BEST PRACTICE FOR CLEANING OF SHIP HULLS

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Abstract

Ships will during their service lives accumulate marine fouling on the hull and in-water hull cleaning is therefore needed. There are many active hull cleaning companies globally operating in hull cleaning hubs like Algeciras (Gibraltar), Pireus (Greece), Singapore Straight, Gulf of Mexico and United Arab Emirates. The port of Algeciras has as an example about 300 hull cleanings per year.

In-water hull cleaning of commercial ships are usually performed when the ship is being loaded or unloaded at a commercial port or when at anchorage. The frequency of hull cleaning vary, but according to ship owners it can be twice per year. The reactive cleaning is often based on the performance of the ship and triggered by increased fuel-consumption. Proactive cleaning on the other hand aim to forego any growth of macrofouling (higher stages of fouling) by frequent removal of microfouling (low stages of fouling)

This report summarizes the methods available for cleaning based on a review of commercial equipment and the information is divided into handling and operation, efficacy in removal and capture and impact on paint. As cleaning is performed on different antifouling paint systems, with varying degree and stage of fouling and with different equipment the performance will be unique for each combination. Further does the fouling vary between different locations on the ship especially between hull and niche areas.

To understand the potential risks of in-water hull cleaning, the effluents from cleaning needs to be collected and analyzed for total suspended solids (TSS), particle size distribution (PDS), and metal concentrations.

In-water hull cleaning on ship hulls coated with biocidal antifouling paint may result in large emissions of biocides to the marine environment. Using data from Soon et al. (2021), up to 10 kg of Cu may be emitted to the environment from a cleaning event with brushes. However, this input can be prevented if a capture system that capture the paint flakes and treat the effluent are used.

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1. Introduction

The biofouling process begins when the ship is immersed in seawater. It is a continual process that is influenced by both environmental conditions (e.g. salinity, temperature) and the operational profile of a vessel. Attached organisms increase drag, reducing a ship's speed and raises fuel consumption. The most common strategy to prevent biofouling is to coat the ship hull with antifouling paints that contain biocides. Antifouling paints also reduces the likelihood of transferring marine species that can become invasive with negative effects in new marine environments. Invasive species are species that spread after introduction to a new area and have an adverse impact on biodiversity, human health, recreational, social and cultural values and economy (EU 2014; Georgiades et al. 2021). Biofouling can be divided into the two major components: macrofouling and microfouling. As shipping is a global industry the biofouling species can be transferred over large distances to different geographic areas. Since most antifouling coatings are not totally effective in preventing biofouling, hull cleaning processes are frequently being performed on ships. During ship hull cleaning processes, fouled species can be detached and spread to new areas. The most common groups of macrofouling worldwide are the hard fouling species such as barnacles, polychaetes, bivalves, bryozoans and soft fouling like tunicates/ascidians, macroalgae and hydroids (Woods et al 2007, NZ and McCollin and Brown 2014 Scotland). Several studies presented below has investigated the species present and share of Non-Indigenous Species (NIS) found on ship hulls. A study of biofouling on commercial ship hulls, investigated in dry docks in Scotland (McCollin and Brown 2014) identified thirty-six organisms within the ten taxonomic groups barnacles, amphipods, isopods, molluscs, bryozoans, hydroids, polychaetes, nemertine worms, anemone and algae. The most common groups were barnacles, algae and molluscs. Regarding location of the biofouling on the ship, barnacles, molluscs and amphipods were present in the following eight areas: hull, stern, keel, bow, propellers, sea chests, thrusters and the waterline. Bryozoans and hydroids were present in all areas except the waterline. Taxonomic groups of nemertine worms, anemone and isopods were only found on single vessels but when found they were present in several areas. The Scottish study was based on 29 vessels in traffic within the North Sea. A study from Hamburg, Germany, of 131 hull fouling samples collected from vessels, found that nearly all ships (96.2%) contained at least one non-indigenous species to European waters (Gollasch 2002). The study by Gollasch 2002 was conducted on commercial ships in traffic worldwide. In Canada a study on non-indigenous species introductions via biofouling based on 40 vessels sampled in Great Lakes ports using video recordings and scrape samples, found a total of 170 fouling taxa, of which 78 were identified to species level (Sylvester et al 2011). About 90% of these species had not been recorded in the sampling ports and were considered non-established NIS. Further in a study from Argentina, 19% of the species found associated with underwater surfaces of a research vessel, had previously not been reported in Mar del Plata, Argentina (Meloni et al 2020). Even if biofouling historically has been carried around on ships, these studies indicates that there is a substantial risk for new introductions of NIS with ships. Further, vessels visiting more regions can gather more species as they are exposed to greater variety of biological communities.

The so called “niche areas” on ships are areas that either are protected from hydrodynamic drag forces (recesses), or areas exposed to higher forces (protrusions) than surrounding surfaces. As most niche areas are difficult to prepare and coat even when the vessel is in dry-dock, they are often not fully covered by anti-fouling coatings (Bohlander 2009). A study by Hopkins and Forrest (2010) measuring fouling cover, biomass and richness found that the highest levels of fouling were associated with dry- docking support strips and other niche areas of the hull where the paint condition was poor.

The niche areas of the ships include both large variance in taxonomy of species and, in relation to their area, a large proportion of the total biofouling on the ship (Davidson et al 2009, Coutts et al 2010b). Factors that influence biofouling in niche areas are the position, size, and design of niche areas. The cleaning of niche areas is in general not considered priority in regard to efficiency in propulsion of ship, which merely is related to biofouling on hull surfaces and propellers. However, biofouling of niche areas and internal seawater systems can reduce engine cooling efficiency, influence vessel safety, and result in unscheduled maintenance and associated costs (Scianni & Georgiades 2019). Many of the niche areas are not easily accessible for underwater cleaning with the larger equipment designed for cleaning of the flat hull surfaces but will instead need customised cleaning solutions (Growcott et al. 2019). The niche areas often require manual cleaning using handheld equipment such as scrapers, handheld rotary brushes and water blast wands (McClay et al. 2015; Morrisey & Woods 2015 and Mika Rouhola, DG Diving Group, Finland, Personal comment).

Regarding regulations for biofouling and hull cleaning activities globally, the IMO Biofouling guidelines are currently (2023) in review. There are today different hull cleaning technologies in use worldwide and the aim of this report is to summarize the methods together with the available knowledge around environmental impact form hull cleaning activities in the search for best practices. This report includes descriptions of the hull cleaning techniques and waste treatment systems regarding process and function. However. are there no data for efficacy of systems available and neither are there any global standards for capture and collection of the hull cleaning waste in place today.

2. Aims and objectives

The overall aim of this report was to review commercially available hull cleaning techniques for ships.

The specific objectives were to

1. Perform a detailed description of different techniques available for cleaning of ship hulls
2. Assess how different hull cleaning techniques remove and/or capture biological material and propose mitigation strategies.
3. Evaluate the emissions of contaminants and paint particles during hull cleaning events and propose mitigation strategies.

3. Material and method

The basis for this work was a literature review including both scientific papers and technical reports as well as information from hull cleaning companies. In general, the reference material was divided into two main categories: technical approaches for ship hull cleaning and possible environmental impact. To find both academic studies and industry reports the following keywords and sentences were used in the literature search to focus on hull cleaning methods from a technical and environmental perspective.

- Hull cleaning methods
- In-water cleaning with capture
- Brush hull cleaning
- Waterjet hull cleaning
- Encapsulation hull cleaning
- Vibration hull cleaning
- Heat hull cleaning
- Environmental impact of hull cleaning methods
- Hull cleaning methods standards
- IMO rules for hull cleaning
- Hull cleaning robots
- Laser induced hull cleaning method
- Effluent treatment after hull cleaning
- Risks associated with in-water cleaning
- Testing of reactive in-water cleaning
-

The references of all selected publications were also evaluated after utilizing the keywords indicated above. As a result, a total of 70 publications were found in the literature review. The publications were all published between 2000 and 2022, with the majority between 2015 and 2019.

The following academic websites were utilized to search papers and scholarly documents in addition to company websites:

- Chalmers Library ì
- Science Direct ì
- Google Scholar ì
- Base ì
- Core ì

4. Background

4.1. Fouling rating classification and measurement of impact on paint

The severity of fouling on a ship hull can be classified according to different scales. One example is the Level of Fouling rank scale developed by Floerl et al 2005 where the fouling rate is given a number that contain both type of fouling and percentage cover (**Table *1***). Another commonly used ranking system developed by US Navy, NSTM (NSTM 2006) instead report the % cover of each fouling group (**Table *2***).

Table 1. Level of Fouling rank according to Floerl et al 2005

Rank	Description	Visual estimate of fouling cover (%)
0	No visible fouling. Hull entirely clean, no biofilm on visible submerged parts of the hull.	0
1	Slime fouling only. Submerged hull areas partially or entirely covered in biofilm, but absence of any macrofouling.	0
2	Light fouling. Hull covered in biofilm and 1-2 very small patches of macrofouling (only one taxon). 1-5 % of visible submerged surfaces fouled.	1-5
3	Considerable fouling. Presence of biofilm, and macrofouling still patchy but clearly visible and comprised of either one single or several different taxa. 6-15 % of visible submerged surfaces fouled.	6-15
4	Extensive fouling. Presence of biofilm and abundant fouling assemblages consisting of more than one taxon. 16-40 % of visible submerged surfaces fouled.	16-40
5	Very heavy fouling. Diverse assemblages covering most of visible hull surfaces. 41-100 % of visible submerged surfaces fouled.	41-100

Table 2. Ranking system developed by US Navy, NSTM (NSTM 2006) where the % cover of each fouling group is reported

Type	Fouling Rating (FR)	Description
Soft	0	A clean, foul-free surface; red and/or black AF paint or a bare 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-colored areas (advanced slime). Bare metal and painted surfaces may by obscured by the fouling.
Soft	30	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 can not be easily wiped off by hand
Hard	40	Calcareous fouling in the form of tubeworms less than ¼ inch in diameter or height.
Hard	50	Calcareous fouling in the form of barnacles less than ¼ inch 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 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 or less in height. Calcareous shells appear clean or white in color.
Hard	90	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.
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.

To assess the paint deterioration from cleaning of the entire ship, Paint Deterioration Rating (PDR) can be used which is a numerical rating of increasing severity on a scale from 10 to 100 in 10-point increments (Table 3) (NSTM, 2006). Paint damage on a limited surface area can instead be defined following the standard test method ASTM D6990-05 (for chipping, damage, corrosion etc).

To assess the impact of cleaning on fouling removal and impact on paint using either of these scales and a sufficient number of replicates, is required to give quantitative and transparent data. Today the results of hull cleanings presented by the operators, at the web pages and in the cleaning reports, are not required to follow any specific methods for estimation of fouling and removal.

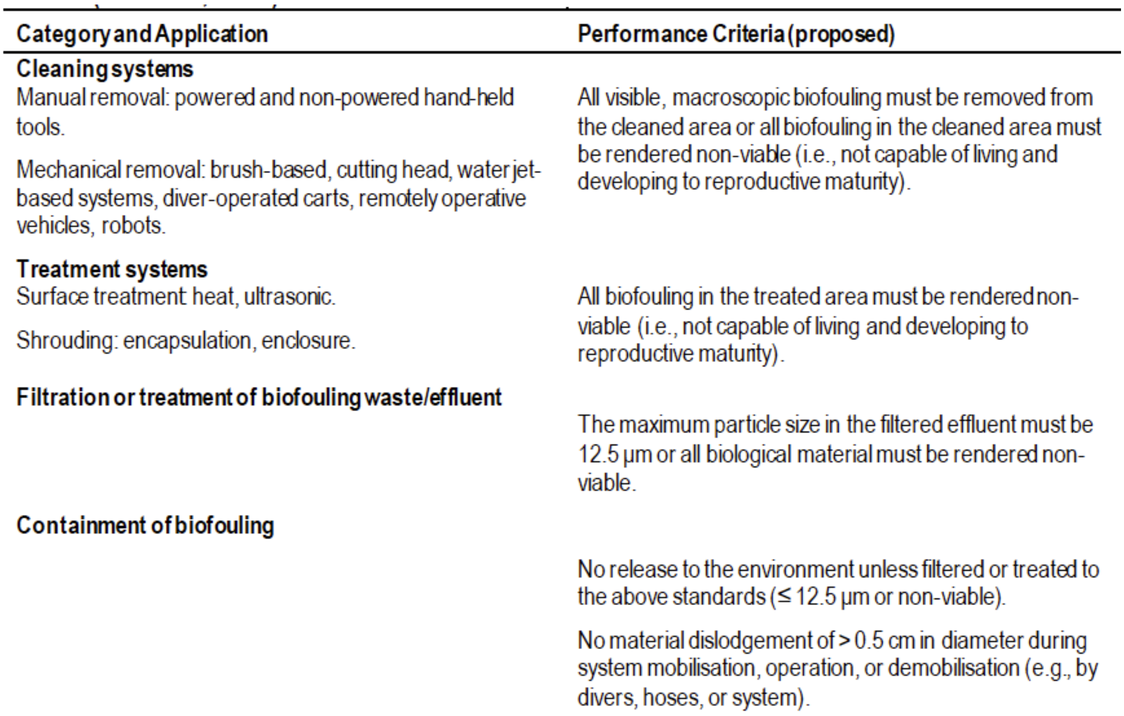
Table 3. Paint deterioration ratings (PDR), from NSTM (2006)

Paint deterioration rating (PDR)	Description
10	Antifouling paint intact, no brush swirl marks
20	Antifouling paint missing from edges, corners, seams, welds, rivets, or bolt heads to expose anti-corrosion paint
30	Antifouling paint missing from slightly curved or flat areas to expose underlying antifouling or anti-corrosion paint, or an antifouling paint with visible swirl marks with the outermost layer; not extending into any underlaying layers of paint
40	Antifouling paint missing from intact blisters to expose anti-corrosion paint, or an antifouling coating with visible brush swirl marks exposing the next underlying layer of antifouling or anti-corrosion paint
50	Antifouling blisters ruptures to expose anti-corrosion paint
60	Antifouling/anti-corrosion paint missing or peeling to expose steel substrate, or corrosion present
70	Antifouling/anti-corrosion paint removed from edges, corners, seams, welds, rivets, or bolt heads to expose steel substrate with corrosion present
80	Ruptured antifouling/anti-corrosion blisters on slightly curved or flat surfaces with corrosion or corrosion stains present
90	Corrosion of steel substrate with no antifouling/anti-corrosion paint cover due to peeling or abrasion damage
100	Area corrosion showing visible surface evidence of pitting, scaling and roughening of steel substrate

4.2. Performance criteria for hull cleaning

Today there are no international standards for performance of hull cleaning, and statements for performance of the various systems found in literature are expressed in different ways. However, in some countries (for example New Zealand) work with performance criteria for cleaning systems has been ongoing for decades (Table 4) (MPI, 2017).

Table 4. Categories of in-water cleaning/treatment systems and their proposed performance criteria (after MPI, 2017).



