Selection of Cavitating Nozzles

There are only a limited number of companies supplying cavitating waterjet systems suitable for hull cleaning. The two most notable commercial suppliers are:

1. Cavidyne/Caviblaster based out of the US (*www.caviblaster.com*)
2. CavitCleaner based out of Montenegro (*www.CavitCleaner.com*)

There are also a handful of companies that specialize in the design of custom cavitating nozzles for industrial operations including VLN Advanced Technologies (www.vln-tech.com) based out of Ottawa, and Dynaflow (www.dynaflow-inc.com) based out of the US.

For this project, we decided to test CavitCleaner and VLN nozzles for the following reasons:

- The CavitCleaner system is very similar to that offered by Cavidyne therefore testing two nearly identical systems would likely yield very similar results. Unlike Cavidyne, CavitCleaner doesn't insist on selling a complete package inclusive of the pressure washing unit (motor-pump). It was important for us to size our own pressure washing unit so that we would have the flexibility to use it with other nozzles, including the VLN nozzles.
- We decided to work with VLN since they could develop a custom solution if required. VLN claims their nozzles also work above water which is a desirable capability for cleaning the hull above the waterline. It is currently not clear if other commercial systems work above water. VLN is also a Canadian company making it much easier to jointly develop technology should we choose to integrate their nozzles based on the outcomes of this project.

Table 2-1 summarizes the cleaning equipment selected for this project.

Table 2-1: Cavitating Waterjet Equipment Selected

Supplier & Model	Operating Conditions	Image
CavitCleaner Stingray dual rotating nozzle	Pressure: 1740 – 2320 psi Flow Rate: 20 L/min to 30 L/min (5.3 – 7.9 gpm)	 
CavitCleaner Evo2 Nozzle	Pressure: 1740 – 2320 psi Flow Rate: 10 L/min – 15 L/min (2.6 gpm – 4 gpm)	
VLN Reverse Flow Cavitating (RFC) Nozzle	Pressure: 2800 psi Flow Rate: 12.5 lpm (3.3 gpm)	

2.1.3 Coating selection & preparation of sample panels

We reached out to four major hull coatings companies (Hempel, International Paints, Jotun, Sherman Williams) as well as ship operators to understand what type and brands of paint were most widely used. We also consulted with TC to determine what coatings were predominantly used on Canadian Coast Guard and Navy Ships.

The primary feedback from the coating companies was to suggest a "hard" silicone coating as these are among the most advanced coating types, and to also test 2 or 3 of the more commonly used self-polishing coatings. International Paints and Hempel were most responsive and keen to work with us on these tests.

International Paints recommended the following coatings for testing:

- Intersleek 1100SR: Highest performance silicone-based coating
- Interspeed 640: Used on a large range of vessel types and operating profiles

Hempel recommended the following coatings for testing:

- Hempaguard X7: Highest performance silicone-based coating with biocide
- Globic 9000 (high end self-polish), Dynamic 9000 (upper mid-tier self-polish), or Atlantic + (low to mid-tier self-polish): Several common self-polishing coatings

Both companies offered to provide coated panels for testing, so we corresponded extensively with them regarding sample preparation and shipping options. In the end, multiple challenges due to COVID-19 (access by personnel to lab/shop space) delayed panel preparation and shipping to Canada risking our ability to meet project timelines. In addition, we learned that there may be additional complications with receiving panels coated with Hempaguard X7 because the biocide it contains is not approved for use in Canada.

As a result, we proceeded to prepare all panels locally and selected the following Hempel coatings approved for use in Canada:

- Hempasil X3+: Non-biocidal hydrogel silicone fouling release coating;
- Olympic 7660: Gradually depleting coating based on gum rosin.

Table 2-2 summarizes the coating selected for these experiments. All four coatings appear on commercial and government vessels operating in Canadian waters.

Table 2-2: Final coatings selection

Supplier	**Coating Selected**
International Paints	Intersleek 1100SR: *Highest performance silicone-based coating*
	Interspeed 640: *Used on a large range of vessel types and operating profiles*
Hempel	Hempasil X3+: *Non-biocidal hydrogel silicone fouling release coating*
	Olympic 7660: *Gradually depleting coating based on gum rosin*

Seven panels were prepared for each coating (painted on both sides). Each panel is 23.75” x 23.75” and contains a mounting hole in each corner that gets fastened to a false floor that is lowered into the test tank for testing. The panels were sand blasted and coated professionally by Park Derochie according to International Paints’ and Hempel’s specifications (see Appendix A for Product Data Sheets for each paint that include specific application instructions).

2.1.4 Pressure washer unit

We sourced the pressure washer unit from Mancorp Industrial Sales Ltd. The pressure washer unit was custom designed and assembled to meet our flow rate and pressure requirements as our needs exceed off the shelf pressure washer units. Significant back and forth was required to ensure the correct combination of pump and motor were selected. The specification for the pressure washer unit is as follows:

- 24 hp Honda GX 690 engine
- High-capacity tri-plex ceramic plunger pump tuned to 8 gallons per minute (gpm) at 3000 psi but configurable to 12 gpm at 2000 psi
- Variable pressure control
- Heavy duty unloader system
- Heavy duty Land tandem axle wheel kit with pneumatic tires & cage frame

2.1.5 Instrumentation

The instrumentation and measurement equipment purchased is summarized in Table 2-3.

Table 2-3: Instrumentation

Instrument	Description	Image
Pressure gauges: used to measure pressure in the plumbing system at the identified locations.	Liquid oil pressure gauges: ▪ 0-5000 PSI range at pump ▪ 0-3000 PSI range at nozzle	
Flow Meter: used to measure flow rate to the cleaning instrument.	Turbine meter with digital display for high pressure applications (https://www.itm.com/pdfs/cache/www.itm.com/g2h07n09gma/datasheet/g2h07n09gma-datasheet.pdf)	
Microscope: used to take pictures of the hull coatings after cleaning.	USB digital microscope with 10x-50x magnification and cradle stand. (https://www.aventools.com/Mighty-Scope-5M-USB-Digital-Microscope-with-Cradle-Stand)	
Dry film thickness gauge: used to measure coating thickness at locations having undergone cleaning.	Electronic coating thickness gauge that uses magnetic and eddy current principles to measure coating thickness for both ferrous and non-ferrous materials (https://www.defelsko.com/positector-6000?gclid=CjwKCAjwnK36BRBVEiwAsMT8WPLNwngPYcGfzrYoiQQyxPCYQpZQ9KeWNaoEjCwkr4XwIjWW--HafBoCD-4QAvD_BwE)	

2.1.6 Final Experimental Setup

The fully assembled experimental setup is shown in Figure 2-5. The cavijet nozzles are shown in Figure 2-6. Figure 2-7 shows the false floor to which the painted panels were secured. Figure 2-8 shows the painted panels.

Several days were spent assembling the overall system and getting it up and running. This work included:

- Cleaning the main tank, secondary tank and all other components and equipment that will come in contact with the water being sampled as part of the experiment.
- Assembling and installing the false floor inside the tank. The painted steel panels will be secured to this false floor.
- Assembling all fittings, pipes, connectors, hoses, valves, water bypass, flow meter and pressure gauge required to control and measure the flow rate and pressure between the pump and cleaning nozzles.
- Setting up the water supply for the pressure washer. This comprises a holding tank and a submersible pump connected by a hose to the intake of the pressure washer. The utility pump was sized to provide the required flowrate to the pressure washer as a standard faucet is insufficient (~3.4 gpm for faucet vs. 7.9 gpm required).
- Manually verifying flowrate measured by flowmeter
  - Tests were completed at about 4.8 gpm and 6.7 gpm, and in both cases the flow meter measured within about 0.1 gpm of that obtained by recording the time required to fill a 15 litre container.
- Verifying achieved flowrate and pressure for the CavitCleaner nozzles, VLN nozzle and the standard waterjet wand supplied with the pressure washer
  - For the CavitCleaner Stingray, at 2300 psi a flow rate of about 5.3 gpm was recorded
  - For the CavitlCleaner Evo2 nozzle, at 2000 psi a flow rate of about 2.45 gpm was observed
  - For the VLN nozzle, at 2800 psi a flow rate of about 2.9 gpm was observed

- Correspondence with suppliers of the cleaning equipment to tune the pressure and flowrates for best results

Figure 2-5: Experimental Setup

Figure 2-6: Cavijet nozzles - Left to right: VLN Nozzles, CavitCleaner Gun, and CavitCleaner Stingray

Figure 2-7: CavitCleaner Stingray placed inside test tank showing false floor

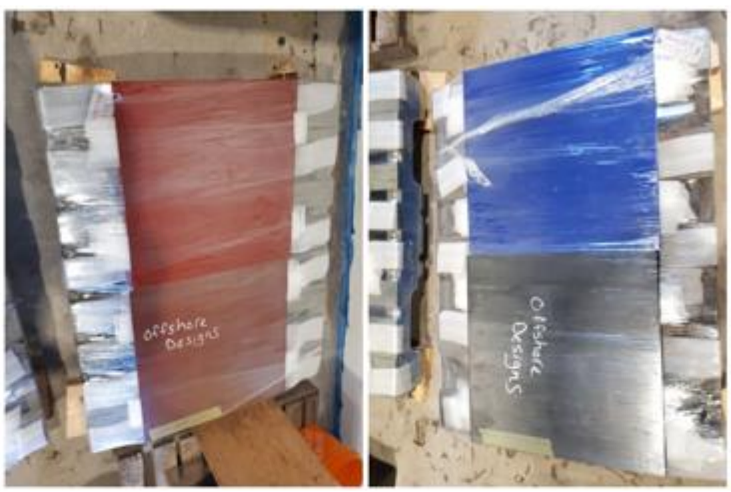


Figure 2-8: Painted panels

2.2 TEST PLAN

The goal of the tests is to assess the impact of the cavitating waterjet nozzles selected on the four different paints over a range of operating conditions.

2.2.1 Test Matrix

A condensed form of the originally planned test matrix is shown in Table 2-4. The expanded test matrix planned for up to 44 tests per paint type for a total of up to 176 tests, with the intent of reducing this matrix where possible based on the results that were observed along the way. For example, when we executed the tests, if no paint damage was observed for the lower nozzle offset distance, then we limited the number of tests with the same parameters but at a higher offset distance. Appendix B provides the expanded matrix and completed test runs for each coating.

Table 2-4: Test matrix summary (Originally Planned)

Nozzle Type		Specified condition						Analysis type[1]				
		Test Type	**Nozzle Offset Distance [in]**	**Angle [deg]**	**Flow Rate [gal/min]**	**Pressure [psi]**	**Run Time/ Speed**	**VIS**	**DFT**	**TSS**	**TM**	**TDM**
	**VLN** *(single nozzle)*	Stationary	0.875” 1.25”	22 45 90	3.3	2,800	5s 20s 60s	X	X	-	-	-
	**Evo** *(single nozzle)*	Stationary	0.875” 1.25”	22 45 90	3.3	2,000	5s 20s 60s	X	X	-	-	-
	**Stingray** *(rotating nozzle)*	Stationary	0.875” 1.25”	22 (fixed)	6.6	2,000	5s 20s 60s	X	X	X	X[1]	X[1]
		Advancing	0.875” 1.25”	22 (fixed)	6.6	2,000	0.1 m/s 0.3 m/s	X	X	X	X[2]	X[2]

Note 1: Abbreviations used to identify tests are provided in Section 2.2.2.
Note 2: Limited laboratory tests on silicone coatings since no metal should be present.

The specified test conditions in Table 2-4 are described as follows:

- Single nozzles (VLN and Evo) were rigidly mounted at the prescribed angle and offset distance
  - Measurements taken at 5 s, 20 s and 60 s of run time
  - 2 offset distances (0.875” and 1.25”) measured from the centreline of the nozzle jet outlet
  - 3 angles (22 deg, 45 deg, 90 deg). The 22 deg angle corresponds to the angle of the Stingray rotating nozzles
- Rotating Stingray nozzles were tested for:
  - 2 offset distances (0.875” and 1.25”)
  - 1 angle (22 deg) as this is fixed
  - Run stationary/in place with measurements taken at 5 s, 20 s and 60 s of run time
  - Run over the panel at a speed of 0.1 m/s and 0.3 m/s
- For all nozzles, the flow rate and pressure were set at the high end of the rated operating condition.

2.2.2 Analysis Type

The analysis types listed in Table 2-4 are described as follows:

- **VIS:** visual observation + digital picture using microscope to inspect for damage
- **DFT:** dry film thickness measurement pre and post running nozzles to measure change in thickness.
- **TSS:** Total Suspended Solids laboratory test to measure for presence of paint particles in water sample post testing.
- **TM:** Total Metals laboratory test to measure for metals content pre and post testing.
- **TDM:** Total Dissolved Metals laboratory test to measure for dissolved metals content pre and post testing.

2.2.2.1 *Water Sampling Methods*

Water samples were taken for select tests as indicated by an "X" in Table 2-4 to test for presence of metals (TM & TDM) and suspended solids (TSS).

The following steps were taken for tests involving the collection of water samples:

1. The water in the main test tank remaining from previous tests was pumped into holding tanks to be disposed of by a liquid waste disposal company once the tests were completed.
2. The main tank and False Floor were thoroughly rinsed out, then wiped clean with paper towels.
3. The main tank was filled with fresh water to approximately 10" water level.
4. The water level was recorded at four corners of the tank in order to calculate starting tank volume
5. The water samples were taken according to procedures provided by AGAT Laboratories and using the supplies provided as follows:
    i. Total Suspended Solids – required filling the container provided by submerging into the test tank.
    ii. Total Metals – required filling the container provided with a syringe, and then adding the preservative that was supplied.
    iii. Total Dissolved Metals – required filling the container provided with a filtered syringe, and then adding the preservative that was supplied.
6. The test was run
7. The water is mixed by hand in the tank to ensure even distribution (water is naturally mixed in tank during tests by nozzle jets)
8. The water level was recorded at four corners of the tank to calculate the new volume at the end of the test.
9. Water samples were taken according to procedures provided by AGAT Laboratories and using the supplies they provided.
10. Samples were stored in a refrigerator, and then subsequently transported to AGAT Laboratories for analysis in a cooler alongside ice packs.

2.2.2.2 *Lab Analysis for metals (TM & TDM)*

For reference, the following metals can be tested for under the TM and TDM tests:

- Al, Sb, As, Ba, Be, B, Cd, Ca, Cr, Co, Cu, Fe, Pb, Li, Mg, Mn, Hg, Mo, Ni, Se, Ag, Na, Sr, Tl, Sn, Ti, W, U, V, Zn

We used AGAT Laboratories for sample analysis. The cost to test for all the metals is $45/sample + $5/sample disposal fee.

It is also possible to test for only specific metals of interests at a cost of $12 for first metal and $6 for additional metal + $5 disposal fee. A test for 2 metals therefore costs $18/sample + $5/disposal fee.

Given the large number of tests and our limited budget for testing, we only focused on metals listed on the Materials Safety Data Sheet (MSDS) provided for each paint type as summarized in Table 2-5.

Samples for metals (TM & TDM) and suspended solids (TSS) were only taken for the Stingray with rotating nozzles as this represents the method that will be used to clean the vessel. It would be too laborious and expensive to take samples for the single nozzle tests as we would have to empty the tank every test, carefully clean and refill. AGAT Laboratories used an inductively coupled plasma mass spectrometry (ICP-MS) instrument to analyze the TM and TDM samples according to Standard Method (SM) 3125B. AGAT Laboratories used a gravimetric instrument to analyze the TSS samples according to SM 2540 C, D, and E.

Table 2-5: Tests for metals

Coating	Metals listed on MSDS	TM and TDM test
International Paints **Intersleek 1100SR** (silicone paint)	No metals listed	Copper, Zinc *(limited tests to confirm no presence)*
International Paints: **Interspeed 640** (ablative paint)	Copper oxide, zinc oxide, Titanium dioxide	Copper, Zinc
Hempel: **Hempasil X3+** (silicone paint)	No metals listed	Copper, Zinc *(limited tests to confirm no presence)*
Hempel: **Olympic 7660:** (ablative paint)	Copper oxide, zinc oxide, titanium dioxide, cupric oxide	Copper, Zinc

2.2.2.3 Dry Film Thickness Measurements

For the rotating nozzle tests, DFT measurements were taken at 1 cm intervals moving inwards from the angles used to centre the CavitCleaner Stingray on the test panel, such that the expected location of the jet impact was at the 7 cm mark. The ruler shown in Figure 2-10 exemplifies the position of the ruler when identifying the DFT measurement locations. For the single nozzle tests, DFT measurements were taken in the area of the anticipated jet impact location on the panel, and where impacts were observed.

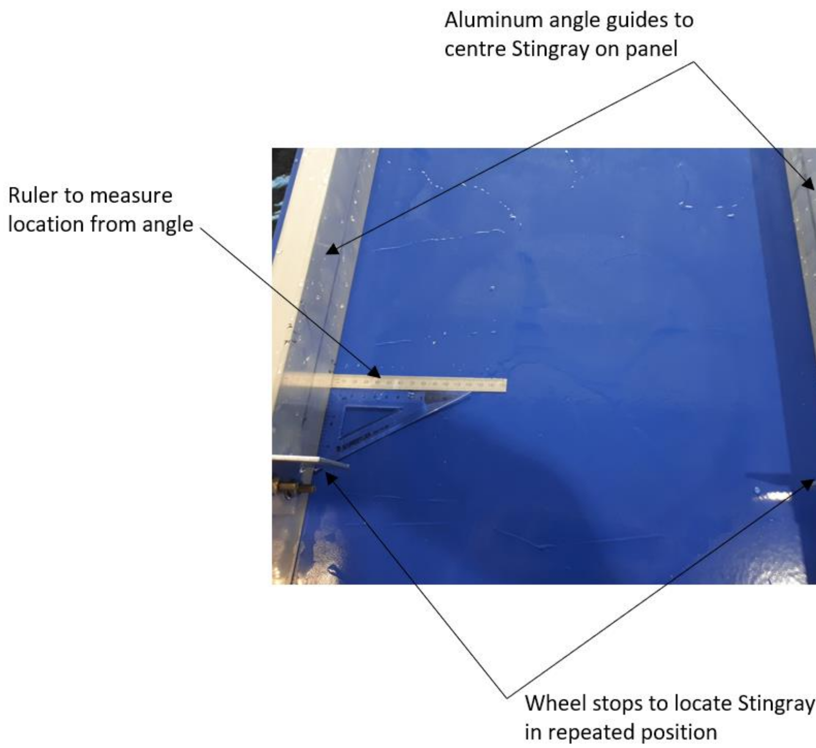


Figure 2-9: Example of ruler location on test panel.

2.2.3 Waste Water Disposal

All the water used over the course of testing was collected in large holding tanks and disposed of by McRae's Environmental through Metro Vancouver's trucked liquid waste program.

2.3 Results

Sections 2.3.1 and 2.3.2 provide the experimental results from the stationary and advancing tests using the CavitCleaner Stingray respectively. Sections 2.3.3 and 2.3.4 provide the experimental results from tests using the CavitCleaner Evo2 and the VLN RFC nozzles. Only numerical results are provided within this section – Section 2.4 provides discussion and analysis of the results.

Table 2-6 summarizes the operating conditions achieved during the tests. We ran at the highest-rated operating pressures of the system to maximize the achieved flow rate. Appendix B provides the matrix of completed test runs.

Total suspended solids values are not reported for the stingray tests as all values except for two were below the detectable limit of 2mg/L, as discussed in Section 2.4.3.

Values for total metals concentration are provided in the tables summarizing the test results using the rotating nozzles in Sections 2.3.1 and 2.3.2. The concentration of dissolved copper was typically 65% - 85% of the total reported copper concentration, while the concentration of dissolved zinc was typically 65%-87% of the total reported zinc concentration.

Table 2-6: Operated Test Conditions

Nozzle Type		**Achieved condition**						**Analysis type**				
		Test Type	**Nozzle Offset Distance [in]**	**Angle [deg]**	**Flow Rate [gal/min]**	**Pressure [psi]**	**Run Time/ Speed**	**VIS**	**DFT**	**TSS**	**TM**	**TDM**
	**VLN** *(single nozzle)*	Stationary	0.875” 1.25”	22 45 90	~3.3-3.45	2,800	**2-3 s** **10 s** **30 s**	X	X	-	-	-
	**Evo** *(single nozzle)*	Stationary	0.875” 1.25”	22 45 90	~2.7-2.8	2,300	**2-3 s** **10 s** **30 s**	X	X	-	-	-
	**Stingray** *(rotating nozzle)*	Stationary	0.875” 1.25”	22 (fixed)	~6.8 - 7.2[1] ~7.1 - 7.4[2]	2,300	5 s 20 s 60 s	X	X	X	X[3]	X[3]
		Advancing	0.875” 1.25”	22 (fixed)	~6.7 - 7.2[1] ~7.1 - 7.4[2]	2,300	0.1 m/s 0.3 m/s	X	X	X	X[3]	X[3]

Note 1: Observed range for CavitCleaner Stingray tests on Hempasil X3 and Intersleek 1100SR coatings
Note 2: Observed range for CavitCleaner Stingray tests on Interspeed 640 and Olympic 7660 (after revising fittings)
Note 3: Limited tests on silicone coatings since no metal should be present

2.3.1 Stationary CavitCleaner Stingray Rotating Nozzle Tests

Stationary tests were performed with the CavitCleaner Stingray. For each coating, analysis results were recorded after cumulative run times of 5, 20, and 60 seconds on the test panel. Table 2-7 details observations from the CavitCleaner Stingray tests on the Hempasil X3 coating.

Table 2-7: CavitCleaner Stingray Tests (Stationary) -- Hempasil X3 Results

Offset [in.]	**Time [s]**	**Total Cu[1] [µg/L]**	**Total Zn[2] [µg/L]**	**DFT[3] [mils]**	**Primary Observations**
0.875”	0	35.2	47	12.6; 13.2	- Only slight sheen visible at the cleaning radius observable through 20 s; observable damage at the cleaning radius after 60 s (see Figure 2-10 and Figure 2-11). - DFT measurements varied at the measurement location. They were generally 12.4 – 12.6 mils through 20 s then, there was a minor decrease to 11.9 mils after 60 s at the measurement location on the ring where very little damage was visible.
	5	-		12.4; 12.6	
	20	-		12.5	
	60	36	71	11.9	
1.25”	0	-	-	n/a [4]	- Slight sheen hardly visible at cleaning radius through 20 s and 60 s (Figure 2-12). - Minor change in DFT thickness observed from 5 s to 60 s cumulative run time.
	5	-	-	8.2	
	20	-	-	7.9	
	60	-	-	7.6	

Notes

[1] Total Cu only recorded at 0s and 60s at 0.875” offset since neither is contained in the coating

[2] Large change in Zn values for 0.875” offset is discussed in Section 2.4.2

[3] Dry Film Thickness (DFT) shown at a repeated location 7cm from panel edge, on slightly visible ring (see section 2.2.2.3)

[4] Had to adjust DFT measurement location at 5 s, 20 s, 60 s compared to 0s due to 0.375” spacers (aluminum blocks) placed under the Stingray wheels to increase the offset distance to 1.25”. DFT at 0 s is not known due to this required change in location on the panel; however minimal, if any impact is expected based on observed changes at the larger time intervals.

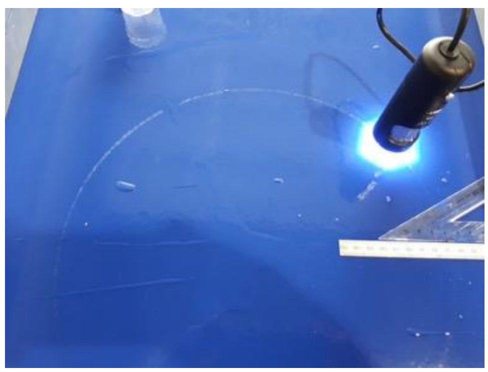
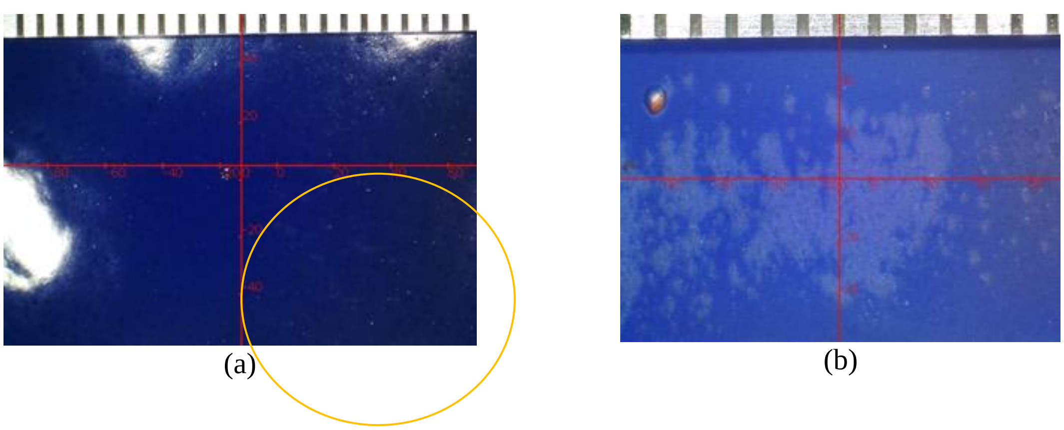


Figure 2-10: Damage on Hempasil X3 at 0.875” offset after 60 seconds.



(a) (b)

Figure 2-11: Damage observed with microscope on Hempasil X3 at 0.875" offset after 60 seconds at (a) routine measurement location (7cm from edge); and (b) a zoomed-in area of max damage. *Scale on ruler = 0.5 mm.*

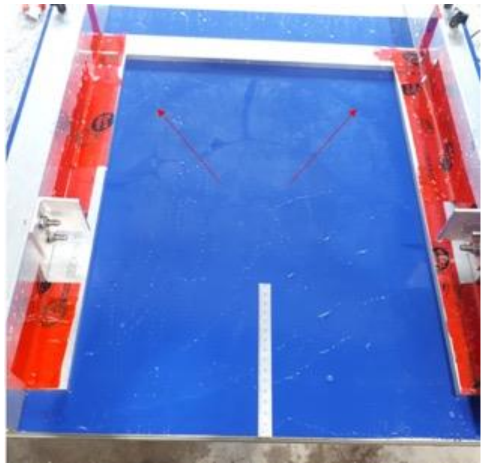


Figure 2-12: Visible sheen from the CavitCleaner Stingray tests on the Hempasil X3 at 1.25" offset after 20 s.

Table 2-8 through Table 2-10 provide observations from the stationary tests of the CavitCleaner Stingray on the Intersleek 1100SR, Interpseed 640, and Olympic 7660 coatings.

Table 2-8: CavitCleaner Stingray Tests (Stationary) -- Intersleek 1100SR Results

Offset [in.]	**Time [s]**	**Total Cu[1] [µg/L]**	**Total Zn[2] [µg/L]**	**DFT[3] [mils]**	**Primary Observations**
0.875"	0	32.2	24	13.5	- No visible impacts on the paint - Runs were not completed at 1.25" offset (due to lack of damage at 0.875")
	5	-	-	13.6	
	20	-	-	13.3	
	60	34	48	13.4	

Notes
[1] Total Cu only recorded at 0s and 60s since Cu is not contained within the coating
[2] Large change Zn values for 0.875" offset is discussed in Section 2.4.2
[3] Dry Film Thickness (DFT) shown at a repeated location 7 cm from panel edge where expected damage would have been visible based on nozzle radius (see section 2.2.2.3).

Table 2-9: CavitCleaner Stingray Tests (Stationary) – Interspeed 640 Results

Offset [in.]	**Time [s]**	**Total Cu [µg/L]**	**Total Zn [µg/L]**	**DFT[1] [mils]**	**Primary Observations**
0.875"	0	40.7	17	24.6	- No visible impacts on the paint - Runs were not completed at 1.25" offset (due to lack of damage at 0.875")
	5	42	19	24.2	
	20	44.4	26	24.2	
	60	46.8	29	23.9	

Notes
[1] Dry Film Thickness (DFT) shown at a repeated location 7cm from panel edge where expected damage would have been visible based on nozzle radius (see section 2.2.2.3).

Table 2-10: CavitCleaner Stingray Tests (Stationary) – Olympic 7660 Results

Offset [in.]	Time [s]	Total Cu [µg/L]	Total Zn [µg/L]	DFT[1] [mils]	Primary Observations
0.875"	0	45.2	62	17.3	- No visible impacts on the paint - Runs were not completed at 1.25" offset (due to lack of damage at 0.875")
	5	46.5	65	17.4	
	20	53.2	67	17.4	
	60	55	68	17.8	

Notes
[1] Dry Film Thickness (DFT) shown at a repeated location 7cm from panel edge where expected damage would have been visible based on nozzle radius (see section 2.2.2.3).

2.3.2 Advancing CavitCleaner Stingray Rotating Nozzle Tests

Table 2-11 through Table 2-14 present the experimental results for the CavitCleaner Stingray advancing over the individual coated test panels at 0.1 m/s. No visible damage was observed in all cases, so tests at the faster advance speed of 0.3 m/s were not performed.

Table 2-11: CavitCleaner Stingray Tests (Advancing) -- Hempasil X3 Results

Offset [in.]	Timing of Test	Total Cu [µg/L]	Total Zn [µg/L]	DFT[1] [mils]	Primary Observations
0.875"	before	31.8	13	13.5	- No visible damage after crossing plate at 0.1 m/s
	after	34.3	16	12.5	

Notes
[1] Dry Film Thickness (DFT) shown at a location 7cm from panel edge where expected damage would have been visible based on nozzle radius (see section 2.2.2.3).

Table 2-12: CavitCleaner Stingray Tests (Advancing) – Intersleek 1100SR Results

Offset [in.]	Timing of Test	Total Cu [µg/L]	Total Zn [µg/L]	DFT[1] [mils]	Primary Observations
0.875"	before	49	22	19.3	- No visible damage after crossing plate at 0.1 m/s
	after	58.8	29	18.7	

Notes
[1] Dry Film Thickness (DFT) shown at a location 7cm from panel edge where expected damage would have been visible based on nozzle radius (see section 2.2.2.3)..

Table 2-13: CavitCleaner Stingray Tests (Advancing) – Interspeed 640 Results

Offset [in.]	Timing of Test	Total Cu [µg/L]	Total Zn [µg/L]	DFT[1] [mils]	Primary Observations
0.875"	before	43.4	19	28	- No visible damage after crossing plate at 0.1 m/s
	after	48	22	27	

Notes
[1] Dry Film Thickness (DFT) shown at a location 7 cm from panel edge where expected damage would have been visible based on nozzle radius (see section 2.2.2.3).

Table 2-14: CavitCleaner Stingray Tests (Advancing) – Olympic 7660 Results

Offset [in.]	Timing of Test	Total Cu [µg/L]	Total Zn [µg/L]	DFT[1] [mils]	Primary Observations
0.875"	before	48	34	20.2	- No visible damage after crossing plate at 0.1 m/s
	after	50.5	36	20.1	

Notes
[1] Dry Film Thickness (DFT) shown at a location 7 cm from panel edge where expected damage would have been visible based on nozzle radius (see section 2.2.2.3).

2.3.3 CavitCleaner Evo2 Single Nozzle Tests

Sections 2.3.3.1 to 2.3.3.4 describe any observed impacts caused by the CavitCleaner Evo2 nozzle on the four coatings tested. Tests were performed once for each condition shown (nozzle offset distance, angle, cumulative time, and coating). This was done to complete the extensive test matrix and identify critical operating points, along with any trends. Repetitions were not performed since the results tended to follow consistent trends at the tested angles.

2.3.3.1 CavitCleaner Evo2 Impact on Hempasil X3

Table 2-15 describes the impacts of the CavitCleaner Evo2 single nozzle on the Hempasil X3 coating. At 22 degrees, no damage was observed through 10 seconds for the 1.25” offset, and through 2-3 seconds at the 0.875” offset distance.

Table 2-15: Observed damage conditions for the Evo2 single nozzle tests on the Hempasil X3 coating.

Distance [in.]	Angle [deg]	Run Time [s]	DFT [mils]	Comments
1.25”	22	0	11.6	- Baseline
		2-3	11.6	- No damage observed
		10	11.5	- No damage observed
		30	10.8	- Start of damage observed (see Figure 2-13)
0.875”	22	0	11.3	- DFT measurement at 0s taken at best prediction of nozzle impact location
		2-3	11.1	- No damage observed after 2-3 s; DFT of 11.1 at predicted impact location
		10	9.9; 8	- Observed damage after 10 s; - DFT = 9.9 at predicted location and 8 at damaged location (see Figure 2-14)
1.25”	45	0	11	- Baseline
		2-3	4.3	- Significant damage observed (see Figure 2-15)
1.25”	90	0	11	- Baseline
		2-3	3.7	- Significant damage observed (see Figure 2-16)

Based on the significant damage observed at an offset of 1.25” at 45 deg. and 90 deg., these angles were not run at an offset of 0.875”.

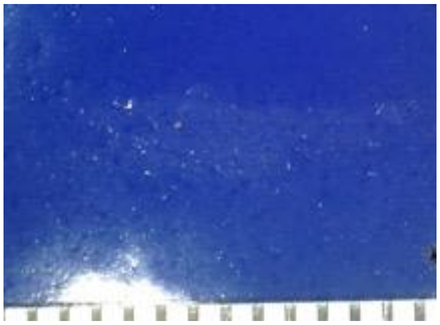


Figure 2-13: Evo2 on X3 - Observed damage after 30 s at 1.25” offset, 22 deg.

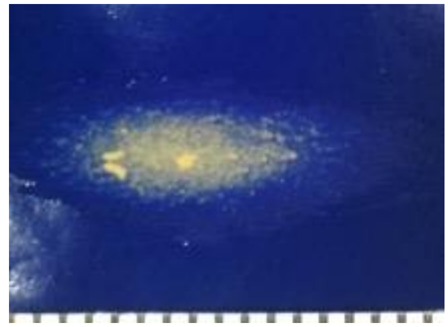


Figure 2-14: Evo2 on X3 - Observed damage after 10s at 0.875” offset, 22 deg.

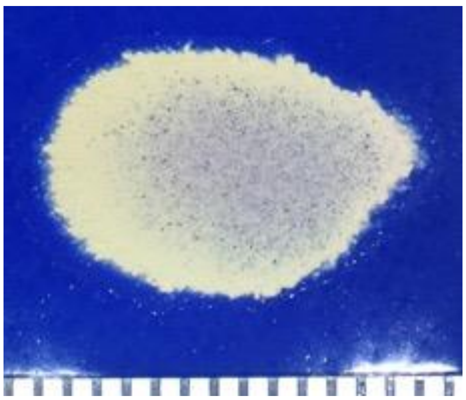


Figure 2-15: Evo2 on X3 - Observed damage after 2-3 s at 1.25” offset, 45deg.

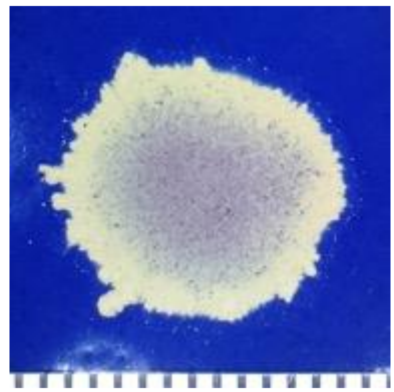


Figure 2-16: Evo2 on X3 - Observed damage after 2-3 s at 1.25” offset, 90 deg.

Note: Scale on ruler = 0.5 mm unless otherwise noted.

2.3.3.2 CavitCleaner Evo2 Impact on Intersleek 1100SR

Table 2-16 describes the impacts of the CavitCleaner Evo2 single nozzle on the Intersleek 1100SR coating. No damage was observed at 22 degrees and an offset distance of 1.25” through 60 seconds of exposure time. Damage was observed at 1.25” offset distance at 45 degrees and 90 degrees. The test was therefore not run at 0.875” offset distance at these two angles. Damage was also observed at 0.875” offset distance at 22 degrees.

Table 2-16: Observed damage conditions for the Evo2 single nozzle tests on the Intersleek 1100SR coating.

Distance [in.]	**Angle [deg]**	**Run Time [s]**	**DFT [mils]**	**Comments**
1.25”	22	0	16.7	- Baseline (Measurement taken at predicted location of nozzle impact)
		2-3	15	- No damage observed
		10	15.3	- No damage observed
		30	15.3	- No damage observed
		60	15.4	- No damage observed
0.875”	22	0	15.2	- Baseline
		2-3	8.6	- Significant damage observed (see Figure 2-17)
1.25”	45	0	15.2	- Baseline
		2-3	7.6	- Significant damage observed (see Figure 2-18)
1.25”	90	0	14.2	- Baseline
		2-3	7.1	- Significant damage observed (see Figure 2-19)

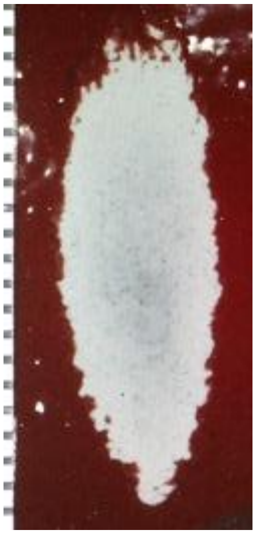


Figure 2-17: Evo2 on 1100SR - Observed damage after 2-3 s at 0.875" offset, 22 deg. *(ruler scale 0.5 mm)*

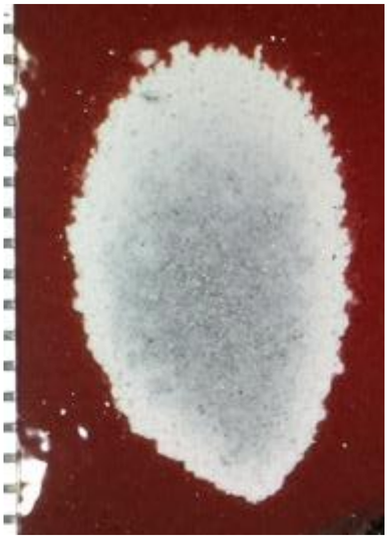


Figure 2-18: Evo2 on 1100SR - Observed damage after 2-3 s at 1.25" offset, 45 deg *(ruler scale 0.5 mm)*

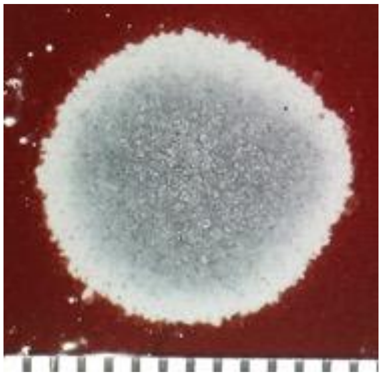


Figure 2-19: Evo2 on 1100SR - Observed damage after 2-3 s at 1.25" offset, 90 deg *(ruler scale 0.5 mm)*

2.3.3.3 CavitCleaner Evo2 Impact on Interspeed 640

Table 2-17 describes the impacts of the CavitCleaner Evo2 single nozzle on the Interspeed 640 coating. No damage was observed at 22 degrees and an offset distance of 0.875" through 30 seconds of exposure time, with physical damage starting to appear after 60 seconds (see Figure 2-20).

Table 2-17: Observed damage conditions for the Evo2 single nozzle tests on the Interspeed 640 coating.

Distance [in.]	Angle [deg]	Run Time [s]	DFT [mils]	Comments
0.875"	22	0	27.1	- Baseline
		2-3	25.6	- No damage observed
		10	26.3	- No damage observed
		30	27.1	- No damage observed
		60	23.9	- Slight damage observed (see Figure 2-20)
1.25"	45	0	26.7	- Baseline
		2-3	27.5	- No visible damage
		10	19.9	- Visible damage (see Figure 2-21)
0.875"	45	0	26.1	- Baseline
		2-3	24.7	- No visible damage
		10	17.4	- Significant damage observed (see Figure 2-22)
1.25"	90	0	25.5	- Baseline
		2-3	17.8	- Significant damage observed (see Figure 2-23)

Based on the damage observed at an offset of 1.25" at 90 deg, the test was not run at an offset of 0.875" at 90 deg.

Figure 2-20: Evo2 on 640 - Observed damage after 60 s at 0.875" offset, 22 deg

Figure 2-21: Evo2 on 640 - Observed damage after 10 s at 1.25" offset, 45 deg.

Figure 2-22: Evo2 on 640 - Observed damage after 10 s at 0.875" offset, 45 deg.

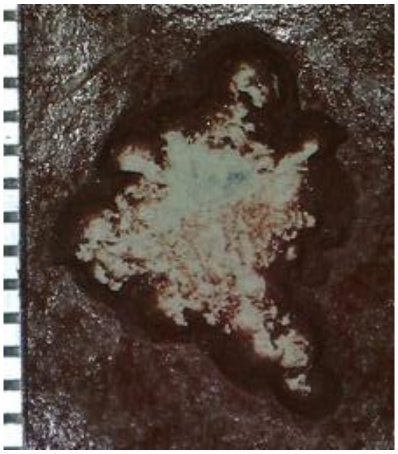


Figure 2-23: Evo2 on 640 - Observed damage after 2-3 s at 1.25" offset, 90 deg

Note: Scale on ruler = 0.5 mm unless otherwise noted.

2.3.3.4 CavitCleaner Evo2 Impact on Olympic 7660

Table 2-18 describes the impacts of the CavitCleaner Evo2 single nozzle on the Olympic 7660 coating. No damage was observed at 22 degrees and an offset distance of 0.875” through 60 seconds of exposure time, so these values are not provided in Table 2-18. Given this lack of damage, the test was not run at a 1.25” offset at 22 deg.

Based on the damage observed, this test was not run at 90 degrees at an offset of 0.875”.

Table 2-18: Observed damage conditions for the Evo2 single nozzle tests on the Olympic 7660 coating.

Distance [in.]	**Angle [deg]**	**Run Time [s]**	**DFT [mils]**	**Comments**
0.875”	22	0	20, 21.7, 21.1	- DFT values provided in vicinity of expected nozzle impact location[1]. No damage observed at either time interval but DFT values provided for reference.
		5	20.6, 20.8, 20.6	
		30	20, 20.5, 20.5	
		60	20.7, 20.6, 20.5	
1.25”	45	0	22	- Baseline
		2-3	21.6	- No visible damage
		10	22.1	- Visible damage (see Figure 2-24)
0.875”	45	0	22.7	- Baseline
		2-3	22.2	- No visible damage
		10	11.2	- Significant damage observed (see Figure 2-25). Damage was in the form of a large flake so may have encountered an adhesion issue here.
1.25”	90	0	22.7	- Baseline
		2-3	13.7	- Significant damage observed (see Figure 2-26)

Note 1: At each time, 3 DFT readings were recorded in a line 1cm apart in the vicinity of where nozzle jet was expected to impact the panel. Multiple values provided here since exact impact location not known due to lack of visible damage.

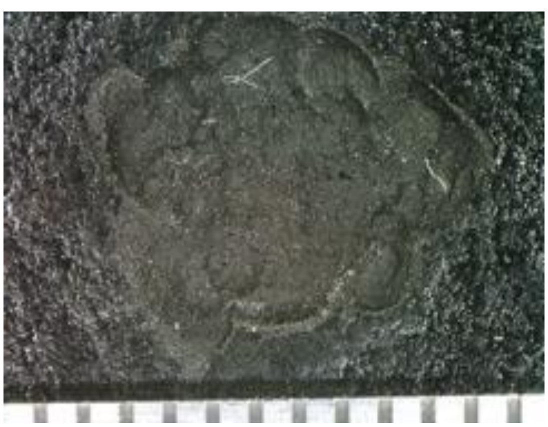


Figure 2-24: Evo2 on 7660 - Observed damage after 10 s at 1.25” offset, 45 deg.

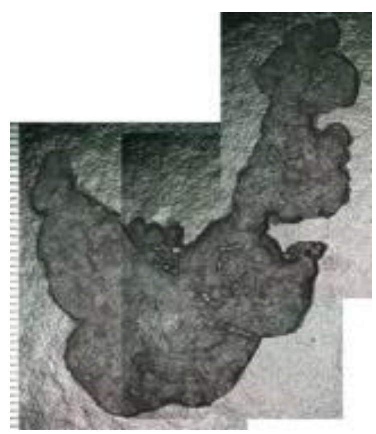


Figure 2-25: Evo2 on 7660 - Observed damage after 10 s at 0.875” offset, 45 deg.

Figure 2-26: Evo2 on 7660 - Observed damage after 2-3 s at 1.25" offset, 90 deg.

Note: Scale on ruler = 0.5 mm unless otherwise noted.

2.3.4 VLN Reverse Flow Cavitating Single Nozzle Tests

Sections 2.3.4.1 to 2.3.4.4 describe any observed impacts caused by the VLN nozzle on the four coatings tested. Tests were performed once for each condition shown (nozzle offset distance, angle, cumulative time, and coating). This was done to complete the extensive test matrix and identify critical operating points, along with any trends. Repetitions were not performed since the results tended to follow consistent trends at the tested angles.

2.3.4.1 VLN Nozzle Impact on Hempasil X3

Table 2-19 describes the impacts of the VLN single nozzle on the Hempasil X3 coating. No damage was observed at an offset distance of 0.875" at 22 degrees through 30 seconds of exposure time, with only minimal damage observed after 60 seconds (see Figure 2-27)

Table 2-19: Observed damage conditions for the VLN single nozzle tests on the Hempasil X3 coating.

Distance [in.]	Angle [deg]	Run Time [s]	DFT [mils]	Comments
0.875"	22	0	10.2	- Baseline
		2-3	10.9	- No damage observed
		10	10.5	- No damage observed
		30	10.4	- No damage observed
		60	9.9	- Start of damage observed (see Figure 2-27)
1.25"	45	0	11-11.4	- Baseline
		2-3	8	- Start of damage observed (see Figure 2-28)
0.875"	45	0	13	- Baseline
		2-3	4.6	- Damage observed (see Figure 2-29)
1.25"	90	0	13	- Baseline
		2-3	4.7	- Damage observed (see Figure 2-30)
0.875"	90	0	13.7	- Baseline
		2-3	4.5	- Damage observed (see Figure 2-31)

Based on the minimal damage observed at 22 deg. at an offset of 0.875", this condition was not run at an offset of 1.25".

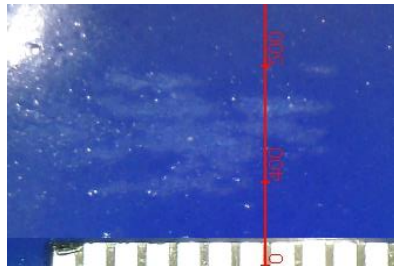


Figure 2-27: VLN on X3 - Observed damage after 60 s at 0.875” offset, 22 deg.