Category and Application	Performance Criteria (proposed)
Cleaning systems	
Manual removal: powered and non-powered hand-held tools. Mechanical removal: brush-based, cutting head, water jet-based systems, diver-operated carts, remotely operative vehicles, robots.	All visible, macroscopic biofouling must be removed from the cleaned area or all biofouling in the cleaned area must be rendered non-viable (i.e., not capable of living and developing to reproductive maturity).
Treatment systems	
Surface treatment heat, ultrasonic. Shrouding: encapsulation, enclosure.	All biofouling in the treated area must be rendered non-viable (i.e., not capable of living and developing to reproductive maturity).
Filtration or treatment of biofouling waste/effluent	The maximum particle size in the filtered effluent must be 12.5 µm or all biological material must be rendered non-viable.
Containment of biofouling	No release to the environment unless filtered or treated to the above standards (≤ 12.5 µm or non-viable). No material dislodgement of > 0.5 cm in diameter during system mobilisation, operation, or demobilisation (e.g., by divers, hoses, or system).

4.3. In-water hull cleaning, reactive cleaning and proactive grooming

Performance monitoring software tools can be used for scheduling of cleaning as they allow for the detection of various degrees of fouling based on the ship's performance and fuel consumption data. This so called “reactive cleaning” is performed on hulls and propellers in water. Historically, ship in-water cleaning (IWC) has been conducted with divers or remotely operated vehicles (ROV), to remove macrofouling from hull and other surfaces without capture of released material (i.e., fouling organisms and coating material). However, without debris capture, IWC of macrofouling can directly lead to discharges of both Non-Indigenous Species (NIS) and harmful Anti-Fouling System (AFS) biocides (Scianni and Georgiades, 2019; Tamburri et al. 2020). It is a risk that reactive cleaning practices affect coating condition so that AFS performance or service life is reduced (Scianni and Georgiades, 2019; Tamburri et al., 2020). Biocidal antifouling coatings may be abraded by reactive in-water cleaning procedures like abrasive brush systems and high-pressure water jets, resulting in that paint particles are released into the surrounding marine environment.

Thus, IWC technology has in recent years developed to enable capture and processing of debris removed from ships. This includes capture systems, filtering, and/or treating the debris and waste effluent that has been removed.

The reactive IWC and capture abilities are influenced by:

- The amount and type of biofouling present
- The kind and age of the antifouling coating systems cleaned
- The in-water cleaning procedure
- The hydrodynamic environment

An alternative to reactive cleaning of macrofouling is to conduct periodic proactive IWC to remove biofilms and microfouling, which also prevents macrofouling growth (Tribou and Swain, 2010; Scianni and Georgiades, 2019; Tamburri et al., 2020). Proactive cleaning can be conducted with soft brushes, water jets, or contactless devices and can include capture and effluent treatment.

Proactive IWC (sometimes called “grooming”) of thin biofilms layers is typically less abrasive than macrofouling removal. The less aggressive proactive cleaning result in less damage to the coating and the surrounding environment. Proactive cleaning is expected to have lower discharge of pollutants than Reactive In-Water Cleaning (Morrisey et al 2013). Proactive cleaning method also decreases the risk of invasive species being transported between ports and it is therefore viewed as a relatively low biosecurity risk (Georgiades et al., 2021). It is however expected that Proactive IWC releases microscopic material (biological and chemical) to the environment. Therefore, chemical emission data related with both reactive and proactive system are in the future likely to be required by water quality regulators. Proactive In Water Cleaning and Capture (PICC) systems are meant to reduce biocide release even more through capture and wastewater treatment. However, there is a scarcity of independently obtained data on chemical discharges connected with Proactive In Water Cleaning (PIC) and PICC systems (Scianni, 2019).

One example of proactive cleaning is the Jotun Hull Skating Solutions device which is targeting the microfouling to avoid marcofouling buildup. According to the paint company Jotun the proactive cleaning solution could over the course of 60 months, reduce CO2 emissions from a typical bulk carrier by 12.5 percent. Algal biofilm has in previous calculations from naval ships been estimated to increase fuel penalty with 15-20% (Schultz 2007). Another proactive cleaning device is the semiautonomous hull cleaning robot Shipshave ITCH (In Transit Cleaning of Hulls) https://shipshave.no

4.4. Forces required to remove different types of biofouling

Adhesion strength is the force needed to remove a marine organism from a given surface and expressed as force per unit area (N / m2) =Pa. Information on this can be used for selecting minimal forces during in water cleaning. In several studies conducted in laboratory the forces needed to detach different biofouling organisms has been evaluated. The attachment strength of biofouling to a surface will vary both with type and stage of organism as well as with the surface and paint characteristics. The forces needed to remove hard fouling has seen to be several orders of magnitude higher than the forces needed for removal of soft fouling (Oliveira and Granhag 2016). To remove hard fouling (barnacles) from hard (epoxy) paint forces of 0,2-3,3 MPa was needed while barnacles was removed from self polishing copolymers (SPC coatings) with forces of 0,5 MPa and from foul-release coatings with 0,03-0,5 MPa (Figure 1). To remove soft biofouling, like microalgae and sporelings of macroalgae, from foul-release coatings, shear stress of 10-280 Pa was needed. The majority of the studies of removal has been conducted on foul-release coatings of various brands and there is less data available for SPC-coatings.

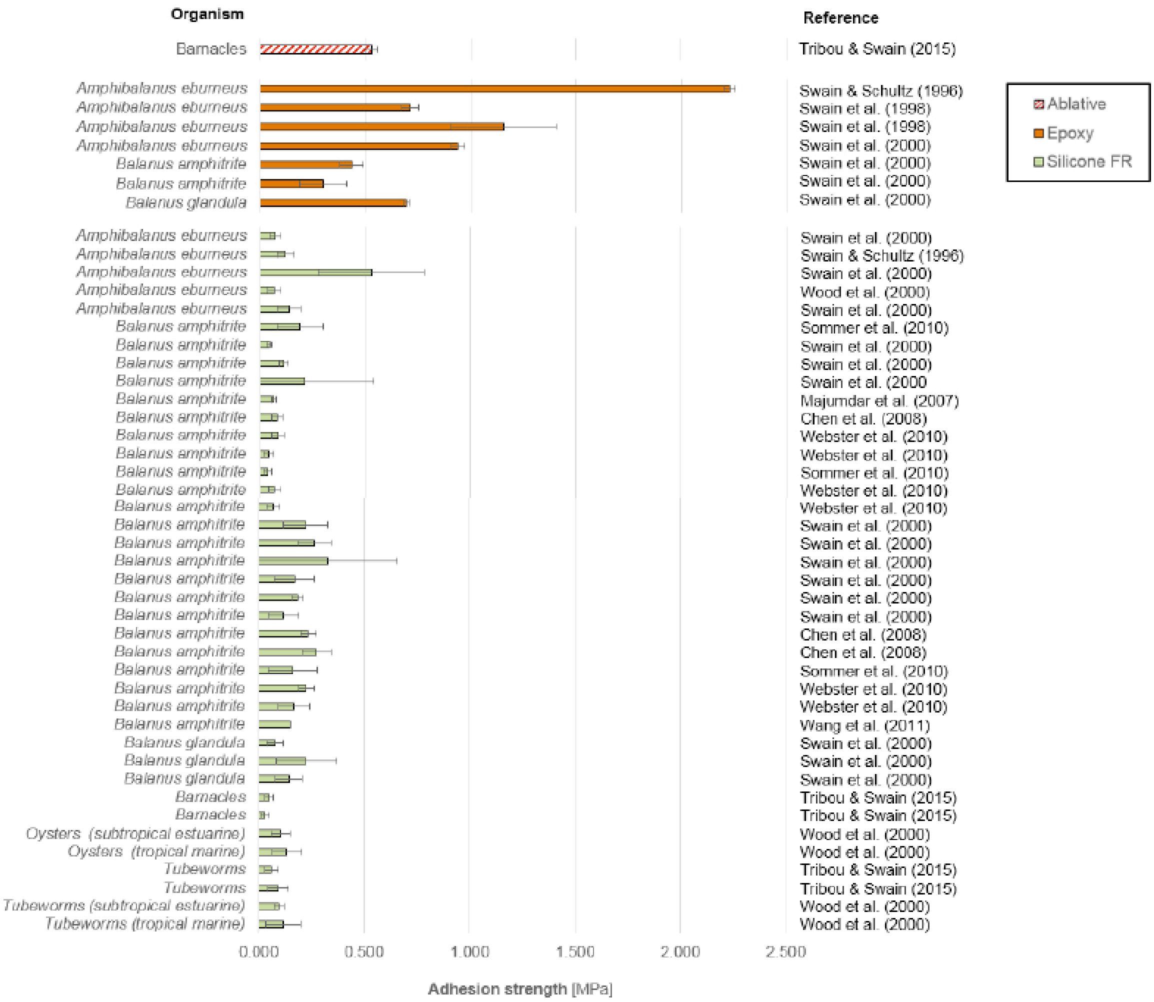


Figure 1. Adhesion strength values for macrofoulers on different types of hull coatings. Legend:*"Ablative": biocide-containing anti-fouling coating; "Epoxy": corrosion protection coating; "Silicone FR": silicone Foul-Release coatings (from Oliveira and Granhag 2016), based on various brands and with data from several locations. For full data : http://www.mdpi.com/2077-1312/4/4/66/s1*

Different criteria of removal has been used as sometimes parts of the organisms are left on the surface. In the compilation above (Figure 1) most of the measurements were considered valid if the baseplate removal was more than 90%. This is according to standard procedure in ASTM Standard D5618-94, where readings are usually considered void if more than 10% of the organism's adhered surface remains on the coating in Oliveira and Granhag (2016). There is a span between minimum and maximum forces needed for removal of hard fouling, as presented in the work by Tribou and Swain 2015. Removal of barnacles from epoxy required 2.23 MPa, from ablative coating 0.53 MPa while from silicone fouling release coating only 0.03-0.05 MPa

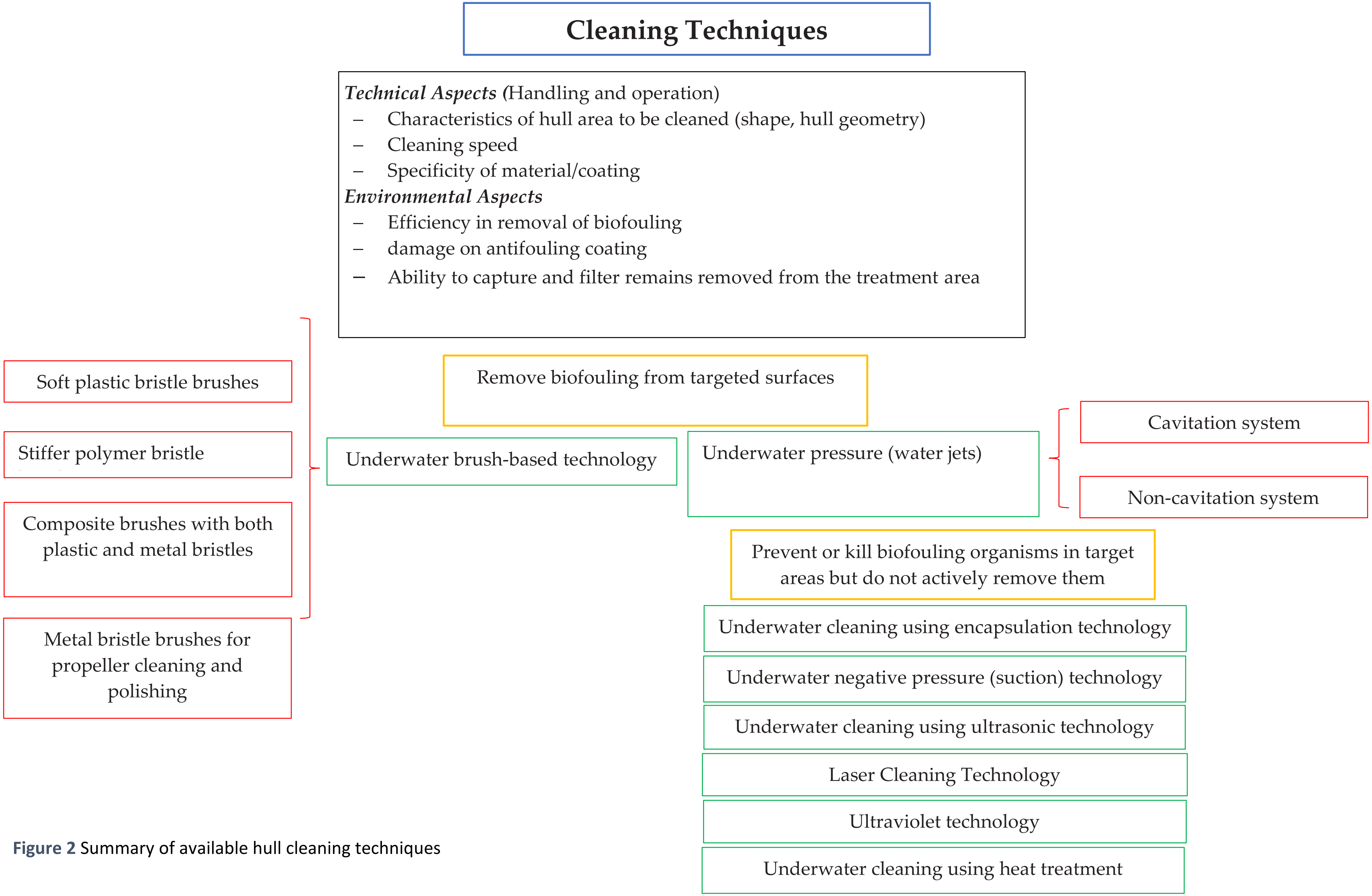
In a field study from Port of Gothenburg the minimal forces to remove biofouling from antifouling coatings during monthly or bimonthly cleanings were determined using an immersed waterjet. The results show that bi-monthly/monthly cleaning, with maximum wall shear stress up to 1.3 kPa and jet stagnation pressure 0.17 MPa, did not cause damage or wear on either the tested biocidal antifouling (AF) or biocide-free foul-release (FR) coatings (Oliveira and Granhag 2020).

5. Description of different techniques available for cleaning of ship hulls

An overview of the current available techniques for hull cleaning are presented in Figure 2. One aim of the report is to perform a literature review to compare the following aspects for the existing underwater cleaning systems:

Technical Aspects including Characteristics of hull area to be cleaned, cleaning speed and Specificity of material/coating and (Operation and Handling)

Environmental Aspects including Efficiency in removal of biofouling, Capture and filtration and reported impact on antifouling coating.



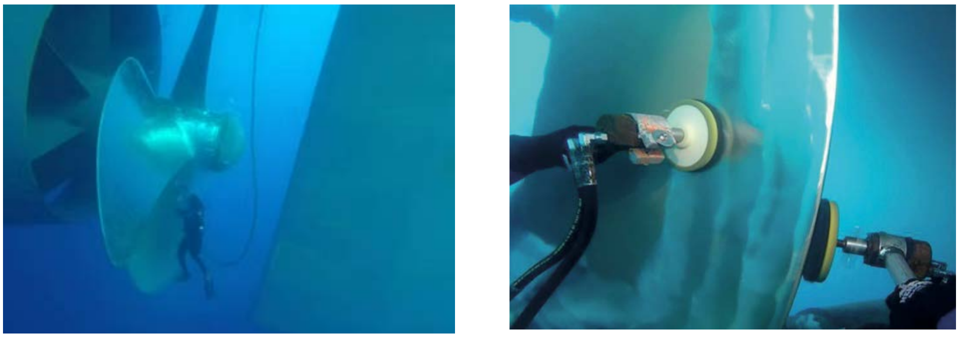
Technical Aspects (Handling and operation)
- Characteristics of hull area to be cleaned (shape, hull geometry)
- Cleaning speed
- Specificity of material/coating

Environmental Aspects
- Efficiency in removal of biofouling
- damage on antifouling coating
- Ability to capture and filter remains removed from the treatment area

Figure 2 Summary of available hull cleaning techniques

5.1. *Brush-based cleaning technology -mechanical forces*

Brush-based cleaning technologies are the most utilized technique in underwater cleaning of surfaces and commercial services are widely available. Brush-based cleaning involves applying mechanical and frictional forces to the surface with a rotary brush (single or multiple, man-held or robotized) to remove built-up material. The efficiency of rotating brush systems is seen to vary and be dependent on the operator (Floerl et al., 2010). Rotating brush systems can be less successful at removing mature assemblages that have grown over a 12-month period and contain robust calcareous organisms. Up to 50% of calcareous tubeworms, oysters, and barnacles were not removed by the rotating brushes and can in some cases remain undamaged and possibly viable. Brushes come in a variety of shape and sizes, where each can be tailored for a specific fouling situation on the flat hull or in the so called niche areas. Cleaning brushes can be changed according to the curvature of the surface and the type of biofouling. Divers utilize single brush machines to clean locations on the ship that the multi-brush machines can't reach, such as running gear (propellers, propeller struts, rudders), bilge keel areas, and sea chests (openings in the hull that operate cooling water). Fouling in these niche area locations can also be cleaned with high-pressure water jet wands (see Figure ***3*** and text below). One example of niche area is the propeller where cleaning is critical for maintaining fuel efficiency. Due to the difficulty of paint adhesion to bronze and hydrodynamic forces such as cavitation erosion, propellers are normally made of nickel aluminium bronze and not usually coated to repel fouling. As a result, they can foul quickly.



a) Niche area cleaning using brush

b) Niche area cleaning using waterjet

Figure 3. Niche area cleaning with both brush and waterjet system (ODFJELL)

Brush cleaning can be either non-abrasive or abrasive, due to variation in brush stiffness and severity of fouling.

5.1.1. Non-abrasive and abrasive brush cleaning

Slime, weak to moderately strongly adhered macrofouling, both soft and hard, and the upper leached layer of paint can usually be removed with soft brushes. Biofouling with strong adhesion, such as calcareous barnacles and lower valve oysters, will be difficult to remove with non-abrasive brushes. Further is non-abrasive cleaning not able to remove thick fouling growth such as dense aggregations of barnacles or calcareous tubeworms, or complex aggregations of hard and soft fouling. New and undamaged paint are not expected to be removed with non-abrasive cleaning, while lifting and delaminating paint flakes that already are loose are prone to be displaced (Gadd et al., 2011).

When abrasive brushing instead is used both soft and hard biofouling, the leached layer of the paint, and in some cases the outside surface of sound paint can be removed. The hardness and density of the brush bristles, application pressure, and the cart's transit speed across the surface would all influence the depth of coating removal. Delaminating and blistering paint would be removed, with the risk that larger flakes would be released from the primary delamination area. Cleaning can further hasten the progression of corrosion by rupturing blisters at the coating-steel contact (Gadd et al., 2011).

5.1.2. Different types of brush cleaning systems

The material of the brush varies with the fouling-type to be removed where nylon or polypropylene is used for slime, algae and soft- bodied organisms while stiffer plastics or steel brushes or abrasive pads to are used to remove hard, calcareous fouling. Different brush materials are also used on different hull materials where nylon or polypropylene are used on fibreglass, aluminium, steel and wood while steel bristles are generally restricted to use on aluminium or steel hulls (Figure 4-6)

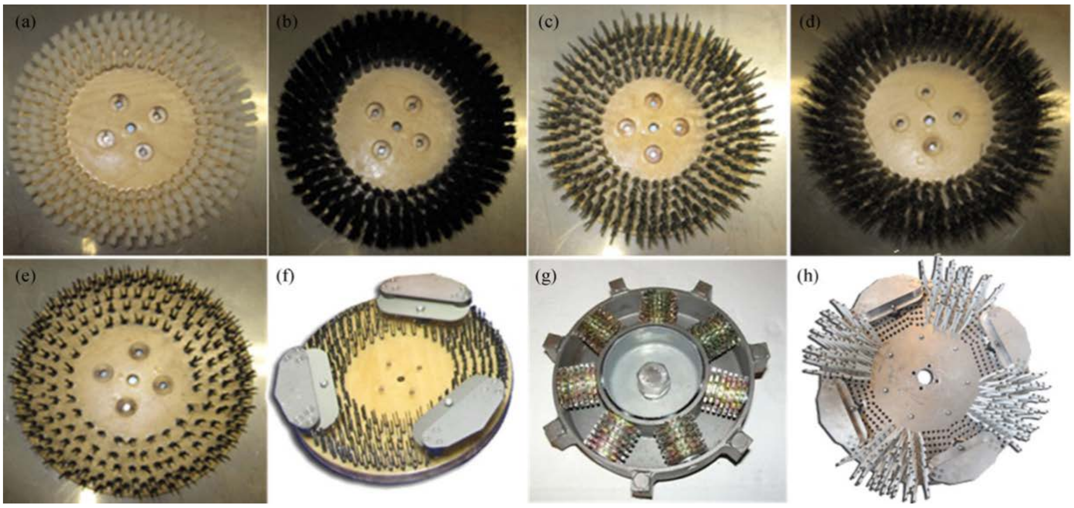


Figure 4 Brushes manufactured by Armada Systems, Inc.: a nylon brush; b polypropylene brush; c grit brush; d stainless steel row brush; e flat wire steel brush; f flat wire with cutouts and blades; g barnacle cutter; h rebuildable heavy barnacle brush (Song and Cui 2020)

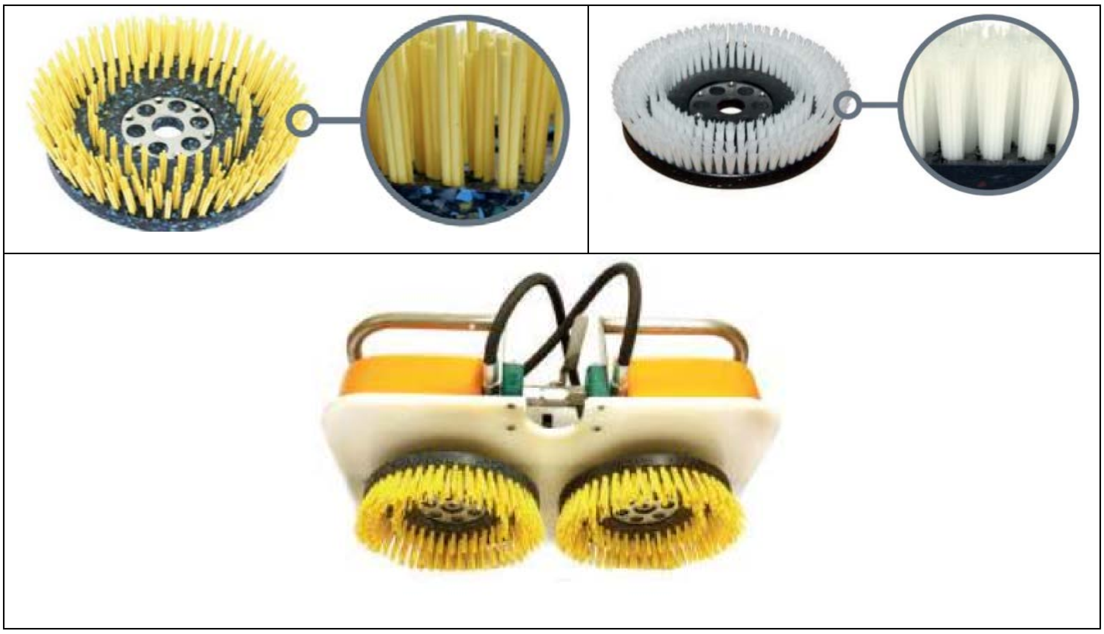


Figure 5. Hull cleaning machine with nylon brush (Cavitcleaner)

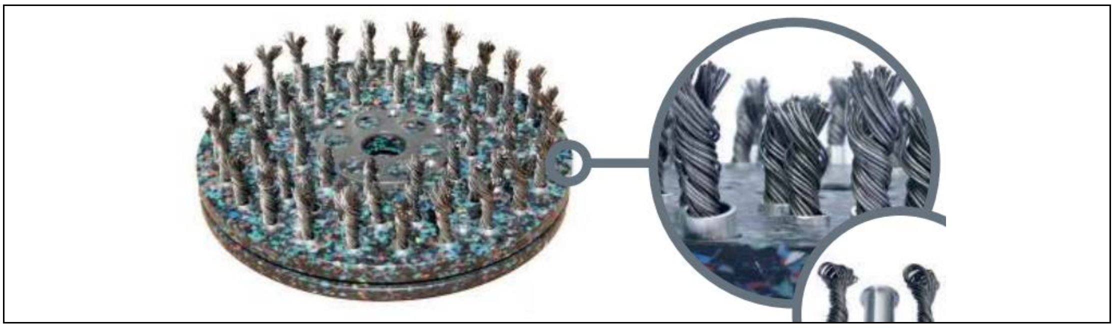


Figure 6. twisted wire for removing medium to heavy shell growth (Cavitcleaner)

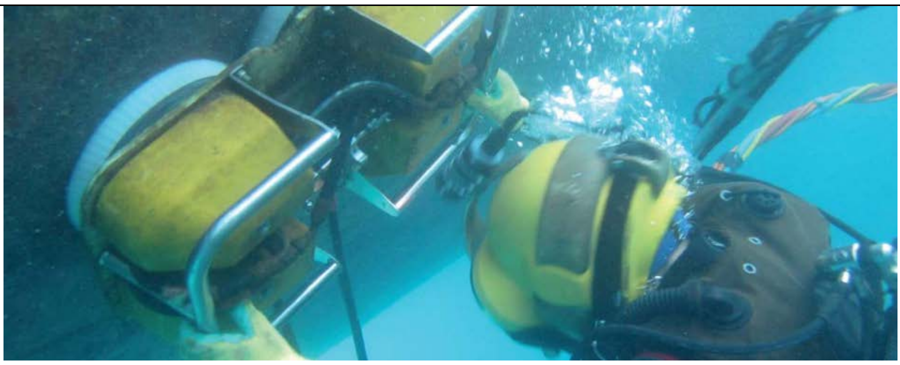


Figure 7. Powered rotary brush. The machine complements the Mini Pamper hull cleaning machine, for cleaning rudders etc, but equally capable of cleaning entire ships hulls (Cavitcleaner)

The rotary brush device can have different type of brush and bristle configurations (Figure 7).Figure 8 show a schematic of removing hard fouling (barnacles) from a surface using abrasive brushes. By use of different shape of the brush details hard fouling can either be removed more directly from the base or be "shaved" from the top to the base. Collection of waste material is possible in some of the brush systems.

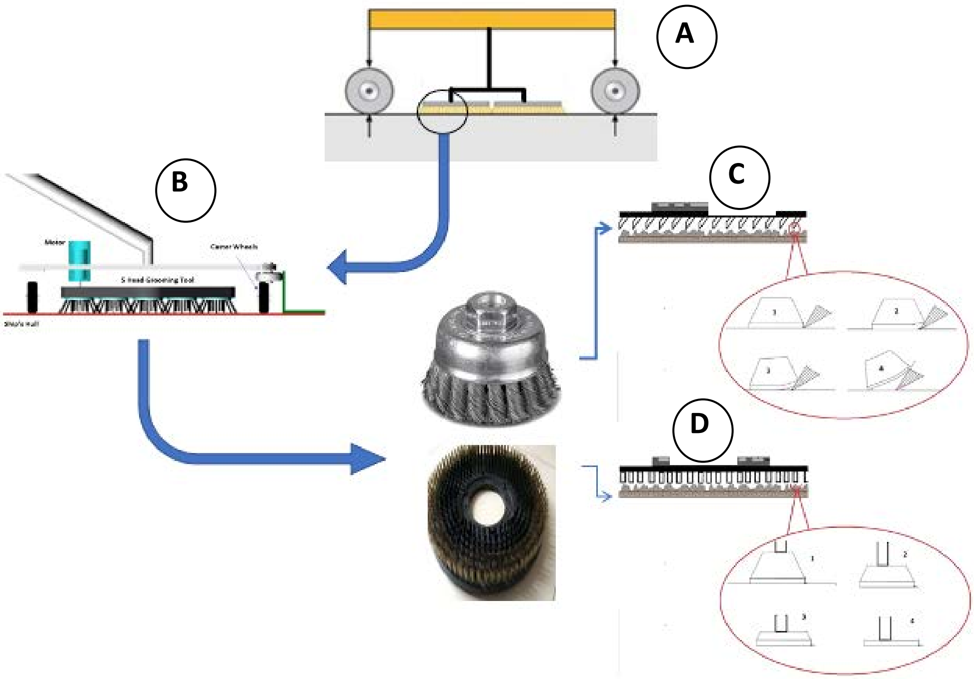


Figure 8. Schematic of removing hard fouling using abrasive brush with different tip options (Cavitcleaner)

5.1.3. Contactless mechanical systems

The principle of contactless- cleaning is to create a turbulent flow that causes the necessary shear force to dislodge the fouling. This method is believed to work if development of marine growth is due to lack of adequate "self-cleaning" water movement across a fouling-release surface. However, if the surface has lost the surface properties that reduce organism adhesion strength, a non-contact system will not clean effectively. For long-term static surfaces where there is vertical growth, the brush / blades can add a mechanical force to remove protruding growth. Example of devices that use contactless methods are from UNC International (Minipamper) and Franmarine (Envioncart). These devices can be operated in containment mode in which solids > 50 µm are removed in a first-stage, screen filtration, and particles down to 5 µm size in second-stage, cartridge filtration. Finally, the effluent can be UV- sterilised (MPI, 2015)

5.2. Water jet technology -hydrodynamic forces

To use high pressure water jets is a common and globally available method to remove biofouling. With the advancement of this technology, pressurized water jets for cleaning steel structures and removing biofouling growth from ship hulls are becoming more widely used. Also in ships niche areas, like for example sea chests, biofouling is removed using high-pressure water and diver-operated wands. Water jets are easily controlled by reducing or increasing the pressure as well as changing the distance and attack angle. The effectiveness of a water jet is determined by the surface material, water pressure, jetting angle, and distance from the cleaning surface (Figure 9). Jet nozzles have been created to allow for effective underwater cleaning. Water-jet providers often claim that there is no loss of antifouling coating for systems using water under high pressure. Protection of the coating could be achieved by directing the water jet at the hull surface at an angle < 90° (MPI, 2015). The fouling will then be removed via horizontal shear rather than a direct force applied perpendicular to the hull. However, there is risk for coating damage if the equipment is not used appropriately.

There are two types of water jet guns that can be used to remove fouling: cavitation and non-cavitation systems (Balashov et al 2011).