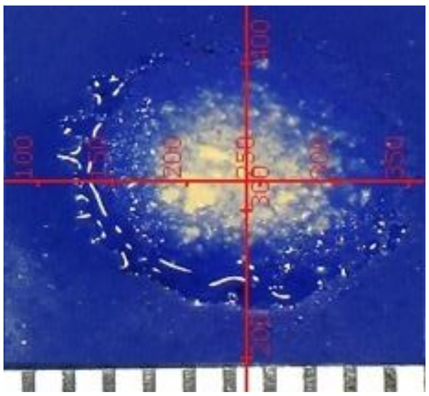


Figure 2-28: VLN on X3 - Observed damage after 2-3 s at 1.25” offset, 45 deg.

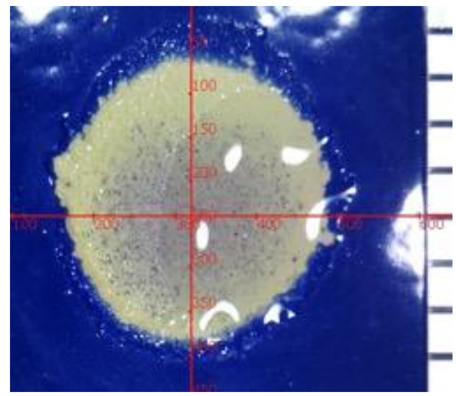


Figure 2-29: VLN on X3 - Observed damage after 2-3 s at 0.875” offset, 45 deg (note ruler scale at 1 mm in this image)

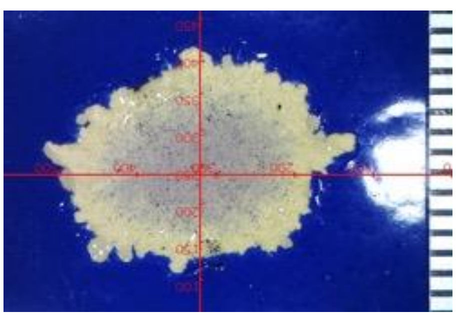


Figure 2-30: VLN on X3 - Observed damage after 2-3 s at 1.25” offset, 90 deg.

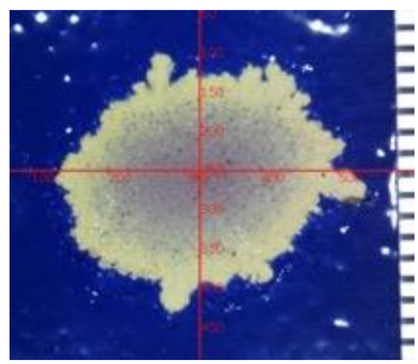


Figure 2-31: VLN on X3 - Observed damage after 2-3 s at 0.875” offset, 90 deg.

Note: Scale on ruler = 0.5 mm unless otherwise noted.

2.3.4.2 VLN Nozzle Impact on Intersleek 1100SR

Table 2-20 describes the impacts of the VLN single nozzle on Intersleek 1100SR. No damage was observed at an offset distance of 0.875” at 22 degrees through 60 seconds of exposure time.

Table 2-20: Observed damage conditions for the VLN single nozzle tests on the Intersleek 1100SR coating.

Distance [in.]	Angle [deg]	Run Time [s]	DFT [mils]	Comments
0.875”	22	0	15.6, 15.8, 16, 16.2	- DFT values provided in vicinity of expected nozzle impact location[1]. No damage observed but DFT values provided for reference.
		2-3	16.5, 15.8, 15.8, 15.6	- No damage observed
		10	15.8, 15.5, 15.7, 16.1	- No damage observed
		30	16.2, 15.4, 15.4, 15.3	- No damage observed
		60	15.5, 15.3, 15.2, 15.3	- No damage observed
1.25”	45	0	16	
		2-3	8.9	- Damage observed (see Figure 2-32)
1.25”	90	0	15.5	
		2-3	7.8	- Damage observed (see Figure 2-33)

Note 1: At each time, 4 DFT readings were recorded in a line 1cm apart in vicinity of where nozzle jet was expected to impact the panel. Multiple values provided here since exact impact location not known due to lack of visible damage.

Based on the minimal damage observed at 22 deg. at an offset of 0.875”, this condition was not run at an offset of 1.25”. Similarly, this condition was not run at an offset of 0.875” at 45 deg. or 90 deg. due to the degree of damage observed at a 1.25” offset.

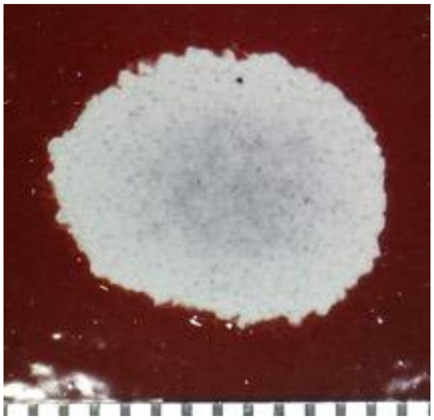


Figure 2-32: VLN on 1100SR - Observed damage after 2-3 s at 1.25” offset, 45 deg.

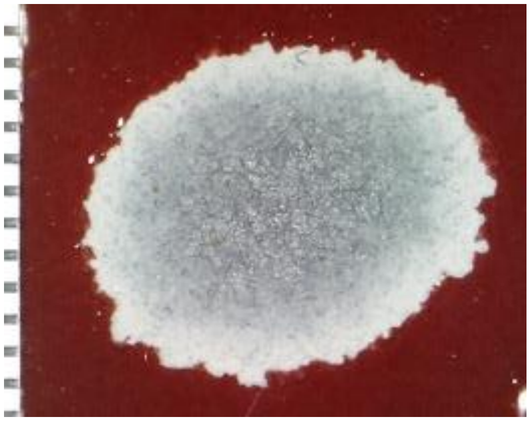


Figure 2-33: VLN on 1100SR - Observed damage after 2-3 s at 1.25” offset, 90 deg.

Note: Scale on ruler = 0.5 mm unless otherwise noted.

2.3.4.3 VLN Nozzle Impact on Interspeed 640

Table 2-21 describes the impacts of the VLN single nozzle on Interspeed 640. No damage was observed at an offset distance of 0.875” at 22 degrees through 60 seconds of exposure time.

Table 2-21: Observed damage conditions for the VLN single nozzle tests on the Interspeed 640 coating.

Distance [in.]	**Angle [deg]**	**Run Time [s]**	**DFT [mils]**	**Comments**
0.875”	22	0	28.1, 28.1, 28.1, 29.7	- DFT values provided in vicinity of expected nozzle impact location[1]. No damage observed but DFT values provided for reference.
		2-3	27.5, 28.8 29.3, 29.8	- No damage observed
		10	28.9, 28, 28.4, 29.6	- No damage observed
		30	27.1, 28.6, 29.5, 29.1	- No damage observed
		60	27.6, 28.5, 29.4, 29.5	- No damage observed
1.25”	45	0	*28 +/- 0.7*	
		2-3	*28 +/- 0.7*	- No damage observed
		10	*28 +/- 0.7*	- No damage observed
		30	*28 +/- 0.7*	- No damage observed
		60	*28 +/- 0.7*	- No damage observed
0.875”	45	0	27.5	
		2-3	28.3	- No damage observed
		10	17.4	- Damage observed (see Figure 2-34)
1.25”	90	0	26.8	
		2-3	28	- No damage observed
		15[2]	18.4	- Damage observed (see Figure 2-35)
0.875”	90	0	27.3	
		2-3	18.9	- Damage observed (see Figure 2-36)

Note 1: At each time interval, 4 DFT readings were recorded in a line 1cm apart in vicinity of where nozzle jet was expected to impact the panel. Multiple values provided here since exact impact location not known due to lack of visible damage.

Note 2: ~15 seconds instead of 10 because couldn’t get protective plate underneath initially.

Based on the minimal damage observed at 22 deg. at an offset of 0.875”, the 22 deg. angle was not run at an offset of 1.25”.

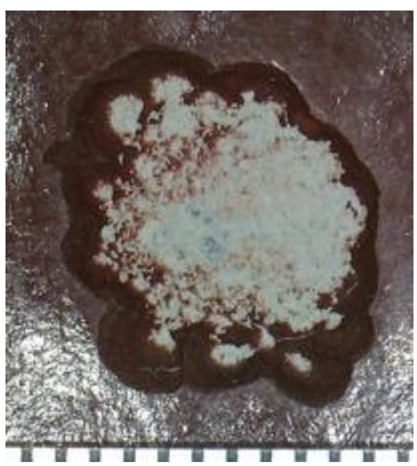


Figure 2-34: VLN on 640 - Observed damage after 10 s at 0.875” offset, 45 deg.

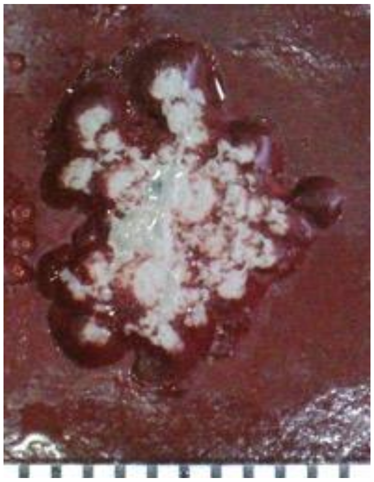


Figure 2-35: VLN on 640 - Observed damage after 15 s at 1.25" offset, 90 deg.

Figure 2-36: VLN on 640 - Observed damage after 2-3 s at 0.875" offset, 90 deg.

Note: Scale on ruler = 0.5mm unless otherwise noted.

2.3.4.4 VLN Nozzle Impact on Olympic 7660

Table 2-22 describes the impacts of the VLN single nozzle on Olympic 7660. No damage was observed at an offset distance of 0.875" at 22 degrees through 60 seconds of exposure time.

Table 2-22: Observed damage conditions for the VLN single nozzle tests on the Olympic 7660 coating.

Distance [in.]	**Angle [deg]**	**Run Time [s]**	**DFT [mils]**	**Comments**
0.875"	22	0	22.8, 22.5, 22.5, 21.3	- DFT values provided in vicinity of expected nozzle impact location[1]. No damage observed but DFT values provided for reference.
		2-3	*(values not recorded)*	- No damage observed
		10	*(values not recorded)*	- No damage observed
		30	22.3, 23, 21.5, 21.8	- No damage observed
		60	22.9, 23.2, 22.9, 21.1	- No damage observed
1.25"	45	0	*23 +/- 0.7*	
		2-3	*23 +/- 0.7*	- No damage observed
		10	*23 +/- 0.7*	- No damage observed
		30	*23 +/- 0.7*	- No damage observed
		60	*23 +/- 0.7*	- No damage observed
0.875"	45	0	22.9	
		4	22.4	- No damage observed
		10	14.1	- Damage observed (see Figure 2-37)
1.25"	90	0	23.1	
		4	24.7	- No damage observed
		10	15.5	- Damage observed (see Figure 2-38)
0.875"	90	0	24.1	
		2-3	14.7	- Damage observed (see Figure 2-39)

Note 1: At each time interval, 4 DFT readings were recorded in a line 1cm apart in vicinity of where nozzle jet was expected to impact the panel. Multiple values provided here since exact impact location not known due to lack of visible damage.

Based on the minimal damage observed at 22 deg. at an offset of 0.875", the 22 deg. angle was not run at an offset of 1.25".

Figure 2-37: VLN on 7660 - Observed damage after 10 s at 0.875" offset, 45 deg.

Note: Scale on ruler = 0.5 mm unless otherwise noted.

Figure 2-38: VLN on 7660 - Observed damage after 10 s at 1.25" offset, 90 deg.

Figure 2-39: VLN on 7660 - Observed damage after 2-3 s at 0.875" offset, 90 deg.

Note: Scale on ruler = 0.5 mm unless otherwise noted.

2.4 DISCUSSION

Section 2.4.1 summarizes the operating conditions where no visible impact on the coatings was observed by paint type.

Sections 2.4.2 and 2.4.3 discuss results and procedural matters regarding the metals concentration and total suspended solids sampling.

Section 2.4.4 discusses observations made regarding the dry film thickness measurements.

2.4.1 Summary of Safe Operating Conditions

Sections 2.3.1 through 2.3.4 above detail the conditions where damage was observed. Table 2-23 through Table 2-26 summarize the conditions where no visible damage was observed.

Table 2-23: Hempasil X3 conditions for zero or minimal impact.

Stingray Rotating Nozzles (Stationary)	- 0.875" offset: No visible impact through 5 s with only a slight visible sheen visible through 20s. - 1.25" offset: No visible impact through 5 s, with only a slight visible sheen visible after 20 s and 60 s.
Stingray Rotating Nozzles (Advancing)	- No visible impact at 0.1 m/s and 0.875" offset (1.25" offset not run).
Evo2 Stationary Nozzle	- 0.875" offset: No visible impact at 22 degrees through 2-3 s - 1.25" offset: No visible impact at 22 degrees through 10 s
VLN RFC Stationary Nozzle	- 0.875" offset: No visible impact at 22 degrees through 30 s

Table 2-24: Intersleek 1100SR conditions for zero or minimal impact.

Stingray Rotating Nozzles (Stationary)	- No visible impacts at 0.875" offset through 60 s (1.25" offset not run)
Stingray Rotating Nozzles (Advancing)	- No visible impact at 0.1 m/s and 0.875" offset (1.25" offset not run)
Evo2 Stationary Nozzle	- 1.25" offset: No visible impact at 22 degrees through 60 s
VLN RFC Stationary Nozzle	- 0.875" offset: No visible impact at 22 degrees through 60 s (1.25" offset not run at 22 deg.)

The results in Table 2-24 are interesting because the rotating Stingray nozzles at 22 deg. and 0.875" offset did not show any damage to the coating, while the Evo2 nozzle at 22 deg. and 0.875" offset showed damage after 2-3 seconds (see Table 2-16). Conversely, 60 seconds of rotating nozzle exposure did not create visible damage at a 0.875" offset distance. Increasing the offset of the Evo2 nozzle to 1.25" resulted in no damage occurring after 60s of exposure at 22 deg.

Table 2-25: Interspeed 640 conditions for minimal impact.

Stingray Rotating Nozzles (Stationary)	- No visible impacts at 0.875" offset through 60 s (1.25" offset not run)
Stingray Rotating Nozzles (Advancing)	- No visible impact at 0.1 m/s and 0.875" offset (1.25" offset not run)
Evo2 Stationary Nozzle	- 0.875" offset: No visible impact at 22 degrees through 30 s - 1.25" offset: No visible impact at 45 degrees through 2-3 s - 0.875" offset: No visible impact at 45 degrees through 2-3 s
VLN RFC Stationary Nozzle	- 0.875" offset: No visible impact at 22 degrees through 60 s (1.25" offset not run at 22 deg.) - 1.25" offset: No visible impact at 45 degrees through 60 s - 0.875" offset: No visible impact at 45 degrees through 2-3 s - 1.25" offset: No visible impact observed at 90 degrees through 2-3 s

The information summarized in Table 2-23 through Table 2-26 indicate that the coatings are all quite robust even when exposed to the rotating nozzles. The only coating showing visible signs of damage was the Hempasil X3, for which a light sheen was visible after 20 seconds at a 0.875" offset distance. More visible damage did occur after 60 seconds. At 1.25" offset, the Hempasil X3 showed only a slightly visible sheen on the nozzle diameter after 20 seconds and 60 seconds.

Table 2-26: Olympic 7660 conditions for minimal impact.

Stingray Rotating Nozzles (Stationary)	- No visible impacts at 0.875” offset through 60 s (1.25” offset not run)
Stingray Rotating Nozzles (Advancing)	- No visible impact at 0.1 m/s and 0.875” offset (1.25” offset not run)
Evo2 Stationary Nozzle	- 0.875” offset: No visible impact at 22 degrees through 60 s (1.25” offset not run at 22 deg) - 1.25” offset: No visible damage at 45 degrees through 2-3 s - 0.875” offset: No visible damage at 45 degrees through 2-3 s
VLN RFC Stationary Nozzle	- 0.875” offset: No visible impact at 22 degrees through 60 s (1.25” offset not run at 22 deg.) - 1.25” offset: No visible impact at 45 degrees through 60 s - 0.875” offset: No visible impact at 45 degrees through 4 s - 1.25” offset: No visible impact observed at 90 degrees through 3-4 s

For the single nozzle tests at 22 degrees, all coatings except the Intersleek 1100 SR were able to withstand at least 2-3 seconds from both the Evo2 and VLN RFC nozzles. This data verified CavitCleaner’s recommendation to keep the nozzles between 15 deg and 25 deg during regular cleaning operations to avoid damage to the coating.

For the single nozzle tests at 45 degrees, both the Hempasil X3 and the Intersleek 1100 were damaged under all conditions. It was shown, however, that both the Interspeed 640 and Olympic 7660 were able to withstand 2-3 seconds of exposure time without visual impact at a 0.875” offset with both single nozzles. The Interspeed 640 and Olympic 7660 further avoided any damage from the VLN nozzle at a 1.25” offset through 60s at 45 degrees. All coatings were damaged at a 90-degree angle during the tests, with only the Interspeed 640 and Olympic 7660 able to withstand 2-3 seconds of the VLN nozzle at 90 degrees from the 1.25” offset without experiencing visible damage.

2.4.2 Metals Concentrations

The metals concentration results are discussed for the stationary and advancing Stingray tests in sections 2.4.2.1 and 2.4.2.2 respectively. Section 2.4.2.3 describes a test performed to characterize the influence of the system (plumbing components and pump) on observed metals concentrations, while Section 2.4.2.4 demonstrates the measurable deviation in zinc and copper values when visible damage was purposefully inflicted on a panel containing copper and zinc (the Olympic 7660). Section 2.4.2.5 provides a comparison of the metals concentration results to the B.C. water quality guidelines for marine life and summarizes observations and conclusions specific to the metals concentrations data.

2.4.2.1 Stationary Stingray Tests

Table 2-27 summarizes the changes in metal concentrations observed during stationary testing of the Stingray (rotating nozzles) on the test panels. The increase in copper concentrations is more pronounced for the Interspeed 640 and Olympic 7660 coatings (6.1 and 9.8 µg/L respectively) compared to the Hempasil X3 (0.8 µg/L) and Intersleek 1100 (1.8 µg/L). This was the expected outcome since these are the two ablative type coatings that contain copper; however, the increased metals concentration changes for the Hempasil X3 and Intersleek 1100 was unexpected since neither of these coatings contains these metals. The difference was particularly noticeable for zinc, with a change of 24 µg/L for the Hempasil X3 and Intersleek 1100.

We deduced that the standard pressure washer system components, namely galvanized and brass fittings, and the brass pump, were a source of copper and zinc (described further in section 2.4.2.3). We replaced valves and fittings with stainless steel components where possible prior to testing the Interspeed 640 and Olympic 7660. This led to smaller concentration increases for zinc showing that the replaced fittings contributed at least in part to the changes in metal concentrations. Replacing the brass pump and select fittings was not immediately possible because it required components that were custom or more challenging to source expediently during the trials. As a result, it is not possible to isolate the impacts on metals concentrations of the equipment from the interactions with the coating during the cleaning process. Section 2.4.2.3 describes a test to characterize the influence of the pump and plumbing system for reference.

Table 2-27: Changes in total metals concentrations for stationary tests within the test tank (0.875” offset distance).

Coating	**Cu Concentration [μg/L]**			**Zn Concentration [μg/L]**		
	Before Test	**After 60s**	**Change**	**Before Test**	**After 60s**	**Change**
Hempasil X3	35.2	36	0.8	47	71	24
Intersleek 1100	32.2	34	1.8	24	48	24
Interspeed 640	40.7	46.8	6.1	17	29	12
Olympic 7660	45.2	55	9.8	62	68	6

Unfortunately, interpretation of these results is limited as we assumed that the quality of the supply water would be relatively consistent from the potable water tap, so we did not take water samples from the supply tank for each individual test. In the “Before Test” column, we see the variation in the zinc and copper concentrations from the tap. As a result, there is some uncertainty caused by the varying metals concentrations in the supply tank. Regardless, we can see that the metals concentration changes in Table 2-27 are small when compared to the concentration changes measured when noticeable damage occurred to the panel as described in section 2.4.2.4. The small metals concentration changes in Table 2-27 are not sufficient to draw firm conclusions about the amount of coating entering the tank water as a result of the cleaning.

2.4.2.2 Advancing Stingray Tests

Table 2-28 provides the change in metals concentrations in the test tank before and after the advancing tests. These tests were all performed after we changed the valves and several fittings to stainless steel – but as mentioned, the brass pump remained as well as some pressure washer and hose fittings that were more difficult to source. As shown, the increase in copper and zinc concentrations are all less than 10 μg/L. The largest observed increase for both metals was for the Intersleek 1100 – the foul release type coating that does not contain these two metals. This stands out, and the noticeable rise compared to the other coatings is attributed to the fact that the equipment was run in the tank for longer for this specific test (for observation and tuning) compared to the tests on the other three coatings; or there may have been an unusual occurrence with the equipment or supply water. Given these advancing tests have a short run-time across the panel (about 6s), the test results are more influenced (compared to the stationary tests) by extended operating time in the tank in the staging area when making general observations or tuning to the target operating point.

Table 2-28: CavitCleaner Stingray Tests Advancing Test Results (0.875” offset, 0.1 m/s advance speed)

Coating	**Cu Concentration [μg/L]**			**Zn Concentration [μg/L]**		
	Before	**After**	**Change**	**Before**	**After**	**Change**
Hempasil X3	31.8	34.3	2.5	13	16	3
Intersleek 1100	49	58.8	9.8	22	29	7
Interspeed 640	43.4	48	4.6	19	22	3
Olympic 7660	48	50.5	2.5	34	36	2

2.4.2.3 Influence of System Components

As mentioned in section 2.4.2.1, we observed that plumbing system components were a source of copper and zinc during the trials. After replacing select valves and fittings, we performed a control test to characterize the impacts of the system on metals concentrations. We operated the CavitCleaner Stingray in a tank without any coated panels for 60 seconds, which resulted in the concentrations reported in

Table 2-29. The impact of the pump and select fittings on copper values remains less than the impact on zinc values.

Table 2-29: Water concentrations during control test after replacing select fittings.

	Total Cu [μg/L]	**Total Zn [μg/L]**
Supply tank	40.4	11
Test tank before trial	39.5	7
Test tank after trial	41.2	26
Concentration of added water passing through system	45.6	74.9

This change in components improved the issue but did not address it completely, as the system still increased the copper and zinc concentrations in the absence of coating effects. Zinc concentration increases significantly more than the copper concentrations, assumed due to the pressure washer fittings we were unable to replace with stainless steel. It is apparent that the plumbing system impacts the metals concentrations in the tanks, so it is not feasible to distinguish the impact of the coating on the metals concentrations during the tests from the increases due to the plumbing system components.

2.4.2.4 Metals Concentration Changes under Damaged Conditions

To further characterize our testing procedures, we performed a test to examine the impact on metals concentrations when noticeable damage occurred to a coating containing copper and zinc. For this test, the Evo2 nozzle was used to purposefully damage the coating on a test panel with the Olympic 7660 coating by spraying it at close range for 60 s.

Table 2-30 details the results from these tests, while Figure 2-40 displays the damage observed on the panel. The copper concentration increased by a factor 72 in the tank, while the zinc concentration increased by a factor of 57.5. Total suspended solids (TSS) are discussed in Section 2.4.3. These tests demonstrate the significant copper and zinc concentrations observed when the coating containing these elements was noticeably damaged.

Table 2-30: Water concentration tests with significant damage (Evo2 nozzle on Olympic 7660 for 60 s).

	Water Volume [L]	**Total Copper**		**Total Zinc**		**TSS**
		Concentration [μg/L]	**Mass [μg]**	**Concentration [μg/L]**	**Mass [μg]**	
Prior to test	72.5	47.2	3420	8	580	<2 mg/L
After test	126.7	3400	431108	460	58326	<2 mg/L

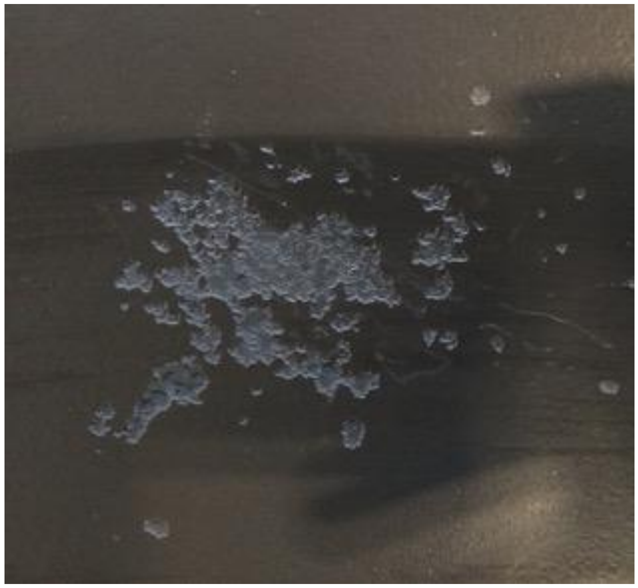


Figure 2-40: Significant Damage for Purpose of Water Concentration Tests

2.4.2.5 Comparison to Guidelines and Summary

For reference, water quality guidelines for marine and estuarine aquatic life provided by the B.C. Ministry of Environment and Climate Change Strategy [2] are provided in Table 2-31.

Table 2-31: Water quality guidelines -- marine life.

	Copper	**Zinc**
Water quality guidelines for marine and estuarine aquatic life	2 µg/L long-term 3 µg/L short-term acute	10 µg/L long-term 55 µg/L short-term acute

The copper and zinc concentration changes observed during the trials are higher than the permitted values for marine habitat; however, these values are the maximum concentrations allowable in a body of water. We are not aware of guidelines related to permissible effluent levels for activities such as in-water hull cleaning.

For further context, Table 2-32 provides wastewater discharge data from the wastewater treatment plants in Metro Vancouver. In 2019, these plants discharged water with the copper, zinc and TSS concentrations shown.

Table 2-32: 2019 Wastewater Treatment Plant Discharge Data [3]

Wastewater Treatment Plant (WWTP)	**Average Daily Discharge (m^3)**	**Average[1] Total Copper (µg/L)**	**Average Total Zinc (µg/L)**	**Average TSS (mg/L)**
Annacis Island	538,025	20.6	38	14
Iona Island	493,230	29.8	53	54
Lions Gate	75,792	36.6	57	54
Lulu Island	68,858	12.4	34	6
Northwest Langley	1,427	30.3	52	19
Note 1: *Average metals and TSS concentrations are determined from the monthly averages provided for each WWTP.*				

From Table 2-27, the largest change in copper concentration observed in the enclosed tank during stationary trials was approximately 9.8 µg/L, while the largest zinc concentration change was 12 µg/L after replacing several plumbing components. For reference, the CavitCleaner Stingray used approximately 7.6 gpm (a single rotating 2-nozzle disc). This converts to ~83 m^3 of water per 24h period for a robot cleaning with two discs (4 nozzles in total), compared to daily discharge volumes of ranging from 68,858 m^3 to 538,025 m^3 from the treatment plants in Table 2-32.

Based on the discussion in this section, it is difficult to draw firm conclusions from the water quality data collected during these trials. Key points from this analysis are summarized as follows:

1. The plumbing system components contributed to the metals concentration changes observed during these trials. It is therefore challenging to draw conclusions regarding changes in metals concentration specifically due to the coatings without devising a test that separates impacts from plumbing components.
2. It may be possible to interpret some trends from the water concentration data. For example, Table 2-27 shows that the change in copper concentration was most significant for the coatings containing copper (6.1 µg/L and 9.8 µg/L) compared to those not containing copper (0.8 µg/L and 1.8 µg/L). However, the contribution of the plumbing to these concentration values limits what can be interpreted due to the coatings since for each test the run time varied slightly to tune and operate the cleaner appropriately. The inlet supply tank conditions also varied as the tank had to be refilled between trials.
3. The copper and zinc concentrations observed during these tests exceed the water quality guidelines for marine and estuarine aquatic life; however, one must consider the following:
   a. The starting concentrations from the tap also exceeded these guidelines, while the pump and system fittings themselves contributed to any increase in the observed metals concentrations.
   b. These trials were conducted in a fully enclosed tank so any impacts are captured locally within the tank. Dilution effects would be greater in the open sea.
   c. Observed changes in copper concentration in the test tank during cleaning are of similar magnitude to those released from municipal wastewater plants into local waters.

Further work to quantify impacts of the cleaning operation on copper and zinc concentrations should include additional testing addressing:

1. Frequent testing of the supply water (tap water), and water passing through the pump system prior to entering the test tank for cleaning panels. This would require a unique tank configuration, or perhaps a water take-off point in the plumbing system near the cleaning head allowing water to be removed for sampling before it enters the tank, but during testing.
2. Further steps added to the testing procedure including recording all time periods that the cleaning head is operational in the test tank. This would include time spent in the staging area to tune the operating condition, and after the test is complete. Alternatively, incorporate a parallel tank to tune the cleaning head for each trial before transferring to the test tank.
3. Updating the plumbing system to entirely stainless steel to avoid any potential impacts from brass and galvanized components. This may not be feasible due to excess cost and availability of components.

The changes suggested above would add significant cost to the test program due to the added frequency of water sampling and associated cost for laboratory data analysis. The added complexity to the testing procedures and equipment would further increase costs, such as:

- Requiring more test equipment (e.g. tanks) or more expensive plumbing components (e.g stainless steel with added take-off points);
- Requiring more staff and time to conduct these procedures.

2.4.3 Total Suspended Solids (TSS) Observations

The total suspended solids (TSS) measurement was below the detectable limit (< 2 mg/L) in all cases except for two tests:

i. The CavitCleaner Stingray advancing test on the Interspeed 640 coating at 0.875" offset measured 2 mg/L prior to conducting the test.

ii. The CavitCleaner Stingray stationary test on the Olympic 7660 coating at 0.875" offset measured 3 mg/L after 20 seconds.

In both cases, concentrations at the subsequent time step had returned to < 2mg/L. Follow-up correspondence with AGAT Labs indicated that 2 mg/L is their standard minimum detectable concentration for TSS, and is lower than "most" labs offering a resolution of 3 mg/L. As a reference point, Table 2-32 indicates that TSS content in wastewater discharge on Sept. 21 was 47 mg/L from Lions Gate, and 8 mg/L from Annacis Island. Note these values address TSS and do not indicate how much of that content is microplastics vs. other contaminants. AGAT labs has indicated they are able to detect values as low as 1mg/L with changes to the sampling procedure – this should be investigated further for future tests.

2.4.4 Dry Film Thickness (DFT) Observations

A DFT gauge (Defelsko Positector 6000, see Table 2-3) was used to characterize nozzle impacts on the coated panels. In general, the DFT gauge did an effective job of quantifying the impact on the panel coating where visible damage occurred. The sensitivity of the instrument's readings, however, made it difficult to measure whether non-visible damage had occurred. This is because a consistent variability of about +/- 0.4 mils, and sometimes up to +/- 0.5 or +/- 0.6 mils, was observed when taking multiple readings at the same location.

Variability in coating thickness was observed when readings were taken at different locations on the panel. DFT readings for the Hempasil X3 were generally the least consistent (+/- 0.5 to 0.6 mils), while readings for the other coatings were typically more consistent (+/- 0.3 to 0.4 mils). The reason for that is not known.

Section 2.4.4.1 discusses DFT observations from the stationary and advancing tests using the CavitCleaner Stingray. Section 2.4.4.2 provides observations from the DFT readings for the single nozzle tests.

2.4.4.1 Observations from rotating nozzle tests

2.4.4.1.1 Stationary tests

Table 2-7 provided DFT measurements from the stationary CavitCleaner Stingray tests on the Hempasil X3. Measurements were taken at 1cm intervals moving in from the edge of the plate, such that the expected area of impact from the nozzle was at the 7cm location. The DFT gauge indicated a decrease from 12.5 to 11.9 mils once damage was observed.

Table 2-33 provides averaged DFT readings at the adjacent measurement locations (4, 5, 6, 8, 9, 10 cm). As shown, there is a change in the DFT measurements recorded at a specific point over the course of the experiment (i.e. at 0, 5, 20 and 60s), even at locations that are not impacted by the cavitating waterjet (ex. 4cm location). This variability in the readings makes it challenging to conclude whether a real change in coating thickness was measured or if that change is withing the tolerance capabilities of the DFT gauge. DFT measurements for the Hempasil X3 tended to be among the most variable during our tests.

Table 2-33: Averaged DFT readings at locations 4 cm through 10 cm for the Hempasil X3 stationary tests

Cumulative Time	@ 4cm [mils]	@ 5 cm [mils]	@ 6 cm [mils]	@ 7 cm [mils]	8 cm [mils]	9 cm [mils]	10 cm [mils]
0 s	14.7	14.5	13.1	12.9	12.9	11.6	10.5
5 s	14.6	13.9	13.4	12.4	12.6	12.4	12.1
20 s	15.8	13.8	13.5	12.5	12.5	12.2	11.6
60 s	14.6	14.0	13.7	11.9	12.0	11.1	11.1

Table 2-8 demonstrates consistency among the DFT values, corroborating the lack of visual damage to the Intersleek 1100SR.

Table 2-9 and Table 2-10 provide results for the Interspeed 640 and Olympic 7660. The DFT readings for both are generally consistent (within the +/- 0.4 mils typical variation). The only exception is the reading of 23.9 mils on the Interspeed 640 after 60s, where the value dipped from about 24.6 mils at 0s and 24.2 mils for the two measurements prior. This minor deviation may be evident of damage that is not visible, though with the variability in readings it is not possible to be certain.

2.4.4.1.2 Advancing Tests

For the advancing tests, DFT dropped from 13.5 to 12.5 mils for the Hempasil X3 (Table 2-11), though as mentioned above DFT readings for panels coated with the Hempasil X3 showed to be the most variable so it is not possible to draw a firm conclusion here (within +/- 0.6) . Values for the Intersleek 1100SR (Table 2-12) and Olympic 7660 (Table 2-14) were generally consistent (within 0.6 mils +/- 0.3). DFT thickness for the Interspeed 640 advancing tests (Table 2-13) showed a DFT reduction from 28 to 27 mils at the expected location of damage at 7cm. Adjacent measurement values (see Table 2-34) demonstrate the variability in the DFT readings during this test. The reduction from 28 mils to 27 mils at 7cm may be indicative of a reduction in the coating thickness due to the cleaning operation; however, given the variability in the adjacent readings before the test it is not possible to draw a firm conclusion.

Table 2-34: DFT readings at measurement locations 3cm through 11cm for the Interspeed 640 advancing tests.

	3cm	4cm	5cm	6cm	7cm	8cm	9cm	10cm	11cm
Before test	25.9	27.2	26.6	27.4	28	28.2	27.3	28.1	28.6
After test	26.7	26.5	27	27.3	27	28.7	26.9	27.6	27.9

2.4.4.2 Observations from single nozzle tests

The single nozzle tests quantified the relationship between observed damage and changes in DFT thickness more accurately than rotating experiments because the precise location of damage is known.

For the CavitCleaner Evo2 tests on the Hempasil X3 at 1.25” offset and 22 degrees, Table 2-15 shows consistent DFT readings (11.6-11.5mils) through 10 seconds where no visible damage was observed. Where damage was observed after 30 seconds (see Figure 2-13) the DFT measurement dropped to 10.8 mils. At the 0.875” offset, more visible damage occurred (see Figure 2-14) DFT readings dropped from around 11.1 mils to 8 mils.

For the CavitCleaner Evo2 tests on the Interspeed 640 at 0.875” offset and 22 degrees, very minor damage (1.5mm in diameter) was observed after 60s (see Figure 2-20). Prior to the damage becoming visible, DFT readings varied between 27.1 and 25.6 mils; however, after 60 s the DFT reading reduced to 23.9 mils.

For the CavitCleaner Evo2 tests on the Olympic 7660 at 45 degrees and a 1.25” offset distance, damage was observed after 10 seconds (see Table 2-18). Interestingly, the DFT reading for these tests varied from 22 mils at start, to 21.6 mils after 2-3 s, to 22.1 mils after 10 s where damage occurred. When attempting to take these measurements, we noted that the DFT gauge was not able to settle to a suitable number for an unknown reason.

The last trial to be discussed in detail with respect to DFT measurements is for the VLN nozzle test on the Hempasil X3 at an offset of 0.875" at 22 deg. Table 2-19 demonstrated the relatively consistent DFT measurements for the Hempasil X3 through 30 s at 10.2 – 10.9 mils. After 60s, minor damage is visible (see Figure 2-27), which corresponded to a reduced DFT measurement of 9.9 mils. At 45 deg and an offset distance of 1.25", damage was observed after 2-3 seconds (see Figure 2-28). This damage is more severe than in Figure 2-27 and corresponds to a DFT reduction from about 11-11.4 mils at 0 s down to 8 mils where visible damage occurred. The more severe damage in Figure 2-29 to Figure 2-31 also resulted in greater reductions in DFT (from between ~13 – 13.7 mils down to 4.5 – 4.7 mils).

2.5 CONCLUSIONS

The following conclusions may be drawn from the experimental tests:

1. The CavitCleaner rotating nozzles did not cause any visual damage to the coatings under anticipated operating conditions. More specifically:

    a. No visual damage was observed on any of the coatings during the advancing tests which represent the intended operating condition.

    b. For the stationary tests, the only coating damage observed was on the Hempasil X3 at a 0.875" offset distance - a slight sheen was visible after 20 seconds or run time, and a ring of damage was visible after 60 s. At a 1.25" offset, the Hempasil X3 only showed a light sheen after 20s and 60s.

    For typical operational conditions, the exposure time at any single location should therefore be limited to 20s to avoid potential damage to the most delicate coatings.

2. For the single nozzle tests, all coatings except the Intersleek 1100SR withstood exposure from both the Evo2 and VLN nozzles at 22 degrees and an offset of 0.875" for 2-3 seconds. The Intersleek 1100 SR was damaged by the Evo2 nozzle after 2-3 s at 0.875" offset but did not experience damage at 22-degrees through 60s from either the VLN nozzle at a 0.875" offset, nor the Evo2 nozzle at a 1.25" offset.

    At 45-degrees, both nozzles were able to consistently damage the coatings, except for:

    a. The Interspeed 640 and Olympic 7660 after 2-3 s of exposure at 0.875" offset from both single nozzles

    b. The VLN nozzle at a 1.25" offset through an exposure time of 60 s.

    All coatings were damaged at a 90-degree angle during the tests, with only the Interspeed 640 and Olympic 7660 able to withstand 2-3 seconds of the VLN nozzle at 90 degrees from the 1.25" offset without experiencing visible damage.

    This data verified CavitCleaner's recommendation to keep the nozzles between 15 deg and 25 deg during regular cleaning operations to avoid damage to the coating.

3. For the stationary rotating nozzle tests, the change in copper concentration in the test tank after 60 s was greater for the coatings containing copper (6.1 µg/L for the Interspeed 640 and 9.8 µg/L for the Olympic 7660) compared to those not containing copper (0.8 µg/L for the Hempasil X3 and 1.8 µg/L for the Intersleek 1100SR). Interpretation of these results is limited by the facts that (i) the hydraulic system components contributed to the observed changes in metals concentrations in water entering the tank,

and (ii) the metals concentrations for the supply water fluctuated and were not monitored for each test. These factors should be addressed during future tests.

4. The copper and zinc concentrations observed during the tests exceed the water quality guidelines for marine and estuarine aquatic life. Notwithstanding, it is important to consider the following factors:
    a. The starting concentrations from the potable water tap (Table 2-27) also exceeded the guidelines for marine life (Table 2-31), while the pump and system fittings themselves contributed to any increase in the observed metals concentrations.
    b. Observed changes in copper concentrations in the test tank during cleaning are of similar magnitude to those released from municipal wastewater plants into local waters.
5. The DFT gauge did an effective job of quantifying the impact on the panel coating where visible damage occurred. However, variability in the gauge readings made it challenging to determine whether non-visible damage had occurred. This is because a consistent variability of about +/- 0.4 mils, and sometimes up to +/- 0.5 or +/- 0.6 mils, was observed when taking multiple readings at the same location.
6. The total suspended solids (TSS) measurement was below the detectable limit (< 2 mg/L) in all cases except for two tests, which returned to <2 mg/L for the subsequent time step. Follow-up correspondence with AGAT Laboratories indicated that 2 mg/L is their standard minimum detectable concentration for TSS, and is lower than "most" labs offering a resolution of 3 mg/L. As a reference point, Table 2-32 indicates that TSS content in effluent from Metro Vancouver WWTPs averaged between 6 mg/L and 54 mg/L in 2019. Note these values address TSS and do not indicate how much of that content is microplastics vs. other contaminants. AGAT Laboratories has indicated they are able to detect values as low as 1 mg/L with changes to the sampling procedure. This should be considered further for future tests.

Future laboratory testing may help to address the limitations identified above; however, the experimental setup still maintains significant differences from field/harbour conditions: it is an enclosed volume where natural mixing with surrounding water does not occur. Furthermore, the panels are free from fouling so the cleaning efficacy and any associated impacts of removing fouling from the coating are not captured. We therefore intend to work with stakeholders to address any outstanding questions to progress to field trials to characterize the cleaning process in harbour on an operational vessel, and to quantify the financial and environmental benefits of routine hull cleaning.

3 DETAIL DESIGN OF HULL CLEANING ROBOT

Prior to starting this project, we completed an internal engineering design study to determine if it was physically possible to use a tethered robot to clean the hull of a moving vessel. As part of this study, we developed the preliminary robot design shown in Figure 3-1. We also sourced major components and worked with consultants to simulate[1] the robot under expected operating conditions to quantify loads (Figure 3-2). This work confirmed that it was possible to maneuver ODL's hull cleaning robot along the sides and bottom of the hull while the vessel was underway at up to 15 knots (highest speed simulated).

One of the outcomes of the preliminary design study was identifying the need to develop a custom set of tracks to maneuver the robot along the hull. No companies were identified that offered an off the shelf product that met our needs. Eddyfi Technologies, a Canadian robotics company, does produce a track that closely matches the payload and traction capabilities we require. But the top speed of these production tracks is only about 25% of our target speed.

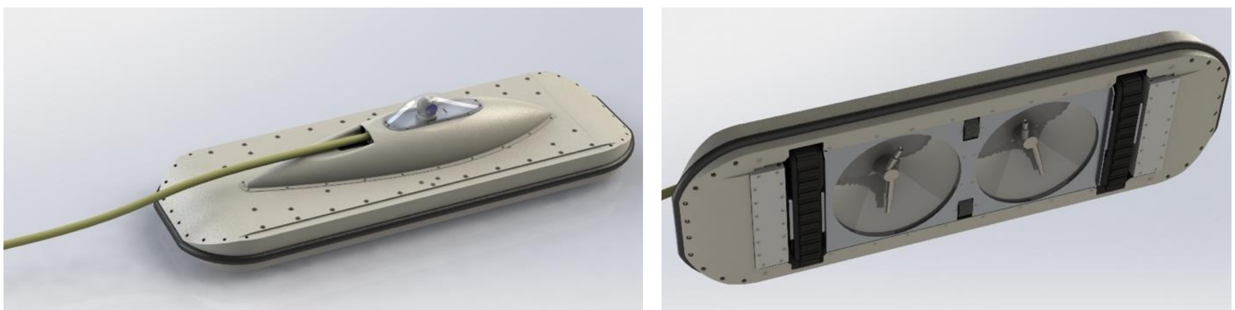
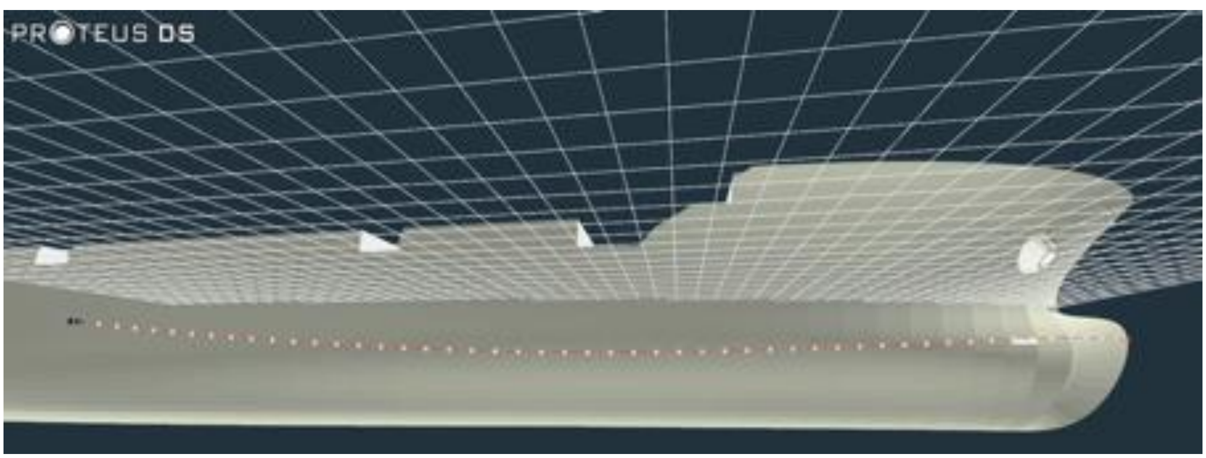


Figure 3-1: Preliminary Design



[1] Simulation completed by Dynamic Systems Analysis using their in-house finite element software ProteusDS. A finite element umbilical and umbilical-hull contact modes were used to calculate the loads.

Figure 3-2: Computer simulation of ODL robot tethered to the bow of a moving vessel

The next step in our technology development path was to complete the detailed engineering design so that we could proceed onto building and field testing the robot on a target vessel.

The key design goals for the robot were as follows:

- Clean the entire hull with exception of bulbous bow, section aft of propeller, and appendages/grates at speeds up to 15 knots – robot needs to be able to generate enough pull force to overcome the drag of the umbilical.
- Remain magnetically attached to the hull and drive above water for deployment & retrieval.
- Clean an average size vessel (200m long) in less than ½ a day – target cleaning rate of 1,200 m^2/h

The steps taken to arrive at a final design were as follows:

a) Physically test key components to quantify performance to inform the detail design (section 3.2).
b) Establish design requirements for the robot (section 3.3).
c) Work with Eddyfi Technologies to develop custom high-speed tracks (section 3.4)
d) Work with engineering consultants and suppliers to complete the final design of the hull cleaning robot including creating a bill of materials (BOM), cost estimate, weight estimate and specification (section 3.5).
e) Assess the ability of the robot to operate in cold climates (section 3.6).