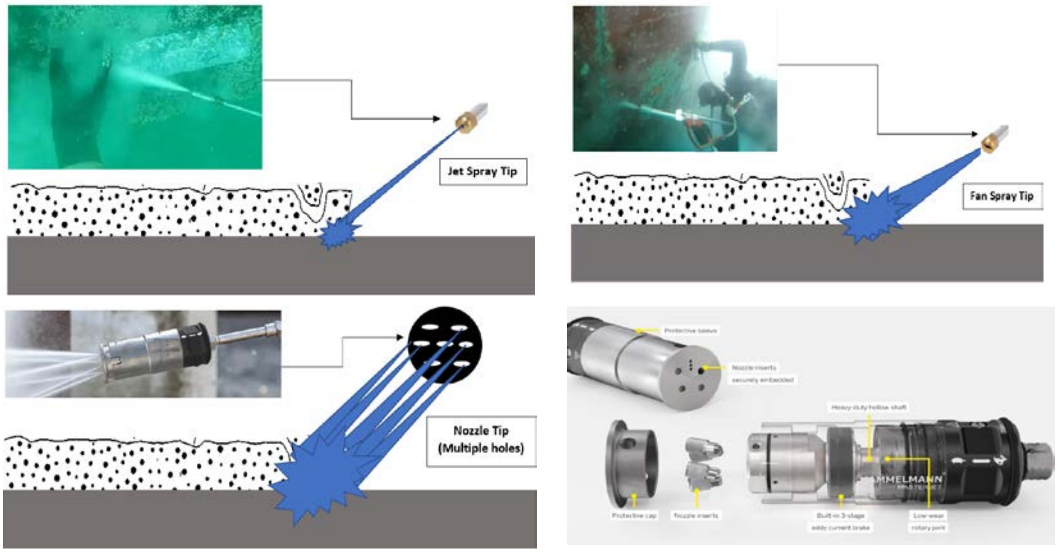


Figure 9. Various shapes of waterjet nozzles give different cleaning radius (Hammelmann)

5.2.1. Cavitating Water Jets

This technique employs cleaning nozzles that produce small gas and steam bubbles that burst when they come into contact with the treated surface. Lower water pressure (70-150 bar) can be utilized to generate high pressure (15104 bar) at the treatment point to remove built-up materials. Biofouling is removed during this process, which has a relatively fast cleaning speed (600-1500 m2 /h) depending on the kind of biofouling. Cavitation is an effective option for underwater cleaning because it involves the rapid creation and collapse of bubbles (vapor cavities) in a liquid. When high-pressure water passes through the cavitation nozzle, it creates a jet with millions of nano voids per second. When in contact with the surface, these vapor cavities implode, generating high-energy shockwaves that remove corrosion, dirt, debris, fouling, instable coatings, and other deposits from ship hulls as well as propellers, thrusters and rudders.

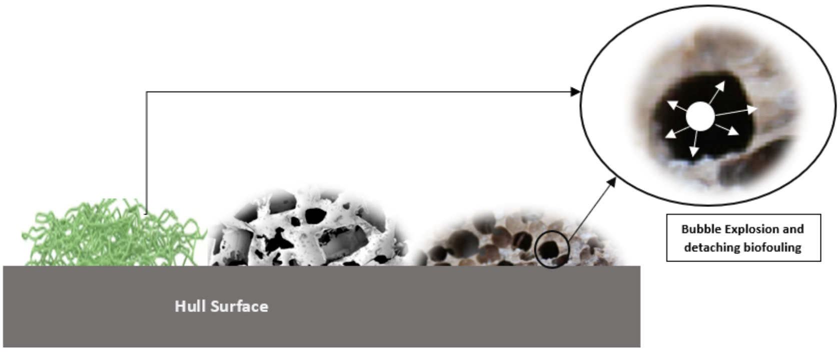


Figure 10. Cavitating water jet and role of bubble explosion to detach biofouling. Green turf schematic of algae and white schematic of animal with calcareous shell.

Figure 10 shows how waterjet cavity act on the surface to remove fouling. Air bubbles penetrate into the fouling colonies and after explosion, the fouling will separate from the surface. Sometimes due to high pressures or old damages on the surface, air bubble penetrate through the surface coating and cause damage to the surface (see *Figure 11*)

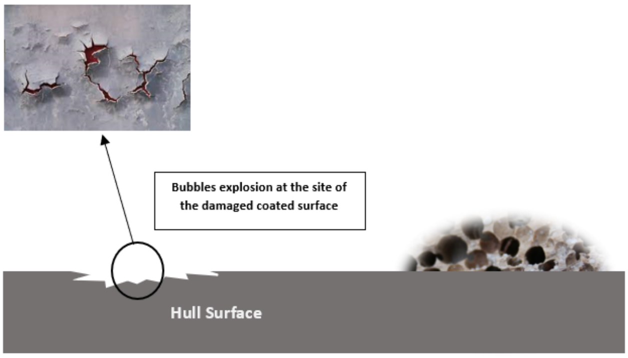


Figure 11. Water jet cavitation hull cleaning can lead to removal of surface coatings

Different types of water jet guns can be applied to remove various types of fouling (Figure 12). The most typical guns for underwater water jet hull cleaning contain an extra lance pointing the opposite direction of the cavitation lance. To counteract the reaction force of the cavitation explosion and reduce diver fatigue, the flow is divided between cavitation and retro lances.

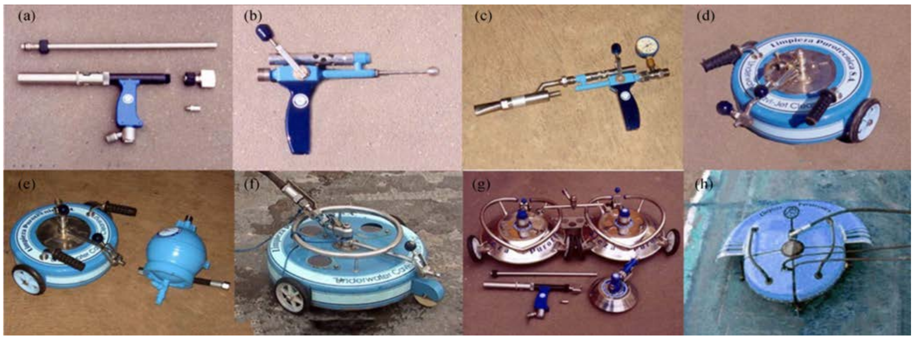


Figure 12. Jet nozzles and cleaning devices manufactured by Cavi-Jet International. a Multisprayer Cavi-Jet pistols. b Single-sprayer Cavi-Jet pistols. c Water-and-sandblasting Cavi-Jet pistols. d Small Cavi-Jet heads. e Cavi-Jet dampers. f Large Cavi-Jet heads. g Twin Cavi-Jet heads. h Cavi-Jet robots (Song et al 2020)

5.2.1.1. *Pressure and Flow*

Cavitation Guns are available for commercial vessels both to prepare underwater surfaces for coating and to remove corrosion, coatings and thick layers of fouling, oysters and barnacles with water pressures up to 1500bar (21,755 psi). In addition to the pressure also the flow determines how fast an underwater surface is cleaned. The flow will vary with type of lance used on the gun and will typically be in the range from 29 LPM (Liters Per Minute) up to 80 LPM or 120 LPM for professional applications (data from Zero Thrust guns). The tip of the water jet can have different number and location of nozzles as well as different directions of the flow (Figure 13)

Version: 2/4 nozzles

Version: 3/6 nozzles

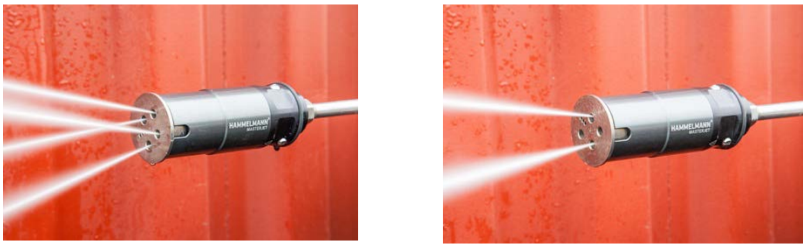


Figure 13. Example of water jet tips for underwater hull cleaning. Different nozzle configurations operate under pressure 1800-3200 bar and flowrate up to 60 LPM (Hammelmann)

5.2.1.2. *ROV Cavitation Cleaning*

Often Remotely Operated Vehicles, ROVs are used for cleaning. Figure 14 shows an ROV while cleaning a surface using cavitation method. Water pressures up to 300bar are used to remove layers of biofouling fouling (4,350 psi).

Figure 14. Waterjet cavitation cleaning with ROV *(DiveWise)*

5.2.2 Non-cavitation system

If the cleaning instead rely solely on the energy contained in the water (cold or hot), a higher working pressure (500-1000 bar) than in cavitation systems are needed to achieve the same cleaning performance (Figure 15). Low-pressure jetting systems will suffice to remove the slime layer from the treated surface effectively and safely (AML Oceanographic).

Figure 15. Non cavitation water jet system (left)[2], High-pressure water cleaning jet technology (right) (HullWiper)

5.3. Laser Cleaning Technology

In the last 30 years, laser technology technology has advanced significantly. In comparison to rotary brush and high-pressure water cleaning, laser cleaning technology, which employs laser radiation to scan the treated hull, has the advantages of faster surface cleaning, precise selective processing, and improved cleaning process management through feedback (Figure 16) (Song, 2004, 2020).

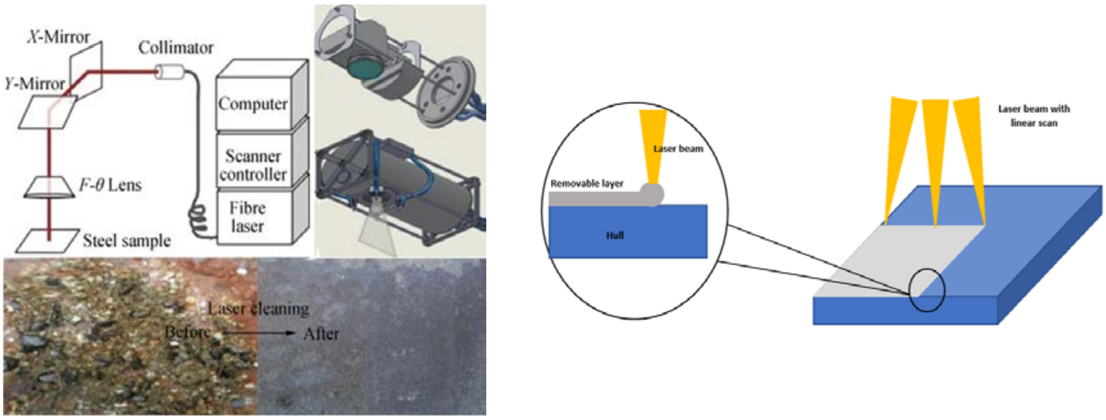


Figure 16 Laser scanning device, the designed ROV and results of underwater laser cleaning, (Song et al., 2020) Right technical implementation of laser cleaning

5.4. Underwater cleaning using encapsulation technology

Enveloping techniques can be an effective approach for killing biofouling on a vessel, regardless of the type and size of biofouling. This method relies on depriving biofouling organisms of resources like light, air and food in order to kill them. However, as the biofouling is not removed, encapsulation will not directly solve the issues of hull resistance and resulting fuel penalties. In addition, significant deficiencies and environmental impact have been observed, with some biofouling material and acids being released into the surrounding medium (Floerl, 2010). During encapsulation acetic acid was added to the entrapped water between hulls and plastic sheets to create a 5 per cent working concentration of acetic acid and vessels were left encapsulated for seven days. This treatment was found to be effective for killing the invasive tunicate *D. vexillum* on targeted vessel hulls (Pannell and Coutts 2007). A highlighted negative point is when the sheets were removed, the acetic acid and biofouling material that had dropped off the hulls were left to naturally degrade in the surrounding marine environment. Also, this method is difficult to automate (still relying on divers for wrapping) and can only be used for moveable convex surfaces (Floerl, 2010). Creation of anoxic conditions during encapsulation could potentially also lead to development of high concentrations of hydrogen sulphide (Woods et al 2007) and formation of insoluble copper salts that can impair antifouling performance. High concentrations of dissolved hydrogen sulphide can cause failure of antifouling coatings on vessel hulls due to reaction of sulphide with free copper released from the coating to form insoluble copper sulphide (In MPI 2015, John Lewis, ES Link Services Pty. Ltd., pers. comm.)

5.5. Underwater cleaning using ultrasonic technology

Ultrasonic cleaning technology has previously been utilized for a wide range of purposes and in the recent decade it has been explored for the hull cleaning industry. This method relies on producing several bursts of ultrasonic radiation in a variety of frequencies at the same time. This energy creates a pattern of positive and negative pressure that alternates. In a phenomenon known as cavitation, the alternating pattern forms small bubbles during moments of negative pressure and implodes them during periods of positive pressure. The implosion creates a micro-jet movement that not only cleans the undersea surface, but also resonates with and destroys microorganisms like algae. For barnacles and other marine organisms that feed on algae this treatment can lead to a slower growth rate.

To clean underwater surfaces with ultrasonic, a number of transducers are arranged to face the surface to be cleaned (distance 2-5 m), and as an industrial product, there are transducers that are simply bonded to the inside of the hull's outer skin, with no hull penetration required (Albitar, 2015, Capelo, 2009, Aldrich, 2020). Ultrasonic cleaning is considered an environmentally friendly process as it has no effect on the treated surface (Floerl et al 2010)

5.6. Underwater negative pressure (suction) technology

Underwater suction devices consist of a vacuum head that collects and contains biofouling materials removed from a target surface using an underwater suction vacuum pump with a filter system. This method has in tests seen to remove 80% of biofouling material (Floerl et al 2010). The device appears to be successful in removing soft-bodied organisms that extend beyond their attachment surface, although it is ineffective at eliminating organisms that are firmly attached (barnacles, tubeworms and cementing bivalves). Additionally, clogging of the nozzle or suction line is a regular issue with the system (Floerl, 2010)

5.7. Underwater cleaning using heat treatment

Thermal shock (70°C) by employing heated sea water in a sealed section of the surface, can be used to kill soft biofouling on underwater surfaces. The treatment's effectiveness is believed to be long-lasting because it destroys not only the algae but also the spores, which will prevent the re-establishing process (Floerl et al 2010). For example the HISMAR robot is recommended that the heat treatment be repeated at regular intervals (every 4-6 months) (Floerl, 2010, Narewski, 2009). The heat treatment can applicable for niche areas but might require techniques like flame torches (Wotton et al. 2004)

In the Hull Surface Treatment (HST) www.tcmarine.com.au/HST, a hull-mounted containment device pumps hot salt water into contact with the marine fouling. It's made to get rid of algae and heat is applied via a square applicator with surrounding soft skirt to contain the heated water and prevent loss of material before it is treated. In this method, dead material can either fall off the hull following treatment, or it can be stuck to the surface until high enough flow speeds are reached for its removal. As biofouling is considered to be killed by the method and if it can be verified that the biofouling is rendered non-viable the biosecurity risk is low. However will temperature and period of exposure required to kill them vary between species. Organisms with thick, calcareous shells, for example, may be insulated from heat. The amount of fouling may also alter the effectiveness of heat treatment.

5.8. Ultraviolet technology

UV light irradiation is widely used for water disinfection, and currently also investigated as a biofouling pre-treatment technique. Investigations of this technique has revealed that, in addition to targeted wavelengths, UV spectrum, and UV dose, the posttreatment incubation period affects biofilm prevention. UV irradiation is a non-chemical method of biofouling control. UV light disinfection inactivates suspended cells. Biofilm microorganisms does however differ from their suspended counterparts in terms of physiology, metabolism, and disinfectant and antibiotic resistance. Further research is needed to discover and improve the aspects that influence biofouling management when UV is used as a pre-treatment technique (wavelengths, doses, and continuous or in cycles exposure). It has been demonstrated that UV has no residual effect after irradiation and that biofilm control increases with higher UV doses and higher levels of suspended cell inactivation (Albitar, 2016, Lakretz, 2010).

6. Advantages and disadvantages of brush and water jet systems

Information found in literature on methods and devices for reactive cleaning were divided into technical and environmental aspects. The technical aspects include availability, specificity of area to be cleaned and cleaning speed and refer to the possibilities and limitations by the hull cleaning companies and the equipment used. The environmental aspects include;

i) Efficiency in removal of biofouling refer to what degree the equipment is capable of removing biofouling in different areas of the ship. This is in interest of ship operator as rough surface will impact drag but also in interest of environmental authority as biofouling can include invasive species.

ii) Impact on antifouling coating refer to documented gentleness or damage to the paint (for this section also see chapter 8 impact on paint where lab-scale tests has measured the removed paint thickness and biocide amounts). This is in interest of ship operator to avoid unnecessary wear of paint and in interest of environmental authority as this removal will lead to production of chemical waste

iii) Capture efficiency refer to collection and filtering of biological and chemical waste to avoid release in the sea. This is in interest of environmental authority as capture will limit release of biological and chemical waste

The advantages and disadvantages for the different technologies brush and water jet are summarized in **Table 5**. In summary the pros and conc for brush and waterjet are quite similar. Brush system can be used both on the vertical sides of hull (brush carts) and in niche areas (handheld brushes). Likewise, water pressure can be used both on vertical sides of hull and in niche areas (water jet wand). Therefore is handling/operation not a limitation and even if niche area cleaning can be challenging for larger equipment then smaller devices or tools can be used instead. Efficiency in removal of biological material is dependent on fouling and the systems do not fully remove all fouling. More impact on paint has been seen for brush systems but they have also been available and used for longer time. Capturing options are available to various degree and can be added when regulations require capture of waste. To find objective evaluations of commercial devices are difficult due to patents, confidential information and the competition situation between different companies and methods used.

Table 5. Summary of pros and cons of brush based and water jet cleaning.

Technology	Brush based	Water jet
Technical Aspects		
Technology's availability	Worldwide, available in large hull cleaning hubs like: Gibraltar, Singapore, Gulf of Mexico and UAE	Worldwide, available in large hull cleaning hubs like: Gibraltar, Singapore, Gulf of Mexico and UAE
Specificity of area to be cleaned (shape, hull geometry)	Clean flat surfaces (brush karts) and niche areas (handheld brush devices)	Clean flat surfaces (water jet device) and niche areas (water jet wands)
Cleaning speed	2000 m2/h	2000 m2/h (max 3000 m2/h)
Environmental aspects		
Efficiency in removing biofouling (Removal)	(pros) High, Brushes with different stiffness available (cons) Possible damage of organisms due to mechanical forces	(pros) High, Different pressure of jets can be used (cons) Possible peeling of "paint and organism -complex"
Impact on antifouling coating	When soft coating with hard fouling the risk for mechanical damage to coating is large	When aged or damaged coating there is risk for peeling of coating flakes
Ability to capture the remains removed from the treatment area (Capture)	Yes, with addition of capture module/system	Yes, with addition of capture module/system

7. Review on how different hull cleaning techniques remove and/or capture biological material.

7.1. Risk of release of biological material during cleaning

All cleaning methods risk to include unintentional dislodging of fouling organisms by divers operating equipment or by parts of the equipment itself, such as hoses and ropes (Hopkins and Forrest 2008; Morrisey and Woods 2015). Post-cleaning surveys showed that cleaning significantly reduced the cover of fouling organisms on the vessel hull but several species across samples persisted and in-water cleaning activities could also sometimes overlook patches (Davidson et al. 2008). Field trials of two vessels cleaned with commercial hull cleaning equipment show that no specific organisms groups are left after cleaning but rather certain areas are not cleaned (Tamburri et al 2020). Further can the removal and percent of biofouling cover left vary with stage of organism. When the fouling rating include adult stages which can reproduce and set larvae they are of higher biosecurity concern. The biosecurity risk were identified also during capture and filtration for both brush and waterjet operated systems (MPI 2015).

The biofouling consists of many different species (described in chapter 2) and they can all potentially be detached during the hull cleaning operation. Recommendation on biological data to be collected if to monitor hull cleaning facilities has been developed by (Woods et al 2007) and include both the organisms that are removed from the hull and smaller stages that can be present in the liquid effluent. The data suggested to be collected are: number, size, % intact organisms, % damaged/fragmented alive, % dead, time out of sea and degree of dryness (Table 6)

Table 6. Biological data to be collected at hull cleaning facilities (Woods et al 2007)

Group	*Count*	*Size of organism or fragment*	*% intact alive (incl. weight)*	*% damaged/ fragmented alive*	*% dead*	*Time out of sea*	*Degree of dryness*
1. Organisms removed from hulls							
Barnacles	X		x	x	x	x	
Bivalves	X		x	x	x	x	
Encrusting bryozoans	X	x	x	x	x	x	X
Erect bryozoans	X	x	x	x	x	x	X
Hydroids	X	x	x	x	x	x	X
Tubiculous polychaete worms	X		x	x	x	x	X
Sponges	X	x	x	x	x	x	X
Colonial ascidians	X	x	x	x	x	x	X
Solitary ascidians	X	x	x	x	x	x	X
Macroalgae	X	x	x	x	x	x	X
Other taxa	X	x	x	x	x	x	X
2. Liquid effluent	Count	Mitochondria intact?	% damaged				
Larvae	X	x	x				
Eggs	X	x	x				
Spores	X	x	x				

7.2. Risk if biology not captured and viability

If the detached fouling organisms, including reproductive propagules, not are retained, they can either settle to rocks or nearby structures or become more widely dispersed by currents (Hopkins and Forrest 2008). It can however be difficult to include an assessment of propagules (eggs and larvae) released from adult organisms during in-water hull cleaning, as it can be hard to distinguish these from other sources of propagules in the water column. Further it can be difficult to tell if material removed from the hull had recently released gametes.

Cleaning systems with a retaining function can collect a high proportion of defouled material (>90%) (see further in chapter 10), however, lost material can include a range of viable taxa as fully intact organisms or viable fragments. The amount of lost material may be small but when considering the surface area of a fouled commercial vessel the likelihood of release and establishment of invasive species is not negligible (Hopkins and Forrest 2008; Hopkins et al. 2010; Morrisey et al. 2013).

7.3. *Viability measures*

Guidelines on viability determination has for example been developed by National Institute of Water & Atmospheric Research, New Zeeland (NIWA) with indicators for viable and non-viable individuals, based on damage to shells and other structures (Woods et al 2007). Checks are conducted for active movement and/or feeding but it can be difficult to determine if a biofouling organism is alive, moribund, or dead following treatment. In addition can many marine species (particularly macroalgae and clonal invertebrates) regenerate from very small fragments. A precautionary approach to the viability assessments can therefore be applied such that, unless an organism could be confidently determined to be non-viable (dead), it is classified as being viable. Vital staining for mitochondria (Janus Green) can be used to stain exoskeleton of crustaceans, the bodies of nemertean worms or the cells of filamentous algae (Woods et al 2007).

Viability of organisms sampled from vessels cleaned during winter and summer were examined in New Zeeland by Woods et al 2007. In-water removal with paint scraper and soft cloth did cause fragmentation and damage to hard bodied and soft-bodied taxa. A higher percentage of soft bodied organisms (approx. 70%) were however undamaged compared of the hard-bodied group where only about 25% were undamaged. (Figure 11a, Woods et al 2007). Due to the large variation in the number of specimens examined on different vessels in different operations, viability analyses could not be carried out on individual taxonomic groups (for example, barnacles, bryozoans, etc.). Number of organisms or fragments of solid fouling found during two hull cleaning projects in New Zealand (37 vessels including both private sailing and commercial vessels) shown that the most common groups were Polychaetes, tubiculous, (9045 organisms or fragments), Barnacles (3490), Bryozoans (2451), Crustaceans, motile (1708) and Bivalves (1220) followed by Ascidians (872), Anenomes (249), Hydroids (210), Flatworms/Nemerteans (126), Algae (132), Polychaetes, errant (86), Sponge (44), Molluscs, motile (17) and Fish (1) (Woods et al 2007)

8. Emissions of contaminants and paint particles during hull cleaning events

Today, the most common strategy to prevent attachment of fouling organisms is to coat the hull with biocidal antifouling paints (Amara et al., 2018). Even if these products can be efficient for several years the paints also leach toxic compounds affecting non-target species and marine ecosystems. Currently over 1000 unique antifouling paints are registered on the market (Paz-Villarraga et al., 2022) where most coatings (76%) contain copper (as cuprous oxide) as biocide to prevent fouling.

8.1. *Paint layer removal with different techniques*

The amount of paint that is removed during hull cleaning vary dependent on paint type and the organisms attached. There are however not many studies published where the coating thickness removed has been investigated. In a review report from 2013, Morrissey et al. (2013) concluded that the coating thickness removed by brushing can be in the range of 12.5 to 75 µm and that industry advice is that the most aggressive brushing methods, using rotating steel bristle brushes, can remove 50-100 µm, whereas less aggressive techniques using nylon bristle brushes can remove less than 25 µm or just the biofouling. In the report by Morrisey et al. (2013), and attempt was made to also calculate the input of copper per cleaning event. Two different scenarios were developed: light and aggressive cleaning. In the light cleaning scenario, 85 to 650 µg/cm^2 was assumed to be released per event, while the aggressive cleaning would result in a higher input, 1994 to 4225 µg/cm^2. Assuming that a ship has a total coated hull surface area of 3850 m^2 (see hull surface assumption in table 7), would imply that approximately 163 kg of copper could be emitted to the marine environment during an aggressive cleaning event (assuming the higher input, i.e. 4225 µg/cm^2), assuming no capture of hull cleaning waste. However, it must be emphasised that the reported thickness removal is mainly derived from expert elicitation and not from real sampling during an actual hull cleaning event.

8.2. Input of biocides and metals from in-water cleaning with no capture of hull cleaning waste

Biocides and metals can reach the marine environment during hull cleaning activities either as paint particles (typically defined as fractions >0.45 µm) or as dissolved species (defined as <0.45 µm). In a recent study by Soon et al (2021a), in-water hull cleaning performed on four ships were monitored, where cleaning effluents were collected and pumped to the shore. The cleaning was performed by divers using a specially designed brush with bristles made of nylon. The total hull surface area of the ships ranged from 140–3850 m^2. The effluent was collected in containers and analyzed for total suspended solid (TSS), particle size distribution, and dissolved metal concentrations. The result showed the release of TSS to range from 12.9 to 37.5 g/m^2 where Fe was the most abundant metal (ranged from 38,600 to 217,000 µg/g) followed by Cu (ranged from 1970 to 64,600 µg/g) and Zn (ranged from 1520 to 38,200 µg/g). Based on the results from Soon et al. (2021a), a low and high emissions scenario was developed in this report to estimate the total load of Cu and Zn from hull cleaning activities and to compare the loads with the continues release of Cu and Zn from antifouling paints. As shown in **Table *7***, the largest input of Cu is from paint particles (248 µg/cm2 in high scenario) as compared to the dissolved input (5.76 µg/cm2, high scenario). In the high scenario, the ship is expected to have a painted hull surface area of 3850 m2, the total input of copper per cleaning event was estimated to be nearly 10 kg. This can be compared with the continues input of copper from a ship painted with a copper-based coating which is on average 24.5 µg/cm2/d (Jalkanen et al. 2021). Using the same hull surface area (3850 m2), would result in a daily release of copper of 0.94 kg, i.e. one order of magnitude lower than the input from a cleaning event. Another way to describe this is that the input of Cu from one cleaning event is equal to 10 days of continuous leaching from the same ship, assuming that the ship is coated with a typical copper-based coating. Hence, a capture system that capture the paint flakes emitted during a cleaning event would result in a large reduction of copper to the marine environment.

For Zinc, the pattern is similar, i.e. the total input is mainly from paint particles. In the high scenario, the total input of copper per cleaning event was estimated to be 7.7 kg **(Table 8**). This can be compared with the continues input of zinc from a ship painted with a copper-based coating which is on average 4.4 µg/cm2/d (Jalkanen et al. 2021). Using the same hull surface area (3850 m2), would result in a daily release of zinc of 0.17 kg, i.e. 45 times lower than the input from a cleaning event. Another way to describe this is that the input of Zn from one cleaning event represent 45 days of continuous leaching from the same ship, assuming that the ship is coated with a typical copper-based coating.

Table 7. Scenarios and assumptions used to calculate copper (Cu) input to the marine environment during a cleaning event with no capture of hull cleaning waste. Hull surface area, total suspended solid (TSS), and Cu concentration in the TSS and as dissolved fraction was derived from Soon et al. (2021a).

Scenario	Hull surface area (m2)	TSS (g/m2)	Cu in TSS (µg/g)	Cu input from TSS (µg/cm2)	Cu input, dissolved fraction (µg/cm2)	Total Cu input, (µg/cm2)	Total Cu input per cleaning event (g/event)
Low	140	12.9	1970	2.5	0.96	3.46	4.8
High	3850	37.5	64,600	242	5.76	248	9500

Table 8. Scenarios and assumptions used to calculate zinc (Zn) input to the marine environment during a cleaning event with no capture of hull cleaning waste. Hull surface area, total suspended solid (TSS), and Zn concentration in the TSS and as dissolved fraction was derived from Soon et al. (2021a).

Scenario	Hull surface area (m2)	TSS (g/m2)	Zn in TSS (µg/g)	Zn input from TSS (µg/cm2)	Zn input, dissolved fraction (µg/cm2)	Total Zn input (µg/cm2)	Total Zn input per cleaning event (g/event)
Low	140	12.9	1520	2.0	2.95	4.95	6.9
High	3850	37.5	38,200	143	57.6	201	7700

Other laboratory studies have shown the total input of copper to be in the range of 12 and 63 μg Cu/cm^2/ cleaning event, depending on cleaning method and type of coating (Earley et al 2014). In the study by Early, a soft-pile carpet (representing best management practice (BMP)) and a medium duty 3M™ pad (representing a more aggressive non-MBP method) was used as cleaning methods.

8.3. Paint fragments/ particles removed /Microplastics

During hull cleaning, the paint layer thickness will decrease but also paint flakes or paint particles can detach. The size of the paint flakes generated during hull cleaning vary with cleaning method and device used, paint type and age and size can vary from a few micrometer to cm (Bohnander 2009, Turner 2010 and Soroldini et al 2018). In a recent study by Soon et al (2021a), the most common size fraction of paint particles after brush-based cleaning was 8-10um. The spread of paint particles will be affected by factors like size, form and density and the particles can be found at large distance from the source (Soroldoni et al 2018). The faith of the fragments will vary with size where larger paint flakes can for example get trapped in sediment where they can affect marine organisms (Turner et al 2008). In a recent study from German Bight, on the composition of microplastics in the marine environment, it was showed that a significant fraction of particles originated from ships antifouling paint (Dibke et al. 2021). In the article a close relation to marine (antifouling) coating particles, i.e., abrased chlorinated rubber-, acryl-styrene-, and epoxide binder-containing particles, was hypothesized to be the main microplastic source, outweighing land-based sources.