3.1 Design Team

Our in-house expertise is primarily in mechanical/marine design and system integration. To round out the team, we worked closely with the following consultants and suppliers to design the instrumentation package, test and select components, design custom tracks and complete the required electrical integration:

- **Eddyfi Technologies:** Design of custom high-speed tracks & support during shop testing of production tracks under expected operating conditions.
- **Vital Engineering:** Design and Finite Element Analysis (FEA) of custom magnet modules.
- **Reach Systems:** Support with integration of cameras, lights, and instrumentation.
- **MacArtney:** Supplier of sub-sea cables, connectors, underwater cameras, and a range of underwater technology.
- **Mark Bustin:** Independent contractor specializing in design and implementation of instrumentation.

In addition, we hired two recent graduates in mechanical engineering from the University of Victoria for 6-month internships to assist with design and testing. The two internships were partly supported by the NRC-IRAP Youth Employment Program (YEP).

3.2 Component Testing

We performed the following physical tests prior to starting the detail design:

- Test capability of Eddyfi's production tracks for our specific application.
- Quantify attraction force of magnets as a function of distance from a steel plate.
- Quantify the coefficient of friction of the tracks on bare steel as well as painted panels – both wet and dry.
- Investigate if tracks will damage the paint.

3.2.1 Performance of Standard Minimag Tracks

The Eddyfi Minimag crawler, equipped with 8000 series tracks is shown in Figure 3-3.

As per Eddyfi's specification, a crawler, equipped with two 8000 series tracks, carrying 140 kg payload over a flat surface has a rated pull of 68 kg under continuous duty. While this basic information is useful, we needed to perform a series of experiments to establish the performance envelope for our specific application.

We therefore completed a series of tests to have first-hand experience operating the tracks and determine their capabilities for our application. For reference, the mass of the as tested crawler was recorded at 31.3 kg.

Figure 3-3: As tested Minimag crawler with 8000 Series tracks

To start, we confirmed the speed of the tracks by running them over a fixed distance and recording the time it took to travel that distance. The measured speed of 0.106 m/s matched the speed displayed in the software program used to control the robot.

Next, we quantified the payload and available pull force by driving the crawler up a vertical ¼" thick steel wall with a range of weights attached to the robot as shown in Figure 3-5. The payload was varied by changing the offset distance (i.e. air gap) between the bottom of the magnets and steel plate (see Figure 3-4). The crawler was secured overhead to an engine hoist to prevent it from falling.

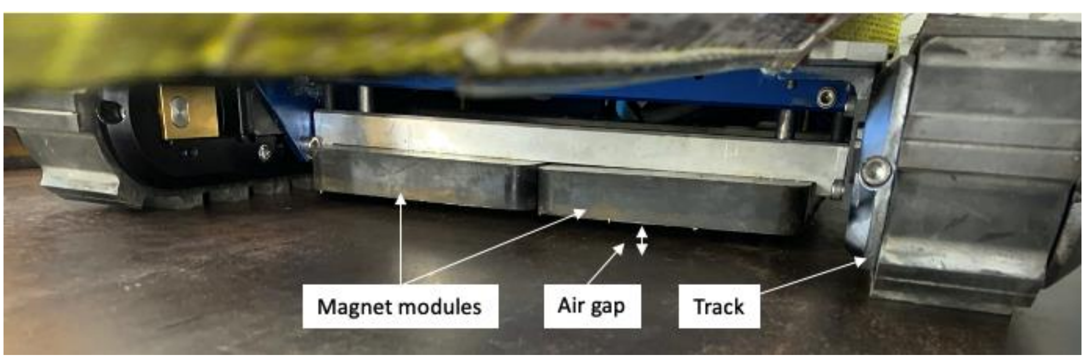


Figure 3-4: Airgap shown between magnet modules and steel plate

The limiting factor for all tests was the traction capability of the tracks on the steel plate. In other words, for a given magnetic attraction force, the robot could only pull up to a certain weight before the tracks slipped.

The maximum pull force recorded was 1,070 N under a 1,653N payload applied by the magnets. Additional magnets would have been required to increase the payload.

Slipping was the limiting factor and not motor stall. We were therefore able to determine the coefficient of friction between rubber tracks and steel plate (see section 3.2.3 for coefficient of friction experiments).

Figure 3-5: Available power test setup

3.2.2 Magnetic Attraction Force

3.2.2.1 Main Magnet Tray

Tests were performed to measure the holding strength of the main magnetic tray as a function of:

a) offset distance from a steel plate
b) plate thickness

The experimental setup for these tests is shown in Figure 3-6. The crawler was placed on the steel plate and secured to an engine hoist via a sling. The sling was secured to the handles on the crawler chassis. A digital scale recorded the pull force exerted by the engine hoist on the crawler. The peak pull force was recorded for each experiment that resulted in the crawler detaching from the steel plate. The mass of the crawler and rigging (26.8 kg +0.9 kg = 27.7 kg) was subtracted to derive the magnetic attraction force. Readings were taken a minimum of two times at the offset distance listed in Table 3-1.

Table 3-1: As tested offset distance between magnet module and steel plate

Offset distance [mm]
25.15
22.85
20.65
18.15
15.15
13.15
10.15
7.65

Figure 3-6: Experimental setup for magnetic strength tests

While performing the first set of tests (Exp A), it was noted that we were initially not pulling on the center of the magnetic attraction force of the robot but rather on the centre of gravity. This caused us to generate a moment that pulled the vehicle off at a lower pull force. Tests were therefore repeated (Exp B) with the location of the sling attachment point better aligned with the magnetic centre. Nevertheless, the initial tests provided important insight into the reduction in magnetic attraction force that occurs if a relatively small moment on the order of 1” is introduced. Figure 3-7 shows the difference in pull force a 1” moment can cause.

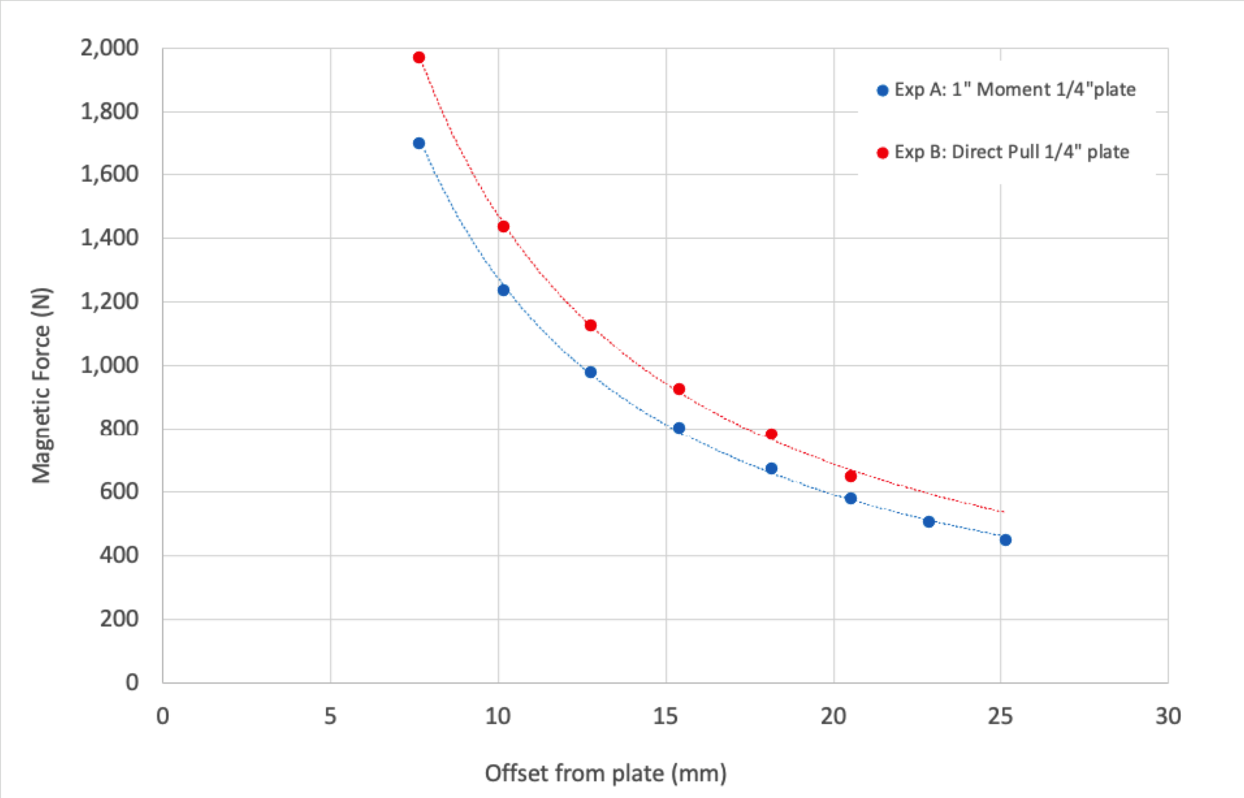


Figure 3-7. 1/4" Magnetic Offset Test showing pulling at centre of gravity and 1" off CoG

The same test matrix was repeated (Exp C) to quantify the effect of plate thickness by stacking two ¼" plates to create an equivalent ½" thick plate (a ½" plate was not available at the time of testing). The two plates were clamped together at the edges and held down by the legs of the engine hoist. But it cannot be verified they did not come apart a small (~ 1 mm) amount during the experiment. As shown in Figure 3-8, there is a small difference between the force required to lift the vehicle off ¼" plate versus two stacked ¼" plate. The measurements show that it is easier to lift the vehicle off two ¼" plates than ¼" plate. This was not the expected outcome.

In general, the attraction force increases as a function of plate thickness up to a certain thickness. Once the plate is no longer saturated by the magnetic field then additional increase in plate thickness no longer impacts the magnetic attraction force.

The tests performed to investigate the effect of plate thickness on magnetic attraction force should therefore be repeated in the future as required. A single ½" thick steel plate should be used to remove the uncertainty associated with stacking two ¼" thick plates.

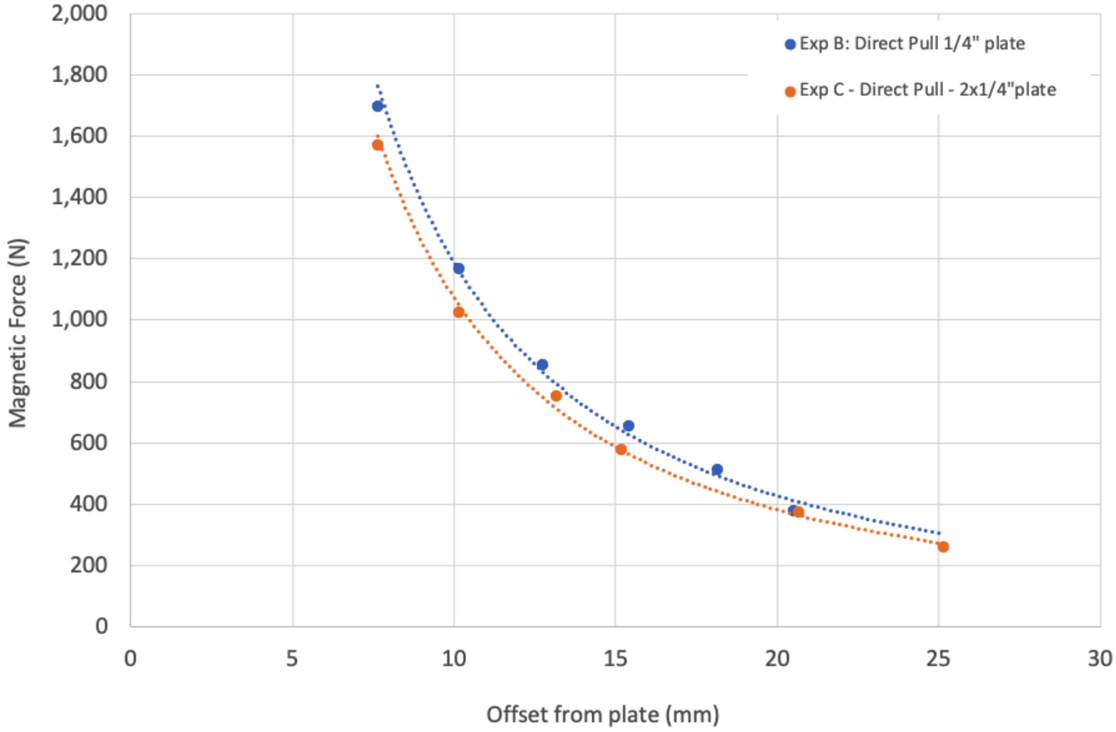


Figure 3-8: Magnetic Offset Test showing difference between 1/4" and 1/2" plate

3.2.2.2 Auxiliary Magnets

Eddyfi supplies additional magnet modules that can be mounted at the front of the crawler chassis. Up to six magnetic blocks can be added as shown in Figure 3-9.

Figure 3-9. Front magnet test setup. Location of force (left), method of shimming magnets (right)

3.2.3 Coefficient of Friction

3.2.3.1 Tracks on Steel Plate

The Friction force is defined as follows:

Friction Force = μ × Normal Force (Equation 1)

Where:

Friction Force = Force that resists sliding of the object

μ = Coefficient of Friction

Normal Force = Force acting on the object perpendicular to the surface

Equation 1 can therefore be used to calculate the coefficient of friction if the friction force and normal force are known.

An experiment was devised to quantify the coefficient of friction. The tests were performed by driving the crawler up the vertical steel wall as shown in Figure 3-5. The coefficient of friction between the dry steel plate and the rubber tracks was calculated based on the force at which the tracks began to slide for a given normal force. For this experiment, the normal force is the magnetic attraction force between the steel wall and crawler.

As shown in Figure 3-5, weights of known mass were secured to the crawler and suspended. The magnetic force was varied until the tracks began to slip and the crawler could no longer advance up the wall. For this condition, the friction force between the tracks and wall were equivalent to the weight suspended below the robot. Equation 1 was then used to calculate the friction coefficient based on a known normal force (magnetic attraction force) and known friction force (force between tracks and wall that equals the suspended weight).

Equation 1 was re-written to reflect the terminology used by Eddyfi to characterize the tracks in terms of pull force (see Equation 2). The pull force is equivalent to the friction force between the tracks and the wall. This pull force directly counteracts the weight suspended from the crawler provided that the crawler is not accelerating. The normal force is the magnetic attraction force between the crawler and wall which is equivalent to the normal force.

Pull Force = μ × Normal Force (Equation 2)

Where:

Pull Force = Friction Force = Weight suspended from crawler (incl. weight of crawler)

μ = Coefficient of Friction

Normal Force = Magnetic attraction force between crawler and steel plate

The pull force as a function of normal force is provided in Figure 3-10. The coefficient of friction of 0.61 can be calculated by taking the slope of the line.

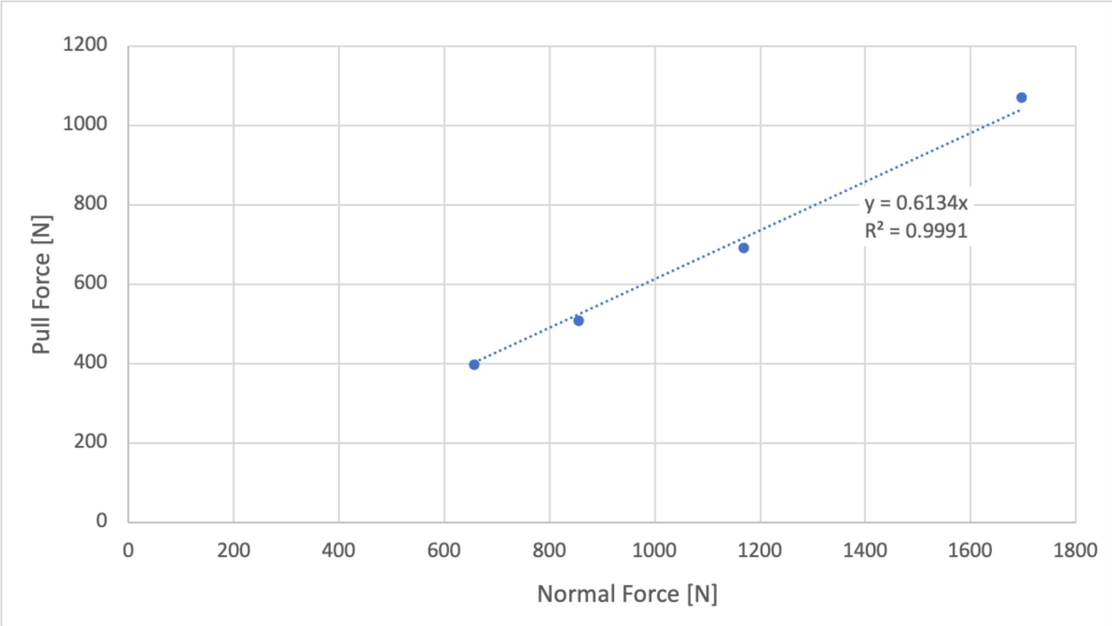


Figure 3-10. Max pull force as a function of normal force before the vehicle slipped

3.2.3.2 Tracks on Painted Panels

As a final test, the Eddyfi crawler was run in both wet and dry conditions on the following four paint types:

1. Hempasil X3 Foul Release paint by Hempel
2. Intersleek 1100 SR Foul Release paint by International Paints
3. Interspeed 640 CDP paint by International
4. Olympic 7660 CDP paint by Hempel

The experimental setup for the tests is shown in Figure 3-11 in graphical format. Pictures of the actual experiment are provided in Figure 3-12. As shown, a temporary watertight basin was built for these experiments. A frame was secured to the bottom of the basin onto which the four different painted panels were mounted. One end of the basin was secured to a beam. The crawler was placed onto the plate and secured to another beam. A digital scale was placed between the fixed beam and crawler to measure the pull force as a function of the weight loaded onto the robot chassis. The robot was slowly driven forward, and the pull force was recorded. A video was taken of the scale for each experiment to capture the static and dynamic coefficient of friction. Experiments were first conducted in dry conditions. The basin was subsequently filled with water to measure the pull force under wet conditions. For clarity, the magnets were removed for these tests.

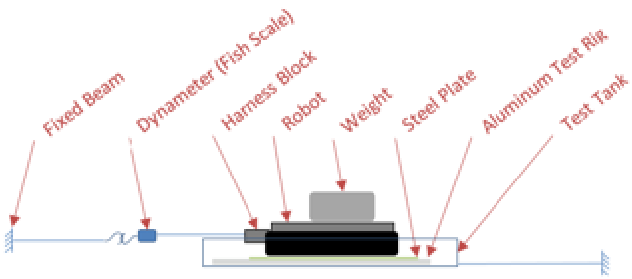


Figure 3-11: Experimental setup for friction tests

Equation 1 was rewritten as follows to calculate the coefficient of friction for this set of experiments:

$$\text{Pull Force} = \mu \times \text{Normal Force} \quad \text{(Equation 3)}$$

Where:

Pull Force = Friction Force = Force recorded using digital scale

μ = Coefficient of Friction

Normal Force = Weight placed on robot + weight of robot

For these experiments, weights of known mass were used to generate the normal force instead of using magnets. The normal force is therefore the sum of the weights placed on the robot plus the weight of the robot. Equation 3 was therefore used to calculate the coefficient of friction based on the measured pull force and known normal force (ie. payload).

Figure 3-12: Experimental setup for testing tracks on paint. Left: crawler with 80 lb payload. Right: crawler with 260 lb payload

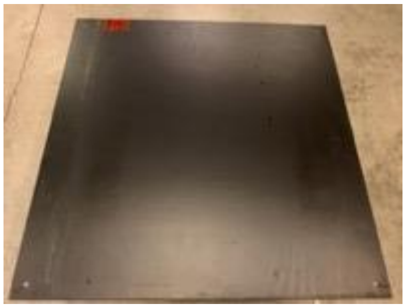
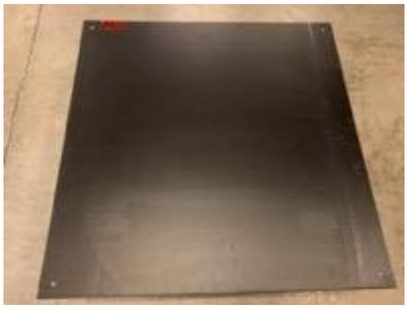
Results from these experiments are deemed proprietary and thus excluded from the public version of this report.

3.2.4 Wear from tracks on painted panels

The physical impact on the painted panels was visually inspected after each set of tests, for both wet and dry conditions. Minimal to no marking of the panels was observed even under the highest load placed on the crawler. At the end of each test, the crawler was driven continuously in an aggressive manner (full speed, turning in place and skidding) with the highest load tested (160 kg – 1574 N). Since the crawler was secured to the post, the tracks were continuously skidding.

Pictures of all the panels post testing are provided in Table 3-2 included noted observations. In general, there is evidence of wear on all panels in the location of highest down pressure where track skidding occurred. We are encouraged by these results since they demonstrate that even when the tracks skid continuously for a substantial time duration, the paint remains intact. And it is likely that a study on track tread and durometer would yield a track design that further reduces the chance of marking up the coating.

Table 3-2: Pictures of painted panels post testing

Coating Type Observations	**DRY TEST** (After 1 min skidding tracks)	**WET TEST** (After 1 min skidding tracks)
Intersleek 1100 SR Wear from tracks observed after dry tests but not after wet tests		
Interspeed 640 Wear from tracks observed after dry tests as well as wet tests – but to a lesser degree		
Hempasil X3 Wear from tracks observed after dry tests as well as wet tests – but to a lesser degree		
Olympic 7660 Similar wear from tracks observed after dry tests as well as wet tests.		

3.3 DESIGN REQUIREMENTS

All the physical tests completed allowed us to inform the detail design of the robot and set requirements for the detail design. The requirements that form the basis of the detail design are provided in Table 3-3.

Table 3-3: Requirements for Detail Design of Hull Cleaning Robot

ID	Requirement	Metric	Description
1	Cleans ships while underway	-min speed 8 kn -max speed 15 kn -(25kn nice to have)	Up to 15 kn encompasses tankers & bulk carriers but not container ships, cruise ships and most navy and coast guard vessels travelling at top speed.
2	Completes clean for 200 m vessel in 24 h or less	-target cleaning rate of 1,200 m^2/h	The target cleaning rate of 1,200 m^2/h is specified as this is the maximum reported capability of two CavitCleaner stingray rotating nozzles.
3	Does not cause damage to existing hull coating	-zero observable or measurable paint damage using a DFT gauge	- applies to both cleaning system and tracks used to navigate along the hull.
4	Does not impact ship speed	-zero change in ship speed during cleaning	no change in ship speed required to operate robot
5	Is capable of cleaning ships up to 300 m long	-300m long ship	Most merchant vessels except for the largest container ships are 300 m or less. A practical limit needed to be placed even though the largest vessels approach 400 m in length.
6	Cleans vessel sides below waterline and flat bottom	Pass/Fail	
7	Cleans soft fouling - up to FR 30 (slime & grass)	Pass/Fail	Not necessary to clean hard fouling (barnacles)
8	Complies with local, national and international regulations.	Pass/Fail	
9	Operates in the dark	Pass/Fail	Can function at night and under the hull where visibility is limited
10	Safe for crew and operator	Pass/Fail	Design cannot endanger crew (e.g. electrocution)
11	Safe for environment (invasive species & chemicals)	Pass/Fail	
12	Must not impact maneuvering requirements including emergency operations.	Pass/Fail	The vessel integration gear cannot interfere with any of the ships mooring arrangements and the robot or gear cannot limit the ability of the ship to conduct emergency braking or maneuvering
13	Cleaned areas to meet Port of Entry requirements re: invasive species (does not apply to niche areas)	Pass/Fail	Any cleaned areas should meet requirements for invasive species to avoid need for re-cleaning same areas in Port.
14	Cleaner head conforms to hull curvature including bulbus bow	Pass/Fail	

Requirement no. 2 is linked to the speed of the Eddyfi tracks and the cleaning rate of the CavitCleaner Stingray rotating nozzles. The cleaning rate of two Stingrays placed side by side is specified as 1,200 m^2/h. But using the standard Eddify 8000 series tracks results in a maximum cleaning rate of only 288 m^2/h. The goal of the detailed design is therefore to increase the speed of the tracks to match the capabilities of the cleaning system more closely.

Testing the Stingray rotating nozzles on the four different paint types as part of Phase 1 provided us with the confidence that the cleaning system will not damage the coating when tuned to the manufacturer's recommended operating conditions.

Similarly, running the crawler overtop of the painted panels without causing damage (with a payload of 1574 N representative of highest load case) provides us with the confidence that the tracks will not damage the paint.

Calculating the coefficient of friction on the different coatings allows us to specify the magnetic attraction force required to handle the tether while the vessel is at speed and maintain the robot secured to the hull. The magnetic attraction force which acts normal to the surface is determined by dividing the pull force by the coefficient of friction. The pull force acts parallel to surface and is the sum of the tension on the umbilical and the weight of the robot when in vertical position.

3.4 DESIGN OF CUSTOM HIGH-SPEED TRACKS

One of the key objectives of this project was to work with Eddyfi Technologies to develop a custom track design capable of meeting both our payload and speed requirements. The Minitrac 8000 – the most capable tracks offered by Eddyfi meets the payload requirements but only at 25% of the target speed, namely 0.1 m/s vs. 0.4 m/s.

3.4.1 Requirements specific to tracks

To start, we provided Eddyfi with design requirements including predicted loading on the umbilical, the weight of the robot and the tether as well as general operational profile (see Table 3-4).

Table 3-4: Custom Track Requirements

Item	Requirement
Torque	▪ Same as Minitrac 8000 as tested (~30 Nm)
Speed	▪ 0.3 – 0.4 m/s
Umbilical pull force:	▪ 400 N during operation
Umbilical weight	▪ 1.1 kg/m in air (fluid filled) ▪ 0.01 kg/m underwater (fluid filled)
Length of umbilical suspended in air during retrieval	▪ 15 m
Hull Cleaner Mass	▪ 70 kg
Coefficient of Friction	▪ 0.5 *(specified based on experiments to encompass majority of coatings – especially most commonly used ablative coatings)*
Operation:	▪ The tracks are required to use skid steering for maneuvering. ▪ The vehicle will be operating in the splash zone, above and below the waterline on ship hulls. ▪ Normal operation below waterline for long durations up to 24h ▪ Retrieval operation above waterline for short durations on the order of 10min ▪ Direction of travel during cleaning up and down vertically along the hull

A target speed range of 0.3-0.4 m/s was provided to Eddyfi instead of a hard number of 0.4 m/s to allow Eddyfi engineers some flexibility in design. If, for example, achieving 0.4 m/s instead of 0.35 m/s, required a custom gearbox, or a motor from a different supplier then Eddyfi has experience using, then this could lead to significantly higher development and equipment costs.

The intended method of cleaning the hull is to start cleaning near the bow and work towards the stern as depicted in Figure 3-13. The hull cleaner will make sweeping passes in a vertical direction from waterline down to the keel and back up again. At the end of every pass, the winch will let the umbilical out the width of the cleaning system (0.8 m).

This vertical cleaning pattern is preferred when compared to having the robot traveling back and forth along the length of the hull (horizontally) for 2 reasons:

1. Vertical passes minimize the number of times the cable is paid in and out. This results in less wear on the winch, pulleys and umbilical and reduces the risk of uneven cable spooling during operation.
2. It is easier to maintain a small overlap distance between vertical passes. The drag on the robot will ensure that the umbilical remains taught such that the arc path followed by the robot is consistent from one sweep to the next (to be verified during field trials). It should therefore not be necessary to rely heavily on video or other sophisticated imaging or positioning methods to control the path of the hull cleaning robot. Conversely, if cleaning is done in a horizontal pattern, the operator would need to maintain a clear visual of the edge of the last pass. This may prove very difficult in practice and would also be challenging to automate in the future – basic feedback such as pressure/water depth would not have adequate accuracy due to the dynamic waterline (ocean waves & wave making by the hull).

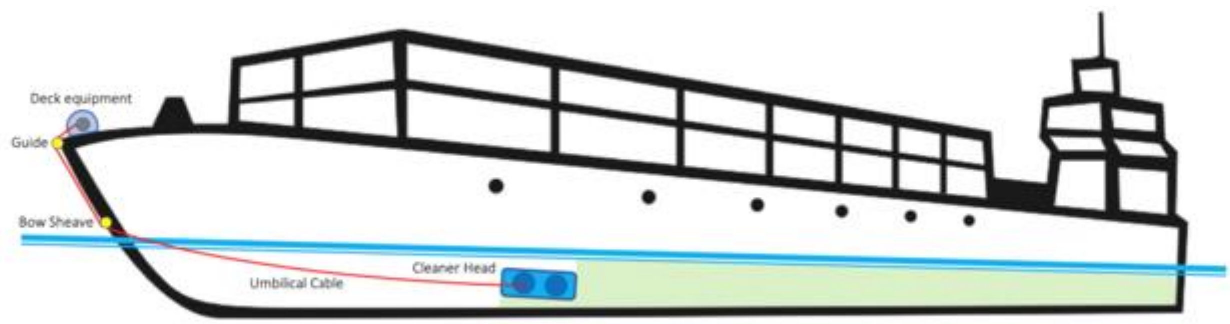


Figure 3-13: Hull cleaner mode of operation

After providing the requirements listed in Table 3-4, we began to explore design alternatives with both Eddyfi and Electromate – Eddyfi's motor supplier and motor specialist. We investigated multiple motor gearbox options and assessed the overspeed capabilities of the motors when operating underwater. Operating underwater provides excellent cooling for the motors which is a key factor when assessing how hard and for what duration the motors can work without overheating.

Ultimately, two options emerged:

1. Completely redesign the tracks by placing a more powerful motor on the outside of the tracks and coupling it directly to the drive wheel. This is a common layout for tracked vehicles and would be a viable option for the hull cleaner as there is adequate internal space to accommodate a motor mounted at 90 deg to the track.
2. Widen the Minitrac 8000 to accommodate a more powerful motor – or multiple motors in parallel inside the track.

Option 2 was selected as the most viable design path to meet our requirements as it could build on an the existing Minitrac product line. Eddyfi's report provided in Appendix A outlines the mechanical and electrical design process in detail including all sizing calculations and justification for design decisions.

3.4.2 Results

The final solution proposed by Eddyfi is to use two motors inside a double wide track as shown in the CAD model in Figure 3-14.

Figure 3-14: CAD model of Dual-motor double wide track

3.4.2.1 Motor-gearbox ratio

Multiple motor-gearbox combinations were considered. Four design alternatives ranging in speed and torque capability were presented to provide us a range of options. The motor-gearbox selection will be finalized once the exact weight of the robot is known, and the performance requirements are verified by testing a prototype in the field.

3.4.2.2 Brake motor

Eddyfi recommended that a motor brake should be added which is not standard on existing tracks. Existing tracks rely on maintaining motor power and using dynamic braking to hold position for short time durations. If power to the motor is lost, the hull cleaner could slide down the hull if the tracks were in the vertical position. Moreover, using dynamic braking for extended periods of time is not recommended as it can burn out the motors. A brake motor is an available option from Maxon – the motor supplier.

The decision whether a brake motor is indeed required will be made once we gain operational experience during field trials. A simple solution to avoid loading up the motors when stationary for prolonged periods of time would be to park the robot with the tracks in a horizontal direction.

3.4.2.3 Operating voltage

For the custom designed tracks, Eddyfi provided several voltage ranges that could be supported by the power electronics onboard the robot along with benefits and consequences of each selection. At this time, it is assumed that a 200-400 VDC option would be selected to minimize the diameter of the tether (higher voltage & lower current = less copper required) and reduce the voltage losses through an umbilical cable that may be up to 300 m in length.

3.4.2.4 Power electronics

Due to the higher power requirements, the drive electronics (motor controller, power converter, circuit boards, etc – see Section 4.1 in Eddyfi Report – Appendix D) cannot be housed inside the tracks as is the case with the production single motor Minitrac 8000. This is partially due to space constraints, but primarily due to the need for greater heat and power dissipation. A separate submersible enclosure is therefore required with an estimated added mass of 6-9 lb/track in air that could be made neutrally buoyant underwater.

3.4.2.5 Mass

The final mass provided for the custom dual motor track is estimated based on the current CAD model at 9.75 kg/track (21.5 lb/track) compared to 5.7 kg/track (12.5 lb) for a standard production Minitrac 8000. The mass of the electronics enclosure estimated at 2.7-4.0 kg (6-9 lb/track) needs to be added to the overall mass of the Eddyfi track system. The total maximum mass of two tracks and electronics enclosure will therefore be 43 kg.

3.4.2.6 Cost/Price

Additional non-recurring engineering (NRE) will be required to complete the engineering, fabrication drawings, assembly and factory testing to produce a custom track

Once this non-recurring engineering is complete, the price of each custom track will be approximitly twice that of a standard Minitrac 8000.

The cost of the standard tracks, custom tracks and NRE required to develop the custom tracks is deamed confidential and thus exluded from the public version of this report.

3.4.3 Conclusions

Eddyfi successfully developed a custom dual motor track solution that meets the operational requirements we provided for our hull cleaning robot (see Table 3-4).

Eddyfi also provided two additional dual-motor alternatives capable of producing higher torque should the weight and/or loads on the robot be greater than our current estimates. The trade-off to achieving higher torque with the same motors is track speed.

The price of the custom dual motor tracks is about twice that of the production Minitrac 8000.

In addition, an upfront investment is required to develop the first production version of the custom dual motor tracks.

Before such an investment is made, it is critical for us to ensure that the design requirements provided to Eddyfi are accurate to avoid incurring additional cost for re-design and replacement of components. The loads and operating conditions can only be verified by field testing a prototype on a moving vessel.

Fortunately, our shop testing and Eddyfi’s analysis have confirmed that the production Minitrac 8000, is well suited for our application - except for speed. It is therefore possible for us to proceed with utilizing these off the shelf tracks for building the initial prototype.

The lower track speed means that it will not be practical to clean large ocean-going vessels using the prototype robot because it would take several days of continuous cleaning. Nonetheless, the prototype robot would be well suited for cleaning smaller vessels such as local barges or ferries as this could be done in less than a day.

3.5 Final Design of ODL’s Hull Cleaning Robot

The final design of the hull cleaning robot is presented in Figure 3-15. This design incorporates the custom dual motor Eddyfi tracks. A drawing with principal dimensions is provided in Figure 3-16. The robot has the following features:

- Capable of cleaning both stationary vessels and while the vessel is in transit at up to 15kn.
- Cleans using two pairs of rotating cavitating waterjets.
- Attaches to the hull surface using magnets.
- Drives along the hull using non-marking powered tracks.

- Remotely operated from the surface via an umbilical (power, communications, and pressurized seawater).
- 4 cameras and 6 LED lights for navigation.
- Frame that pivots above centre to conform to curved hull surface.

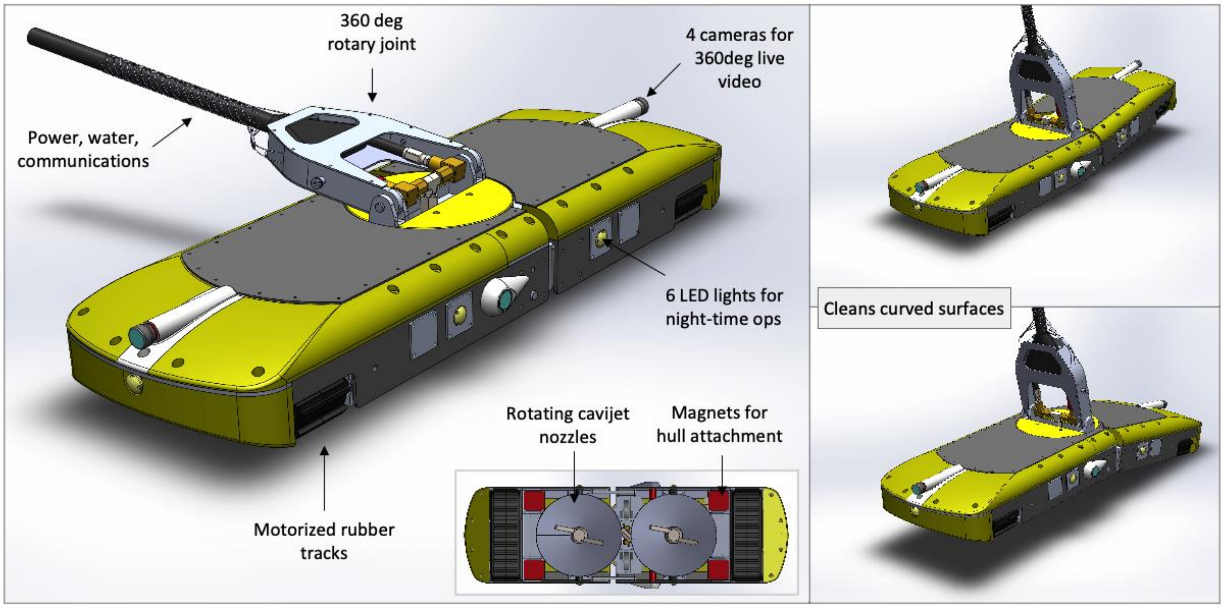


Figure 3-15: CD CAD model of Final Design

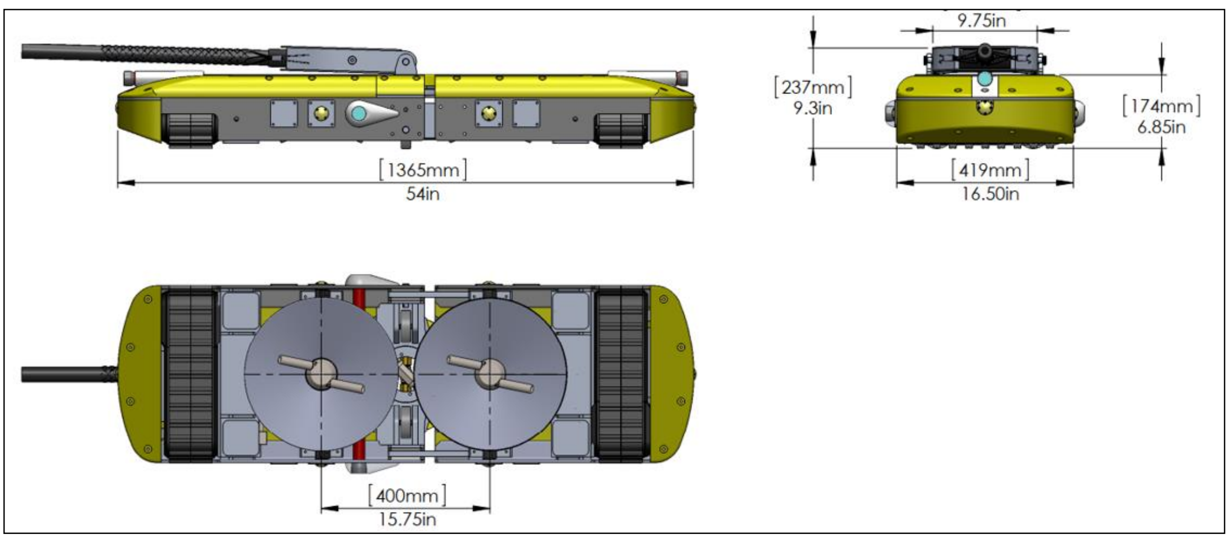


Figure 3-16: CAD model showing principal dimensions

Table 3-5 provides a specification for the final design. The two main factors that govern the final speed of the tracks are the robot mass and how well it adheres to the hull (coefficient of friction between rubber tracks and hull coating). If the robot is very heavy, a high magnetic attraction force is required to ensure the robot can counteract the drag forces on the umbilical when operating underwater and the force of gravity when operating above water. One of our guiding design principles was therefore to minimize the mass of the robot.

The final mass of the robot was calculated to be 74 kg. This mass is very close to the 70 kg estimate we provided Eddyfi. Based on the outcomes of Eddyfi design study, it is therefore possible that we may be able to use a gearing ratio that allows us to achieve our target speed of 0.39 m/s.

Table 3-5: Final design specification

Parameter	Value
Length	1.365 m (54 in)
Width	0.42 m (16.5 in)
Height (excluding rotary joint)	0.174 m (6.85 in)
Mass	74 kg (163 lbs)
Cleaning system	Pair of rotating cavijet nozzles
Operating water pressure	160 bar (2300 psi)
Flow Rate	53 l/min (14 gpm)
Cleaning width	0.8 m (31.5 in)
Speed	0.27-0.39 m/s (1.28ft/s)
Cleaning rate	778- 1,120 m^2/h
Surface supply voltage	400 VDC
Umbilical Diameter	1.375

As explained in section 3.4.3, the design speed of the robot will be finalized by field testing an initial prototype equipped with Eddyfi's standard Minitrac. As shown in Figure 3-17, limited changes need to be made to the design to make use of the standard track vs. the dual motor and double wide track.

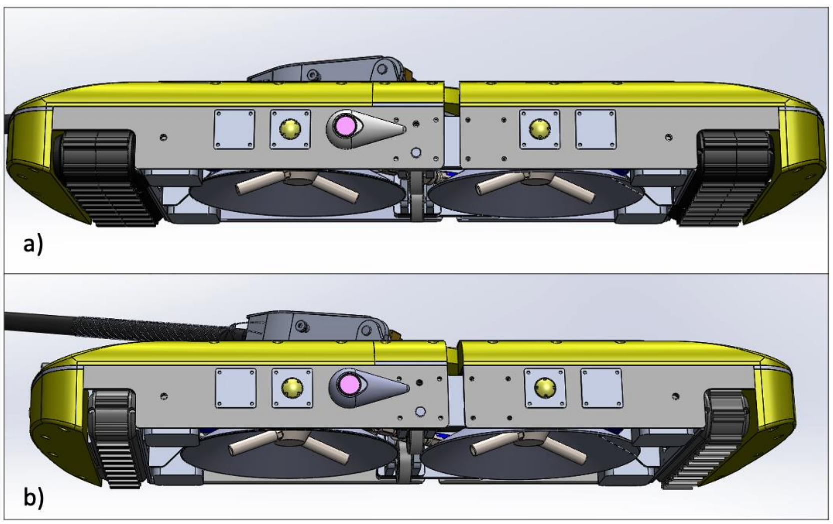


Figure 3-17: a) Final design with custom tracks vs. b) prototype with standard tracks

3.5.1 Design of Hydrodynamic Shell

The hydrodynamic shell comprises all components shown in yellow in Figure 3-15. The shell serves the purpose of:

a) providing buoyancy,
b) streamlining the shape of the robot to minimize drag and to
c) protect sensitive components from impact.

The shell will be fabricated by machining the profiles shown in Figure 3-18 out of closed cell foam designed for marine applications (LAST-A-FOAM R-3318). The pieces are then sanded smooth and painted. The dimensioned drawing shown in Figure 3-18 was provided to Dependable Industries Ltd for quotation. Dependable Industries is a Surrey, BC based company that has a 5-axis CNC cutting machine capable of machining complex shapes out of high-density foam.

Combined, all off the hydrodynamic components that comprise the shell provide 20 kg of buoyancy. The shell therefore offsets approximately 25% of the robot's mass when submerged. Components such as the electronics enclosure will provide additional buoyancy. But in general, a hydrodynamic shell 3-4 times in volume would be required to make the robot neutrally buoyant. Increasing the size of the shell has cascading effects because it increases the drag on the robot as well as the robot's weight above water.

The shape of the shell was designed based on general hydrodynamic best practices such as rounding corners, maintaining curvature, and avoiding sharp transitions.

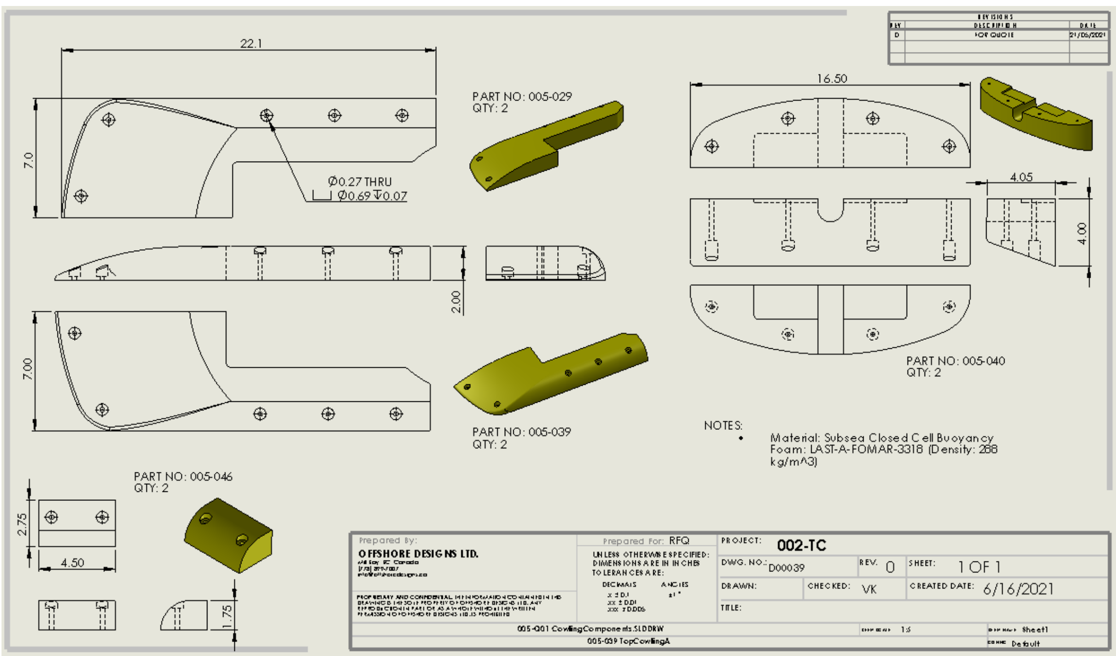


Figure 3-18: Hydrodynamic Shell Components

The drag force (F_d) was estimated to quantify design loads using Equation 2:

$F_d = 0.5 \cdot C_d \cdot \rho \cdot A \cdot v^2$ (Equation 2)

Where,

C_d = drag coefficient
ρ = density (1027 kg/m^3 for seawater at 10 deg C)
A = frontal area (m^2)
V = speed of water near ship hull (m^2/s)

A drag coefficient of 0.3 was used for the calculation based on published data for drag of vehicles in close proximity to a surface (see Figure 3-19). As shown in Figure 3-19, a relatively streamlined vehicle such as (b) has a drag coefficient of 0.24. A vehicle with a sharp windshield such as (c) has a drag coefficient of 0.35. Streamlining that windshield lowers the drag coefficient to 0.23. Based on these examples, a nominal drag coefficient of 0.3 was deemed achievable. Advanced analysis such as computational fluid dynamics (CFD) simulations of the waterflow along the shell were not warranted.