8.4. Handling of Waste

In Sweden, the handling of waste material derived during hull cleaning operations is regulated through the waste regulation (Avfallsförordningen 2020:614). If a hull cleaning operation is conducted within a harbour, the hull cleaning operator (verksamhetsutövaren) is obliged to classify the waste material. If a cleaning operation is conducted on a ship hull coated with biocidal antifouling paints, the waste material will most likely be classified as hazardous waste under Avfallsförordningen as the waste should be classified with the code 16 03 05 “Organic waste that contains hazardous substances and that according to 2 kap. 3 § shall be considered as hazardous waste”. If so, the requirement is that the waste/sludge is handled in accordance with the waste regulation and taken to an approved waste facility. In the port of Malmö, hull cleaning operations on commercial ships have only been allowed to be conducted on biocide-free antifouling systems. However, since the paint may also contain plastic components, the regulatory authority (tillsynsmyndigheten – Malmö municipality) argued that the waste material should be treated as organic waste under the code 16 03 06 “Other organic waste”. In practice, this led to that the hull cleaning operator send the waste to a waste company.

9. The cleaning process and sampling during cleaning

9.1. Cleaning process and steps included

This chapter explain the process for the capture and handling of removed material in connection with in-water cleaning. Manned or unmanned cleaning systems can be divided into the main parts: Control, Cleaning, Storage, Separation and Treatment units. An in-water cleaning system consist of a combination of the units shown in Figure 17. In the control unit, remote control of ROVs, communication devices with divers, video displays, etc. are housed.

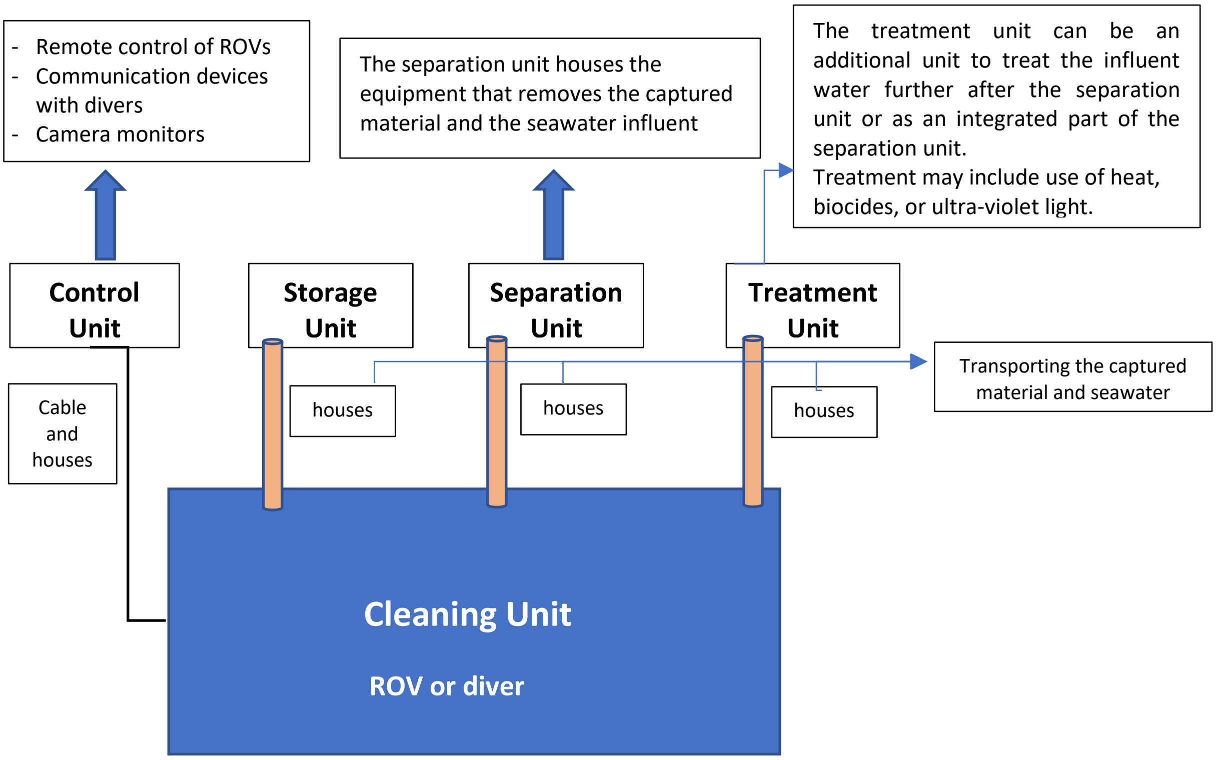


Figure 17. Schematic figure of a cleaning system consisting of units for Control, Cleaning, Storage, Separation and Treatment

Cleaning of the hull, propeller, and/or specialized regions is done with the cleaning unit. The cleaning unit can be operated either by a diver or a remotely operated vehicle (ROV). In some cases, the cleaning unit collect material and treat it directly while in other cases the caught debris and seawater can be transported from the cleaning unit to a storage container, separation and/or a treatment unit. Some cleaning systems pump the debris and seawater gathered into a storage unit, such as a barge or a tanker. The caught material and seawater in the storage unit can than further be piped to the treatment and separation unit (s). Cables will also be used in the system both for communication and to provide power to the ROV or other cleaning technology.

9.2. Sampling procedures during cleaning to control water quality

To evaluate the consequences of in-water cleaning on local water quality a series of biofouling and water quality samples are suggested to be taken and analyzed (Woods et al 2007). This sampling has been suggested both for cleaning of hull and niche areas. To sample the biological waste material, the samples can be divided into biofouling samples and water samples (Figure 18).

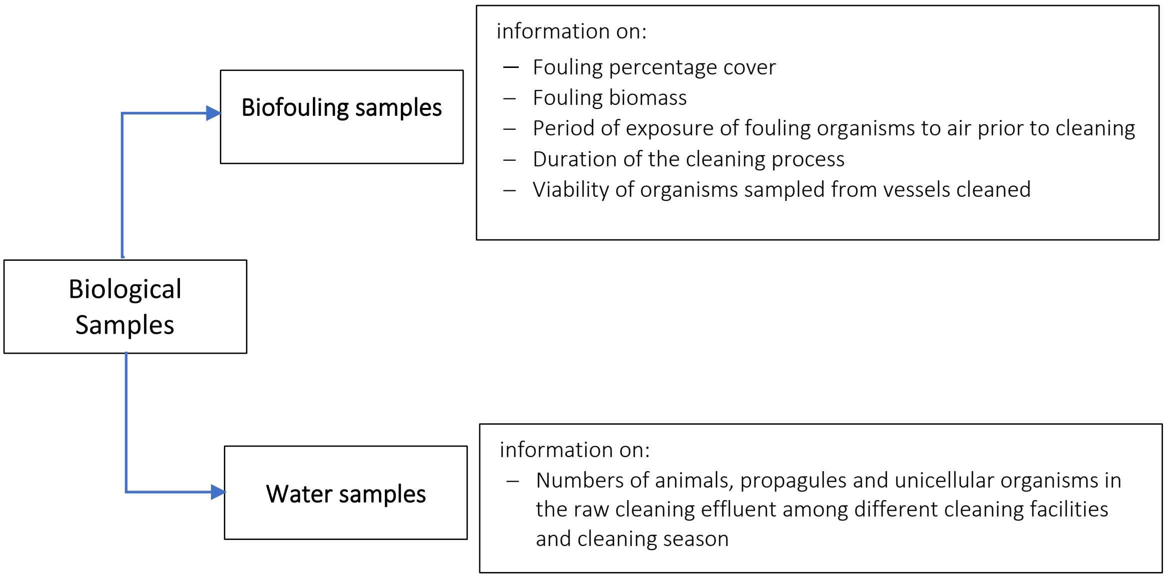


Figure 18. Sampling of the biological waste material

The type of biofouling and waste material in samples are determined in laboratory. A general setup for the collection of water samples during an in-water cleaning test at the unit and at distance from the activity are presented in Figure 19.

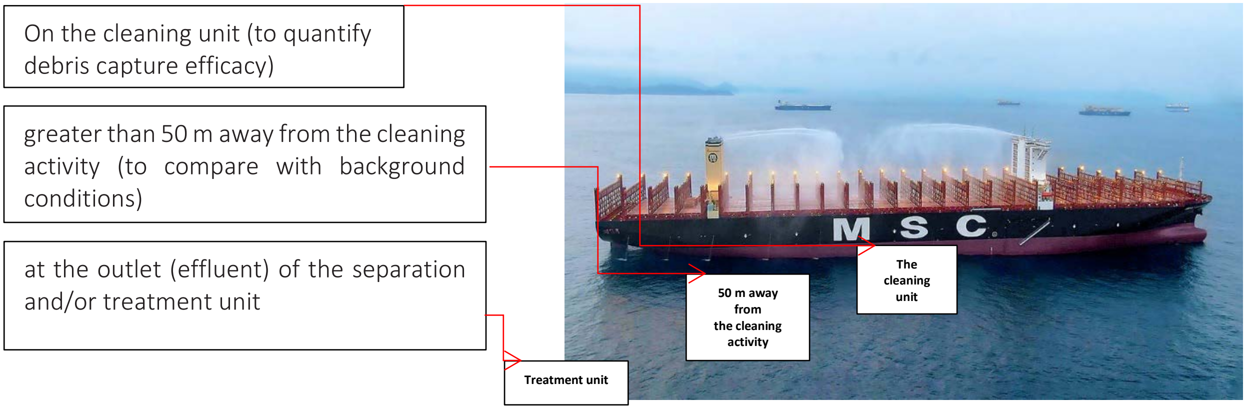


Figure *19*. Setup for collection of water and wastewater samples during hull cleaning

Sampling design for testing biofouling removal and water quality has been suggested for example by Tamburri et al 2020 (biofouling and water quality), Jones and McClary et al 2021 (water quality) and Soon et al 2021a (biofouling and water quality). Figure 20 show overviews of the biofouling and water quality testing sample design. In a designated Test Area of the ship, quadrats for taking biofouling samples are shown. In the quadrats biofouling are measured before and after the cleaning event and compared to uncleaned control areas. Water quality samples were taken at several shipside stations, 50 meters (S1), 5 meters (S2), and 0.5 meters (S3), away from the cleaning event. At station S4 a sample was taken to capture influent when pumped from the cleaning unit to the dock's processing container. The effluent released from the processing container was sampled at Station S5. Three further background water quality samples were taken (Tamburri et al, 2020). Water quality samples during cleaning can also be taken as illustrated by Jones and McClary 2021 (Fig 10b) where samples are taken from 3 sites of the ship (bow, amidship and stern) and at three stations around the niche areas.

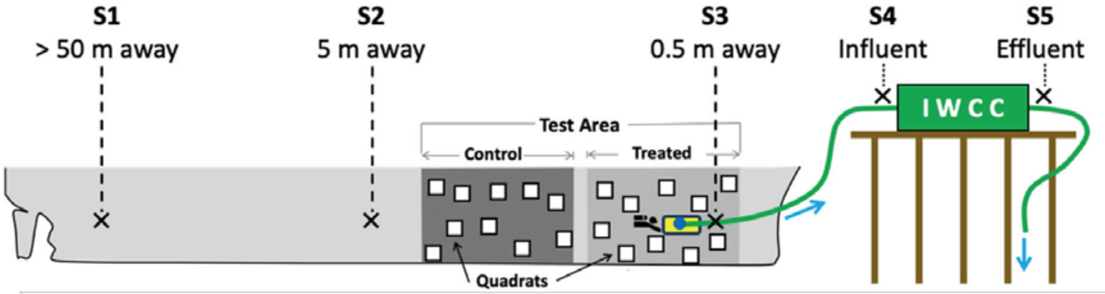


Figure 20 Overview of a suggested sampling design for biofouling and water quality testing (Tamburri et al, 2020)

In a recent study (Soon et al 2021a) the following method was used for biofouling sampling. Divers estimated the area subjected to cleaning using quadrats (50 cm x 50 cm), with six quadrats used for three ships and eight quadrats used for one ship. To gather samples representing the complete hull surface of a ship, quadrats were uniformly placed along the water line at the front, center, and back of the ship hull. Divers cleaned the hull surface within each quadrat until apparent biofoulings were removed with a specifically designed brush (nylon bristles, 25 mm and 1 mm, 30 bristles/cm2) linked to a tube (= 35 mm). The brush-tube-diaphragm pump system was used to pump all waste generated during the in-water cleaning phase to the shore (Soon et al, 2021a).

10. Capturing systems

The handling of hull cleaning waste differs dependent on operator and cleaning system. In some cases the waste (including both solid and liquid phase) are discharged directly into the sea (ie no treatment). The solid material can also be separated from the wastewater and the liquid, either filtered or unfiltered, are discharged into the sea. If capture of waste is performed it can be conducted either by the cleaning device or in a system that is connected to the Port Reception Facilities. The waste from cleaning can further be stored in facilities or transferred into the municipal treatment system (see below for description of options)

The resulting wastewater from hull cleaning operations consists primarily of sea water, various sorts of marine growth (from algal slime to hard fouling organisms) and anti-fouling paint particles. There is a biosecurity risk associated with containment, capture and extraction of the biological waste material removed and a chemical contamination risk connected with antifouling paint particles. The risk will be dependent on efficacy of material capture during cleaning and integrity of the pumping system that is used to transfer waste to the treatment or disposal system. There are different options to handle the waste from hull cleaning. The waste can either be treated within the cleaning system or transferred to the shore for treatment as illustrated in Figure 21.

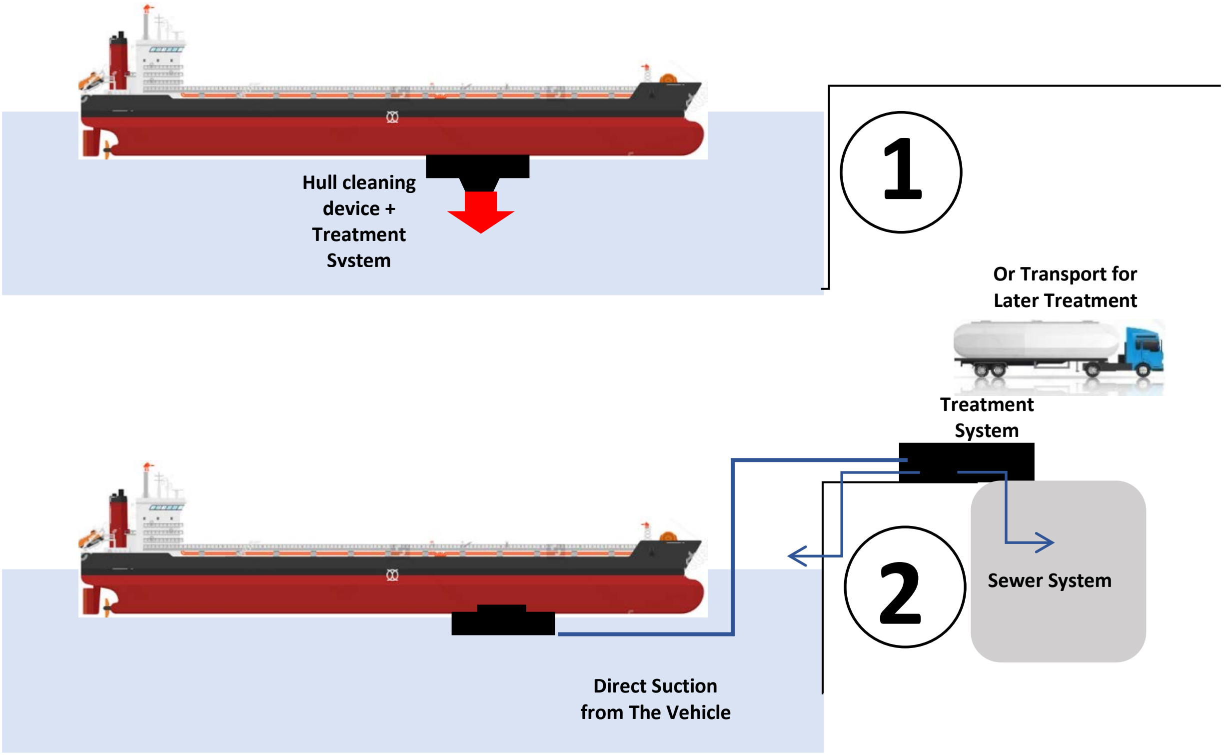


Figure 21. Options for collection and treatment of waste

In option 1 (Figure 21) the waste treatment system is attached directly to the cleaning vehicle. In this setup the cleaning vehicle would not need external piping system (ie less disturbance and potential damage to adjacent ship areas caused by piping). In option 2 (Figure 21) the waste is transferred from the cleaning device to shore, either to a pierside processing plant (and treated water can be transferred back to the sea) or transported to the sewer system or truck for later treatment. Another potential solution is that the hull would be cleaned with equipment without capture and instead using a tarp that enclose the waste which is pumped ashore or to barge for treatment.

The volume of hull cleaning waste that is generated can be estimated from size of ship and amount of fouling. In a study based on 31 hull cleaning reports from the port of Algeciras, Spain, the range of hull cleaning waste collected varied between 10-90 kg, with average amount of 30 kg (per cleaning). With use of diving reports giving biofouling composition and percentage cover the fouling-composition was found to be 28% hard fouling and 72% of soft fouling. The hard fouling included acorn barnacles, gooseneck barnacles, mollusks and tubeworms while the soft fouling included brown, green and red algae and microfouling (slime) (Barcenas 2018). The concentration of heavy metals (mainly copper and zink) will be dependent on the type, status and age of antifouling paint (see chapter 8).

10.1. Waste capture with suction device

To assess containment and waste capture of two systems designed for hull and niche area cleaning, Jones and McClary (2021) used the tracer dye Rhodamine WT Red. The area of effective capture were estimated by adding dye at increasing distance from the system. The Hull Cleaning System tested were found to effectively entrain dye from 5-10 cm distance from the cleaning head and occasionally from 20-25 cm distance. At further distance from the cleaning head 45-50 cm the dye was not entrained by the hull cleaning system. The niche area cleaning system were seen to entrain dye from 5-10 cm but not from 25 cm distance. The niche area device was also tested for leakage of dye from the device and no leakage were detected. The results indicate that the suction from the hull cleaning system were sufficient for retention of removed material. A great concern were however that the system had to be stopped in order to be able to perform the test, which could have major impact on the results. Also, when using the niche area cleaning device, dislodgement of biofouling was found during setup and attachment.

Capture systems can be coupled to the device in both brush-based and waterjet technologies (Figure 22)

Figure 22. Example of commercial cleaning device with capture.To the left brush with suction propeller and sealing (rubber edging) . To the right high pressure waterjet with magnetic attachment (Fleetcleaner)

10.2. Pier side treatment

Pierside treatment of waste can be used for both brush based and water jet based cleaning and the set-up varies between companies. Figure 23 depicts a wastewater treatment process that includes hull cleaning with a robot, transfer of waste material into a tank, and a two-step filtration procedure.

The hull cleaning robot during cleaning
Picture courtesy of ECOsubsea

Suction line connected to the discharge outlet from cleaning device

Two tanks for filtration of effluent

Figure 23. Example of pier side waste water treatment process (ECOsubsea and Fleetcleaner)

In this example (from ECOsubsea) the untreated process water is pumping at a flow rate of approximately 50 gpm from an 18,000 gallon tank (Tank 1) through one 10-um filter cartridge arranged in series with two 5-um filter cartridges installed in parallel. From the filter cartridge array, the water was conveyed through a pressure vessel containing 2,000 pounds of organo-clay (modified zeolite). The treated water was discharged into a second 18,000 gallon tank (Tank 2).

Figure 24 shows a shore based and movable wastewater treatment system in the cleaning area in which the effluent is sucked into the first tank and after passing two tanks (two steps filtration), clean water is discharged into the sea.

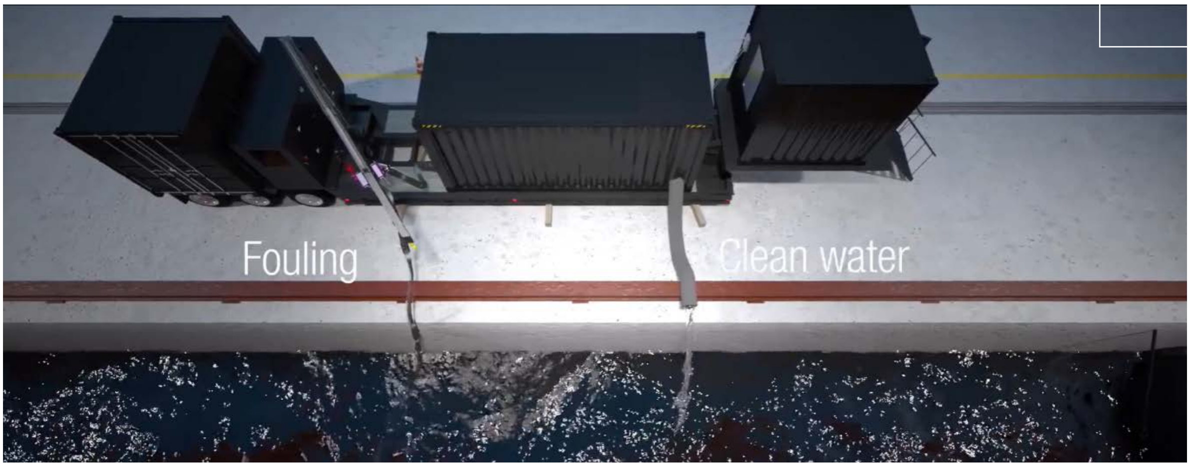


Figure 24. Filtering setup on shore with discharge of filtered water back to sea (ECOSubsea)

11. Filtering systems to collect biological material and paint particles

There is a biosecurity risk associated with the filtration of captured waste. The risk will be dependent on efficacy of removal of biological material from the effluent stream to a minimum particle size. Further is it important that cleaning rates and filtration rates correspond to avoid overloading filters.

Example of a filtering setup that remove both solids and dissolved metal are illustrated in Figure 25.

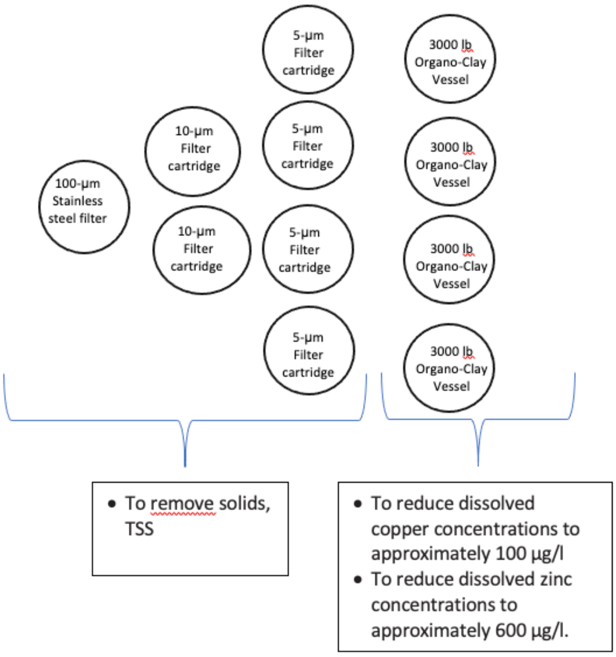


Figure 25. A schematic illustration of a filtering system filters of various sizes (100 -5 microns) are used to remove solids and organo-clay (modified zeolite) filter to reduce dissolved metals/ biocides

The filter-size suggested to remove solid waste waste in the effluent were compiled by Soon et al (2021a).

11.1. Total Suspended Solids (TSS) and Particle Size Distribution (PSD)

Water quality can be determined by measurement of Total Suspended Solids (TSS) and Particle Size Distribution (PSD). During hull cleaning these parameters are used to measure amount and size of biofouling (which can be either fragments or possible small stages like spores) as well as antifouling paint particles.

11.2. Total suspended solids (TSS)

Total suspended solid (TSS) is a measure of the undissolved solid matter in a water mass that remains on the surface of a filter after all the water has been evaporated. Total suspended solid (TSS) is widely used as one of the important parameters of water quality. TSS adversely affects the aquatic ecosystems by blocking sunlight and subsequently reduce the photosynthesis. The suspended solids are also responsible as carrier of pollutants like phosphorous, mercury, heavy metals, hydrophobic organic compounds etc.

11.3. Process of measuring TSS

To process samples for TSS measurements both saltwater and wastewater samples are filtered through pre-weighed GF/F filter paper. Before weighing, the residue on the filter is dried overnight in a 60°C oven and kept in a desiccator. The drying procedure is continued until the weight remained consistent (less than 0.5 mg weight loss) (Soon et al, 2021a). To measure water impurity by use of TSS the mass of particles remaining on the filter is divided with total volume of water that passed through the filters. The TSS test procedure, can include the capacity to categorize particles depending on their sizes.

11.4. Description of TSS Sample collection during hull cleaning

In a study Soon et al (2021a) investigating hull cleaning waste from four ships (3 using SPC coating and 1 ablative paint) the suspended solids mainly contained fine paint particles and seaweed. The concentration of TSS in the effluents had an average of 173,4 mg/L which was 7-17 times higher than in the ambient water (Soon et al 2021a). The prevailing sea state and weather conditions is critical for TSS sampling as explained in Tamburri et al 2020 where for example heavy rainfall will bring debris from land and impact the background TSS-concentration. In the study by Soon et al 2021a the mean release of TSS from a unit hull surface area was found to be 25,7 g/m2 and particles with sizes of ≥8 µm contributed 75–94% of the TSS.

11.5. Particle size distributions (PSD)

Particle size distributions (PSD) is a high-resolution method to determine accurate and precise size of particles, by use of various filter sizes. The particle size distribution in the wastewater is analyzed by filtering the samples through pre-weighed filter papers of different pore sizes, ranging from 0.2 to 300 µm. The residue retained on the filter is than measured in the same way as described for the TSS analysis.

From the contaminant release perspective, Soon et al 2021a has shown that particles in the size 8-10 um was most common (when cleaning on SPC and ablative paint).

Methods for water quality sampling are suggested by Woods et al 2007 (Table 9) where TSS, Particle Size Distribution (PSD) and biocides are measures to be able to use the performance criteria I and II (C and D in Table 11.2 from Woods et al 2007). I) Concentration of TSS and dissolved harmful waste substances in the surrounding waters should not increase compared to a measurement from ambient water in the same location during the same time period. II) The discharge/effluent from any in-water cleaning system should not exceed the thresholds for dissolved harmful substances in a measurement from ambient water in the same location during the same time period

Table 9. Table over water quality collection sampling summary (table from Woods et al 2007)

Sample	Location	When sampled	Type of sample	Sample depth	Analyses	Relevant performance criteria
Cleaning unit	Attached to cleaning unit	1x, during cleaning	Time integrated	Varies over cleaning period	TSS, PSD and biocide	C and D
Separation and/or treatment unit outlet	Just after the separation and/or treatment unit	1x, during cleaning	Time integrated	NA	TSS, PSD and biocide	B, C and D
Background during cleaning	Adjacent to the ship, at least 50 metres from cleaning activity	1x, during cleaning	Time integrated	Mid-draft	TSS, PSD and biocide	C and D
Optional pre-clean background within 24 hours	Berth or anchorage	1x, during cleaning	Discrete	Mid-draft	TSS, PSD and biocide	C and D
Optional post-clean background within 24 hours	Berth or anchorage	1x/day prior to test	Discrete	Mid-draft	TSS, PSD and biocide	C and D

A. The in-water cleaning process removes at least 90% of macrofouling (ie individuals or colonies visible to the human eye).

B. The separation and/or treatment of captured materials during in-water cleaning both: (1) removes at least 90% (by mass) of material from seawater influent and (2) at least 95% of particulate material in effluent water is < 10 µm in equivalent spherical diameter (ESD).

C. Local water quality parameters of TSS, in the vicinity of the cleaning unit and at the effluent discharge point from the separation and/or treatment systems, are not elevated above ambient levels during the same time period.

D. When applicable, dissolved and particulate biocides found in AFC (eg, copper and zinc), in the vicinity of the cleaning unit and at the effluent discharge point from the separation and/or treatment systems, are not elevated significantly above ambient levels during the same time period.

Figure 26 shows a schematic diagram where samples for analysis of TSS, Particle Size Distribution (PSD) and biocides are taken during the cleaning process (upper box) and after treatment in the treatment unit (lower box). A mixer is inserted in the tank to create a homogeneous solid liquid (waste water).

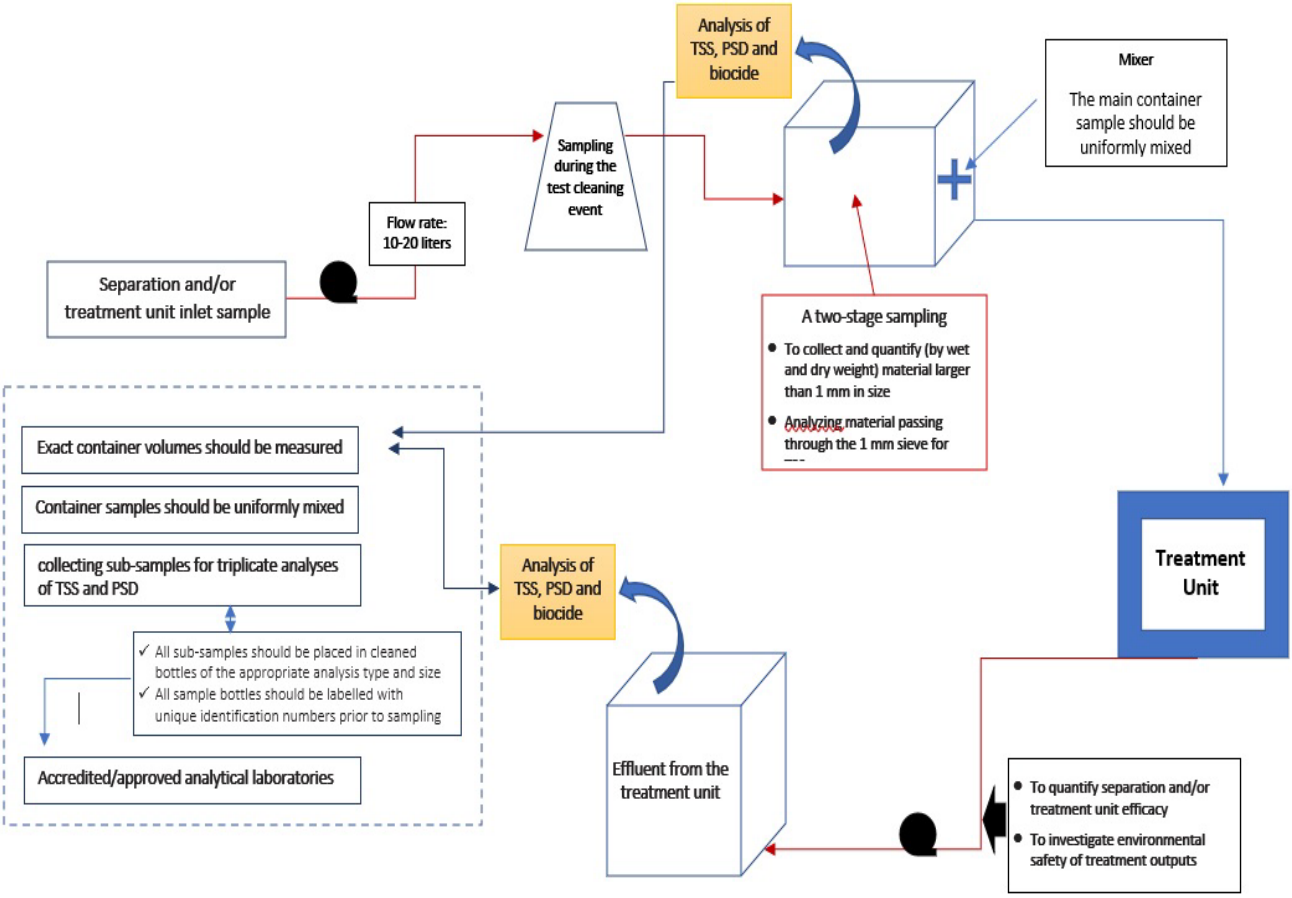


Figure 26. A schematic diagram where samples for analysis of TSS, Particle Size Distribution (PSD) and biocides are taken during the cleaning process (upper box) and after treatment in the treatment unit (lower box). A mixer is inserted in the tank to create a homogeneous solid liquid (waste water).