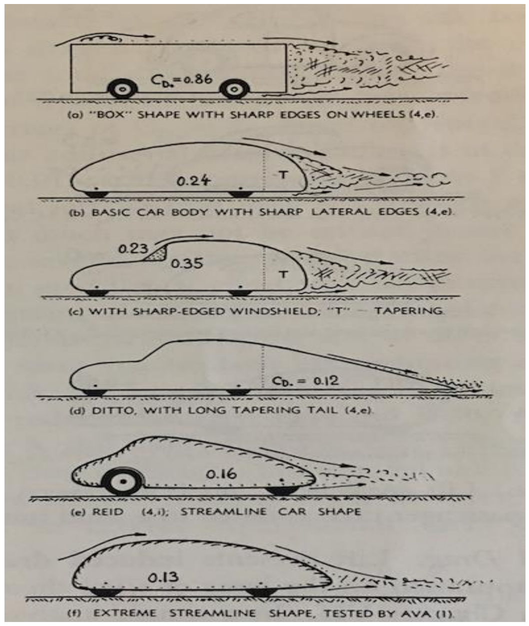


Figure 3-19: Drag coefficients of vehicle shapes close to ground [4]

3.5.2 Mechanical Design

The structural components are designed primarily out of aluminium to minimize the weight of the robot. Non-structural components such as spacer for the magnets, wear pads at the frame's pivot joint and the bearing surfaces used for the main rotary joint are made of high-density polyethylene (HDPE) to reduce weight and add buoyancy. HDPE is a plastic with good impact and wear resistance properties that does not expand or degrade in saltwater.

A list of loading scenarios was compiled to quantify the loads to inform the mechanical design (see Table 3-6). Typical operating conditions were considered such as while the robot is cleaning or during launch or retrieval. Off-design conditions such as a track failure or the magnets coming in direct contact with the hull were also considered. Finally, extreme off-design conditions were considered such as an impulse load resulting from the robot being dropped from a height of 3 m, or the robot becoming detached from the hull and trolling behind a vessel travelling at 15 kn.

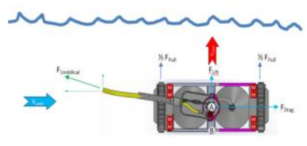
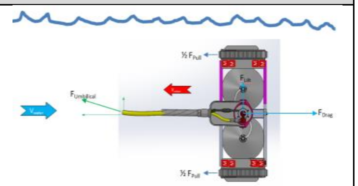
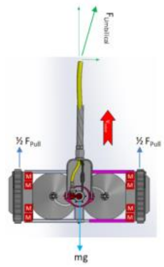
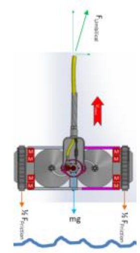
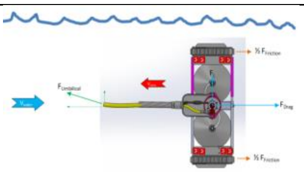
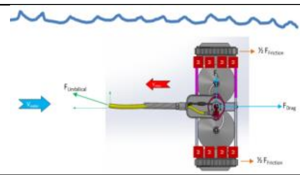
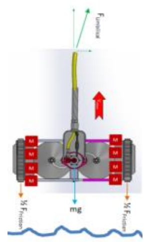
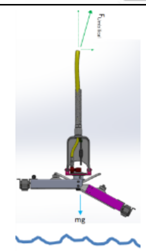
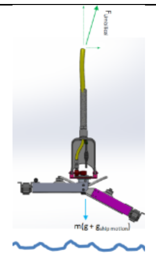
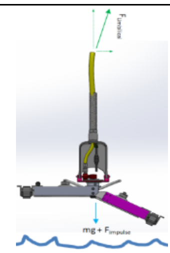
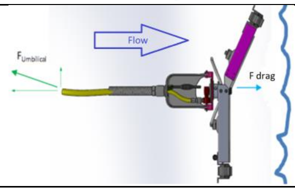
The load at the umbilical-robot connection was calculated for each of these conditions to ensure this critical connection is strong enough to maintain the robot secured to the umbilical.

These load cases were used as the basis for all other mechanical calculations completed to size the structural components and specify the materials. Example structural calculations include:

- Reaction forces at the central robot hinge and resulting loads and stresses in the pins and hinge components.
- Loads in the pins and bushings attaching the 360-degree rotary joint to the cleaning robot.
- Loads and stresses in the main longitudinal frame members running along the side of the robot.
- Reaction loads at the central wheels caused by the magnets.

Our final structural design can withstand all the loading scenarios listed in Table 3-6 except for case 10. Designing the pivot joint to handle an impact load (case 10) that is nearly 70x higher than normal operating conditions (case 2) would necessitate a very robust and heavy design. For example, aluminium components would need to be replaced with steel. Steel is 3 times heavier than aluminium. Instead, we decided to design the pivot joint to meet normal and majority of off-design loads while still maintaining a lightweight robot. We will mitigate against the extreme loads by implementing safe handling procedures. We will also experiment with relieving dynamic/peak loads on the connection by adding flexible elements such as elastic bands that act as dampers.

Table 3-6: Load Cases

Load Case *Operating Condition* Force at umbilical-robot joint	**Free Body Diagram**	**Load Case** *Operating Condition* Force at umbilical-robot joint	**Free Body Diagram**
1. Cleaning *Normal Operation* 885 N		**2. Retrieval** *Normal Operation* 1,696 N	
3. Driving vertically above water *Normal Operation* 184 N		**4. Winching in – track failure above water** *Off-Design* 1,636 N	
5. Winching in + track failure *Off-Design* 3,464 N		**6. Winching in + track failure + magnets bottom out** *Off-Design* 4,842 N	
7. Winching in – track failure and magnets bottom out above water *Off-Design* 3,054 N		**8. Hanging above water** *Off-Design* 726 N	
9. Hanging above water + ship accelerations *Off-Design* 2,904 N		**10. Impulse load** (3m drop) *Off-Design – extreme* 114,600 N	
11. Robot "Trolling" behind the ship *Off-Design – Extreme* 20,639 N			

3.5.3 Design of Magnet Modules

We worked with Vital Engineering (VE) to design the magnet modules. Magnet modules comprise the magnet itself and the housing that encapsulates the magnet(s).

The magnetic modules needed to satisfy the following requirements and design criteria:

1. Design gap between hull surface and magnet housing is ½" (12.7 mm)
2. Total force exerted by all magnetic modules needs to be at least 1,600 N
3. Total quantity of magnetic modules secured to robot must be either 4 or 6, arranged near device's tracks. Each module can comprise multiple magnets.
4. The most lightweight and compact solution is sought.
5. A simple solution is preferred with no moving parts and no hull contact points.

Three design concepts were initially evaluated for a module (magnet (s) + housing) comprising:

1. An array consisting of magnets arranged in a Halbach array pattern.
2. A magnetic array consisting of magnets whose magnetic field is pointing in the same direction.
3. A single magnet

VE used in-house magnet strength calculation sheets to compare the effectiveness of each of the above three configurations by calculating the magnetic pull strength on a steel plate at a distance of 15.2 mm. The 15.2 mm distance was specified based on an initial assumption that the magnets would be housed in a machined housing with a 2.5mm thick base plate. The base plate would therefore increase the offset distance between magnet and plate from 12.7mm to 15.2 mm. The calculations showed that a single magnet of the same total volume as concept 1 and concept 2 produced the greatest magnetic force. While Halbach arrays (concept 1) are effective in concentrating magnetic fields, they were determined to be sub-optimal in an application where a static pull force is required at a gap comparable to the magnet size. This conclusion was reached by VE by quantifying the attraction force of a Halbach array consisting of 4x magnets 1 x 1 x 2" in size oriented as shown in Figure 3-20.

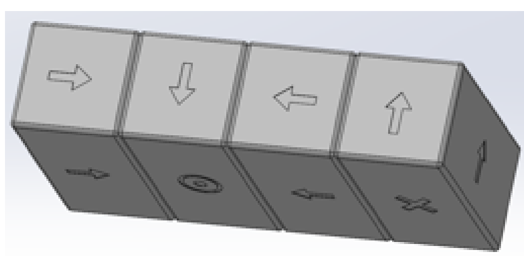
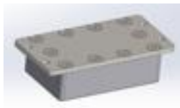
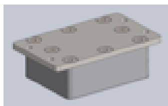
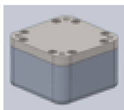


Figure 3-20: Halbach magnetic array considered

Furthermore, VE determined based on first principles calculations that a single magnet outperforms magnetic arrays consisting of multiple magnets with the same magnetic orientation in terms of pull force (with the same overall mass of magnetic material).

VE subsequently analyzed 3 design variants utilizing single magnets sealed inside a custom enclosure. An image of the 3D CAD model of each variant is provided in Table 3-7 along with the size and pull force obtained for each magnet from empirical data published on the K&J magnetics website [5].

Table 3-7: Magnetic module design variants considered

Design Variant #	CAD Model	Magnet Type	Magnetization Direction	Pull Force per Magnet at 15.2mm distance
1		Rectangular, 4x2x1", N52	Through 2" thickness	420 N
2		Rectangular, 3x2x1", N52	Through 2" thickness	290 N
3		Round puck, 3" dia., 1.5" thk, N52	Through 1.5" thickness	510 N

Design Variant 1 uses a single 4x2x1" magnet (same overall size as the array shown in Figure 3-20) and provides magnetic pull force of ~420N per module at the specified distance. This means that the total of 1600 N pull force specified can be achieved (and even slightly exceeded) with 4 such magnetic modules.

If 6 modules are preferred, the magnet may be made smaller by using a single 3" x 2 x 1" magnet housed inside a smaller enclosure (Variant 2)

For a different magnetic module form-factor, four 3" dia., 1.5" thick round magnets may be utilized (Variant 3)

The mechanical design of the three variants is similar. The cross-sectional view of the variant 1 assembly is shown in Figure 3-21 as an example. The magnet (1) is placed inside a custom machined aluminum case (2) and a lid (4) is bolted to the top. A "gap material" (3) is placed between the magnet and the lid to prevent magnetic saturation of the magnet lid and to maximize the pull force of the magnetic modules.

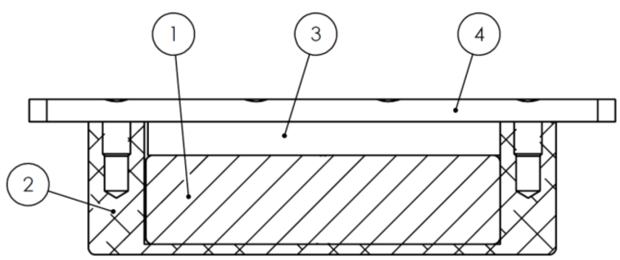


Figure 3-21: Section view of magnetic module containing 4x2x1" magnet (design variant 1)

A Finite Element Analysis using Solidworks Software pas performed on Variant 1 and 3 to ensure that the aluminum magnetic housing could withstand the mechanical stresses imposed by the magnet. The results for variant 1 are shown in Figure 3-22. Variant 2 was not analyzed because using only four magnet modules to achieve the required attraction force was easier to incorporate into the design vs six modules.

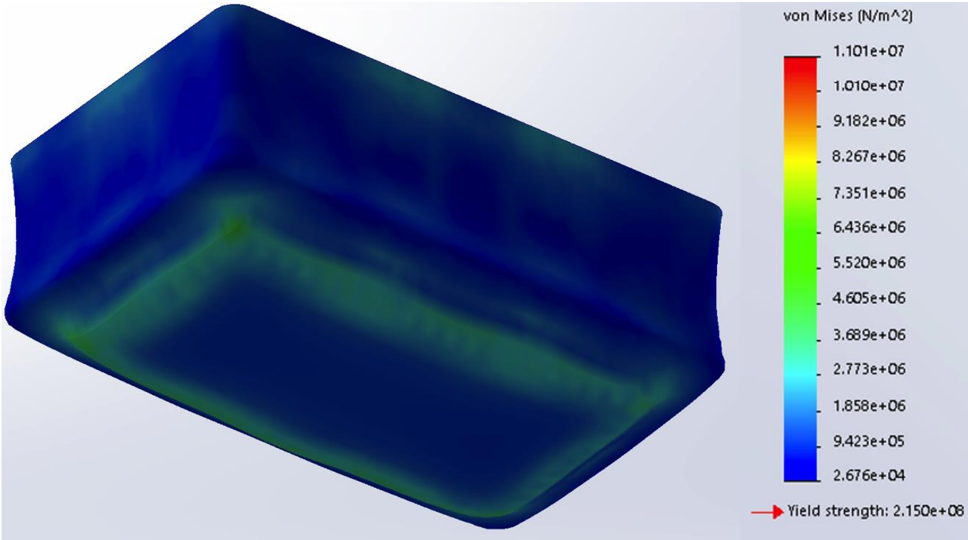


Figure 3-22. Mechanical stresses on design variant 1 magnet housing at 1500N magnetic attraction force

The load shown in Figure 3-22 is the downward force exerted by the magnet when the magnetic module is in contact with a steel plate (worst case scenario). In this scenario, the magnet is separated from a steel plate by the thickness of the magnet case bottom, which is 3 mm. The magnetic pull force in this condition is about 1500 N. As we can see from the above diagram, the lid withstands the applied force with a safety factor of ~20.

Similarly, stress analysis on the magnet case for the design variant 3 was performed. The results are shown in Figure 3-23.

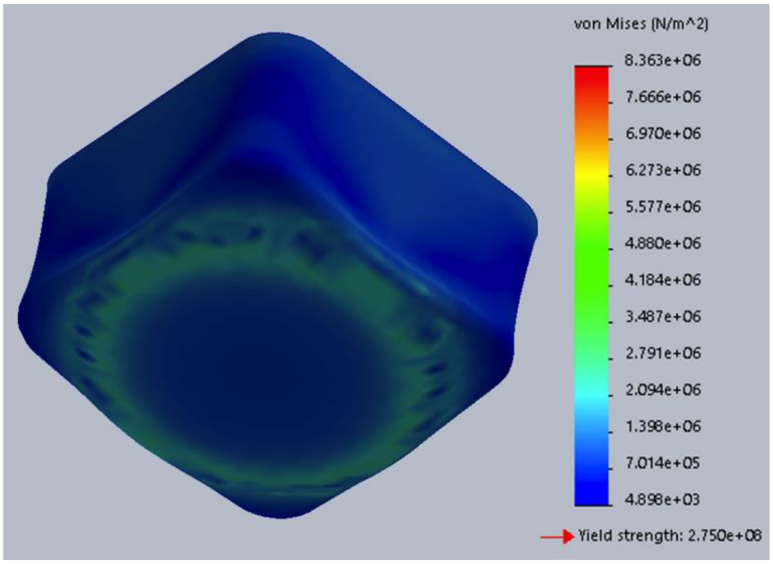


Figure 3-23. Mechanical stresses on design variant 3 magnet housing at 1650N magnetic attraction force

The thickness of the magnet case bottom for variant 3 is nominally 3.3 mm. The pull force considered is 1,650N, which is the pull force expected when the magnetic module is in contact with a thick steel plate. Under these conditions, the module lid withstands the applied force with a safety factor of ~30. This was determined by comparing the highest local stress calculated on the magnet housing (visually shown as the von Mises stress in Figure 3-23) to the yield strength of aluminum (275 MPa or 2.75e08 N/m^2).

Table 3-8lists critical parameters for all three variants. VE suggested that magnetic modeling could be done to further refine the performance parameters. Such modeling may be done in the future to optimize the design. But at this stage of technology development, it is more critical to build a prototype and obtain field data. The gap distance can be adjusted by a few millimeters if the magnetic force needs to be increased or decreased.

Table 3-8. Main technical parameters for the 3 design variants considered

Parameter	Variant 1	Variant 2	Variant 3
Pull force at ½" (12.7mm) distance between magnetic module and thick steel plate	420 N	290 N	510 N
Overall size (L x W x H)	168 x 84 x 44 mm	142 x 84 x 44 mm	86 x 86 x 54 mm
Mass of each module	2.05 kg	1.63 kg	2.15 kg
Number of modules required for 1600N pull force at design gap	4	6	4
Total mass of modules required	8.2kg	9.8kg	8.6kg

Ultimately Variant 3 was selected as the most suitable design because it was efficient in terms of weight and the square form resulted in the smallest overall footprint of the robot. The location of the magnetic modules is shown in Figure 3-15.

3.5.4 Hydraulic System

Water, pressurized to 205 bar (3000 psi) is supplied from on-board the vessel via a 5/8" inner diameter high pressure hydraulic line inside the umbilical. The inner diameter of the hydraulic line was sized to minimize pressure losses along a 300m long umbilical. The umbilical is terminated with a custom moulded Y to break out the hydraulic line and electrical wires. The hydraulic line connects to a ½" inner diameter 90 deg swivel. The inner diameter of the fittings on the robot were reduced from 5/8" to ½" to save on size and weight. This was possible because hydraulic losses are minimal over very short distances. The high-pressure water continues to flow through a series of elbows and fittings with built in swivels that ensure the main rotary join has full range of motion. Finally, water flow is split via a T fitting and fed to the cavitating water jet assemblies. Flexible high-pressure lines (shown in blue) are used to connect the cavitating water jets to the main hydraulic system. The addition of the flexible lines allows the robot's frame to pivot about the centre and thus better conform to the hull surface.

3.5.5 Electrical System & Instrumentation

A block diagram of the electrical and instrumentation system is provided in Figure 3-24.

The electrical and instrumentation system is described as follow:

- A 400 VDC power supply integrated with the Eddyfi controller sends power to the tracks, instrumentation, lights and cameras via the umbilical. The tracks operate at 48 V, and all auxiliary systems at 12 V or less. The 400 V is therefore stepped down onboard the robot using a DC-DC converter. For reference, medium voltage (400 V) is supplied via the umbilical as opposed to a lower voltage such as 48V in order to minimize losses over a long umbilical length.
- The tracks are controlled by Eddyfi's topside control unit via RS-485 protocol.
- The robot is equipped with 6 Lumen Subsea LED lights supplied by Blue Robotics (https://bluerobotics.com). These are very cost-effective lights compared to most products on the market.
- Four Luxus Compact PUR (polyurethane) cameras supplied by MacArtney are integrated into the body of the robot. These analogue cameras are designed to be fully submersible up to 200 m, are

lightweight, compact, and very cost effective. We completed a very detailed review of available subsea cameras – both analogue and digital. The typical price for commercial subsea digital cameras was more than $6,000 CAD with some models with pan and tilt capability exceeding $25,000 CAD/camera. Conversely, subsea analogue cameras typically cost $1,000-3,000 CAD and are in general are considered to still be more reliable and thus lower risk for our initial prototype design. We do expect that in the mid-term we will develop a custom digital video camera solution or cost-effective options will emerge on the market that are easy to integrate.

- The video signal from the four analogue cameras is combined and transmitted to the surface.
- An Arduino Due microcontroller is used to convert and transmit the analogue signal from the pressure sensor, load cells, depth sensor, temperature sensor and IMU (Inertial Measurement Unit used to measure accelerations) to allow for continuous monitoring of the robot.
- The pressure sensor is installed in-line with the hydraulic system to ensure that the pressure supplied to the cavijets is correct. The pressure supplied to the cavijets needs to be well controlled to ensure a constant stream of cavitating bubbles.
- An Arduino Shield (i.e add on) is used to increase the accuracy of the load cells. The load cells are mounted between the frame and the magnets to measure the magnetic attraction force between the robot and the hull.

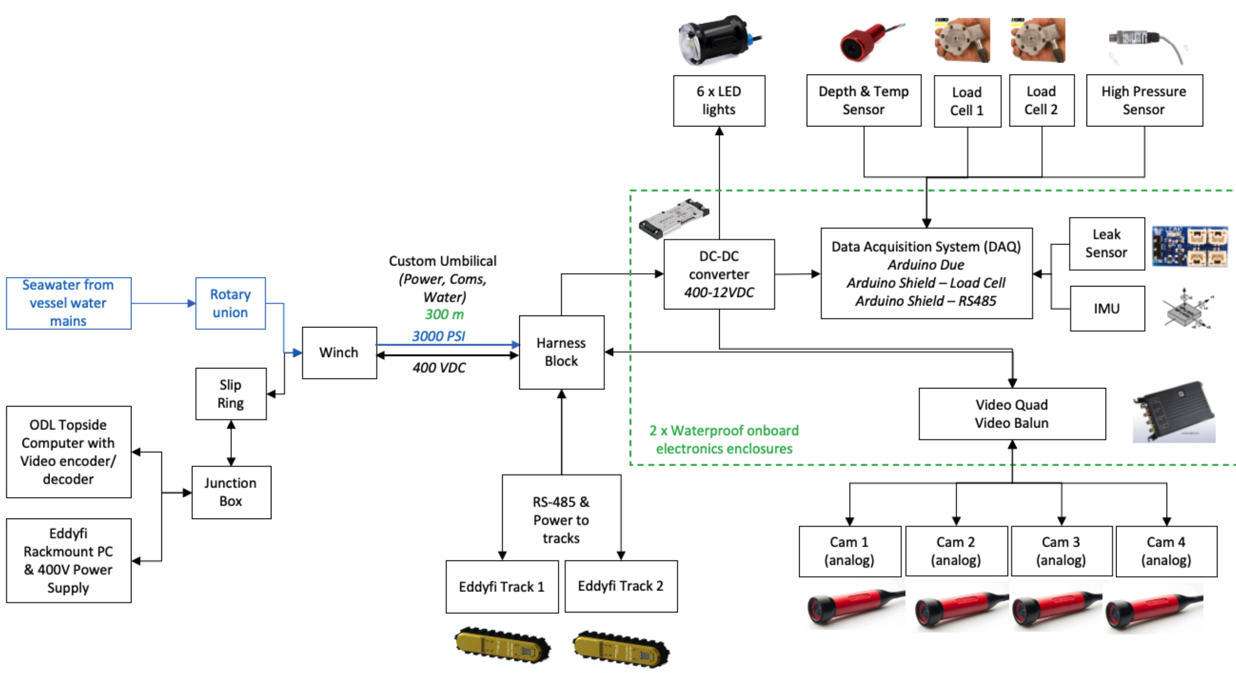


Figure 3-24: Block diagram of electrical and instrumentation system

3.5.6 Bill of Materials & Cost Estimate

A bill of materials was compiled to estimate the weight and cost of the robot.

The total mass of the robot was calculated at 73.9 kg. The mass for the custom structural components was calculated by assigning material properties to each component in the 3D Solidworks model. The mass of purchased parts was obtained from supplier data sheets.

The total cost of all components comprising the robot is approximately $210,000 CAD. This cost includes all robot components as well as the umbilical, topside power supply, pump-motor and rack mounted PC that allows the operator to remotely control the robot from the deck of the vessel. The cost of a winch and additional equipment required to launch, operate and retrieve the robot is not included as design/sourcing these components was outside the scope of this project.

The cost of purchased components was obtained from pricing available online or by requesting quotes. The cost of minor components such as fasteners, hydraulic hose, electrical wiring, and penetrators were estimated as they will mostly be finalized during assembly.

The fabrication cost of structural components was determined by sending CAD drawings for quote to fabricators.

A significant portion of components were designed such that they could be shape cut by waterjet without the need for additional machining which significantly increases cost. Viking Profiles, a Richmond BC based company, quoted all shape cut components – the quote includes material supply.

The cost of material for machined components was obtained from McMasterCarr, an online industrial supplier. We estimated the cost of machining based on experience working with A-MAC Machinery and Fabrication – a custom fabricator based in Surrey, BC. Obtaining quotes for one-off machined items was difficult because the machinist typically charges based on time spent working on the component.

3.6 Operation In Cold Climates

Transport Canada requested that we assess our hull cleaning system for operation in cold climates.

The following cold climate operating temperatures were obtained from the Canadian Coast Guard (CCG) and were assumed to be typical of vessels operating in cold climates:

Design water temperature (freezing point of saltwater) = -2 deg. C

Mean daily low air temperature: - 30 deg. C

The CCG noted that ships can operate in colder air temperatures in the -40 to -45 deg C but it would be unrealistic for anyone to operate equipment outdoors at such low temperature.

The approach taken to assessing cold climate operation was to evaluate the main components comprising the system and identify each component's minimum operating temperature.

A component level breakdown is provided in provided in Table 3-9.

Table 3-9: Minimum temperature ratings for main components comprising ODL's overall hull cleaning system

Item	Part Number	Manufacturer	Min. Rated Operating Temp.	Notes
Winch	Cormac Q3	MacArtney	-20°C	MacArtney has designed winches for use in arctic and could investigate
Rubber Covered Fire Hose	Ex 1.5" dia rubber covered fire hose: T7QDYZX0C1-01	Fire Hose Supply	-34°C	Supplies water from ship mains to pressure washer unit
Pressure Washer System				
Engine	GX 690	Honda	-25°C	
Pump			Not rated	
Fittings			Not rated	

Umbilical	Custom	Umbilicals International	-20°C (dry)	
Hull Cleaning robot				
Tracks	Minitrac 8000 (current production track)	Eddyfi	0°C	Rated to 0°C but has been successfully deployed in -15°C
Cavijet nozzles	Cavit Cleaner	Evo2	Not rated	
Electrical connectors	Ex: LPBH5M	Subconn	-40°C	
Electronics general (electronics onboard robot not yet finalized)	Ex: Arduino Due	Arduino	0°C	In general, most electronics loose capability or stop functioning below 0 deg C unless adapted to cold weather
Hydraulic Hoses	GH781	New-line	-45°C	

The main consideration for our system is the freezing of water in the hoses, pipes, nozzles and connectors since we are using a water-based cleaning system. Theoretically, the water in the umbilical downstream of the pump will be pressurized at approximately 2,300 PSI. At this pressure, the freezing point of saltwater drops to -13.9 °C [6]. But practically speaking, it may be difficult to ensure that the water in the umbilical remains pressurized. If it were to freeze, there is a significant risk that the hydraulic fittings or umbilical could be damaged.

As shown in Table 3-9, most of the other equipment can operate at or below freezing temperatures. While commercial grade electronics are typically rated at 0°C, measures can be taken to operate in colder climates such as housing in a sealed compartment, ensuring there is no condensation that can freeze, and in general selecting more industrial grade components. It is also important to keep in mind, that for most of the time, the cleaning robot will be submerged underwater where temperatures will not drop below -2 °C. Given that Eddyfi's crawlers have been successfully deployed and operated in -15°C, it can be assumed that the electronics will not be the limiting factor for winter operations.

The following measures can be taken to safeguard the equipment for operation in cold climates:

- Winch, pressure washer unit and all controls equipment can be housed in a heated enclosure, either below deck (if practical) or inside a container.
- Run hose supplying water from the ship's water main to the pressure washer unit in such a way as to avoid exposing to exterior temperatures. The feasibility of this proposed solution would depend on the location of the pressure washer unit and vessel layout.
- Ensure the umbilical is purged of water until the robot is in position and ready to begin the clean. This would avoid having stagnant low-pressure water in the umbilical. Likewise, once the cleaning operation is complete, the umbilical would need to be purged with compressed air to avoid freezing.
- All equipment, including the robot should be stored in a warm environment with adequate time allotted between usage to allow all condensation to evaporate. The equipment should only be taken out into the cold environment when required.

Even with the above steps taken, it is difficult to determine if in practice it would be possible to safeguard all equipment for operation in sub-zero air temperatures. Until demonstrated otherwise, it is therefore recommended that the minimum rated operating temperature for the hull cleaning system be kept at or above 0°C.

4 ENVIRONMENTAL IMPACT OF IN-WATER HULL CLEANING

In-water cleaning of ship hulls poses several environmental risks including:

- Release of Non-Indigenous aquatic Species (NIS) into a new environment where they are able to establish, thus placing local ecosystems at risk – referred to as invasive species.
- Release of chemical contaminants from the vessel's hull coatings into the surrounding waters that can have a detrimental effect to the local ecosystem.

One of the main objectives of this project was to gain a deeper science-based understanding of the environmental risks posed by in-water cleaning both in harbour and out at sea. This understanding will help to determine if our proposed approach of cleaning while the vessel is underway without the use of filtration is environmentally responsible.

4.1 RISK OF SPREADING INVASIVE SPECIES

We worked with Bailey Environment Consulting to assesses the risk of spreading invasive species as a result of in-water hull cleaning – both in harbour and while the vessel is underway. Bailey Environmental produce a stand-alone report to summarize the findings that is provided in Appendix C.

A foul release (FR) scale from FR 0 to FR 100 (see Table 4-1), as adopted by the US Navy [7], is used to characterize the degree of fouling on the vessel.

As shown in Table 4-1, FR ratings up to 30 are considered as soft fouling - the fouling primarily comprises slime, grass, and non-calcareous organisms. Above FR 30, the fouling becomes more severe with the onset of calcareous fouling and is thus classified as hard fouling.

Table 4-1: Characterization of hull fouling adopted by US Navy

Characterization	Fouling Type	Fouling Rating (FR)
A clean, foul-free surface; red and/or black AF paint or a bare metal surface	Soft	0
Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling	Soft	10
Slime as dark green patches with yellow or brown colored areas (advanced slime). Bare metal and painted surfaces may by obscured by the fouling	Soft	20
Grass as filaments up to 3 inches (76 mm) in length, projections up to 1/4 inch (6.4 mm) in height; or a flat network of filaments, green, yellow, or brown in color; or soft non calcareous fouling such as sea cucumbers, sea grapes, or sea squirts projecting up to 1/4 inch (6.4 mm) in height. The fouling cannot be easily wiped off by hand	Soft	30
Calcareous fouling in the form of tubeworms less than ¼ inch in diameter or height	Hard	40
Calcareous fouling in the form of barnacles less than ¼ inch in diameter or height	Hard	50
Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height	Hard	60
Combination of tubeworms and barnacles, greater than ¼ inch in diameter or height	Hard	70
Tubeworms closely packed together and growing upright away from surface. Barnacles growing one on top of another, ¼ inch or less in height. Calcareous shells appear clean or white in color	Hard	80

Dense growth of tubeworms with barnacles, ¼ inch or greater in height; Calcareous shells brown in color (oysters and mussels); or with slime or grass overlay	Hard	90
All forms of fouling present, Soft and Hard, particularly soft sedentary animals without calcareous covering (tunicates) growing over various forms of hard growth	Composite	100

Bailey Environmental assessed the risk of spreading invasive species from in-water hull cleaning by considering multiple factors such as water depth, distance from shore, water temperature, salinity, and ocean current circulation patterns.

Due to project constraints, the detailed portion of the study focused on the Pacific Northwest region stretching from Alaska down to California. A list of non-indigenous species (NIS) that were likely introduced to British Columbia via hull fouling is provided in Table 3 of Bailey's report. Based on this list, it was determined that some of these known NIS are characterized as FR 30 and above. For this reason, as well as multiple other factors provided in Section 4 of Bailey's report, a hull with an FR 0-20 rating was deemed less likely to lead to effective establishment of NIS.

Out of the 88 NIS that were introduced to BC waters, 16 were singled out in the report as they are thought to have been introduced to BC waters through hull fouling (see Table 3 in report provided in Appendix C). Furthermore, two species, Botrylloides violaceus and Mytilus galloprovincialis were singled out for consideration in more detail as they are both well established in BC waters and have a strong reputation as global invaders. As is the case with most NIS listed in Table 3 of the report, both of these NIS have a broad temperature tolerance (5-25 deg °C for Botrylloides violaceus, up to 31 deg for Mutilus galloprovincialis) and salinity tolerance (20-38 PSU for Bytrolloides violaceus and 10-38 PSU for Mutilus galloprovincialis).

Finally, the ocean currents along the Pacific Northwest coastline were considered to provide an understanding of a safe distance from shore to perform in-water hull cleanings without risking NIS reaching shallow waters where they could establish. As explained in Section 8 of the report and shown in Figure 4-1, when the North Pacific Current approaches the west coast of North America, it splits into the California current that runs south and Alaska current that runs north. As a result of these currents, the California coast generally experiences upwelling, as the water is pulled away from the coast, and Alaska coast experiences downwelling, as the water pushes towards the coast. On the coast of British Columbia, currents are highly variable, with upwelling in the summer and downwelling in the winter. Based on this understanding of ocean currents, it was concluded that the risk of NIS reaching shore is much lower when heading south along the US Pacific coast because the currents would take the NIS out to sea.

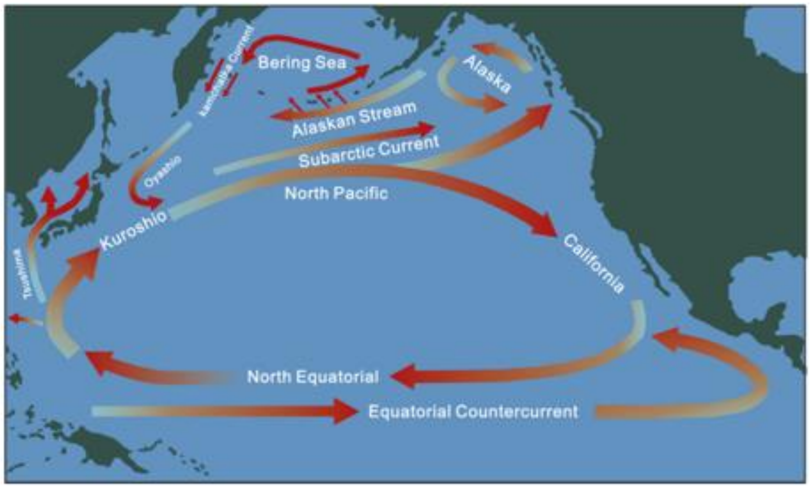


Figure 4-1: Ocean currents in North Pacific [8]

The outcome of the environmental impact assessment of in-water cleaning both in harbour and out at sea is summarised in Table 4-2. It is important to note that the recommended best practice presented in Table 4-2 only consider risks associated with spreading of invasive species – the risks associated with chemical contamination of water due to removal of the coating are assessed in the subsequent section of this report.

The recommendations made in Table 4-2 were categorized based on the operating region of the vessels and are summarized as follows (see Section 8 of report in Appendix C for detailed rational):

- For vessels operating exclusively between neighbouring ports (ex. Salish Sea), cleaning at any fouling level may be acceptable.
- For vessels operating along the Pacific Northwest (Alaska to California), it is recommended that in-water cleaning for fouling ratings of FR 20 or below be permitted while in port, as the species contributing to fouling at this stage are unlikely to establish as NIS, particularly with regular cleaning. This is because the slime layer, which, is deemed a lower biosecurity risk, includes unicellular algae and bacteria, but may also contain the microscopic life stages of the macrofouling organisms before they reach sexual maturity. Therefore, regular cleaning at fouling ratings up to FR 20 may further reduce the spread of NIS by reducing the likelihood/rate of macrofouling.
- For vessels operating along the Pacific Northwest, it is recommended that in-water cleaning for fouling ratings exceeding FR 20 be performed either:
- 50 NM from shore and in water depths greater than 500 m when traveling south of Vancouver Island because the California Current will carry the NIS out to sea.
- 200 NM from shore and in water depths greater than 2000 m when traveling north of Vancouver Island because the Alaska Current may carry the NIS towards shore.
- For vessels operating on transoceanic routes, the same recommendations are made as for vessels operating along the Pacific Northwest.

Table 4-2: Recommended in-water cleaning best practice for the Northeast Pacific – based only on risk of spreading invasive species

Foul Rating	**FR 0**	**FR 10**	**FR 20**	**FR 30**	**FR 40**	**FR 50**	**FR 60**	**FR 70**	**FR 80**	**FR 90**	**FR 100**
Characterization	**Clean Hull**	**Incipient Slime**	**Advance Slime**	**Soft Non-calcareous**	**Calcareous**	**Calcareous**	**Calcareous**	**Calcareous**	**Calcareous**	**Calcareous**	**Composite**
General Description - Biofouling Type *(adopted from US Naval Ship Tech Manual – 2006)*	–	Slime – light shades of red and green	Slime – dark green patches with yellow or brown	Grass as filaments up to 3" long Projections up to 0.25" height Sea cucumbers, sea grapes, sea squirts up to 0.25" height	Tubeworms less than 0.25" diameter or height	Barnacles less than 0.25" diameter or height	Combo of tubeworms and barnacles less than 0.25" diameter or height	Combo of tubeworms and barnacles greater than 0.25" diameter or height	Tubeworms closely packed barnacles on top of each other 1/4" or less in height	Dense growth of tubeworms with barnacles, 0.25" or greater in height Oysters Mussels	Soft sedentary animals without calcareous covering (tunicates) growing over hard growth
Neighbouring Ports											
Min Depth (m)	In harbour										
Min Distance from Shore (nm)	In harbour										
Coastal											
Min Depth (m)	0 (in harbour or during coastal transit)			2,000 (500 [a])							
Min Distance from Shore (nm)	0 (in harbour or during coastal transit)			200 (50 [a])							
Transoceanic											
Min Depth [m]	0 (in harbour or during transit)			2,000 (500 [b])							
Min Distance from Shore [nm]	0 (in harbour or during transit)			200 (50 [b])							
Canadian Regulatory Body	Port Authority	Port Authority	Port Authority	Port Authority, IMO, TC (for vessels 24 m and larger)							

NOTES:

[a]Exception for vessels travelling south in the California Current that do not navigate at least 200 nm from shore.

[b]Specific exceptions should be based on the localized oceanographic conditions at each port.

[c]Place holder upon completion of laboratory experiments

Based on all the work completed by Bailey Consulting and our research of publicly available documents, we created a summary table that classifies the risk of spreading invasive species from in-water hull cleaning based on the vessel's area of operation (see Table 4-3). It is important to note that this table does not consider the risk of chemical contaminants. As shown in Table 4-3, the risk of spreading invasive species while cleaning soft fouling up to FR 20 is low for all ocean-going vessels. For fouling ratings exceeding FR 20, only vessels operating between nearby ports should be cleaned. All other vessels should be cleaned in deep ocean, or an effective capture system should be used.

Table 4-3: Risk of Spreading invasive species because of in-water hull cleaning

Risk of spreading invasive species						
Area of Operation	Light Fouling < FR30			Heavy Fouling >= FR30		
	In Harbour	In Transit		In Harbour	In Transit	
		Coastal	Deep Ocean		Coastal	Deep Ocean
Neighbouring Ports	*low risk*	*low risk*	*low risk*	*low risk*	*low risk*	*low risk*
Pacific Coast Region				*high risk [1]*	*high risk [1]*	
Trans Oceanic						

Notes:

[1] *unless using capture system*

4.2 RISK OF CHEMICAL CONTAMINATION OF LOCAL WATERS

Cleaning biofouling off of ship hulls may result in the removal of the underlying hull coating. The severity of the damage to the coating, leaching rates and resulting environmental impact, depends on the paint type and cleaning tools used. For the purposes of this report, the chemical contamination that may result from in-water cleaning is divided into two categories: metals and microplastics.

4.2.1 Metals

Measuring the change in metal and dissolved metal concentrations before and during cleaning is a method often used to quantify the environmental impact of hull cleaning. Copper is typically the metal tested for since it is the most commonly used biocide in antifouling coatings [9].

A technical paper issued by New Zealand Government in 2013 [9] provides a very thorough assessment of the potential environmental risk of in-water cleaning. Copper concentrations were used as an indicator of chemical contamination risk and compared to local water quality guidelines. Computer modelling of various cleaning scenarios showed that the environmental concentrations of copper could exceed acceptable levels depending on factors such as the vessel area being cleaned, the number of vessels cleaned per day, the technique used and the rate of flushing (i.e., water circulation within the harbour).

The models were applied to two New Zealand ports: Lyttleton and Auckland. The port of Auckland was noted to have better water circulation compared to Lyttleton. Based on the analysis, a summary table was presented in section 5.8 of the New Zealand report concluding that for:

- Lytton Port: the total copper release during cleaning of soft fouling exceeded the chronic criterion when a single 200 m vessel is cleaned in harbour based on lower copper release estimate. If the upper copper release estimates were used for the analysis, the chronic copper limits were exceeded after only 0.137 vessels/day were (theoretically) cleaned.
- Auckland Port: the total copper release during cleaning of soft fouling exceeds the chronic criterion when a single 200 m vessel is cleaned in harbour/day based on the upper copper release estimate. The results for the lower copper release estimate were not provided.

The above analysis would need to be performed for each harbour to set limits on the number of vessels that could be cleaned per day. But, in general, the above findings indicate that cleaning one or perhaps a few average size ships/day (i.e ~200 m long) in harbour would be the upper limit even for harbours with good water circulation. And for sheltered harbours, perhaps only one vessel could be safely cleaned per week (or the cleaning operation may need to be spread out over several days to remain below allowable copper concentrations).

4.2.2 Microplastics

More recently, microplastic pollution resulting from paint removal during in-water cleaning has been identified as a potential source of microplastics in the oceans. The most comprehensive source found on this topic was a 2019 report by the IMO [10] on the topic of microplastic contamination due to shipping. The report produced the following key findings (paraphrased from the executive summary of the IMO report):

- Whereas plastics were previously regarded as an eyesore, but of little significance as a pollutant, it is now recognized that uptake of plastics can impact species and communities directly and that they may bioaccumulate or be directly taken up by humans.
- Anti-fouling systems and marine coatings in general commonly contain a relatively high content of polymer material (e.g. epoxy or acrylic).
- While the release of biocides and heavy metals from marine anti-fouling systems has been considered, the issue of plastics has seen limited attention.
- Limited work does begin to recognize marine coatings as a source of possible microplastics, particularly self-polishing anti-fouling products, which are designed to slough off during a ship's normal operations. However, specific studies on this matter could not be identified.

- Based on the findings presented in the IMO 2019 report, it was concluded that the release of microplastics needs to be considered when assessing the environmental impact of in water hull cleaning, but there was no further investigation into the topic.

4.2.3 Risk of chemical contamination

We sub-divided marine coatings under the following five categories for the purposes of the risk assessment:

1. Hard Epoxy non-biocidal coatings such as the coatings used on ice breaking vessels.
2. Foul Release (FR) non-biocidal coatings such as Hempasil X3 by Hempel and the Intersleek 1100SR by International Paint – two of the paints physically tested in Phase 1 of this project.
3. Foul Release (FR) coatings with biocide such as the Hempasil X7 by Hempel.
4. Self-Polishing Copolymer (SPC) coatings
5. Controlled Depletion Polymer (CDP) coatings such as the Interspeed 640 by International Paint and Olympic 7660 by Hempel – two of the other paints physically tested in phase 1 of the project.

For 1. hard epoxy and 2. non-biocidal FR coatings, the main risk is that some of the paint will be removed during the cleaning operation resulting in the release of microplastics. These coatings do not contain metals (typically copper and zinc) that are the active ingredients in biocides and therefore there is no risk of increasing local metals concentrations.

For 3. FR coatings with biocides, 4. SPC and 5. CDP paints, there is a risk that there will be metals released into the local waters in addition to microplastic pollution resulting from removal of paint.

Table 4-4 summarizes our overall assessment of the risk of chemical contamination resulting from the release of metals and microplastics during in-water hull cleaning operations - both in harbour and while out at sea. It is important to note that our risk assessment assumes that non-abrasive cleaning tools are used such as soft brushes or waterjets with pressures tuned to preserve the coating.

Table 4-4: Risk of chemical contamination of water because of in-water hull cleaning.

Paint Type	Light Fouling <= FR20			Heavy Fouling > FR20		
	In Harbour	In Transit		In Harbour	In Transit	
		Coastal	Deep Ocean		Coastal	Deep Ocean
All Coatings	*moderate risk - limit # ships/day or use IWCC*	*low risk*	*low risk*	*moderate risk - limit # ships/day or use IWCC*	*low risk*	*low risk*

Based on our current knowledge, we deemed the risk of exceeding allowable contamination levels to be moderate for all five types of coatings when cleaning in-harbour without capturing and filtering all contaminants. This is especially true if many ships are being cleaned in a harbour with poor circulation. Harbours may therefore need to limit the number of vessels cleaned to not exceed allowable limits.

If the cleaning is done at sea, either in coastal waters outside of the port or in deep ocean, then the chemical contaminants will disperse across a large body of water and will therefore remain below acceptable limits.

Diluting metals commonly used in biocides such as copper and zinc may be acceptable as these metals naturally exist in the ocean. It is our understanding that if diluted significantly below acceptable limits, these metals will not pose a threat to the environment.

Conversely, as explained in Section 3.2.2, the impact of microplastics is not well understood but it can be assumed that the general objective should be to avoid the release of microplastics.

4.3 Combined Risk: Invasive Species + Chemical Contaminants

We combined our findings and the outcomes of the environmental impact assessment completed by Bailey Environmental Consulting, to create a summary table that considers both the risk of spreading invasive species and chemical contaminants (see Table 4-5).

Table 4-5: Combined Risk of in-water cleaning in harbour and out at sea

<table>
<tr><th rowspan="3">Trade Route</th><th colspan="3">Light Fouling <= FR20</th><th colspan="3">Heavy Fouling > FR20</th></tr>
<tr><th rowspan="2">In Harbour</th><th colspan="2">In Transit</th><th rowspan="2">In Harbour</th><th colspan="2">In Transit</th></tr>
<tr><th>Coastal</th><th>Deep Ocean</th><th>Coastal</th><th>Deep Ocean</th></tr>
<tr><td>Neighbouring Ports</td><td rowspan="3">moderate risk [1,2]</td><td rowspan="3">low risk</td><td rowspan="3">low risk</td><td>moderate risk [1,2]</td><td>low risk</td><td rowspan="3">low risk</td></tr>
<tr><td>Pacific Coast Region</td><td rowspan="2">high risk</td><td rowspan="2">high risk</td></tr>
<tr><td>Trans Oceanic</td></tr>
</table>

1 - use IWCC - In Water Cleaning and Capture

2 - limit # of ships/day

As proposed in Table 4-5:

- Cleaning of lightly fouled ships in harbour should be monitored to remain below acceptable chemical contamination criteria. The risk of spreading invasive species is likely low when removing light fouling in harbour.
- Cleaning of lightly fouled ships outside of harbour while in transit poses a low environmental risk since exceeding chemical contamination criteria is unlikely due to dispersion. The risk of spreading invasive species is also low.
- Cleaning of heavily fouled ships in harbour should be limited to vessels operating between neighbouring ports. The water quality should be monitored, and limits placed on the number of vessels cleaned as required to remain below acceptable chemical contamination limits.
- Cleaning of heavily fouled ships in harbour that engage in coastal or transoceanic trade should not be permitted unless an effective capture system is used capable of capturing all organic matter.

5 REGULATIONS FOR IN-WATER HULL CLEANING

There is presently no international convention in place governing the practice of in-water hull cleaning of large ocean-going vessels. Global guidelines issued by the International Maritime Organization (IMO) [11] do exist that specifically address the control and management of biofouling to minimize the transfer of invasive species.