Following standards and/ or approved methods are used in sampling for TSS and PSD.

US EPA Residue, Non-Filterable (Gravimetric, Dried at 103-105°C) (EPA 160.2): Published 1971

ISO Particle size analysis – Image analysis methods (13322-1): Published May 2014.

US EPA Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma Mass Spectrometry (EPA 200.8): Published 1994.

US EPA Inductively Coupled Plasma – Mass Spectrometry (EPA 6020A): Published January 1998

12. Brief overview of available In-water cleaning Standards and guidelines

Guidelines for the testing of ship biofouling in-water cleaning systems has recently been developed by international subject matter experts in a work coordinated by Alliance for Coastal Technologies, Maritime Environmental Research Center and Maritime Administration in US (ACT/MERC, 2022).

The Industrial Standard for in water cleaning was developed by industry (including hull cleaning companies) in a work headed by BIMCO (BIMCO 2021). Figure 27 shows the diagram of wastewater quality requirements according to Industry (Industrial Standard for in water cleaning).

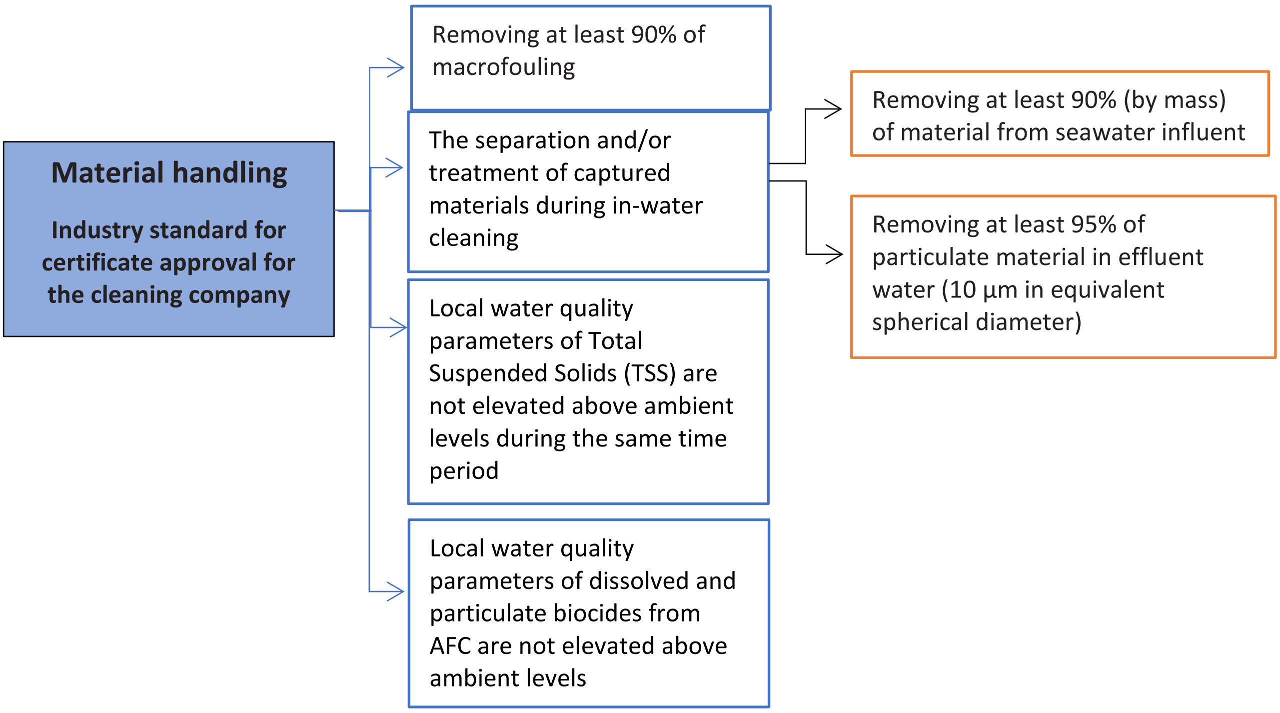


Figure 27. Diagram of wastewater quality requirements according to Industry Standard for in water cleaning (from BIMCO-ICS 2021)

12.1. Guidelines for hull cleaning activities

In general, the cleaning company should seek information on the required testing and environmental sampling protocols for each port where the cleaning will be performed. Local regulations, such as those governing the disposal of material collected during a cleaning operation, must be followed. Throughout the cleaning operation, particularly while mobilizing and demobilizing the equipment, the cleaning business must have protocols in place to prevent the discharge of materials. If nonreturn valves are available, they should be explained. Procedures for material handling, as well as the capture, separation, and/or treatment of seawater, must be in place by the cleaning company.

Today the global regulation around Biofouling including hull cleaning is the IMO Biofouling Guidelines, 2011 (under review 2023). There are several countries and areas with national or local legislation like for example California (CSLC), 2017 and New Zeeland (MPI), 2018. All vessels arriving New Zeeland must arrive with a “clean hull”. The definition clean hull varies with the vessels itinerary and applies to all hull and niche areas of a vessel. If the commercial vessel fall into the so called short stay category (visit less than 21 days) and only visiting approved port of first arrival it is allowed a slime layer, gooseneck barnacles and slight fouling of early stage biofoulers (e.g. barnacles, tubeworms and bryozoans)

12.2. Example from New Zealand for handling of waste material in hull cleaning facilities

In-water cleaning in New Zealand, according to Woods et al. (2007), should be conducted in such a manner that:

All fouling material removed is collected ideally down to a particle size of 50–60 µm and disposed of in landfill as appropriate.

All macro (>1 mm) material from vessels cleaned out-of-water should be collected and disposed of in landfill as appropriate.

All liquid effluent (runoff) from out-of-water vessel water blasting/cleaning should be collected and treated in a liquid effluent treatment system prior to discharge or recycling for water blaster use.

This effluent should be coarse pre-screened (for example, to 1 mm) before entry into the liquid effluent treatment system. This will reduce inorganic and organic build-up within the treatment system and thus maintain system effectiveness (for example, removal of boundary layer acceleration of suspended particles caused by sediment bed build-up) and extend the period between maintenance sediment removals. Material caught on the pre-screen should be disposed of in landfill as appropriate.

All liquid effluent should be processed through multiple settlement tanks to facilitate settling out of any marine organisms and particles (that is, vessel hull paint flakes).

Where discharge of treated effluent will be directly to the sea, following processing in settlement tanks, all liquid effluent should be fine filtered/screened, preferably to a size range of 10–20 µm, but 50–60 µm is an acceptable minimum to remove the smallest of most types of marine organisms before discharge.

As an alternative to discharge of treated effluent to the sea or sewage system, treated liquid effluent could be stored and then recycled for water blasting other vessels rather than discharged. This theoretically increases the residence time of any remaining marine organisms in freshwater (and thereby reduces their chances of survival) and reduces total freshwater usage by the cleaning facility.

12.3. Post cleaning safety and environmental requirements

After cleaning following steps are to be completed:

After completing all in-water cleaning activities, the equipment should be removed from the water and brought back to their original positions.

All underwater gratings shall be safely restored to their original state.

All remaining material in the in-water cleaning system including the hoses, separation and treatment units shall be contained and disposed of in a safe manner. The cleaning company shall ensure the material does not find its way into the local marine environment.

When confirmation has been received that all cleaning equipment and personnel have been removed from the water, the ship can be made operational by releasing locked out or tagged out systems.

13. Disposal and treatment of waste from hull cleaning

As alternative to filtering systems the waste may be treated to kill any organisms present by, for example, heating, adding chlorine compounds or exposing to UV light. Methods for disposal of waste products can be stipulated by Port Authorities, local government, or other regulatory requirements. The residual liquid effluent can be discharged to the sea or transferred or contained in bulk tanks for on-shore disposal.

Landfilling

Waste disposal for non-hazardous and hazardous landfills is regulated by municipal, state, and federal rules. When waste does not exceed the threshold limitations, it is termed non-hazardous, and no further action is required before it is disposed of in a landfill.

Thermal treatment

The goal of thermal treatment is to destroy the waste's hazardous organic components and lower the volume of solid waste that must be disposed of. The main thermal techniques for processing blasting debris include pyrolysis, combustion, and hydrothermal reactions.

Physical and physicochemical separation

In hull cleaning wastewater, paint chips are the most common source of pollutants. To separate paint chips from waste and reduce hazardous waste to be disposed of and/or recycle reusable abrasives, physical and physicochemical methods such as sieving, air classification, magnetic separation, flotation, and electrostatic separation have been developed.

Hydrometallurgical treatment

Using acids, bases, aqueous solutions, or other solvents, hydrometallurgical technology selectively dissolves metal(s) and recovers or removes the desired metal(s) from waste by precipitation, electrolysis, solvent extraction, or ion exchange. Blasting waste is hydrometallurgical treated to recover valuable metals or metal compounds, or to eliminate harmful species and render trash non-hazardous.

Removal of Microplastics

Wastewater treatment plants (WWTPs) are focal point for the removal of microplastic particles. WWTPs are capable of removing substantial quantities of larger microplastic particles but are inefficient in removing particles with any one dimension of less than 100 µm, with influents and effluents tending to have similar quantities of these smaller particles (Freeman et al, 2020).

14. Conclusions -Best practise for hull cleaning

Detailed description of different techniques available for cleaning of ship hulls

Brush and waterjet are the most common methods used for cleaning of ship hulls. They have equal performance in terms of cleaning speed. The majority of hull cleaning providers are capable of cleaning both flat hull surfaces and in niche areas. The technologies use different types of brush combinations and number of karts or water jet sections. For removal of biofouling the companies claim that their method is successful as stiffness/brush type or water jet pressure can be selected due to severity of fouling. The companies also state that the cleaning will not cause damage to paint due to the possibility to select brushes/ waterjet forces.

Assess how different hull cleaning techniques remove and/or capture biological material and propose mitigation strategies

With capture and filtering the biological material will be collected. The filter size used will determine degree of removal of biological material from the water and with filter size of 2 micron even the smaller propagules or spores will be collected. As there is no standard practice for vessel owners/companies to examine the hull fouling on their vessels to determine whether Non Indigenous Species (NIS) are present, a precautionary approach could be adopted assuming that all hull-fouling material removed during hull cleaning may contain NIS and that every NIS should be treated as a potential invasive species unless known as otherwise. In Sweden, the handling of waste material derived during hull cleaning operations is regulated through the waste regulation (Avfallsförordningen 2020:614). The classification of the waste will have an impact on how the waste will be used and treated. If a cleaning is performed on biocidal antifouling coatings, the waste material will most likely be treated as hazardous waste, but if a cleaning is performed on biocide-free coatings, it will likely be treated as “other organic waste” as the waste may contain plastic components.

Evaluate the emissions of contaminants and paint particles during hull cleaning events and propose mitigation strategies

In-water hull cleaning on ship hulls coated with biocidal antifouling paints paint may result in large emissions of biocides to the marine environment. Using data from Soon et al. (2021), up to 10 kg of Cu may be emitted to the environment from a cleaning event with brushes. However, this input can be prevented if a capture system that capture the paint flakes and treat the effluent are used. In addition, proactive cleaning is preferred as it is less aggressive and result in less damage to the coating.

Best practice in hull cleaning

In short, the best practice for in water hull cleaning can be summarized

-Proactive cleaning is preferred as the lower stages of fouling is easier to remove, also less forces are required with less chance of damage the coating/hull

-Capture and filtration are needed as there will be both viable biological maerial and chemicals released during cleaning

- Cleaning of niche areas should be highlighted and prioritized as they contain both high diversity and high number of marine species.

14.1. Todays limitations, approaches and future outlook

There is cleaning equipment available to clean the niche areas but it can be a challenge to add systems for capture. For some of the niche areas (that do not affect propulsion or ship operation) there might be lack of incentive for cleaning from the ship operators perspective. There are different drivers for cleaning in different areas of the ship, hull is cleaned to reduce biofouling and fuel consumption. Some niche areas are important to clean (for example cold-water intake) but some niche areas are less important for ship owner to clean.

-The share of Non-Indigenous Species (NIS) will not be known and will be difficult to predict. As today there are no standard practice for shipping companies to examine the hull fouling to determine whether Non-Indigenous Species (NIS) are present, a precautionary approach could be adopted assuming that all hull-fouling material removed during hull cleaning may contain NIS and that they should be treated as a potential invasive species unless known as otherwise.

-Total Suspended Solids (TSS) and Particle Size Distribution (PSD) are today used to measure both size of biofouling (which can be either fragments or possible small stages like spores) as well as antifouling paint particles. The size requirement for filtering can be discussed both from biosecurity and contaminant release perspectives. From biosecurity perspective it is concluded that even a seemingly negligible level of biofouling may still harbor viable microscopic recruits and imply potential risks of NIS incursion (Zaiko et al 2016). The work by Sherman et al 2020 (Assessment of reproductive propagule size for biofouling risk groups) further identifies the theoretical minimum viable propagule sizes of different macrofouling groups from identified risk taxa that could generate an adult organism if released during in-water cleaning of biofouling. More studies and use of new (DNA-based) technologies could be applied to measure the “viable fraction” or calculate the expected “viable fraction” theoretically. This could help in finding the useful limits for filtering which are considered biosecure.

15. References

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Figure 5 Cavitcleaner CEO Kirk Hannaford, https://cavitcleaner.com

Figure 6 Cavitcleaner CEO Kirk Hannaford, https://cavitcleaner.com

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Figure 13 Hammelmann https://www.hammelmann.com/

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Figure 15 HullWiper enquiries@hullwiper.com

Figure 16 Prof Weicheng Cui (Song et al 2020)

Figure 20 (Tamburri et al 2020) Prof Mario Tamburri

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Figure 23 Ecosubsea/Fleetcleaner https://ecosubsea.com/services-solutions/ /https://www.fleetcleaner.com/technology/

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