At the time of writing, regulations specific to in water hull cleaning do exist in individual countries and regions across the world such as New Zealand and California. An exhaustive review of country specific regulations was outside the scope of this project.

In Canada, biofouling of vessels above 24 m in length falls under the jurisdiction of Transport Canada and local port authorities. For example, the Vancouver Fraser Port Authority requires that a permit be obtained prior to performing a hull clean [12].

Biofouling of vessels under 24 m in length falls under the jurisdiction of the Department of Fisheries and Oceans (DFO).

A permit may also be required from The Canadian Environmental Protection Act (CEPA). Under CEPA, disposal that requires a permit encompasses the disposal of a substance at sea from a ship. But it does not include disposal of a substance that is incidental to or derived from the normal operations of a ship. Additional clarification is therefore required to determine whether in-water cleaning would be considered within normal operations and thereby not require a permit.

A comprehensive review of rules and regulations that are pertinent to in-water hull cleaning is presented in Section 7 of the Environmental Impact report completed by Bailey Environmental Consultants as part of this project. The report is provided in Appendix C.

A review of ballast water regulations was also completed since ballast water exchange is a known vector for spreading invasive species. At present, ballast water is more heavily regulated compared to vessel biofouling including the existence of an IMO Convention for the Control and Management of Ship's Ballast Water and Sediments that came into force on September 8th, 2017. In addition to the IMO Convention, there are also many local rules and regulations that provide very useful metrics such as water depth and distance from shore for safe ballast water exchange that were used as a starting point for assessing the environmental impact of cleaning at sea. A comprehensive review of ballast water regulations is presented in Section 7.4 of Bailey's report (see Appendix C).

Regulations and guidelines that address ship hull cleaning are quickly evolving. Bailey Environmental completed their regulatory review at the end of September 2020.

On October 26, 2020, the United States Environmental Protection Agency released a proposed regulatory framework under the Vessel Incidental Discharge Act (VIDA) [13] that clearly outlined what hull cleaning activities can be safely carried out in harbour. The proposed regulations are in general terms in agreement with the conclusions reached by Bailey Environmental that are presented in section 4 of this report.

On June 3rd, 2021, Transport Canada released guidelines on ship hull cleaning for public review on "Let's Talk Transportation" [14]. These proposed guidelines also support the conclusions reached by Bailey Environmental and proposed regulations in the US.

Conclusions from Bailey Environmental's environmental impact study and a review of recent guidelines and regulations lead ODL to believe that routine hull cleaning will likely be permitted worldwide provided that:

1. The cleaning method does not damage the hull coating causing release of pollutants, and;
2. Cleaning is limited to microfouling (FR 20 or less – see Table 4-1) for foreign vessels.

6 ANALYSIS OF CO_2 EMISSIONS REDUCTION POTENTIAL

The annual CO_2 emissions were calculated to quantify the difference between operating a clean vessel vs. a vessel with light fouling. A 7% increase in powering (7% increase in fuel consumption) was assumed for the light fouling condition. A 5-10% fuel penalty is a generally accepted value in industry for a lightly fouled hull condition. This estimate originates from research conducted by Schultz et al. [15].

Comparing a clean hull to a fixed percentage increase due to fouling for the entire year is a very basic scenario. It assumes a vessel arrived clean in harbour, became lightly fouled during an extended stay and then continued to sail without accumulating additional growth. In practice, the growth may have continued to accumulate over the course of that year. But this added complexity was not considered when quantifying the extra fuel consumption and calculating the added GHG emissions.

The inputs used and the results of the calculations are provided in Table 6-1. Four different types of commercial vessels were considered for the analysis. Ship particulars, service speed, typical days at sea per year and daily fuel consumption were obtained for each vessel type from company websites as well as through correspondence with the vessel owners/operators. The analysis was therefore performed for specific vessels. However, the name of the specific vessels is not provided because vessel owners did not review and approve the estimates derived by ODL.

The fuel price used for the analysis was for Very Low Sulphur Fuel Oil (VLSFO) as recorded on April 30, 2021 as was the USD to CAD exchange rate [16].

As explained earlier, Table 6-1 reports the extra fuel consumed by the vessel and resultant CO_2 emissions if it continues to operate with a lightly fouled hull (7% additional fuel consumption). These additional emissions could be significantly reduced, or even eliminated with routine hull cleaning.

Based on the calculations, operating a clean vessel could save ship operators $230 kCAD/year in fuel costs for a typical 200m long bulk carrier and $2M CAD for a large 360m container ship. In addition, operating a clean vessel would avoid annual emissions of 1,333mT of CO_2 for a bulk carrier and over 10,000mT of CO_2 for a large container ship [17].

Table 6-1 puts these CO_2 values in context by comparing the CO_2 emissions to number of cars on the road, size of wind turbines generating clean power, gallons of diesel fuel consumed, and acres of forest required to absorb that amount of CO_2 in 1 year [18].

The motivation for operating a clean vessel is therefore very clear for ship owners who are interested in saving fuel costs while doing their part to reduce GHG emissions caused by Marine Transportation – an industry that accounts for approximately 3% of global GHG emissions.

IMO has set a goal of reducing GHG emissions from ships by at least 50% by 2050 compared to 2008.

On April 21, 2021, John Kerry, the US special presidential envoy for climate argued to cut shipping's CO_2 emissions to zero by 2050.

Developing technologies that enable ship owners to clean frequently to maintain a clean hull can therefore have a very meaningful contribution towards IMO's goal.

Table 6-1: GHG emissions calculations

Inputs

Price of VLSFO (marine fuel-global 20 port avg):	514	USD/mt	(April 30, 2021 https://shipandbunker.com/prices
	632	CAD/mt	(USD = 1.23 CAD)

Metric	bulk carrier	tanker	LNG carrier	container ship (13,100 TEU)	*Unit*	*Basis*	
Length (LOA)	200	250	300	366	*m*		
deadweight (DWT)	60,000	111,920	113,000	141,823	*mT*		
displacement	*72,400*	*136,488*	*138,126*	*196,266*	*mT*	*estimated based on DWT*	
surface area	*10,271*	*16,089*	*18,890*	*23,280*	*m^2*		
service speed	12	13.5	18	20	*knots*		
estimated time to clean vessel	10	16	19	23	*h*	1000	*m^2/h (500-1200)*
Days at sea/year	200	260	300	270	*days*		
Fuel consumption	26	65	100	175	*mT/day*		
Fuel cost-baseline							
Cost/day	16,438	41,094	63,222	110,639	*CAD*		
Cost/year	3,287,544	10,684,518	18,966,600	29,872,395	*CAD*		
Extra fuel - fouled ship							
Extra fuel/day	2	5	7	12	*mT/day*		
Extra fuel/day	1,151	2,877	4,426	7,745	*CAD/day*	7%	*fuel penalty*
Extra fuel/year	230,128	747,916	1,327,662	2,091,068	*CAD/year*		
Extra CO2 - fouled ship							
Extra CO2/day	6	14	22	38	*mT/day*	3.114	*g/g fuel for LSFO* [1]
Extra CO2/year	1,133	3,684	6,539	10,300	*mT/year*		
Equivalent to:							
Number of cars on the road	246	801	1,422	2,239	*cars*	*on average, 4.6 mT/car/year* [2]	
Size of wind turbine running 24/7 @35% CF	0.5	1.7	3.0	4.8	*MW*	*0.7 mT CO2 reduced/MWh* [2]	
Gallons of diesel consumed	111,236	361,517	641,747	1,010,751	*gallon/year*	*10.190x10^{-3} mT CO2/gallon of diesel*	
Acres of forest required to absorb the CO2 in 1 year	1,472	4,784	8,493	13,376	*acres*	*0.77 mT CO2 = 1 acre of forest* [4]	
	6	19	34	54	*km^2*		

Sources:

[1] Third IMO GHG Study 2014, Table 59

[2] United States Environmental Protenction Agency: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

7 CONCLUSIONS

All the work completed over the course of this project was instrumental to advancing our robotic ship hull cleaning technology from a preliminary design stage to a final design that is ready for fabrication and field trials.

The outcomes of the project as summarized as follow:

Experimental Testing of cavitating waterjet cleaning system

- Experimental testing of cleaning system on marine coatings demonstrated that cavitating waterjets do not cause any visual damage (examined under microscope) to the coating when operating in accordance with manufacturer's recommendations.
- Damage to the coating was clearly visible if the cavitating waterjet nozzles were run outside recommended operating conditions such as too closely to the surface. The amount of paint removed was documented for each test using a dry film thickness gauge.
- Analysis of water samples collected before and after operating the cleaning system showed an increase in both copper and zinc concentrations in the water post cleaning. The increase was more significant for the coatings containing biocides (Olympic 7660 by Hempel and Interspeed 640 by International Paints) compared to the foul release type non-biocidal coatings (Hempaguard X3 by Hempel and Intersleek 1100 SR by International Paints).
- The increased concentrations measured for certain cases were above British Columbia's water quality guidelines for aquatic life. It was also determined that the metals concentrations in the potable tap water used for the experiments also exceeded water quality guidelines. Furthermore, the brass pump and non-stainless-steel fittings that comprise the cleaning system also contributed to increasing the metals concentration. Future tests need to better isolate the contribution of metals specifically from the coating vs. the supply water or equipment components.
- In general, the increase in metals concentrations was on the order of microns/litre when performing tests in an enclosed volume. The metals concentrations would therefore be diluted to well below the BC water quality guidelines when operating the hull cleaning robot while underway in open water. The metals concentrations would also be diluted when cleaning in harbour due to natural mixing caused by wind, waves, tides, and marine traffic. It is difficult to determine with certainty based on work to date if the dilution when cleaning in harbour would be below BC's water quality guidelines. Limited field testing in harbour on a fouled vessel is the most direct method of determining if our technology can be safely used in harbour without negatively impacting the environment.

Detail design of hull cleaning robot prototype

- The detailed design of the robot was completed that meets the performance requirements for both in-harbour and on-the-go cleaning. An overview of the mechanical, electrical, hydraulic, instrumentation/controls/telemetry systems is provided in Section 3.0 along with a 3D CAD model, specification, bill of materials, cost estimate and weight estimate are provided within the report.
- Custom high-speed tracks were designed by Eddyfi Technologies that meet the design requirement set for cleaning rate. The custom tracks can travel at speeds of up to 0.4 m/s compared to 0.1m/s for Eddyfi's standard production tracks. The higher speed better matches the capabilities of the rotating cavijet cleaning system. The price of these custom tracks is approximately twice that of the standard production model and an upfront investment is required to develop the first production model. We therefore decided to proceed with using Eddyfi's standard crawler tracks for an initial prototype. Field testing a prototype will confirm if final design requirements for the tracks are correct before an investment is made to build the custom tracks.

- A high-level assessment of the hull cleaning system for operation in cold temperatures concluded that the minimum rated operating temperature for the hull cleaning system be kept at or above 0°C to ensure the water supplied to the cavitating waterjets does not freeze.

Environmental Assessment and Regulatory review of cleaning while underway and in harbour:

The environmental impact study completed by Bailey Environmental Consultants in September 2020 provided us with clear science-based guidelines for performing hull cleanings both in-harbour and underway for local and international vessels (see Table 4-2).

Conclusions from Bailey Environmental's environmental impact study and the recent guidelines and regulations suggest that routine hull cleaning without capture and filtration will be permitted in Canadian and US ports provided that:

1. The cleaning method does not damage the hull coating to the point of exceeding allowable levels of pollutants, and,
2. Cleaning is limited to microfouling (FR 20 or less) for foreign vessels.

Cleaning of local vessels will therefore likely be permitted for any level of fouling as long as the coating remains intact.

We do not yet have the field data to determine if it will be possible to clean in harbour using the cavijet technology (without a containment system) without exceeding allowable limits for metals concentrations. The next step on our technology development path is to perform a limited stationary in-harbour test and take water samples before and during the cleaning process.

If the metals concentrations exceed allowable limits, then it will be clear that cleaning the vessel while underway (with that specific coating) is a more environmentally responsible solution.

If field testing shows that regular cleaning of vessels can be done in harbour in an environmentally responsible manner without the need for capture and filtration, then the need for an On-The-Go robot will be limited to:

a) cleaning foreign vessels with moderate to heavy growth to mitigate against the risk of spreading invasive species in harbour, and
b) vessels operators who prefer to clean in transit because their busy schedules to not allow for a clean in harbour.

Analysis of CO_2 emissions reduction potential

Annual CO_2 emissions were calculated for a range of vessels to quantify the difference between operating a clean vessel vs. a vessel with light fouling. A 7% increase in powering (7% increase in fuel consumption) was assumed for the light fouling condition.

The analysis showed that operating a clean vessel could save ship operators $230 kCAD/year in fuel costs for a typical 200 m long bulk carrier and $2M CAD for a large 360 m container ship. In addition, operating a clean vessel would avoid annual emissions of 1,333 mT of CO_2 for a bulk carrier and over 10,000 mT of CO_2 for a large container ship.

The motivation for operating a clean vessel is therefore very clear for ship owners who are interested in saving fuel costs while doing their part to reduce GHG emissions caused by Marine Transportation – an industry that accounts for approximately 3% of global GHG emissions.

8 REFERENCES

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APPENDIX A PRODUCT DATA SHEETS FOR COATINGS

Product Data
HEMPASIL X3+ 87500

fouling release coating 87500 : BASE 87509 : CROSSLINKER 98951

Description: HEMPASIL X3+ is a third generation fouling release coating based on silicone hydrogel. HEMPASIL X3+ is biocide free, two-component and has a high solids content.

HEMPASIL X3+ provides a smooth, low surface energy and repellent surface with unique fouling release properties. A hydrogel micro layer prevents fouling organisms from firmly adhering and provides self-cleaning properties. Therefore, HEMPASIL X3+ possesses a high fuel saving potential compared to traditional antifoulings. During extended idle periods the coating may accumulate some fouling.

HEMPASIL X3 does not contain organotin compounds acting as biocides and complies with the International Convention on the Control of Harmful Antifouling Systems on Ships as adopted by IMO, October 2001 (IMO document AFS/CONF/26).

Recommended use: For vessels with service speeds above 8 knots. The product can also be used for propellers. Also ideal for use in power plant water inlets on pipes and grates to prevent biofouling.

Availability: Part of Group Assortment. Local availability subject to confirmation.

PHYSICAL CONSTANTS:

Shade nos/Colours:	59151* / Red
Finish:	Glossy
Volume solids, %:	71 ± 1
Theoretical spreading rate:	4.7 m^2/l [188.5 sq.ft./US gallon] - 150 micron/6 mils
Flash point:	28 °C [82.4 °F]
Specific gravity:	1 kg/litre [8.3 lbs/US gallon]
Dry to touch:	3 approx. hour(s) 20°C/68°F
Fully cured:	7 day(s) 20°C/68°F
VOC content:	260 g/l [2.2 lbs/US gallon]
Shelf life:	2 year (25°C/77°F) for BASE and 1 year for CROSSLINKER (25°C/77°F) from time of production. Depending on storage conditions, mechanical stirring may be necessary before usage.

**other shades according to assortment list.*

The physical constants stated are nominal data according to the HEMPEL Group's approved formulas.

APPLICATION DETAILS:

Version, mixed product:	**87500**
Mixing ratio:	BASE 87509 : CROSSLINKER 98951 17.8 : 2.2 by volume
Application method:	Airless spray / Brush (touch up) see REMARKS overleaf
Thinner (max.vol.):	No thinning see REMARKS overleaf
Pot life:	2 hour(s) 20°C/68°F
Nozzle orifice:	0.019 - 0.021 "
Nozzle pressure:	150 bar [2175 psi] (Airless spray data are indicative and subject to adjustment)
Cleaning of tools:	HEMPEL'S THINNER 08080
Indicated film thickness, dry:	150 micron [6 mils]
Indicated film thickness, wet:	225 micron [9 mils]
Overcoat interval, min:	According to specification.
Overcoat interval, max:	According to specification.

Safety: Handle with care. Before and during use, observe all safety labels on packaging and paint containers, consult HEMPEL Safety Data Sheets and follow all local or national safety regulations.

Product Data
HEMPASIL X3+ 87500

HEMPEL

APPLICATION CONDITIONS:	Use only where application and curing can proceed at temperatures above: 0°C/32°F. The temperature of the surface and that of the paint itself must also be above this limit. Apply only on a dry and clean surface with a temperature above the dew point to avoid condensation. In confined spaces provide adequate ventilation during application and drying. Curing requires a relative humidity of: minimum 30%, maximum 85%. The special application properties furthermore necessitate extra consideration as to possible windy weather. The on-site representative from Hempel is to be consulted.
PRECEDING COAT:	According to specification. Recommended systems are: HEMPASIL tiecoat
SUBSEQUENT COAT:	None.
REMARKS:	
Good painting practice:	It is of the utmost importance that thorough protection and cleaning procedures are followed before and after application respectively. It is advisable to apply HEMPASIL SYSTEM after all other exterior painting is complete. This is to avoid silicone contamination of other painted surfaces. **Before** application cover all surfaces surrounding the areas to be applied with plastic sheeting to avoid overspray. **After** application clean all equipment very thoroughly.
Application(s):	A well executed spray application is necessary. This paint material has special application properties and it is recommended first to make a small-scale application to get familiar with the properties.
Film thicknesses/thinning:	Thinning: Not recommended. In exceptional cases use THINNER 08080 (max 5 vol%)
Cleaning of tools:	Very thorough cleaning with THINNER 08080 is necessary. DISPOSE OF CLEANING SOLVENTS AFTER USE. DO NOT RE-USE SOLVENTS AFTER CLEANING.
Storage Conditions:	Must be stored under absolutely dry conditions, protect against seeping humidity.
Undocking:	Minimum: 24 hour(s)
Overcoating note:	One coat normally recommended.
Note:	**HEMPASIL X3+ 87500 For professional use only.**
ISSUED BY:	HEMPEL A/S 8750059151

Product Data Sheet
HEMPEL'S ANTIFOULING OLYMPIC 7660

HEMPEL

Description:	HEMPEL'S ANTIFOULING OLYMPIC 7660 is a tin free ablative antifouling bottom paint, based on polyamide polymer and containing cuprous oxide. Due to its self-renewing effect this product maintains a continually bio-active surface during its entire life. By providing a constantly active surface during its lifetime, this antifouling is gradually sacrificed in the process. The color of the system changes in accordance with the colors of the coats applied. Light red 50300 changes to whitish in direct contact with seawater. This product does not contain organotin compounds acting as biocides and complies with the International Convention on the Control of Harmful Antifouling Systems on Ships as adopted by IMO October 2001 (IMO document AFS/CONF/26).
Recommended use:	As an antifouling for maintenance of bottom on vessels operating in global trade and with short idle periods.
Availability:	Not included in Group Assortment. Availability subject to confirmation. **This product is not registered for sale or use in the USA.**

PHYSICAL CONSTANTS:

Shade no./Color:	51110 / Red*
Finish:	Flat
Volume solids, %:	57 ± 1
Theoretical spreading rate:	5.7 m²/litre - 100 micron 228.6 sq.ft./US gallon - 4 mils
Flash point:	25°C/77°F
Specific gravity:	2.1 kg/litre - 17.7 lbs/US gallon
Dry to touch:	5 hours at 20°C/68°F
VOC content:	368 g/litre - 3.1 lbs/US gallon
	**Other shades according to assortment list.*

The physical constants stated are nominal data according to approved formulas.

APPLICATION DETAILS:

Application method:	Airless spray / Brush
Thinner (max.vol.):	*See REMARKS overleaf*
Nozzle orifice:	0.023" - 0.027"
Nozzle pressure:	250 bar/3625 psi
Cleaning of tools:	HEMPEL'S THINNER 08080
Indicated film thickness, dry:	100 micron/4 mils *(see REMARKS overleaf)*
Indicated film thickness, wet:	150 micron/6 mils
Recoat interval, min:	According to specification
Recoat interval, max:	According to specification

Safety: Handle with care. Before and during use, observe all safety labels on packaging and paint containers, consult Hempel Material Safety Data Sheets and follow all local or national safety regulations.

Product Data Sheet
HEMPEL'S ANTIFOULING OLYMPIC 7660

SURFACE PREPARATION:	**Existing antifouling**: Remove possible oil and grease etc. with suitable detergent, followed by high pressure fresh water cleaning for a thorough removal of any possible weak structure of leached antifouling. Allow the surface to dry before coating. **Sealer**: Whether to use a sealer coat/tiecoat or not depends on the type and condition of the existing antifouling.
APPLICATION CONDITIONS:	The surface must be completely clean and dry at the time of application, and its temperature above the dew point to avoid condensation. In confined spaces provide adequate ventilation during application and drying.
PRECEDING COAT:	According to specification.
SUBSEQUENT COAT:	None. At later redocking direct overcoating - after a very proper cleaning and a thorough removal of possible loose outer layer - can as a general rule only take place with itself or similar ablative antifoulings. For other antifoulings measures of different kinds will be necessary, contact the nearest Hempel Office. After the high pressure fresh water cleaning of the old ablative antifouling it is essential that it becomes through dry before painting.
REMARKS:	This product contains heavy particles. Stir well before use.
Certificate/Approval:	Canadian PMRA Registration numbers: 21656, 21657, 21658
Film thicknesses/thinning:	May be specified in other film thicknesses than indicated depending on purpose and area of use. This will alter spreading rate and may influence drying time and overcoating interval. Normal range dry is 60 - 100 micron/2.4 - 4 mils. In case of multi-coat application, drying time and minimum overcoating interval will be influenced by the number of coats and by thickness of each coat applied - reference is made to the corresponding painting specification. May be applied in a dry film thickness up to 150 micron/6 mils per coat. This will require extra drying time. Recommended total max dry film thickness approx. 300 micron/12 mils. Keep thinning to a minimum to ensure that correct film thickness is obtained.
Undocking:	Minimum undocking time depends on drying condition of the paint film, corresponding painting specification gives further information. It is recommended to apply one coat only for possible outfitting, remaining layer(s) before delivery. If the full system is applied before launching, the paint film may show mud cracking by drying out at a delivery dry-docking. Usually this have no negative influence on later performance.
Overcoating note:	**Recommended number of coats:** As per specification depending on existing hull condition, trading pattern, and intended service life. No maximum recoat interval, but after prolonged exposure to polluted atmosphere, remove accumulated contamination by high pressure fresh water cleaning and allow to dry before applying next coat.
Note:	**HEMPEL'S ANTIFOULING OLYMPIC 7660 is for professional use only.**
Issued by:	HEMPEL (USA), Inc. 766051110

Intersleek 1100SR

International

Advanced Fluoropolymer Foul Release Coating

PRODUCT DESCRIPTION Advanced fluoropolymer foul release coating for the control of slime.

INTENDED USES For use at Newbuilding or Maintenance & Repair.

PRODUCT INFORMATION

Colour	FXA991-Grey, FXA992-Blue, FXA997-Red, FXA999-Black and a limited range of colours
Finish/Sheen	Gloss
Part B (Curing Agent)	FXA993 (Part B), FXA994 (Part C)
Volume Solids	72% ±2% (ISO 3233:1998)
Mix Ratio	9 volume(s) Part A to 2 volume(s) Part B to 1 volume(s) Part C
Typical Film Thickness	Range: 150 - 200 microns dry (208 - 278 microns wet) may be specified depending upon end use.
Theoretical Coverage	Range: 4.80 - 3.60 m²/litre at 150 - 200 microns dft, allow appropriate loss factors
Method of Application	Airless Spray, Brush
Flash Point (Typical)	Part A 46°C; Part B 22°C; Part C 36°C; Mixed 33°C
Induction Period	Not required

Drying Information	0°C	15°C	25°C	35°C
Touch Dry [ISO 9117/3:2010]	5 hrs	3 hrs	2 hrs	60 mins
Hard Dry [ISO 9117-1:2009]	15 hrs	6 hrs	4 hrs	2 hrs
Before Flooding	48 hrs	36 hrs	20 hrs	17 hrs
Pot Life	140 mins	90 mins	60 mins	30 mins

Note The interval prior to flooding may be reduced to 24 hours at temperatures between 5°C and 20°C provided that the ship remains at rest for a minimum period of 2-3 days after flooding. At temperatures between 0°C and 5°C, the absolute minimum time to flooding is 48 hours and the ship must remain at rest for a minimum of 4 days after undocking. However, the coating may suffer intercoat detachment in any areas that are subject to mechanical abrasion due to, eg. fendering or impact damage.

Overcoating Data - see limitations	**Substrate Temperature**							
	0°C		15°C		25°C		35°C	
Overcoated By	Min	Max	Min	Max	Min	Max	Min	Max

Note May be overcoated by self, either when fresh or after prolonged immersion provided surface is in good, clean condition. Consult International Paint.

REGULATORY DATA

VOC

240 g/lt as supplied (EPA Method 24)
238 g/kg of liquid paint as supplied. EU Solvent Emissions Directive (Council Directive 1999/13/EC)
252 g/lt Chinese National Standard GB23985

Note: VOC values are typical and are provided for guidance purposes only. These may be subject to variation depending on factors such as differences in colour and normal manufacturing tolerances.

This product does not contain organotin compounds acting as biocides and as such is in compliance with the International Convention on the Control of Harmful Anti-fouling Systems on ships as adopted by IMO in October 2001 (IMO document AFS/CONF/26).

Intersleek 1100SR

International.

Advanced Fluoropolymer Foul Release Coating

CERTIFICATION	When used as part of an approved scheme, this product has the following certification: Product recognised by the following classification societies as compliant with the International Convention on the Control of Harmful Anti-fouling Systems on Ships, 2001 (AFS 2001): • Bureau Veritas • DNV GL • Lloyds Register • Korean Register of Shipping Consult your International Paint representative for details.
SYSTEMS AND COMPATIBILITY	Consult your International Paint representative for the system best suited for the surfaces to be protected.
SURFACE PREPARATIONS	Use in accordance with the standard Worldwide Marine Specifications. All surfaces to be coated should be clean, dry and free from contamination. High pressure fresh water wash or fresh water wash, as appropriate, and remove all oil or grease, soluble contaminants and other foreign matter in accordance with SSPC-SP1 solvent cleaning. Intersleek 1100SR must always be applied over Intersleek tie coat within the required overcoating interval. Consult International Paint for detailed application advice and recommendations.

Intersleek 1100SR

Advanced Fluoropolymer Foul Release Coating

APPLICATION

Mixing	Material is supplied in 3 containers as a unit. Always mix a complete unit in the proportions supplied. (1) Agitate Part A with a power agitator (2) Combine entire contents of Part A and Part B and mix thoroughly with a power agitator. (3) Add entire contents of Part C and mix thoroughly with a power agitator. Carefully add Part C (under slow power-mixing) into the Part A / Part B mix. **These products are moisture sensitive and they should not be opened until just before they are needed.**
Thinner	Not recommended. Use International GTA007 only in exceptional circumstances. DO NOT thin more than allowed by local environmental legislation.
Airless Spray	Recommended Tip Range 0.38-0.53 mm (15-21 thou) Total output fluid pressure at spray tip not less than 211 kg/cm² (3000 p.s.i.)
Conventional Spray	Application by conventional spray is not recommended.
Brush	Application by brush is recommended for touch up areas only. Multiple coats may be required to achieve specified film thickness.
Roller	Application by roller is recommended for small areas only. Multiple coats may be required to achieve specified film thickness.
Cleaner	International GTA007/GTA822
Work Stoppages and Cleanup	Do not allow material to remain in hoses, gun or spray equipment. Thoroughly flush all equipment with International GTA007/GTA822. Once units of paint have been mixed they should not be resealed and it is advised that after prolonged stoppages work recommences with freshly mixed units. Clean all equipment immediately after use with International GTA007/GTA822. It is good working practice to periodically flush out spray equipment during the course of the working day. Frequency of cleaning will depend upon amount sprayed, temperature and elapsed time, including any delays. Do not exceed pot life limitations. All surplus materials and empty containers should be disposed of in accordance with appropriate regional regulations/legislation.
Welding	In the event welding or flame cutting is performed on metal coated with this product, dust and fumes will be emitted which will require the use of appropriate personal protective equipment and adequate local exhaust ventilation. In North America do so in accordance with instruction in ANSI/ASC Z49.1 "Safety in Welding and Cutting."

SAFETY

All work involving the application and use of this product should be performed in compliance with all relevant national Health, Safety & Environmental standards and regulations.

Prior to use, obtain, consult and follow the Material Safety Data Sheet for this product concerning health and safety information. Read and follow all precautionary notices on the Material Safety Data Sheet and container labels. If you do not fully understand these warnings and instructions or if you can not strictly comply with them, do not use this product. Proper ventilation and protective measures must be provided during application and drying to keep solvent vapour concentrations within safe limits and to protect against toxic or oxygen deficient hazards. Take precautions to avoid skin and eye contact (ie. gloves, goggles, face masks, barrier creams etc.) Actual safety measures are dependant on application methods and work environment.
EMERGENCY CONTACT NUMBERS:
USA/Canada - Medical Advisory Number 1-800-854-6813
Europe - Contact (44) 191 4696111. For advice to Doctors & Hospitals only contact (44) 207 6359191
China – Contact (86) 532 83889090
R.O.W. - Contact Regional Office

Intersleek 1100SR

Advanced Fluoropolymer Foul Release Coating

LIMITATIONS

Minimum acceptable substrate temperature at the time of application is 0°C. A minimum Relative Humidity of 30% is required to ensure satisfactory curing. Longer cure times will be required if the Relative Humidity falls below 30%. Care should be taken to avoid overspray onto other coated areas.
Intersleek 1100SR must be applied over Intersleek tie coat within the required overcoating interval.
All equipment must be thoroughly clean prior to use, and before re-use with other materials, to prevent contamination. Liquid cleaners for Intersleek 1100SR must not be allowed to contaminate other paints. Precautions should be taken to prevent silicone contamination of adjacent areas.

Overcoating information is given for guidance only and is subject to regional variation depending upon local climate and environmental conditions. Consult your local International Paint representative for specific recommendations. Apply in good weather. Temperature of the surface to be coated must be at least 3°C above the dew point. For optimum application properties bring the material to 21-27°C, unless specifically instructed otherwise, prior to mixing and application. Unmixed material (in closed containers) should be maintained in protected storage in accordance with information given in the STORAGE Section of this data sheet. Technical and application data herein is for the purpose of establishing a general guideline of the coating application procedures. Test performance results were obtained in a controlled laboratory environment and International Paint makes no claim that the exhibited published test results, or any other tests, accurately represent results found in all field environments. As application, environmental and design factors can vary significantly, due care should be exercised in the selection, verification of performance and use of the coating.

UNIT SIZE

Unit Size	Part A		Part B		Part C	
	Vol	Pack	Vol	Pack	Vol	Pack
10 lt	7.5 lt	10 lt	1.67 lt	2.5 lt	0.83 lt	1 lt
5 US gal	3.75 US gal	5 US gal	0.83 US gal	1 US gal	0.42 US gal	0.5 US gal

Part C is supplied in a polyethylene container
For availability of other unit sizes consult International Paint

UNIT SHIPPING WEIGHT (TYPICAL)

Unit Size	Unit Weight
10 lt	12.2 Kg
5 US gal	48.3 lb

STORAGE

Shelf Life: 12 months minimum at 25°C. Subject to re-inspection thereafter. Store in dry, shaded conditions away from sources of heat and ignition.

WORLDWIDE AVAILABILITY Consult International Paint.

IMPORTANT NOTE

The information in this data sheet is not intended to be exhaustive; any person using the product for any purpose other than that specifically recommended in this data sheet without first obtaining written confirmation from us as to the suitability of the product for the intended purpose does so at their own risk. All advice given or statements made about the product (whether in this data sheet or otherwise) is correct to the best of our knowledge but we have no control over the quality or the condition of the substrate or the many factors affecting the use and application of the product. Therefore, unless we specifically agree in writing to do so, we do not accept any liability at all for the performance of the product or for (subject to the maximum extent permitted by law) any loss or damage arising out of the use of the product. We hereby disclaim any warranties or representations, express or implied, by operation of law or otherwise, including, without limitation, any implied warranty of merchantability or fitness for a particular purpose. All products supplied and technical advice given are subject to our Conditions of Sale. You should request a copy of this document and review it carefully. The information contained in this data sheet is liable to modification from time to time in the light of experience and our policy of continuous development. It is the user's responsibility to check with their local representative that this data sheet is current prior to using the product.

This Technical Data Sheet is available on our website at www.international-marine.com or www.international-pc.com, and should be the same as this document. Should there be any discrepancies between this document and the version of the Technical Data Sheet that appears on the website, then the version on the website will take precedence.

www.international-marine.com

Interspeed 640

International

TBT Free Polishing Antifouling

PRODUCT DESCRIPTION

A high performance, TBT free, polishing antifouling. Enhanced biocide release mechanism. Prevents coating build -up. At subsequent drydockings, it is only necessary to top up the system. Low VOC.

INTENDED USES

As a TBT free, polishing antifouling. As a multiple coat system for extended in-service periods.
For use at Newbuilding or Maintenance & Repair.

PRODUCT INFORMATION

Colour	BRA640-Red, BRA641-Blue, BRA642-Black, BRA643-Ocean Green
Finish/Sheen	Not applicable
Part B (Curing Agent)	One pack
Volume Solids	62% ±2% (ASTM D2697-86)
Mix Ratio	One pack
Typical Film Thickness	100 microns dry (161 microns wet), 100 - 125 microns dry practical range equivalent to 161 - 202 microns wet
Theoretical Coverage	6.2 m²/litre at 100 microns dft, allow appropriate loss factors
Method of Application	Airless Spray, Brush, Roller,
Flash Point (Typical)	Single Pack 28°C (Setaflash) (ASTM D-3278)

Drying Information	5°C	10°C	25°C	35°C
Touch Dry [ASTM D1640 7.5.1]	12 hrs	6 hrs	4 hrs	2 hrs
Before Flooding	12 hrs	12 hrs	8 hrs	7 hrs

Note For Major Refurbishment and Repair if total dft is >300μm or a single coat is >150μm dft, the flooding times must be increased as follows:
24 hours at 10°C or less and 18 hours at 25°C or above.

Overcoating Data - see limitations

	Substrate Temperature							
	5°C		10°C		25°C		35°C	
Overcoated By	Min	Max	Min	Max	Min	Max	Min	Max
Interspeed 640	24 hrs	ext	20 hrs	ext	6 hrs	ext	4 hrs	ext

REGULATORY DATA

VOC 385 g/lt (3.21 lb/US Gal) as supplied (EPA Method 24)

Note: VOC values are typical and are provided for guidance purposes only. These may be subject to variation depending on factors such as differences in colour and normal manufacturing tolerances.

EPA Federal EPA Registration No. 2693-142
For specific state registrations contact your International Paint representative.
See Page 4 for additional Regulatory Data.

This product does not contain organotin compounds acting as biocides and as such is in compliance with the International Convention on the Control of Harmful Anti-fouling Systems on ships as adopted by IMO in October 2001 (IMO document AFS/CONF/26).

Interspeed 640

TBT Free Polishing Antifouling

CERTIFICATION

When used as part of an approved scheme, this product has the following certification:

Product recognised by the following classification societies as compliant with the International Convention on the Control of Harmful Anti-fouling Systems on Ships, 2001 (AFS 2001):

- Lloyds Register
- Det Norske Veritas
- Bureau Veritas
- Germanischer Lloyd

Consult your International Paint representative for details.

SYSTEMS AND COMPATIBILITY

Consult your International Paint representative for the system best suited for the surfaces to be protected.

SURFACE PREPARATIONS

Use in accordance with the standard Worldwide Marine Specifications.
Paint only clean, dry surfaces. Remove all grease, oil, soluble contaminants and other foreign matter by "solvent cleaning" (SSPC-SP1).

NEWBUILDING
Dependent on yard procedures. Consult International Paint.

Unpainted surfaces:
Prepare surface and apply recommended primer. Apply one or more coats of Interspeed 640 as specified. (Consult the relevant primer data sheet for surface preparation and overcoating information.)

Recoating and Upgrading of approved systems:
Use controlled close high pressure fresh water washing (minimum 3,000 psi, 211kg/sq. cm.) to clean the entire area, and remove any leached layer at the surface of the existing antifouling system.

Repair corroded areas with the recommended anticorrosive primer and apply a spot coat of Interspeed 640 within the overcoating interval specified for the primer (consult the relevant primer data sheet for surface preparation and overcoating information).

Apply the specified number of full coats of Interspeed 640.

Interspeed 640

International.

TBT Free Polishing Antifouling

APPLICATION	Apply by airless spray only. Application by other methods, brush or roller, may require more than one coat. Strain material through a minimum 60 mesh screen before application. Apply at 163 microns wet which will yield 100 microns dry film thickness. Consult the following equipment recommendations and/or utilize suitable equal.
Mixing	This material is a one pack coating. Always mix thoroughly with a power agitator before application.
Thinner	DO NOT THIN BEYOND YOUR STATE'S COMPLIANCY. Material is supplied at spray viscosity and normally does not need thinning. If thinning is necessary, thin up to a maximum of 4 ounces/gal. (118 ml) with International GTA007 Thinner.
Airless Spray	Minimum 28:1 ratio pump; 0.021" - 0.026" (533-661 microns) orifice tip; 3/8" (9.5mm) ID high pressure material hose; 60 mesh tip filter
Brush	Use appropriate size China bristle brush.
Roller	Use All Purpose Roller cover with 3/8" (9.5mm) pile smooth to medium nap. Prewash roller cover to remove loose fibers prior to use.
Cleaner	International GTA007
Work Stoppages and Cleanup	Clean all equipment immediately after use with International GTA007. It is good working practice to periodically flush out spray equipment during the course of the working day. Frequency will depend upon factors such as amount sprayed, temperature and elapsed time including work stoppages. Monitor material condition. All surplus materials and empty containers should be disposed of in accordance with appropriate regional regulations/legislation.
Welding	In the event welding or flame cutting is performed on metal coated with this product, dust and fumes will be emitted which will require the use of appropriate personal protective equipment and adequate local exhaust ventilation. In North America do so in accordance with instruction in ANSI/ASC Z49.1 "Safety in Welding and Cutting."
SAFETY	**All work involving the application and use of this product should be performed in compliance with all relevant national Health, Safety & Environmental standards and regulations.** **Prior to use, obtain, consult and follow the Material Safety Data Sheet for this product concerning health and safety information. Read and follow all precautionary notices on the Material Safety Data Sheet and container labels. If you do not fully understand these warnings and instructions or if you can not strictly comply with them, do not use this product. Proper ventilation and protective measures must be provided during application and drying to keep solvent vapour concentrations within safe limits and to protect against toxic or oxygen deficient hazards. Take precautions to avoid skin and eye contact (ie. gloves, goggles, face masks, barrier creams etc.) Actual safety measures are dependant on application methods and work environment.** **EMERGENCY CONTACT NUMBERS:** **USA/Canada - Medical Advisory Number 1-800-854-6813** **Europe - Contact (44) 191 4696111. For advice to Doctors & Hospitals only contact (44) 207 6359191** **China – Contact (86) 532 83889090** **R.O.W. - Contact Regional Office**

Interspeed 640

International

TBT Free Polishing Antifouling

LIMITATIONS

Apply in good weather when air and surface temperatures are above 2°C. Surface temperature must be at least 3°C above dew point. For optimum application properties, bring material to 21-27°C prior to mixing and application.
Unmixed material (in closed containers) should be maintained in protected storage between 4-38°C.
Prolonged atmospheric exposure of this product may detract from antifouling performance.
Recommended maximum exposure time before flooding:
Temperate conditions - 6 months
Tropical conditions - 3 months
These times may be extended under certain conditions. Contact your International Paint representative for advice.
Overcoating information is given for guidance only and is subject to regional variation depending upon local climate and environmental conditions. Consult your local International Paint representative for specific recommendations.
Technical and application data herein is for the purpose of establishing a general guideline of the coating and proper coating application guidelines. Test performance results were obtained in a controlled laboratory environment and International Paint makes no claim that the exhibited published test results, or any other tests, accurately represent results actually found in all field environments. As application, environmental and design factors can vary significantly, due care should be exercised in the selection, verification of performance and use of the coating.
In the overcoating data section 'ext' = extended overcoating period. Please refer to our Marine Painting Guide - Definitions and Abbreviations available on our website.

ADDITIONAL REGULATORY DATA

It is a violation of federal law to use this product in a manner inconsistent with its labelling.
Refer to container label for information concerning Precautionary Statements, Directions for Use and Storage and Disposal.

UNIT SIZE

Unit Size	Vol	Pack
5 US gal	5 US gal	5 US gal

UNIT SHIPPING WEIGHT (TYPICAL)

Unit Size	Unit Weight
5 US gal	94 lb

STORAGE

Shelf Life: 24 months minimum from date of manufacture when maintained in protected storage at 4-38° C. Subject to reinspection thereafter. Store in dry, shaded conditions away from sources of heat and ignition.

WORLDWIDE AVAILABILITY

Consult International Paint.

IMPORTANT NOTE

The information in this data sheet is not intended to be exhaustive; any person using the product for any purpose other than that specifically recommended in this data sheet without first obtaining written confirmation from us as to the suitability of the product for the intended purpose does so at their own risk. All advice given or statements made about the product (whether in this data sheet or otherwise) is correct to the best of our knowledge but we have no control over the quality or the condition of the substrate or the many factors affecting the use and application of the product. Therefore, unless we specifically agree in writing to do so, we do not accept any liability at all for the performance of the product or for (subject to the maximum extent permitted by law) any loss or damage arising out of the use of the product. We hereby disclaim any warranties or representations, express or implied, by operation of law or otherwise, including, without limitation, any implied warranty of merchantability or fitness for a particular purpose. All products supplied and technical advice given are subject to our Conditions of Sale. You should request a copy of this document and review it carefully. The information contained in this data sheet is liable to modification from time to time in the light of experience and our policy of continuous development. It is the user's responsibility to check with their local representative that this data sheet is current prior to using the product.

This Technical Data Sheet is available on our website at www.international-marine.com or www.international-pc.com, and should be the same as this document. Should there be any discrepancies between this document and the version of the Technical Data Sheet that appears on the website, then the version on the website will take precedence.

www.international-marine.com

APPENDIX B COMPLETED EXPERIMENTAL TEST MATRIX

Table B.1: Completed Test Matrix on the Hempaguard X3

Hempaguard X3

Test No.	Test Date	Test Time	Coating	Panel No	Nozzle	Test type (stationary or advancing)	Offset Distance (inch)	Angle (deg)	Target Flow Rate (gpm)	Target Pressure (psi)	Achieved Flow Rate (gpm)	Achieved Pressure (psi)	Cumulative Time (s)	Speed of advance (m/s)
X3-101	2020-09-18	2:15pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	0.875	22	0	0	0	0	0	0
X3-102	2020-09-18	2:38pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	0.875	22	3.3	2800	3.28	2800	2-3	0
X3-103	2020-09-18	3:03pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	0.875	22	3.3	2800	3.28	2800	10	0
X3-104	2020-09-18	3:22pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	0.875	22	3.3	2800	3.3	2800	30	0
X3-104A	2020-09-18	3:35pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	0.875	22	3.3	2800	3.28	2800	60	0
X3-105	2020-09-18	1:05pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	0.875	45	0	0	0	0	0	0
X3-106	2020-09-18	1:22pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	0.875	45	3.3	2800	3.28-3.3	2800	2-3	0
X3-109	2020-09-18	1:40pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	0.875	90	0	0	0	0	0	0
X3-110	2020-09-18	1:59pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	0.875	90	3.3	2800	3.28-3.3	2800	2-3	0
X3-117	2020-09-18	4:43pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	1.25	45	0	0	0	0	0	0
X3-118	2020-09-18	4:47pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	1.25	45	3.3	2800	3.3	2800	3	0
X3-121	2020-09-18	4:24pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	1.25	90	0	0	0	0	0	0
X3-122	2020-09-18	4:32pm	Hempaguard X3	X3- 1A	VLN	Single Stationary	1.25	90	3.3	2800	3.3	2800	3	0
X3-125			Hempaguard X3	X3- 1A	Evo	Single Stationary	0.875	22	0	0	0	0	0	0
X3-126	2020-09-28	5:10PM	Hempaguard X3	X3- 1A	Evo	Single Stationary	0.875	22	2.8	2300	2.8	2300	2-3	0
X3-127	2020-09-28	5:30pm	Hempaguard X3	X3- 1A	Evo	Single Stationary	0.875	22	2.8	2300	2.8	2300	10	0
X3-128			Hempaguard X3	X3- 1A	Evo	Single Stationary	0.875	22	2.8	2300	2.8	2300	30	0
X3-133	2020-09-28	2:22pm	Hempaguard X3	X3- 1A	Evo	Single Stationary	0.875	90	0	0	0	0	0	0
X3-134			Hempaguard X3	X3- 1A	Evo	Single Stationary	0.875	90	2.8	2300	2.8	2300	2-3	0
X3-137	2020-09-28	3:19pm	Hempaguard X3	X3- 1A	Evo	Single Stationary	1.25	22	0	0	0	0	0	0
X3-138			Hempaguard X3	X3- 1A	Evo	Single Stationary	1.25	22	2.8	2300	2.8	2300	2-3	0
X3-139			Hempaguard X3	X3- 1A	Evo	Single Stationary	1.25	22	2.8	2300	2.8	2300	10	0
X3-140			Hempaguard X3	X3- 1A	Evo	Single Stationary	1.25	22	2.8	2300	2.8	2300	30	0
X3-141			Hempaguard X3	X3- 1A	Evo	Single Stationary	1.25	45	0	0	0	0	0	0
X3-142	2020-09-28	4:19pm	Hempaguard X3	X3- 1A	Evo	Single Stationary	1.25	45	2.8	2300	2.8	2300	2-3	0
X3-145	2020-09-28	4:45pm	Hempaguard X3	X3- 1A	Evo	Single Stationary	1.25	90	0	0	0	0	0	0
X3-146			Hempaguard X3	X3- 1A	Evo	Single Stationary	1.25	90	2.8	2300	2.8	2300	5	0
X3-037	2020-09-13	11:47am	Hempaguard X3	X3 - 2A	Stingray	Stationary	0.875	22	6.6	2300	0	0	0	0
X3-038	2020-09-13	12:09pm	Hempaguard X3	X3 - 2A	Stingray	Stationary	0.875	22	6.6	2300	6.8-6.9	2300	5	0
X3-039	2020-09-13	12:45pm	Hempaguard X3	X3 - 2A	Stingray	Stationary	0.875	22	6.6	2300	6.8-6.9	2300	20	0
X3-040	2020-09-13	1:10pm	Hempaguard X3	X3 - 2A	Stingray	Stationary	0.875	22	6.6	2300	6.83	2300	60	0
X3-041	2020-09-16	1:30pm	Hempaguard X3	X3 - 2B	Stingray	Stationary	1.25	22	6.6	2300	0	0	0	0
X3-042	2020-09-16	1:43pm	Hempaguard X3	X3 - 2B	Stingray	Stationary	1.25	22	6.6	2300	7	2300	5	0
X3-043	2020-09-16	2:34pm	Hempaguard X3	X3 - 2B	Stingray	Stationary	1.25	22	6.6	2300	7.1	2300	20	0
X3-044	2020-09-16	3:00pm	Hempaguard X3	X3 - 2B	Stingray	Stationary	1.25	22	6.6	2300	7.07	2300	60	0
X3-045	2020-10-02	1:23pm	Hempaguard X3	X3 - 3A	Stingray	Advancing	0.875	22	6.6	2300	0	0	0	0.1
X3-046	2020-10-02	1:27pm	Hempaguard X3	X3 - 3A	Stingray	Advancing	0.875	22	6.6	2300	7.1	2300	(end)	0.1

Table B.2: Completed Test Matrix on the Intersleek 100SR

Intersleek 1100SR

Test No.	Test Date	Test Time	Coating	Panel No	Nozzle	Test type (stationary or advancing)	Offset Distance (inch)	Angle (deg)	Target Flow Rate (gpm)	Target Pressure (psi)	Est. Achieved Flow Rate (gpm)	Est. Achieved Pressure (psi)	Cumulative Time (s)	Speed of advance (m/s)
1100-001A	2020-09-29	9:45am	Intersleek 1100SR	1100 - 1A	VLN	Stationary	0.875	22	3.3	2800	0	0	0	0
1100-001B			Intersleek 1100SR	1100 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.4	2800	2-3	0
1100-002			Intersleek 1100SR	1100 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.4	2800	10	0
1100-003			Intersleek 1100SR	1100 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.4	2800	30	0
1100-003B	2020-09-29	10:23am	Intersleek 1100SR	1100 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.4	2800	60	0
1100-013A	2020-09-29	9:15am	Intersleek 1100SR	1100 - 1A	VLN	Stationary	1.25	45	3.3	2800	0	0	0	0
1100-013B	2020-09-29	9:20am	Intersleek 1100SR	1100 - 1A	VLN	Stationary	1.25	45	3.3	2800	3.4	2800	2-3	0
1100-16A			Intersleek 1100SR	1100 - 1A	VLN	Stationary	1.25	90	3.3	2800	0	0	0	0
1100-016B	2020-09-29	9:30am	Intersleek 1100SR	1100 - 1A	VLN	Stationary	1.25	90	3.3	2800	3.4	2800	2-3	0
1100-019A-1	2020-09-28	7:04pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	0.875	22	2.8	2300	0	0	0	0
1100-019B-1	2020-09-28	7:16pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	2-3	0
1100-019A-2	2020-09-30	2:55pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	0.875	22	2.8	2300	0	0	0	0
1100-019B-2	2020-09-30	3:26pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	2-3	0
1100-028A	2020-09-28	5:50pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	1.25	22	2.8	2300	0	0	0	0
1100-028B	2020-09-28	5:54pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	1.25	22	2.8	2300	2.8	2300	2-3	0
1100-029	2020-09-28	6:25pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	1.25	22	2.8	2300	2.8	2300	10	0
1100-030	2020-09-28	6:38pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	1.25	22	2.8	2300	2.8	2300	30	0
1100-030B	2020-09-28	6:54pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	1.25	22	2.8	2300	2.8	2300	60	0
1100-031A	2020-09-28	7:19pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	1.25	45	2.8	2300	0	0	0	0
1100-031B	2020-09-28	7:42pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	1.25	45	2.8	2300	2.8	2300	2-3	0
1100-034A			Intersleek 1100SR	1100 - 1A	Evo	Stationary	1.25	90	2.8	2300	2.8	2300	0	0
1100-034B	2020-09-28	7:44pm	Intersleek 1100SR	1100 - 1A	Evo	Stationary	1.25	90	2.8	2300	2.8	2300	2-3	0
1100-037	2020-09-13	4:00pm	Intersleek 1100SR	1100 - 2A	Stingray	Stationary	0.875	22	6.6	2300	0	0	0	0
1100-038	2020-09-13	4:18pm	Intersleek 1100SR	1100 - 2A	Stingray	Stationary	0.875	22	6.6	2300	6.83	2300	5	0
1100-039	2020-09-13	4:39pm	Intersleek 1100SR	1100 - 2A	Stingray	Stationary	0.875	22	6.6	2300	6.86	2300	20	0
1100-040	2020-09-13	5:03pm	Intersleek 1100SR	1100 - 2A	Stingray	Stationary	0.875	22	6.6	2300	6.84	2300	60	0
1100-045	2020-10-02	12:55pm	Intersleek 1100SR	1100 - 3A	Stingray	Advancing	0.875	22	6.6	2300	0	0	0	0.1
1100-046	2020-10-02	1:00pm	Intersleek 1100SR	1100 - 3A	Stingray	Advancing	0.875	22	6.6	2300	7.2	2300	(end)	0.1

Table B.3: Completed Test Matrix on the Interspeed 640

Interspeed 640

									Target		Est. Achieved			
Test No.	Test Date	Test Time	Coating	Panel No	Nozzle	Test type (stationary or advancing)	Offset Distance (inch)	Angle (deg)	Flow Rate (gpm)	Pressure (psi)	Flow Rate (gpm)	Pressure (psi)	Cumulative Time (s)	Speed of advance (m/s)
640-001	2020-09-29	10:30am	Interspeed 640	640 - 1A	VLN	Stationary	0.875	22	3.3	2800	0	0	0	0
640-002			Interspeed 640	640 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.4	2800	2-3	0
640-003			Interspeed 640	640 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.4	2800	10	0
640-004			Interspeed 640	640 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.4	2800	30	0
640-005			Interspeed 640	640 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.4	2800	60	0
640-006			Interspeed 640	640 - 1A	VLN	Stationary	0.875	45	3.3	2800	0	0	0	0
640-007	2020-09-29	1:57pm	Interspeed 640	640 - 1A	VLN	Stationary	0.875	45	3.3	2800	3.4	2800	2-3	0
640-008	2020-09-29	2:03pm	Interspeed 640	640 - 1A	VLN	Stationary	0.875	45	3.3	2800	3.4	2800	10	0
640-011			Interspeed 640	640 - 1A	VLN	Stationary	0.875	90	3.3	2800	0	0	0	0
640-012	2020-09-29	12:04pm	Interspeed 640	640 - 1A	VLN	Stationary	0.875	90	3.3	2800	3.4	2800	2-3	0
640-021	2020-09-29	1:04pm	Interspeed 640	640 - 1A	VLN	Stationary	1.25	45	3.3	2800	0	0	0	0
640-022			Interspeed 640	640 - 1A	VLN	Stationary	1.25	45	3.3	2800	3.4	2800	2-3	0
640-023			Interspeed 640	640 - 1A	VLN	Stationary	1.25	45	3.3	2800	3.4	2800	10	0
640-024			Interspeed 640	640 - 1A	VLN	Stationary	1.25	45	3.3	2800	3.4	2800	30	0
640-025	2020-09-29	1:57pm	Interspeed 640	640 - 1A	VLN	Stationary	1.25	45	3.3	2800	3.4	2800	60	0
640-026	2020-09-29	12:15PM	Interspeed 640	640 - 1A	VLN	Stationary	1.25	90	3.3	2800	0	0	0	0
640-027			Interspeed 640	640 - 1A	VLN	Stationary	1.25	90	3.3	2800	3.4	2800	2-3	0
640-028	2020-09-29	12:22pm	Interspeed 640	640 - 1A	VLN	Stationary	1.25	90	3.3	2800	3.4	2800	15	0
640-029			Interspeed 640	640 - 1A	VLN	Stationary	1.25	90	3.3	2800	3.4	2800	30	0
640-030			Interspeed 640	640 - 1A	VLN	Stationary	1.25	90	3.3	2800	3.4	2800	60	0
640-031	2020-09-29	2:21pm	Interspeed 640	640 - 1A	Evo	Stationary	0.875	22	2.8	2300	0	0	0	0
640-032			Interspeed 640	640 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	2-3	0
640-033			Interspeed 640	640 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	10	0
640-034			Interspeed 640	640 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	30	0
640-035	2020-09-29	3:00pm	Interspeed 640	640 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	60	0
640-036	2020-09-30	2:20pm	Interspeed 640	640 - 1A	Evo	Stationary	0.875	45	2.8	2300	0	0	0	0
640-037			Interspeed 640	640 - 1A	Evo	Stationary	0.875	45	2.8	2300	2.8	2300	2-3	0
640-038	2020-09-30	2:33pm	Interspeed 640	640 - 1A	Evo	Stationary	0.875	45	2.8	2300	2.8	2300	10	0
640-051	2020-09-29	3:23pm	Interspeed 640	640 - 1A	Evo	Stationary	1.25	45	2.8	2300	0	0	0	0
640-052			Interspeed 640	640 - 1A	Evo	Stationary	1.25	45	2.8	2300	2.8	2300	2-3	0
640-053	2020-09-29	3:46pm	Interspeed 640	640 - 1A	Evo	Stationary	1.25	45	2.8	2300	2.8	2300	10	0
640-056	2020-09-29	3:13pm	Interspeed 640	640 - 1A	Evo	Stationary	1.25	90	2.8	2300	2.8	2300	0	0
640-057	2020-09-29	3:19pm	Interspeed 640	640 - 1A	Evo	Stationary	1.25	90	2.8	2300	2.8	2300	2-3	0
640-061	2020-10-01	5:47pm	Interspeed 640	640 - 2B	Stingray	Stationary	0.875	22	6.6	2300	0	0	0	0
640-062	2020-10-01	5:55pm	Interspeed 640	640 - 2B	Stingray	Stationary	0.875	22	6.6	2300	7.1	2300	5	0
640-063	2020-10-01	6:07pm	Interspeed 640	640 - 2B	Stingray	Stationary	0.875	22	6.6	2300	7.12	2300	20	0
640-064	2020-10-01	6:17pm	Interspeed 640	640 - 2B	Stingray	Stationary	0.875	22	6.6	2300	7.17	2300	60	0
640-069	2020-10-02	12:20pm	Interspeed 640	640 - 3A	Stingray	Advancing	0.875	22	6.6	2300	0	0	0	0.1
640-070	2020-10-02	12:24pm	Interspeed 640	640 - 3A	Stingray	Advancing	0.875	22	6.6	2300	7.2	2300	60	0.1

Table B.4: Completed Test Matrix on the Olympic 7660

Olympic 7660

									Target		Est. Achieved			
Test No.	Test Date	Test Time	Coating	Panel No	Nozzle	Test type (stationary or advancing)	Offset Distance (inch)	Angle (deg)	Flow Rate (gpm)	Pressure (psi)	Flow Rate (gpm)	Pressure (psi)	Cumulative Time (s)	Speed of advance (m/s)
7660-001	2020-09-29	6:34pm	Olympic 7660	7660 - 1A	VLN	Stationary	0.875	22	3.3	2800	0	0	0	0
7660-002			Olympic 7660	7660 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.45	2800	2-3	0
7660-003			Olympic 7660	7660 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.45	2800	10	0
7660-004	2020-09-29	6:40pm	Olympic 7660	7660 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.45	2800	30	0
7660-005	2020-09-29	6:45pm	Olympic 7660	7660 - 1A	VLN	Stationary	0.875	22	3.3	2800	3.45	2800	60	0
7660-006			Olympic 7660	7660 - 1A	VLN	Stationary	0.875	45	3.3	2800	0	0	0	0
7660-007	2020-09-29	5:35pm	Olympic 7660	7660 - 1A	VLN	Stationary	0.875	45	3.3	2800	3.45	2800	4	0
7660-008	2020-09-29	5:44pm	Olympic 7660	7660 - 1A	VLN	Stationary	0.875	45	3.3	2800	3.45	2800	10	0
7660-009			Olympic 7660	7660 - 1A	VLN	Stationary	0.875	45	3.3	2800	3.45	2800	30	0
7660-010			Olympic 7660	7660 - 1A	VLN	Stationary	0.875	45	3.3	2800	3.45	2800	60	0
7660-011	2020-09-30	11:42am	Olympic 7660	7660 - 1A	VLN	Stationary	0.875	90	3.3	2800	0	0	0	0
7660-012	2020-09-30	11:58am	Olympic 7660	7660 - 1A	VLN	Stationary	0.875	90	3.3	2800	3.44	2800	2-3	0
7660-021	2020-09-29	6:04pm	Olympic 7660	7660 - 1A	VLN	Stationary	1.25	45	3.3	2800	0	0	0	0
7660-022			Olympic 7660	7660 - 1A	VLN	Stationary	1.25	45	3.3	2800	3.45	2800	2-3	0
7660-023			Olympic 7660	7660 - 1A	VLN	Stationary	1.25	45	3.3	2800	3.45	2800	10	0
7660-024			Olympic 7660	7660 - 1A	VLN	Stationary	1.25	45	3.3	2800	3.45	2800	30	0
7660-025	2020-09-29	6:28pm	Olympic 7660	7660 - 1A	VLN	Stationary	1.25	45	3.3	2800	3.45	2800	60	0
7660-026	2020-09-29	5:48pm	Olympic 7660	7660 - 1A	VLN	Stationary	1.25	90	3.3	2800	0	0	0	0
7660-027			Olympic 7660	7660 - 1A	VLN	Stationary	1.25	90	3.3	2800	3.45	2800	4	0
7660-028	2020-09-29	6:01pm	Olympic 7660	7660 - 1A	VLN	Stationary	1.25	90	3.3	2800	3.45	2800	10	0
7660-031	2020-09-29	4:44pm	Olympic 7660	7660 - 1A	Evo	Stationary	0.875	22	2.8	2300	0	0	0	0
7660-032			Olympic 7660	7660 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	5	0
7660-033			Olympic 7660	7660 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	10	0
7660-034			Olympic 7660	7660 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	30	0
7660-035	2020-09-29	5:17pm	Olympic 7660	7660 - 1A	Evo	Stationary	0.875	22	2.8	2300	2.8	2300	60	0
7660-036	2020-09-30	12:39pm	Olympic 7660	7660 - 1A	Evo	Stationary	0.875	45	2.8	2300	2.8	0	0	0
7660-037			Olympic 7660	7660 - 1A	Evo	Stationary	0.875	45	2.8	2300	2.8	2300	2-3	0
7660-038	2020-09-30	12:58pm	Olympic 7660	7660 - 1A	Evo	Stationary	0.875	45	2.8	2300	2.8	2300	10	0
7660-051	2020-09-29	4:09pm	Olympic 7660	7660 - 1A	Evo	Stationary	1.25	45	2.8	2300	0	0	0	0
7660-052			Olympic 7660	7660 - 1A	Evo	Stationary	1.25	45	2.8	2300	2.8	2300	2-3	0
7660-053	2020-09-29	4:23pm	Olympic 7660	7660 - 1A	Evo	Stationary	1.25	45	2.8	2300	2.8	2300	10	0
7660-056	2020-09-29	4:33pm	Olympic 7660	7660 - 1A	Evo	Stationary	1.25	90	2.8	2300	0	0	0	0
7660-057	2020-09-29	4:42pm	Olympic 7660	7660 - 1A	Evo	Stationary	1.25	90	2.8	2300	2.8	2300	2-3	0
7660-061	2020-10-01	7:10pm	Olympic 7660	7660 - 2A	Stingray	Stationary	0.875	22	6.6	2300	0	0	0	0
7660-062	2020-10-01	7:14pm	Olympic 7660	7660 - 2A	Stingray	Stationary	0.875	22	6.6	2300	7.12	2300	5	0
7660-063	2020-10-01	7:23pm	Olympic 7660	7660 - 2A	Stingray	Stationary	0.875	22	6.6	2300	7.12	2300	20	0
7660-064	2020-10-01	7:41pm	Olympic 7660	7660 - 2A	Stingray	Stationary	0.875	22	6.6	2300	7.12	2300	60	0
7660-065	2020-10-02	10:25am	Olympic 7660	7660 - 2B	Stingray	Stationary	0.875	22	6.6	2300	0	0	0	0
7660-066	2020-10-02	10:30am	Olympic 7660	7660 - 2B	Stingray	Stationary	0.875	22	6.6	2300	7.2	2300	5	0
7660-067	2020-10-02	10:40am	Olympic 7660	7660 - 2B	Stingray	Stationary	0.875	22	6.6	2300	7.2	2300	20	0
7660-068	2020-10-02	10:54am	Olympic 7660	7660 - 2B	Stingray	Stationary	0.875	22	6.6	2300	7.2	2300	60	0
7660-073	2020-10-02	11:41am	Olympic 7660	7660 - 3A	Stingray	Advancing	0.875	22	6.6	2300	0	0	0	0.1
7660-074	2020-10-02	11:50am	Olympic 7660	7660 - 3A	Stingray	Advancing	0.875	22	6.6	2300	7.2	2300	60	0.1
7660-077	2020-10-02	2:28pm	Olympic 7660	7660 - 1A	Evo	Hand held blasting	N/A	N/A	2.8	2300	2.8	2300	0	0
7660-078	2020-10-02	2:41pm	Olympic 7660	7660 - 1A	Evo	Hand held blasting	N/A	N/A	2.8	2300	2.8	2300	120	0

APPENDIX C ENVIRONMENTAL IMPACT REPORT BY BAILEY ENVIRONMENTAL CONSULTING

Environmental Assessment of the Potential for Robotic In-water Ship Hull Cleaning

BAILEY
Environmental Consulting

Prepared for:

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Submission Date: *February 18, 2021*

Disclaimer

This report was produced for the use of Offshore Design Limited (ODL) to provide a high-level overview of the regulatory environment that governs in-water hull cleaning combined with the potential biological impacts of in-water hull cleaning. This information is intended for ODL's use to support continued development of their innovative in-water hull cleaning technology and to answer the following questions:

1. *Can in-water hull cleaning be done in an environmentally friendly way, and*
2. *If the technology is developed, would the regulatory environment allow in-water hull cleaning to proceed.*

The information presented here is strictly the opinion of Bailey Environmental Consulting Inc. and does not reflect the ideas or opinions of ODL or any other regulatory body (e.g., such as Transport Canada).

This report is not intended to be exhaustive literature research regarding the regulatory environment (in part because legislation pertaining to these activities is evolving), nor an exhaustive analysis of the potential biological implications of in-water hull cleaning. This report is intended as a high-level overview and starting point for discussions surrounding this topic. The scope of this report did not include engaging directly with regulators (such as Fisheries and Oceans Canada or port authorities such as the Vancouver Fraser Port Authority), or industry (such as BC Ferries). The scope of this report did not include complex oceanographic modelling and focused on British Columbia as an example.

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Acronyms and Definitions

µg/L	micrograms per liter
AFS	Anti-fouling system
AIS	Aquatic Invasive Species
Ballast	Water added to a vessel to improve stability
BC	British Columbia
Biofouling	The accumulation of aquatic organisms such as micro-organisms, plants and animals on surfaces and structures that are immersed in or exposed to the aquatic environment.
CCGV	Canadian Coast Guard Vessel
CEPA	*Canadian Environmental Protection Act*
cm	centimeters
CPAs	Canadian Port Authorities
DFO	Fisheries and Oceans Canada
Diel	Daily
EEZ	Exclusive Economic Zone
FR	fouling rating
GHG	Green House Gas
Grooming	The frequent and gentle cleaning of a ship hull coating, when it is in port or idle, to prevent the establishment of fouling.
Holoplankton	A plant or animal spending their entire life as a plankton
IMO	International Maritime Organization
knots	nautical miles per hour (1 knot = 1.15 miles/hour; 1.85 km/hour)
m	meters
mm	millimeters
Macrofouling	The settlement and growth of organisms such as plants or invertebrates on a submerged surface.
MEPC	Marine Environmental Protection Committee
Meroplankton	A plant or animal spending only a portion of their life cycle as plankton
Microfouling	The settlement and growth of unicellular algae and/or bacteria on a submerged surface creating a slime-like consistency.
NIS	Non-indigenous Species
nm	nautical miles
ODL	Offshore Designs Ltd.

Ontogenetic	Development of an organism from egg to adult
Plankton	Organisms that passively float in the ocean unable to swim against currents
PCR	Pacific Coast Region
PSU	Practical Salinity Unit
RFI	Request for Information
ROV	Remotely Operated Vehicle
TBT	tributyltin
TC	Transport Canada
VFPA	Vancouver Fraser Port Authority
WQG	Water Quality Guidelines

1 Summary

Offshore Designs Ltd. (ODL) is proposing the development of a robot capable of frequent cleaning of biofouling off large ocean-going vessels during transit between coastal harbours and/or while moored in harbour. The frequent removal of biofouling (particularly at the microfouling state) decreases the ship's drag, thus improving fuel efficiency (i.e., reducing fuel costs) and therefore reducing Green House Gas (GHG) emissions. Frequent cleaning of fouling minimizes the spread and establishment of invasive organisms.

In-water ship hull cleaning is currently done with a variety of methods in harbour by divers or remotely controlled cleaning robots. Certain harbours (e.g., in Europe, Australia, New Zealand, Unites States, Canada) mandate that suction and filtration systems are used to capture all organic and in-organic material removed to minimize the environmental impacts of non-indigenous species (NIS) and/or antifouling paint. However, many other ports allow hull cleaning to proceed without any mitigation against the spread of invasive species or local water contamination. The regulations around ship hull cleaning are often local (nation state or port-specific) and evolving.

This report aims to evaluate the regulatory and biological feasibility of the conceptual in-water cleaning robot by 1) identifying local, national, and international regulations pertaining to in-water hull cleaning and 2) assess the biological implications of hull cleaning (i.e., spread of invasive species and potential pollution from coating removal during the cleaning process). Considering the regulatory and biological limitations, and the function of the conceptual cleaning robot, we conclude with proposed guidelines for effective and safe in-water cleaning based on the level of biofouling with particular emphasis on depth, distance from shore and oceanographic conditions.

2 Proposed Robot

The proposed robot is in the conceptual stages and is intended to be able to clean light stages of fouling frequently, in-water (either in harbour or in transit between harbours). By cleaning frequently in-water, the risk of spreading invasive species is minimized, fuel savings are maximized (thereby reducing GHG emissions), and high cost of cleaning out of water is reduced as buildup of biofouling organisms is lower (i.e., amount of time spent in dry dock is reduced), and lost time for commercial operations (i.e., the vessel is not in service while in dry dock and therefore revenue is decreased). There may be additional advantages such as reduced underwater noise emissions. The tethered cleaning robot would be temporarily attached to the ship hull using magnetics on submersible powered tracks (Figure 1).

The three stages of the project include:

1. **Phase 1:** (in progress): experimental testing to assess the potential environmental impact of cleaning different types of hull coatings, both to ensure the paint is not damaged by the cleaning system and adhesion method and that the water quality meets guidelines (e.g., for

visible flakes or particles, copper, zinc). Lab experiments will be on different coatings in collaboration with two major suppliers (i.e., Hempel and International Paints). Cleaning method will use cavitating waterjet technology, which is generally accepted as causing less damage to paint compared with brushes (that physically contact the hull surface) and waterjets (that operate at higher pressures).

2. **Phase 2:** regulatory and biological assessment of the feasibility and potential environmental impacts of cleaning while the vessel is in harbour and in transit between harbours (e.g., depth, distance from shore). This report summarized Phase 2.
3. **Phase 3:** using the results of Phases 1 and 2, transition from conceptual to complete detailed design of the hull cleaner and initiate field testing.

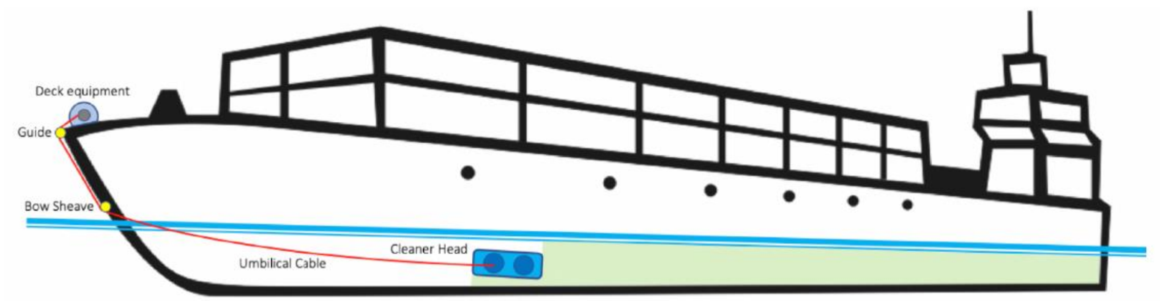

Figure 1: Conceptual Drawing of Cleaning Robot

3 Background

A number of projects and investigations were completed or are presently underway in Canada to evaluate in-water ship hull cleaning strategies. Specifically, the projects assess whether in-water hull cleaning technologies reduce fuel consumption and underwater noise. Transport Canada (TC) aims to understand how each technology meets the Marine and Environmental standards of Canada. Two Canadian projects are described in the sections below for context. This robot cleaning project is being completed under TC's Clean Marine Stream 1 – Emerging Technologies program. TC is interested in new technologies that will reduce GHG emissions of vessels while fulfilling marine environmental safety standards with regards to the release of organisms and contaminants (i.e., anti-fouling coatings).

3.1 Recent Federal Request for Information

A recent (December 2019) Request For Information (RFI) issued by Public Works and Government Services Canada (PWGSC, EN600-10LOI) suggests that the Canadian Government is evaluating technology options currently available that would allow for in-water cleaning of Navy and Coast Guard vessels. According to the RFI, the purpose is to:

> *"…develop an understanding of current and emerging technologies for in-water cleaning and grooming so that general operating procedures, standards and guidelines can be developed for Government of Canada use. The intent of gathering this information is to collaboratively explore and modernize the current way in which vessel cleaning is undertaken, and to shape a national strategy for vessel cleaning services that better meet the needs of government and preserves the marine environment."*

According to the information presented in this RFI, Canada's fleet of Navy and Coast Guard vessels does not currently perform in-water vessel cleaning and grooming as a normal practice – it is typically done while vessel is dry docked.

3.2 Port of Vancouver Hull Cleaning Project

Transport Canada and the Vancouver Fraser Port Authority (VFPA) recently evaluated 'Whale Shark', a Canadian underwater hull cleaning technology developed by Subsea Global Solutions (https://www.sgsdiving.com/) that aimed to capture and filter all effluent from the hull cleaning process, for use in the Port of Vancouver (Vancouver Fraser Port Authority, 2019). Transport Canada was interested in determining: 1) whether the Whale Shark was environmentally safe, and 2) whether there were benefits to fuel consumption/underwater noise emissions from hull cleaning (Vancouver Fraser Port Authority, 2019). The results of this evaluation were considered to be inconclusive, and recommendations were made to increase sample size and to change data collection methods in order to obtain more accurate results (Vancouver Fraser Port Authority, 2019). From 2017 – 2018, the project evaluated three vessels pre- and post-hull cleaning, including one bulk vessel and one tanker in the Port of Vancouver, and an additional Canadian Coast Guard Vessel (CCGV), *Cygnus*, in Conception Bay, Newfoundland. It should be noted that CCGV *Cygnus* was cleaned by Divers not Whale Shark but contributed to the overall findings of the project.

The project focused on three components:

1. **Containment and capture of debris and contaminants released during underwater hull cleaning using 'Whale Shark'**

   Although Whale Shark was able to remove debris from the hull, it was not effective in capturing debris following removal from the ship (i.e., a cloudy plume of debris was observed during cleaning). Water quality analysis results showed exceedances of metal contaminants above guidelines[1]. Based on these results, the 'Whale Shark' was not

[1]Although specific information on the exceedances was not publicly available, the most common metal of concern associated with hull cleaning is copper, which has guidelines of 2 µg/L for chronic toxicity and 3 µg/L for acute toxicity in British Columbia (British Columbia Ministry of Environment, 2019).

considered to effectively contain and capture debris and contaminants, so the assessment was not performed on any other vessels.

2. **Noise pre- and post-hull cleaning**

   Two of the three vessels were cleaned using the 'Whale Shark' to evaluate whether hull cleaning significantly impacted the underwater noise levels emitted by the vessel. Noise levels were recorded 1) prior to hull cleaning, 2) after the hulls of the ships had been cleaned, and 3) after both the hulls and the propellers of the ships had been cleaned.

   Noise levels were monitored as vessels passed over the Strait of Georgia and evaluated by JASCO Applied Science. Noise monitoring data suggest that hull cleaning did not seem to significantly impact noise levels. Observational data indicate that 'Whale Shark' did not clean the entire hull, leaving several sections fouled, including the bulkhead and stern end. This could account for the lack of difference between noise monitoring readings. Additionally, it is unknown what level of fouling the vessels had before the cleaning.

   The third vessel, the CCGV *Cygnus*, was cleaned by Divers. Noise studies for the CCGV *Cygnus* were undertaken in Conception Bay, Newfoundland. The assessment revealed that cleaning did not significantly change the vessel's noise levels. Numerous variabilities and uncertainties in this trial resulted in inconclusive evidence.

3. **Fuel savings pre- and post-hull cleaning**

   Analysis of fuel consumption pre- and post-cleaning (both those evaluated by Det Norske Veritas in the Port of Vancouver and the trials for CCGV *Cygnus*) was also inconclusive. Post-hull cleaning trials for the CCGV *Cygnus* showed some promise with observations of less power required to obtain higher speeds after cleaning, and further reduced with propeller cleaning.

The results indicated that 'Whale Shark' did not effectively contain and capture debris and contaminants, while noise and fuel consumption tests proved inconclusive. Recommendations were made to improve data collection methods, to better understand the benefits of hull cleaning. 'Whale Shark' was therefore not considered for use by the Vancouver Fraser Port Authority's Environmental Program due to these inconclusive results (Vancouver Fraser Port Authority, 2019).

4 Biological Overview

The pelagic ocean (i.e., open ocean) can be divided into five different zones (Figure 2) and includes the epipelagic (0 – 200 m), mesopelagic (200 – 1,000 m), bathypelagic (1,000 – 4,000 m), abyssopelagic (4,000 – 6,000 m), and hadalpelagic (>6,000 m). Each zone is inhabited by different organisms, with various adaptations to deal with life at various depths (e.g., increased pressure and decreasing light with increased depth). The epipelagic layer roughly coincides with the euphotic zone, in which enough light penetrates the ocean surface to enable photosynthesis. The deeper layers of ocean encompass organisms adapted to live under high pressure, low light, low temperature, low food, and low oxygen conditions (George, 1971). Many pelagic organisms are known to undergo extensive diel (i.e., daily) or ontogenetic (i.e., developmental) vertical migrations, effectively connecting the epipelagic zone to the deep ocean (e.g., Angel, 1984; Iwasa, 1982; Lampert, 1989; van Haren and Compton, 2013).

Within their lifecycle, many marine organisms have a pelagic phase (e.g., larval, propagules) referred to as the planktonic stage, during which organisms are unable to swim against currents, drifting within the water column. Depending on the organism, they may spend their entire life (holoplankton) or only a portion of their life (meroplankton) as plankton. Meroplankton are typically those that exhibit a planktonic larval or early life stage(s), settling on the benthos (e.g., crab, sea cucumber) or gaining the ability to swim against currents once they have reached their adult life stage (e.g., tuna, squid, jellyfish). The planktonic phase encourages dispersal, thus reducing kin competition (Burgess *et al.*, 2016), and can be transported over vast spatial scales with immense implications for ecosystem functioning. When transported beyond their natural range, only a fraction of species become established in their new environment as invasive/non-indigenous species (NIS). While there are many ecological and physiological factors determining whether a species can effectively establish themselves in a new environment, the majority are associated with reproduction (Geburzi and McCarthy, 2017). Specifically, effective invasive species generally have a larval planktonic phase and exhibit early sexual maturity, short generation times, high fecundity and rapid growth rates (Geburzi and McCarthy, 2017). Other factors controlling successful establishment include plasticity in resource utilization and abiotic conditions (temperature and salinity tolerance) (Crowl *et al.*, 2008; Blasi and O'Connor, 2016; Griffen *et al.*, 2011). Finally, given that a species is able to survive and reproduce in their new environment, they must also be able to compete-with or out-compete local species when it comes to food, shelter and settlement areas (Levine *et al.*, 2004; DeRivera *et al.*, 2005; Geburzi and McCarthy, 2017; Katsanevakis *et al.*, 2013).

Environmental Assessment of the Potential for Robotic In-water Ship Hull Cleaning

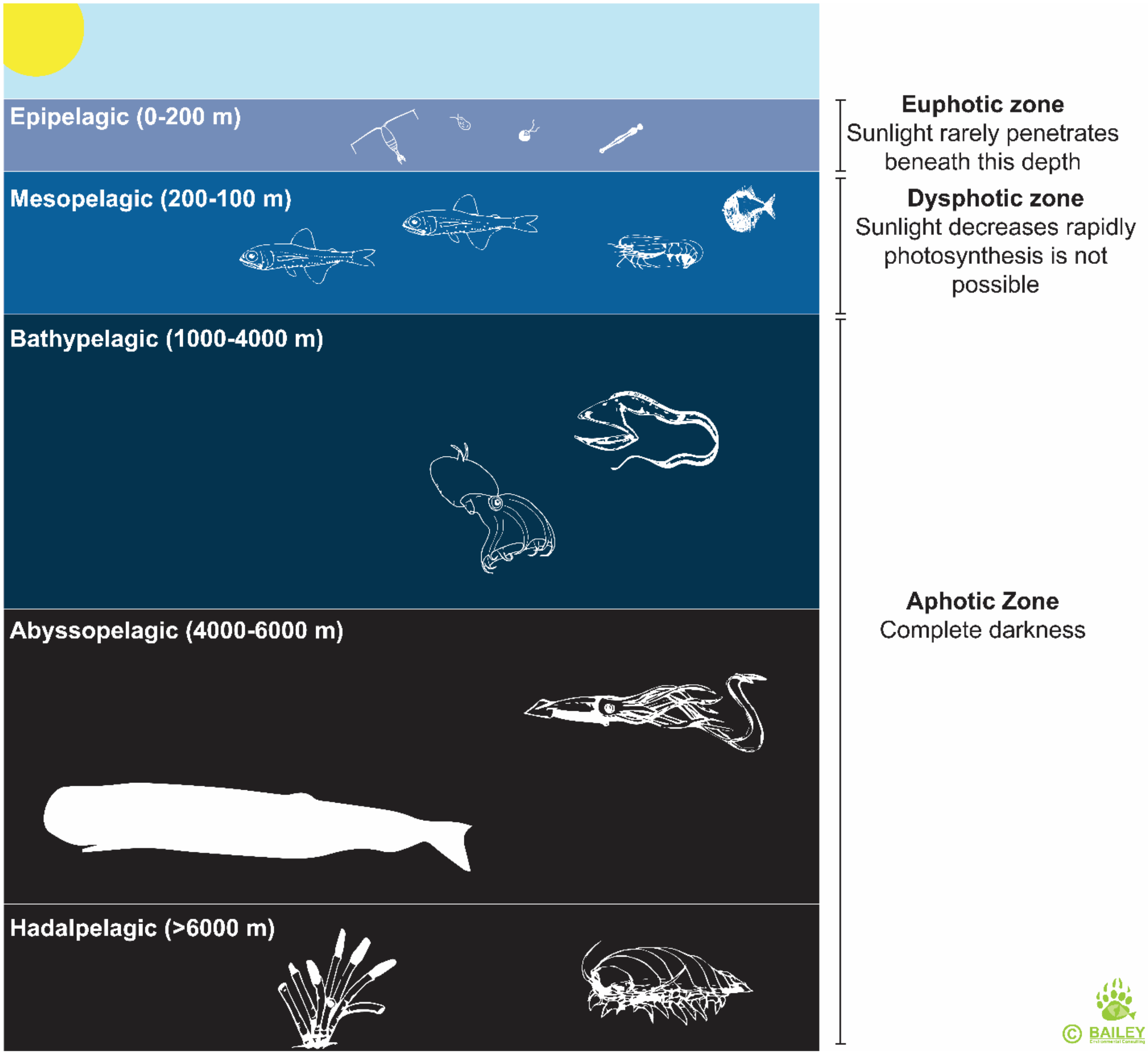

Figure 2: Conceptual diagram showing pelagic (left) and photic zones (right) with depth

5 Vectors for NIS Spread

While natural spread of NIS may occur, anthropogenic spread is the main vector by which species can be transported beyond their natural range, and includes shipping (52%), corridors/canals (40%), aquaculture (16%) and aquarium trade (3%) (Katsanevakis *et al.*, 2013). Secondary spread can occur on a more localized scale via recreational vessels and commercial vessel introduction in harbours (Ferrario *et al.*, 2017). To prevent secondary spread of NIS, proper management to prevent introduction is critical. Prevention of NIS introduction via commercial vessels focuses primarily on ballast water management, while regulations for fouling in the Pacific Ocean are minimal (except for New Zealand and Australia). Below is an overview of both fouling and ballast water including current methods applied to reduce the spread of NIS.

5.1 Fouling

Fouling involves the settlement and/or growth of marine organisms on submerged surfaces (Figure 3), providing another vector by which organisms can be transported long distances in the ocean. Fouling can be broken into two categories: macrofouling and microfouling. Macrofouling refers to the growth of organisms such as plants or invertebrates (e.g., barnacles, mussels, macroalgae) on a submerged surface, while microfouling refers to the growth of unicellular algae and bacteria on a submerged surface creating a slime like consistency, this may also contain the microscopic early life stages of macrofouling organisms (Figure 3).

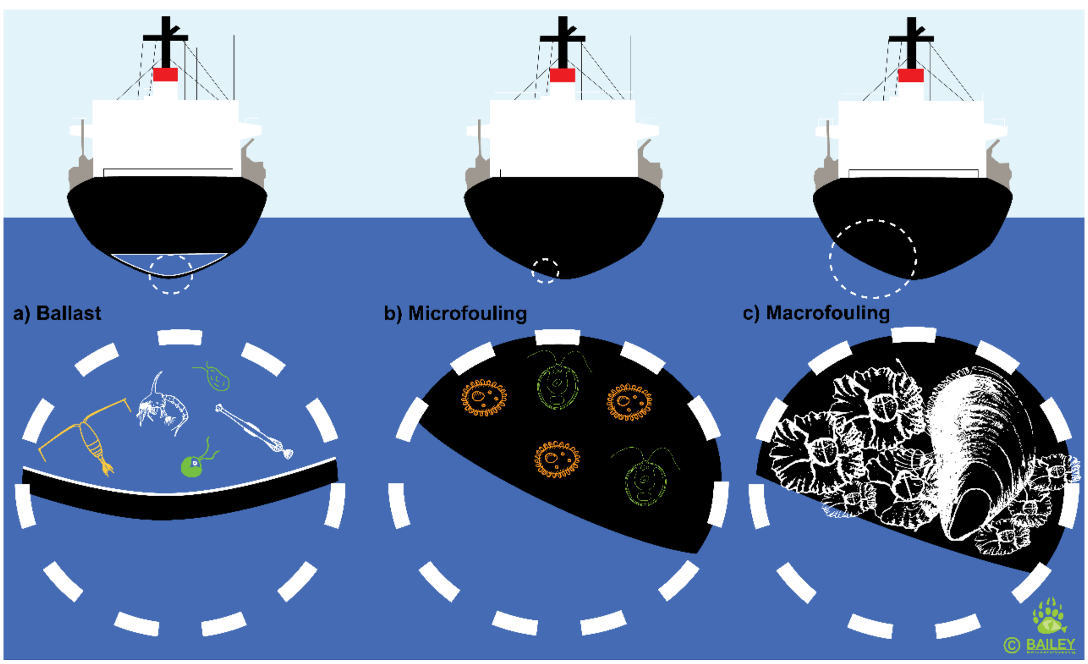

Figure 3: Conceptual diagram demonstrating the differences between a) ballast, b) micro- and c) macrofouling transport of invasive species.

The degree of fouling on a submerged surface can be categorized based on the *Fouling Rate System* on a scale of 0 to 100, which is in accordance with the US Navy (US Navy, 2006) (Table 1). This rating system classifies fouling based on the composition of fouling organisms. Specifically, soft fouling less than FR20 includes exclusively plant matter, while soft fouling FR30 includes plant matter and soft bodied invertebrates (e.g., sea cucumbers, sea grapes, sea squirts). Hard fouling ratings (> FR30) include calcareous invertebrate species.

Table 1: Fouling Rating System (US Navy, 2006)

Type	Fouling Rating (FR)	Description
Soft	0	A clean, foul-free surface; red and/or black antifouling paint or a base metal surface
Soft	10	Light shades of red and green (incipient slime). Bare metal and painted surfaces are visible beneath the fouling.
Soft	20	Slime as dark green patches with yellow or brown coloured areas (advanced slime). Bare metal and painted surfaces may be obscured by the fouling.
Soft	30	Grass as filaments up to 3 inches (76 mm) in length, projections up to ¼ inch (6.4 mm) in height; or a flat network of filaments, green yellow, or brown in colour; or soft non-calcareous fouling such as sea cucumbers, sea grapes or sea squirts (e.g., Ascidian: *Molgula manhattensis*), projecting up to ¼ inch (6.4 mm) in height. The fouling cannot be easily wiped off by hand.
Hard	40	Calcareous fouling in the form of tubeworms less than ¼ inch (6.4 mm) in diameter or height.
Hard	50	Calcareous fouling in the form of barnacles less than ¼ inch (6.4 mm) in diameter or height.
Hard	60	Combination of tubeworms and barnacles, less than ¼ inch (6.4 mm) in diameter or height.
Hard	70	Combination of tubeworms and barnacles, greater than ¼ inch (6.4 mm) in diameter or height.
Hard	80	Tubeworms closely packed together and growing upright away from surface. Barnacles growing one on top of another, ¼ inch (6.4 mm) or less in height. Calcareous shells appear clean or white in colour.
Hard	90	Dense growth of tubeworms with barnacles, ¼ inch (6.4 mm) or greater in height. Calcareous shells brown in colour (oyster and mussels); or with slime or grass overlay.
Composite	100	All forms of fouling present, soft and hard, particularly soft sedentary animals without calcareous covering (tunicates) growing over various forms of hard growth.

On vessels, fouling is referred to as occurring on the hull or in 'niche' areas, which are more difficult to clean (e.g., propellers, thrusters, sea chests, intake pipes, grates, apertures and/or free flooding spaces[2]). During transportation, the presence of these organisms on a ship can lead to established invasive populations via detachment/dispersal of viable material and spawning (Hopkins and Forrest, 2008) and may increase ship drag up to 70% (Galil *et al.*, 2019; Schultz *et al.*, 2015). Therefore, fouling may result in both ecological change and increased GHG emissions.

Fisheries and Oceans Canada (DFO) established an annual Maritimes Biofouling Management Program on the east coast of Canada (Fisheries and Oceans Canada, 2018). The program monitors the introduction, establishment and spread of Aquatic Invasive Species (AIS) including the clubbed tunicate (*Styela clava*), vase tunicate (*Ciona intestinalis*), European sea squirt (*Ascidiella aspersa*), golden star tunicate (*Botryllus schlosseri*), violet tunicate (*Botrylloides violaceus*), pancake batter tunicate (*Didemnum vexillum*), compound sea squirt (*Diplosoma listerianum*), Green shore crab (*Carcinus maenas*), Japanese skeleton shrimp (*Caprella mutica*),and the lacy-crust bryozoan (*Membranipora membranacea*). No such monitoring program has been established for the west coast of Canada.

5.1.1 Methods to Prevent Fouling

Antifouling technologies are used to reduce the amount of biofouling on submerged marine structures (e.g., jetties, docks and ship hulls), and encompass non-biocidal coatings, biocidal coatings, and Marine Growth Prevention Systems (MGPS) to inhibit the growth of fouling communities.

Coatings

Chemical antifouling refers to the application of coatings containing chemicals and/or biocides. For example, the organotin tributyltin (TBT), which contains at least one tin-carbon bond (Amara *et al.*, 2018). TBT was used from the mid-1900s and was incredibly effective in inhibiting the settlement of fouling communities (Amara *et al.*, 2018; Cao *et al.*, 2011; Piola *et al.*, 2009). In the 1970s, concerns arose over TBT toxicity on marine life, with small concentrations resulting in deformities in shellfish, imposex in gastropods (i.e., development of male sex organs on females and vice versa leading to sterility), intersex in gastropods (i.e., phenotypic disturbance in sex determination), and strong bioaccumulation in marine vertebrates (Piola *et al.*, 2009; Coray and Bard, 2007). TBT was phased out in the 1990s and its use banned by the International Maritime Organization Marine Environmental Protection Committee (Banerjee *et al.*, 2011; Amara *et al.*, 2018; Turner, 2010).

Following the TBT ban, manufacturers returned to antifouling coatings containing copper derivatives, which had been used for antifouling as early as *c.* 700 BC (Piola *et al.*, 2009). Currently, copper-based coatings are the most widely accepted approach to antifouling (Amara et

[2] Note this list of niche areas is not exhaustive

al., 2018; Turner, 2010). Although they are less effective than TBT at reducing biofouling, they are also less toxic to marine life (Amara *et al.*, 2018; Piola *et al.*, 2009). To improve the efficacy of copper-based coatings many manufacturers add biocides (e.g., Irgarol 1051, zinc pyrithione, copper pyrithione, dichlofluanid, chlorothalonil, Sea Nine 211, diuron, TCMS pyridine, ziram, zineb; Amara *et al.*, 2018; Banerjee *et al.*, 2011; Turner, 2010). Biocides leach slowly and steadily from the coating over time providing a barrier around the ship to fouling organisms (Turner, 2010). However, some biocides use toxic effects to inhibit settlement and growth of marine organisms, and are therefore considered acutely toxic and are harmful to marine life (Amara *et al.*, 2018; Banerjee *et al.*, 2011).

Additional effects on marine life include the release of antifouling paint particles which may include metals and biocides during ship maintenance and normal wear and tear of the vessel. Thus, high concentrations of these contaminants may be accumulated by benthic invertebrates through exposure and consumption (Turner, 2010). In addition, copper leaches from paint slowly while the vessel is in the water, at a rate of approximately 4 – 7 $\mu g/cm^2/day$[1], leading to contamination of surrounding waters (USEPA, 2011). It is difficult to relate this leach rate to water quality standards, as the resulting concentration of copper in surrounding waters will depend on the volume of water (dilution) and flushing rates in a harbour. In California, copper concentrations in marinas are significantly higher than outside reference sites (Singhasemanon *et al.*, 2009). In fact, dissolved copper concentrations in several marinas in California were found to exceed chronic (3.1 µg/L) and acute (4.8 µg/L) copper water quality standards (Singhasemanon *et al.*, 2009).

In British Columbia, water quality guidelines (WQG) are more conservative, with a chronic WQG of 2 µg/L and an acute WQG of 3 µg/L for copper exposure (Britih Columbia Ministry of Environment, 2019). These guidelines are based on acute and chronic toxicity studies in marine algae, invertebrates and fish.

Antifouling coatings may exert selective pressure on the types of fouling communities that surfaces are able to carry. Some organisms are resistant to copper antifouling coatings, including calcareous tube worms, barnacles, hydroids, bryozoans, bivalves and certain algal species (e.g., *Ectocarpus siliculosus; Enteromorpha (=Ulva) compressa*) (Piola *et al.*, 2009). The tolerance of these organisms to copper indicates a tolerance to metals and potentially other pollutants (Piola *et al.*, 2009). Organisms that are able to establish themselves on surfaces with antifouling paint are excellent candidates for invasive species and likely have a competitive advantage compared to any native species, especially in the highly polluted harbours where they are likely to be introduced (Piola *et al.*, 2009).

A non-toxic alternative to copper-based antifouling coatings is an enzymatic coating. Enzymatic coatings are designed to degrade the bio-adhesives that organisms use to attach to ship hulls. These types of antifouling coatings may be effective if designed correctly; however, issues such as temperature tolerance, stability and longevity of enzymes still need to be addressed (Banerjee et al., 2011; Cao *et al.*, 2011).

Marine Growth Prevention Systems (MGPS)

MGPS techniques have also been developed with varying degrees of effectiveness, including electrolysis, radiation and modification of surface topography. Electrolysis of seawater can be used to produce products such as hypochlorous acid, ozone bubbles, hydrogen peroxide and bromine. These strong oxidants spread over the ship's hull and limit the ability of organisms to interact with the ship's surface. However, this method is energetically expensive and may lead to accelerated corrosion of steel parts (Cao *et al.*, 2011). The use of magnetic fields, ultraviolet radiation, radioactive coatings and vibrational acoustic technology have also been explored, but were deemed impractical or too energetically expensive (Cao *et al.*, 2011).

MGPS coatings have also been developed, aiming to modify surface topography and properties to limit settlement of biofouling organisms. These include hydrophobic surfaces, hydrophilic surfaces, amphiphilic surfaces, and surfaces designed with microtopography (Banerjee *et al.*, 2011; Cao *et al.*, 2011). Some of these coatings have proven to be effective at reducing settlement of biofouling organisms, especially in combination with biocides, but are not yet commonplace (Banerjee *et al.*, 2011; Cao *et al.*, 2011).

5.1.2 Hull Cleaning: Current Methods

To reduce biofouling and the transport of NIS regular hull cleaning is required. If regular hull cleaning is not performed, organisms, or viable fragments of organisms, may be rubbed off of hulls during docking procedures or naturally fall off during transit, allowing them an opportunity to settle onto nearby wharfs or into the water column (Hopkins and Forrest, 2008). The longer an organism is attached to a hull, the more likely they are to reach reproductive maturity, in which case, viable propagules may be released into the marine environment (Hopkins and Forrest, 2008). New environmental cues may also be encountered in a harbour, such as changes in salinity or temperature, triggering reproductively mature organisms to release propagules (Hopkins and Forrest, 2008). Maintaining a clean hull is critically important in reducing the risk of NIS establishment in new marine environments. However, cleaning a hull does not come without its own set of potential effects:

1. the release of organisms from the hull into the water column during cleaning, and
2. the release of antifouling coatings into the water column potentially leading to contamination of the surrounding environment (USEPA, 2011).

Different methods of hull cleaning may be able to contain NIS and contaminants more effectively than others. Hull cleaning methods include both in-water cleaning and dry-dock practices. In-water cleaning poses much greater risks for both the introduction of NIS and release of contaminants into the water column than shore-based options (Pagoropoulos et al., 2018). Most in-water cleaning methods are unable to reach niche areas (e.g., sea chest, intake pipes, thrusters and propellers), potentially allowing a larger accumulation of fouling organisms (Hopkins and Forrest, 2008). Dry-dock hull cleaning avoids debris entering the ocean and allows all niche areas to be cleaned, but is more costly and time-consuming than in-water cleaning (Floerl *et al.*, 2010). Dry-docking also allows for the reapplication of antifouling paint, which becomes important particularly if hull cleaning damages antifouling coatings (Hopkins and Forrest, 2008). As a result, dry-dock hull cleaning has historically been encouraged over in-water cleaning operations (Floerl *et al.*, 2010; Hopkins and Forrest, 2008).

Dry-dock Hull Cleaning

During dry dock cleaning, ships are removed from the water so that their hulls can be scraped and washed to remove all biofouling. This practice allows for the complete capture of biofouling debris if the debris and effluent from washing are treated appropriately. Safe disposal practices in dry docks means transporting solid biofouling debris to a landfill for disposal which can be costly [and not all dry-docks follow strict regulations (Floerl *et al.*, 2010)]. One study found that dry-dock hull cleaning resulted in a 37.8% survival rate of viable organisms that were removed from the hull, so it is vital to capture and dispose of all material that is removed from the hull (Woods *et al.*, 2012). Effluent must also be treated carefully, and options for safe disposal include releasing effluent into a municipal sewage system or filtering effluent for release or re-use (Woods *et al.*, 2012). By treating effluent, the concentration of viable organisms is further reduced by 98.5% (Woods *et al.*, 2012). In contrast, the release of organisms during in-water hull cleaning practices can be much more difficult to control.

In-water Hull Cleaning

Various methods can be employed for in-water hull cleaning including diver-operated rotating brush systems, Remotely Operated Vehicles (ROV) equipped with brushes and water jets, heat treatments and encapsulation (see Table 2 for a summary comparing in-water hull cleaning options[3]).

[3] Table 2 is intended as a snapshot of various technologies and not intended to be a complete and thorough review of each technology currently available.

Table 2: Summary of Methods for In-water Hull Cleaning

Method	Description	Time/Speed	Cost (CAD)	Advantages	Disadvantages	Status
1) Diver-Operated Rotating Brush Systems						
Diver-operated rotating brush systems	Divers operate large motorized brushes made of nylon, steel or abrasive discs, or waterjet devices.[1,2] Vacuum filtration units may be installed but are not common[1,3]	48 – 72 hours, depending on dive crew and vessel size[1,3]	AUS: $4,300 – $9,500[1] USA: $13,100 – $39,400[1]	Relatively cheap and widespread (available in many ports) compared to other methods	• Not effective in removing all biofouling[1,3] • Cannot reach niche areas[1,3] • Abrasive brushes damage antifouling paint[1] • High survival rate of removed organisms (62.3%)[1,3] • Filtration technologies not often used to capture the organisms[1,4] • With filtration up to 12% of debris[3]	Most common
2) Remotely Operated Vehicles (ROV)						
Automated Hull Maintenance Vehicle	• In-water inspection and maintenance of U.S. Naval ships1,5 • Rotating brushes clean debris from hull1,5 • Brushes encapsulated by vacuum seal mantle to capture, filter and collect debris1	Unknown	Unknown	May effectively capture removed debris, however data is not publicly available[1,5]	Unknown	Developed for U.S. Navy, not available to public, publicly available data is limited[1,5]
CleanROV	• Uses thrusters, cameras and positioning systems to navigate hull1 • Uses high-pressure water-blasting technology1,5 • Vacuum and filtration system to capture/filter/contain debris1	5 hours for 140 m vessel (800 – 1,000 m^2/hour) [1]	$9 – 14 per square foot[1]	Claims to collect/contain ~95% of debris removed but data is not available[1]	• Designed to clean 80% of submerged surface[1,5] • Cannot clean niche areas (designed for flat hulls & minimum curvature)[1,5] • Can only remove early stages of fouling (not heavily fouled hulls)[1,5]	Available for use in some ports (e.g., Norway, Spain) [1]
Hull Identification System for Marine Autonomous Robotics	• Developed to inspect and maintain ship hulls automatically and manually using a joystick1 • Uses water-jet technology1 • Suction extraction system to capture/contain debris1	0.48 m/s[1]	Unknown	Can collect ~95% of debris removed[1]	• Cannot clean niche areas[1] • Can only clean lightly to moderately fouled vessels (not heavily fouled vessels)[1]	European Union and not yet available for use (lack of funding) [1]
3) Heat Treatments						
Hull Surface Treatment System developed in New Zealand[1]	• Lethally hot water provided to an underwater thermal applicator from a diesel-powered boiler on a support vessel • Thermal applicator which magnetically attaches and moves along hull on wheels • Thermal applicator moves to a new section automatically after four second treatment/exposure	16 h with one unit for 200 m vessel	$49,500 (180 m vessel) $495,500 – $595,500 to purchase system	Able to treat some niche areas including sea chest gratings, intake/outflow pipe openings	• Cannot target flat-bottomed keels, rudders, or propellers • Does not scrape dead organisms from hull, so drag may not be reduced (although dead organisms may fall off during transit)	Under development

Method	Description	Time/Speed	Cost (CAD)	Advantages	Disadvantages	Status
4) Encapsulation Technologies						
IMProtector	• Aims to kill biofouling communities rather than remove them[1] • Vessel is encapsulated in a plastic envelope to create an anoxic environment to suffocate/kill organisms[1]	Min. 45 min (estimated for 15 m vessel) for encapsulation[1] 24 h to kill mobile fauna[1] 4 – 9 days to kill all fauna[1]	Up to $23,000 per treatment[1]	• Limits release of live organisms into the water column[1] • Limits hull scraping and contains debris, so contaminant release is minimal[1] • May be able to kill organisms in niche areas as well[1]	• Time required to reach mortality-causing anoxic conditions may be higher than time spent in port[1] • Does not scrape dead organisms from hull, so drag may not be reduced (although dead organisms may fall off during transit) [1]	Not considered sufficiently developed or reviewed[1]

References: [1]Floerl *et al.*, 2010; [2]Pagoropoulos *et al.*, 2018; [3]Hopkins and Forrest, 2008; [4]Woods *et al.*, 2012; [5]USEPA, 2011

5.2 Ballast Water

Ballast water acts as a one of the main vectors for invasive species introduction internationally (Geburzi and McCarthy, 2017). Vessels routinely take up and discharge sea water as ballast water, which is held in tanks or cargo holds of ships to allow for stability and maneuverability in rough seas or when the ship does not have heavy cargo to weigh it down (Buck, 2010). Water is often taken up or discharged at sea during waste-water discharge, and at port during cargo loading and unloading. The water being loaded into the vessel’s ballast tank may contain high concentrations of planktonic organisms, including phytoplankton and zooplankton (Figure 3), which can be transported large distances before being discharged (Tsolaki and Diamadopoulos, 2010). If organisms are discharged in port, they have the potential to successfully establish themselves as a new population.

In order to reduce the risk of introducing planktonic organisms to new ports, the majority of international ballast water discharge requirements specify a depth and distance offshore that vessels are able to discharge ballast water in order to prevent planktonic stages from settling on suitable substrates (e.g., nearshore/benthos) under suitable abiotic conditions (i.e., temperature and salinity) for establishment (Buck, 2010). Many of these guidelines were first presented in ‘Canada’s Voluntary Guidelines for the Control of Ballast Water Discharges from Ships Proceeding to the St. Lawrence River and Great Lakes’ in 1989. These guidelines recommended that ballast water be exchanged beyond the continental shelf, where freshwater currents were less likely to bring organisms to shore (Scriven et al., 2015). These guidelines were also the first to promote ballast water exchange in the open ocean prior to coming to port, in which vessels exchange their port-obtained water for open-ocean water. The reasoning for this was that organisms from the open-ocean were expected to have narrow salinity tolerances and would be unlikely to settle in freshwater systems; however, this method was designed for vessels transitioning from marine to freshwater systems and is not effective for vessels remaining in marine waters (Buck, 2010; Scriven et al., 2015). These guidelines also presented exemption zones, where vessels that remained on the continental shelf were not required to exchange ballast water; however, this practice enables the range expansion of introduced species (Scriven et al., 2015).

Alternative methods have been established (and some technologies are currently in use) to treat ballast water more effectively through chemical or mechanical means (Tsolaki and Diamadopoulos, 2010; Werschkun *et al.*, 2014), and these treatments are now required for ships from member states of the Ballast Water Management Convention (2004) (International Maritime Organization, 2004, 2011a).

5.3 Summary of Hull Fouling and Ballast as Vectors for NIS Spread

Both ballast water exchange and hull fouling represent potential vectors for the spread of invasive species. While ballast water exchange is primarily a risk for transporting planktonic life stages, hull fouling may be more of a risk for transporting later-stage organisms that may be reproductively active, as well as newly settled species. While a plethora of information is available regarding the introduction of invasive species via ballast water, biofouling is poorly studied in comparison, and regulations are only now being considered (Sylvester et al., 2011). Because of the similar concern with invasive species, this report provides an overview of both biofouling and ballast water existing international and national regulations in Section 7 below.

For both ballast water and hull fouling, the current methods in place to minimize the spread of invasive species focus on preventing organisms from reaching and settling on suitable habitat for colonization by implementing vector regulations. Invasive species control measures for ballast water include open-ocean exchange at prescribed distances from shore in order to minimize the direct transfer of organisms between ports as well as Ballast Water Management Systems, which focus on treating ballast water by mechanical or chemical means to reduce viable organisms in the water (Buck, 2010; Tsolaki and Diamadopoulos, 2010). In contrast, hull cleaning is currently performed in ports and dry docks and does not include an intermediate open-ocean or in transit cleaning step to reduce the potential for direct transfer of organisms between ports. While hull treatment options are being developed, there is no international regulatory authority evaluating, approving or controlling the effectiveness of treatment options as is the case for ballast water.

In both the treatment of ballast water and the mechanical cleaning of hulls, there are additional risks to consider through the release of potentially harmful environmental pollutants. Chemical treatments of ballast water are becoming more common and may pose risks to the marine environment upon release (Tsolaki & Diamadopoulos, 2009). Similarly, the cleaning of hulls can lead to the release of biocidal antifouling coatings such as copper, which can be toxic to marine organisms (Amara et al., 2018; Banerjee et al., 2011).

In summary, both vectors have been demonstrated to be high risks for both invasive species transfer and environmental pollution. Both should involve careful consideration and regulation in order to reduce the potential risks; however, hull cleaning does not have the same degree of regulation and research as ballast water exchange. Thus, we provide regulations for hull cleaning and ballast water internationally, with an emphasis on the west coast of North America and more specifically British Columbia.

6 Invasive Species in British Columbia

An estimated 88 NIS have been introduced in British Columbia (BC) through varying methods, 65 of which are invertebrate species (Jamieson *et al.*, 2000). Many of these NIS have become established, self-sustaining populations (Jamieson *et al.*, 2000). This assessment focuses on 16 invertebrate species that are thought to have been introduced to BC waters through hull fouling (described in Table 3), many of which were introduced in the Strait of Georgia and its surrounding waters, forming well-established populations in this area (Figure 4).

Table 3: List of Non-Indigenous Species (NIS) that have invaded British Columbia waters via hull fouling

Phylum	Class	Species	Native Range	Known Invasion Impacts	Method(s) of Introduction in BC	Introduction Status in BC	Confirmed Locations in BC	Qualities for Successful Invasion	Reproduction	Feeding Preferences	Habitat	Comments
Mollusca	Gastropoda	*Rapana venosa* (Veined Rapa Whelk) Subclass: Prosobranchia Order: Neogastropoda Family: Muricidae	Northeast Pacific, from the southern Pacific coast of Russia to southern Japan, including the Sea of Japan, Yellow Sea, and East China Sea[7,10]	Implicated in decline of native mussel beds (75.6% decrease in mussel bed cover) in the Black Sea (*M. galloprovincialis*) leading to a decrease in abundance of demersal fishes[3] Known to cause local severe (>80%) population declines and a reduction in species richness[4] Adversely affects native bivalves in Rio de la Plata estuary[6] Competes with native oyster drills in Chesapeake Bay (*Urosalpinx cinerea* and *Eupleura caudata*)[8]	Sea chest/hull[1,10]; in oyster introductions[10]	Failed[10]	Found in a sea chest in BC waters in 2011, several specimens found over the years in BC - no known existing populations[10]	• Long-living: lifespan more than 10 – 15 years[4,8] • Fast-growing[4] • High fecundity: high reproductive output (50 – 500 egg capsules, each capsule with 200 – 1,000 eggs, multiple times per season)[4] • Strong dispersal potential: 14 – 80 days in planktonic stage before settling (long-distance travel possible, travel in ballast water possible)[4] • Broad temperature tolerance: 4 – 27°C[4] • Broad salinity tolerance: 12 – 32 PSU[4]	Separate sexes[4,7] Reach reproductive maturity in 1 – 3 years[4,7] Lay eggs in mats on hard surfaces (e.g., rocks, artificial structures, garbage)[4,7] Pelagic larvae hatch from eggs after 14 – 21-day incubation Larvae spend 14 – 80 days in plankton, then settle to bottom to develop[4,7]	Generalist feeders[4,9] Feed on bivalves (e.g., oysters, mussels, clams)[4,9]	Favours sandy/muddy bottoms where it can bury itself[4,9] Can be found on artificial and natural rocky bottoms if there are bivalve prey[4]	Control efforts in Chesapeake Bay include a bounty for collected Whelks and encouraging local restaurants to cook them[4]
Mollusca	Bivalvia	*Mytilus galloprovincialis* (Mediterranean Mussel) Subclass: Pteriomorphia Order: Mytiloida Family: Mytilidae	Mediterranean Sea and the Atlantic coast of southern Europe[11,12,10]	Led to increase in reproductive potential in rare African Black Oystercatcher in South Africa by providing a consistent food source[13] Potentially caused mass mortalities in swimming crabs in South Africa[13] Strongly compete with/has displaced South African native mussels *Choromytilus meridionalis* and *Aulacompya ater* - more tolerant to desiccation, 200% greater reproductive output[15] Led to increase in species habitat complexity and species richness in South Africa as it could survive higher in the intertidal than native mussel species[15]	Ship hull and aquaculture[11]	Established[11]	Vancouver Island: Union Bay, Yellow Island, French Creek, Nanaimo, Chemainus, Victoria, Sooke[12]; east coast Vancouver Island has hybrid zones[14]	• Fast-growing[15] • Strong dispersal potential: planktotrophic larval stage, spend 2 – 4 weeks in plankton[13,10] • High fecundity: 1.5 to 3.5 million eggs[15,10] • High recruitment: settlement of up to 2 million recruits/m^2 [(13,15)] • Broad temperature tolerance tolerates up to 31°C • Broad salinity tolerance: 10 – 38 PSU[10] • Desiccation tolerance[15]	Separate sexes[10] Reach reproductive maturity at <1 year[10] Can produce 1.5 – 3.5 million eggs[10] Fertilized eggs develop into planktotrophic larvae which develop into a shelled veliger[10] Larvae settle after 2 – 4-week planktonic phase, juveniles can move via byssal threads to suitable habitats[10]	Filter feeders[10] Ingest phytoplankton and other suspended materials[10]	Intertidal and shallow subtidal sites[12,10]	Able to hybridize with *M. trossulus* and *M. edulis* - stable hybrid zones exist in BC with varying differences in growth and survival based on environment[14] Recreational boating is a major vector for primary and secondary spread of NIS including *M. galloprovincialis*[16]

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Phylum	Class	Species	Native Range	Known Invasion Impacts	Method(s) of Introduction in BC	Introduction Status in BC	Confirmed Locations in BC	Qualities for Successful Invasion	Reproduction	Feeding Preferences	Habitat	Comments
		Teredo navalis (Naval Shipworm) Subclass: Heterodonta Order: Myoida Superfamily: Pholadoidea Family: Teredinidae	Unknown[10]	Devastating for maritime cultural heritage and submerged wooden structures[18] Massive destruction of wooden constructions such as dike protectors, sluices and dolphins in the 1730s in Netherlands and 1820's[19]	Ship hull[11]	Introduced[17]	Found in Pendrell Sound, BC in 1963[10]	• Strong dispersal potential: planktonic larval phase of 11 – 35 days; adults can travel upstream with tidal currents over at least 20 km distances[19] • High fecundity: 1 – 5 million eggs per season[10] • Broad temperature tolerance: functional at 5 – 35°C, hibernate under 0°C[19] • Broad salinity tolerance: functional at 5 – 35 PSU, cease boring under 10 PSU[19]	Sequential hermaphrodites, start life as male, transform to female[10] Males release sperm into water column and fertilized eggs are brooded in the female's gills (1 – 5 million eggs per season[10] Larvae hatch and remain in gills until veliger stage then remain in water column for 11 – 35 days[10] Larvae settle and metamorphose, bore into wood within 2 – 3 days of settling[10]	Specialized feeders on any wood[10]	Marine bivalves specialized to bore into wood[19]	If shipworms encounter optimal conditions, they can destroy fir piles 15 cm in diameter in 6 weeks[20] In 1995 estimated shipworm damage in the US cost ~200 million[20] Most effective deterrent is creosote but banned in many places due to toxicity and carcinogenicity[20] Shipworm attacks are expected to increase in the Netherlands due to climate change[20]
Arthopoda; Subphylum Crustacea	Malacostrea	*Caprella mutica* (Japanese Skeleton Shrimp) Subclass: Eumalacostraca Superorder: Peracarida Order: Amphipoda Suborder: Caprellidea Infraorder: Caprellida Superfamily: Caprelloidea Family: Caprellidae	Russia through the Japanese Archipelago, including Peter the Great Bay in Russia and the Sea of Japan[22,24,25]	Displaced native species *P. phasma* and *C. linearis* in the lab within 48 hours[23]	Anthropogenic means; concern that dispersal will spread via ship hulls (present in 22% of hulls surveyed)[21]; found in 33% of marine fouling communities, 22% hulls and sea chests from domestically operated commercial vessels[21]; could be through Pacific oysters, hull fouling or ballast[10]	Introduced[21]	Present on southern Vancouver Island since at least 1995, first record in Puget Sound in 1998, expansion throughout northwest Pacific to northern BC and Alaska[21]	• Fast-growing[24] • Strong dispersal potential: lacks a pelagic phase but strong potential to use vectors (e.g., algae, ship hulls) for dispersal[22,24]; can survive 20 days without food[22] • High fecundity: reach sexual maturity quickly, high reproductive output[24] • High population densities: up to 200,000 individuals/m^2 outside its native range[24] • Strong competitor: aggressive interactions (e.g., combat) with native amphipods, competitively superior[22,24,25] • Broad temperature tolerance: <2 – 30°C[22,25] • Broad salinity tolerance: 16 – 40 PSU[25]	Separate sexes[22,24] Reach sexual maturity after ~1 month[22,24] Females produce broods of ~11 – 25 individuals (max. observed was 82)[22] Females will produce ~2 broods in their lives, ~20 days apart[22] Brood young in a brood pouch, juveniles hatch directly from the brood pouch (no larval stage)[22,24] Juveniles moult every 3 – 11 days (depending on conditions) until sexual differentiation/maturation[22,24]	Predominantly detritivores but can also filter feed[24] Generalist/opportunistic feeders (easy to survive in ballast water)[22,24]	Sheltered bays ~13 m deep amongst macroalgae in native habitat[24] Outside of its native range, it is most common on human made structures e.g., boat hulls, floating pontoons, aquaculture infrastructure[24] Avoids benthic predators by living higher up on artificial structures e.g., pilings[24]	Secondary spread through recreational boats is common[24,16] May swim/drift to new locations to expand range Cannot invade brackish waters (cannot tolerate salinities lower than 16 PSU)[25] Estimated lifespan is 6 months to 2 years[22,24]

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Phylum	Class	Species	Native Range	Known Invasion Impacts	Method(s) of Introduction in BC	Introduction Status in BC	Confirmed Locations in BC	Qualities for Successful Invasion	Reproduction	Feeding Preferences	Habitat	Comments
		Gammarus tigrinus Subclass: Eumalacostraca Superorder: Peracarida Order: Amphipoda Suborder: Gammaridea Family: Gammaridae	Atlantic coast of North America from Labrador to Florida[26,27]	Has become one of the most abundant gammarids in shallow/soft/mixed-bottom environments in Europe[26] In the Baltic Sea, has higher reproductive potential than native G. duebani and is often more successful[26]	Ship hull[1] – potentially not actually introduced to waters (not found elsewhere)[10]	Present on ship during survey[1]	Present on ship hull in 2011, not thought to be introduced in BC[10]	• High fecundity: small size at breeding[26] • Strong competitor: competitive dominance[26] • Broad temperature tolerance: 5 – 35°C[27] • Broad salinity tolerance: 0 – 25 PSU[27]	Separate sexes[10] Females have one or more broods per year[10]	Omnivore[27]	Shallow, soft and mixed-bottom habitats[26] Euryhaline species lives in both fresh and brackish water[27,29] Restricted to shallow lagoons, bays and estuaries[27,29]	Concerns that this species will become cosmopolitan through shipping[29]
Arthopoda; Subphylum Crustacea	Malacostrea	*Ampithoe valida* Subclass: Eumalacostraca Superorder: Peracarida Order: Amphipoda Suborder: Gammaridea Family: Ampithoidae	Atlantic Coast of North America from New Hampshire to Chesapeake Bay[11,30,31]	N/A	Ship hull and aquaculture[11]	Established[11]	Found in Prince Rupert and Vancouver Harbours in 2005, Haida Gwaii in 1957[10]	• Broad temperature tolerance: -2 – 27°C[10] • Broad salinity tolerance: 9 – 35 PSU[10]	Separate sexes[31] Males reach sexual maturity at 24 – 44 days, females at 28 – 61 days[31] Females brood embryos in external thoracic brood chamber, where they develop for 10 days, hatch and leave the brood pouch 14 days post fertilization (no larval stage)[31] Female produces 2-3 broods per year with 3-60 eggs[31]	Specialized feeders on algae including eelgrass, *Enteromorpha*, *Ulva*, *Ceramium*, etc. [31]	Tube dweller among eelgrass, green algae e.g., Ulva and red algae[31] Often found on floats, pilings and docks[31] Intertidal to 30 m depth[31] Brackish or saline waters[31]	Estimated lifespan is 191 – 242 days[31] Tube dweller but can swim rapidly for short periods[31]
		Melita nitida Subclass: Eumalacostraca Superorder: Peracarida Order: Amphipoda Suborder: Gammaridea Family: Melitidae	Atlantic coast of North America from southwestern Gulf of St. Lawrence to Yucatan Peninsula[32]	None reported[10]	Ship hull and aquaculture[11]	Established[11]	Strait of Georgia[34]; estuaries from Howe Sound all the way to California[10]	• Strong dispersal potential: can be transported in ballast water/on ship hulls[34] • Broad temperature tolerance: 0 – 32°C[10] • Broad salinity tolerance: 0 – 35 PSU[10]	Offspring are retained in the brood pouch for ~10 days and hatch as juveniles (no larval stage)[10] Mean brood size of 30[10]	Feed on epiphytic algae, seagrass, etc. [10]	Intertidal and subtidal zone[33] Often found under Pacific oysters or boulders Prefers muddy-bottom areas, mesohaline regions of estuaries[34] Found on floats, pilings, ships[34]	Some uncertainty about identity - similar to *M. setiflagellata* and may be confused for this on the west coast[10]

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Phylum	Class	Species	Native Range	Known Invasion Impacts	Method(s) of Introduction in BC	Introduction Status in BC	Confirmed Locations in BC	Qualities for Successful Invasion	Reproduction	Feeding Preferences	Habitat	Comments
		Monocorophium acherusicum Subclass: Eumalacostraca Superorder: Peracarida Order: Amphipoda Suborder: Gammaridea Family: Corophiidae	Northeastern Atlantic[11]	Widespread fouling pest, has impacted culture of seaweeds and oysters in Japan by growing on pilings[10] May impact phytoplankton abundance[10]	Ship hull and aquaculture[11]	Established[11]	Ranges from Vancouver Island to Baja California[10], found in the Strait of Georgia in 1939[10]	• Broad temperature tolerance: 0 – 30°C[10] • Broad salinity tolerance: 6 – 40 PSU[10]	Separate sexes[10] Brood embryos that hatch as juveniles (no larval stage)[10] Brood size ranges from 2 – 70 eggs and is directly related to female size[10]	Omnivorous[36] Feed on mesoplankton fragments, seagrass, benthos diatoms, detritus, etc.[36]	Lives in a tube made of fine sediment Primarily subtidal[36] Thrives in reduced salinity[36] Builds tubes on a wide variety of surfaces including algae, hydroids and buoys[36]	Found on a barge in the subantarctic: Macquarie Island[35] Found living commensally in hermit crab shells in the Bay of Biscay - built tubes inside the shell and use hermit crab's waste for food[36]
		Monocorophium insidiosum Subclass: Eumalacostraca Superorder: Peracarida Order: Amphipoda Suborder: Gammaridea Family: Corophiidae	North Atlantic[11]	Competes with native amphipods[37]	Ship hull and aquaculture[11]	Established[11]	Current known range is from California to Howe Sound and Strait of Georgia[10]	• Broad temperature tolerance: 0 – 30°C[10] • Broad salinity tolerance: 1.6 – 37 PSU[10]	Separate sexes[10] Brood embryos that hatch as juveniles (no larval stage)[10] Females have brood 1 – 36 embryos at a time and have 3 – 7 broods in their lifetime[10]	Use antennae to capture food at the mouth of their tubes[10] Feed on phytoplankton and organic detritus[10]	Can live on floating pontoons e.g., marinas, jetties and fish farms[37]	Lifespan decreases with increasing temperature, ~223 days at 10°C to 110 days at 20°C[10]
Cnidaria		*Diadumene lineata* (Orange striped anemone) Subclass: Zoantharia Order: Actiniaria Suborder: Thenaria Family: Diadumenidae	Northwest Pacific, likely Hong Kong or Japan[11,38,39,41,43]	None reported[10]	Ship hull and aquaculture[11,41]	Established[11]	Widely reported on Pacific coast since 1850[41]; confirmed locations include Salish Sea[41], West Coast Vancouver Island[11], Strait of Georgia[11]; east coast Vancouver Island[10]	• Broad temperature tolerance: 0 – 40°C[10] • Broad salinity tolerance: 12 – 74 PSU[10]	Can reproduce both sexually and asexually (longitudinal fission/pedal laceration) Sexual reproduction forms embryos which develop into swimming planula larvae 18h post-fertilization[42] Sexual reproduction has not been observed outside of its native range[42], but viable eggs were observed in specimens in BC[41]	Feed on zooplankton, small epibethos[10]	Primarily high intertidal[39] Marine and estuarine[40] Found on/under rocks, pilings, oyster reefs and salt marshes in dense numbers[38,39,40] Often in clonal aggregations[38]	Broad distribution in BC may be from post-introduction dispersal[41] Recreational boating is a major vector for primary and secondary spread of NIS including *D. lineata* [10]
Annelida	Polychaeta	*Heteromastus filiformis* Order: Capitellida Family: Capitellidae	North Atlantic[11]	N/A	Ship hull[11]	Established[11]		• Long-living: individual aged at 2 years[10] • Broad temperature tolerance: reported in temperate, Arctic, tropical and sub-tropical areas[10] • Broad salinity tolerance: 5 – 40 PSU[10]	Eggs are laid in capsules on the sediment surface[10] Larvae hatch and are planktonic/planktotrophic for 17 – 18 days, then settle[10]	Feed on detritus[10]	Buries itself head-down in muddy/sandy sediments[10]	

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Phylum	Class	Species	Native Range	Known Invasion Impacts	Method(s) of Introduction in BC	Introduction Status in BC	Confirmed Locations in BC	Qualities for Successful Invasion	Reproduction	Feeding Preferences	Habitat	Comments
		Polydora cornuta Subclass: Palpata Order: Canalipalpata Suborder: Spionida Family: Spionidae	Charleston Harbour, South Carolina (original description, Bosc, 1802)[46,48]	Widely recognized pest in *Crossostrea gigas* culture on the East coast of North America - can develop dense colonies on the outside of oyster and mussel shells, smothering them with mud from tubes[10] When it occurs in high densities, it becomes the dominant suspension feeder[10]	Ship hull and aquaculture[11]	Established[11]		• High fecundity: early maturation, high larval production[48] • Strong dispersal potential: planktotrophic larval stage that can survive in ballast water, high distribution by shipping/aquaculture[48] • High recruitment[48] • Broad temperature and salinity tolerance[48]	Separate sexes[44] Females can store sperm for later use/successive spawnings[44] Females produce egg capsules in their mud tubes, larvae hatch and are released into the plankton[44,45] Larvae settle eight days after hatching[44,45] Individuals become sexually mature 38 days after hatching[45]	Deposit feeder[47]	Estuaries and sea ports[48] Builds mud-tubes in bottom[45] Primarily soft-bottomed areas[47]	Considered one of the worst invasive polychaetes[47] Lifespan of 40 – 59 days[45]
		Pseudopolydora kempi Subclass: Palpata Order: Canalipalpata Suborder: Spionida Family: Spionidae	Northwest Pacific[11] first described in a Brackish Lake in India[50,10]	N/A	Ship hull and aquaculture[11]	Established[11]	Found on Rathtrevor Beach, Parksville in 1951 (first record on the west coast)[10]	• Strong dispersal potential: planktonic phase of 2 – 4 weeks[10] • Broad temperature tolerance: up to 29°C[10] • Broad salinity tolerance: 1.6 – 37 PSU[10]	Eggs are laid in egg capsules, which are deposited in strings in the female's tube[10] Females lay ~15 – 20 egg capsules[10] Embryos hatch and spend 2 – 4 weeks in the plankton[10]	Deposit feeder, can shift to suspension feeding[49]	Intertidal mudflats and shallow, muddy subtidal waters[10] Make mucoid tubes in sandy mud[49,50]	
Chordata; Subphylum Tunicata	Ascidiacea	*Botrylloides violaceus* (Violet Tunicate) Order: Stolidobranchia Family: Styelidae	Asian Pacific Northwest (potentially Japan)[54,56]	Colonizes floating structures and overgrows existing organisms which is a threat to aquaculture (including in Atlantic Canada) and decreases overall species richness[54] Considered a major biofouling risk in native habitats as well (e.g., Japan, China) [54] Outcompetes the Netherland's native tunicate B. schlosseri in lab studies[55] Grew over/smothered mussels, solitary tunicates and algae in Scotland[10]	Ship hull or aquaculture[11]; likely secondary spread through long-distance dispersal through sexually produced propagules or fragmentation/asexual propagules[53]	Established[56]	Nanoose Bay, Silva Bay, Thetis Island, Maple Bay, Patricia Bay, Cadboro Bay, Victoria Harbour[52]; a model predicted that there are no completely unsuitable areas in BC for establishment of these organisms, but the most suitable locations were along the west coast of Vancouver Island where there is significant aquaculture[56]; widespread in southern BC, more common on human made structures and distribution in natural rocky reefs is more limited[57]; Royal Victoria Yacht Club and eelgrass on west coast Vancouver Island[57]	• Strong dispersal potential: planktonic larval phase[54]; commonly fouls ship hulls with strong attachment[52,54,16]; able to disperse via rafting (e.g., algae)[54] • Broad temperature tolerance: 5 – 25°C[56] • Broad salinity tolerance: 20 – 38 PSU[56]	Hermaphroditic[54] Colonies expand via asexual budding of individual zooids or through fusion with other colonies[54] Zooids can asexually bud one week after development[51] In sexual reproduction, 1 – 2 eggs lodge within the tunic, eggs are fertilized and undergo embryogenesis, the mother zooids disintegrate after ovulation leaving the brood pouch with larvae behind, the free swimming larvae break free and swim for 4 – 10 hours before settling[54]	Feed on plankton, detritus[10]	Found on oyster reefs, marinas/docks, rocky substrate, grasses, vessels, driftwood[10]	Extremely abundant in BC in comparison to other ascidians in fouling communities[52] The most widely distributed non-indigenous ascidian on anthropogenic structures in the world[57] Recreational boating is a major vector for primary and secondary spread of NIS including *B. violaceus*[16]
		Didenmum spp (Colonial Tunicate) Likely Didenmum vexillum	Asian Pacific Northwest Japan[62, 64]	Strong competitor for resources (i.e., attachment substrates and food). Can grow over other organisms if necessary.[62] Implications for natural ecosystems and industries requiring clean waters (i.e., fishing and aquaculture) as it may outcompete indigenous species.[62 ,64]	Hull fouling[63] Aquaculture[64]	Introducted[63]	Strait of Georgia[63]	• Strong dispersal potential: planktonic larval phase; commonly fouls ships; forms strong attachments with substrates[64] • Broad thermal tolerance (9-23°C)[64] • Can inhabit both polluted and clean areas.[63]	Colonies expand via asexual budding of individual zooids or through fusion with other colonies[64]	Feed on plankton, detritus[10]		Specific invasive species of *Didenmum* in BC waters is uncomfired; however, it is likely *D.vexillum*.

Environmental Assessment of the Potential for Robotic In-water Ship Hull Cleaning

Phylum	Class	Species	Native Range	Known Invasion Impacts	Method(s) of Introduction in BC	Introduction Status in BC	Confirmed Locations in BC	Qualities for Successful Invasion	Reproduction	Feeding Preferences	Habitat	Comments
Bryozoa	Gymnolaemata	*Conopeum seurati* Order: Cheilostomata Suborder: Malacostegina Family: Electridae	Mediterranean and Atlantic coast of northern Europe[58]	Competes with native Didacna sp. in the Caspian Sea by growing over its shell and competing strongly for food[59]	Potentially ship hull[58]	Introduced[58]	Confirmed in Port Alberni - may be first record in northeast Pacific[58]	• Broad temperature tolerance[58] • Broad salinity tolerance: <1 PSU[58] • Desiccation tolerance[58]	Planktonic larval phase[60] Larvae grow in the plankton, develop a shell and then settle/metamorphose[60]			

References:

1) Sylvester et al., 2011
2) Savini and Occhipinti-Ambrogi, 2006
3) Snigirov et al., 2013
4) Fey et al., 2010
5) Kerckhof et al., 2006
6) Lercari and Bergamino, 2011
7) Harding, 2006
8) Harding and Mann, 2016
9) Giberto et al., 2008
10) Fofonoff et al., 2018
11) Gillespie, 2007
12) Wonham, 2004
13) Branch and Steffani, 2004
14) Shields et al., 2008
15) Robinson et al., 2007
16) Clarke Murray et al., 2011
17) Carlton, 1992
18) Appelqvist et al., 2015
19) Paalvast and van der Velde, 2011a
20) Paalvast and van der Velde, 2011b
21) Frey et al., 2009
22) Cook et al., 2007
23) Shucksmith et al., 2009
24) Boos et al., 2011
25) Ashton et al., 2007
26) Jänes et al., 2015
27) Daunys and Zettler, 2006
28) Berezina, 2007
29) Ba et al., 2010
30) Faasse, 2015
31) Hiebert, 2015a
32) Gouillieux et al., 2016
33) Borowsky, 1980
34) Faasse and Van Moorsel, 2003
35) Lewis et al., 2006
36) Gouillieux, 2019
37) Minchin, 2007
38) Piazzola and Hiebert, 2015
39) Hancock et al., 2017
40) Ma et al., 2020
41) Konecny and Harley, 2019
42) Moore et al., 2014
43) Saunders et al., 2013
44) Rice and Rice, 2009
45) Takata et al., 2011
46) Dağli and Ergen, 2008
47) Karhan et al., 2003
48) Radashevsky and Selifonova, 2013
49) Hiebert, 2015b
50) Blake and Woodwick, 1975
51) Yamaguchi, 1975
52) Simkanin et al., 2012
53) Bock et al., 2011
54) Carver et al., 2006
55) Gittenberger and Moons, 2011
56) Epelbaum et al., 2009
57) Simkanin et al., 2013
58) Lu et al., 2007
59) Riedel et al., 2006
61) Cook and Hayward, 1966
62) Bouyssou, (2013)
63) Jamieson et al., (2000)
64) Ordóñez et al., (2015)

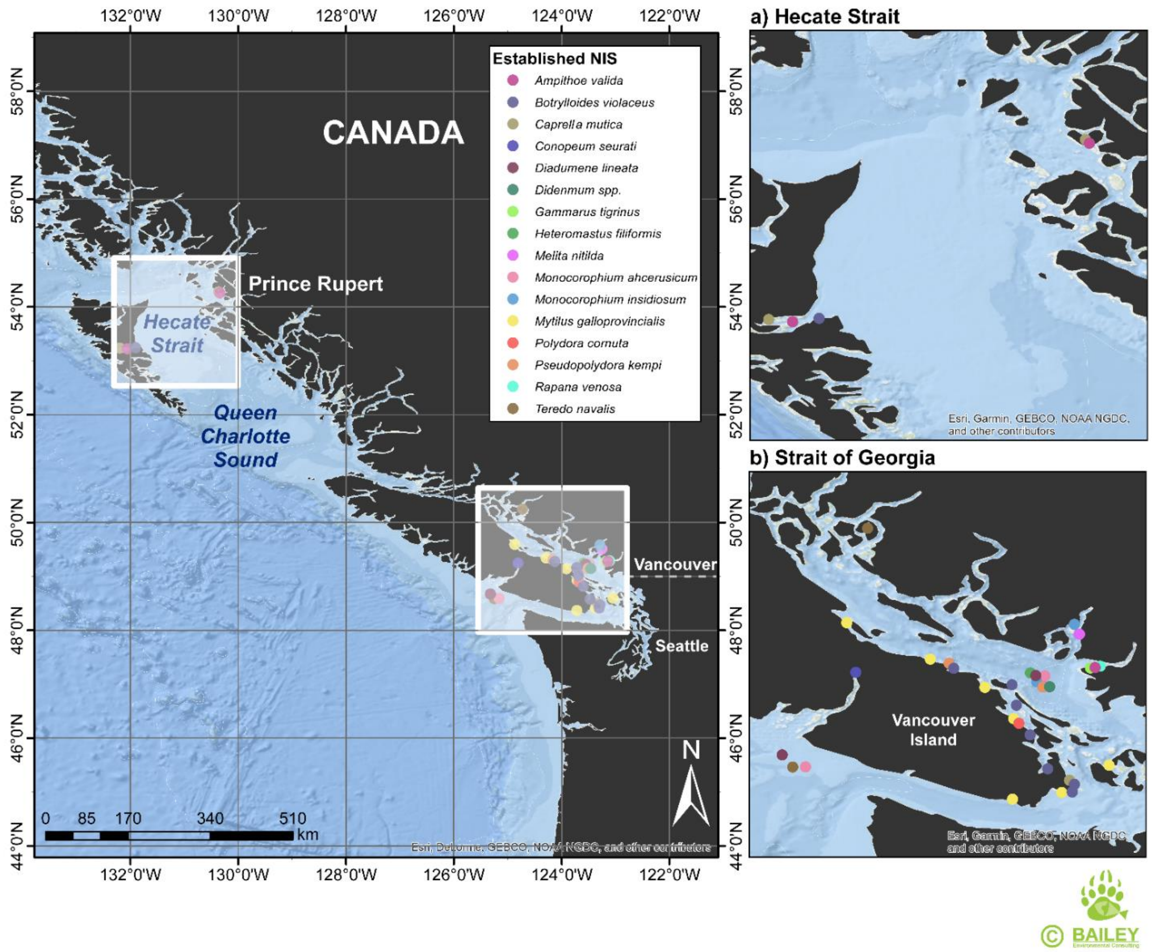

Figure 4: Records of established populations of non-indigenous species (NIS) in British Columbia. Data were compiled based on references provided in Table 3

Species introduced to BC waters through hull fouling successfully establish themselves in their new environment due to their prolific life histories, broad environmental tolerances, and ability to withstand extreme changes in temperature and salinity (Table 3). Specifically, these species generally exhibit high reproductive outputs via broadcast spawning, asexual budding, and/or large brood sizes, increasing their dispersal potential. As adults, many of these species attach firmly to hulls of ships or raft on other biota (e.g., algae, seagrasses) as adults. Further, during their larval planktonic phase, they can survive for long periods of time (e.g., up to four weeks) freely floating in the water column. The planktonic phase and rafting behavior allows rapid spread throughout BC due to the strong currents. Following this initial introduction, it is likely that secondary invasions via recreational vessels and natural spread help organisms to extend their distributions (Figure 5). As many of these organisms have strong planktonic phases, spread throughout BC in currents and through algal rafting is possible.

Two of these species, *Botrylloides violaceus* and *Mytilus galloprovincialis* are described in more detail below. Both are well established in BC and have strong reputations as global invaders.

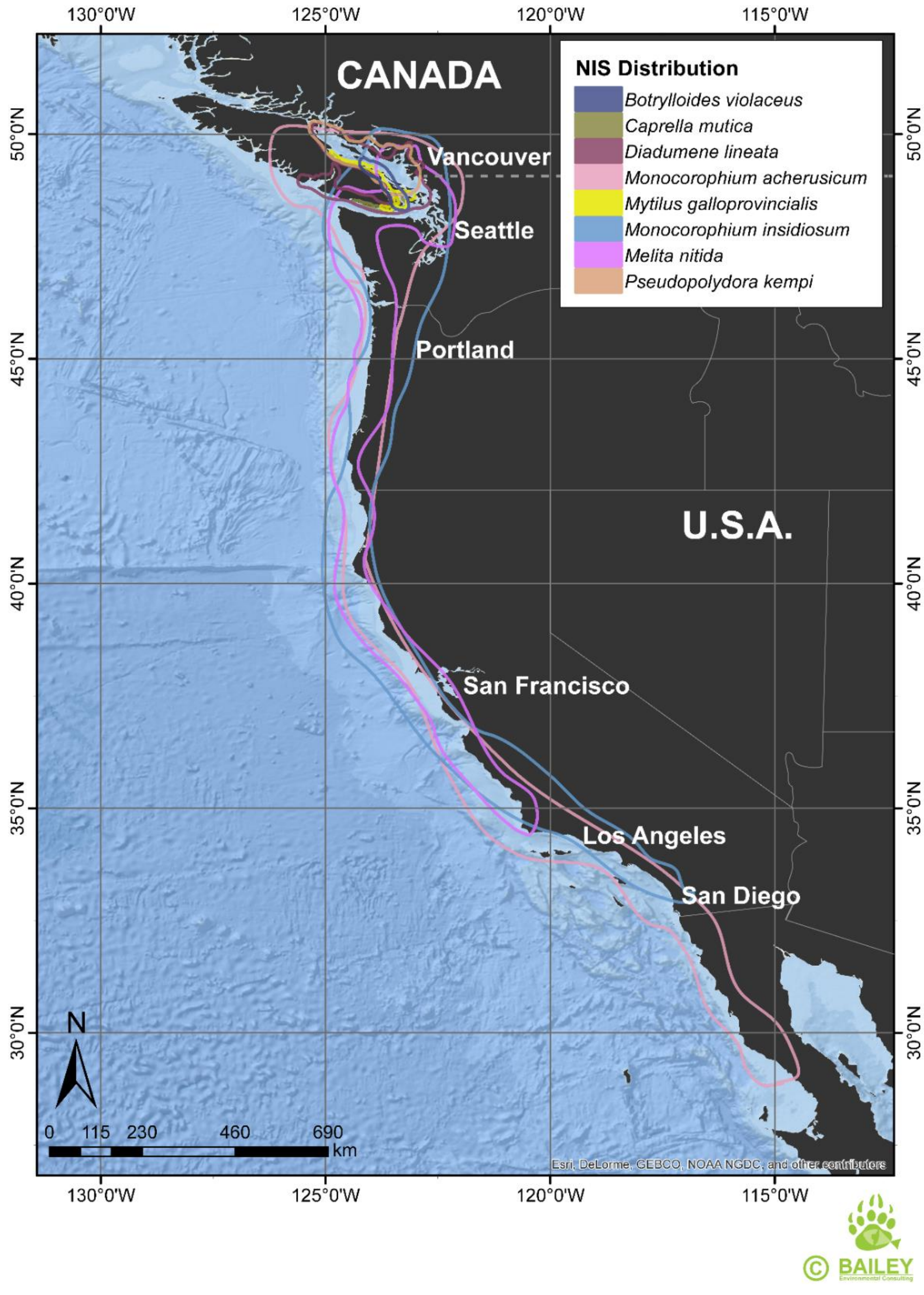

Figure 5: Approximate species distribution following successful establishment (based on general distribution information from literature). Data were compiled based on references provided in Table 3

Botrylloides violaceus **(violet tunicate)**

Native range: Pacific Northwest (likely Japan) (Carver et al., 2006; Epelbaum et al., 2009)

B. violaceus is a colonial tunicate that can be found in two different forms: a flat, encrusting mat, or in thick, irregular lobes, depending on the substrate (Carver et al., 2006; Epelbaum et al., 2009). It is a highly successful invader, as it reproduces both sexually and asexually allowing for rapid spread (Carver et al., 2006; Yamaguchi, 1975). Parent zooids begin asexually budding one week after reaching full development. A single parent colony can develop into 100 colonies in 1 – 2 weeks (Yamaguchi, 1975). It's ability to rapidly cover surfaces, form strong attachments, and tolerate a wide range of environmental conditions along with its lack of natural predators makes it a strong member of ship fouling communities (Carver *et al.*, 2006; Simkanin *et al.*, 2012; Epelbaum *et al.*, 2009). Although it does not have a planktonic larval phase common to many successful invaders, *B. violaceus* has excellent dispersal potential due to is asexual budding and rafting on algae and pleasure crafts, allowing it to disperse over long distances (Carver et al., 2006; Clarke Murray et al., 2011).

As the most widely distributed non-indigenous ascidian in the world, it outcompetes native and non-indigenous ascidian species for space (Simkanin et al., 2012, 2013). It has successfully colonized both the Pacific and Atlantic coasts of North America, as well as many locations in Europe (Bock et al., 2011; Carver et al., 2006; Gittenberger and Moons, 2011; Minchin, 2007). In both introduced and native habitats, *B. violaceus* reduces species richness by overgrowing and outcompeting many native species (Carver et al., 2006; Gittenberger and Moons, 2011).

This species has successfully established itself on the Pacific coast, with strong populations in BC. *B. violaceus* has is widespread on Vancouver Island and has been found as far north as Haida Gwaii (Epelbaum et al., 2009; Gillespie, 2007; Simkanin et al., 2013, 2012; Yamaguchi, 1975). Epelbaum et al., (2009) modelled the potential range expansion of *B. violaceus* in BC and concluding that are no parts of BC unsuitable as habitat for this invasive tunicate.

Mytilus galloprovincialis **(Mediterranean mussel)**

Native range: Mediterranean Sea and the Atlantic coast of southern Europe (Fofonoff et al., 2018; Gillespie, 2007; Wonham, 2004)

M. galloprovincialis reproduces sexually via broadcast spawning, with females producing 1.5 – 3.5 million eggs (Fofonoff et al., 2018). Fertilized eggs develop into planktonic larvae floating freely for 2 – 4 weeks before settling onto a substrate (Fofonoff et al., 2018). Using their byssal threads, juveniles can move from their initial settling point to a more suitable substrate (Fofonoff et al., 2018). Recruitment rates for *M. galloprovincialis* are high, with up to 2 million larval recruits per m^2 (Branch and Steffani, 2004). These filter feeders persist in both intertidal and subtidal environments, are able to withstand desiccation in the high intertidal, and have broad temperature and salinity tolerances, making them adaptable to new environments (Fofonoff et al., 2018; Robinson et al., 2007; Wonham, 2004).

M. galloprovincialis has been documented worldwide (i.e., Korea, Japan, Hawaii, and Canada; Branch and Steffani, 2004; Fofonoff et al., 2018; Robinson et al., 2007; Wonham, 2004). It's ability to rapidly spread following introduction has been well documented (Branch and Steffani, 2004; Robinson et al., 2007).

On the Pacific coast of North America, *M. galloprovincialis* was likely introduced through aquaculture or ship fouling (Gillespie, 2007). Since its arrival, it has successfully established and integrated itself into the mussel community, hybridizing with the two native mussels (*M. edulis* and *M. trossulus*), and forming stable hybrid zones in California, Oregon, Washington, and British Columbia (Fofonoff et al., 2018; Shields et al., 2008; Wonham, 2004). These hybrids exhibit differences in growth, survival and reproductive potential based on specific microenvironments, with no one hybrid or parent genus dominating over another (Shields et al., 2008). The impacts of the incorporation of *M. galloprovincialis* into BC, and the rest of the Pacific coast of North America, are poorly documented; however, these differences may allow mussel species to thrive in additional areas of the coast (Fofonoff et al., 2018; Shields et al., 2008; Wonham, 2004).

7 Regulatory Background

7.1 Fouling

There are no uniform global regulations for the cleaning of hulls, nor uniform regulations that dictate the frequency that hull cleaning must take place (Pagoropoulos *et al.*, 2018). The International Maritime Organization (IMO) provides guidelines for the control and management of biofouling to minimize transfer of invasive species; however, these guidelines are completely voluntary (International Maritime Organization, 2011b). The IMO guidelines recommend that ships develop biofouling management plans, maintain records of all cleaning, maintain and install antifouling systems, conduct inspections of their hulls and generally clean and maintain the ship (USEPA, 2011; International Maritime Organization, 2011b). In the Pacific Ocean, Australia and New Zealand have developed thorough biofouling guidelines. Below, we include the New Zealand regulations as this region is highly susceptible to NIS and represents a temperate marine system comparable to BC, Canada.

7.1.1 International

IMO Recommendations for Biofouling Management

The IMO Marine Environmental Protection Committee (MEPC) provides guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species (MEPC 207(62); International Maritime Organization, 2011b). Although these guidelines are completely voluntary, the IMO established them to provide a global approach to biofouling. The IMO is committed to refining the guidelines as new scientific and technological advances are made. Port

States, flag States, coastal States and other parties that can assist in mitigating the problems associated with biofouling and should exercise due diligence to implement the Guidelines to the maximum extent possible.

MEPC 207(62) (International Maritime Organization, 2011b) recommends the implementation of a Biofouling Management Plan for all ships. This plan should provide detailed descriptions of the anti-fouling systems currently in place as well as the operating profile. Specifically, this plan should be separated into individual parts of the vessel that are submerged/susceptible to biofouling. Examples of systems that should be described include:

- type(s) of anti-fouling coating systems applied;
- details of where anti-fouling systems are and are not applied or installed;
- manufacturer and product names of all coatings or products used in the anti-fouling coating systems; and
- anti-fouling system specifications (including dry film thickness for coatings, dosing and frequency for a Marine Growth Prevention System, etc.) together with the expected effective life, operating conditions required for coatings to be effective, cleaning requirements and any other specifications relevant for paint performance.

Reports on the performance of the ship's anti-fouling systems should be included, and if applicable, anti-fouling systems (AFS) certificate or statement of compliance and all other documentation should also be referenced as appropriate.

The ship's operating profile will determine the performance and specifications of the ship's anti-fouling systems and operational practices, and should include the following:

- typical operating speeds;
- periods underway at sea compared with periods berthed, anchored or moored;
- typical operating areas or trading routes; and
- planned duration between dry-dockings/slippings.

Finally, the management plan should specify areas of the vessel that are susceptible to biofouling such as hull areas, niche areas, and seawater cooling systems. It should also describe the actions to be taken if the ship is operating outside of the desired operating profile, or if excessive unexpected biofouling is observed, and any other actions that can be taken to minimize the accumulation of biofouling on the ship.

IMO MEPC 207(62) provides clear guidelines for how Port States, flag States, coastal States and other parties can maintain effective in-water inspection, cleaning and maintenance pertaining to biofouling in SECTION 7 (International Maritime Organization, 2011b):

SECTION 7: IN-WATER INSPECTION, CLEANING AND MAINTENANCE

7.1 Despite the use of effective anti-fouling systems and operational practices, undesirable amounts of biofouling may still accumulate during the intended lifetime of the anti-fouling system.

To maintain a ship as free of biofouling as practical, it may be advisable for the ship to undertake in-water inspection, cleaning and maintenance.

In-water inspection of ships

7.2 In-water inspection can be a useful and flexible means to inspect the condition of anti-fouling systems and the biofouling status of a ship. In-water inspections should be undertaken periodically as a general means of routine surveillance, augmented by specific inspections as necessary to address any situations of elevated risk. Specific occasions when an in-water inspection may be appropriate, include the following:

- before and after any planned period of inactivity or significant or unforeseen change to the ship's operating profile;
- prior to undertaking in-water cleaning to determine the presence of known or suspected invasive aquatic species or other species of concern on the ship;
- after a known or suspected marine pest or other species of concern is discovered in a ship's internal seawater cooling systems; and
- following damage to, or premature failure of, the anti-fouling system.

7.3 It is recommended that ship operators identify niche areas on the ship that may accumulate biofouling to enable these areas to be effectively targeted during inspections. Areas may include the following:

- propeller thrusters and propulsion units;
- sea chests;
- rudder stock and hinge;
- stabilizer fin apertures;
- rope guards, stern tube seals and propeller shafts;
- areas prone to anti-fouling coating system damage or grounding (e.g., areas of the hull damaged by fenders when alongside, leading edges of bilge keels and propeller shaft "y" frames).

7.4 Dive and ROV surveys can be practical options for in-water inspections although they do have limitations regarding visibility and available dive time compared with the area to be inspected, and difficulties with effectively accessing many biofouling prone niches. Such surveys should be undertaken by persons who are suitably qualified and experienced and familiar with biofouling and associated invasive aquatic species risks and the safety risks relating to in-water surveys. Regulatory authorities may have recommended or accredited biofouling inspection divers.

In-water cleaning and maintenance

7.5 In-water cleaning can be an important part of biofouling management. In-water cleaning can also introduce different degrees of environmental risk, depending on the nature of biofouling (i.e., microfouling versus macrofouling), the amount of anti-fouling coating system residue released and the biocidal content of the anti-fouling coating system. Relative to macrofouling, microfouling can be removed with gentler techniques that minimize degradation of the anti-fouling coating system and/or biocide release. Microfouling removal may enhance a ship's hull efficiency, reducing fuel consumption and greenhouse gas emissions. It is, therefore, recommended that the ship's hull is cleaned when practical by soft methods if significant microfouling occurs. In-water cleaning can also reduce the risk of spreading invasive aquatic species by preventing macrofouling accumulation.

7.6 It may be appropriate for States[4] to conduct a risk assessment to evaluate the risk of in-water cleaning activities and minimize potential threats to their environment, property and resources. Risk assessment factors could include the following:

- biological risk of the biofouling organisms being removed from the ship (including viability of the biofouling organisms or the ability to capture biofouling material);
- factors that may influence biofouling accumulation, such as changes to the operating profile of the ship;
- geographical area that was the source of the biofouling on the ship, if known; and
- toxic effects related to substances within the anti-fouling coating system that could be released during the cleaning activity, and any subsequent damage to the anti-fouling coating system.

7.7 Personnel proposing to undertake in-water cleaning should be aware of any regulations or requirements for the conduct of in-water cleaning, including any regulations regarding the discharge of chemicals into the marine environment and the location of sensitive areas (such as marine protected areas and ballast water exchange areas). Where significant macrofouling growth is detected, it should be removed or treated (if this can be done without damaging the anti-fouling system) in accordance with such regulations. Where available, appropriate technology should be used to minimize the release of both anti-fouling coating or paint debris, and viable adult, juvenile, or reproductive stages of macrofouling organisms. The collected material should be disposed of in a manner which does not pose a risk to the aquatic environment.

7.8 For immersed areas coated with biocidal anti-fouling coatings, cleaning techniques should be used that minimize release of biocide into the environment. Cleaning heavily fouled anti-fouling coating systems can not only generate biofouling debris, but prematurely depletes the anti-fouling coating system and may create a pulse of biocide that can harm the local environment and may impact on future applications by the port authority for the disposal of dredge spoil. Depleted anti-fouling coating systems on hulls will rapidly re-foul. In-water cleaning or scrubbing of heavily fouled hulls for the purpose of delaying dry-dockings beyond the specified service life of the coating is, therefore, not recommended.

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[4] Where 'States' refers to Port States, flag States, coastal States. IMO Member States can be found at: http://www.imo.org/en/About/Membership/Pages/MemberStates.aspx

7.9 Immersed areas coated with biocide-free anti-fouling coating systems may require regular in-water cleaning as part of planned maintenance to maintain hull efficiency and minimize the risk of transferring invasive aquatic species. Cleaning techniques should be used which do not damage the coating and impair its function.

New Zealand – Biofouling Management

All vessels entering New Zealand's territorial waters from international waters must provide evidence of biofouling management prior to arrival. Guidelines for biofouling on vessels are provided in the Craft Risk Management Standard (initiated in November 2018). It does not apply where a vessel has not entered the territorial waters of another country ever or since it was last verified as compliant.

Vessels must arrive in New Zealand with a clean hull. A hull is considered clean when no biofouling of live organisms is present other than within specified thresholds. These thresholds differ for long-stay (i.e., ≥ 21 days, or those visiting from certain areas[5]) and short-stay (i.e., ≤ 20 days, and only visiting certain areas[5]) vessels (Table 4).

Table 4: Biofouling Thresholds for New Zealand based on Stay Length and Hull Part

Stay Length	Hull Part	Allowable Fouling
Long-stay	All hull surfaces	Slime layer; Goose barnacles
Short-stay	All hull surfaces	Slime layer; Goose barnacles
Short-stay	Wind and water line	Green algae growth of unrestricted cover and no more than 50 mm in frond, filament or beard length; Brown and red algal growth of no more than 4 mm in length; Incidental (maximum of 1%) coverage of one organism type of either tubeworms, bryozoans or barnacles, occurring as: • isolated individuals or small clusters; and • a single species, or what appears to be the same species.
Short-stay	Hull area	Algal growth occurring as: • no more than 4 mm in length; and • continuous strips and/or patches of no more than 50 mm in width. Incidental (maximum of 1%) coverage of one organism type of either tubeworms, bryozoans or barnacles, occurring as: • isolated individuals or small clusters that have no algal overgrowth; and • a single species, or what appears to be the same species

[5] Certain areas are covered in section 37 of The New Zealand Biosecurity Act as 'Places of First Arrival'

Stay Length	Hull Part	Allowable Fouling
Short-stay	Niche areas	Algal growth occurring as: • no more than 4 mm in length; and • continuous strips and/or patches of no more than 50 mm in width. Scattered (maximum of 5%) coverage of one organism type of either tubeworms, bryozoans or barnacles, occurring as: • widely spaced individuals and/or infrequent, patchy clusters that have no algal overgrowth; and • a single species, or what appears to be the same species; and Incidental (maximum of 1%) coverage of a second organism type of either tubeworms, bryozoans or barnacles, occurring as: • isolated individuals or small clusters that have no algal overgrowth; and • a single species, or what appears to be the same species.

Reference: https://www.mpi.govt.nz/dmsdocument/11668/direct

One of the following measures must be applied to meet the clean hull requirement:

- Cleaning before visiting New Zealand (less than 30 days before visit), or immediately upon arrival in an approved facility or system (within 24 hours of arrival). All biofouling must be removed from all parts of the hull.
- Continual maintenance using best practice including: application of appropriate antifouling coatings; operation of marine growth prevention systems on sea-chests; in water inspections with biofouling removal as required.
- Application of approved treatments.

The following information must be held on the vessel and provided if requested:

- Information on the antifouling regime and any marine growth prevention systems used
- Whether the vessel is applying the IMO Biofouling Guidelines
    - Includes employing a biofouling management plan, showing the hull maintenance and inspection regime, and records of biofouling management kept
- If applicable to the vessel, its latest International Antifouling System Certificate or International Antifouling System Declaration
- Date and report details from the latest hull biofouling inspection (undertaken either on land or in-water) that was initiated by the operator or person in charge of the vessel

7.1.2 Canadian Legislation

Although the Canadian legislation does not directly regulate in-water hull cleaning activities, the following Acts identify important considerations for in-water cleaning. In addition, the Canadian Port Authorities (CPAs) individually manage actions within their jurisdictional waters.

Canadian Marine Act

The *Canada Marine Act* gives CPAs the power to enforce actions within their waters. Within British Columbia, rules vary between ports, while some ports do not list any in-water cleaning requirements (Table 5).

Table 5: In-water Cleaning Requirements for British Columbia Port Authorities

Port Authority	In-water cleaning permitted?	Details
BC, Canada		
Nanaimo Port Authority[1]	Unknown	None listed
Port Alberni Port Authority[2]	No	The port advises that vessels be dry docked for cleaning. No in harbour cleaning is currently permitted.
Prince Rupert Port Authority[3]	No	Above water line cleaning only. All precaution must be taken to prevent paint, solvents or any other deleterious substances from entering the water.
Vancouver Fraser Port Authority[4]	Conditional (but generally not permitted)	Any persons wishing to perform underwater inspection and cleaning must first complete a service request through the Pacific Gateway Portal. Cleaning via diving is permitted only when the permit has been completed and approved by the Operations Centre.

References:

[1]Port of Nanaimo (2019); Suncor (2018); [2]Port Alberni Port Authority (2014); [3]Prince Rupert Port Authority (2020); Vancouver Fraser Port Authority (2020) [4]

7.1.3 *Canadian Environmental Protection Act*

The *Canadian Environmental Protection Act* (CEPA), which came into force in March 2000, focuses on “pollution prevention and the protection of the environment and human health in order to contribute to sustainable development”. Under CEPA **disposal** (which requires a permit) refers to the “disposal of a substance at sea from a ship, an aircraft, a platform or another structure, but does not include disposal of a substance that is incidental to or derived from the **normal operations of a ship**, an aircraft, a platform or another structure or of any equipment on a ship, an aircraft, a platform or another structure, other than the disposal of substances from a ship, an aircraft, a platform or another structure operated for the purpose of disposing of such substances at sea”. It is currently unknown whether in-water cleaning would be considered within normal operations.

Under CEPA a permit issued by Environment and Climate Change Canada is required for disposal at sea of any substance (i.e., organic or inorganic matter), whether animate or inanimate. It remains to be determined whether in-water hull cleaning falls within this category as matter that is capable of being dispersed in the environment, or if it falls under the exceptions to a disposal at sea permit as animate matter that is, or complex mixtures of different molecules that are, contained in effluents, emissions or wastes that result from any work, undertaking or activity.

7.1.4 United States Legislation (West Coast)

The United States Coast Guard, as well as the International Association of Classification Societies Ltd., require ships to dry dock at least once every five years in order to inspect the ship's hull (USEPA, 2011). Ships intending to perform hull clean require a US Vessel General Permit. All in-water hull cleaning must be conducted in a manner that minimizes the discharge of both fouling organisms and antifouling coatings, and those vessels coated with copper-based antifouling coatings must not produce a visible plume during cleaning (USEPA, 2011). In 2008, the Environmental Protection Agency further required that for any vessel performing in-water cleaning, operators must select appropriate soft cleaning brushes to minimize release of antifouling paints into the water column, limit the use of hard brushes for hard growth removal, use vacuum cleaning technologies in conjunction with any mechanical scrubbing to contain antifouling coatings and organisms and reduce their release into the environment, and minimize release of copper-based antifouling coatings into the water (USEPA, 2011).

Several states have their own set of rules and regulations regarding in-water hull cleaning. For example, underwater cleaning is prohibited in California, except for vessels that use biocide-free antifouling coatings or with special permission from the State Lands Commission and State Water Board (USEPA, 2011). Ships must remove fouling from hulls and niche areas on a regular basis and submit annual husbandry reporting forms (USEPA, 2011). While some states allow underwater cleaning in the case of an emergency (e.g., Maine), other states prohibit underwater cleaning discharges within three miles of shore (e.g., Massachusetts) (USEPA, 2011). Hawaii monitors incoming vessels and evaluates them for high-risk arrivals. They also have rapid response and investigation protocols in case of high risk events, and only permit out of water cleaning (USEPA, 2011).

In addition to State specific regulations, individual ports also provide their own guidelines to hull cleaning (Table 6).

Table 6: In-water Cleaning Requirements for USA West Coast Port Authorities

Port Authority	In-water cleaning permitted?	Details
Port of Anacortes[1,2]	Unknown	None listed
Port of Bellingham[1,3]	No	In-water cleaning prohibited

Port Authority	In-water cleaning permitted?	Details
Port of Seattle[1,4]	No	Above water line only - hull cleaning of vessels treated with soughing or ablative antifouling paints and time-based compounds is prohibited. Minor painting, scraping and refinishing is permitted above the water line but must be contained and all debris collected.
Port of Los Angeles and Long Beach[1,5]	Yes – Conditional	Underwater hull cleaning on vessels with biocide-based antifouling coatings is prohibited. Recommends that underwater hull cleaning on vessels with non-biocide coatings not occur in Port. If such practices occur, best management practices must be followed.
Port of Hueneme[1,6]	Yes – Conditional	Underwater hull cleaning on vessels with biocide-based antifouling coatings is prohibited. In-water hull cleaning of vessels with non-biocide-based antifouling paints, propeller polishing and other in-water maintenance is not recommended in the Port, but is allowed providing rules, regulations and best management practices are followed.
Port of San Diego[1,7]	No – Conditional	Removal of growth attached to bronze propellers and unpainted propeller shafts may be permitted if proven that it will not adversely affect the environment.

References:
[1]USA EPA (2013); [2]Port of Anacortes (2019); [3]Port of Bellingham (2020); [4]Port of Seattle (2020); [5]County of Los Angeles (2018); Port of Long Beach and Port of Los Angeles (2020); [6]Port of Hueneme (2019); [7]Port of San Diego (2019)

7.2 *Canada Shipping Act*

Section 190 (g) of the *Canada Shipping Act*, gives Transport Canada authority over the release of aquatic organisms or pathogens from vessels:

‘190(1) The Governor in Council may, on the recommendation of the Minister, make regulations respecting the protection of the marine environment, including regulations.

(g) for preventing or reducing the release by vessels into waters of aquatic organisms or pathogens that, if released into those waters, could create hazards to human health, harm organisms, damage amenities, impair biological diversity or interfere with legitimate uses of the waters.’

Although the Section does not mention specific activities, in-water hull cleaning meets the criteria for the authority of Transport Canada.

7.3 Federal *Fisheries Act*

The Federal *Fisheries Act* applies to Canadian fisheries waters with respect to sedentary species (i.e., those that are immobile or under the seabed in their harvestable stage), and any portion of the continental shelf of Canada that is beyond the limits of Canadian fisheries waters. Under the most recent *Fisheries Act* amendments in August 2019, the *Fisheries Act* prohibits the carrying on of a work, undertaking or activity, other than fishing, that results in the death of fish[6] [Section 34.4(1)], and the carrying on of a work, undertaking or activity that results in the harmful alteration, disruption or destruction of fish habitat [Section 35(1)] or release of deleterious substances (Section 36). Specifically, the disposal of deleterious substances[7] or the deposit (on the shore, beach, bank, or in water) of remains or organs of fish or marine animals is prohibited under the *Fisheries Act*. Whether a *Fisheries Act Authorization* is required for in-water cleaning activities will depend on the condition of the material being released (e.g., organisms or antifouling coatings).

7.4 Ballast

NOTE: these regulations are included because they provide an example of regulations that help control the impact of invasive species. Ballast water regulations are NOT applicable to biofouling.

Ballast water regulations for the west coast of North America are outlined below. Generally, the regulations follow the Economic Exclusive Zone (EEZ) for each country, stating that those vessels exchanging ballast that travel beyond 200 nm from shore must conduct an exchange in waters 200 nm from shore at least 2,000 m deep before entering the given country's waters. The exceptions to these guidelines are also similar, allowing ballast exchange for vessels remaining within 200 nm of shore to be conducted in areas 50 nm from land in waters at least 200 – 500 m deep. Further exceptions are made for different states, where vessels remain within similar waters.

7.4.1 Canadian Waters

Background

DFO established Canada's first ballast water restrictions as a means to reduce the threats of toxic phytoplankton on local mussel farms in 1982. In 1989 Canada established the first voluntary rules for ballast water exchange, with many updates since. In 2004 the IMO finalized the International Convention for the Control and Management of Ships' Ballast Water and Sediments which created a standard for ballast water treatment and called for the eventual phasing out of ballast water exchanges and recently came into force in 2017. Canada has recently (2019) proposed new Ballast Water Regulations which will help comply with the IMO regulations.

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[6] **Fish** refers to (a) parts of fish, (b) shellfish, crustaceans, marine animals and any parts of shellfish, crustaceans or marine animals, and (c) the eggs, sperm, spawn, larvae, spat and juvenile stages of fish, shellfish, crustaceans and marine animals.

[7] **Deleterious substances** includes (a) any substance that would degrade/alter/contribute to the degradation of water quality rendering it deleterious to fish, fish habitat or use by humans, or (b) any water that contains a substance in a quantity or concentration or that has been treated, processed or changed (e.g., by heat), from the natural state that if added to the water would degrade/alter/contribute to the degradation of water quality rendering It deleterious to fish, fish habitat or use by humans.

Transport Canada concurrently created a '*Guide to Canada's Ballast Water Regulations'* to provide information on the Designated Areas to Exchange and Canadian freshwater ports referred to in the proposed new '*Ballast Water Regulation*s'.

Under the **Ballast Water Regulations (SOR/2011-237)** exceptions for ballast water exchange are made when the vessel operates exclusively in waters under Canadian jurisdiction. However, ballast water taken in from outside of Canada must be managed to (a) minimize the introduction of harmful aquatic organisms or pathogens into the ballast water and their release with the ballast water into Canadian waters; or (b) remove or render harmless harmful aquatic organisms or pathogens within the ballast water. Exceptions are made for vessels that operate exclusively between ports, offshore terminals and anchorage areas on the west coast of North America north of Cape Blanco.

The requirements for transoceanic and non-transoceanic navigation ballast water exchange are described below. If these requirements for transoceanic and non-transoceanic navigation ballast water exchange cannot be met because doing so is infeasible or would compromise the stability or safety of the vessel or the safety of persons on board the vessel, alternate exchange areas have been identified. On the west coast of Canada, this includes areas at least 50 nm west of Vancouver Island and Haida Gwaii, and at least 50 nm west of a line extending from Cape Scott to Cape St. James where the water depth is at least 500 m (excluding Bowie waters within 50 nm of Bowie Seamount).

Ballast Water Exchange: Transoceanic Navigation

This section applies in respect of a vessel that exchanges ballast water and, during the course of its voyage, **navigates more than 200 nm** from shore where the **water depth is at least 2,000 m**. Ballast water that is taken on board a vessel outside of Canadian waters must not release ballast in Canadian waters unless an exchange has been conducted before the vessel enters Canadian waters in an area at least **200 nm** from shore where the **water depth is at least 2,000 m**. Exceptions exist for those vessels operating in the Laurentian Channel.

Ballast Water Exchange – Non-transoceanic Navigation

This section applies in respect of a vessel that exchanges ballast water and **does not**, during the course of its voyage, navigate more than **200 nm** from shore where the water depth is at least **2,000 m**. In this case vessels, that take on ballast outside of Canadian waters may conduct an exchange in areas at least **50 nm** from shore where the water depth is at least **500 m**.

7.4.2 US Waters

Washington State Rules for Ballast Water Exchange[8]

Until otherwise required to meet performance standards under *WAC 220-650-090 (Treatment requirements)* and prior to discharging ballast water into Washington waters, vessel owners or operators must exchange their ballast water to meet or exceed state interim open sea exchange requirements or use an approved exchange alternative. An open sea exchange is intended to reduce the number of higher risk coastal organisms in a ballast tank by replacing them with open sea organisms that are less likely to invade waters of the state, and by changing the salinity and other ambient water conditions to further reduce populations of remaining coastal species. Vessel owners or operators who do not discharge ballast water into waters of the state are exempt from this section but must continue to meet the reporting and other requirements under *WAC 220-650-030.*

Generally, ballast water exchanges must be conducted in open ocean areas, depending on the port of origin. Regardless, each vessel requires a ballast water reporting form. Vessels originating from outside of the Washington State EEZ, must perform an open sea exchange in waters at least 200 nm from any shore and at least 2,000 m deep. Coastal voyages (vessels do not voyage beyond 200 nm from shore) are required to perform ballast water exchange at least 50 nm from shore in waters at least 200 m deep.

Oregon State rules for Ballast Water Exchange[9]

Under Oregon law, a vessel may discharge ballast waters into waters of the state if:

- The vessel conducts an open ocean exchange (at least **200 nm from shore** and in waters at least **2,000 meters deep**); or
- The discharged ballast was **solely sourced within 'common waters' of the state**, identified as the West Coast region of North America between **40° N and 50°N**; or
- A coastal exchange of ballast water takes place (at least **50 nm from shore** and in waters at least **200 meters deep**) for coastwise voyages with ballast water solely sourced from the Pacific Coast region south of **40°N or north of 50°N.**

California State rules for Ballast Water Exchange[10]

California State's *Marine Invasive Species Program* seeks to be a world-leading program that reduces the risk of aquatic non-indigenous species introduction into California's waters by:

[8] **Source:** https://app.leg.wa.gov/WAC/default.aspx?cite=220-650-070

[9] **Source:** https://www.oregon.gov/deq/FilterDocs/bwpFSballastmanage.pdf

[10] **Sources:** http://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=PRC&division=36.&title=&part=&chapter=2.&article=

- The development, implementation, and enforcement of innovative vessel biofouling and vessel ballast water management strategies and policies.
- Use of the best available technology and peer-reviewed science.
- Partnerships with stakeholders to improve awareness of invasive species issues and assess program efficacy.

Ballast water and Biofouling regulations fall underneath the *Marine Invasive Species Act*. The legislation applies to all vessels (≥ 300 gt), United States and Foreign, carrying, or capable of carrying, ballast water into the coastal waters of the state after operating outside of the coastal waters of the state.

Ballast Water and Biofouling Management Requirements [71203 – 71210]:

Ballast water exchange/discharge abide by the following guidelines:

(1) Exchange of ballast water in **mid-ocean waters** before entering the coastal waters of the state,

(2) All ballast water is retained on board the vessel,

(3) Ballast water is discharged at the same location[11] it was taken up (must be able to demonstrate that ballast discharged was not mixed with ballast water taken on in an area other than mid-ocean waters),

(4) Use of an alternative, environmentally sound method of ballast water management that, before the vessel begins the voyage, has been approved by the commission or the United States Coast Guard as being at least as effective as exchange, using mid-ocean waters, in removing or killing non-indigenous species.

(5) Discharge the ballast water to a reception facility approved by the commission.

(6) Under extraordinary circumstances, perform a ballast water exchange within an area agreed to by the commission in consultation with the United States Coast Guard at or before the time of the request.

Under the interpretation of the above guidelines, ballast water exchange/discharge must be made under the following guidelines:

- Vessels calling at a California port or place arriving from a port or a place located outside of the Pacific Coast Region (PCR; Figure 6), and are carrying ballast water sourced from

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https://govt.westlaw.com/calregs/Document/IB3E79871F1F54DF6A641216613E432F7?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)

[11] **Same location** means an area within 1 nm (6,000 feet) of the berth or within the recognized breakwater of a California port, at which the ballast water to be discharged was loaded

outside the PCR, are required to conduct ballast water exchange at least **200 nm** (Figure 6) from any land (including islands) at a depth of at least **2,000 meters.**

- Vessel arriving at a California port or place from within the PCR, and carrying ballast water sourced from within the PCR, are required to conduct exchange at least 50 nm (Figure 6) from any land at a depth of at least 200 meters.

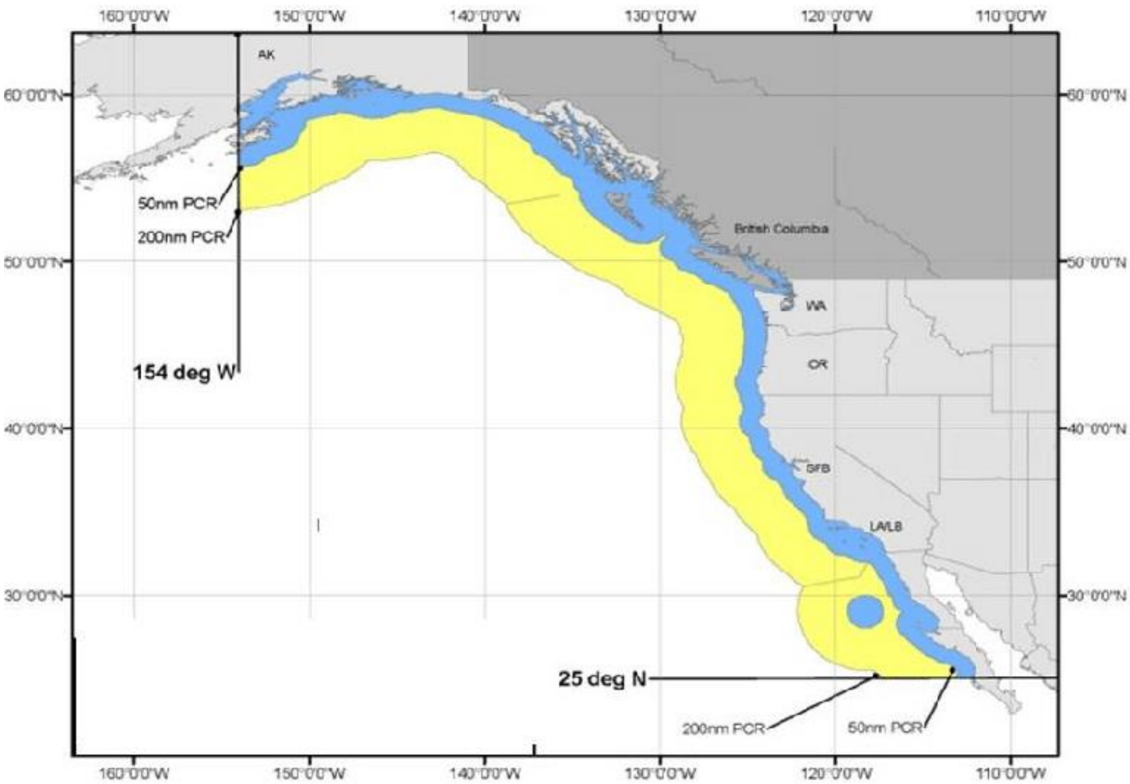


Figure 6: Map depicting the areas considered within/outside of the Pacific Coast Region (PCR) under California State's ballast water regulations

8 Discussion

This report aims to identify the risks of in-water cleaning and to develop sound guidelines under which in-water cleaning may be performed. Specifically, we aim to address concerns regarding the environmental impacts of invasive species establishment. The project is currently in phase 1, which involves laboratory experiments on different anti-fouling coatings to ensure that the robot is capable of cleaning and maneuver over ship hulls without damaging/releasing the anti-fouling coating into the marine environment.

Assuming that the robot is capable of effectively cleaning the hull of the ship without damaging the antifouling coating (currently under experimental testing), it is conceivable that the robot may effectively reduce the spread of NIS. The degree of fouling that the robot is capable of removing from the hull of the ship and its ability to target niche areas will ultimately determine the performance of the robot, when it comes to balancing the costs of fuel efficiency and spread of NIS. On commercial vessels, niche areas (i.e., bilge keels, propellers, rudders, sea chests, gratings, thrusters, tunnels) make up approximately 10% of the total hull wetted surface area (Moser *et al.*, 2017). Noting that it only takes one individual specimen to effectively establish and spread, by reducing biofouling on ship hulls up to 90% the proposed robot provides a means by which the spread of NIS between dry dockings may be effectively reduced.

8.1 Proposed Best Management Practices for In-water Cleaning – Northeast Pacific

This report identified 16 NIS introduced to British Columbia waters by biofouling, all of which are invertebrate species. When part of hull fouling, these NIS would be considered FR30 and above. Their success as NIS is attributed to their prolific life histories (e.g., broadcast spawning, asexual budding, large brood size, larval planktonic phase), broad environmental tolerances, and ability to withstand extreme changes in temperature and salinity. Two well established NIS are present in BC, the violet tunicate (*Botrylloides violaceus*) and the Mediterranean mussel (*Mytilus galloprovincialis*). Within the US Navy Fouling Rating System, *B. violaceus*, one of the most successful invasive tunicates globally, falls within FR30, while *M. galloprovincialis* falls within FR90. Because *B. violaceus* is a strongly successful invader and falls under category FR30, the proposed in-water cleaning guidelines (Table 7) have been developed under the premise that fouling ratings of 0 – 20 are less likely to lead to effective establishment of NIS[12]. In-water cleaning is currently not permitted in most ports, meaning that fouled hulls may lead to spread of NIS, particularly those exceeding FR20. By cleaning regularly at fouling ratings below FR30, it is possible to effectively reduce the likelihood that ship hulls will reach higher fouling ratings, which most commonly encompass the most successful invertebrate invaders. Our proposed guidelines for in-water cleaning are provided in Table 7, with further detailed justification outlined in the sections below.

Neighbouring Ports – Northeast Pacific

The Salish Sea (including Puget Sound, Strait of Juan de Fuca and Strait of Georgia) is a highly dynamic semi-enclosed inland sea, exchanging waters with the northeast Pacific primarily through the Strait of Juan de Fuca. The region is subject to strong tidal currents and freshwater input from the Fraser River, leading to considerable spatial variation (e.g., temperature, salinity) and microhabitats suitable for NIS (Pawlowicz *et al.*, 2019; Jamieson *et al.*, 2000). The area is highly efficient at trapping floating objects, as demonstrated using Lagrangian floats (Pawlowicz *et al.*, 2019). It is therefore conceivable that organisms dislodged from a submerged surface within the

[12] Note that we have adopted a conservative approach in proposing in-water hull cleaning guidelines. These proposed guidelines are intended as a starting point for further discussions with applicable regulatory agencies and port authorities and may be refined with further information.

Salish Sea are likely to be transported throughout the area and may establish strong populations. This is further demonstrated by the distribution of NIS in the Strait of Georgia, which once established rapidly spread throughout (Figure 4). Once a vessel has entered these waters with hull biofouling, the spread of NIS may be inevitable. If vessels are exclusively operating within the Salish Sea or between neighbouring ports within this area, cleaning at any fouling level may be acceptable. Regular in-water cleaning for vessels travelling between adjacent ports, or while in harbour during the early stages of fouling (i.e., FR 0 – 20), may effectively reduce the spread of NIS by targeting hull cleaning in the early stages of growth before highly successful invertebrate invaders are able to attach, while also potentially improving fuel economy.

Cleaning during Coastal Transit – Northeast Pacific

In the North Pacific Ocean, currents are largely driven by the interaction between the Alaska Gyre and the North Pacific Subtropical Gyre particularly down the coast towards California (Thomson, 1981). As the North Pacific Current approaches the coast it splits into the Alaska Current, which pushes north, and the California Current which pushes south. As a result of these currents, the California coast generally experiences upwelling, as the water is pulled away from the coast, and the Alaska coast experiences downwelling, as the water pushes towards the coast (Thomson, 1981). On the coast of British Columbia, currents are highly variable, with upwelling in the summer and downwelling in the winter (Thomson, 1981). The currents along the west coast of North America alone are capable of naturally spreading and transporting Dungeness crab larvae from northern Washington State to southeastern Alaska (Park *et al.*, 2007).

For coastal voyages between non-neighbouring ports it is recommended that in-water cleaning for fouling ratings of FR20 or below be permitted while in port, as the species contributing to fouling at this stage are unlikely to establish as NIS, particularly with regular cleaning. This is because, the slime layer, which is deemed a lower biosecurity risk, includes unicellular algae and bacteria, but may also contain the microscopic life stages of the macrofouling organisms before they reach sexual maturity (Scianni and Georgiades, 2019). Therefore, regular cleaning at fouling ratings up to FR20 may further reduce the spread of NIS by reducing the likelihood/rate of macrofouling.

In the event of coastal voyages where vessel fouling ratings exceed FR20, we would argue that a distance of 200 nm offshore and 2,000 m deep (in line with ballast water exchange regulations) is more than sufficient for in-water cleaning to be conducted, particularly for those vessels moving south along the coast. This is because for vessels travelling south (i.e., south of Vancouver Island) there is a low likelihood of survival of NIS as they are swept away from the continental shelf into deep waters away from suitable settling substrate is extremely low (i.e., because the California Current is an upwelling region, meaning that water in this region is being pulled away from the shore). Therefore, vessels travelling south that do not navigate greater than 200 nm from shore where the water depth is at least 2,000 m and have fouling ratings exceeding FR20 can reasonably perform in-water cleaning in areas 50 nm from shore and at least 500 m deep (Figure 6; in line with ballast water regulations).

For vessels travelling north up the coast (i.e., north of Vancouver Island), we recommend that cleaning be conducted as soon as the vessel reaches 200 nm offshore and 2,000 m deep, as the Alaska current leads to downwelling on the coast (i.e., onshore currents and lower primary production). This lower primary production suggests decreased food and nutrient availability, and therefore decreased likelihood of survival of potential NIS. However, assuming that the majority of these species can remain in the water column for 2 to 5 weeks and the Alaska Current flows up to 29 cm/s parallel to the coastline (Reed, 1980), an organism dislodged from a vessel during in-water cleaning may therefore be able to travel 189 to 474 nm in 2 and 5 weeks, respectively. Therefore, reaching suitable coastal substrate following dislodgement 200 nm from the coast is possible, though other factors such as sinking out of the mixed layer and predation will further reduce the likelihood of NIS establishment.

Cleaning during Open Ocean Transit – Northeast Pacific

We recommend that the same guidelines apply for vessels undergoing transoceanic open ocean transits as those that apply for coastal transit. Briefly, we recommend that transoceanic vessels with fouling ratings exceeding 20, perform in-water cleaning at a distance of 200 nm and 2,000 m deep. It is important to consider onshore transport and localized currents for the region in question, as described above. However, vessels that do not navigate greater than 200 nm from shore where the water depth is at least 2,000 m and have fouling ratings exceeding FR30 can reasonably perform in-water cleaning in areas 50 nm from shore and at least 500 nm deep (Figure 6; in line with ballast water regulations). Fouling ratings of 20 or below on transoceanic vessels, may be safely conducted while in port, as the species contributing to fouling at this stage are unlikely to establish as NIS.

Table 7: Proposed Best Management Practices for in-water Hull Cleaning in the Northeast Pacific

Foul Rating	**FR 0**	**FR 10**	**FR 20**	**FR 30**	**FR 40**	**FR 50**	**FR 60**	**FR 70**	**FR 80**	**FR 90**	**FR 100**
Characterization	**Clean Hull**	**Incipient Slime**	**Advance Slime**	**Soft Non-calcareous**	**Calcareous**	**Calcareous**	**Calcareous**	**Calcareous**	**Calcareous**	**Calcareous**	**Composite**
General Description - Biofouling Type *(adopted from US Naval Ship Tech Manual – 2006)*	–	Slime – light shades of red and green	Slime – dark green patches with yellow or brown	Grass as filaments up to 3" long Projections up to 0.25" height Sea cucumbers, sea grapes, sea squirts up to 0.25" height	Tubeworms less than 0.25" diameter or height	Barnacles less than 0.25" diameter or height	Combo of tubeworms and barnacles less than 0.25" diameter or height	Combo of tubeworms and barnacles greater than 0.25" diameter or height	Tubeworms closely packed barnacles on top of each other 1/4" or less in height	Dense growth of tubeworms with barnacles, 0.25" or greater in height Oysters Mussels	Soft sedentary animals without calcareous covering (tunicates) growing over hard growth
Neighbouring Ports											
Min Depth (m)	In harbour										
Min Distance from Shore (nm)	In harbour										
Coastal											
Min Depth (m)	0 (in harbour or during coastal transit)			2,000 (500 [a])							
Min Distance from Shore (nm)	0 (in harbour or during coastal transit)			200 (50 [a])							
Transoceanic											
Min Depth [m]	0 (in harbour or during transit)			2,000 (500 [b])							
Min Distance from Shore [nm]	0 (in harbour or during transit)			200 (50 [b])							
Paint Type Allowed											
Canadian Regulatory Body	Port Authority	Port Authority	Port Authority	Port Authority, IMO, TC (for vessels 24 m and larger)							

NOTES:

[a]Exception for vessels travelling south in the California Current that do not navigate at least 200 nm from shore.

[b]Specific exceptions should be based on the localized oceanographic conditions at each port.

[c]Place holder upon completion of laboratory experiments

9 Summary

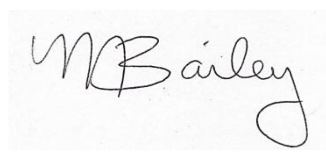
The information herein is solely the opinion of Bailey Environmental Consulting Inc. and does not reflect the ideas or opinions of ODL or any other regulatory body. Rather, this report aims to provide background information to support the development of ODL's in-water hull cleaning technology. This report is not intended to provide an exhaustive review of the literature, as current regulations are ever evolving.

It is the opinion of Bailey Environmental Consulting Inc. that in-water cleaning using ODL's technology may be conducted safely from the perspective of NIS spread. It remains to be determined whether the robot will be capable of cleaning the hull of a ship without damaging the antifouling coating, and to what degree of fouling the robot will be capable of cleaning.

10 Closure

We trust this assessment meets your requirements. Should you have further questions or inquiries, please do not hesitate to contact Michelle Bailey directly at 604-250-2964 or michelle@baileyenvironmentalconsulting.com

Kind regards,



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